The Evolution of Research Collaboration in South African Gold Mining: 1886-1933

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Many individuals, institutions, and organizations have assisted and encouraged the analysis that follows. Like a good adventure it began with an urgent choice between two routes on a river with many subsequent highs and lows, including a break from co-operative game theory to find myself looking into the eyes of a giraffe. While this research marks the culmination of a long journey, the adventure continues. Hence, I would specifically like to acknowledge the inspiration that a unified South African nation had in encouraging me to embark on this odyssey and for the motivation it continues to provide.

ABBREVIATIONS

AAC	Anglo-American Corporation
AECI	African Explosives and Chemical Industries
AGRS	African Gold Recovery Sydicate
AMM	Association of Mine Managers
AS & TS	Associated Scientific and Technical Societies of South Africa
BIC	Bushveld Igneous Complex
BSAEC	British South African Explosives Company
C-P	Continuous and Pure
C-R	Continuous and Rival
CMMSSA	Chemical, Metallurgical and Mining Society of South Africa
COMRO	Chamber of Mines Research Organisation
COMSA	Chamber of Mines of South Africa
CORDIS	Community Research and Development Information Service
COST	Co-operation in the field of Scientific and Technical Research
CPC	Coal Producers Committee
CSF	Collective Supply Function
CT	Cape Technikon
D-P	Discrete and Pure
D-R	Discrete and Rival
DASA	Dental Association of South Africa
DBMC	DeBeers Mining Company
EMMC	Empire Mining and Metallurgical Congress
ERPM	East Rand Proprietary Mines
ESCOM	Electricity Supply Commission
ESS	Evolutionary Stable Strategy
EU	European Union
EUREKA	Pan-European network for market-oriented, industrial research and development
FER	Far East Rand
FRI	Fuel Research Institute
FWR	Far West Rand
GFSA	Gold Fields South Africa
GPC	Gold Producers Committee
GS of SA	Geological Survey of South Africa
GSSA	Geological Society of South Africa
HSRC	Human Sciences Research Council
ICT	Information and Communication Technology
INUS	Insufficeint, but Necessary part of a complex of conditions which together are Unnecessary but Sufficient for the effect
IRC	Industrial Research Committee
ISCOR	Iron and Steel Corporation
IMSSA	Institute of Mine Surveyors of South Africa
JCI	Johannesburg Consolidated Investment Corporation
JCMMSA	Journal of the Chemical, Metallurgical and Mining Society of South Africa
JSAIE	Journal of the South African Institution of Engineers
JSB	Johannesburg Sanitary Board
MASA	Medical Association of South Africa
MIM	Mining and Industrial Magazine
MLST	Malukmahomed Lappa Sultan Technikon
MMOA	Mine Medical Officers' Association

MTC	Mine Trials Committee
MWU	Mine Workers Union
NCOS	Natal Coal Owners Society
NRC	Native Recruiting Corporation
OFS	Orange Free State
PET	Port Elizabeth Technikon
PGSSA	Proceedings of the Geological Society of South Africa
PT	Pretoria Technikon
PUK	Potchefstroom University
RCORC	Rand Central Ore Reduction Company
RDIC	Rock Drill Investigations Committee
RGB	Research Grant Board
RMAC	Rand Mutual Assurance Company
SA	South Africa / South African
SAAA	South African Association of Assayers
SAAAS	South African Association for the Advancement of Science
SABBSI	South African Branch of the British Standards Institute
SABS	South African Bureau of Standards
SACI	South African Chemical Institute
SAICE	South African Institute of Civil Engineers
SAIE	South African Institution of Engineers
SAIEE	South African Institution of Electrical Engineers
SAIME	South African Institution of Mechanical Engineers
SAIMM	South African Institute of Mining and Metallurgy
SAIMR	South African Institute of Medical Research
SAMEJ	South African Mining and Engineering Journal
SAMJ	South African Medical Journal
STCIR	Scientific and Technology Committee on Industrial Research
TAC	Technical Advisory Committee
TCOA	Transvaal Coal Owners Association
TB	Tuberculosis
TEBA	The Employment Bureau of Africa
TIME	Transvaal Institution of Mechanical Engineers
TNU	Transvaal National Union
TWR	Technikon Witwatersrand
UCT	University of Cape Town
UFH	University of Fort Hare
UFS	University of the Free State
UNISA	University of South Africa
UoN	University of Natal
UoP	University of Pretoria
UoS	University of Stellenbosch
USA	United States of America
VFP	Victoria Falls Power Company
Wits	University of the Witwatersrand
WNLA	Witwatersrand Native Labour Association
ZAR	Zuid-Afrikaansche Republiek

Chapter One:
Introduction

1.1 INTRODUCTION

This dissertation examines the evolution of research collaboration in South African gold mining between 1886 and 1933. It is original in terms of both its historical focus and its methodological approach. The dissertation highlights the importance of collaborative research and its contribution to innovation and economic growth. Three distinct methodological approaches to understanding research co-operation are examined. Rather than argue for one approach over another, or propose a new approach altogether, I show complementarities among the methodologies contribute to a deeper understanding of the collaborative research phenomenon. Two case studies on the collaborative development of key technologies illustrate the role of collaborative research in an innovation system as well as the evolution of collaborative research and its relationship to broader socio-economic conditions.

At the outset, a few definitions facilitate understanding of the issues. Research collaboration is the act and process of knowledge creation among individuals, institutions, and organizations.[1] As a recurrent socio-economic process, research collaboration is a component of local, sectoral, and national systems of innovation. National, local, and sectoral systems of innovation are functional concepts that define the learning processes (flows), which build knowledge bases (stocks).

A majority of contemporary analyses on collaborative research examine it as a fundamental feature in the emergence of a modern knowledge-based economy (European Commission, 2002a). The analysis of the cases in this study illustrates several of the properties highlighted in this recent theoretical literature on research collaboration: the coordination of agents through non-market and non-hierarchical mechanisms, the importance of collaboration to developing an internationally competitive technology, and the often crucial coexistence of competition and cooperation. Hence, this analysis shows that while much vaunted in the current setting, research collaboration are established phenomenon with historic precedents to guide our modern understanding of them.

The case studies cover the periods before (Case One) and after (Case Two) the formation of the South African nation. Although analyzing only part of the sectoral and national systems of innovation, this study provides insight into the complex structure that is a system of innovation. Witwatersrand gold mining has played a central role in the economic development of South Africa.[2] It has also been a major force in shaping the political economic environment. As such, it instilled a predominant style on the national system of innovation.

Analyzing the central contribution made by technological change to industry dynamics, the dissertation also highlights a neglected dimension in South Africa's historiography. Most South African economic historiography concentrates on labor issues; to the extent that if technology is analyzed at all, it is firmly set within a political economic environment defined by labor and

[1] Research collaboration and collaborative research are used interchangeably without distinction.

[2] The Witwatersrand is an ancient inland sea that existed around 3 to 2.7 billion years ago. Wave action deposited gold particles in layers on the shore of this sea, which were subsequently silted over. The basin is around 350km long and 150km wide. Younger rock formations gradually developed over the basin, covering the gold deposits. A majority of the basin remains buried, but at its northern edge tectonics have exposed the ancient shoreline. It was here, in a region know as the central or main reef, that the first mining of the Witwatersrand occurred (Viljoen and Reimold, 1999, p. 20).

capital relations.[3] Johnstone (1976) investigated social conflict and resolution in the application of jackhammers on the gold mine stopes, but the overriding dynamic in his narrative was the conflict between capital and labor. Similarly, Leger (1987, 1990, and 1992) placed changes in stoping practices within the broader context of racial discrimination. While acknowledging that the broader social environment has an influence on a technology's development, this dissertation pays attention to the way technologies can also transform social and economic relations. That this change in focus sheds new light on South Africa's historiography is best illustrated in the reinterpretation it creates about the history of the 'colour bar' in South African mining.

The 'colour bar' was a system of racially based restrictions on occupational mobility that gave the most lucrative forms of employment to whites, while limiting blacks to unskilled and low paid positions.[4] After the 1922 Rand Revolt, which allowed the large-scale Taylorization of stoping work because of the diffusion of lightweight rock drills, underground production was transformed. Stoping and the huge underground labor force engaged in it were no longer structurally dependent on the artisanal skills of miners in underground operations. Further removal of racial occupational mobility restrictions held potential gains in operating efficiencies. However, the structure of production at the time meant that the benefits of further efficiencies did not appear to justify the costs in socio-political capital they would entail. Therefore, the mining companies, despite a legal ruling in 1923 entitling them to do so, did not remove other *de facto* racial occupational mobility restrictions. The security of operating efficiencies with the diffusion of lightweight rock-drills for stoping also gave the mines a basis to advance their strategic interests by allowing a re-structured labor force to re-impose *de jure* racial occupational mobility restrictions in 1926.

It is generally accepted that technological change is a crucial component of sustained economic growth. Yet, in the existing literature, processes of learning and application of knowledge in production are poorly understood. Research collaboration has further difficulties as it involves the complex social processes of trust and cooperation. Nonetheless, collaborative research is a recurrent factor in successful innovations. The European Union's technology policy demonstrates the recognized importance of collaboration, giving a central role to the promotion of cooperative research and development (Cusmano, 2000, p. 25). The dissertation uses case study material to reflect on three different theoretical approaches to collaborative co-ordination of the innovation process.

Within the economics literature on research collaborations, informal collaborations are typically neglected because of difficulties in quantifying, systematically tracking, and studying them in detail. This occurs despite recurrent findings of the importance of informal collaboration in analyses of collaborative research. For instance, Link and Bauer's (1989) study of research collaborations in U.S. manufacturing found that nearly 90% are informal. The case studies on the Witwatersrand, which follow, demonstrate that when tracing development of a particular innovation (or a group of related innovations) there is often significant implicit collaboration underlying explicit research collaboration. Significantly, promotion of explicit collaboration without appropriate regard for the implicit structures can decrease incentives and destabilize collaboration. For example, colleagues in different divisions of a research laboratory may have developed an extensive, but informal, system for discussing each other's research. If their boss then decides to implement a formal discussion session to facilitate interactions in their daily routine, the net effect could be to decrease total collaboration.[5] Therefore, determining the

[3] A notable exception to this is Smit and Pistorius' (1998) examination of the emergence of a dominant design in an electronic initiation system for blasting.
[4] See Chapter Eight for a detailed discussion of racial occupational mobility restrictions.
[5] Government's promotion of formal collaboration could similarly undermine a pre-existing informal structure.

nature and extent of formality/informality in a pre-existing research collaborations can enhance effective policy actions.

Conducting an analysis of this type requires detailed research into interrelationships and socio-political influences, as well as economic relationships among the various agents. South Africa's gold mining industry has a special appeal for an investigation of this type. Because of its importance to South African economic growth, there is a substantial economic historiography to draw upon. This study is an initial investigation into a complex topic. The Witwatersrand facilitates analysis of this topic by providing a context to trace dynamic features across decades of industry history. This sort of long-run analysis has not previously been attempted in the empirical work on research collaborations. Another feature of gold mining that makes this sort of analysis attractive is that it involves production of an undifferentiated good with near perfectly elastic demand. Therefore, it is safe to assume a homogeneity in demand, and this somewhat simplifies consideration of supply and demand influences in defining areas of collaboration and competition.

There is a rich stock of empirical data on South African gold mining extending over the entire history of Witwatersrand mining. The Chamber of Mines of South Africa (COMSA) has served as a repository for this information, but a variety of technical societies and their respective journals are also abundant in details of the industry's development.

Combining a variety of theoretical perspectives and cases of significant innovations in a nation's predominant economic sector creates insights not possible from a focus on any single component. While fruitful, it requires crossing over several specialist borders with only a general knowledge of the terrains. Therefore, in combining literatures on the economics of technological change, South Africa's historiography, and technical literature on mine engineering and metallurgy, an indulgence of the reader's patience is requested. It is hoped that such patience is rewarded by the insights arising from this inter-disciplinary perspective.

1.2 ANALYTICAL APPROACHES

This dissertation differentiates between three perspectives on research collaboration: industrial districts, collective action, and distributed innovation. These approaches are distinguished by their selection of events which cause research collaboration. Based on these focuses, three analytical models are formulated. Part One introduces the analytical approaches with chapters on each discussing their empirical and theoretical heritage, and specifying stylized models for use in analysis. Part One concludes with a chapter reviewing the approaches and their relationships in analyzing the phenomenon of collaborative research. Given the expansive literature the approaches cover: agglomeration externalities, collective action, and economics of technological change, there is no attempt at comprehensiveness. Interest is concentrated upon aspects of these literatures related to cooperative research.

Each perspective is described according to its structure, causal conditions, and effects. Static and dynamic components in the approaches are specified in the section on structure. The section on causal conditions specifies how ingredients described in the structure form events that generate collaboration in research and possibly other activities. Lastly, the section on effects specifies the resulting relationships within and between the collaborative system, the broader innovative system, and the socio-economic system. The distinction among the approaches by their causal conditions generating research collaboration, leads to a more comprehensive analysis of the case studies than would be possible unilaterally. This differentiation of the approaches to research collaboration by their selection of causal conditions also marks an original conceptualization and comparison of these methodologies. Therefore, before reviewing prominent characteristics of the empirical models, we briefly discuss what we mean by causation.

In the social sciences, like the natural sciences, causality establishes knowledge that one thing causes another. Our interest in 'the cause' of a phenomenon typically originates because we want to promote or prevent the effect of that phenomenon *e.g.,* one may want to promote research collaboration to increase productivity. Analysis of 'the cause' of a phenomenon is problematic because it involves specification along the lines of: event b was caused by event a.

However, most events for which causal explanations are appropriate have many causes. Carnap (1994) illustrates the multitude of causes through the example of 'the cause' of a collision between two cars on a highway. Each individual looking at the total picture from a certain perspective selects specific causal conditions as causing the collision. The police say high speed caused the accident. A road engineer says a poor road surface caused the accident. A psychologist says the man's disturbed mental state caused the accident. A mechanical engineer says a structural defect in the car caused the accident. A mechanic says that a worn brake lining caused the accident. In each case it is possible to say that if that condition had not existed the accident might not have happened. Therefore, we refrain from reference to 'the cause' of a phenomenon, preferring instead 'causal conditions' which are a necessary part of a more complex network of circumstances.

John Mackie (1974) provides a formal definition of causal conditions, called INUS conditions: "[They are] an Insufficient, but Necessary part of a complex of conditions which together are Unnecessary but Sufficient for the effect" (p. 61). If we were omnipotent and knew all the causal conditions for the car accident, we would know 'the cause' of the accident. Since we are human, we select factors relevant to our individual interests as causal conditions, a point illustrated in the selection of causal conditions made in the example above.

Any causal hypothesis in science depends on causal selection *i.e.* the choice of causal conditions for analysis among the multitude of known and un-known causal conditions. In the approaches detailed below, each one considers causal conditions that partially explain the phenomenon of research collaboration. Therefore, our understanding of the cases is severely constrained without reference to the causal conditions of all the approaches.

1.2.1 Industrial District

The industrial district approach, Chapter Two, takes as its foundation Alfred Marshall's writings on location specific knowledge externalities and a body of literature, primarily focused on agglomeration externalities, which has developed around it. Aspects of this literature that stress economic development and technological progress are given particular attention and form the basis of the analytical model.

In comparison to the other two approaches, the industrial district stresses geographic density and social interactions in creating knowledge. It thereby provides useful contextual background, but only a tangential examination of the dynamics of causal conditions for collaboration. The approach is inherently biased towards incidental collaboration, with research collaboration being a by-product of the agglomeration externalities in the district.

1.2.2 Collective Action

Collective action, Chapter Three, builds on a tradition rooted in the theory of public goods and game theoretic conceptions of their provision. Mancur Olson's writings on collective action form the theoretical underpinnings of the collective action approach. It is augmented by contemporary writings on collective action and evolutionary game theory. [6] There is a distinct application of the collective action approach in this analysis. It is a means of coordinating exchange under cooperative governance. Therefore, collective action is formulated as a third high-level governance structure, distinct from market or hierarchical exchange.

Within the collective action analyses, research collaboration is a dynamic common resource problem. It creates a public good, better technologies, whose benefits are only temporarily and imperfectly excludable.[7] Collective action concentrates upon explicit motivations in providing a common resource. This leads to consideration and examination of interests and motivations of agents for actively engaging in collective action. However, in so doing it structurally neglects interactions with the broader political economic system.

1.2.3 Distributed Innovation

The literature on the economics of technological change is the foundation of the distributed innovation approach in Chapter Four. It also takes research collaboration to be part of a more general means of coordination through cooperative governance. As a third form of governance, distinct from markets or hierarchies, this approach draws on the network governance literature. Distributed innovation, that is research collaboration, is just one aspect of the more general and inter-related process of distributedness in productive functions. The architecture of collaboration has a distinct role, characterized by power and dependency relations that influence the effectiveness and efficiency. In so doing, it allows roles for both explicit and spontaneous provision of public goods and services.

Compared to the other approaches, distributed innovation provides a deeper conception of innovation and its relationship to collaborative efforts in its development. In its conceptualization of the structure of collaborative networks, there is an implicit assumption of a relatively modern and developed institutional infrastructure. Thus, within an environment of strong human, financial and physical resource scarcity, the distributed innovation approach tends to underplay the role of constraints in facilitating or hindering distributedness.

1.3 CASE STUDIES

Two eras of collaborative innovation in South Africa's gold mining industry are analyzed. Each case study illustrates the general evolution of research collaboration that occurred in the industry during their respective periods. Both cases consist of two chapters, the first provides a brief on the technology, its relationship to the productive structure, and the socio-economic context under which it was initiated, the second applies the stylized models to analyze the case. Each approach is applied in both cases. Owing to the complementarities in the approaches, the order of analysis is differentiated by their respective analytical insights over the two cases. In the first case study the industrial district approach is thoroughly reviewed before considering additional

[6] Specifically, Hardin (1982) and Sandler (1996) are used to specify a more fully developed model.

[7] Intellectual property rights are finite in their length of protection. Other means such as inter-organizational personnel recruitment and results based reverse engineering will all limit the extent and duration of excludability possible over intellectual property.

insights from features in the collective action and distributed innovation approaches. Similarly, in the second case the distributed innovation approach is thoroughly reviewed before examining additional insights from the collective action and industrial districts approaches.

The idea of analyzing cooperation among gold mines might sound a dubious endeavor. Competition in mining is assumed by some to be concentrated in the initial stages when mining companies are seeking to secure mineral rights and once they have been established cooperation is natural. In this thinking, control of mineral rights facilitates administrative control of a mine and an associated income flow to the head office. Other mines could then be brought in as (preferred) investors, with potential pooling of minority mineral rights and consolidation of mineral producers' going concerns.

This predisposition to cooperation is contended in many mineral commodities, but more so in gold because of the nearly perfectly elastic demand faced by gold mining firms.[8] Such assumptions overlook important differences in the levels of cooperation, its durability, and its change over time. Each of the analytical approaches used explicitly considers the extent and dynamics of cooperation and competition. They show that cooperation is not automatic, but is a dynamic process with flexible boundaries over the system of production.

Constructing a shared infrastructure near a newly discovered mineral deposit might seem a natural context for cooperation between two mining companies, but it is not inevitable. Cooperation rests upon their being able to finding a mutually agreeable basis to coordinate their efforts. In any context where a good or service is produced with some degree of non-excludability, the potential for free-riding emerges. This can lead to non-provision of the non-excludable good or service despite clear potentials for mutual gain through cooperation.

Another potential obstacle to cooperative provision of a good or service is the strategic actions of agents. While strategic actions can promote cooperation as well as hinder it, it adds a level of complexity to analyzing the relative influence of cooperation and competition. A farm is similar to a mine in its possession of the land and scope for cooperation amongst competitors. Yet, a neighboring farm can always loom as a potential source of take-over.

Informal and formal collaboration in areas besides research has a long history in South Africa's mining sector, particularly among Witwatersrand gold mining companies. Producers established an African labor recruitment monopoly that lasted over a half-century, and for much of the industry's history there were deep cross holdings and financing. This breadth of collaboration is accommodated within each analytical approach through a theory of collaboration beyond the boundaries of any one-dimensional collaborative or coordinated concern. Because of this, empirical analysis also requires discussing the context in which research collaboration occurred. The introductory chapter to each case provides this context, as previously mentioned.

1.3.1 Case One: The Cyanide Method of Gold Extraction

The first case study, on the adaptation and refinement of a technological process that allowed cyanide extraction of gold from its host rock is presented in Part Two. This case falls within a general period of initial development of mining that occurred in South Africa between 1850 and 1902. This development corresponded in part to an international phenomenon and in part to geological features of the South African minerals. The research collaboration investigated covers a ten-year period from 1892 to 1902. During this time, technologies were developed that translated the promise of cyanide based gold extraction into a large-scale industrial reality.

[8] Conventional wisdom was challenged in the 1990s when excess production seemingly depressed the gold price.

In this instance, early in the industry's history there was little hegemony or explicit effort to promote collaboration beyond the natural product of social and professional interactions. Nonetheless, there is evidence of a definite social identity being established through explicit coalition building. There were also other cooperative endeavors occurring in the industry during this period. While the agents directly involved were not the same, there were early indications of the formation of an enduring 'development focused' network of gold miners.

Strictly speaking, the research collaboration that produced a cyanide-based extraction technology occurred within the Zuid Afrikanse Republic's (ZAR) national system of innovation. Yet, the ZAR provided no technical or educational support for the mines. Despite its terrific economic impact, the ZAR treated Witwatersrand gold mining as an enclave that needed accommodation rather than as an emerging sector of it national economy.[9] The Witwatersrand mining community nevertheless established a local innovative system, reliant on linkages with the Cape Colony and the international mining community.

1.3.2 Case Two: Changing Witwatersrand Stoping Practices

The second case, Part Three, is on changing stoping practices in mining operations. It covers just over 30 years from 1903, when the Second Anglo-Boer War was over, to 1933, when the price of gold rose with the suspension of the gold standard. The transformation of stoping practices was another landmark in the technological development of the industry, which required the coordinated development of a multitude of inter-dependent technologies. It established an instituted economic process that was perpetuated from the gold mines on to the general economy, thereby racially limiting the potential economic opportunities for a majority of South Africa's people.

In this case there is considerable evidence of active research diffusion supported by an enhanced infrastructure and the industry's general development. The group system emerged as an organizational structure that would dominate South Africa's mining industry for the majority of the 20th century. One mining-finance group contributed the majority of resources to cooperative efforts in this instance of research collaboration. That mining-finance group was strongly motivated by the broader socio-economic context of production.

With the formation of the Union of South Africa in 1910, a South African national system of innovation came into existence. It drew upon the various colonial and national innovation systems that preceded it. During this period the private sector, primarily the Witwatersrand gold mining industry, provided significant guidance over and direction within the national system of innovation.

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[9] There is some evidence of change in attitude by the ZAR government in the latter 1890s, but there was still a significant identity gap between the ZAR and Witwatersrand gold mining when the Second Anglo-Boer War commenced in 1899.

1.4 IMPLICATIONS

This dissertation contributes to two areas of research, one theoretical, and the other empirical. Through its application and deconstruction of three distinct, but complementary, approaches to the analysis of research collaboration, a potential for congruence is developed. In economics, the market mechanism or hierarchical authority is typically assumed to govern actions. This comparative analysis of research collaboration shows that a third form of governance – i.e. collective governance – can be equally important. While the present analysis has concentrated upon research collaboration, several other economic activities are shown to operate under it as well. In this, a large and exciting area of further research and theoretical advance is possible. In our modern economy where communications are increasingly independent of physical distances, understanding the operation of collective governance is important. Through it, valuable insights into otherwise seemingly quizzical phenomenon are created. For instance, collective governance controls development of Apache, the most popular web server for nearly a decade, in which programmers donate their labor to debug and modify the software cooperatively.

Lastly, it is important to reiterate the difference between this analysis of the early Witwatersrand gold mining industry and those that have preceded it. Placing technological change and its relationship to the socio-economic environment in a central position is unique in South African historiography. These two case studies are only illustrative of the broad range of research that can be conducted using the rich empirical data that the industry possesses. As such it is hoped that the present analysis encourages further examinations of technological change in the industry, for it holds many important keys to understanding current dynamics as well as illustrating and contributing to the literature on the economics of technology change.

Part One

Analytical Approaches

"There was a sly cat, in a certain house, and the mice were so plagued with her at every turn that they called a court to advise upon some means to secure their safety. 'There's nothing like hanging a bell about the cat's neck,' says one of the mice, 'to give warning beforehand when she is coming.' They all looked upon this as an ingenious plan. 'Well,' says another, 'and now we are agreed upon the bell, who shall put it about the cat's neck?' But there was no one ready to bell the cat."

(Aesop's Fables)

Chapter Two:
Industrial District

2.1 THE INDUSTRIAL DISTRICT ANALYTICAL TRADITION

Despite bursting of the dot com bubble, industrial districts like the Silicon Valley remain popular policy targets, seemingly able to promote economic development and competitiveness. Typically, industrial districts do not originate as policy initiatives. While contemporary support of industrial districts can be critical factors in their growth, most emerge from a pre-existing localized production and learning system. Firm and general organizational interactions are then critical to the dynamics of an industrial district. The localized nature of Witwatersrand gold mining therefore provides initial motivation for using this approach to analyze research collaboration in the district.

Industrial clusters, technological districts, and localized industrial systems are just a few of the many appellations associated with the industrial district approach. Ideas about economic benefits from division and specialization in production date at least as far back as Adam Smith's discussion of efficient specialization in a pin factory. Initially, most discussions were concerned with internal economies realized at the plant level or under the aegis of a firm. Alfred Marshall was an early writer on the concept of positive externalities, where economies, outside the boundaries of a specific plant or management structure, are depended on for general development of the industry's location (Baptista, 1998, p. 13). Following Marshall's writings, a revival of interest in external economies began with the emergence of individually small plants, but collectively competitive locations in Italy around the late 1970's (Brusco, 1990, p. 14). As a preface, the remainder of this section sketches the Marshallian and Italian concepts and a selection of subsequent traditions from the vast literature on industrial districts. Section 2.2 then specifies the industrial district model used to analyze research collaboration in South Africa's gold mining industry.

A 'Marshallian industrial district' is characterized by an industry's geographic concentration i.e. localization.[1] Localization is often the product of physical conditions, but it is also intertwined with its political-economic history (Marshall, 1936, p. 269). Therefore, in defining a Marshallian industrial district one must consider the production system, its resource requirements, and the district's social capital.[2] Marshall identifies three types of benefits from localization of an industry. Most important to our present endeavor is the benefit from establishing a 'neighborhood' of knowledge in that industry. The community where the industry is established possesses a valuable stock of explicit and implicit knowledge about the industry embodied in its people and institutions. In particular, the implicitness of this knowledge and its limited communicability creates location specific incentives for firms and individuals to follow in the same industry.[3] Trade specialization is thus reinforced by localized knowledge, innovation occurring through a process whereby new techniques are offered, evaluated, and developed by the community (Marshall, 1936, p. 271).[4]

[1] Marshall's industrial district concept is well illustrated in J. McGaw's *Most Wonderful Machine* (1987), which analyzes the socio-economic evolution of 19th century paper manufacturing technology in Berkshire County, Massachusetts.

[2] The concept of social capital and empirical measures of it is surveyed in OECD (2001).

[3] The district's industrial character is therefore an example of a path dependent process with the potential for lock-in. See: Arthur (1990, 1989, 1988), Arthur et al. (1987).

[4] This is a notable departure from a large literature on technological progress that conceives of the firm as the source of innovation. It is also, in part, a product of Marshall's conception of an industrial district as an alternative to an internalized large-scale organization, consisting of large numbers of small businesses in the same industry.

Localization also creates a collective economy of scale effect. This facilitates the emergence of specialized services with positive economies for the location's industry. Collective economies of scale also increase the amount of expensive specialized equipment available locally. Demand for increasingly specialized equipment does not exist based upon any individual firm's scale of operations, but sufficient demand does exist collectively. Finally, localization has a favorable effect on the labor market. It offers employers a place where they have a good chance of finding the skills they want and offers employees a pool of employers who value their skills (Marshall, 1936, pp. 271-272). An industrial district then acts as a clearinghouse of specialized skills. Employees are able to use and receive reimbursement for their specialized skills; while employers are able to tap a stock of workers with the skills they desire, thereby alleviating some of the scarce skills restraint.

There are also negative features of a Marshallian industrial district. If a district is specialized in an industry(ies) with a very small market(s), it is possible that there is not enough demand to employ the district's entire labor force (Marshall, 1936, p. 272). There is also a risk of sectoral volatility and downturns becoming amplified in the district. This is especially likely if the district lacks a diversity of industries to hedge sectoral exposure (Marshall, 1936, p. 273). Limited coordination and identified collective interests may also generate negative effects within a district as resources are inefficiently allocated. Lastly, excessive localization can generate overcrowding, pollution, and resource scarcity. These negative externalities may offset or even surpass the positive externalities of localization.

Contemporary theoretical interest in industrial districts began with application of Marshall's writings to the Italian experience in the mid-1980s (Becattini, 1990). There were three notable changes from prevailing economic analyses in the Italian industrial district literature. First, the object of analysis shifted from individual firms to a small geographic area with its productive system distinguished by numerous small and interconnected firms. Despite being small, these firms used world-class technologies and produced internationally competitive products. Because it challenged the notion that big (Fordist) hierarchically organized production systems were the only means to compete internationally, the competitive ability of the Italian industrial districts attracted attention. Second, this research highlighted the important coexistence of cooperation and competition at the firm level (Becattini, 1990 p. 15).[5] Lastly, in contrast to the predominant tradition in economics, socio-cultural factors were important and integral parts of the analysis.

There are currently numerous traditions in analyzing industrial districts, with a diversity of features distinguishing these traditions.[6] For the purpose of our current analysis, a few developments to the Marshallian and Italian industrial district models warrant mention. In the mid-1990s there began a continuing effort to analyze the presence and role of industrial districts in economically developing nations (Schmitz and Nadvi, 1999, p. 1504). Most of this research focuses on small firms, following from the Italian district legacy, and demonstrates several features of clusters that make them particularly useful to small and medium enterprises (SMEs). The present analysis abandons the SMEs focus of the industrial district literature; even in the early days, individual mines employed thousands and had massive fixed capital expenditures. A further feature in the literature on industrial districts has been a tendency to focus either on their

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[5] In the Italian experience, characterized by manufacture of relatively high quality differentiated goods, vertical cooperation predominates while competition is primarily horizontal (Becattini, 1990).

[6] For example, Baptista (1998) distinguishes analyses based on their sub-disciplines e.g. Urban and Regional Economics, Economic Geography, New Growth Theory, etc. Division could also be made upon how relationships and functions within districts are characterized. See: Baptista and Swann (1998), Dicken and Malmberg (2001).

production systems or on their knowledge systems (Dicken and Malmberg, 2001, p. 348).[7] Explicitly defining both types of systems, their relations, and interactions reduces this bias in the present analysis. Lastly, there is a tendency in the literature to assume all externalities in a district are spontaneous. However, policy applications such as government funded science parks imply that at least to a certain extent, the externalities can be strategic (Eliasson, 2000, p. 227).

Contemporary industrial district literature tends to focus on spontaneous externalities. In part, this tendency originates from an emphasis on the positive benefits from collaboration and coordination inside industrial districts. Despite mention by Marshall and others, negative effects are essentially neglected.[8] Resolving this tendency in the approach is not pursued at present. Nonetheless, the collective action model (Chapter Three) gives considerable attention to these negative effects and strategic externalities, forming thereby a useful counterpart to the industrial district model described below.

2.2 AN INDUSTRIAL DISTRICT MODEL FOR ANALYSIS

The model used to analyze research collaboration from an industrial district perspective is a characterization of the Becattini (1990) and Maillat (1996) approaches. However, in line with Eliasson's (2000) assertions about the forces of causality in a cluster of organizations, the present approach distinguishes between the origins of technological progress. Hence, we differentiate between advances in basic science leading to commercial technologies and commercial technologies leading to advances in basic science.

Within the industrial district, research collaboration can occur through a variety of formal and informal means. Section 2.2.3 considers these along with other effects that result from a district's existence. Presentation of the industrial district model begins Section 2.2.1 with a description of structural elements that generate, sustain, and destroy districts and thereby research collaboration specific to them. Section 2.2.2 considers the causal conditions which facilitate the emergence of an industrial district.

2.2.1 Structure

The industrial district encompasses a physical space that is "...a socio-territorial entity which is characterized by the active presence of both a community of people and a population of firms in one naturally and historically bounded area" (Beccattini, 1990, p. 38). There are two structural relationships operating in the district with external linkages, the production system, and the knowledge system.[9] A third structural relationship, the socio-political system, operates within the confines of the district. Interactions and interrelationships from the productive and knowledge systems underpin the socio-political system. These systems consist of five components: community, market(s), socio-territorial entity, firms & institutions, and human resources.

Production System

The production system defines the structure of inter-firm coordination of productive activities. It is industry and geographically specified, bound by a common origin in a specialized product or core activity. Around this core, ancillary resources arise that increase the efficiency of the

[7] This tendency in the literature appears to originate from a focus on either pecuniary externalities or technological externalities, but not both simultaneously.

[8] A notable exception is Schmitz (1999, p. 477) raising the possibility of negative effects from strategic action.

[9] This distinction and terminology follows from Bell and Albu (1999, p. 1722-1723).

production system. The production system generates products, services and techniques rooted in traditional know-how acquired and developed in the region. It includes the product designs, materials, machines, labor inputs, and transaction linkages involved in the production of goods and services to a given specification (Bell and Albu, 1999, p. 1723). In specifying the production system, its configuration is an important determinant of inter-temporal agglomeration dynamics. This importance results from a collective realization of economies external to the firm, but internal to the productive system. Its collective nature means that it is greater than the sum of its parts, the loss of any single component does not endanger the entire system. The productive system also forms a variable mechanism of coordination among economic agents. Rather than being unique to an industrial district, productive systems are ubiquitous in market economies and are definable for any commercial production process. All productive systems are influenced by markets, existing territorially defined strategic interdependencies, non-territorially defined hierarchies, and divisions of labor (Maillat, 1996, p. 71-72). Historic resource endowments influence the growth path of the productive system, but the driver of the industrial district's dynamics is its knowledge and socio-political systems (Soubeyran and Thisse, 1999).

Knowledge System

The knowledge system consists of the flows and stocks of knowledge in the territory; it is not specific to any single function but is a pervasive iterative relationship.[10] It also contains the organizational systems involved in generating and managing changes in products, processes, or the organization of production (Bell and Albu, 1999, p. 1723). If local firms have tight and complex interdependencies in their production and knowledge systems, they facilitate the flow of information as well as the transfer and creation of knowledge within the industrial district. These involve both formal and informal connections between individuals, organizations, and institutions within the district. Because knowledge is embedded in individuals and organizational routines, knowledge transfers between individuals or organizations are not complete. However, if the individual or organization is engaged in activities or practices which parallel those of the transferring agent, the amount of knowledge transferred is much more complete than when their activities and practices diverge considerably. Therefore, specialized and localized communities of knowledge are important means for circulating and reproducing a knowledge base (Lave and Wenger, 1991). These dense and specialized communities of knowledge are also critical to the creation and development of new knowledge (Constant, 1987). While a knowledge system is partially discernable, because of its formal and informal structure, it is likely to be largely implicit. Within the industrial district, the major force determining efficiency of production and fostering endogenous competitiveness is its knowledge system. However, its effectiveness depends in-turn on the socio-political system linking the agents in the district.[11]

Socio-Political System

In this model, the socio-political system consists of the structure and dynamics of relations between the knowledge and production systems.[12] It is a geographically delineated institutional environment governing the interaction of agents. The socio-political system is shared by the collection of individuals, firms, financial institutions, local government organizations, research institutions and the like, which compose the production and knowledge systems. It provides the

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[10] "Knowledge system" is comparable to the innovation networks used in the distributed innovation model in Chapter 4.

[11] For evidence see Maskel's (1996) examination of small Danish clusters specialized in the export of low-tech goods.

[12] The term 'socio-political system' is analogous to 'overlapping activities' in the collective action model, and 'relationships' in the distributed innovation model.

basis of trust under which formal and informal exchanges occur. Within the socio-political environment, there are three source of trust: personal trust based on inter-personal relations (Sabel, 1992), system based trust (Luhmann, 1979), and institutionally based trust (Zucker, 1986).[13] Regardless of its origin, trust facilitates cooperation or interdependent relations among agents. However, inter-agent information stocks and flows are liable to be strongest when inter-agent contacts are dense, a feature facilitated by geographic proximity. In a district then, low inter-agent information costs support the emergence of trust and co-operation (Lorenzen, 1998, p. 26). Following Maillat's conception, learning within the district's knowledge system reflects the constituents' ability to adjust their behavior to changes in the socio-political system.[14] Innovations are created and developed, which alter the balance between cooperation and competition. These innovations also change the relationship between the various partners (Maillat, 1996, p. 73). As the socio-political system creates new resources and changes the productive system, it facilitates development of the district's productive system. When the socio-political system fails to respond to change, the associated productive system may well fail. It is not just through knowledge creation that the socio-political system generates advantage for the productive system. The socio-political system can also mobilize resources to match emerging market opportunities and challenges; this in turn leads to further learning and change in the knowledge system. Before expanding this discussion on the effects resulting from the existence of an industrial district and the causal conditions that lead to its emergence, the remainder of this section reviews the structural components that make up the industrial district.

Socio-territorial Entity

The socio-territorial entity defines an industrial district. It is geographic, with a production system whose primary market(s) is external. Socio-political and knowledge systems are similarly demarcated within the 'socio-territory'. The geography of the industrial district therefore forms the boundary of endogenous actions in the model. But, self-containment is not an ideal of the industrial district model; in contrast, most discussion of industrial districts concerns their ability to compete on external markets. Geographic proximity facilitates network connectivity, improves the effectiveness of collaborations and inter-organizational transactions, fosters social cohesion, and instills a sense of collective consciousness (Sengenberger and Pyke, 1990, p. 4). Activities within the district are organized through a mixture of cooperative and competitive principles (Sengenberger and Pyke, 1990, p. 16).

Community

The industrial district's community helps generate strategic externalities. There are two overlapping communities: business and social. Planned cooperation found in districts is sustained by a large overlay between these two communities (Sengenberger and Pyke, 1990, p. 19). This facilitates trust, the social community supports a set of values that underwrites inter-organizational exchange in the business community. Maximizing individual business returns is not the sole objective, benefits to the community are also identified with self-interest through their indirect returns. Thus, self-interest is not replaced, but it encompasses a broader definition than that commonly associated with 'atomistic' behavior. Social institutions such as kinship, ethnicity, political affiliation, or religion foment a community identity, allegiance to which may be formal or informal. Thus, an industrial district's historical community development strongly influences the endogenous constraints placed on 'individualistic' behavior (Beccattini, 1990, p. 39).

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[13] This distinction of sources of trust follows from Lane (1997).

[14] Maillat (1996) uses the term 'innovative millieu' rather than socio-political system.

Firms & Institutions

Firms and institutions in this industrial district model include all organizations and institutions engaged, even if indirectly, in the same broad production process.[15] This is not to say their only role is in the production system. Firms and institutions are also part of the knowledge and socio-political systems. As such, business organizations are not the only 'firms' in an industrial district; the district's 'firms' include its non-profit and government organizations. For example, a university, through its training of potential employees and provision of research, is a firm in the district although it is not directly involved in the vertical production process.[16] Personal relationships between the members of the firms that operate in district are characteristic of and related to the deep interactions between community and the production system.[17]

Human Resources

Human resources, in the industrial district, shape and are shaped by the production process. They are heterogeneous and defined by unique power relationships with the production, knowledge, and socio-political systems. There is typically an emphasis placed on the positive effects resulting from the relationship between human resources and the production system. These positive effects of locally specialized production on the district's human resources are not automatic, substantial portions of the human resources in an industrial district may have little or no influence over the knowledge system or the socio-political system.[18] An example in the contrasting and differing roles of heterogeneous human resources is found in the case of lightweight rock drills for stoping.[19] Under the system that emerged following a reorganization of stoping work, there was very limited integration of underground workers know-how to the knowledge system. In fact, the production process was designed so that knowledge transfers were one-way. 'Know-how' was instilled upon the African miners while they were precluded from contributing to organizational knowledge. The human resources of the industrial district encompass a spectrum of distinct entities often defined by the socio-political system and thereby limited in their influence in the dynamic evolution of the district's production system.

Markets

Product and factor markets are the two principal types of markets in an industrial district. Product markets are typically externally oriented in a district. The specialized good or service of

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[15] Conception of the firm in this model differs from that typical to the Italian industrial district approach in that a multiplicity of firms each differentiated along some unique production process, variable in time and space, is not stressed. The distributed innovation model adopts a conception more in line with the Italian; see Chapter Four.

[16] An industrial district with horizontal and vertical collaboration is a broader conception than that found in the Marshallian and Italian traditions which concentrate on vertical collaboration. Allowing for both types of collaborations increases the potential for and complexity of non-trivial power asymmetries. These power asymmetries are particularly significant in developing economies (Humphrey and Schmitz, 2000, Schmitz and Knorringa, 1999). Soubreyran and Weber (2002) have modeled industrial district formation with heterogeneous firms.

[17] These relationships are not limited to firms that operate in different phases of the production process, vertical relationships, as typifies the Italian industrial district approach (Beccattini, 1990, p. 41).

[18] In the Italian industrial district tradition there is an implicit tendency to assume homogeneity of human resources, this becomes synonymous with the features of the district and the presence of an industrial district. Relaxing this homogeneity, a measure of the industrial district's strength can be defined according to the degree by which heterogeneous human resources share equal power relations with the production, knowledge, and socio-economic systems.

[19] See Part Three, particularly Chapter Eight, for further descriptions.

the district is assumed to have a competitive advantage on the global market. The feedbacks and linkages with the product market help create and perpetuate its competitive advantage. Horizontal product market relationships and vertical factor market ties also provide a basis for coordination and collaboration, planned and unplanned in the district. These endogenous market relations contribute to the district's competitive advantage through knowledge diffusion and learning effects. Product and factor markets then are both areas where the district cooperates and competes.

2.2.2 Causal Conditions

The presence of special factor endowments in a socio-territorial entity are the causal conditions for an industrial district's existence. These special factor endowments enable a critical density of firms and institutions to become established. The consequential externalities (or lack there of) then result in the district's subsequent growth (or decline). What are these special factor endowments?

In the literature, there is no definitive definition of these endowments. However, the literature implies a few: 1) Complementary human and natural resources 2) Connection(s) with an external market(s) and 3) Local entrepreneurism. Unfortunately, after an industrial district exists, it is difficult to say how much of these special factor endowments were latent and how much resulted from the district's presence.

Complementarities between human and natural resources in a district exist with respect to some productive activity. The human resources in this context are not only the stock of individual know-how, know-what and know-who, but also the built environment. Natural resource endowments are similarly broad, including physical resources like minerals as well as environmental resources like climate and water.

Connection with an external market allows geographically based specialization to occur. These connections might exist as a result of other productive activities driven by the internal dynamics of the district's economy. Nonetheless, they will also be influenced by external political-economic dynamics such as the political borders in which the district is located.

Lastly, local entrepreneurism must be present in order to successfully organize and develop the productive activity of the socio-territorial entity for the external market. Without this entrepreneurial initiative, the benefits from geographical specialization and the emergence of an industrial district will never occur. Nevertheless, it is difficult to distinguish whether local entrepreneurship led to the emergence of an industrial district or whether the emergence of an industrial district generated local entrepreneurism. In fact, all of the special factor endowments can be criticized as being responses to the existence of an industrial district rather than causes of its emergence.

The endowments identified above as being causal conditions for the creation of an industrial district need not occur concurrently. One of these factors, or a sub-set, might be strong enough to generate responses from the others. It is also possible that further research will result in better refinement of what the special factors are that create an industrial district. Regardless, within the context of the present analysis it is important to note that these special factor endowments, which create an industrial district, are largely fortuitous. If these endowments are present to a sufficient extent, an industrial district will emerge.

The cases that follow illustrate some of the difficulty associated with distinguishing which of the special factor endowments acted as casual conditions in the emergence of an industrial district. In both instances, the innovative activity that took place in these technologies occurred because of the presence of large gold deposits along the central and eastern Witwatersrand. Consequently, the natural resource endowment appears to be the only special factor endowment necessary for the emergence of an industrial district.

Nevertheless, David and Wright (1997) demonstrated that a major influence on North America's abundant mineral endowment were its human resources. These individuals identified and developed economical methods to extract mineral resources which in other regions were considered either marginal or uneconomic. Similarly, while the Witwatersrand's gold deposits attracted human resource to the deposits,[20] the co-incidence of a highly experienced mining community nearby in Kimberley meant that a situation of cumulative causation occurred.

The early gold mining companies of the Witwatersrand developed technologies, the focus of the two case studies that follow, which increased the scale of economic gold deposits on the Witwatersrand and attracted more investment. This in turn led to further exploration and development of innovations in extraction that virtuously expanded the quantity of economic gold deposits. While the gold deposits were necessary for the emergence of an industrial district, the proximity of competent mining financiers located nearby at Kimberley was also necessary for the emergence of an industrial district. Therefore, it was the presence of the inclusive set of special factor endowments that formed the causal conditions for the emergence of the Witwatersrand industrial district and not just the presence of some particular special factor endowment.

2.2.3 Effects

Once an industrial district emerges, its endurance depends upon the strength of localized externalities. These externalities are captured through a process of co-location. Benefits (and costs) from co-location in a district are not automatic. What is derived from co-location is a facilitating force for ensuing collaboration (Schmitz, 1999, p. 466). There are two means of co-location, they are not mutually exclusive and merely serve to distinguish between internal and external locational choices. First, firms already in the same physical location can move into or expand their operations in the inter-related productive system that defines the district. Second, firms from other physical locations can relocate to participate in the districts inter-related productive system.[21]

Three factors determine locational choice: 1) The strength and nature of agglomeration externalities 2) The intensity of price competition and 3) The level of transportation costs.[22] The motivations leading to locational choice can be analyzed using game theory in order to capture the inter-dependence of firm's decisions.[23] Given the inherent spatial specialization of an industrial district, there is an implication that only a few competitors exist in a given global market. Pricing and output decisions by these firms are non-trivial to other firms' choices

[20] For further details on this era see Chapter Six, Section 6.2.3.

[21] Because of the productive system being conceived of as the locus where economic gains are realized, the firm's locational choice is concentrated upon, but the force could originate from input factors as well as product market demand.

[22] See Bellflamme et al. (2000) for an elaboration on the role price competition plays in locational choice, for the role of agglomeration externalities see Quah (2002), Gonda & Kakizaki (2001), Krugman & Venables (1996), and on transport costs see Ottaviano and Thisse (2002).

[23] See for instance Bellflamme et al. (2000), Soubeyran & Weber (2002), and Soubeyran & Thisse (1999).

whether to enter the district's production system. The presence of several firms in the same specialized global market can increase the number of competitors, which would lower the market price of their product. Because of locational market specialization, a pecuniary externality is generated that can discourage co-location. The cases that follow are set within an environment where gold production occurred under the international gold standard, which eliminated the opportunity for firms to influence the market price. Hence, this market disincentive to co-location is set aside. Further, because of the high cost of gold per gram, transport costs account for a negligible percentage of total costs. Thus, we can also discount the influence of transport costs in determining locational choice. Our present analysis therefore focuses on the influence of agglomeration externalities in determining the growth or decline of a district and its associated competitiveness.[24]

Agglomeration externalities are created by two distinct processes, industry specialization, and complementarities (Baptista and Swann, 1998, p. 529). The notion of positive agglomeration externalities is interrelated to a production process characterized by increasing returns. Increasing returns are not indefinite, eventually the density becomes such that congestion effects overwhelm benefits. Industry specialization within the district allows an indirect internalization of knowledge spillovers. The district thereby benefits not only through increased community welfare, but also by generating a comparative advantage over a similar industry in a non-district setting through faster and more complete diffusion of knowledge. Industry specialization also generates labor market pooling and training externalities. Complementarities arise from related economic activities, which through interaction within the district's community generate new applications of knowledge from one industrial specialty to another. These complementarities realize minimum-market-threshold-values across the individual organizations found in the district and allow for specialized intermediate goods and services.

A functioning industrial district generates a host of positive and negative effects. Positive agglomeration externalities in a district can be divided into six types. Three were identified by Marshall: technological externalities, benefits from labor markets pooling and training, and emergence of inter-firm demand supporting specialized subsidiary trades and intermediates (Marshall, 1936, pp. 271-272).[25] Since Marshall, a few other agglomeration benefits in a district have been identified: concentration of research activities, deep production networks, and benefits in complementarities realized from locating in cities (Venables, 2000, p. 2).

Technological spillovers in a district are taken to generate a positive externality through their facilitating diffusion of knowledge. Therefore, appropriability losses from knowledge spillovers must be considered. Nonetheless, within a district, external economies from knowledge spillovers are not lost to the individual firm or person, as they benefit indirectly through their positive effects on the others in the district. Technological externalities or knowledge spillovers in a district occur as knowledge is transmitted within and between nearby organizations.[26] Technical universities, research institutes, and advanced firms are typical sources, but feedbacks from all organizations in the district contribute.

Transmission of the technological spillovers takes several distinct routes. Personnel turnover, when people with competence move from one firm to another and when people leave to form

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[24] For further discussion, see Kilkenny and Thisse (1999), Soubeyran & Thisse (1999), and David et al. (1998).

[25] Marshall distinguishes between specialized subsidiary trades and machinery, so there are technically four Marshallian externalities. There is also no mention of labor training externalities in Marshall, but it is included with labor market pooling as a logical extension.

[26] Rivera-Batiz and Romer (1991) analyze the flow of information / ideas and its impact within a setting of economic integration.

their own firms is the most important means of technological spillover in a district. Other important sources of spillovers are subcontractors learning from purchasers and vice versa, as well as when competitors learn through imitation of technological leaders. These last sources of spillovers usually occur in mature industries with a reasonably codified body of knowledge (Eliasson, 2000, p. 224).[27]

The positive learning effects are not limited to knowledge spillovers, but are also related to the technological infrastructure. A district's infrastructure of firms, universities, research institutes, etc. also facilitates the search process for ideas and inventions, which generates innovation and technological progress.[28] These are not just supply-side effects, as consumer demand for the district's products and services provides a concentrated source of useful information feedbacks in the innovative process (Baptista and Swann, 1998, p. 527). Thus, in addition to technological spillovers, concentration of research activities within a district generates a learning infrastructure that enhances the business community's competitiveness.

Labor market pooling is another important competitive benefit accruing to businesses in an industrial district. This externality works in two ways to attract workers with the necessary skills. First, it lowers the workers' risk of transient unemployment and costs of potentially having to relocate at great distance for similar employment because there are many local employers who require their skills. Second, it lowers the employers' costs of quality screening and job vacancy since they are part of a community of organizations which utilize similarly skilled individuals creating thereby a greater pool of available workers due to normal turnover (David et al. 1998, p. 157).[29]

Another benefit of a specialized labor market is in the training provided by employers and pursued by employees. An employer who subsidizes the technical training of an employee is contributing to their organization's productivity but also to the district's. Assuming other employers in the district share the same perception, providing training to their employees is not an appropriability issue. Even if an employee moves to another company after training, there is a pool of better-trained employees available for the industry to draw on to replace them. Since their special skills are valued, employees also have an incentive to pursue further training as their investment in education is directly translated to an increase in their market value in the district.

A district facilitates provision of specialized subsidiary trades and intermediate goods and service. These related inputs are provided because of inter-firm demand pooling to meet the aggregate demand present in an industrial district because of firms being engaged in roughly the same production process. As a result, there is an availability of externally provided traded and non-traded inputs for the district's production process with increased specificity, variety, and at a lower cost than is possible through internal provision or in non-concentrated industries.[30] This occurs because the fixed costs and the purchasing agents' demand for specialized equipment and services are diffused in a district. A special cable manufacturer finds itself in very different

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[27] See Chapter Four, Section 4.2.1 for a description of codified and noncodified knowledge.

[28] Evidence of this localization of learning, at least regionally, is presented in Feldmann and Lichtenberg (1997). Using European Union data, they find that a nation's firms specialized in the same fields as its universities and public research organizations. They also found that as research projects increased in their expected codification, so the geographical localization of the research project decreased.

[29] Labor pooling can also allow a location to establish a niche within the global division of labor. Maskell (1996) adopts this perspective in his study of internationally competitive low-tech specialization in Denmark.

[30] For further details on the process by which sufficient downstream demand for intermediate inputs supports firms upstream at a larger scale of efficiency, see Stigler (1951).

market when there are three medium sized firms than when it finds itself with only one large firm demanding its product.

Proximity and connectivity within the district also facilitates coordination in production. As a result of deepened production networks, endeavors previously undertaken by a single organization are diffused through cooperation and coordination of actions across the district's firms and institutions.[31] Thus, diffusion of production gives rise to a general but important positive externality in a district, the reduction of discrete units of risk and uncertainty. A research project or a capital-intensive production process will have a certain quantity of risk and uncertainty associated with them. That risk and uncertainty is reduced when spread across agents in an industrial district and thereby the attractiveness of investment increased. This process was recurrent in South African mining history.[32] The dilution of risk and uncertainty also mobilizes entrepreneurial resources. Districts muster more 'ordinary' entrepreneurs willing to take smaller risks and accept lesser amounts of uncertainty than the 'extraordinary' entrepreneurs (Schmitz, 1999, p.478).

Finally, a distinction exists as to the incidence of the externalities. Often focus is on externalities to the firm, but internal to the industry. However, it is also possible for there to be externalities to an industry, but internal to other local productive activities. Urban system models typically focus on these types externalities, not internalized by a firm or an industry, but by other geographically proximate industries (Kilkenny and Thisse, 1999, p. 1389). With these inter-industry externalities, there are effective complementarities from urban co-location. Labor market scope, financial and managerial services, and research infrastructure are but a few examples. While they are not unique externalities, encompassing as they do aspects in almost all of the other externalities, their incidence at a geographically specific, but industry independent level makes them a distinct type of agglomeration externality.

Externalities within an industrial district are not just positive. As Marshall and others point out, negative effects also arise from agglomeration. Given the specialization associated with a district, they will potentially reach a point where demand, even in an ever more globalized world, does not warrant further increases in productive capacity. At this level of production, the employment opportunities are effectively fixed. If the working age population of the district is greater than this fixed level of employment, there is a potential for the district to perpetuate a situation of chronic unemployment. In part then, the very success of the district ends up creating a negative situation in the job market for at least part of the population in the socio-territorial entity that it comprises.

Another potential negative effect associated with the specialization of an industrial district is its sectoral exposure to volatility.[33] If the largely exogenous market for the district's product or service should experience a downturn, the entire economy of the socio-territorial entity would languish. This negative sectoral exposure to product or service volatility is most frequently observed in districts which produce natural resources. It is important to note that this exposure

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[31] Other organizational arrangements with similar effects are formal partnerships.

[32] A relatively large-scale example of this was development of the Far West Rand Gold Fields. When the area was being developed, despite potential monopolization, other mining houses were invited to participate in order to reduce the entry costs of the pioneering mining house. See Cartwright (1967, Chapter 14 & 15), Johnson (1987, Chapter 1), Lang (1986, pp. 351-354), Cartwright (1968, pp.199-206), and Gregory (1962, pp. 33-35).

[33] Allocative inefficiencies because of collective dynamics could also be considered a negative externality, but they are largely ignored in the industrial district literature and so discussion of them is left for Chapter Three in the context of the collective action approach to research collaboration.

to volatility also has an upside during growth, but the amplified impacts of a downturn lead to this effect being classified as negative externality (Marshall, 1936, p. 273).

Lastly, there is a class of negative externality created by the 'excessive localization' that is associated with the district's success. There are three types of effects in this class of negative externality: congestion, pollution, and resource scarcity (Venables, 2000, p. 5). Congestion occurs as the population of individuals and enterprises become increasingly crowded in the finite geographic space of the district. Transport and accommodation costs will rise as a result which acts to diminish the attractiveness of locating in the district. Pollution is another negative effect associated with the increased growth of a district. Not only does congestion generate pollution, but the convergence of similar productive activities also causes a concentration of specialized industrial waste.[34] The convergence of similar productive activities will also generate a condition of resource scarcity if beyond the sustainable generative capacity of the district or if an adequate import supply of factor inputs is not secured.

2.3 CONCLUSION

In the industrial district approach, fortune determines whether the necessary special factor endowments lead to the creation of a district. Once formed, the district's growth or decline depends upon the quantity and quality of agglomeration externalities and external market demand for its product(s). Table 2.1 details the principle components of the industrial district approach.

A strong conceptualization of the institutional environment emerges from the analysis of the structure and interactions of resources: human, physical, financial etc. However, the industrial district approach devotes limited attention to how these resources and relationships evolve over time. While it provides significant insights into the district's current structure, it is much less telling about the underlying dynamics.

TABLE 2.1 The Industrial District Model

Structure: Components	Structure: Relationships	Causal Conditions	Effects
1) Socio-territorial Entity 2) Community 3) Firms & Institutions 4) Human Resources 5) Markets	I) *Production System* II) *Knowledge System* III) *Socio-Political System*	1) Special Factor Endowments	1) Agglomeration Externalities

Within the district, collaborative research is the product of geographically confined interactions. While it is assumed beneficial, as the borders of competition and cooperation move over time, one would expect some variation in the scale of research collaboration to be desirable. Unfortunately, joint action and the explicit provision of externalities is not part of the industrial district approach. Therefore, it is complemented by approaches, like collective action, which explicitly formulate motivations for research collaboration and other collective goods.

[34] This latter feature of pollution need not be an entirely negative externality since the concentration of related productive activities also increases the potential for scale economies in recycling.

Chapter Three:
Collective Action

3.1 THE COLLECTIVE ACTION ANALYTICAL TRADITION

Intellectual property is normally non-rival and non-excludable, i.e. a public good. Intellectual property rights: copyrights, patents and trademarks, attempt to increase the appropriability of intellectual property in order to encourage innovation and facilitate the flow of information. However, not all intellectual property is protected. Some intellectual property is not protected because the perceived value does not exceed costs of protection. Other intellectual property is unprotected because of perceived mutual gains from its circulation. In both cases, we assume that agents realize the value of intellectual property exchange and circulation. The losses faced by an agent are offset by the gains received from others behaving similarly.

Given these circumstances, the collective action approach provides a useful tool to examine how the common interests of the group supersede individual interests in collaborative research. [1] While ever-increasing international interactions and the associated specialization create a pressing need for collaboration, group and aggregate social interests are not always co-incident. Actions in pursuit of group (or sub-group) benefits may worsen, rather than enhance, social well-being and lead to an outcome inferior to the pursuit of individual self-interest.

The collective action approach has several components parallel to the industrial district and distributed innovation models. For example, the notion of collective governance is similar to the idea of network governance in the distributed innovation model.[2] Likewise, public externalities are akin to the agglomeration externalities in the industrial district model.[3] While these correspondences demonstrate complementarities in the other approaches used to analyze research collaboration, they also indicate discontinuity.

The collective action approach develops a theoretical heritage from mid-20th century writings on the theory of public goods and game theory (Hardin, 1982, p. 17). Mancur Olson in his book *The Logic of Collective Action* (1965) pioneered a generalized analysis of group action undertaken to provide a public good. Group provision of a non-excludable good or service contrasted with preceding analyses, which were concerned with consumption of public goods (Olson, 1982, p. 19). With attention on provision, Olson differentiates between the common interests of a group and the individual interests of its members. In the *Logic,* individual members of the group producing the public good had little direct incentive to voluntarily support its provision. Subsequent research has shown that this limited individual incentive was just one type of many different types of structures collective action could take.[4]

In this analysis, collective governance is assumed to be a unique governance structure that a subset, group, of the population uses to provide a public good. As a distinct governance structure for organizing transactions, collective governance follows Ronald Coase's distinction between governance by firms and by markets (1937). Hence, we take collective governance to be

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[1] Collective action more generally refers to activities that require coordination of efforts by a group containing two or more individuals. Thus, collective action is present when there is interdependency of actions among individuals. For further discussion on the type of public good provided Section 3.2.1.

[2] See Chapter Four, Section 4.1.

[3] See Chapter Two, Section 2.2.3.

[4] For an examination of these other influences, see Chapter Two in Sandler (1996).

a third dimension in transaction cost theory's two-dimensional market-hierarchies continuum.[5] This assumption is similar to Walter Powell's contention that networks are a third governance structure (1990).[6] However, no governance structure is taken to be exclusive in its economic coordination. Collective, market, and hierarchical governance co-exist, to varying degrees, in most groups, organizations, and institutions. Governance of one sort or another is determined on a basis of dominance rather than exclusivity.[7]

Research collaboration is a complex dynamic process. Yet, we utilize a relatively simple analytical structure, the repeated prisoner's dilemma, to analyze these dynamics. This follows the spirit of Olson's analyses. Justification is in its analytic simplicity rather than its comprehensiveness. Although the prisoner's dilemma model emphasizes self-interest,[8] we allow for "altruistic" behavior arising from reciprocity whose origins are self-interested.

There are several informative precedents for analyzing research collaboration in the collective action approach. Richard Parkin employs a game theoretic framework on a comparative analysis of inter-firm cooperation in the London and Italian furniture industries (1999). Robert Allen identifies informal collective action as a unique source of innovation in his case study of blast furnace development over a 25-year period in England's Cleveland District (1983). Eric von Hippel has done substantial work on collective action in a variety of studies. In a recent analysis, he examined collective provision of software support services in the open source software format (Lakhani and von Hippel, 2000). Building on a case study of U.S. mini-mill steel producers and a review of other empirical evidence, he proposed a game theoretic formulation to explain the cases' observed inter-firm know-how trading (Von Hippel, 1988, Chapter 6). The structure of collective action in American publicly provided agricultural research between 1951 and 1985 has also been examined (Khanna 1993 and Khanna *et al.* 1994).[9]

3.2 A COLLECTIVE ACTION MODEL FOR ANALYSIS

The model synthesizes previous works on collective action to identify the key components in a collective action analysis of collaborative research. We assume that research collaboration is the central structure for inter-firm generation of innovation. In deference to relative simplicity, the collaborative innovation structure and related causal conditions are assessed as an evolutionary Prisoner's Dilemma. Representative works, namely Hardin (1982) and Sandler (1996),[10] from the large field of research into collective action are used to discuss key analytical components.

Section 3.2.1 gives a structural description of the model, defining the players and specifying the components' hypothesized relationships. Following these structural details, Section 3.2.2 details the causal conditions under which collective action leads the emergence of collaborative research. Section 3.2.3 then considers the effects of collaborative research on net social welfare.

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[5] Further details on transaction cost theory's market-hierarchy continuum can be found in Williamson (1975, 1985).

[6] There is a tendency to apply the term 'network' as both a relational structure and governance mechanism. Collective action is a parallel governance mechanism, but the groups and their activities form the relational structure. In this, it is similar to the distinction between firm and hierarchy in transaction cost theory. Also see, Chapter Four, Section 4.1.

[7] An elaboration on the coexistence of various governance structures, defined by the predominate form can be found in Streeck and Schmitter (1985) and Hamilton and Feenstra (1998).

[8] See Bardhan (1993).

[9] For more detail on these studies see Section 3.2.2.

[10] Russell Hardin's *Collective Action* (1982) provides a game theoretic elaboration of Olson's *Logic*, while Todd Sandler's *Collective Action* (1996) refines many of Hardin's collective action propositions using advances in game theory.

3.2.1 Structure

There are two structural relationships: 1) the collective supply function and 2) the convention system; and two structural components: 1) overlapping activities and 2) the public - collective good produced; which must be identified since together they define the group structure of collaborative research. Following Sandler, the collective supply function (CSF) [11] is defined as: "How individual contributions to the collective action are aggregated to arrive at the amount of the collective good that is available to all to consume" (1996, p. 20). There are an infinite number of possible CSFs. We discuss a few types of CSFs to illustrate general features and the influence that the CSF has in determining the realization of collective action. This discussion will then guide our subsequent collective action analysis in the case studies of which CSF characterizes provision of collaborative research.

"Summation" is the type of CSF implicitly used in most of the *Logic*. It assumes that everyone shares the provision and benefits of collective action equally. It can be expressed by the equation: $Q = \sum_{i=1}^{n} q_i$, where Q is aggregate supply of the collective good, q_i is individual *i*'s provision, and *n* is the group size. A problem with the summation CSF is that it does not allow for the level of individual provision and benefit to influence the level of group provision.

A CSF that avoids this problem is the "weakest link", under which the smallest individual provision level determines the group's. This CSF structurally limits free riding and occurs in situations where mutual dependence on independent action is strong. An example of weakest link CSF might be a multi-national military alliance where the weakest nation's border security sets the collective level of security against invasion. Weakest link CSFs can be expressed by the equation: $Q = min(q_i,...,q_n)$.

A CSF related to weakest link is "best shot". Under it, the largest individual provision level establishes the group's provision. A best shot CSF is highly vulnerable to free riding and occurs in situations like the search for a cure of a disease. Once invented the cure is available to all whether they contributed or not. Best shot CSFs can be expressed by the equation: $Q = max(q_i,...,q_n)$. There can also be heterogeneity in provision and benefits from collective action. A "weighted" CSF represents this type of provision, it can be expressed by the equation: $Q = w_1q_1 + w_2q_2 + ... + w_iq_i$, where w_i is the weighted provision/benefit for individual *i*, $\sum_{i=1}^{n} w_i = 1$, and $0 \leq w_i \leq 1$.

If collective action involves multiple outputs and varying degrees of publicness they can be incorporated in the CSF by differentiating each unit of collective action, q_i, according to its units, γ, of the private output, x, and its units, δ, of the public output, y. Thus, individual, i, receives, $x_i = \gamma\ q_i$, units of the private output and, $y_i = \delta\ q_i$, units of the public output. Once the CSF is specified and inserted in the individual's utility function, $U_i = U_i\ [CSF]$, it is used to optimize provision subject to the resource constraints and establish the equilibrium(s). This final step situates the CSF as a structural feature in the causal conditions for collaborative research.

Deciding which CSF best describes provision is difficult, in part this results from the public nature of the goods. A public good is a generic title under which a variety of goods can be distinguished. Because of the distinct influence these different types of public goods have on provision, one needs to identify the type of public good(s) that characterizes the output(s) from a collaborative research initiative.

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[11] Rather than Sandler's 'technology of publicness', this term is used to avoid confusion over types of technology.

Again following Sandler (1996), we distinguish between pure public goods and impure public goods. When a good (or service) is both non-excludable and non-rival, it is a pure public good. Non-excludability means the good's providers cannot limit its consumption from non-providers. Non-rivalry means one person's consumption does not reduce the amount available to others. If a good is partially excludable and/or partially rival, it is an impure public good.[12] Impure public goods can be further differentiated. If a good is excludable but non-rival, such as a musical performance, it is a club good.[13] Similarly, when a good is rival but not excludable, such as a quite picnic spot in a park, it is a rival public good. A third type of impure public good are inherently private goods, but are treated as public goods because of social consensus, public education is an example of this type of quasi-public good.

All of the above types of public goods can also be discrete, continuous, or step. If a public good is discrete, its provision either occurs or does not. If a public good is continuous, the amount of the good provided is variable. Lastly, if a public good is step, within discrete provision levels, the quantity of the good provided is variable. Relationships between the nature of the public good and its influence on provision (or lack there of) are discussed further in Section 3.2.2 below.

Institutional characteristics are also fundamental determinants to successful collective action. In general, when institutional characteristics are favorable to collaborative research they ensure that individuals' see beyond their own self-interests and identify with the interest of the group. A motto from a federation of South African labor unions expresses this group identity: "An injury to one is an injury to all!"[14] If there is not identification with the group's interests, there is no certainty that a public good will be provided even if it is in the mutual self-interest of the group's members. In this model, there are two principle institutions through which self-interests are transferred to the group: overlapping activities and convention systems.

Overlapping activities are the interactions of individual agents within and between groups. They connect the knowledge of the various agents in order to develop a stock of "common knowledge" that enables the realization of conventions.[15] Knowledge conditions and opportunities for cooperation are thereby intertwined. Overlapping activities are varied and multi-dimensional, working in a variety of ways to support cooperation among otherwise self-interested individuals. They create an opportunity for low cost sanctions, either material or moral. If there were two individuals in a community who both owned and operated their own microbreweries and were active in the same community residents association, we would say that their breweries and residents association were overlapping activities.

Overlapping activities allow an agent to establish a reputation of credibility from previous and diverse behavior. These signals then augment agent and group social capital. Knowledge and sanctions may interact constructively. The stock of knowledge about potential sanctions created by overlapping activities reduces the risks of cooperation because players know those whom they interact with are similarly well intentioned (Olson, 1982, p. 186). If our two brewery owners shared similar agendas on the community association, this stock of social capital might facilitate their forming a collective purchasing agreement for their microbreweries.

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[12] A private market good is both excludable and rival; as such, it is optimally allocated under market governance in pursuit of individual self-interest.

[13] Originating with Buchanan (1965), a vast literature has been written on club goods, see Cornes and Sandler (1996) for a selective review.

[14] Congress of South African Trade Unions (COSATU).

[15] Foss (1999) shows that common knowledge can be an important basis in facilitating leadership in coordination games.

The amount of overlapping activities between agents is assumed a function of the degree of homogeneity in a group's membership.[16] An increase in the quantity of overlapping activities within the group is associated with a greater homogeneity among the group's members. Recanatini and Ryterman (2000) provide an interesting example of how overlapping activities can be crucial to collective action. Analyzing formerly communist transition economies, they show that collective governance, under the institution of business associations, emerged to coordinate economic activities because of the gap left by removal of central hierarchical coordination authority and in the presence of acutely inefficient market structures.

When overlapping activities result in a multitude of near simultaneous contacts between agents, concurrent iteration occurs, which reduces the need for inter-temporal repetition in providing a collective good. This concurrent iteration, built upon varied experiences and brought about through overlapping activities, is equivalent to 'altruism' or 'trust' (Olson, 1982, p. 187). Overlapping activities are then the mechanism with which the group's stock of social capital or trust is built-up. As signals of future behavior, these contributions bring a value to the current stock of social capital based upon their implied continuation. While overlapping activities augment the group's social capital, which discourages defection against the collective, it is through the convention system that defection is penalized.[17]

The convention system generates expectations about the players' mutual behavior, with the threat of punishment via sanction. These sanctions are drawn from the value of the group's social capital or trust. As a counter-part to a group's overlapping activities, its convention system penalizes defection from co-operation, depleting thereby the group's stock of social capital or trust. Depletions from this stock of social capital or trust are assumed to signal further similar actions. The sword of the convention system, as the response to defection over the group, thereby facilitates collective action.

The convention system can penalize an agent defecting from co-operation by three principal means. When an agent violates the group's trust, and is detected, we assume they are expelled from the group. The expulsion of an agent from the group is the most direct punishment that a convention system can impose. If a group of microbrewers had established a collective purchasing association, a member who undermined the association through unilateral negotiations with suppliers would be expelled upon detection. That defecting brewer must then weigh the value of the unilateral supplier contract with the cost of exclusion from the collective purchasing association.

In situations where a public good is being provided, it might not be possible to exclude a defecting agent or non-member from the benefits of the good. A group might therefore engage in the provision of multiple outputs, some of which are excludable.[18] Collective provision of these different types of outputs thereby facilitates collective action by making non-contribution prohibitive because of the potential to exclude them from some of the goods provided.[19] If a metal piping manufacturer can only obtain economic steel inputs through its collective purchasing association, its chances of defection or free riding, on that association's export promotion would be substantially curtailed.

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[16] Homogeneity can be in terms of members' utility functions and strategic interests.

[17] See Lorenzen (1998).

[18] The excludable goods maybe impure public goods or private goods. Sandler refers to this type of overlapping activity as 'joint products' (1996, p. 11).

[19] The joint-production of excludable and non-excludable goods to facilitate collective action is discussed further in Section 3.2.2 as selective incentives.

Another means of punishing and deterring defection against the group results from detected action against the group's trust sullying an agent's reputation. An agent who is expelled from a group is given a dubious reputation that will probably exclude them from future collective action with that group and any other group who know of the agent's previous defection. This increases the shadow of the past on the future. Although it might be in an agent's self-interest to defect against the group it is currently a member of, such an action would give the agent a bad reputation and could lead to exclusion from future potentially beneficial co-operation. Collective provision is thereby facilitated because of the future, if uncertain, costs a poor reputation might have.

Given these punitive powers of the convention system, it becomes critical that defection against the group is detected. If a member(s) sees a high probability that their defection against the group will be undetected, it can increase their incentives to defect since their reputation will not be affected. We assume detection of members' behavior depends primarily on group size.

Within their overlapping activities, group size proxies as an indicator of group's interaction. Larger groups are negatively associated with the probability of interaction. Therefore, the strength of the convention system decreases as group size rises since the probability of interaction declines. Interaction being the primary means of detecting defection, limited interaction narrows and constrains the scope for cooperation. In a very large group, where contact is approximately random, the limited interaction effectively precludes the existence of overlapping activities and means that the convention system is unlikely to contribute to cooperation. Fortunately, in many situations, non-random interactions are significant and the associated opportunities for cooperation enlarged.

Through its influence on the convention system and overlapping activities, group size changes individual benefits from cooperation. While group size can influence the causal conditions for research collaboration, it does this indirectly. Olson (1982) held group size as having a crucial role to the realization of collective action. However, further analysis of collective action showed that group size is not necessarily fundamental to collective action (Sandler, 1996, pp. 35-54). Too great a focus on group size obscures the roles of the CSF and the nature of the good provided. For instance, the type of collective good provided could mean that group size has no influence over an individual's value from cooperation if the collectively provided good is non-rival.[20]

In the cases of collaborative research that follow, it is easier to identify the overlapping activities that existed between agents than it is to infer the historic structure of the convention system. By means of illustration, the overlapping activities of two microbrewers' membership in the same collective purchasing association and community residents association is much easier to see than the convention system by which the two microbrewers were discouraged from defecting from these co-operatives. As a general characteristic of this type of analysis, the social detail of the convention system's emergence and structure is liable to be prohibitively complex (Olson, 1982, p. 188).

Another complication in analyzing the structural features of a collaborative research initiative is the tendency to focus on 'winning' events. Many analyses focus on incidents where the convention system and overlapping activities led to successful collective action and collective provision, rather than where they failed. Careful microanalysis of both the convention system

[20] Section 3.2.2 has further illustration of the influence the CSF and the public-collective good have in collective action.

and overlapping activities is needed to (attempt to) understand the causal conditions for collaborative research. Influences on the convention system's emergence and dynamic changes in its benefits must be examined along with the structure and dynamics of overlapping activities. In our present endeavor, this entails examination of the overlapping activities and the convention system within and between each case of research collaboration and explicit detail (hypotheses) with respect to their influence on the costs and benefits of cooperation.

In the collective action approach, coordination is not so much spontaneous, as the product of the convention system and overlapping activities. Often, numerous small relationships support cooperation even where group size is large. This overlap of activities creates a situation where conventions and sanctions become interwoven, hence enforceable over a large number of members. Again, understanding the complexities of the convention system is a prerequisite and major impediment to formulating policies that support the convention system's facilitating role in collective action. If historical coincidence leads to a new opportunity for collective action among familiar agents with some pre-existing convention system among them, resolution of a collective action problem is much easier. This could explain the speed of collective action initiatives on the Witwatersrand goldfield. In this instance, collective initiatives appear to be a legacy of the convention system established at the Kimberley diamond mines.

3.2.2 Causal Conditions

In this collective action model of research collaboration, we distinguish between the causal conditions, which lead to the emergence of collaborative research, and the effects of that research collaboration's existence. Section 3.2.1 identified four fundamental structural factors in the emergence of a collaborative research initiative: 1) The CSF 2) The nature of the collective good 3) Overlapping activities and 4) The convention system. These four factors determine the group structure, which if favorable forms the causal conditions for collaborative research. Below, we examine general influences on the causal conditions. Details of these influences are then analyzed in the game theoretic model of a repeated Prisoners' Dilemma. A review of other collective action analyses on the causal conditions for research collaboration concludes this section.

To begin our discussion of the structural influences on collective action we examine the restricted environment of a "summation" CSF. Under the summation CSF we assume provision can be either discrete or continuous, but that there are no scale or scope economies in provision, no moral or material overlapping activities in the convention system, and no strategic influences on the costs and benefits of cooperation. In this context, collective action is only successful in providing an output without any institutional mechanisms when the group is "privileged". A privileged group is one in which at least one member of the group finds the benefit from the collectively provided good to be greater than the costs of the collectively provided good.[21]

Table 3.1 uses numerical examples to illustrate several features of collective action under the summation CSF. Each row uses nine columns to represent a distinct collective action scenario. Column one indicates the number of members in the group. Column two indicates the total cost of providing the collective good. Column five represents the value of the collective good to each individual in the group, while column six represents the total value of the collective good to the

[21] Following Hardin (Chpt. 3, 1982), a more formal definition of a "privileged group" is: The net benefit of collective action to a member, *i*, of the group is given by the equation $A_i = V_i - C$, where A_i is the advantage to member-*i* of its contribution to collective provision; V_i is the gross return from the collective good to member-*i*; and *C* is the total contribution member-*i* makes to provision. If for some member-*i* of the group, $A_i > 0$, then the group is privileged.

group. Column three indicates the group benefit from the collective good relative to its total costs. Column four reports the costs of collective provision per member of the group. Column seven gives the value of the collective good to each group member relative to its total costs, and column eight reports the compliment of this value per member relative to its total costs or the disincentive to pay. Lastly, column nine reports the minimum size of the sub-group necessary to provide the collective good. This is the minimum number of agents needed to provide the collective good. More specifically, this "*k*-value" is the total number of individuals whose collective value per member, column seven, just exceeds the total costs of provision, column two.[22] For example, in row one the total costs of provision equals five and value per member is four, therefore, two individuals are the minimum number necessary to form a sub-group that successfully provides the collective good.

When the public good is discrete and rival, D-R public good, an increase in the number of members lowers the probability of collective action. This is illustrated as group size increases from 5 to 100 in the move from row 1 to 2 in Table 3.1. The value of the collective good per member decreases from 4 to 0.2. The return on expenditure towards collective provision, the value of the collective good to an agent divided by the total costs, dropped from 0.8 to 0.04. Given these changes, the minimum size of a sub-group of agents that could provide the collective good rises from two agents out of the five members to 26 agents out of the 100 members.

A discrete and pure public good, D-P public good, is not affected by the increase in group size. The D-P public good case is seen in the table through a move from row 1 to 3, with the minimum sub-group size for collective provision remaining at two despite the rise in members from five to a hundred. A continuous and pure public good, C-P public good, incurs constant individual costs as the group size increases, which lower returns to the individual and decrease the likelihood of collective action. Moving from row 1 to 4 demonstrates the C-P public good, the minimum sub-group size necessary for collective provision rising from two to twenty-six. Finally, a public good can be continuous and rival a C-R public good. Collective action is again unlikely in this case, as is illustrated in the move from row 1 to 5, where the minimum subgroup size rises from two to fifty-one.

TABLE 3.1 The Type of Public Good and Collective Action

	Number of Members (*n*)	Total Costs (*c*)	Ratio of Group Benefit to Total Cost (*n*Vi/c*)	Cost per Person (*c/n*)	Value of Good to Member-i (*Vi*)	Group Benefit (*n*Vi*)	Return to Member-i per Expenditure (*Vi/c*)	Disincentive to Pay (1-*Vi/c*)	Minimum Sub-group Size (*k*)*
Row/ Column	1	2	3	4	5	6	7	8	9
1	5	5	4	1	4	20	0.8	0.2	2
2	100	5	4	0.05	0.2	20	0.04	0.96	26
3	100	5	80	0.05	4	400	0.8	0.2	2
4	100	100	4	1	4	400	0.04	0.96	26
5	100	100	2	1	2	200	0.02	0.98	51

* This is the minimum number of members needed to provide the good, *i.e.* (min $k \mid k*Vi > c$)

Adapted from: Russel Hardin (1982) *Collective Action.*

[22] If any of these scenarios were "privileged" the minimum sub-group size, *k*-value, for the row would equal one, *i.e.* a single agent finds it in their interest to unilaterally provide the collective good.

Even with its simplified structure, the numerical examples in Table 3.1 illustrate the complexity of influences on collective action. If we allowed for economies of scale or scope, the realization of collective action would also be influenced. They could increase the likelihood of provision by decreasing costs sufficiently with an increase in group size to generate an increase in the value per member. Similarly, relaxing the symmetry assumed in the 'summation CSF' could alter the prospects for provision. If there is significant asymmetry within demand for a collective good, it can enhance or dissipate collective action. The essential determinant in these cases is whether there exists an alternative to collective action for the more intense demanders. For instance, a sub-group with a particularly strong demand for security may opt to hire a security guard rather than increase the provision of police (Olson, 1982, p. 73). Another source of asymmetry originates in the definition of the collective good. In this case, members of a group might want the same good, but for a variety of reasons. For example, environmental regulations may represent conservation to some, market opportunities for others, and a trade barrier to someone else. History is another important source of asymmetries that can effect collective action. For instance, an existing co-operative endeavor would probably place a greater emphasis, value, on preventing a loss of quality in provision than it would on improving its quality of provision (Olson, 1982, p. 83).[23] Clearly, both the CSF and the nature of the public good can influence the realization of collective action.

Provision was not certain in any of the scenarios found in Table 3.1, *i.e.* none of the scenarios was privileged. If provision were to occur in one of the scenarios, it would require a relationship of mutual trust between that scenario's minimum sub-group. In row one, for instance, at least two of the group's five member would have to work cooperatively to provide the good. It is in facilitating that cooperation between agents that institutional characteristics play an important role in ensuring the attainment of collective action.

Overlapping activities build and represent the stock of trust between agents. This social capital among agents contributes to features like a sense of community, which makes cost sharing likely, as monitoring and enforcement costs are relatively low.[24] When a member of the group knows that their contribution is (partially) matched, the unit cost of the public good to each is reduced. Thereby, the strength of interactions can increase the likelihood of collective action and augment the quantity of collectively provided goods.

Collective action often involves the provision of goods which are non-excludable. Because of this limit excludability, free-riding becomes a major obstacle to collective action. As a result, selective incentives are one of the more powerful mechanisms that the convention system has to encourage cooperation. Selective incentives apply to goods that are, at least partially, excludable. Thus, individuals can only obtain the selective incentive, the excludable good, if they have also contributed to provision of the other non-excludable good(s). Selective incentives can be positive or negative, formal or informal. For example, a large proportion of the representation a labor union provides employees to employers is non-excludable. There is an incentive to free ride, but many unions induce payment of dues through the selective incentive of membership payment as a condition for workers to get or keep their job (Olson, 1982, p. 21).

Khanna et al. (1994) using data from 48 states for the period between 1951 to 1985, tested whether agricultural research in the United States was a pure public good or a joint product, with some research outputs being pure public goods and the other state specific research being

[23] There is liable to be a significant role played by uncertainty reinforcing this type of asymmetry.

[24] Group size is assumed inversely related to interactions, *i.e.* when a group is small, each member's (non-) contribution significantly affects other members.

private, excludable, goods. They found an overwhelming number of states have behavior consistent with the joint-product model.[25] This indicates that selective incentives may be important to the strong provision of agricultural research by the states during this period.[26]

Socially selective incentives are another important mechanism available to the convention system to facilitate provision. Socially selective incentives arise from the trust/social capital built up in overlapping activities. They encourage cooperation by making defection harmful to the agent's reputation and leading to his expulsion from other cooperative activities within the group as well as carrying the probable exclusion from future cooperative initiatives. Availability of these socially selective incentives is directly related to the strength of strategic interactions and inversely related the group's social heterogeneity (Olson, 1982, p.24).

In order to move beyond mere appreciative theorizing about why or why not collective action occurs a more explicit framework is needed. Game theory is a useful tool to these ends. While acknowledging the potential complexity of provision, the repeated prisoner's dilemma provides a reasonably simple, but indicative, model to analyze collaborative research. It is used below to introduce game theoretic analyses of the causal conditions for collaborative research.

A one-shot two-player prisoner's dilemma is depicted in Figure 3.2 below. A prisoner's dilemma exists if two conditions are met. First, the value of its four possible outcomes must be such that $f > c > d > e$, where f is the payoff to the player defecting while the other player cooperates; c is the individual payoff to both when both cooperate; d is the individual payoff to both when both defect; and e is the payoff to a player cooperating while the other defects. The second condition is that there does not exist an opportunity for each player to profitably alternate between being exploitee and exploiter ($2c > f + e$).

Following Von Hippel's (1988) model of "know-how trading" between competitors, a player's knowledge stock can be expressed in terms of total rent value, R_{Total}. This rent is further divisible between that which is common knowledge, R_C, and that which is unique to the player, R_U, such that $R_{Total} = R_C + R_U$. A unit of knowledge contains some, potentially trivial, amount of both common and proprietary knowledge. Therefore, each unit of knowledge, which in aggregate constitute the total knowledge stock, can be expressed as: $R_{total} = R_c + R_u$. In research collaboration, the collaborators can exchange (trade) any unit of knowledge from their aggregate knowledge stocks. A unit is considered 'non-rival knowledge', with relatively little competitive advantage if $R_c > R_u$ and 'rival knowledge' with relatively significant competitive advantage if $R_u > R_c$.

Both players begin with one unit of unique knowledge, R_u, of identical value between them, and one unit of common knowledge, R_c, again of identical value between players. The pre-play value for each player is then: $R_c + R_u$. A cooperative trade, c, between the two players will result in each player having both units of knowledge post-trade, and each with a post-trade rent: $R_{total} = 2*R_c$. Post-trade each player loses that increment of the rent, R_u, unique to her, but gains the rent from the added knowledge unit. All four possible outcomes of a two-player one-shot game are depicted in Table 3.2.

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[25] Using the same data, Khanna (1993) tested the Nash-Cournot Joint Product model and the Lindahl model. The resulting analysis was inconclusive, with some states rejecting both models, some fitting both models, and others fitting either the Nash-Cournot or the Lindahl model.

[26] Khanna et al. (1994) report that real expenditures on research increased by 110% during the period they analyzed.

TABLE 3.2 Payoffs in a One-Shot Prisoner's Dilemma in Research Collaboration

		Player - One	
		Cooperate	Defect
Player - Two	Cooperate	c,c	f,e
	Defect	e,f	d, d
Where: $c = 2^*R_{c,}$, $f = 2^*R_c + R_u$, $e = 2^*R_c + R_u$, and $e = R_c$			

The two conditions for the game to be a prisoner's dilemma, ($f > c > d > e$) and ($2c > f + e$), hold if $R_c > R_{u.}$, that is it must be 'non-rival knowledge'. If this were a single meeting, the optimal action for both players would be mutual defection with collective action in collaborative research failing.[27] However, the exchange of knowledge is not likely to occur as a one-off trade. Transferring a unit of knowledge typically takes repeated interactions. Therefore, we model knowledge trading as a repeated (iterated) prisoner's dilemma.

In a repeated prisoner's dilemma, unless interactions continue forever, a player will eventually pursue their own self-interest and defect. There are two provisos to this outcome. First, if the resulting exclusion from further cooperation deters them, then cooperation might continue. Second even if interactions continue indefinitely, the value of continued cooperation must be discounted against the rewards of defecting today. As a result, in a repeated game where future returns from cooperation are not discounted substantially, a player's best strategy depends on the strategy of the other player, *i.e.* conditional cooperation or defection predominates (Axelrod, 1984, p. 15). In repeated games, a strategy that is resistant to alternative (invading) strategies is called an evolutionary stable strategy (ESS).[28] Given a two-player repeated prisoners' dilemma with the two conditions of know-how trading from above met, conditional cooperation (tit-for-tat) is ESS (Axelrod, 1984, Chapter 9). Hence, in the repeated prisoner's dilemma, collective action for research collaboration is an optimal action. On the other hand, if the knowledge being exchanged was rival, $R_c < R_{u.}$, then the conditions for a repeated prisoner's dilemma do not hold and the research collaboration will fail because the know-how would instill a competitive advantage to the agent greater than the value of the decreased production costs realized by trading.

Von Hippel's (1988) analysis of know-how sharing was among the first to examine collaborative research in a game theoretic formulation.[29] As sketched above, Von Hippel formulated know-how trading as a repeated prisoner's dilemma, with mutual cooperation being the long-run equilibrium, as long as the know-how being exchanged between agents was non-rival. Examining the conditions where know-how is non-rival, he concludes that in many instances the value of savings in the agent's marginal cost of production would exceed the value of retaining the proprietary knowledge.

Eaton and Eswaran (1997) place Baumol's (1993) elaboration of Von Hippel's (1988) model in a game theoretic framework of coalition formation. In their "technology-trading" coalitions, firms freely trade proprietary technologies with other coalition members, receipt of this information thereby lowering marginal costs of production. Defection occurs when a firm does not share its proprietary technology, giving it one round of lower marginal production costs over the other

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[27] See Abreu et al. (1991) for an elaboration of the one-shot and iterated prisoner's dilemma model.

[28] See Axelrod (1984) and Parkin (1999) for a discussion of evolutionary stable strategies in the context of a prisoner's dilemma.

[29] Allen (1983) was the first to identify collective action as a unique source of innovation.

firms in the coalition, and resulting in its subsequent exclusion from the coalition and any other coalition. They show, under both Bertrand and Cournot competition, sub-game perfect equilibrium is achieved from continued technology-trading after a defecting agent is expelled. In the Cournot case, where firms in the coalition trade technologies and then set quantities, the continued cooperation of non-defecting members imposes an ever greater cost on the defectors, the equilibrium of continued cooperation thereby sustaining collusion at even higher discount rates than when the coalition is dissolved in the event of cheating.

Collectively provided research collaboration can be divided between two components: 1) codified knowledge and information, and 2) non-codified, tacit, knowledge and information. Codified knowledge and information are subject to the legal application of (intellectual) property rights while non-codified, tacit, knowledge and information are not subject to these property right. As codified knowledge is derived from non-codified knowledge, the stock of non-codified knowledge will always be greater than the stock of codified knowledge in an innovation system. Know-how trading as discussed applies to exchanges of codified knowledge between producers engaged in some combination of horizontal and/or vertical competition. That sort of conceptualization captures only a minority of the potential inter-organizational learning. The industrial district model suggested several other learning processes, such as learning through producer-user interactions.

Richard Parkin (1999) models the Marshallian externalities in an industrial district as a coordination problem in a repeated prisoners' dilemma framework. He begins by establishing that with randomly paired players (agents), two ESSs exist: 'tit-for-tat' and 'unconditional defection', the choice depending on the discount rate and the payoff to mutual cooperation. In an industrial district, pairing is not likely to be random since the population of agents is bounded in a unique socio-territorial entity. Interactions within the local community thereby create a social analogue of non-random pairing (Parkin, 1999, p. 68). Examining whether non-random pairing increases the likeliness that 'tit-for-tat' is played, he shows that non-random pairing lowers the discount factor through which 'tit-for-tat' is played. By increasing the fraction of 'tit-for-tat' players, a rise in the degree of community (non-random pairing) thereby increases the average payoff across the population of agents (Parkin, 1999, p. 71).

Innovations from which know-how can be traded are not clearly predictable events, their frequency and scale varies from agent to agent as a partially random process. Some agents will be more innovative than others, but occasionally even less innovative agents create a highly valuable innovation. Eaton and Eswaran (2001) consider the effects of these stochastic innovations varying in value, as well as the indivisibility of innovations on the innovation sharing equilibrium.

They examine the conditions when voluntary innovation sharing is an efficient mechanism to diffuse innovations and find the prospects for research collaboration are much more circumscribed. Modeling a stage game, in each period the firms' actions and associated payoffs from innovation sharing are determined by a random probability of innovation and its associated value. In any period, mutual defection is the dominant strategy equilibrium, but because of the lower marginal costs of production that sharing generates, mutual cooperation, *i.e.* sharing, is pareto-efficient.

Eaton and Eswaran (2001) demonstrate that agent's expectations about other members' ability to reciprocate limit cooperation when the probability of innovation is random. If innovations are divisible, they found that small innovations were more likely to be shared than large innovations. However, if innovations are indivisible, only agreements to share large innovations were durable. They also found that increased homogeneity in the firms' products facilitates innovation sharing because of a tendency for greater complementarities between innovations. Lastly, they showed that over time, the degree of cooperation between firms typically varies because of the discovery of significant innovations, and fluctuations in the interest rate that affect the discount rate.

This section has highlighted important determinants of the casual conditions for research collaboration. In our case studies of historic technologies collaboratively developed on the Witwatersrand, these factors must be examined in turn. What was the minimum sub-group size necessary for provision? What was the nature of the technology collaboratively developed and was it provided in conjunction with other goods that acted as selective incentives? How significant were codified and non-codified exchanges that led to the development of these technologies? To what extent did the community facilitate cooperation? Lastly, what role did the competitive significance of these innovations play in their cooperative development? The answers to these questions should emerge through the description of the four factors that determine the group's structure. When a favorable group structure exists, we have the causal conditions for collaborative research.

3.2.3 Effects

Once a collaborative research initiative emerges, its subsequent growth or decline depends on how this provision affects and is affected by internal and external conditions. In the collective action approach these issues reduce to how collaborative research, directly and indirectly, affects net social welfare. Cooperation among agents in one activity often coexists with competition among agents in another area. For example, organizations may cooperate to avoid price competition, but compete on innovativeness or brand identification to eliminate each other as rivals (Olson, 1982, p. 203). Over time, it is likely that the environment, which supported competition in some areas and cooperation in others, will change. Therefore, in considering the effects of providing collaborative research, this section also considers the dynamic relationship between collaborative research and other activities.

Collective provision of research can raise or lower net social welfare.[30] The net effect on social welfare depends on whether there is a divergence or convergence between the group collectively providing research collaboration and society's interests. When a divergence between group and social interests exists, the group's interest is "narrow" and collective provision of research collaboration decreases net social welfare. On the other hand, when a convergence between group and social interests exists, the group's interest is "encompassing" and collective provision of research collaboration increases net social welfare.

In analyzing the effects of collaborative research, an important step is determining whether the group's interest is narrow or encompassing. The structure of the group's overlapping activities and its convention system should provide the necessary information to infer its type of interest. The nature of the group's interest is important beyond its influence on the impact of collaborative research. It determines how collaborative provision of research interacts with collective action in other areas, as well as how the group identifies with and responds to the broader interests of society.

When a group has an encompassing interest, it has an incentive to sacrifice some of its direct benefits for the betterment of society. [31] This results from their recognition of the indirect

[30] Throughout the remainder of this section, we assume collective action for research collaboration is successful.

[31] A group with encompassing interests is similar in their identity with society to that of the individual who identifies her interests with that of the group's.

benefits from improved condition in the broader population. A union's concern with the economic health of its firm or industry is an example of an encompassing interest (Olson, 1982, p. 48).

When a group has a narrow interest, it does not view development of and benefits to society in general as being coincident with their own. As such, a group with a narrow interest will seek as large a proportion of direct benefits for themselves as possible. By way of example, South Africa's history is illuminating. Before its democratization, through a complex process, a white racial minority group directed economic development towards its own self-interests rather than the broader social welfare.

Thus, a group with a narrow interest that seeks a larger portion of social benefits for themselves can be contrasted with a group that has an encompassing interest and seeks to grow the total social benefits available. Our concern with collective provision of research collaboration focuses attention on social benefits deriving from inter-organizational know-how sharing and technological development. However, as the South African example illustrates, it is possible that the resultant knowledge creation and technological progress in the interest of a group are not co-incident with the interests of society. Over time, the advancement of group welfare maybe such that eventually the broader interests of society preclude the continued collective provision of research in the narrow interest of the group. It is therefore necessary to be as explicit as possible about the group involved in collective provision and their coincidence (or lack there of) with broader society.

When collective provision is occurring in one good, be it research collaboration or anything else, the overlapping activities and convention system which support that initiative lower the risks and uncertainties involved with collective action in the provision of another good.[32] Networks of interdependencies thereby exist, with the general health of collective provision in all areas affecting each other. If our microbrewers are having problems with the collective provision of research, their collective purchasing agreement may also be strained. Mowery *et al.* (1998) provide evidence of the directed nature of inter-organizational contacts by showing complementary changes in the organizations' technology portfolios as collaboration develops.

Beyond its directly associated costs and benefits, collective provision of research collaboration indirectly affects overall social efficiency in exchange. Stable societies tend to accumulate collusion and organizations for collective action over time. These collective institutions raise the complexity of social regulation and effective policy formulation as well as bureaucratic costs. In these circumstances, despite benefits in providing a particular good or service collectively, the net effect on social welfare may be negative.

Another complication involves the variety of mobilization and organization around groups' interests in a society. Urban areas and locations with political authority tend to be more activated than other areas, as a result groups from more urban and politically central locations will have a higher likelihood of collective provision than other locations. Therefore, socially optimal outcomes may not occur through comprehensive interest group bargaining since the interests groups tend to represent narrow interests (Olson, 1982, p.39).[33]

[32] By way of contrast, in the industrial district model, similar effects are automatically assumed to operate in an environment characterized by the co-location of similar organizations.

[33] The underlying collective supply function is also a critical influence on these effects of provision.

Dynamic efficiencies in resource allocation may also suffer because of collective action. The necessity for intra-group consensus before taking action towards collective provision can slow decision-making in a group with encompassing interests. This does not mean that collective governance is less flexible than alternative allocative arrangements, such as hierarchical governance. However, there could be a loss in dynamic efficiency associated with the collective provision of a good or service.[34] A critical question emerges in assessing the extent of these effect, what equivalent knowledge and technologies could be developed with alternative methods of provision and what are their associated comparative (in)efficiencies?

Attempting to assess the comparative advantages and disadvantages of alternative research structures, when a collaborative structure exists, requires one to conduct a counter-factual analysis. If one determines it possible to develop equivalent knowledge and technologies non-collaboratively, then one must conduct a similarly rigorous appraisal of the relative static and dynamic efficiencies of the alternatives. Even if there is no alternative research structure, one needs to assess whether the collectively provided research increases or decreases net social welfare.

Again, this is no easy task and caution is needed when making policy recommendations from such an assessment. Given the current political economic structure of a society, the resultant knowledge competencies and technologies may decrease net social welfare. However, over time, that political economic structure may change and narrow interests might become encompassing. Therefore, one must consider the net effect of short run losses in comparison to long run gains, as well as the potential for short run gains and long run losses. Such an analysis is complex and requires rigorous consideration of relevant quantitative and qualitative influences.

3.3 CONCLUSION

The collective action approach to research collaboration places a great deal of attention on the vehicle through which new technologies are cooperatively created and developed. Less attention is paid to the technologies themselves. Table 3.3 presents an overview of the components in the collective action model. The convention system and the collective supply function, defined the underlying structural relationship in which collective action occurred. Overlapping activities, also help form and perpetuate incentives for collaboration. In conjunction with the collective goods themselves, these four structural factors determine whether the group structure has the causal conditions for research collaboration.

TABLE 3.3 The Collective Action Model

Structure: Components	Structure: Relationships	Causal Conditions	Effects
1) Public – Collective Goods 2) Overlapping Activities	I) *Convention System* II) *Collective Supply Function*	1) Favorable Group Structure	1) Net Social Welfare

The collective action approach provides an understanding of the dynamics driving the research collaboration and the competitiveness it supports. This dynamic conceptualization is an important advantage over the industrial district approach. However, while indirect influences on the causal conditions for research collaboration can be incorporated, they play a much more limited role than in the industrial district approach. Thus, while in principle multiple interacting activities can occur under the collective action approach doing so adds an exponential degree of complexity to an analysis and precludes clear interpretation. Further, the collective action approach assumes the predominance of active collaboration. When research collaboration is

[34] The potential trade-offs are discussed further with respect to network governance in Chapter Four, Section 4.1.

primarily occurring as an indirect product of interactions an approach focused on these, such as the industrial district, contributes more to our understanding than collective action. Therefore, complementarities between the industrial district and collective action approaches in a general analysis of research collaboration are clear.

Chapter Four:
Distributed Innovation

4.1 THE DISTRIBUTED INNOVATION ANALYTICAL TRADITION

Distributed innovation has deeper roots in the literature on the economics of technological change than the two previous models. Rather than examining innovation in isolation, innovation forms part of an economic system that includes production and non-production relationships. The approach uses systems of innovation literature as its foundation. Other traditions augment the systems of innovation literature. Prominent among these literatures is that on networks, which considers production and innovation as distributed activities.

Three features of research collaboration in the distributed innovation approach distinguish it from the majority of literatures that formed the industrial district and collective action approaches.[1] First, it assumes that production and innovation are usually distributed processes with power and authority asymmetries among agents. Second, it places the innovative process as the central investigative unit. Lastly, the distributedness (network) itself is a governance and organizational structure, capable of creating knowledge and other resources.

While acknowledging the significance of innovation for productivity growth and competitiveness, economists up through the 1950s made little effort towards the empirical study of innovation. In the 1960s, individual innovations were analyzed for the characteristics of each innovation's commercial and technical success within the constraints of uncertainty (Freeman, 1991, p. 499). In the early 1970s, determining factors of innovative successes and failures were analyzed systematically through comparative empirical studies. These studies demonstrated the importance of formal and informal networks (Freeman, 1991, p. 500). By the late 1980s, researchers had developed databases that systematically measured innovative cooperation; however, they carried an empirical focus on formal cooperative agreements.[2] An important phenomenon identified from the databases was a significant rise in (formal) cooperative agreements throughout the 1980s and 1990s. The distributed innovation tradition views these as part of a long history of collaboration in production and innovation (Coombs et al. 2001, p. 5). This position conflicts with the prevailing theory of industrial organization: transaction cost economics.

Typically, transaction cost economics places innovative or productive networks as intermediates, combining market and hierarchical governance. However, a growing number of technological collaborations in the 1980s and 1990s seemed strategic. Therefore questions emerged around the validity of formulating networks as intermediate governance structures.

In a transaction cost perspective, markets would be the most efficient mode of exchange was it not for transaction costs. Firms are competitive because of their ability, through hierarchical governance, to economize on transaction costs. There is thus an innate transaction cost burden borne by networks that could be eliminated through hierarchical organization of exchange within the firm.

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[1] In this section, the term 'distributed' is used interchangeably with 'network' and 'cooperative' and independently of whether innovative or, productive functions are being discussed.

[2] A useful industry defined database on formal cooperative agreements is the MERIT-CATI data bank. See: Hagedoorn et al. (2000), and Hagedoorn and Schakenraad (1992).

Despite the cost burden, empirical evidence documents an increasing preference for network arrangements. Within the transaction cost approach, two possibilities explain this phenomenon. First, these networks might represent temporary deviations that competition will replace. Alternatively, the networks may be an entirely new form of industrial organization (Coombs et al. 1996, p. 6).

Compared with formal research collaboration before the 1980s, the upsurge of 'new' collaborations at first seems of a different sort. When 'traditional' formal research collaboration crossed borders, they were often as substitutes for foreign direct investment and involved a diffusion of technology. Domestic collaborations of the 'traditional' sort were typically undertaken on a basis of cost sharing or cost minimization (Yamin, 1996, p. 168). Inherent to 'traditional' collaboration was an interchangeable build or buy conceptualization of research and development.[3]

The upsurge of 'new' formal collaborations in the 1980s tended to involve technologically similar firms, in leading sectors, cooperating to develop new capabilities (Freeman, 1991, p. 509). These differences in the collaborations lent some support to contentions that we were observing the emergence of a novel organizational form.[4] However, the distributed innovation tradition, and the other approaches used in this analysis, would consider both 'traditional' and 'new' collaborations part of the same long-run pattern of distributedness in economic activities.

While arguments about the emergence of a new organizational structure tend to focus on the rise of formal collaborations, several other analyses, including the case studies that follow, demonstrate the larger significance of informal strategic collaborations.[5] One needs to examine both the informal and formal dimensions of a collaboration to develop a holistic understanding of its *raison d'être*. Therefore, the increasing use of formal manifestations should not be taken as a new phenomenon, rather they indicate a change in the process (mode) under which distributed innovation occurs.

The heart of the distributed innovation's analytical tradition is the systems of innovation literature, i.e. national, sectoral, and technological systems (Coombs *et al.* 2001, pp. 7-11). Explicit roles are attributed to the external, as well as the internal, learning environment in any individual economic agent's (organization's) competitiveness and innovativeness. The distribution of innovative and productive activities forms a distinct governance structure and organizational form, with its own identity and momentum. This conception lends itself to a network analysis of research collaboration as a distributed process. There are several types of network investigations, stemming from the concept's use in a variety of disciplines and contexts. Accordingly, a brief review of the network tradition applied to analyze distributed innovation concludes this section.

The network concept originated as an engineering tool for management of complex systems like communications and transport. In the 1960s and 1970s, sociologists used it to analyze norms, exchange, and power (DeBresson and Amesse, 1991, p. 363). In the late 1970s, a network representing coalition structure was added to a cooperative game theoretic model. This introduced variability in the value of cooperation based on the structure of the coalition (Dutta and Jackson, 2001, p. 4). It was not until the mid-1990s that analyses began to directly examine cooperative network structures, rather than representing them by various configurations of

[3] This is a stark simplification, ignoring the role in organizational learning, which in-house research plays (Chesnais, 1996, p. 28).

[4] See Teece (1996) and Larédo & Mustar (1996).

[5] See for example Lorenz (1992), Vincenti (1990), Barden and Good (1989), and Braun and Macdonald (1978).

coalitions. The network as an analytical tool is still maturing, stability and efficiency conditions as well as its dynamic formulation being prominent areas of modeling development (Dutta and Jackson, 2001, p. 16-17).

At one level, networks represent relationship structures, but they are more than the sum of their interacting components. Within the economy, the nature of the goods and services strongly determine the value of network governance and organization. Generally, networks are most powerful when trust and commitment to trading partners is important and vice versa. This occurs in learning and innovative situations, where product quality is variable and non-contractible.[6] Further, early in a technology cycles when tacit knowledge is particularly important, networks are likely to be a superior governance structure.

4.2 A DISTRIBUTED INNOVATION MODEL FOR ANALYSIS

The distributed innovation model used in the present analysis is based on Coombs, Harvey and Tether (2003) and Coombs, Richards, Saviotti and Walsh Eds. (1996). Distributedness is held, in line with associated literature on networks, as unique governance and organizational structure. The structural relationships and components of the distributed innovation model are given in Section 4.2.1. This is followed in Section 4.2.2 by a discussion of the causal conditions for the emergence, the sustainability, and the subsequent decline of a distributed innovative structure. As with the other analytical models, review of the model concludes in Section 4.2.3 with a summary of the origins and consequences of effects from distributed innovation.

4.2.1 Structure

Structural Relationships

We assume every economic agent has some contact with other agents in the course of their operations. This contact may be limited or extensive and inter- or intra-organizational in nature. If inter-agent contact is more than a once-off occurrence, it forms a relationship subject to some existent authority and governance structure. In an organizational environment, a basic distinction exists between two types of relationships. First, are relationships primarily based around the provision of a product(s). Second, are relationships primarily based around the provision of innovation(s). These two types of structural relationships will obviously overlap and vary dynamically. Nonetheless, the distinction is crucial to differentiate between collaborative production and collaborative research activities.

Product Provision

Product provision encompasses those operational activities directly involved in the transformation of resources into other goods and services. Agents involved in providing a product are classified by their general economic functions, regardless of their sector or nation, which form the industrial division of labor in market economies. Artificial borders that legally define operating entities are thereby pushed to the background. Focus rests firmly on the real network of relationships that transforms factor inputs into products.

Mutual dependencies are one type of relationship through which product provision occurs. These inter-class relationships between economic agents are 'vertical divisions'. An example of a

[6] In highlighting this, Bowles and Gintis (2000) point out that these are also features of services and the increasing importance of the service sector in our modern economy will support an increasing role for network governance.

vertical division with four classes of agents would be a (diffused) production value chain consisting of raw materials, manufacturers, retailers, and consumers. Each class of agent is dynamic and socially differentiated. A new class of economic agent, say distributors, may emerge while others, perhaps retailers, may disappear over time.[7] In some instances, several classes of economic agents have similar qualitative relations to the production configuration; these can be differentiated by the nature and extent of their mutual dependency.

Another differentiation in product provision is along distinct stages of production, which run parallel to each other without an intersection in their classes of economic agents.[8] These stages of production are 'parallel divisions'. A parallel division might exist between gambling and food retailing. The existence of a parallel division indicates there are extremely limited vertical relations of mutual dependency. As with vertical divisions, parallel divisions are dynamic processes. For instance, introducing slot machines near checkout counters at a supermarket would remove the parallel division between gambling and food retailing.

Innovation Provision

Innovative activities involve input and output processes. Innovative inputs can be distinguished by their source and nature. When formed around a relationship of mutual dependency, either directly in the innovative process or indirectly through output feedbacks or productive relationships, the source of the innovative input is considered ongoing. If the innovative input was only brought in on an *ad hoc* basis when need, the source of the innovative input would be considered transient. The distinction between transient and ongoing innovative inputs is significant since it tells us whether the input is in some way permanently deployed within an innovation system or not. We identify four sorts of innovative inputs that can be either ongoing or transient to an innovative-productive network: those from human capital, those from organizational routines, those from learning-by-doing, and those from output feedbacks.

Knowledge is of two sorts: tacit and codified. Codified knowledge is expressed and transmittable through media in a formal systematic manner, even if these might be culturally specific. Codified knowledge might then be thought of as 'book smarts' and is the sort of knowledge that formal education typically instills in its pupils. On the other hand, tacit knowledge is that which is known, but not explained. It is 'heuristic, subjective and internalized knowledge [that] is not easy to communicate and is learned through practical examples, experience and practice' (Senker and Faulkner, 1996, p. 77). Tacit knowledge underwrites codified knowledge by providing the basis to understand and apply it. Codified knowledge therefore depends on tacit knowledge, but tacit knowledge can exist on its own.

Following Senker and Faulkner (1996), there are two processes of codifying tacit knowledge: through research and through routinization. When research results in codification, it may be differentiated by type. If the research sought to advance the (codified) knowledge frontier, the resultant knowledge codification is 'knowledge-push'. Alternatively, when the research seeks to provide codified solutions and/or understanding of a phenomenon in the production process, the resultant knowledge codification is 'technology-pull'. Lastly, tacit knowledge may also be codified through routinization. This occurs when previously successful practices are applied to new areas in expectation of their providing codified solutions.

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[7] Specialization increases the aggregate number of classes of economic agents performing different functions.

[8] This formulation is akin to the French notion of a *filière* containing the value-added stream of a given vertical configuration. Several parallel divisions thereby represent distinct *filières*. See Jacquemin and Rainelli (1984).

Despite efforts to codify knowledge, there are several reasons why tacit knowledge is continually important for innovation and these form inherent reasons for distributedness in innovation.[9] First, as codified knowledge and techniques advance they generate additional tacit knowledge. There is also an adherence to 'practices that work', which perpetuates tacit knowledge as business organizations incur costs in codification and risk losing competitive advantage. Finally, technological complexity inhibits codification and this tends to increase relatively as new technological systems are developed (Senker and Faulkner, 1996, pp. 83-84).[10]

Tacit knowledge, while originating from the same sources as codified knowledge, tends to be most efficiently transferred through repeated interactions.[11] Thus, a network structure is a reasonable representation of knowledge transfer when its tacitness is relatively significant. When tacit knowledge pre-exists, it resides in and may be transferred through a social network.[12] However, while access to tacit knowledge may be socially based, if the knowledge is generated through research, that knowledge resides within the relevant theoretical field's network. Hence, inter-personal interactions are less important and 'virtual communications' can play a significant role.[13]

The outputs of innovative functions are characterized by their relationship to productive functions. Consequently, those related to cognitive functions are referred to as 'learning' while those related to creation of technological artifacts are referred to as 'technological development'. Both are resource using and creating processes, but over time and on average we assume they enlarge the net stock of resources through productivity improvements. Learning and knowledge are prerequisites for technological development, but while feedbacks from technological development can support learning, it is not a certainty.[14] Dodgson (1996) describes learning in a business organization, which forms a definition of learning used throughout the case studies in this analysis. 'Learning can be described as the ways firms build, supplement and organize knowledge and routines around their competencies and within their cultures, and adapt and develop organizational efficiency through the use of these competencies' (p. 55).

Learning occurs within a market environment beset by uncertainty; it offers gains from enhanced efficiency, but at the same time destabilize routines, which insulate the organization from the vagaries of the market. The governance structure under which an organization learns engenders particular learning trade-offs. Predominately market-based exchanges work most efficiently transmitting codified data and information. When exchanges are primarily hierarchical and networked, learning trade-offs become more context specific. In a hierarchically dominant organization, such as a large vertically integrated 'Fordist' firm, information flows are typically uni-directional. While this hierarchical form has a long and successful history, lately organizations with more extensive inter- and intra-organizational networked exchanges seem to hold a distinct

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9 Tacit knowledge is extremely difficult to contract and therefore is more efficiently arranged under distributed or hierarchical governance.

10 Cowan (2001) examines the process of knowledge codification and its limitation with various types of tacit knowledge.

11 Tomlinson (1999) uses longitudinal career data to trace uncodified knowledge carried by occupational mobility and locate centers of learning as well as tacit knowledge flows.

12 Cowan and Jonard (2001) use simulations identify the structure of networks that facilitate optimal creation and circulation of scientific knowledge.

13 For a review of the knowledge transfer process and the effect of information and communication technologies see Cowan et al. (2001).

14 Knowledges with differential power forms a methodology of knowledge and its organization in Jørgensen (1999).

competitive advantage.[15] These new challengers to Fordist hierarchical dominance take a variety of structural forms, from Japanese manufacturing giants to small firms in industrial district (Morgan, 1996). The challengers share innovative and productive functions in which learning occurs under predominantly networked governance.

Structural Components

The networked provision of a product or innovation often utilizes established relationships with other agents. This creates a situation where path dependency or at least a tendency towards a fixed, yet adaptable, pattern emerges. These tendencies form 'instituted economic processes', which are the structural features of an economy. Analyzing research collaboration, our general concern is with instituted modes of distributedness, but more particularly with instituted modes of distributed innovation.

An analysis of the mechanisms of competition and coordination between agents is fundamental to understanding these instituted modes of distributedness. In addition to ex-post insights, these mechanisms are crucial influences on the dynamic patterns of provision and innovation. Therefore, our ex-ante ability to analyze and make policy recommendations regarding distributedness also hinges on our understanding of these structural components.

Innovative Object of Analysis

Distributed innovation emphasizes the innovative process characterizing the case study's research collaboration. Therefore, the actual objectives of these innovative efforts are a central feature. It is not details of the 'technological artifact', but its impact on structural inter-relationships and the dynamic transformations of these interrelationships that are of particular concern. Technological characteristics of the artifact do play a role in the distributed innovation approach;[16] it is just that analytic focus rests more on the process than the product.

Mechanisms of Economic Coordination

Inter- and intra- class relationships of economic agents form mechanisms through which economic coordination is organized and regulated. The quality of these relationships between and among classes of economic agents partially defines the degree of trust and reciprocity. Through its direct relationship to the frequency of interaction between members, *i.e.* a homogeneous group interacts more frequently than a heterogeneous group, and thus, as with the collective action approach, homogeneity of the group determines the quality of relations, and in turn trust and reciprocity. In the distributed innovation approach homogeneity can be based on profession, ethnicity, gender, race, geography, religion, or ideology. Since trust rises with homogeneity, environments with strong homogeneity will be characterized by relatively more distributed economic activities (Powell, 1990, p. 326).

The inter- and intra- class relationships are closely related to the overlapping activities discussed in the collective action approach, and the mechanisms these relationships form to organize and regulate coordination are akin to the role played by the convention system in that approach. Trust and reciprocity thereby facilitate distributedness by limiting competitive exploitation of

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[15] This phenomenon has previously been mentioned with respect to the present approach in Section 4.1 and the industrial district approach in Chapter Two, Section 2.1.

[16] Mangematin (1996, pp. 125-126) proposes specific relationships and constraints from the technical artifact on the organizational structure of innovation.

exchanges and by providing durability, which insulates members against exogenous change and distributes the costs of establishing relations (Dodgson, 1996, p. 69).

Distributed innovation is more explicit than the collective action approach in its introduction of the role played by power and mutual dependency in vertical divisions as a mechanism of inter-agent coordination. A vertical division (value-added chain) is characterized by relationships of relative power disparities among the differentiated inter-class functions of agents. The concentration of agents within any given class determines the intra-class substitutability of agents and thereby their intra-class power. The inter-class power of an agent depending in turn on both the power of the class in which they reside and their authority within that class. As a result, a shift in a class's inter-class power will also affect economic coordination within that class's agents.

Conceptualization of vertical and parallel divisions requires an expansion in the notion of power beyond that of concentration within a class of economic agent.[17] Within a vertical division, power can also reside in that ability to control access to various resources, such as to finance, to markets, to knowledge, or to labor. As such, it opens opportunities for one class of economic agent with an identified and common interest to wield its power to realize coordination across parallel divisions. These coordinative abilities are not limited to collective product provision, similar relationships are present within the provision of innovations as well as between productive and innovative provisions.

Mechanism of Competition and Cooperation

Classical 'direct competition' typically occurs between organizations producing a comparable output, which is within the same class of economic agent (Coombs *et al.* 2003, p. 20). The diffused innovation approach admits the possibility of competition between different classes of economic agents. This 'indirect competition' occurs as the different agents seek to increase their share of rewards along the value chain. Direct competition can also occur between broadly comparable parallel divisions, such as oil and coal. Likewise, indirect competition can also take place across production networks.

Using this conceptualization casts analysis of cooperation and competition in a different light. End consumers are distinct economic agents, a unique class required for every vertical configuration and often spanning several parallel divisions. They form a component, subject to and instigating societal and dynamic change in the value chain, across productive and innovative functions. Adopting this perspective avoids an analysis of research collaboration embedded in a supply-side or demand-side model. Rather, the innovative process of concern is framed by different demand-supply configurations (Coombs *et al.* 2003, p. 27).

The mechanisms through which a balance of competition and cooperation is established are networked structures, defined by the relationship between and within classes of economic agents, vertical division of production configurations, and the borders of parallel divisions. This is an important point of departure from traditional analyses since it allows for systematic description of simultaneous competition and cooperation within and between classes of economic agents. With this background on structural characteristics, attention turns to the causes and effects of collaborative research in the distributed innovation approach.

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[17] This means an analytical move beyond single market concentration to locate structural concentrations of power between classes of ecnomic agents.

4.2.2 Causal Conditions

In the distributed innovation approach, as the name suggests, distributedness pervades innovative and productive activities. However, only under certain conditions will collaboration (distributedness) dominate these processes. This section discusses the causal conditions for innovation to be primarily a distributed process, *i.e.* it discusses the causal conditions for collaborative research.

The present distributed innovation model of research collaboration assumes that resources are allocated, exchanged, and governed by three modes: the hierarchy, the market, and the network (distributedness). A variety of factors influences the dynamic division of economic functions among classes of economic agents. These factors create and destroy classes of agents as well as changing the coordination and distribution of economic activities among them. Certain contextual conditions act as 'pull-factors' favoring networks as the predominate mode of resource allocation, exchange and governance. In addition, certain decision criteria or 'push-factors' also favor a distributed mode. The combination of these push and pull factors form the constraining circumstances for research collaboration.

Pull Factors

Generally, distributedness requires a context in which inter-agent exchange generates a benefit. Powell (1990) defines this condition as: "The basic assumption of network [distributed] relationships is that one party is dependent on resources controlled by another and that there are gains to be had by the pooling of resources" (p. 303). These realized or potential gains from non-market and non-hierarchical inter-agent resource exchanges are the pull-factors of distributedness. We can identify three pull-factors favoring distributed innovation: 1) The rapid processing and application of information about a technology 2) The exchange of intangibles and 3) the ability to facilitate the establishment of technological standards.

In some situations, the ability to rapidly process and apply information about a technology instills a competitive advantage that acts as a pull-factor favoring distributed innovation. For instance, during periods when new technologies are adopted and developed or when established technologies are significantly changed, a timely response by concerned economic agents becomes a priority.[18] The distribution of innovation across a network facilitates swift evaluation of new technologies, and generates systemic performance information and learning through evaluation. Hence, the comparative speed of a network encourages its rise over market or hierarchically based arrangements (Powell, 1990, pp. 325-326). Historical evidence shows that eras of large-scale technological change often feature research collaborations (DeBresson and Amesse, 1991).[19]

Another pull-factor favoring distributed innovative arrangements is their superior ability to exchange intangibles; be they tacit knowledge, skills, or competencies. Because of the interactive nature of distributed exchanges, they give richer qualitative details about a technology and transmit more tacit knowledge, skills, or competencies than is possible through market based exchanges. In addition, distributed innovation tends to avoid the internal structural conflicts and potentially circumscribed information exchanges because of bureaucratic competition, which

[18] Military conflict can also be a stimulus for inter-organizational innovation as noted in Thornton and Thompson's analysis of learning spillovers in America's shipbuilding yards during the Second World War (2000).

[19] This phenomenon may explain some of the contemporary rise in collaborations correlated with the 'information revolution'. It has also been noted as a feature in the second industrial revolution in Nuvolari's study of the Cornish pump (2001).

often characterizes hierarchical exchanges. As a result, when transmission of intangibles is important, such as early in a technological life cycle where a large proportion of knowledge about a technology is uncodified, distributed (networked) configurations are advantageous.

Lastly, situations where technological standards are being established tend to act as pull-factors favoring distributed innovative arrangements. Networked innovative development generates a force towards equilibrium in the search and selection of competing technologies. This force towards equilibrium among competing technologies is particularly potent when a new technology is emerging and there is a variety of alternatives with no clear indication of the ultimate successor. Therefore, in comparison to market and hierarchical exchange, a network is distinctly placed to facilitate the establishment of technological standards.[20]

Push Factors

Several incentives or "push-factors" also favor a distributed structure predominating an innovative system. Push-factors are the decision making criteria upon which management commits resources to a distributed endeavor. We can distinguish between two types of incentives toward a distributed structure. The first, leads to "intra-class" cooperation between actual and potential rivals within the same class of agents. The second, leads to "inter-class" cooperation, based on cooperation among agents of different classes, encompassing different stages of the production process and indirectly competing for placement along the value chain.

If intra-class cooperation predominates, the majority of cooperation occurs between agents primarily from the same class, *i.e.* direct competitors. An example of intra-class research collaboration could be a group of pizzerias cooperatively developing an improved pizza oven. Cooperation among direct competitors is assumed to occur with little additional economic coercion, beside the intrinsic value of cooperation itself. A common class interest from cooperation is identified among these direct competitors, actual and potential rivals alike. Identification of positive-sum gains from cooperation occurs and prevents agents from defection and reversion to atomistic behavior. Therefore, distributed innovation, forming on this basis of common class interest is distinct from that involving several classes of economic agents.[21]

When inter-class cooperation predominates, the majority of cooperation occurs between different classes of economic agents. Cooperation between a pizzeria and their topping supplier to develop a better pizza oven would be an example of inter-class research collaboration. Because each class of agent encompasses a different stage in the production process, they indirectly compete for placement along the value chain.[22] Research collaborations based on inter-class cooperation are characterized by mutual dependency and power asymmetries between classes of agents in the production configuration. With dependency, there is an implied notion of power. This power is not absolute as even in a vertical division dominated by a monopoly or monopsony there is some room for negotiations between classes of agents.

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[20] Of course, a standard is more easily imposed under a hierarchy, but if economies beyond the individual organization are to be realized the standard must be adopted by others.

[21] These 'intra-class' innovative cooperatives are related to idea of internalized knowledge spillovers in an industrial district and a 'privileged' group in collective action.

[22] However, within vertical divisions common interests are still identifiable and thereby intra-class cooperation can occur in a context that would otherwise be characteristic of inter-class cooperation.

Constraining Circumstances

Strategic considerations are often a dominant factor supporting distributedness over a market-based or a hierarchal structure. Although the strategic nature of collaboration was discussed with respect to the industrial district and collective action approaches,[23] the distributed innovation approach provides greater analytic definition by distinguishing between intra- and inter-class strategic factors. Even within the same class of agent, the negotiations associated with cooperation imply uncertainty and a dynamic distribution of power. Mutual dependencies and power asymmetries that characterize classes of economic agent, instituted formally or informally, form "the constraining circumstances of economic co-ordination", which drive the dynamics of cooperation underpinning collaborative innovation (Coombs *et al.* 2001, p.28). In our pizzeria example, a dominant pizzeria might use it power to threaten price competition if the pizzerias do not cooperate in the development of an improved pizza oven.

Three distinct forces can be identified as changing and shaping the constraining circumstances. One would be an agent's attempt to reposition themselves in the production configuration. For example if the pizzeria was using its purchases from the toppings supplier, the supplier might purchase another pizzeria in order to remove some of the value chain authority held by the original pizzeria. Another means of changing the constraining circumstances originate from external market, regulatory or technological changes. If new hamburger cooking technology emerged that was a major challenge to the pizzerias' market share, incentive to cooperatively developing a new pizza oven would be expected to be significantly higher. Lastly, the dynamic incorporation of new agents and/or the replacement of existing agents can significantly alter the constraining circumstances. The emergence of several additional pizza-topping suppliers, with the number of pizzerias staying the same, would substantially alter the balance of power between the two classes of agents.

In distributed innovation, management forms a distinct decision-making class. Their decisions must, explicitly or implicitly, consider other classes of economic agents through a calculation of their relative power and mutual dependency.[24] Management is vested with control of interests above and below their own, which we may illustratively call shareholders and labor. Their relationship to these other interests is a partial determinant of the potential for cooperative action. If management's interests are not coincident with the short-run interests of shareholders, the scope for distributed innovation is increased as narrow self-interests are, at least partially, deferred to group benefits (Tylecote, 1996, p. 35).[25]

Research collaboration occurs because of favorable push and pull factors that support a distributed structure over alternative market or hierarchical arrangements. While contextual conditions act as pull-factors, research collaboration can only occur if there is inter-agent cooperation. The nature of this cooperation differs quite a bit depending on whether it is within or between classes of economic agents. These push-factors might be an attempt by particular class of agents to capture a greater share of value-added in their vertical division or they may involve an inter-class effort to defend a vertical division from a challenge posed by an emergent technology. Regardless, both push and pull factors form the causal conditions for the emergence and durability of research collaboration.

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[23] See Chapter Two, Section 2.2.1 and Chapter Three, Section 3.2.2.

[24] The managing class can also increase (or decrease) the propensity for distributed innovation by their particular attitudes towards risk, uncertainty, and discounting of future returns.

[25] The necessity for accommodating labor's interests because of broader political economic constraints is illustrated in the case of changing stoping operations, where Afrikaner political authority limited restructuring of gold mining operations. See Chapter Eight, Section 8.2.3.

4.2.3 Effects

Theorizing about distributed innovation originates from a tradition built around empirical observations in technologically intensive and dynamic activities. This has created an analytical predisposition to the beneficial aspects of distributed innovation. Negative effects from 'networking' are not neglected, but their consideration tends to be constrained around discussions of alternative modes of organization. The focus on the distributed mode for organizing innovations also leads to less consideration of the innovation generated than the structure of distributed provision.

Innovations Generated

Innovations have different "scales" which are defined by three dimensions: 1) the extent they transform their associated productive-innovative configurations, 2) their technological complexity, and 3) their dynamic evolution (Coombs *et al.* 2001, p. 29). By definition then an innovation's scale rises with any combination of longer innovative time frames, a greater complexity of technologies, or by the degree to which its impacts on agents' costs transform productive functions. Through its transformation of the productive functions, an innovation's scale affects the relationships within and between classes of economic agents. For instance, an innovation may increase the value and power of a distributor in a value chain. As a further result, the distributor(s) may then devote further resources to increasing their power and value captured along the value chain, which may alter the path of subsequent innovative developments.

Distributed Relationships

All distributed processes involve a divesture of authority from the individual agent to the distribution. There is then, from the individual's perspective, a potential cost from this lost autonomy. Dependency is placed on the research collaboration whose operation is by definition of limited control to an individual agent. Distributedness also represents a potential loss of competitive advantage from diffusion of innovations to actual or potential rivals (Tylecote, 1996, p. 40).

In terms of social efficiency, distributed innovation limits the potential actors with whom one engages in exchange. The network defines whom one interacts with and thereby may prevent an agent from finding (or accessing) a trading partner for a mutually advantageous exchange (Bowles and Gintis, 2000, p.11). Networks represent barriers to new entrants and there by competitive advantage or disadvantage for those within, without, or competing between networks (Powell, 1990, p. 305). As a structural feature, this exclusionary nature of networks can be an innovative disadvantage.[26] Nonetheless, from the perspective of social efficiency, distributed innovation assumes that when a networked structure predominates, it is the result of its being the most efficient organizational structure, unless there are distortionary incentives.[27]

An example of placement within a network and exclusion from alternative networks influencing the survival of a business organization comes from the competing Beta-max and VHS video standards (Coombs *et al.* 2001). While technologically the Beta-max design was as good as (if not superior to) the VHS standard, the VHS network proved competitively superior. An enterprise with strong ties to the Beta-max standard would likely have suffered adverse consequences from

[26] This may or may not equate to being a technological disadvantage.

[27] An example would be public sector subsidies of collaborative research.

its allegiance to that distributed arrangement. Therefore, those aligned to the Beta-max network could be said to have incurred a competitive disadvantage compared to those in the VHS network.

Durable connections found in networks enhance trust and reciprocity, which generates a favorable environment for economic exchange. Strong(er) social capital may thereby be created from distributed processes. As an environmental feature, this lowers contracting cost as an increased spectrum of economic exchanges can be relatively less completely contracted. There is also an enhanced reduction of uncertainty directly associated with elevated social capital. Where networks have a strong influence then, in comparison to alternative structures, there will be a general reduction of risk and uncertainty in all aspects of economic activity.[28]

The inherent advantages of distributed innovation in dealing with innovative contexts in which tacit knowledge and systemic activities are required have also been mentioned previously. A major benefit deriving from distributed innovation is its spreading of risks and decreasing of financial hurdles to innovative development. In comparison to market of hierarchical organization, distributed innovation is probably a less expensive route, and if absorptive capacities are reasonably similar, faster (Tylecote, 1996, p.40).[29] Steward and Conway (1996) raised another positive aspect of distributed innovation concerning social structures. They point out that the interaction of agents founded around distributed innovation creates a tendency for agents to become more similar. In a way, this is the same as the generation of trust and reciprocity already mentioned, but it is deeper. These interactions dynamically transform agents and facilitate incorporation of ideas and information from socially distant economic agents (Steward and Conway, 1996, p.205). This generates a wealth from diversity in the network, raises the issue of the influence network structure has in determining performance, and thereby whether the net effect of distributed innovation is positive or negative.

Distributedness not only transforms the agents, but the innovations generated as a result. As touched upon in the description of innovations generated by collaborative research above, stable environments support particular modes of distributed innovation that are reflected in the character of innovations produced. This occurs as 'Fairly long historical periods can be characterized by the (coordinated) dominance of one class of economic agent over a whole value chain, during which production and innovation processes occur as "normal business" within particular parallel sectors' (Coombs *et al.* 2001, p. 24)[30]. Through the technologies they create, innovative systems reinforce existing power and dependency relationships in a value chain.

4.3 CONCLUSION

Distributed innovation uses the systems of innovation approach to create an analysis whereby research collaboration is central, but not necessarily predominant over other structures which facilitate competitiveness. Table 4.1 presents an overview of the components in the distributed innovation model. Through its utilization of networks, distributed innovation allows interactions to facilitate inter-organizational research collaboration. In so doing, it does not limit itself to

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[28] These are also characteristic effects of an industrial district, Chapter Two, Section 2.2.3, and collective action, Chapter Three, Section 3.2.2.

[29] In Ernst's (1998) examination of the causes behind Taiwan's competitiveness in personal computer components, inter-organizational knowledge is shown to be a critical component driving its competitiveness. This interaction was not just between the state and domestic businesses, but contained important international networks that facilitated the sector's economic development.

[30] This seemingly opens a novel interpretation of the role played by the prominent and durable position of South Africa's mining finance houses on its economy.

geographically proximate interactions like the industrial district approach. Rather, interaction can occur in a geographically dispersed setting across the network.

TABLE 4.1 The Distributed Innovation Model

Structure: Components	Structure: Relationships	Causal Conditions	Effects
1) Innovative Object	I) *Product Provision*	1) Push Factors	1) Distributed Relationships
2) Mechanisms of Coordination	II) *Innovation Provision*	2) Pull Factors	2) Innovations Generated
3) Mechanisms of Competition		3) Constr. Circumstances	

Another important advantage to the distributed innovation approach is its allowing for both intentional and unintentional innovative collaborations, both are taken as part of a general inter-agent innovative process. The distributed innovation approach does have its drawbacks. Its analytical framework was developed for analysis of relatively developed innovative systems. Nonetheless, distributed innovation provides a strong foundation upon which a comprehensive methodology for the examination of research collaboration could be established.

Chapter Five:
A Review of Approaches to Collaborative Research

5.1 INTRODUCTION

An increasingly important feature of the global economy is inter-agent coordination in production and innovation. Several characteristics of the modern economy seem to support an increased use of collaborative research.[1] These attributes have led to research collaboration being put forward as a defining characteristic of twenty-first century innovation, replacing the in-house R&D department that characterized twentieth-century innovation, and the inventor-entrepreneur that typified nineteenth-century innovation (Freeman and Soete, 1997, p. 225). Through analysis of the case studies that follow, research collaborations are shown not to be new phenomena, but features of the innovation process with a long and important history. This chapter begins with a contextual review of the three approaches to research collaboration, it then summarizes important features of each as well as methodological differences and similarities.

Technology policy has followed the analytical attention given to collaborative research, enhancement of collaborative research being a goal in many national and regional technology policies. Perhaps the best example of this promotion of research collaboration is in the European Union (EU), where there are three major initiatives actively promoting research collaboration. These initiatives are its Framework Programs, aimed at creating an integrated European research system, its EUREKA program, strengthening European competitiveness by facilitating inter-organizational research cooperation, and its COST framework, supporting coordination of nationally funded research on a European level. The importance of collaborative research for contemporary innovation policy is highlighted in one of the recent EU Framework Programs: "Organising co-operation at different levels both within Europe and internationally, co-ordinating national or European policies, networking teams and increasing the mobility of individuals and ideas is therefore a requirement resulting from the development of modern research in a global environment" (European Commission, 2002b, p. 4).

The rising number of formal research collaborations during the 1980s and 1990s coincided with a general increase in the number of inter-firm collaborations in a variety of productive activities (Hagedoorn, 2002, p. 479). Theoretical analysis of research collaboration has largely followed this rise in formal collaborations, resulting in a methodological bias toward the formal aspect of collaborative research. A review of literature on research partnerships gives a flavor of the typical treatment given to informal research collaboration: "Very little is known about informal partnerships. We do know that many firms informally partner with one another in short-term research endeavors, but by the fact that they are informal there is not a systematic way to track these partnerships quantitatively much less study them in detail" (Hagedoorn *et al.* 2000, p. 569).[2]

Research collaborations, be they predominately formal or informal in structure, should generate, and/or diffuse knowledge between agents. Knowledge is a non-standard good with varying degrees of codification and tacitness. As the tacitness of knowledge rises, it becomes increasingly rooted in practices and not easily transmitted through formal media like journals and reports. With high degrees of tacitness, the most efficient transmission of knowledge is through structures that facilitate direct interaction. Thus, as two (or more) agents consider entering or

[1] See Smith (2002), Archibugi & Lundvall eds. (2001), OECD (1996), and DeBresson & Amesse (1991).

[2] As increasing attention is being paid to research collaboration, recent analyses have given more explicit attention to informal aspects of research collaboration. See for example Baumol (2002) and Nelson (2002).

continuing a research collaboration, the nature of the knowledge expected from the collaboration influences the structure of that research collaboration.

Figure 5.1 A Conceptual Map of Comparative Methodological Coverage

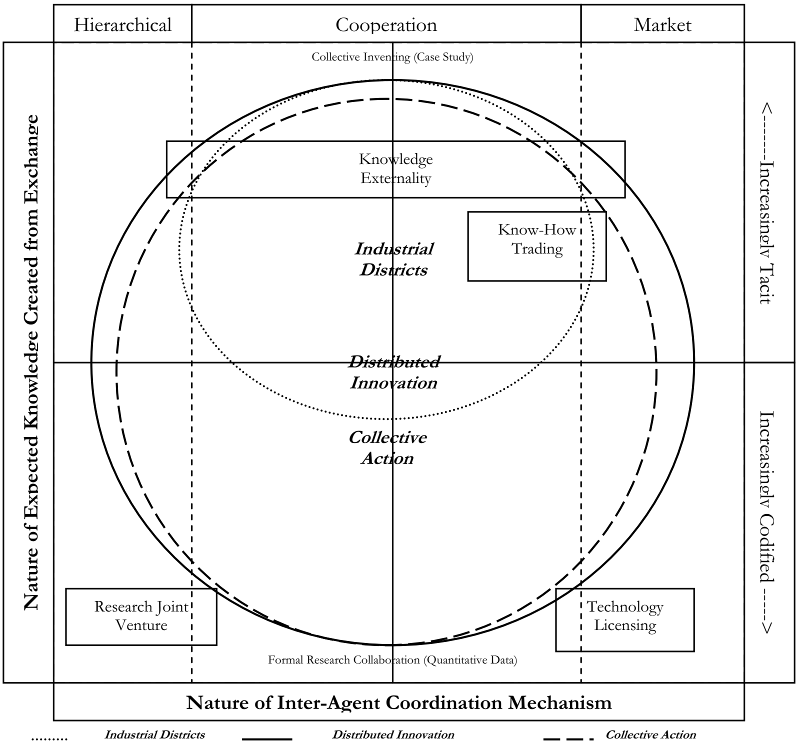


Figure 5.1 above depicts four collaborative research structures and the three approaches to collaborative research according to the nature of their expected knowledge and their predominate inter-agent coordination mechanism. Along the vertical-axis, Figure 5.1 represents the nature of expected knowledge created from exchange, with highly tacit knowledge to the north and highly codified knowledge to the south. The horizontal-axis portrays the predominant inter-agent coordination mechanism with hierarchy to the west, through cooperative coordination in the center, and on to market based coordination in the east.

In the figure, both formal research joint ventures and technology licensing generate relatively codified knowledge from their exchanges, but neither is coordinated through a predominately cooperative governance structure. In contrast, knowledge externalities and know-how trading tend to be predominantly cooperative structures although diverging somewhat in their level of tacitness and by the expansiveness of their coordination mechanisms. We discuss characteristics of the three approaches depicted in Figure 5.1 in detail below, but it is worth noting that the industrial district approach tends to focus on relatively tacit and predominately cooperative exchanges while both distributed innovation and collective action encompass broader perspectives. In general, tacit technologies tend to be cooperatively coordinated, while codified technologies tend to be coordinated hierarchically or through the market. By way of illustration, when there is an emergence of a new group of innovations, like biotechnology in the 1990s, where tacit knowledge is high, we would expect the role of cooperative governance to be high, anecdotal evidence of this is found in the geographic concentration of biotechnology organizations in the Silicon Valley.

There are empirical analyses supporting the hypothesis that geographical concentration facilitates the transmission of tacit knowledge. Jaffe, Henderson, and Trajtenberg (1993) used patent citations to trace the pattern of knowledge localization. They found supporting evidence for geographic concentration in the fact that the frequency of patent citations was correlated to the patents' state of origin. Audretsch and Feldman (1996) found that in industries where new knowledge plays a more important role, there is a greater propensity for innovations to cluster geographically. Finally, Feldman and Lichtenburg (1997) used indicators of knowledge tacitness from R&D projects in the EU CORDIS database. Projects that generated relatively codified results, such as processes and prototypes, were less centralized than projects that generated relatively tacit results, like new methodologies, skills, and know-how. The hypothesis that geographic concentration of projects generated relatively tacit knowledge was supported by evidence that those projects which yield above-average publication or announced results, that is codified outputs, tended to be more geographically decentralized.

Central to some popular discussions about the knowledge economy is the 'death' of distance because of increasingly prevalent information and communication technologies (ICTs).[3] This simplification misrepresents the reality of ICTs influence on collaborative research. ICTs enable the creation of 'virtual' concentrations, such as a community of open-source developers, but not every technology develops in these settings. Where ICTs appear to really be making a marked difference is in their facilitating increasingly specialized physical locales that are inter-connected and coordinated through ICT supported networks (Feldman, 2002). Hence, a more appropriate incantation would be distance is dead, long live distance. The cases in this analysis will demonstrate that co-location was terrifically important, but access to global knowledge networks was also crucial. While it is not a contention that the rise of ICTs is non-revolutionary, it is a revolution with precedents.

Through its comparative application of methodologies that consider both informal and formal dimensions of research and productive collaborations, this analysis marks an important step in advancing theoretical and empirical understanding over this complex phenomenon. Tracing two sequential cases of innovation where research collaboration has an important role, this analysis highlights critical dynamic features. In particular, it shows that as the industry and technology change, the structural relationships and causative forces in research collaboration evolve. Associated with this, the explanatory insights of the respective methodologies also vary.

Each methodology has a distinct set of associated causal conditions for research collaboration. The industrial district approach examines special factor endowments, collective action considers favorable group structure, and distributed innovation analyzes push and pull factors. None of the methodologies attempt to cover all of the causal conditions for research collaboration. Even collectively they do not form 'the cause' of research collaboration, instead they are a selection of factors that developed through each of the approaches distinct analytical traditions. Hence, when we consider the complementary understanding of both cases developed through all the approaches, shortcomings in even a relatively comprehensive approach like distributed innovation become apparent. This analysis does not attempt to decide which methodology in

[3] See for instance Cairncross (1997).

'the best' for a particular case or comprehensively. In each case all of the approaches are applied, thereby bringing attention to as many facets of research collaboration as possible.

Until we derive a better understanding of the complex nuances of innovation and its inter-relationship to productive activities it is premature to propose a comprehensive methodology on the causal conditions for research collaboration. As such, given our current knowledge, the best way to analyze existing research collaborations, their creation, growth, and destruction, as well as to formulate policies to enhance their positive benefits is through a process of appreciative theorizing at a level close to the empirical subject matter. Before turning to a comparative summary of the approaches, we briefly review each methodology in-turn.

5.2 THE APPROACHES

5.2.1 Industrial District Approach

Features of the Methodology

Chapter Two described the industrial district approach. While Marshall was among the first economists to identify localized inter-organizational positive externalities, it was not until the late 1970s that the concept became popularized through it application to an increasing number of small, but internationally competitive, localized industries in Italy. The ability of small and medium enterprises in the Italian industrial districts to challenge large hierarchically organized firms offered an important alternative to predominating notions of positive economies of scale being realized only through an internalization of operations.

Table 5.1, below, reproduces the summary of features in the industrial district approach from Chapter Two. There are five structural components in the model: human resources, firms and institutions, markets, community and the socio-territorial entity. There are two principal types of markets in an industrial district, product and factor markets. The externally oriented product market is in a specialized good or service which the district is assumed to have a competitive advantage. Contacts in both the product and factor markets facilitate coordination and collaboration in the district. The geographically defined boundaries of endogenous actions demarcate the socio-territorial entity. Firms and institutions are effectively the agents of innovation in the district and include all organizations and institutions directly or indirectly involved in the local production, knowledge, and socio-political systems. Human resources in the district influence and are influenced by the production process and are defined by their power relationships with the production, knowledge, and socio-political systems. There are two communities in a district the business and the social, overlay between them sustains planned cooperation. As such, the district's community generates trust which constrains self-interested behavior.

TABLE 5.1 The Industrial District Model

Structure: Components	Structure: Relationships	Causal Conditions	Effects
1) Socio-territorial Entity	I) *Production System*	1) Special Factor Endowments	1) Agglomeration Externalities
2) Community	II) *Knowledge System*		
3) Firms & Institutions	III) *Socio-Political System*		
4) Human Resources			
5) Markets			

The three structural relationships in a district are all geographically defined systems: production, knowledge and socio-political. The socio-political system is a counterpart to the district's community in that it uses the stock of trust to enforce cooperation. The socio-political system also responds to change in the production and knowledge systems altering the scale and scope of competition and cooperation in the district thereby. The production system defines the structure of local inter-firm production in a core activity, around which ancillary resources arise to enhance its competitiveness. Through the production system, economies external to individual firms are internalized within the district. Lastly, the knowledge system includes all flows and stocks of knowledge within the territory. The specialized nature of an industrial district means that a community of knowledge develops, which makes the knowledge system a major force in determining the district's endogenous competitiveness.

In the industrial districts approach the presence of three special factor endowments form the causal conditions for research collaboration: 1) complementary human and natural resources, 2) connections with external markets, and 3) local entrepreneurism. These special factor endowments need not be present in equal strength for an industrial district to emerge, as just one or two of these factors may dominate the causal conditions for research collaboration. Whatever the combination, beyond some critical point, the presence of these special factor endowments leads to the emergence of a district. Hence, the causal conditions for research collaboration in the industrial district approach are largely fortuitous.

Once an industrial district is created, its growth or decline depends on the subsequent co-location of firms/agents. This co-location of firms/agents *i.e.* whether to stay in, move to, or move away from a location, depends on the comparative strength or weakness of three factors: 1) agglomeration externalities 2) price competition 3) transport costs. In the cases that follow, we can ignore the effects of price competition and transport costs. Therefore, the net effect of agglomeration externalities determines the growth or decline of a district. Since the predominance of negative agglomeration externalities would be deleterious to the district's continued existence, most analyses feature positive agglomeration externalities that increase the districts' competitiveness and socio-economic welfare. This analysis identifies six categories of positive agglomeration externalities: 1) technological externalities 2) labor market pooling 3) inter-firm demand pooling 4) concentration of research activities 5) production network access and 6) complementarities from co-location. The three categories of negative agglomeration externalities include: 1) exposure to sectoral downturn 2) limited market demand 3) excessive localization *i.e.* congestion, pollution and resource scarcity.

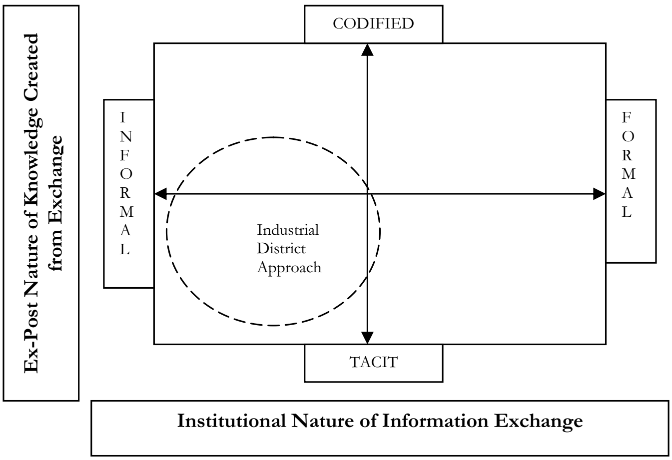
In the industrial district approach, research collaborations tend to feature localized mobility of human resources. This mobility driven knowledge creation is assumed to be positive and enhance the district's competitiveness. As a result, there is little analytical scope for strategic knowledge creation. There maybe negative dynamics associated with this localized mobility, such as firms free-riding on the training of a mobile workforce. This might be accepted because of the strategic value placed upon inter-firm knowledge creation that would be lost if they attempted to limit the negative dynamics, *i.e.* restrict worker mobility. However, the bias towards positive collaborative learning effects typically precludes their analysis in the industrial district approach.

The industrial district approach gives a central role to a diffused local knowledge system in enhancing a district's competitiveness, but it does not incorporate a comprehensive formulation of technological change.[4] In concluding this discussion of the industrial district methodology,

[4] OECD (2001), Baptista (1998), Baptista and Swann (1998), Bell & Albu (1999) are examples of recent efforts toward more thorough integration of technological change into industrial district analyses.

Figure 5.2 places the approach within a typology of research collaboration. This is not a comprehensive typology of research collaboration, it merely indicates the comparative scope of the methodologies used in this investigation. In the figure, the nature of information exchange, formal or informal, and the ex-post nature of knowledge created from the exchange defines the approaches. Thus, the industrial district methodology is placed in the lower-left quadrant with its analytical focus on research collaborations that are principally informal and involve tacit knowledge creation.

Figure 5.2 The Industrial District Approach in a Typology of Research Collaborations



An Inter-Methodology Comparison

The industrial district approach emphasizes externalities. Therefore, when applied to analyze research collaborations it tends to focus on the conditions underlying collaboration rather than the collaboration itself or the technology generated from the research collaboration. This is in contrast to the collective action and distributed innovation approaches. Collective action focuses on the vehicle through which research collaboration occurs and on the purposeful measures supporting collaborative research. Distributed innovation focuses on the relationship between research collaborations, the technologies generated because of them, and the effect these have on cooperation and competition dynamics.

Describing the context of agglomeration externalities places the industrial district approach into a static or comparative static framework. Thus, the industrial district approach provides useful insights into the structure of research collaborations that are largely informal. Nonetheless, the approach does not add much understanding about how that structure transforms into something more or less formal, nor does it provide much knowledge about the technological and value-chain effects of collaborative research.

5.2.2 Collective Action Approach

Features of the Methodology

Chapter Three described the collective action approach to research collaboration and reviewed its methodology. Collective action's theoretical heritage comes from public good and game theories. Mancur Olson is Marshall's counterpart in the collective action methodology, pioneering the analysis of group provision of a non-excludable good or service. Since Olson's original writings in the mid-1960s, a vast literature has arisen on collective action. While previously used to analyze cooperatively developed technologies, its inter-temporal application in this analysis to cooperatively developed technologies is unprecedented.

Table 5.2 summarizes the structure, causal conditions, and effects of the collective action approach. There are two structural components in the model: the public/collective good provided and the overlapping activities. The public/collective good(s) provided is the collectively provided good or service that is being analyzed, it can be a pure or impure public good and either discrete or continuous. Overlapping activities are the simultaneous contacts in a variety of activities that augment the stocks of social capital (trust) from which defection can be penalized. These contributions imply continued behavior to positively augment the group's stock of social capital. Through overlapping activities, concurrent iteration occurs which replaces inter-temporal repetition and expands the potential space for cooperation.

TABLE 5.2 The Collective Action Model

Structure: Components	Structure: Relationships	Causal Conditions	Effects
1) Public – Collective Goods 2) Overlapping Activities	I) *Convention System* II) *Collective Supply Function*	1) Favorable Group Structure	1) Net Social Welfare

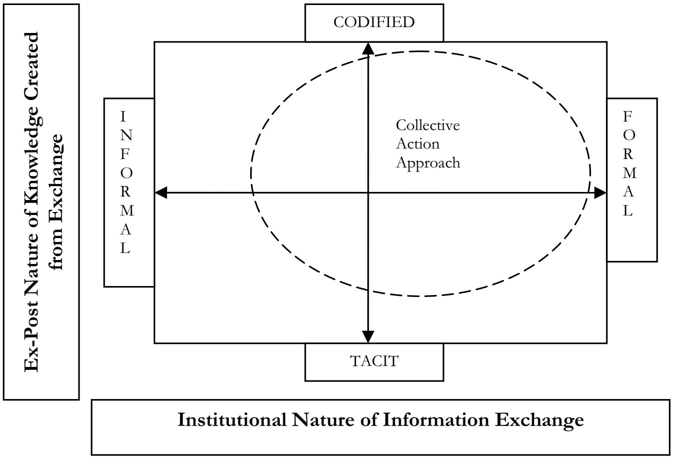
There are two structural relationships in collective action: 1) the convention system and 2) the collective supply function. The collective supply function specifies how each group member's contribution is added to the total supply of the collective good. The convention system is the mechanism through which withdrawals from the group's stock of social capital are penalized. The convention system can penalize withdrawals of social capital and thereby facilitate cooperation by three means. First, the convention system can exclude the defecting agent from the continued benefits of the collectively provided good. Second, selective incentives can be used to exclude the defecting agent from a private good that is collectively provided when the public good nature of the collective good prevents its direct exclusion, such as in the case of a pure public good. Lastly, socially selective incentives threaten an agent with exclusion from future, and other existing, cooperative initiatives if the agent defects against the group's collective interests.

In the collective action approach, a favorable group structure forms the causal conditions for collaborative research. The four structural factors determine whether the group structure is favorable. When the collective supply function and the collective good are such that the group is privileged, the collaborative research initiative will occur. If the group is not privileged, successful provision of the collaborative research initiative will only occur when mutual trust and dependency support the collective supply function and the collective good. The group's overlapping activities and its convention system create the conditions of trust and dependency, which underwrite collective action in the non-privileged case.

Once collective provision occurs, its continuation primarily depends on its innovative performance. Innovative performance depends, in turn, on its effect on net social welfare.

Typically, the effect of collectively provided research is in comparison to other collaborative and non-collaborative structures. A potential drawback to collaborative research over non-collaborative structures is the necessity for consensus within a group. Building this consensus can complicate the group's social regulation and slow the initiative's responsiveness compared to market or hierarchically organized initiatives. A primary determinant of research collaboration's net effect on social welfare is whether the group's interest is narrow or encompassing. If the group has an encompassing interest, the group views broader social interests as coincident with its own. Therefore, advancing group interest increases net social welfare and reinforces its continued operation. On the other hand, if the group has a narrow interest, the group views its self-interest as their primary concern. In this case advancing its interest may decrease net social welfare, increasing pressure against its operation. The case of changing stoping practices, in Part Three, illustrates how a narrow interest shaped the nature of technology change to the detriment of the general social welfare.

Figure 5.3 The Collective Action Approach in a Typology of Research Collaborations



The collective action approach takes direct account of the nature of the technology created through a process of research collaboration. However, it does not give a systematic role to the dynamics of the technologies. This conceals the role played by technological or production imperatives in the success or failure of research collaboration in the technologies' provision. Figure 5.3 gives an indication of the scope of the collective action methodology. Collective action traditionally focuses on formal collaborative research initiatives because of their greater tractability. However, its inherent ability to describe a variety of research collaborations appears much more comprehensive.

An Inter-Methodology Comparison

The collective action approach allows strategic motivations to make a group intentionally provide a public-collective good, but these add considerable complexity to the analysis. A general assumption of correspondence between the members' benefits and their contribution to the supply of the collective good is used to relate the collective supply function to the causal conditions for a collaborative research initiative. Identification of the underlying collective supply function, the nature of the collective good provided, the overlapping activities, and the convention system thereby become critical to the resultant analytical insights in this approach.

In comparison to the industrial district approach, this explicitness in the motivations for research collaboration allows the collective action approach to examine detailed implications of the effects of research collaboration. For example, the collective action approach allows one to distinguish the range of values in which information will be shared and where it will be kept proprietary. The differentiation between the welfare of the group and the broader social welfare is also a distinct theoretical advantage of the collective action approach, since it allows divergence or convergence between them to play a role in the stability of a cooperative initiative. However, unlike the distributed innovation and industrial district approaches there is not a distinct conceptualization of the innovative or productive systems. This limits the approach in its ability to analyze interactions between the collaborative research initiative and the broader political-economic system.

The collective action methodology can take a wide or narrow focus on research collaboration depending upon analytical interest. Thus, it can take direct account of the collaboratively developed technology, which is not possible in the industrial district methodology. Nonetheless, compared with the distributed innovation approach this conceptualization of technology is limited by its indirect relationship to the general political-economic system. The dynamics associated with research collaboration are more thoroughly treated in the collective action approach than in the industrial district approach. However, technology dynamics in the collective action approach are less developed than in the distributed innovation approach.

5.2.3 Distributed Innovation Approach

Features of the Methodology

Chapter Four discussed the distributed innovation approach to research collaboration. This approach, part of the literature on the economics of technology change, draws heavily upon the systems of innovation tradition. Its analytical roots emerged in the 1980s and 1990s to explain the increasing number of inter-organization technological collaborations observed. Although developed to explain distributedness of innovative activities in the new 'knowledge economy', distributed innovation provides valuable insights in the cases that follow regarding century old technologies fundamental to development of the Witwatersrand's industrial economy.

Table 5.3 lists the structure, causal conditions, and effects of distributed innovation. There are three structural components in the model: the innovative object, the mechanism of coordination, and the mechanism of competition. The innovative object of analysis includes the collaboratively provided artifact or learning, but it also encompasses the innovative object's impact on structural inter-relationships and its dynamic transformation of these relationships. Mechanisms of coordination are the economic relationships through which cooperative activities are organized and coordinated. These mechanisms build trust and reciprocity, which is enhanced in groups with higher levels of homogeneity. The trust and reciprocity necessary to achieve cooperation within a class of economic agents depends on the structure of intra-class power, which is assumed a function of agent concentration. Conversely, the trust and reciprocity necessary for cooperation between classes of economic agents depends on the inter-class and intra-class power of the respective agents. Mechanisms of competition establish the balance between competition and cooperation, and reside within the relationships among classes of agents, the vertical production divisions, and the borders of parallel divisions. Two types of competition are distinguished: 1) indirect and 2) direct. Indirect competition occurs between different classes of economic agents and between production networks. Direct competition occurs within a class of economic agents and between parallel divisions.

There are two structural relationships in the distributed innovation approach. The first is product provision, the operations through which inputs are transformed into outputs. Within product provision, we distinguish between vertical divisions, the upstream/downstream divisions that define an "economic class of agents" and parallel divisions, which form distinct streams of production without intersecting classes of agents and with extremely limited vertical relations of mutual dependency between other parallel divisions. Innovation provision is the other structural relationship, it defines the manner through which knowledge inputs are transformed into knowledge outputs. There are four types of knowledge inputs, each of which can be provided on a transient or on-going basis: 1) human capital 2) organizational routines 3) learning by doing and 4) output feedbacks. The nature of these different types of knowledge inputs: transient/on-going, tacit/codified, influence the comparative attractiveness of a distributed innovate structure. Knowledge outputs are characterized by their relationship to productive functions.

TABLE 5.3 The Distributed Innovation Model

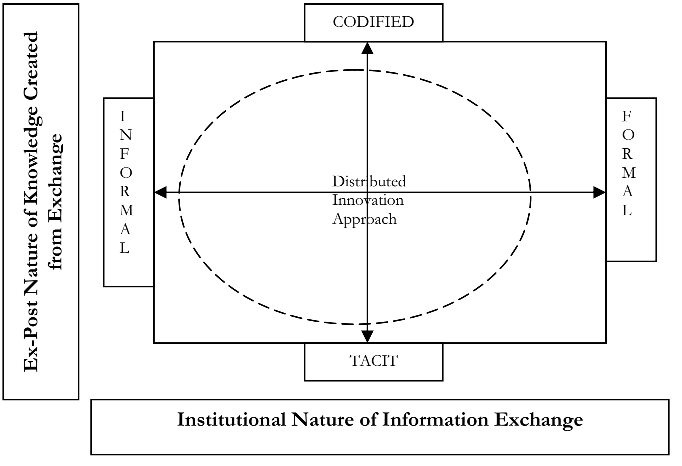
Structure: Components	Structure: Relationships	Causes	Effects
1) Innovative Object	I) *Product Provision*	1) Push Factors	1) Distributed Relationships
2) Mechanisms of Coordination	II) *Innovation Provision*	2) Pull Factors	2) Innovations Generated
3) Mechanisms of Competition		3) Constr. Circumstances	

Research collaboration occurs in the distributed innovation approach when a combination of push factors, pull factors, and constraining circumstances favor collaborative research over market or hierarchically provided research. There are three pull factors favoring a distributed structure: 1) rapid processing/application of information about a technology 2) the exchange of intangibles and 3) the ability to facilitate the establishment of technological standards. Push factors favoring a distributed structure may be sub-divided between intra-class cooperative forces, where primarily direct competitors find a common class interest in cooperation, and primarily inter-class cooperative forces, where mutual dependency among primarily distinct classes of economic agents favors cooperation. The mutual dependencies and power which drive cooperation depend on the constraining circumstance, which are altered in three ways: 1) by agents repositioning themselves in the production configuration 2) by external market pressure for change and 3) by dynamic entry/exit of agents within or outside their class.

Distributed innovation distinguishes between the effects of innovations generated collaboratively and the effects of the collaborative structure on other distributed relationships. The innovations generated under a collaborative structure are defined by three-dimensions: 1) the extent to which they transform the associated productive and innovative configurations 2) their associated technological complexity and 3) the dynamic rate of the technology's evolution.
Collaborative research is assumed to predominate because the networked structure is more efficient than alternative structures. Distributedness in research builds social capital as well as depending upon it, which expands the potential scope for other cooperative endeavors. However, the distributed innovation approach does acknowledge that networks exclude as well as include with possible adverse effects of social efficiency. Distributedness of research activity inherently spreads risks and lowers financial hurdles to the development of innovation. Lastly, an effect hypothesized from the distributed innovation approach is that over time distributedness increases the homogeneity of agents and thereby virtuously reinforces further cooperation.

Research collaborations are assumed pervasive in the distributed innovation approach, so it focuses on the extent of distributedness. Through a systems approach, innovation occurs within the context of production and vice-versa. This reflects the centrality of the technology's creation and evolution within the distributed innovation approach. Figure 5.4 gives an indication of the scope of the distributed innovation approach. As with collective action, distributed innovation covers a spectrum of institutional forms for information exchange, but it tends to have a slightly greater focus on informal structures.

Figure 5.4 The Distributed Innovation Approach in a Typology of Research Collaborations



An Inter-Methodology Comparison

The distributed innovation's foundation in the systems of innovation perspective makes innovation and its interrelationship to other activities more central than the other approaches. Lundvall et al. (2002) give an expansive description of the innovation systems perspective: "Innovation systems work through the introduction of knowledge into the economy (and into society at large). It requires learning by individuals and organizations taking part in processes of innovation of different kinds. The efficiency of these learning activities and, hence, the performance of the innovation systems depends on economic, political and social infrastructures and institutions. It also depends on past experiences as they are reflected in the tangible and intangible aspects of the structure of production and on values and policies" (Lundvall et al. 2002, pp. 225-226).[5]

Through its inter-relating productive and innovative functions the distributed innovation approach is related to, but developed beyond, the industrial district approach. This gives an important analytical richness to the approach not found in collective action. For example, the distributed innovation approach can demonstrate how a class of economic agents could cooperate to develop a technology that increases their portion of profits along the value chain. However, its descriptive clarity comes at a cost, as there is less predictive clarity in the distributed innovation approach than in collective action. In contrast to the industrial district approach, the inter-and intra-class networks that compose the innovative activities in the distributed innovation approach are not geographically bound. This removes the problem of defining geographic

[5] This 'expansive' definition of innovation systems is distinguished because of a tendency in practice for innovation system analyses to be narrowly focused on formal research and development systems in more economically developed nations (Lundvall *et al.* 2002, p. 226).

boundaries and shifts it one of identifying the structure and dynamics of relationships within and between parallel divisions.

Distributed innovation is a highly informative approach to analyze research collaborations. Its heritage within the economics of technology change literature ensures that it provides a richer treatment of the innovation process related to research collaboration than the other two perspectives. Through its treatment of power asymmetries and structural dependencies among agents, distributed innovation also marks an important deepening of the systems of innovation perspective.[6] Nevertheless, the complexity of research collaboration is not fully captured within the distributed innovation approach. This necessity for further development is acknowledged by the principle authors of the approach: "We would admit, however, that further integration of ideas is possible, and emphasise that this paper presents a perspective under development, rather than one in final form" (Coombs et al. 2003, p. 29).

5.3 A COMPARATIVE SUMMARY

The discussion above highlighted several differences and similarities between the approaches. The remainder of this chapter revisits those likenesses and distinctions by way of previewing the approaches' use in analyzing each case of research collaboration in a technology, and the evolution of that collaborative research structure over time. Table 5.4 provides a summary and comparison of all three approaches.

In terms of structure, all three approaches allow for some means by which trust is developed and subsequently used to facilitate a collaborative research endeavor. Community in the industrial district approach, overlapping activities in the collective action approach, and mechanisms of competition in the distributed innovation approach all act to develop a stock of trust or social capital. In all three approaches, this stock of social capital is used to encourage cooperation that facilitates research collaboration. The distributed innovation approach refers to these powers against defection from cooperation as mechanisms of coordination, while the collective action approach refers to them as the convention system, and the industrial district approach calls them the socio-political system.

While sharing a fundamental means to support collaborative research endeavors, the analytical approaches vary in their structural analysis of research collaboration. Both the industrial district approach, through the productive system, and the distributed innovation approach, through product provision, directly consider the role played by production of some good or service in the collaborative provision of a technology for that good or service. Similarly, the industrial district approach, through the knowledge system, and the distributed innovation approach, through innovation provision, directly consider the role played by the innovative system in collaborative provision of a technology for that good or service. In contrast, these are only indirectly considered in the collective action approach through their effect on the collective supply function. However, the technology created by the research collaboration is not directly considered in the industrial district approach, its concern being upon the underlying conditions in which a technology is collaboratively developed, *i.e.* the agglomeration externalities in the district. Both the collective action approach and the distributed innovation approach provide direct analysis of the collaboratively created technology, respectively as the collective good provided and the innovative object of analysis.

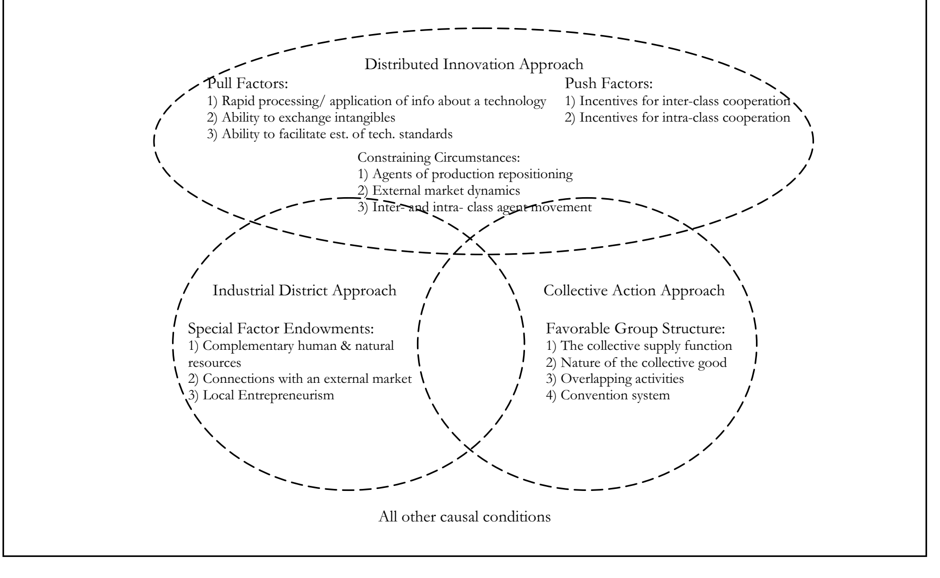
[6] The need to 'deepen' the system of innovation perspective is discussed in Lundvall *et al.* (2002, pp. 221-224).

TABLE 5.4 A SUMMARY AND COMPARISON OF THE ANALYTICAL MODELS

Industrial District Approach			
Structure: Components	Structure: Relationships	Causal Conditions	Effects
1) Socio-territorial Entity 2) Community 3) Firms & Institutions 4) Human Resources 5) Markets	I) *Production System* II) *Knowledge System* III) *Socio-Political System*	1) Spcl. Factor Endowments	1) Agglomeration Extrn.
Collective Action Approach			
Structure: Components	Structure: Relationships	Causal Conditions	Effects
1) Public – Collective Goods 2) Overlapping Activities	I) *Convention System* II) *Collective Supply Function*	1) Favorable Group Structure	1) Net Social Welfare
Distributed Innovation Approach			
Structure: Components	Structure: Relationships	Causal Conditions	Effects
1) Innovative Object 2) Mechanisms of Coordination 3) Mechanisms of Competition	I) *Product Provision* II) *Innovation Provision*	1) Push Factors 2) Pull Factors 3) Constr. Circumstances	1) Distributed Relationships 2) Innovations Generated

The causal conditions for research collaboration vary and differentiate each of the approaches. Figure 5.5 depicts the three approach and their respective causal selections. The entire space in Figure 5.5 represents all causal conditions for research collaboration *i.e.* 'the cause' of research collaboration. As a mortal being, it is impossible to know the relative scope of any selection of factors with respect to all the causal conditions. Therefore, the relative scope of the three approaches indicated in Figure 5.5 may in fact represent nothing more than a dot in comparison to all the other causal conditions for collaborative research. Even a cursory reflection on other disciplines in the social sciences that analyze cooperative behavior significantly reduces the scope of the three approaches considered.

Figure 5.5 The Causal Conditions for Research Collaboration



Nonetheless, a diversity of causal conditions are captured by these three approaches. In the industrial district approach, the presence of special factor endowments creates the causal conditions for research collaboration. Agglomeration externalities are a fundamental characteristic of an industrial district, which support the collaborative development of a technology. The collective action approach regards a favorable group structure as the causal conditions for collaborative research. The potential scale and scope of collectively providing a technology is determined by the group structure. Lastly, the distributed innovation approach considers push factors, pull factors, and constraining circumstances associated with the technology as forming the causal conditions for research collaboration and its subsequent growth or decline.

Because of their selection of causal conditions, each approach distinctly examines the relationship between the resulting technology, the collaborative system, the broader innovative system, and the socio-economic system. Hence, once technologies are being collaboratively developed, the distributed innovation approach focuses on the influence those technologies have on subsequent research collaborations and their effect on the associated dynamics of the productive and innovative systems. In contrast, the collective action approach focuses on whether the structure through which the technology was collectively provided would be supported or undermined by the technologies. Lastly, the industrial district approach considers whether the agglomeration externalities, which generate the research collaboration that creates the technologies, are sustained or damaged by the technologies; thereby whether further co-location and positive agglomeration externalities are created. All of the approaches consider the broader effects of the collaboratively developed technology. In each, the degree of cooperation and the boundaries of competition are influenced by the innovations generated in the cooperative initiatives.

In conclusion, while the industrial district approach focuses on the circumstances in which research collaborations occur, the collective action approach concentrates on the collaborative vehicle through which technologies are developed, and the distributed innovation approach highlights the influence that the technology itself carries over the political-economic environment. Everyone of the approach thereby enhances our understanding of certain aspects of research collaboration and the associated technologies generated from them. Research collaborations are complex phenomenon that the simple analytical clarity of any one approach does not adequately capture. This investigation will show that employing all three methodologies leads to a more thorough understanding of collaborative research and its associated technologies.

Part Two

The Cyanide Method of Gold Extraction, 1892-1902

"[Metallurgy on] the Witwatersrand today is the most perfect and complete of any gold fields in the world. The evident reason for this is the concentration of energy and skill in a limited area. The free exchange of ideas allows no room for the secret process. Exchange of ideas takes place from day to day between men working in similar lines, and such interchange has led up to gratifying results. I am glad to say that many of the men who have aided in perfecting the processes for the production of gold are members of the Chemical and Metallurgical Society, many of whom I see here tonight"

(Charles Butters, Presidential Address CMSSA, 1897)

Chapter Six:
Development of Cyanide Technology

6.1 INTRODUCTION

This chapter introduces the case on industrialization of gold metallurgical technology with development of cyanide based extraction process. Before the cyanide based extraction technology the future of mining on the Witwatersrand looked doubtful. The case unfolds between 1886 and 1902, beginning with initial Witwatersrand gold mining and ending with the conclusion of the Second Anglo-Boer War. Within a few years of introduction, the cyanide based extraction technology demonstrated an ability to facilitate mining at 'deep levels' in non-oxidized gold bearing host rock. In these sulfide ores (pyrites), the established amalgamation method was extremely inefficient and most of the mines were uneconomic without an alternative metallurgical technology.

The cyanide process held tremendous promise as a low cost solution for the pyritic gold deposits upon its demonstration in 1890. Early production from pilot plants was similarly encouraging. Nonetheless, several additional technical challenges needed to be resolved for cyanide to be the low-cost extraction savior of the Witwatersrand. These solutions, provided through research collaboration, are the focus of this case study.

By way of introduction, this chapter reviews the technological development of cyanide based extraction. Section 6.2, examines economic development in Southern Africa related to mining activities before the Witwatersrand gold mining rush.[1] It provides background to the characters and institutions in both cases and includes a summary of the gold production process. In Section 6.3, the cyanide technologies and their relation to the gold mining production process are detailed.

6.2 SOCIO-ECONOMIC ANTECEDENTS OF WITWATERSRAND MINING

Southern Africa is an area with a rich mineral heritage, and this section reviews the socio-economic features that preceded gold mining on the Witwatersrand. It focuses on an era characterized by the migration of many peoples across Southern Africa. Three general categories of people European, African, and Khoisan were intra- and inter-actively involved in these movements.[2] A few of the principal causes for this geographic transformation are touched upon, with a focus on the role of mineral resources. Because of its influence on Witwatersrand gold mining, particular attention is given to the diamond pipe mining near Kimberley.

6.2.1 Frontier Development

The Portuguese were the first Europeans to explore the Southern African coast in the late 15th and early 16th centuries, but it was not until 1652 that permanent European settlement occurred when the Dutch East Indian Company established a refueling station in Table Bay (Cape Town). The Dutch did not aggressively promote settlement of the interior, but gradually over the 18th century settler communities reached the Sundays River watershed in what is today the western portion of the Eastern Cape Province (Davenport and Saunders, 2000, Chapter 2). By the late

[1] The term Southern Africa is used throughout this case rather than South Africa. While largely interchangeable in territorial coverage, distinction is made because political authority was unconsolidated in this period.

[2] These names are offered openly with Europeans, Africans (Nguni speakers), and Khoisan encompassing a variety of heterogeneous people.

18th century, European power was changing and as the Napoleonic wars raged, Britain eventually took control of Table Bay and the hinterland in 1806.

When the Cape was officially transferred to Britain in 1815, the colonial administration began encouraging a more 'British' character. Promoting settlement by British nationals was the principle means by which this policy was realized. There gradually emerged tensions between English speaking settlers and their Dutch-speaking predecessors. The British colonial government introduced several changes, which to settlers from the Dutch era (Afrikaners) marked a loss of local authority. Prominent among these administrative changes were those regarding the ownership of slaves and the replacement of Dutch with English as the language for public affairs. [3] Table 6.1 details some important dates in the region's political economy before discovery of the Witwatersrand gold deposits. In this period prior to 1886, British Colonial authorities did not aggressively assert its rule over the Southern African interior. Only near the end of this period, as European nations began to vie with each in the 'Scramble for Africa', did a shift in policy emerge (Davenport and Saunders 2000, pp. 213-17).

The native African inhabitants of the region met the Afrikaner migration into the Southern African interior with hostility. This resistance to their settlement augmented social cohesion among the Afrikaners and solidified a distinct identity (Davenport and Saunders 2000, p.77). [4] The first attempt at self-government by the Afrikaners was in Natal in 1839; however, in 1842 Britain seized control of Natal, making it a British colony. The loss of Afrikaner sovereignty in Natal did not end their pursuit of self-governance. In 1852, Afrikaner independence was recognized for the Transvaal or the Zuid Afrikanse Republic (ZAR), as it was known from 1859. Similarly, in 1854 the Orange Free State (OFS) was granted self-governance. Although these republics were primarily subsistence agrarian communities, they inaugurated wide-spread European settlement across a Southern African interior that possessed immense mineral deposits.

TABLE 6.1 Select Socio-Political Dates in Southern Africa until 1885

1806	British re-occupy Table Bay (Cape Town), with official transfer in 1815
1817	Tshaka ruler of the Zulus as unrest emerges between African peoples in south-east Africa
1820	British began colonization of Eastern Cape with its nationals
1837	Large Afrikaner migration from Eastern Cape - the Great Trek
1839	Natal declared Afrikaner republic
1842	Natal is succeeded to British control
1852	Zuid Afrikanse Republic (ZAR), the Transvaal, granted self-governance
1854	Orange Free State granted self-governance
1857	Xhosa cattle-killing tragedy following Nongqawuse's prophecy
1860	Indian nationals brought to Natal sugar plantations as indentured servants
1871	Griqualand West recognized as an independent territory
1875	Black Flag Revolt, Kimberley
1877	British occupy ZAR
1879	Afrikaner Bond published
1880	Conflict with the British in ZAR, 'first Anglo-Boer war' begins
	Griqualand West incorporated into Cape colony
1881	ZAR re-attains independence from Britain ending the first Anglo-Boer war
1884	Germany stakes claims in Southern Africa as European nations race for colonization
1885	Railroad completed between Cape Town and Kimberley

[3] The British banned the slave trade in 1807. Between 1807 and 1834, when slavery was abolished, the British legislature imposed increasing tax burdens on slave owners.

[4] This gradual process led to the emergence of an identity rooted in their experience on the Southern Africa frontier. In 1879, 'the Bond' formalized this identity, uniting around the Afrikaans language and a system of education suited to rural whites. The Bond became a political movement and sign of Afrikaner distinction from other Europeans.

From the 1850s, another group spread across Southern Africa, the European prospector. The emergence of these miners is discussed at length in Section 6.2.3 below. In their pursuit of mineral wealth, they had an undeniable influence shaping the Southern African frontier. Across Southern Africa, this diverse citizenry pursued an international fever for precious minerals that held the promise of wealth and fame for the rugged individual. In the miners' exploitation of the mineral deposits, impoverished Africans provided an immensely valuable resource endowment of low-cost labor. The Witwatersrand gold deposits further instituted their roles, but throughout the latter-half of the 19th century four groups: Africans, Afrikaners, British Colonials, and Mining[5] drove exploitation of mineral deposits across Southern Africa.

6.2.2 Political Economic Inheritance

In its rule of the Cape in the early 19th century, the British initially continued the mercantile economic policy of Dutch East Indian Company. Preferential tariffs were imposed on Cape wines in 1813 and by 1823, wine accounted for 88 percent of the Cape Colony's exports (Viljoen, 1983, p. 30). Wine exports reached their peak in the mid-1820s, after which they declined as Britain repealed imperial preference duties and increased imports of Iberian wines. By the 1840s, wool overtook wine as the leading export from the Cape Colony. The Southern African wool industry emerged with British settlement of the Eastern Cape. Wool's economic contribution peaked in the 1860s at around 75 percent of exports, but by the 1870s with drought and the opening of the Suez Canal, the future of agricultural expansion in the Cape was doubtful (Viljoen, 1983, p. 30). Fortunately for the Cape's economy, diamonds were discovered in the 1870s just as the prospects of its agricultural exports declined. Besides just replacing agriculture, the emergent mining industry provided a better foundation for economic development (Frankel, 1938).[6]

Before the mineral discoveries, Afrikaners were primarily subsistence agriculturists. When the first alluvial gold rush in the eastern Transvaal began in the early 1870s, the ZAR found itself in financial crisis and bureaucrats capable of running a modern nation state were scarce (Rosenthal, 1970, p. 83). By the mid-1870s, the Afrikaner republic faced a constituency reluctant to provide the infrastructure needed for further economic development and an uprising of Africans near the eastern Transvaal gold fields. Hence, the ZAR was perched on bankruptcy when the British occupied Pretoria in 1877 ostensibly to install good governance, but also in support of mining interests on the Kimberley diamond fields. In 1881, the British returned self-governance to the ZAR in order to conclude the First Anglo-Boer War. British occupation placed the Afrikaner republic in a better position, but on the eve of the 1886 Witwatersrand gold discoveries, the ZAR was encircled by European controlled colonies, a land-locked nation with virtually no infrastructure.

Financial development of the Southern African region largely traced the emergence of the mining economy. However, at least in banking, agriculture achieved some precedents in development. The first modern bank in Southern Africa was the Cape of Good Hope in 1836 (Jones, 1988, Chapter 1). In 1862, Standard Bank, the first British imperial bank arrived in the Cape. While originally envisaged to finance primary sector exports, by the late 1870s it had

[5] The term 'Mining' is used for a group, which during this period was primarily ex-pat Westerners. They were prospectors, skilled artisans, metallurgists, mining engineers, and mining financiers. Issues of sub-divisions have been brought up in discussions of the Jameson Raid. Yet, their primary reason for being in Southern Africa was mining and their incomes were derived directly from the activity of mining. In this context, more traditional terms like 'the Chamber of Mines' or 'Powerful mining magnates' denote too narrow a portion of this group's population.

[6] An indication of the limited capacity for agriculture based economic development is that by the mid-1860s only 18 towns in Southern Africa had populations greater than 1,000.

become the *de facto* central bank for the Cape (Jones, 1996, pp. 90-98). The Kimberley diamond deposits shifted the economic heart of the Cape back to Cape Town from the agricultural economy of Port Elizabeth. The diamond diggings themselves did not generate a huge financial infrastructure, since early consolidation of the diamond companies was an internal process of capital consolidation at the diggings. Only in the late 1880s, after the unification of pit ownership was imminent, did foreign investment become a significant factor (Frankel, 1938, Chapter 3). The biggest material impact of the diamond deposit was on infrastructure. Kimberley's growth gave rise to a pooling of both private and public finance to provide the large-scale capital requirements of a railroad infrastructure into the Southern African interior.

TABLE 6.2 Some Scientific, Educational, and Professional Institutions and Societies in SA until 1885[7]

1820	Royal Observatory at the Cape
1825	The South African Museum, Cape Town
1829	University of Cape Town (UCT)*
1855	The Albany Museum, Grahamstown
	St Andrew's College, Grahamstown – See Rhodes*
	Grey College, Bloemfontein - See UFS*
1866	University of Stellenbosch (UoS)*
1869	Theological School of the N.G. Kerk – See PUK*
1873	University of South Africa (UNISA)*
1877	Royal Society of South Africa*
	*Transactions of the Royal Society of South African (TRSSA)**
	The National Museum of the Orange Free State, Bloemfontein (now the National Museum)
1882	Port Elizabeth (PE) Technikon*

Southern Africa's knowledge and innovative infrastructure paralleled the financial, with extensive development occurring only after discovery of mineral resources. Table 6.2 lists a few of the more important institutions and societies that emerged before 1886. Museums are among the oldest scientific and educational institutions in Southern Africa, dating back to the early Dutch settlers at the Fort in Cape Town (Naudé and Brown, 1977, p. 60). Throughout this early period, most research across Southern Africa focused on describing and documenting the diverse natural environment.

Basic education in 19th century Southern Africa was principally the product of Missionaries. In addition, several colleges began offering higher level courses.[8] Only two institutes were teaching courses equivalent to university level during this period, the University of Cape Town (UCT) and University of Stellenbosch (UoS). However, these institutes were not allowed examine the students or bestow degrees. Only when an examining institution, the University of South Africa (UNISA), became established in 1873 did a Southern African tertiary system get established.

In the early years of mining activities, international mobility of skilled individuals was the principal source of technical know-how. In general, the nature of the Southern African deposits led to a premium on individuals with a combination of practical experience deep-level mining in the Americas and formal mining education in Europe (De Waal, 1983). The mining sector required many ancillary goods and services. As these products began to be domestically provided and mining production became more systematic, there was a shift in the focus of Southern African science away from descriptions of the local natural environment to a focus on utilizing the region's natural resources in industrial applications (Talbot, 1977, p. 26).

[7] For continuity name changes are mainly ignored. Those with changes are demarked by an astrix (*) and can be found in Appendices One, Two and Three for Journals, Associations and Institutions respectively.

[8] Among the colleges established during this period several subsequently became full-fledged universities were: South African College (UCT), St. Andrew's College (Rhodes), Grey College (UFS), Stellenbosch Gymnasium (UoS), Theological School of the N.G. Kerk (PUK), and Port Elizabeth Art School (PET).

6.2.3 <u>Southern African Mining 1846-1885</u>

The pursuit of mineral wealth, especially gold, was an important force in the European exploration that occurred in the 15th and 16th centuries. Throughout most of the international economic expansion over the past 500 years, gold has provided the basis of credit expansion. Until the mid-19th century, techniques used to recover gold stagnated. Subsequently, a new era of international exploration begun that led to the discovery of deposits that required new methods of mineral processing. Typified in the 1848 California gold discovery, a series of 'gold rushes' worldwide ushered in a new ideal where digger's democracies prevailed and wealth awaited those ambitious enough to go out and seize it. Morrell (1940) provides an excellent description of this phenomenon. In Southern Africa, the first rush in this new era occurred at the Namaqualand copper deposits.

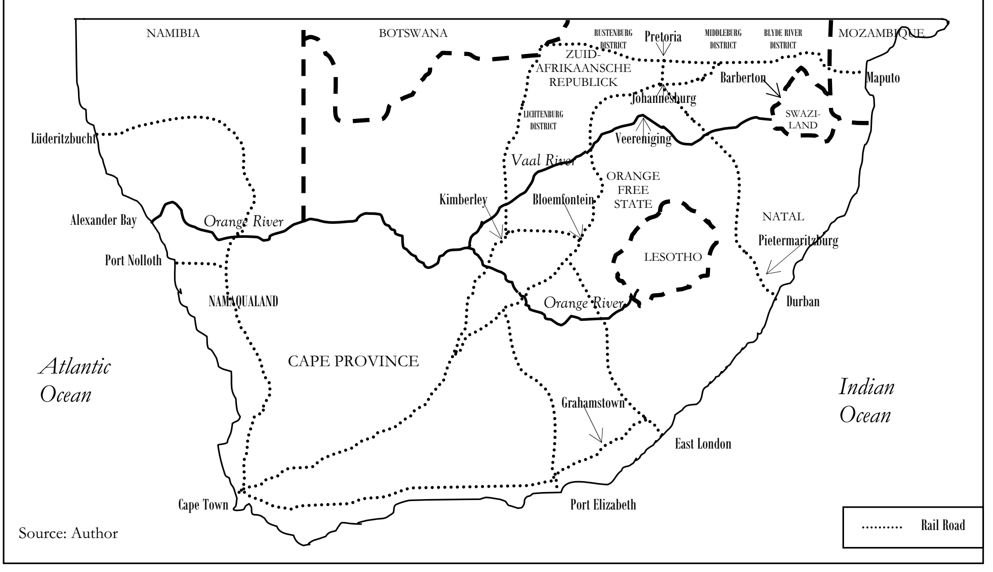
In 1846, western mining techniques were introduced on copper mines in Namaqualand (Northern Cape) (Smalberger, 1975, p. 14). A significant rush of fortune seekers to the region occurred in 1853. Despite the remoteness of the location, by 1860 copper had risen to be the Cape Colony's second biggest export (Smalberger, 1975, p. 69). By the early 1860s, there was systematic mining of the deposits. While subsequent diamond and gold rushes dwarfed copper, another mineral, coal, was exploited around this time; its legacy would be more enduring on the economic development of the region.

In the 1860s, extraction of the large Southern African coal deposits began; subsequent growth of Kimberley and Johannesburg assuring an enduring future for the coal industry. The Cape government offered a £100 reward in 1852 to encourage the search for coal deposits. This led to the eventual establishment in 1864 of the first Southern African colliery in the Stormberg Mountains of the Eastern Cape (Lang, 1995, p. 13). Shortly thereafter, coal mining began in KwaZulu-Natal for the Pietermaritzburg community and by the late 1860s, there was coal mining for the local community near Bethal in Mpumalanga (Lang, 1995, p. 15). With the growth of Kimberley throughout the 1870s, demand for energy rapidly outstripped what the sparse surrounds could provide. Thus, 1879 saw establishment of the Vereeniging colliery on the edge of the Vaal River, its coal transported to the diamond mines via ox-wagon (Coulter, 1930, p. 262). Coal was not the only industry to get a kick-start from the diamond discoveries, the search for gold was part and parcel with diamond prospecting following the 1869 alluvial diamond rush.

As far back as 1853, the ZAR knew of alluvial gold deposits in its territory, but word of these early discoveries was suppressed by the nascent ZAR to avoid a rush of prospectors (Rosenthal, 1970, pp. 9-14). Following the diamond discoveries, however, the search for further mineral wealth could not be contained. In 1871, knowing that gold discoveries were imminent and with a pressing need for additional revenue, the ZAR revised its gold law to improve income flows (Rosenthal, 1970, p. 82).

By 1873, a gold rush had commenced along the Blyde river watershed in the eastern portion of the ZAR. As with many gold rushes in the region, the initial small-scale alluvial mining gave way to larger systematic underground mining. These predecessors to the Witwatersrand were important contributors to the evolution of the gold mining law in the ZAR, instilling as part of the international gold rush phenomenon a legal system with Spanish origins that had developed following the 1849 California rush (Rosenthal, 1970, p. 26). Towards the early 1880s, several significant mines were developed in the Blyde River district. Around this time, alluvial gold was found in Barberton. In 1885, discovery of a significant gold bearing reef near Barberton led to development of a huge speculative market, virtually overnight. The Kimberley community played a substantial role in the investments that accompanied Barberton's boom and bust (Hocking, 1997, p.43). Following Barberton, the next major gold rush was that of the Witwatersrand. Before that story and our first case study, we consider the legacy borne by diamonds and the Kimberley community on the Witwatersrand's development.

Map 6.1 Southern Africa



Source: Author

Diamonds and Kimberley

This section highlights precedents from the Kimberley diamond fields that carried on to the Witwatersrand. Three aspects of these early years at Kimberley were especially enduring: 1) Establishment of physical and financial infrastructure 2) A hierarchy of production with distinct linkages to the broader socio-political system 3) Collaboration in the system of production. Following a brief review of the industry's development each of these legacies are considered in turn.

In 1866, a Khoisan servant on the banks of the Orange River picked up a peculiar pebble. The farmer's children acquired the stone and used it as a toy until a visitor spotted it and suspecting it to be a diamond sought verification. Geologic knowledge was particularly scarce in those days. The 'Eureka' diamond, as it would become known, traveled nearly 600kms from the farm near Hopetown to Grahamstown in order to get positive verification (De Klerk, 1997, p. 329). Despite announcement of the discovery in the press throughout Europe and North America, skepticism about the geology of the Southern African deposits delayed a rush to the diamond fields (Rosenthal, 1970, pp. 27-28). Nonetheless, by 1869 further discoveries led to a full-scale rush for alluvial diamonds. These alluvial diggings were typically mined by a claim holder and assisted by local Africans in the digging and sort of the diamond bearing soil. The alluvial deposits were quickly cleared and late in 1870 activity at the alluvial diggings rapidly declined.

However, early in 1870 the first non-alluvial, kimberlite, diamond pipes were discovered. This marked an entirely new geological occurrence and era of diamond mining. By 1871 mining on the 'dry-diggings' centered around four diamond pipes: Kimberley, DeBeers, Bultfontein, and

Dutoitspan. On the dry-diggings each claim was a mere 2.9 square meters, only individuals could own a claim, no individual could own more than two claims and the owner forfeited his claim if it was inactive for eight consecutive days (Worger, 1987, p. 16). Besides claim restrictions, the surface area of these diamond bearing pipes was small although they continued to substantial depths. In 1872, the combined area mined at the Kimberley and DeBeers pipes encompassed 12.8 hectares, at Dutoitspan 6 hectares and at Bultfontein 3.2 hectares.

The geology of the deposits quickly led to a situation where many individuals were interested in mining a small area to greater and greater depths. As the pipes were dug deeper, significant differences in the quality of the pipes' diamonds deposits became apparent. The Kimberley pipe was the richest, followed by DeBeers and more distantly the pipes at Dutoitspan and Bultfontein. The concentration of the richer diamond deposits led to substantial sub-division of the already small claims.[9] Even with sub-division, the scarcity of claims led to rapid price escalation and claims quickly became unaffordable to most prospectors on the fields.

The increasing exclusivity of claim ownership led to the emergence of claim-owner and share-worker classes. The share-workers worked the claim for the claim-owners. Despite paying for the equipment and African labor to extract the diamonds from the claims, the share-workers also gave up to 50% of the diamonds they extracted to the claim-owners. Nevertheless, there were many individuals seeking opportunities for share-work, so claim-owners began to hire share-workers with the largest supply of African laborers in order for their claim and the diamonds it possessed to be dug as fast as possible.

Originally, the dry-diggings used ancient labor intensive techniques from India that required little capital investment (Williams, 1905, Chapter 5). These were relatively inefficient techniques, particularly as mining in the pipes went deeper. By the mid-1870s production problems were occurring at all four pipes because of the general depth and retention of single claims as the unit of production. The multitude of distinct and increasingly deep mining operations on the Kimberley pipe were originally accessed by an elaborate roadway scaffolding, but by 1872 its collapse in places necessitated replacement by a haulage system with wires emanating in a spider like fashion to the edge of the pit (Hocking, 1997, p. 36). While some relief came in 1873 when the maximum number of claims an individual could own rose from two to ten, it was only when claim ownership restrictions were removed late in 1876 that significant consolidation began to occur.

Relaxation of claim ownership restrictions initiated a new era of corporate ownership and production on the diamond fields. This consolidation generally increased the capital intensity of production with an introduction of mechanical equipment that required increasingly skilled workers. European, mainly British, miners were needed to operate and maintain this equipment and so a new class of labor began work on the diamond fields. Share-work was no longer available as consolidation occurred and these individuals either left or took-up jobs supervising the African laborers. The new methods of production restored profitability to many operations, but economies in production drove a race to secure ever larger claims on all of the pipes. Adding to productive pressures favoring larger operators, the 1876 relaxation of claim ownership also re-instituted mining boards with a structural favor to larger operations. The services controlled by the mining board, such as pumping of water from the pits and clearing collapsed areas of the pit made them increasingly important forces over the various claim's competitiveness especially as the pits grew deeper and deeper. Thus, the lack of influence over the mining boards and

[9] For example, Kimberley went from 450 claims early in 1870 to over 1,600 by the middle of the year (Worger, 1987, p. 18)

productive economies of scale put smaller claim holders in a position of accelerating disadvantage compared to larger operations.

By the early 1880s, the greater wealth of deposits at the De Beers and Kimberley pipes meant unification of control at either of them would effectively enable consolidation at the other three pipes and monopolize global production of diamonds. Hence, a terrific urgency characterized efforts to control both of these central pipes. Worger (1987) identifies quite distinct processes of unification between the Kimberley and DeBeers pipes. Owing to the comparative richness of the Kimberley deposits it was able to attract investment from the London diamond merchants. DeBeers in contrast did not initially attract significant foreign investment inflows, but by the early 1880s local joint-stock companies were driving large speculative investment.

In this intermediate era of corporate production, smaller companies were largely eliminated and a few companies controlled operations at each pipe. However, consolidation remained incomplete and the remaining companies were perpetuating the productive difficulties of diversified ownership at a larger scale. At both the Kimberley and De Beers pipes, the two companies at the forefront of ownership consolidation were the two companies with the greatest influence on the mining boards. These two firms were the DeBeers Diamond Corporation headed by Cecil John Rhodes and Charles D. Rudd and the Kimberley Central Diamond Corporation headed by Barney Barnato.

Faster development at the Kimberley pipe, because of its richer deposits, created lessons in production that informed operations at the DeBeers pipe and compensated for its lower-grade deposits. Unification of the diamond pipes and industry only came after discovery of the Witwatersrand gold deposits. In the end, the DeBeers Diamond Corporation securing financial support from Nathan Rothschild in 1888 gave it the power to consolidate ownership at DeBeers and Kimberley in turn. Only then could production focus on the physical geology of the deposits rather than legal ownership boundaries and full-scale industrial production begin. [10] Before that final consolidation of production, Kimberley had already transferred several important legacies to the gold mining industry on the Witwatersrand.

Infrastructure

The Kimberley community that emerged because of the diamond deposits created a significant infrastructure that facilitated development of the Witwatersrand. One of the most important legacies was its establishment of a railroad infrastructure. The Cape Town parliament inaugurated construction of a railroad to Kimberley in 1872. Covering 960 kilometers, the line reached Kimberley in 1885. Following territorial conflicts with the Orange Free State, a shorter 750-kilometer Port Elizabeth-line joined the Cape Town-line at De Aar joined it in 1884 (Reunert, 1898, pp. 189-90). Access to the Kimberley market also generated other rail ventures, such as the East London and Graaff-Reinet lines which had reached the latter in 1879. While the real take-off of rail infrastructure awaited the gold discoveries of the Witwatersrand, by 1886 was a substantial foundation.

Another legacy of Kimberley was in the financial infrastructure. Despite ownership restrictions, Kimberley launched Southern Africa's first stock exchange in 1875 (Rosenthal, 1970, 38). The slow evolution of capital-intensive mining facilitated a largely self-financed industry to develop outside of the London diamond merchants' investment on the Kimberley pipe. However, while the Standard Bank and a couple of other banks established branches in Kimberley by the mid-

[10] This consolidation also facilitated control of diamond supplies and the general stability of the industry.

1880s; its greatest impact on the local financial infrastructure was facilitating associated investments in railroad infrastructure (Frankel, 1938).

Kimberley was the first industrial town in Southern Africa; diamonds exceeded wool exports in 1880, thereby inaugurating South Africa's mineral based economy. While the local population fluctuated rather dramatically in the early years, its significance is reflected in the fact that the Cape Colony's White population rose from 181,592 in 1865 to 287,121 in 1881 (Rosenthal, 1970, p.40). This population's demand for goods and services led to the emergence of a significant merchant class in Kimberley. In order to get supplies to Kimberley before the completion of the railroads transport riders were used. Rural Afrikaners played a significant role in this transport riding industry, marking an important break from that community's focus on subsistence agriculture.

Electric telegraphs reached Kimberley in 1876, with local manufacture of beer and soda water occurring there in the 1870s (Rosenthal, 1970, p. 37). Following industry consolidation around DeBeers Mining Corporation (DBMC), an important source of domestic capital investment was created. DBMC engaged in several substantial investments in Kimberley's municipal services, KwaZulu Natal collieries, railroads, fruit orchards, explosive production, and exploration companies such as the British South Africa Company (Farnie, 1956, p. 127).

Social Hierarchy of Production

As production techniques on the Kimberley diamond fields evolved, the social hierarchy of production changed. Throughout, a fundamental division in the system of production existed between the African and non-African (White) populations. When mining began on the non-alluvial pipes some Africans became claim-owners on the lower-grade deposits.[11] This class of claim-owning Africans was severely disliked by the local White population who prohibited African claim-ownership in 1871. As the British Colonial government refused to sanction these racial restrictions a small class of African claim-owners persisted throughout early mining operations at Kimberley. For the vast majority of Africans the Kimberley diamond mines represented an important means to earn a living, particularly following confrontation for land during the 1850s and 1860s between Europeans and Africans.

Initially, the Kimberley diamond fields opened a range of opportunities for Africans. Not only was there demand for them on the mines, but a significant number also found employment on the railroads. Demand for foodstuff also created an opportunity for African agriculturalists who began producing food for the growing mining industry. However, racial discrimination prevailed and by the mid-1870s increasing restrictions were placed upon the Africans to reduce their self-sufficiency and institutionalize them as a disenfranchised class of low-cost labor (Bundy, 1972).

Within the White population there were at least three distinct communities directly involved in production: prospectors-supervisors; European Miners; and Mining Professionals. Among the earliest White population was the prospector. As mentioned above, the geology of the non-alluvial diamond deposits quickly limited opportunities for prospectors. Those prospectors who were unable to secure claim-ownership or those claim-owners who lost ownership had only share-work available to them as an alternative. However, following initial industrial production after the relaxation of claim ownership restriction in 1876, the only employment opportunity for these individuals on the mines was as a supervisor of the African laborers. Through-out these early years the white prospectors come share-workers come supervisors continued to identify

[11] Worger (1987) estimates that around 100 Africans owned claims at Bultfontein in 1870.

with their more successful brethren who formed the Mining Professional community. This identification with the Mining Professional community occurred despite their comparative economic impoverishment (Worger, 1987, p. 158).

While relaxation of claim-restrictions in the mid-1870s effectively eliminated share-workers it heralded the entry of another class of white workers, the European Miners. European Miners were skilled miners and artisans who came to Kimberley as increasingly systematic mining methods and equipment began being deployed under industrial consolidation. The overwhelming proportion of these European miners were from the tin mines of Cumberland and the coal mine of Cornwall in England (Williams, 1905, Chapter 14). These European Miners brought a legacy of trade unionism to Kimberley and Southern Africa in turn, initiating the first industrial action on the diamond fields in 1883. There was little binding the European Miners to the White Supervisor or the Mining Professional communities.

Mining professionals were originally a community of claim-owners, but as company ownership began to develop diamond merchants took an increasing role. Turrell (1987) describes this transformation and development of an upper class of mining capitalists as the Kimberley diamond merchants took an increasingly active role in diamond production. Another component of the mining professional community was the mining engineer. Until the late 1880s, mining engineers with experience in Europe introduced systematic mining.[12] Mining capitalists led the mining professional community during this era of Kimberley diamond mining. The race to consolidate ownership required frequent interactions amongst these individuals and created a learning environment where a critical understanding of mining operations formed under a collective identity.

Alliances and competition between the various groups fighting for industry consolidation gradually increased in-group production cooperation. In this drive, strategic inter-personal relations were exploited and developed. These interpersonal business relations within the mining professional community were crucial to the eventual consolidation of operations.[13] The shared identity that emerged at Kimberley provided an important foundation for co-operation once the Witwatersrand gold deposits were discovered.[14] Two prominent dimensions of this identity were political and ethnic.

British Colonial expansion in this Victorian Era dominated the political identity of the Kimberley mining professional community Cecil John Rhodes exemplifies an individual from Kimberley associated with this identity. Rhodes nurtured an alliance with the Cape Afrikaners from the late 1870s that he eventually parlayed into his election as prime minister of the Cape in 1890 (Davenport and Saunders, 2000, p.109). Rhodes entered the Cape parliament in 1881 and used his connections there to advance his business interests. In his biography of Rhodes, Robert Rotberg (1988) noted that his natural instinct for collaboration found a fostering environment in the technical imperatives of early diamond mining at Kimberley (p.111).

Several social institutions were associated with this British Colonial identity. One of the first to make a mark on Kimberley was the colonial Victorian all-male club. Modeled after the socially exclusive clubs in London, this provided prominent members of the mining professional

[12] These methods proved inadequate and by the late 1880s, international experience in hard rock, deep mining had accumulated in the Americas and so it fell to an American mining engineer, Gardner Williams, to implement a comprehensive mining system for the Kimberley diamond pipes.

[13] These relations are detailed in Turrell (1987).

[14] Emden (1935) details ties to Kimberley by mining capitalists from major mining-finance group on the Witwatersrand.

community an informal environment to meet, socialize, and conduct business across the boundaries of their organizations. A few of the more important of these clubs established on the Southern African frontier were the Kimberley club established in 1881, the Rand Club established in 1887, and the Salisbury Club established in 1893.[15] Another social institution associated with this British Colonial identity was English Freemasonry. In 1872, the first lodge was established in Kimberley, Rhodes joined that lodge in 1881, and Ernest Oppenheimer joined in 1886 (Butterfield, 1978, p. 40). In 1878, the first English Freemasonry lodge in the Transvaal was established in Pretoria (Butterfield, 1978, p. 76). This lodge emerged because of the 1877 installation of British civil servants in Pretoria and is evidence of the general sociological baggage that accompanied British colonization in Southern Africa.

The ethnic ties of the Jewish community were another important social institution associated with the rise of diamond wealth in Kimberley. With a long historic tradition in diamond dealing and cutting, many early Jewish arrivals to the diamond fields had kinship ties with the large European diamond dealers. Alfred Beit, Jules Wernher, Barney Barnato, George Albu, Sammy Marks and Lionel Phillips are a few prominent examples of members from the Jewish community who, after getting established at Kimberley, subsequently played an important role in the development of the Witwatersrand.[16] Thus, at both Kimberley and Johannesburg, the Jewish community played a major role advancing economic development in Southern Africa (Farnie, 1956, p.127). Jewish ethnicity formed an important social network with significant commercial experience, which supported identity development of the mining professional community. That identity enabled the establishment of several co-operative precedents in the system of production that would be emulated on the Witwatersrand.

Collaboration in the System of Production

While a frontier environment for at least part of its early history, Kimberley nevertheless realized collaboration in several areas that directly and indirectly supported the local industry. These areas of collaboration were largely explicit initiatives undertaken by and largely focused on benefiting the mining professional community. However, technical knowledge gained from leading producers at the Kimberley created a knowledge resource generated with distinct benefits and costs among diamond producers. As mentioned previously, the Kimberley diamond pipe was often the first to encounter technical challenges and develop solutions. These solutions were incorporated into operations at the other diamond pipes enabling them catch-up with the leading edge producers from Kimberley (Williams, 1905, Chapter 8). This structure of local knowledge externalities probably enhance the aggregate productivity of producers on the Kimberly diamond fields, but it also gave a productive advantage to intra-industry rivals at the DeBeers pipe and played a significant role in shaping the eventual consolidation of the Kimberley diamond industry in 1889.

In other areas of production collaboration was relatively difficult to achieve. The initial diffused structure of claim ownership undoubtedly made collaboration a challenge. As consolidation occurred the industry was increasingly able to realize collaboration in areas like participation in African labor registration, limit local and formalizing recruitment channels for African labor recruitment and contracting, imposing mandatory strip-searches of mining workers for illicit diamonds, and closing the African labor living quarters or compounds. Obviously, these areas of collaboration enhanced the mining professional's interests. Understanding of why these areas of

[15] For more on the role played by these clubs in Southern African communities other than Johannesburg see: Black 1980; Roberts 1978; Timmins 1963; and Warner 1965.

[16] The Jewish community also played a leading role as merchants, establishing many of the first stores and hotels in Kimberley. See: Arkin (1956).

collaboration only occurred when industrial consolidation was well underway is facilitated by referring to the collective action approach from Chapter Three.

Recalling the discussion of the nature of public goods and their relationship to realizing collective action presented in Table 3.1 of Chapter Three we can analyze the challenge faced in achieving collaboration during the early years of Kimberley diamond mining. Costs rose as each member joined in providing most of these collective goods, while at the gross benefits remained fixed. Thus, the early years of Kimberley diamond mining presented a situation similar to that of the discrete-rival good in Row 5 of Table 3.1, but as the industry consolidated by the mid-1880s we shifted to a situation more akin to Row 1. In Row 1, the industry is still not 'privileged' but the absolute and relative number sub-group members necessary to achieve collective action decreased. As the industry consolidated, deepening interactions and social institutions among producers built social capital which further increased the scope for collective action.

Even before industry consolidation, the collective interests of the mining professional community were advanced in several ways. The best examples of these early advances of the mining professional community's interests were in the co-optation of the State. The influx of prospectors in search of diamonds generated tensions with the Afrikaners in the district. In response to this hostility, the initial alluvial miners declared their own independent diggers democracy. When the non-alluvial diamond pipes near Kimberley were discovered there were four groups claiming governing authority: the mixed race Griquas, the ZAR, the OFS, and the diggers themselves. Under British arbitration, political authority of the Kimberley pipes was granted in 1871 to the Griqua and became the British colony of Griqualand-West with political authority vested with the British Colonial Office. In order to increase local control, Griqualand-West was transferred to the Cape Colony in 1880 with the Cape parliament becoming responsible for enacting legislation over the region. Thus, annexation and eventual incorporation of Griqualand-West into the Cape Colony was intertwined with attainment of political authority to realize legislation needed for technical consolidation.[17]

Another demonstration of the State's early willingness to act in the collective interest of the Kimberley diamond industry was its occupation of the ZAR. When the British occupied Pretoria in 1877 one of there first acts was the removal of the transit or exit tax on African laborers crossing the territory (Worger, 1987, p. 98). Both the ZAR and OFS had imposed these mobility taxes in order to reduce the number of Africans going to work on the diamond fields. In other efforts to assist the diamond industry with its supply of African laborers, the State enacted regulations in 1872 that required Africans to carry passes in order to limit the African community's ability to leave the diamond mines.[18]

Industrial consolidation was accompanied by refined policies by the State in support. To reduce the opportunities for livelihood outside of engagement with the mining industry, the State passed a hut tax on the African communities in 1879. A Police Magistrate Court was also established in 1879 to significantly enhance enforcement of the 1872 pass laws.[19] This court was assisted by municipal regulations that designated racial locations in order to make police enforcement of these racial physical mobility restrictions easier (Worger, 1987, p. 130).

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[17] See Chapter Two in Newbury (1989) for details.

[18] These regulations were ineffective as limited capacity to enforce them made them prohibitively expensive for producers. See: Worger (1987, Chapter Three).

[19] See Chapter Nine for further details on the role played by pass laws and hut taxes in securing a stable supply of low-wage Africans for the Witwatersrand gold mines.

The State adoption of a presumption of guilt in the Diamond Trade Act of 1882 clearly signaled its alignment with the mining professional community. After some initial dithering, with repeal of claim restrictions in 1876, the State had already established its bias towards the interests of larger diamond producers.[20] Other evidence of the mining professional community's influence over life in Kimberley comes from its ability to cover-up a large outbreak of small-pox in 1883-1884 (Worger, 1987, p. 106). Lastly, State co-optation with increasingly large operators on the diamond fields was reflected in the fact that the mines were under no legal obligation to compensate a miner or his heirs from death or injury on the mines (Worger, 1987, p. 152).

TABLE 6.3 Important Dates in the Southern African Mining Industry until 1885

GOLD MINING	
1853	Alluvial gold on Jukskei River (Limpopo Watershed), Gauteng
1873	Alluvial gold rush Blyde River region, Mpumalanga Drakensberg Escarpment
1882	Alluvial gold rush Barberton Mountains, Mpumalanga
DIAMOND MINING	
1866	Alluvial diamond 'Eureka' near Hope Town, Northern Cape
1869	Alluvial diamond rush 'Star of South Africa', Orange Free State/Northern Cape
1870	Kimberlite diamond discovery Jagersfontein, Orange Free State (1871 Kimberley)
1880	De Beers Diamond Corporation established
SUNDRY MINING	
1853	Copper mining rush Okiep District, Namaqualand, Northern Cape
1865	Coal mining for Pietermaritzburg in Klip River Region, Kwa-Zulu/Natal.
1868	Coal mining locally near Bethal (Steenkoolspruit), Mpumalanga.
1879	Coal mining for Kimberley diamond mines at Vereeniging, Gauteng

Besides Kimberley and its important precedents, several mineral discoveries and booms preceded the Witwatersrand; Table 6.3 lists a few of the more significant. Most of these followed discovery of alluvial diamonds, which ignited massive prospecting across the Southern African interior. In its scale and legacy, the most important precedent to the Witwatersrand was the Kimberley diamond deposits. Kimberley expanded the mining know-how and financial capacity of Southern Africa. In building these critical factors, it created momentum to overcome technical hurdles and uncertainties associated with early development of the Witwatersrand. It also created a distinct class of financial entrepreneurs within a community of miners that subsequently pioneered the Witwatersrand's systematic extraction.

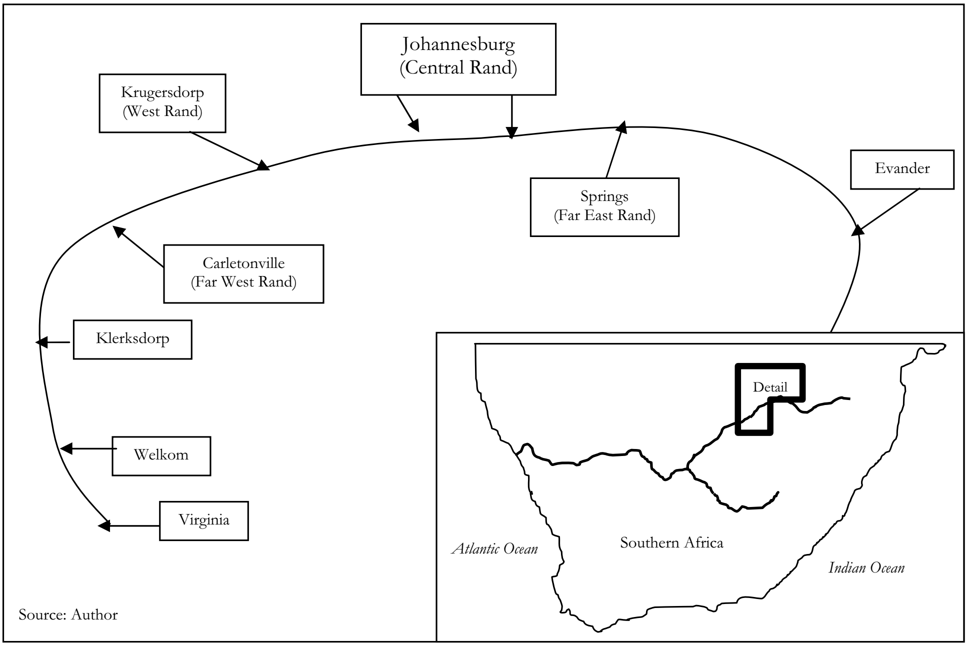
6.2.4 Overview of the Gold Mining Production Process

Before turning to specifics on cyanide technologies below and the subsequent case on changing stoping practices in Part Three, this section introduces the process of gold mining on the Witwatersrand. Three groups of procedures encompass a mine's life: project, production, and decommissioning. Project procedures include the exploration and identification of the mineral deposit, feasibility studies, design, construction, and commissioning of the operations. Production procedures are day-to-day operations. Because mining involves adjusting procedures slightly as different geological characteristics of the ore body are encountered, this might better be described as continuous adjustments in the operating procedures to extract the mineral resource. Lastly, decommissioning is the closure of the mine site after completing the warranted degree of mineral extraction. The case studies are on aspects of the first two phases.

Exploration is a fundamental activity in mining. It ensures that the mining firm has future deposit to extract, which given the nonrenewable nature of mineral deposits, is their raison d'être. Exploration is also critical to identifying the specific structure of the mineral deposit and is thereby a critical input in the design and operation of a mine.

[20] See Chapter One in Worger (1987) for details.

Map 6.2 The Witwatersrand Basin



Mineral rights, infrastructure support, market evaluation, estimated extraction costs, processing costs, and the potential variability of all these must be considered to determine whether mining the deposit is economical. Three distinct stages comprise the project phase:

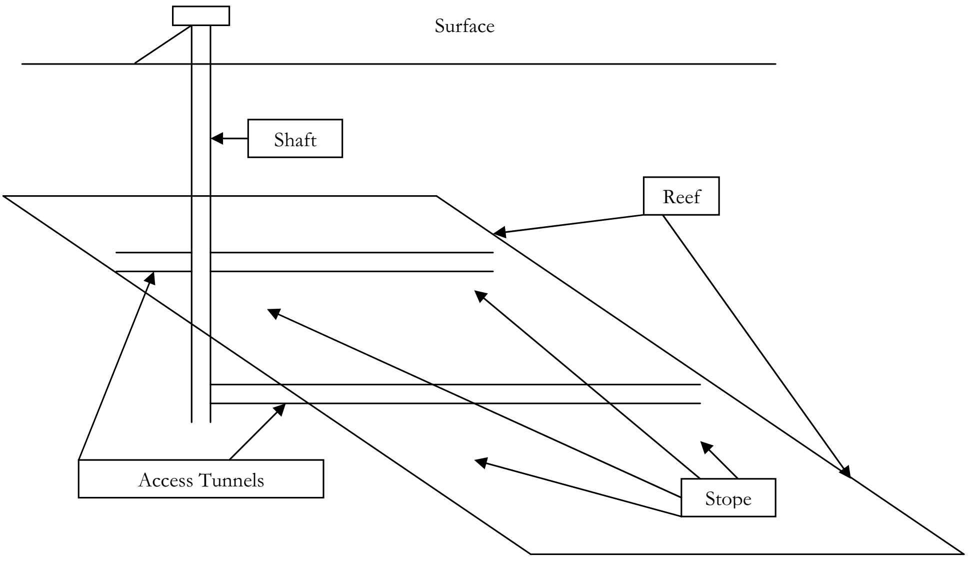
1. Preliminary investigations - initial cost estimates, research and development (R& D) to derive scope, and front end engineering.
2. Preliminary evaluations/feasibility studies - initial engineering completed, final scope development, detailed estimating.
3. Project scope and cost defined/preliminary project execution - detailed design, drafting, and project management. Financial resources are brought together for development.

Based on analysis of the deposit and its location during this phase many crucial estimates are made whose accuracy will strongly influence realization of project viability. Detailed plans and revisions occur during the early stages of this phase, but the large scale of capital expenditures typically means that the mining method and mine plan are locked in. With viability established, the first stage of development involves building headgear and sinking a shaft to access the gold bearing rock or 'reef'.

Tunnels are excavated at various levels from the shaft to intersect the sloping shores of the gold bearing rock; these tunnels are called 'cross-cuts'. Once the reef has been intersected, it is extracted through a series of additional tunnels across, up, and down the gold bearing deposits. The removal of gold bearing rock is a process referred to as 'stoping'. The stopes connect upward and downward to access tunnels (See Figure 6.1). This stoping process is somewhat analogous to the removal of a layer of icing in a multi-layered cake. In this case the layer of icing being about a meter or two thick with thousands of meters of rock above and between subsequent layers, all of which slope to greater depths and are fractured from tectonic action.

Mining the reef involves a process of drilling and blasting similar to that used to extract the tunnels. Several holes at various angles are drilled into the rock, filled with explosives, and then the rock is blasted out. The rock blasted on the stopes is transported to tipping stations, sent down a rock chute, and then hauled to the surface via a shaft. On the surface, the gold bearing rock is separated from surrounding rock before being sent for processing to extract the gold.

FIGURE 6.1 The Layout of a Gold Mine



6.3 CYANIDE TECHNOLOGY DEVELOPMENT

6.3.1 Previous Practices

Once the gold bearing host rock reaches the surface of the mine, it is processed to acquire a high purity gold metal, a stage in the production process referred to as metallurgy. Initially, metallurgy on the Witwatersrand involved three stages: milling, concentration, and pyrometallurgy. In the milling phase, the ore was first sent to crushers to break-up large pieces. It was then brought to stamp-mills where water was added and the ore ground to a small size, producing a pulp,[21] with a ratio of one part gold bearing ore to five parts water (King, 1949, p. 141). Pulp was then passed over amalgam plates (large copper plates covered in mercury). This process of concentration worked because of the higher specific gravity of gold. Lighter minerals in the pulp cannot sink through the mercury and become waste tailings. After concentration through amalgamation, the gold amalgam enters a pyrometallurgical stage to separate the mercury and gold. This process, called retorting, heats the gold laden mercury to 800°C for several hours boiling and vaporizing the mercury,[22] and leaving a sponge gold. This extraction process removed between 75 to 80% of the gold from the host rock (Adamson, 1972, p. 88).

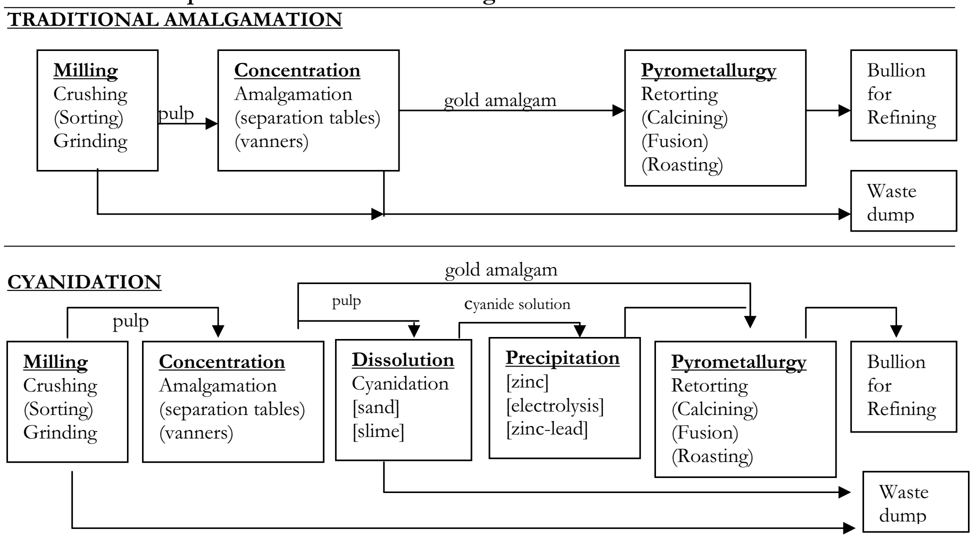
[21] 'Pulp' is perhaps best thought of as a gold bearing muddy substance.
[22] The vaporized mercury being captured and water-cooled in a condenser for re-use on the amalgam plates.

6.3.2 Technological Challenge

Once mining of the Witwatersrand commenced in 1886, the miners followed the gold bearing layer deeper and deeper into the ground. Eventually they reached depths where the gold bearing host rock was not oxidized and the amalgamation method lost its effectiveness. At that time metallurgy in general, but gold metallurgy in particular was in its infancy. Only with the California rush of 1849, when amalgamated copper plates were introduced, had any systematic industrial gold metallurgy been attempted (CMMSSA, 1934, p. 298). By the mid-1880s, the only alternative extraction technology to amalgamation was a process called chlorination. Invented around 1840, the chlorination process was so expensive in its fixed and variable costs that only relative rich ores could be treated economically. The Witwatersrand in that era was abundant in relatively low-grade ores. Thus, in the latter half of 1889, a dark cloud emerged on the industry's future as the sulfide layer was intercepted and recovery with amalgamation only extracted 50 percent of the gold from the host rock. The speculative bubble burst; by early 1890, the market value of the mines plummeted 70 percent, and a third of Johannesburg population departed (Edwards, 1994, p. 251). The first era of the Witwatersrand's development was over and another, built around the cyanide process, began (Webb, 1903, p. 23).

Chlorination and cyanidation methods are similar in that they introduce two additional stages to the extraction process: dissolution and precipitation. Therefore, both were radical departures from previous methods of extraction through concentration alone. Where cyanidation held a huge advantage over chlorination was in economies of operation, making the difference between profit and loss for many of the Witwatersrand mines (Gray and McLachlan, 1933, p. 383). The cyanide process had been experimented with in laboratories previously, but it was only through the efforts of John S. MacArthur and his work with the Forrest Brothers in Glasgow during the mid-1880s that an industrial process of cyanide extraction was developed. It is telling then that in 1896 COMSA was able to successfully contest and get the MacArthur-Forrest patents repealed.[23]

FIGURE 6.2 Representation of the Metallurgical Processes



[23] Gray and McLachlan (1933) review the patent battle, giving its scientific and legal background.

When the cyanide process was introduced on the Witwatersrand in 1890, it was met with great skepticism as many competing methods were being floated as saviors of the beleaguered gold field. MacArthur's Cassel Company operated the first pilot plant on the Witwatersrand in June 1890 at the Salisbury Mine (MacArthur, 1908, p. 205). After favorable results at the Salisbury Mine, a local company, the African Gold Recovery Syndicate (AGRS), was granted license over the process patents. At the Robinson mine in December 1890, the AGRS opened the first commercial plant using the cyanide process. With successful operation, the Robinson mine took over the plant from AGRS when their lease expired in June 1891. The demonstrated efficiency of the process at the Robinson Mine led to its subsequent diffusion across the Witwatersrand (Caldecott, 1908, p. 125). Looking back, the future of cyanide seemed assured, however, as a new industrial process many refinements were needed before supremacy was realized. Those challenges led to an influx of metallurgical professionals from around the world and gave birth to one of the early professional societies in Johannesburg, the Chemical and Metallurgical Society or the 'Cyanide Club' as it was popularly known. This analysis focuses on a selection of those refinements and the role played by research collaboration.

The first challenge was demonstrating cyanidation's commercial superiority over alternative methods i.e. chlorination. In the cyanide process, concentration through amalgamation is followed by dissolution and precipitation phases (see Figure 6.2). After separating the tailings between relatively fine slime and coarse sand, the pulp was charged with cyanide. Central to the process is the chemical bond that cyanide forms with gold. The gold bearing cyanide solution can then be separated from tailings. The next stage is precipitation, where gold is separated from the cyanide solution before being sent on for pyrometallurgical processing. Two innovations from dissolution and precipitation phases are investigated: slime treatment and precipitation techniques. These three examples are representative of the various, primarily, incremental innovations made through research collaboration in this period.[24]

6.3.3 Solutions

Chlorination vs. Cyanidation

The chlorination method was known among the miners as an alternative to amalgamation before the sulfide layer was intercepted on the Witwatersrand. Chlorination could recover 99 percent of the gold from the host rock, but was expensive and therefore only justified in treating rich concentrates. In 1889, when amalgamation began to falter, chlorination was introduced on the Witwatersrand, but met with little success (Williams, 1899, p. 726). The Corner House mining-finance-group subsequently hired an American metallurgist, Charles Butters, to establish chlorination plants at its mines and develop the method. In August 1891, Butter's opened the first chlorination plant at the Robinson Mine.[25] In 1893, the COMSA established a Concentrates sub-committee to investigate the best concentration techniques. Improved concentration technology favored chlorination over cyanide. However, in their report of 1894, no significant improvements in concentration were found that could expand the application of the chlorination process.[26]

During the 1890s, through its continual evolution and lower associated cost structure, cyanide superseded chlorination. Table 6.4 compares the two methods usage across the Witwatersrand.

[24] Details of the many improvements on the process are discussed in Butters (1897, 1898), Williams (1899), and Webb (1903).

[25] Hence, the Corner House's Robinson Mine had both cyanide and chlorination methods operating simultaneously.

[26] See Hatch and Chalmers (1895, p. 208).

In 1892, chlorination accounted for 17 percent of the gold extracted from pulp after amalgamation. By 1899, nearing the end of its days, chlorination only extracted four percent of the gold after amalgamation. The competition between chlorine and cyanide by the late 1890s is best summarized by Mr. Butter's own words: "There has been a great deal of study given to the use of chlorine as a dissolving agent, but its use is very limited in comparison with that very easily handled solvent, cyanide, so that I am prepared to state that cyanide is slowly but surely displacing chlorine on the Witwatersrand for all purposes. I have no doubt that upon these fields the use of chlorine will be discontinued...I must admit now that [with current cyanide methods] as high a percentage of extraction can be obtained with cyanide as with chlorine" (Butters, 1897, p. 83). While a few chlorination plants continued to operate after the Second Anglo-Boer War, by 1905 all chlorination on the Witwatersrand mines had ceased.

Table 6.4 Extraction Methods on Non-Amalgamated Gold[27]

Year	1892	1893	1894	1895	1896	1897	1899*
Chlorination	17%	13%	10%	9%	8%	7%	4%
Cyanidation	83%	87%	90%	91%	92%	93%	95%

Source: Chamber of Mines Annual Reports 1892-1899, Compiled by Author.
* No breakdown was reported in 1898

Extraction of Gold from Slime

Initially, the cyanide method was applied after amalgamation to relatively coarse sand. Because the cyanide solution would not penetrate the fine material, all the 'slime' went untreated to dams, despite its gold content. Slime accounted for between 30 to 40 percent of the pulp from the mills after amalgamation and represented an important shortfall in economies from the cyanide process. Slime dams accumulated across the Witwatersrand, building a stock of gold awaiting an innovation for its liberation.

The members of the Chemical and Metallurgical Society of South Africa (CMSSA) actively contributed to development of such a process. By 1897, they succeeded in developing an economic means of treating slime. The series of advances leading to the emergence of this process are chronicled in their *Proceedings* between 1894 and 1899.

Early in 1894, John R. Williams, working at a Corner House mine, first experimented with a slime treatment process: decantation (Williams, 1897, p.93). [28] William Bettel, working first at a Johannesburg Consolidated Investment Company (JCI) group mine then at a Farrar group mine, made an important contribution to the process by developing sorting and leaching techniques. [29] The zinc precipitation method, which did not work well on the dilute cyanide and lime solution used in decantation, hindered further advances in the treatment of slimes. Thus, decantation as a method to extract gold from the slimes depended on development of alternative precipitation methods. In 1896, alternative precipitation methods facilitated construction and operation of the first decantation based slime treatment plant at the Crown Reef mine (Williams, 1897, p.93). [30] This plant marked the first time in the ten-year history of the Witwatersrand that all the gold bearing ore was processed.

[27] These are percentages of gold bearing tailings after amalgamation.
[28] The slime decantation process involved several large vats in which through a gradual process of mixing the gold in the slime became attached to the cyanide in liquid solution and separated from the sediment.
[29] Bettel (1894; 1895)
[30] See Stent and Adamson (1949, p. 199) for a summary of the decantation method.

Charles Butter's Rand Central Ore Reduction Company (RCOR) made further refinements in slime treatment.[31] Another important source of innovation in slime treatment came from the sharing of experiences amongst the professional metallurgists of the CMSSA in various aspects of slime treatment through presentations, publications, and discussions. Together these efforts by individuals, business organizations and collaborations made slime treatment a reality, thereby improving the cyanide method and marking a major advance in the metallurgical history of the Witwatersrand (Thurlow and Prentice, 1928, p. 253).

Gold Precipitation

After the gold has formed a bond with cyanide and impurities filtered off to create a clear solution, precipitation follows. Precipitation involves the separation of gold from cyanide solution. When the MacArthur-Forrest process was first introduced on the Witwatersrand in 1890, precipitation utilized zinc shavings. The gold bearing cyanide solution was discharged into a box with zinc shavings, where gold precipitated on the shavings. This slimy precipitate then went on for pyrometallurgical roasting and smelting into bullion.[32] With the introduction of electrolysis-based precipitation in 1894, a real threat to the zinc shaving method emerged. Then in 1898, an improved lead-zinc process began to gain favor.

Electrolysis precipitation, specifically the Siemens-Halske process, was developed in Germany in 1887 and used at mines in Europe, Siberia, and the United States from 1888. Andries von Gernet, working for the RCORC, introduced the process to the Witwatersrand in 1894 at the Worcester mine. The process worked on low strength cyanide solutions, regardless of its acidity, which favored its use in the precipitation of slimes (Von Gernet, 1894). A period of intense debate about the comparative superiority of the two processes followed.[33] Electrolytic precipitation is a reasonable simple process; electrodes are surrounded by the gold bearing cyanide solution and the gold precipitated upon the cathode covered in lead foil. These auriferous lead sheets are then sent for pyrometallurgical treatment.

At the outset, the electrolitic process held several advantages over zinc. First, the electrolitic process had lower royalty charges.[34] Second, the electrolitic process was able to treat the acidic ores of the Witwatersrand without the addition of lime. Third, through the lower requisite strength of cyanide solution, electrolysis carried variable cost savings. Lastly, electrolysis produced a higher-grade product following pyrometallurgy.

Zinc was fundamentally more durable and since electrolysis had higher fixed costs, both processes had approximately equal total costs for treating sands. Nonetheless, initially the zinc process could not treat low strength cyanide solutions, which left electrolysis as the only means to precipitate gold from the low strength solutions produced in the decantation treatment of slimes. However, electrolytic precipitation also had limitations in its treatment of low-grade gold solutions and so alternative precipitation technologies were investigated (Adamson, 1972, p. 121).

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[31] Among the refinements were methods of treating accumulated slime (Caldecott, 1897), and a continuous slime treatment process (Rand, 1899).

[32] Roasting involves the super-heating of the precipitate in a manner similar to retorting in the amalgamation process previously discussed.

[33] This debate is richly illustrated in John Yates (1896) paper and discussion to the CMSSA.

[34] In 1896, the initial advantage the Siemens-Halske process had through its lower royalty charge was lost when the MacArthur-Forrest patents were ruled invalid. See Gray and McLachlan (1933).

In mid-1898, W. K. Betty, at the Corner House's Crown Deep Mine, began using a lead-zinc couple to precipitate gold. In October 1898, Betty's assistant T. Lane Carter, presented results of the three successful months they had had with this method to the CMSSA, precipitating another intense debate among the society's members (Carter, 1898). In 1894, John MacArthur patented a zinc-lead couple with immersion in lead acetate. That couple was used in the Lydenburg District of Mpumalanga from 1895, but not on the Witwatersrand because previously lead remained in the gold bullion following pyrometallurgy. Pyrometallurgical refinements in 1897 reduced the difference in bullion grade, opening the door to zinc-lead precipitation (Johnson, 1913, p. 246). By March 1899, twelve out of sixteen slime treatment plants were using the zinc-lead method, the electrolytic challenge dispelled.

6.3.4 Subsequent Technological Evolution

Nearly a century of literature records the principles and development of Witwatersrand metallurgical practices.[35] The terrific scale and common geological structure of the Witwatersrand Basin deposits generated this long and detailed history of its gold bearing host ores. As a result, despite years of extraction, the basics of Witwatersrand metallurgy have not required any radical technological changes since the adoption of the cyanide process.

In the 1910s, zinc dust replaced the zinc shavings in precipitation, but zinc-lead precipitation ruled the Witwatersrand until displaced by the carbon-in-pulp process in the 1970s (Janisch, 1986, p. 305). Tube-mills were introduced on the Witwatersrand in 1904 and shortly thereafter adopted as secondary grinders on a wide-scale across the Witwatersrand (Adamson, 1972, p. 23). As production shifted from the central to the Far East Rand, development of an 'all tube-milling' process advanced, culminating by the early 1920s in an 'all sliming' process (Thurlow and Prentice, 1928, p. 254).[36] Over the ensuing decades, numerous refinements reformed the dissolution stage, but these built on the foundations established in this first decade after the introduction of cyanide on the Witwatersrand.

6.4 CONCLUSION

This chapter described the industrialization of a gold metallurgical technology, cyanide based extraction, on the Witwatersrand. It marked one of the most important innovations to emerge from the Witwatersrand's system of innovation. Therefore, this technological experience indicates a best practice in research on the Witwatersrand during the 1890s.

At this time, political power was diffused in the Southern African region, creating little inkling of a national system of innovation in even a crude sense. However, important learning clusters did exist and none more important than the Witwatersrand. The industrial research structure that emerged on the Witwatersrand was characterized by research collaboration in production techniques. The next chapter analyzes the research collaboration in this case of innovation. This overview highlighted significant collaborative precedents, particularly those at Kimberley, which seemingly facilitated research collaboration. However, the legacy of research collaboration in this instance similarly influenced the subsequent case of transforming stoping practices in Part Three.

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[35] See: *A Text Book of Rand Metallurgical Practice* (1912, 1913, 1926); King ed. (1949); Adamson ed. (1972).

[36] Details on the evolution of slime treatment from decantation to 'all sliming' can be found in Adamson (1972, pp. 91-100), Stent and Adamson (1949), and Thurlow and Prentice (1928).

Chapter Seven:
An Analysis of Research Collaboration in Cyanide Technologies

7.1 INTRODUCTION

This case describes research collaboration's role in the development of a metallurgical technology that made mining of the massive Witwatersrand gold deposits economically viable. It demonstrates the ability of an open community of practitioners to develop and diffuse a critical competitive technology. The structure of collaborative research in development of cyanide based extraction technologies is the focus of the first section of this chapter. After describing that structure, effects and causal conditions of the collaborative research initiative are analyzed. Thereby, a relatively comprehensive picture emerges of factors which drove research collaboration in development of cyanide based extraction technologies emerges.

7.2 STRUCTURAL FACTORS

While distinct causal conditions and associated effects differentiate the analytical approaches, in each of the two cases they are describing a common environment in which research collaboration occurred. Therefore, rather than reviewing the various approaches' contextual conditions in isolation, we take an encompassing approach. Without repeating common elements this section describes important factors in the collaborative development of cyanide based extraction technologies. Throughout emphasis is placed on the most relevant contextual conditions; with brief mention of linkages, or lack there of, to the respective theoretical approaches.

7.2.1 The Technologies

Three challenges were identified in Chapter Six to development of a viable metallurgical process that could treat the massive quantity of deep level Witwatersrand gold deposits. Solutions to these challenges created a technology that defines the *Innovative Object* and *Public-Collective Good* in the Distributed Innovation and Collective Action approaches respectively. While initially cyanide had lower total and variable costs compared to chlorine-based extraction, it generated large quantities of non-extracted gold in slimes. In the mid-1890s, a method to treat the gold suspended in the slime emerged. Since slime (fine pulp) accounted for 30 to 40% of treated gold-bearing ore at depth, the slime treatment process led to major economies in cyanide-based extraction. However, precipitation of the low-grade gold solution generated by the slime treatment process created its own difficulties. Electrolytic precipitation was used initially, but its industrialization was problematic. Development of zinc-lead precipitation in the late-1890s provided a reliable way to precipitate the low-grade gold solutions generated by slime treatment. Continual incremental technological innovations and information diffusion propelled development of both of these solutions to the initial challenges of industrializing cyanide-based extraction and by the end of the 1890s cyanide-based extraction developed on the Witwatersrand was clearly superior to chlorine-based extraction.[1] Not only would cyanide-based extraction prove a durable technology, but its open community of practitioners similarly heralded an enduring practice of collaboration in critical competitive technology for the industry.

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[1] We assume that the cyanide process was in fact the more efficiency technology and that this is not a case of technological lock-in of a comparatively inefficient technology. For a brief introduction to the literature and controversy associated with technological choice, see David (1985); Cowan (1991); Liebowitz and Margolis (1990 and 1995).

Cyanide-based extraction technology opened up the Witwatersrand for deep level mining and exploitation of a gold deposit on a globally unprecedented scale. It transformed mining activities on the Witwatersrand from low investment intensity outcropping to high investment intensity systematic underground mining. Cyanide-based extraction thereby initiated an unprecedented process of industrialization of gold mining. The resulting size and scope of mining and extraction transformed inter-agent relationships. Even established mining financiers from Kimberley faced an entirely different scale of operations on the deep level gold mines. This evolution of the gold mining industry greatly influenced regional industrialization and productive activities across southern Africa.

A president of the Chemical and Metallurgical Society, G.S. Stanley, noted the enduring significance of cyanide-based extraction technology: "I need only emphasize that if gold metallurgy had not greatly advanced from the state in which it was at the commencement of activity on the Witwatersrand these fields and the whole country would have been in a very different position to-day, for the recovery obtainable would not have enabled the treatment of more than a small proportion of the tonnage since milled... Indeed, a greatly lessened gold production during the last half century could scarcely have been without great effect on world affairs" (CMMSSA, 1934, p. 295).

7.2.2 The Product Market

An industrial district is inherently oriented towards providing a good or service whose demand is beyond that of its own borders. From its inception Witwatersrand gold sales were principally for the export market. The Bank of England regulated that export market in support of the British Pound's function as the international monetary standard. Thus, between 1886 and 1902, the Bank of England fixed the international market price of gold at £4.2 per troy ounce.[2] Russell Ally (1994) examines the relationship between Witwatersrand gold producers and the Bank of England from 1886 to 1926. He details how the Witwatersrand gold deposits played a fundamental role in monetary expansion under the fixed commodity system. Ally argues that although British authorities were obviously acting in the interests of financial activities based in the City of London, there is little evidence to suggest that those financial interests were directly involved in the escalation of hostilities by British authorities that eventually led to the Second Anglo-Boer War.[3]

Table 7.1 Witwatersrand Gold Mining Statistics 1886-1902

	1886	1887	1888	1889	1890	1891	1892	1893	1894
Gold Output (Kgs)	254	1,240	7,084	10,915	13,690	21,413	33,251	40,130	56,142
Avg Price (£)	4.2	4.2	4.2	4.2	4.2	4.2	4.2	4.2	4.2
	1895	**1896**	**1897**	**1898**	**1899**	**1900**	**1901**	**1902**	
Gold Output (Kgs)	62,758	63,005	85,336	118,923	113,151	10,852	8,041	53,437	
Avg Price (£)	4.2	4.2	4.2	4.2	4.2	4.2	4.2	4.2	

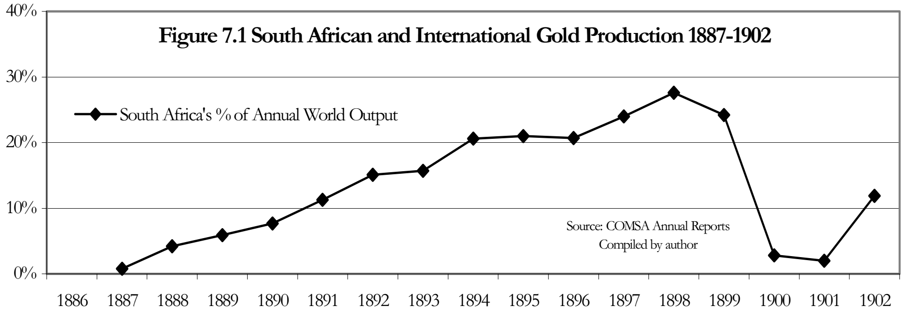
Note: Between 1886 and 1933 the South African Rand was pegged to the Pound Sterling at 2Rand per 1£. Source: COMSA Annual Reports. Compiled by author.

Table 7.1 shows the rapid growth of gold output from the Witwatersrand. Between 1887 and 1898, the amount of gold produced on the Witwatersrand grew at an average annual rate of 42%. The impact of this growing supply of gold on the international market can be seen in Figure 7.1. By 1898, Gold produced on the Witwatersrand accounted for nearly 30% of annual global production. In this early era, the Witwatersrand clearly played a major role in the international

[2] One troy ounce is equal to 31.1 grams or one kilogram is equal to 32.15 troy ounces.

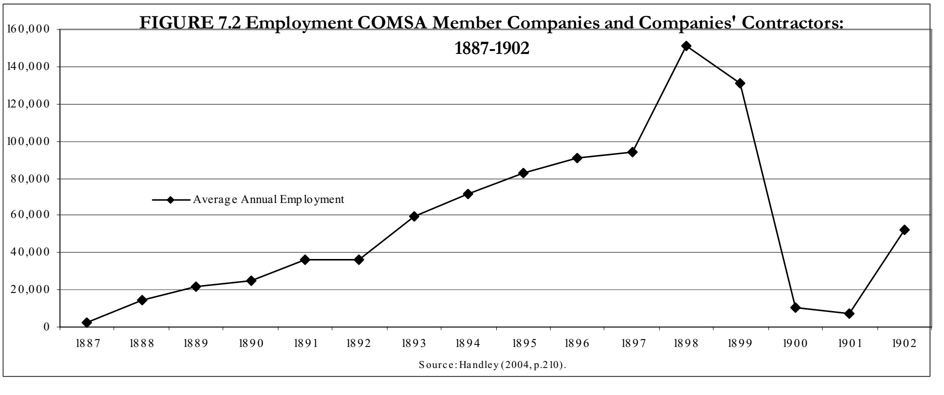
[3] See Section 7.2.3 below.

monetary system, even if that role would subsequently expand further.[4] Monetary stability and durability of the international monetary system under the British gold standard created a unique final product market characterized by limited volatility and uncertainty. The nature of the international gold market therefore reduced the risks associated with the large capital investments required mine the Witwatersrand deposits. Hence, a mutually advantageous situation emerged between Witwatersrand gold producers and the international gold market, with both providing stability facilitating their mutual development.



7.2.3 The Social Structure of Production

Between 1886 and 1902 Africans, European Miners, and Mining Professionals were the three principal groups directly involved in the production of gold on the Witwatersrand. These agents form *Human Resources* in production from the Industrial District approach. While there are no readily available statistics for these groups' proportions, contemporary data from the Kimberley diamond mines and later periods from the Witwatersrand indicate the ratio of African to White labor was probably around eight to one.[5]



Based on employment data from COMSA member companies and their contractors, Figure 7.2, we estimate the White labor force grew from a few hundred individuals in 1887 to around 17,000

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[4] See Chapter Nine, Section 9.2.2.

[5] The racial differentiation, White and African, is the only available basis to distinguish between groups of labor on the mines during this period. White labor therefore includes both Mining Professionals and European Miners.

in 1898. Similarly, the African labor force grew from a few thousand in 1887 to over 134,000 in 1898. Between 1887 and 1898, employment by COMSA members and their contractors grew at an average annual compound rate of 37%.

Each group was marked by diverse internal dynamics, but Mining Professionals were the primary agents involved in the collaborative development of a cyanide based extraction technology. While mining financiers, mine managers, metallurgists, and mining engineers were all part of the Mining Professional class it was the metallurgist who formed the key community of practitioners who openly collaborated in the development of this critical technology. These metallurgists were brought to design more efficient gold extraction techniques in the mills on the Witwatersrand's surface from the early 1890s. This immigration of metallurgists generated knowledge externalities in metallurgy and other fields that were internalized within the Witwatersrand. The President of the COMSA, George Rouliot, reflects the positive externality from the co-location of metallurgists in a contemporary quote: "To-day [the Witwatersrand] is the most flourishing goldfield in the world... The position of your Society reminds me of what takes place when there is a successful campaign anywhere. The name of the victorious general is flashed all over the world, and is known everywhere... However clever, and thoughtful, those responsible for the establishment and control of the mines may have been, they would never have been able to lay before the world such a record as we have done if they had not been backed up by all those who hold secondary control in the management of the mines; and that is why it gives me great pleasure to-day to publicly acknowledge the immense services which have been rendered to the industry by your Society and by everyone of you" (CMMSA, 1899, p. 642).

Among the Mining Professionals were mining financiers who headed the mining-finance groups that financed the building and running of the gold mines.[6] Mine managers were also part of the Mining Professionals. They were the men in charge of running operations on the Witwatersrand, which included mine supervisors, mill supervisors, and mine accountants. Lastly, mining engineers were Mining Professionals. They planned underground operations, designing new mines and new sections in existing mines as well as constantly adapting mining operations to the changing contours, faults and grades of the gold bearing reef.

European Miners consisted of artisans and skilled miners. Artisans were skilled tradesmen who maintained the equipment employed in the mining operations. Skilled miners were experienced in the drilling and breaking of earth underground. However, following precedents from Kimberley, they supervised Africans who actually drilled the holes for explosives and subsequently cleared the broken ground.[7] Despite difference, the European Miners were overwhelmingly British expatriates (Katz, 1994).[8]

Africans were also diverse, these men from across southern Africa often had to seek work on the Witwatersrand because of policies from exclusively White governments. Among these policies were hut taxes and pass laws developed in support of the Kimberley diamond mining industry. Not many statistics are readily available on the composition of the African labor force during this period, but in the mid-1890s approximately 50% were reportedly from Mozambique; another 20% were from northern Botswana, Malawi, Zambia, and Zimbabwe; and the remaining 30% were from southern Botswana, Lesotho, Swaziland, the Cape and Natal Provinces, the OFS and

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[6] These were colorful individuals like Cecil J. Rhodes, Barney Barnato, Ernest Oppenheimer and J.B. Robinson on whom a substantial literature has been written. See for example: Rotberg (1988), Gregory (1962), Cartwright (1962), Cartwright (1971), Emden (1935), Jackson (1970), and Mendelsohn (1991).

[7] Precedents in the organization of European Miners at Kimberley were discussed in Chapter Six, Section 6.2.3.

[8] Their jobs' different associated authority over production played an important role in the case on transformation of stoping practices.

the ZAR (Van der Horst, 1943, p. 136-137). A recruitment industry emerged during this period to supply the mines with its politically disenfranchised African labor force. Despite efforts by the industry to constrain independent recruiters because of the added costs they imposed, the industry was unable to organize a co-operative system of African labor recruitment during this period.[9]

Between 1886 and 1902 these three agents composed the majority of the Witwatersrand's total population. Although Johannesburg was central, a variety of smaller settlements stretched along the Witwatersrand from Boksburg in the east to Roodeport in the west.[10] Contemporary accounts place the greater Witwatersrand population at around 3,000 individuals in 1887; 40,000 in1889 and over 100,000 by 1895 (Lewis, 1964, p. 53). The population of Johannesburg alone eclipsed that of Pretoria by 1888 (Rosenthal, 1970, p. 191). The only census during this period was a Johannesburg census, conducted by the Johannesburg Sanitary Board (JSB).[11] That census showed a predominately male total population of 82,000 in July of 1896. Accordingly, 65% of 39,500 White people in Johannesburg were male and 94% of the 42,500 Black population were male (Van Onselen, 1982a, p. 104).

This influx of people associated with gold mining rapidly transformed the area along the outcropping deposits of the Central Rand. Nonetheless, the Witwatersrand mining community formed an enclave in a rural environment. A contemporary mining engineer noted this point: "As you all know, we live under very peculiar circumstances. If you go [40 kilometers] from this reef – the Witwatersrand mining area – which is about [65 kilometers] in extent, you are in an entirely different country" (Miller, 1898, p. 128).

Initially, the Afrikaner ZAR government in Pretoria appointed a military official to govern the Witwatersrand. Later in 1886, the ZAR appointed a mining commissioner and authorized the election of a local Diggers' Committee in Johannesburg. The Diggers' Committee was replaced by the Johannesburg Sanitary Board (JSB), which governed until October 1897 when Johannesburg was granted municipal status. However, Afrikaner concerns over Johannesburg's autonomy led to each municipal ward electing two councilors, one of whom had to be a ZAR citizen *i.e.* an Afrikaner.

TABLE 7.2 Important Socio-Political Dates in Southern Africa: 1886-1902

1887	Transvaal Chamber of Mines (now Chamber of Mines of South Africa)
	First newspapers published in Johannesburg
1890	ZAR naturalization restrictions increased
	Lower-house created to represent non-ZAR citizens
1892	Railroad completed between Cape Town and Johannesburg
1895	Jameson Raid
	Pass Laws created
	Railroads completed from Durban and Maputo to Johannesburg
1897	Industrial Committee appointed
1899	Second Anglo-Boer War begins
1902	Second Anglo-Boer War concludes

Political authority and political geography of the area defines the *Socio-territorial Entity* in the Industrial Districts approach. The Afrikaner ZAR government in Pretoria was reticent to lose political control of this rich mineral enclave. Nevertheless, uncertainties regarding potential State

[9] See Section 7.2.4 for more details.

[10] See Map 6.2 in Chapter Six for the location of these townships along the Witwatersrand Basin.

[11] In that census Johannesburg was defined as the area within a five kilometers radius of the central Market Square.

hostility added another risk that the Mining Professional community in general and the mining financiers in particular actively sought to reduce.

A symbol of Afrikaner hostility towards Witwatersrand mining was a ZAR policy of granting monopoly concessions.[12] Monopoly concessions involved the ZAR granting exclusive rights to produce specific articles in exchange for payments by the concessionaire to the ZAR as well as other up-stream and down-stream preferred purchase and supply conditions.[13] The concessions represented a heavy indirect tax on the disenfranchised management class of Mining Professionals on the Witwatersrand.[14] As a result, the concession policy became the focus of protests by the Mining Professionals against the Afrikaner State during this era.[15] In 1892, repeal of the concessions policy formed the central platform for establishment of the Transvaal National Union (TNU). Driven by the Mining Professional community, the TNU codified opposition to Afrikaner rule in the ZAR. Many of the TNU leaders were part of the Reform Committee, who sought to over throw the ZAR government in the ill-fated Jameson Raid in the closing days of 1895.

British Colonial knowledge, if not support, of the Jameson Raid was thinly veiled (Davenport and Saunders, 2000, pp. 218-219). This shadow of British Imperialism over ZAR autonomy brought back recent memories as Afrikaners only regained control of the ZAR from the British Colonial government in 1881. Thus, the increasingly accommodating line taken by the ZAR towards the Witwatersrand after the Jameson Raid reflects Afrikaner efforts to forestall direct conflict with the British.[16] Among the actions taken to placate the Witwatersrand gold mining industry, the ZAR increased enforcement of geographical mobility restrictions on Africans to facilitate a supply of low-paid labor to the goldmines.[17] The ZAR also undertook a formal inquiry into the effects of its concessions policy through the 1897 appointment of an Industrial Commission of Inquiry into the Mining Industry.[18] In 1898, a new State Attorney was appointed to reform and improve the quality of the police force on the Witwatersrand (Van Onselen, 1984, p. 14). However, even while the ZAR moved to accommodate the Witwatersrand British Colonial ambitions for the territory grew.

Britain had effectively encircled the ZAR through its colonial expansion in the 1890s. Besides the critical scale of the Witwatersrand's economy for the surrounding British colonies, the Witwatersrand represented an important source of gold to underwrite its international pound

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[12] The true hostility of this policy is definitely debatable since it was also facilitating the broader industrialization of the region. Hence, as gold production on the Witwatersrand grew the ZAR expanded its economic development program of monopoly concessions. See: Van Onselen (1982a).

[13] The ZAR granted concessions ranging from Johannesburg sewerage, water supply, waste removal, municipal lighting, and municipal transport to cyanide based gold extraction, dynamite, and rail operations.

[14] Initially, local government was the only area of political authority open to the groups that composed the mining communities of the Witwatersrand. While exclusion of the Africans was common practice, it was a point of contention for the White communities. By 1890, the rapid growth of the Witwatersrand gold mining industry and the White immigrant population running it forced the ZAR to change its restrictive naturalization qualifications in from a five year period and £25 fee to a less costly £5 fee with a virtually prohibitive 14 year waiting period. As indirect acknowledgement of these excessive restrictions on citizenship, the ZAR also created a lower-house of legislation that non-citizens could serve in, but whose proposals had to be ratified by the upper-house which remained the sole domain of ZAR citizens. See: Davenport and Saunders (2000).

[15] See for example: Rosenthal (1970), Cartwright (1964), Lang (1986).

[16] Details on this accommodation of Mining Professional's interests by the Afrikaners following the Jameson Raid can be found in Walker (1959, Chapter 12), Jeeves (1978), Kubicek (1979), and Lang (1986, Chapter 8).

[17] The increased control of African labor also held benefits for Afrikaner agriculture, but these do not appear to be central to this enforcement drive.

[18] Lang (1986) describes this inquiry (pp. 105-112).

sterling standard.[19] The ZAR's selling of some of the Witwatersrand's gold through Germany from 1898 rather than exclusively through the London market undoubtedly strained the two governments' relations further (Davenport and Saunders, 2000, p. 220). Thus, drawing on the political exclusion of the White mining communities, British efforts to exert its colonial authority over the Witwatersrand intensified. After a series of petitions from the White mining community on the Witwatersrand British troops were built up along the border of the OFS and ZAR before the Second Anglo-Boer War began in October 1899. Johannesburg saw virtually no action and was occupied by the British in May 1900 and the Second Anglo-Boer concluded in May 1902 with political authority being official transferred to the British Colonial administration of Lord Alfred Milner.

Exerting opposition to another groups' political authority is a direct, but imperfect, means to facilitate co-operation within a group. Hence, the apparent threat posed by Afrikaner political authority facilitated development of social capital amongst Mining Professionals on the Witwatersrand. This strengthening of intra-group trust established a common cause, which drove the industry's productive structure forward for decades to come. The shared identity and social capital thereby developed did not span all the groups that made up the Witwatersrand's labor force. In comparison, divisions within the other two primary groups involved in production, Africans and European Miners, would be exploited in transforming stoping practices.[20] Therefore, while not neglecting the other two groups the remainder of this section concentrates on the nature of social capital provision within the Mining Professional community and the role it played in the moral economy operating over that community.[21]

During this initial period of development, gold mining was the economy of the Witwatersrand, but it was not an economy. As the initial prospectors arrived on the Witwatersrand they created localized demand for foodstuff and lodging as well as equipment and supplies to process the gold bearing reef. As the scale of Witwatersrand gold mining grew, so too did the associated industries and individuals that provided these goods and services.[22] Although these other groups contributed to shaping the broader socio-economic dynamics of the Witwatersrand, they had tangential roles in the co-operative development of cyanide- based gold extraction technologies.

Africans were an internally fractured and isolated community during this period, characterized by transient employment. The geographic diversity of the Africans working on the Witwatersrand created intra-group social and cultural differences that limited development of social capital. The initial proletarianization of the Africans also constrained development and exertion of their labor market power. Further, while African and European Miners had a large overlap in mining operations, they formed separate classes of workers. That division of mine workers increased management's, *i.e.* mining professionals', authority over production.

Following the precedent established on the Kimberley diamond fields, most of the Africans working on the Witwatersrand were lodged in compounds near the mines. Given the lack of

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[19] See Ally (1994).

[20] See Chapters Eight and Nine.

[21] Social capital governing production of gold on the Witwatersrand corresponds to Community, Overlapping Activities, and Mechanisms of Co-operation in the Industrial District, Collective Action, and Distributed innovation approaches. Simultaneously, the Witwatersrand's moral economy matches up with the Socio-Political System, the Convention System and the Mechanism of Competition in the Industrial District, Collective Action, and Distributed innovation approaches.

[22] These other groups were diverse, but included a Jewish merchant community, Africans who did not work on the mines, an Asian merchant community, and a relatively impoverished and dispossessed Afrikaner community.

female companionship, compound life undoubtedly created intense interactions that fostered a sense of community and common cause. The tight nit nature of compound life was manipulated by mine management to divide the general African community by playing ethnically divided compounds against each other.

Another social institution that characterized the African community during this period was the consumption of alcohol. Initially used as a tool to attract African labor to work on the mines, by the mid 1890s excessive drinking led the mining professionals to effect a prohibition on the sale of alcohol to Africans (Van Onselen, 1982a, p. 67). Despite the removal of the inducement of access to alcohol, Africans still went to work on the Witwatersrand gold mines. Africans were denied political representation during this period and so racial geographical mobility restrictions like pass laws could be imposed to co-opt Africans to work on the mines. Although they lacked access to political authority, the Africans resisted the exertion of that authority upon them.[23]

In contrast to the Africans, the predominantly British nature of the European Mining community provided an effectively stronger basis for social cohesion. Katz (1994) estimated that among the White workforce 85% were British nationals,[24] 58% of the British were Cornish and a third of the Cornish were from the tin mining district of Redruth (p.65). The remaining 15% was composed of British colonial nationals,[25] 6%, South African nationals, 5%, and miners from other parts of Europe and America, 4%. Most of these migrants were single men, repatriating their earnings to their families back home.

A significant institutional import of the European Mining community to the Witwatersrand was trade unionism. This trade unionism developed from their domestic craft unions, which protected the employment of skilled workers from less skilled and unskilled workers (O'Meara, 1978, p.168). However, during this early period of sectoral development no trade unions were established.

The social institutions that provided contacts among the European Mining community were less extensive than those of the Mining Professionals. Life for the European Miner was typically based out of a hostel or boarding house.[26] When not working, European Miners had an array of drinking establishments and houses of prostitution in which to pass their time.[27] Sports provided additional entertainment possibilities. A British cultural identity is reflected in the early sports established on the Witwatersrand by 1889 Johannesburg had established rugby, soccer, and cricket grounds.

The European Mining community's skills gave them significant authority over day to day production on the Witwatersrand. However, divisions existed between artisans and miners within the European Mining community. Artisans were part of the European Mining community from a production standpoint, but they saw themselves as separate from the skilled miners (Katz, 1994, pp. 67-73).

While European Miners shared a general expatriate social and cultural heritage with the Mining Professional community, the Mining Professionals drew a distinct class-based division from

[23] See Chapter Nine, Section 9.2.3 for details on some of the means by which Africans opposed the political authority of the minority White communities.

[24] The 'White' workforce includes Mining Professionals, but their numbers were negligible compared to the European Miners.

[25] Canada, New Zealand, Australia, and West Africa.

[26] For details of the living conditions of the European Miners see Katz (1994, Chapter 6).

[27] See: van Onselen (1984a).

them. The management role of the Mining Professionals also hierarchically separated from the European miners that ran operations underground and maintained the equipment. In turn, the European Miners separated themselves from the African laborers they supervised, generating and perpetuating a heritage of racist and class-based division on the gold mines (Bozzoli, 1977, p. 12).

The Mining Professional community consisted of mining financiers, mine managers, metallurgists, and mining engineers. However, these divisions did not prevent them from developing significant social capital. Each division had its own institutions that were typically linked to their respective professional focuses, [28] but they also shared a common community identity that was a powerful force shaping political economic development of the Witwatersrand.

Mining financiers played a dominant role influencing that identity. Business and community connections from Kimberley formed the backbone connecting Witwatersrand mining financiers during this period.[29] Emden (1935) details, the deep personal networks among the Witwatersrand mining financiers. These networked relations built camps of contending mining interests supported by cross-holdings.[30] This demonstrates the differing levels in which competition and cooperation can simultaneously occur. While cooperation was prevalent in areas like COMSA's political lobbying, competition co-existed between coalitions seeking to secure the requisite financial resources. That co-existence of competition and co-operation directly facilitated establishment of an open community of metallurgists developing and diffusing a critical competitive technology.[31]

Bozzoli (1981) analyzes the formation of social identity and the ideological structure of the Mining Professional community. Despite the variety of nationals in the community, she highlights an emergence of a distinctly 'South African British' identity embedded through language, cultural and social institutions. According to Bozzoli three factors strongly influenced development of that identity; interpersonal networks from Kimberley, an international British mining culture, as well as tension between the ZAR's political authority and the economic authority of Witwatersrand mining operations.

Emden (1935) alludes to this South African British identity: "Many multi-colored stones – coming from the most varied countries – compose the mosaic of the men of South Africa. The cement which held them together was the 'sturdy individualism' of the Anglo-Saxon race which took the lead from the earliest days in Kimberley and on the Rand; only those could be assured of real success who in conscious and quick assimilation attached themselves to that great tradition" (p. 222).

Victorian gentlemen's clubs and civic institutions were prominent social institutional facilitating development of social capital and consensus around the community's identity. The Rand Club, a Victorian gentlemen's club established in 1887, was a favorite social center for mining financiers and mine management.[32] The first English Freemasonry chapter on the Witwatersrand was

[28] Metallurgists had established the Chemical, Metallurgical and Mining Society in 1894, mining engineers had the South African Institution of Engineers established in 1892, mine managers established the Association of Mine in 1892, and the mining financiers established the COMSA in 1889.
[29] See Chapter Six, Section 6.2.3.
[30] The political and inter-organizational minority interests offered by the Corner House are noted in the correspondence of Lionel Phillips (Fraser and Jeeves, 1977, pp. 55-56).
[31] See Section 7.2.5 for details.
[32] See DeVilliers and Brooke-Norris (1976).

established in 1888 and from 1892 a rapid spread of Masonic chapters accompanied rising exertion of the South African British identity.[33]

This institutionalization thereby expanded the moral economy and created a multitude of socio-economic contacts among the Mining Professional community. Stocks of social capital expanded facilitating low-cost sanctions such as social exclusion, generating expectations of reciprocity, and increasing the probability of detecting free riding. Evidence of this social capital abounds in contemporary discussions about the industry. Caldecott (1894) is typical: "In conclusion, I must say that to one who has been exiled for some years from a community such as this, one of the chief advantages of returning to it is the possibility of learning something both from what is said during the meetings of this Society and from daily contact with men such as those who compose its members, and by whose energy and skill the Rand has been raised to its present proud position of the greatest gold-producing centre in the world" (p. 26). These knowledge flows characterizing Mining Professionals facilitated and provide evidence of an open community of metallurgists developing cyanide based extraction technologies.

Hierarchically, productive authority over Witwatersrand gold mining activities was vested within the Mining Professional community. Their intra-group social capital complemented that hierarchical authority and allowed them a greater promotion of industry interests with the ZAR and surrounding British Colonial authorities. In so far as the Witwatersrand's gold mining operations affected the broader local economy, the Mining Professionals saw their interests as encompassing those of other local communities. Nonetheless, the Mining Professionals did not see the social well-being of those other communities as being their concern. A contemporary quote by the Director of Education is indicative: "Children are still crammed into unwholesome and insanitary houses; efficient schools are still allowed to struggle on from hand to mouth, hundreds are attending no school at all...Nor do I see much hope in obtaining the money we want from private donors. As things are at present, men can have no interest in the land, beyond getting a few pounds and go away...If men could feel at home here, if they could feel that this was to be the home of their children and their children's children, many would put their hands in their pocket and help us in our difficulty" (Robinson, 1898, p.219). This division of interests in other groups' social well-being is also evidence of the class divides that characterized the organization of production.

Differences existed within all three of the primary groups involved in Witwatersrand gold mining. However, these differences do not appear critical to intra-group cohesion. Despite internal differences, mining professionals were able to nurture a significant moral economy and thereby enhance the industry's competitiveness. Mining professionals' position as management and its associated authority both within the industry and within the broader regional economy undoubtedly enhanced the potential impact of intra-group co-ordination. Nonetheless, the potential for unilateral exertion or consolidation of that authority held considerable benefits that undermined intra-group co-operation. Therefore, before turning to specifics around the role of co-operation in development of cyanide based we consider the organizational structure of the industry and its role in fostering or impeding co-operation.

7.2.4 The Organizational Structure of Industry[34]

Between 1886 and 1902, Witwatersrand gold mining quickly grew to overshadow diamond mining at Kimberley and form the core of southern Africa's economy. Built from the massive

[33] See Butterfield (1978).

[34] For a brief list and history of the mining-finance groups during this period see Appendix Four.

Witwatersrand basin gold deposits as well as know-how and know-who from Kimberley, a large industry quickly took shape. Nonetheless, the industrial structure that emerged around the Witwatersrand at this time was relatively narrow in scope. A basic mining production chain existed. In addition, transport, wholesale and retail trades, and early manufacturing formed distinct vertical streams of production even if they were still emerging at this time. This section considers how these organizational structures encouraged or impeded collaboration. First, we consider structures upstream and downstream from the gold mines. Next, relationships between Witwatersrand gold mining and parallel sectors are reviewed before concluding with a discussion of the inter-organizational structure of gold production.

Competition and cooperation coexisted within the gold mining productive stream. In the review of the product market in Section 7.2.2 gold was shown to be an undifferentiated final good with a fixed price. The market share of a mine was thus only affected by its endowment of gold and its production efficiency. While this apparently facilitated cooperation in production technologies on the Witwatersrand cooperation was not automatic. Even with the fixed price of gold, production efficiencies could have formed an area of inter-firm competition. Cooperation would be particularly difficult if more efficient mines used their greater profits to buy more claims, purchase excludable political influence, or to buy the less efficient and profitable mines.

In terms of upstream inputs, competition for financial capital was apparently strong during this period although differentiated between speculative and productive focuses.[35] Nonetheless, this competition took place at the level of the mining-finance group rather than the individual mines. Once claim ownership was established and the large fixed capital investment made for a mine, production innovations were limited. A mine's method of production could not be simply transformed since it is largely determined by the original plant layout and design. This inability to change the structure of production to increase efficiency significantly reduces incentives to acquire or take-over an existing mine. Kubicek (1979) says that this likely led to a general structure on the Witwatersrand of cooperation between the mines and mine holding companies in operations, while their European based financial controllers engaged in destructive competition for speculative and development capital.

Organizationally, precedents transferred from the diamond mines of Kimberley influenced production on the Witwatersrand. In particular, Kimberley had demonstrated a means to translate the pre-industrial hierarchy found on the southern African frontier into an industrial class structure of mine professionals, European miners, and African laborers. As a result, Witwatersrand gold mining companies established institutions for African labor control and co-optation. Expectations also arose about the role of the state in supporting mining interests and in particular state assistance securing low-wage African labor.

During the 1890s, COMSA increased its role in African labor recruitment for the industry. In 1893, COMSA established a Native Labour Department and following the ZAR's increased enforcement of Pass Laws it established the Rand Native Labour Association in 1897, the predecessor of the eventually African labor recruitment monopoly. Despite these efforts, ever-increasing numbers of labor recruiters prevented COMSA from creating a monopsony in low-cost African labor during this period. In fact, persistent up-stream competition for inexpensive African labor endured for nearly thirty years before COMSA established a stable African labor recruitment monopoly (Jeeves, 1985).

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35 See Kubicek (1979).

Considerable debate exists around the conflicts ZAR's monopoly concessions created within the Witwatersrand mining industry as well as between the industry and the State.[36] In light of the present analysis it is important to realize that many of the concessions were taken up by the mining industry itself. This was largely because the mining industry wanted to develop the necessary infrastructure to support their industry's development. Another important aspect of concession procurement was that structurally, the concessions gave an additional source of intra-industry authority to the associated mining-finance groups that controlled them.

The municipal transport concession for a horse-drawn tramway was operated a company of mining financier Sigismond Neuman (Van Onselen, 1984a, p. 165). Barney Barnato's JCI operated the principal waterworks for Johannesburg from 1888 to 1903 (Sander, 2000, Chapter One). Kinship linkages with Witwatersrand mining companies also connected the industry to the highly controversial explosives concession (Cartwright, 1964, Chapter Four). The concessions policy was the foundation of the ZAR's industrial policy and led to establishment of secondary industries in brick & tile works, a brewery & distillery, fruit & meat preserving plants, a tannery and a boot factory (Arkin, 1956, p. 141).

Despite these effects on economic development, the monopoly concessions policy was a prominent target of industrial lobbying efforts by COMSA. Available evidence suggests that COMSA continually fought these concessions because of the additional costs they imposed on the industry. Nonetheless, while continuing its concessions, the ZAR increasingly sought ways to accommodate the mining industry as the loss of its viability and the threat of British colonial usurpation grew following the Jameson Raid (Harries, 1986).

TABLE 7.3 Important Dates in Southern Africa's Mining Industry: 1886-1902

GOLD MINING	
1886	Conglomerate gold rush Witwatersrand Main Reef, Gauteng
1889	Stock market collapse following initial interception of sulfide layer
1890	McArthur-Forrest Cyanidation demonstrates high recovery from pyritic ores
1893	Chamber of Mines establishes Native Labour Department
1894	Stock market boom
1896	McArthur-Forrest Patents rescinded
1897	Rand Native Labor Association cooperative formed
DIAMOND MINING	
1889	Diamond production consolidated and Diamond Syndicate established
1895	Structure of Diamond Syndicate modified
1902	Discovery of diamond deposits and establishment of Premier Diamond Mine near Pretoria
SUNDRY MINING	
1887	Coal mining for Witwatersrand gold mines in East Rand Region, Gauteng
1893	Asbestos mining begins in Northern Cape
1896	Coal mining for Witwatersrand gold mines near Witbank, Mpumalanga

In addition to holding industrial undertakings, many mining-finance groups also had significant property development divisions. These divisions facilitated the expansion of the necessary housing infrastructure to accommodate the growing workforce.[37] Demand for other mining commodities grew along with the Witwatersrand economy. Most notable in this regard was coal as an energy source.[38]

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[36] Most of this literature focuses on mining financiers, their business organizations and the Jameson Raid of 1895. See Katz (1995); Harries (1986); Richardson and Van Helten (1984); Jeeves (1978); Kubicek (1972); and Blainey (1965).

[37] See for example Sander (2000) and Cartwright (1965).

[38] Lewis & Marks colliery was producing coal for Kimberley at Vereeniging when the Witwatersrand was discovered. The energy demands of the Witwatersrand rapidly transformed coal mining in southern Africa with the

Within the Witwatersrand gold mining industry cooperation occurred in many areas, several of these under the stewardship of COMSA have already been mentioned. Founded in 1889, COMSA represented the Witwatersrand gold industry as a political lobby. It rapidly expanded its portfolio by also promoting infrastructure development and facilitating inter-organizational exchanges of know-how between mines. In the face of high royalty charges for the cyanide process, it established a Patent Committee in 1892. Enduring for over a century, the Patent Committee considered the admissibility of intellectual property rights over intellectual property that could be important to the industry. As previously mentioned, in the 1890s COMSA expanded its operations to include coordinating African labor provision to the mines, doing so it developed a key area of cooperation among the mines and staked out its enduring value as a cooperative institution in the industry (Lang, 1986, p. 78).

Cooperation between mining-finance groups did not just occur under the aegis of COMSA. An example was development of the Rand Mutual Assurance Company (RMAC) in June 1894. After investigating the market for insurance to cover workers' injured at work, three mines of the Corner House and the Gold Fields (GFSA) mining-finance groups decided to pool their resources and provide liability cover at costs below prevailing market rates.[39] A cooperative initiative between the three mines, RMAC pioneered workers' compensation in southern Africa independently of COMSA.[40]

Rapidly overshadowing Kimberley's diamond industry, the Witwatersrand gold industry transformed domestic financial capital markets. Kimberley financiers were the main source of early financial investment on the Witwatersrand. They brought with them a legacy of intense competition for financial resources, but geologically driven cooperation in production and innovation. In 1889, when the sulfide ores were intercepted, the capital intensive cyanide plants needed to treat these ores quickly exhausted local finance. Typically building on the reputation of prominent Kimberley financiers, mining-finance groups evolved to meet this greater demand. The financiers' experience on the Kimberley diamond fields came with ties to the European diamond industry. These contacts enabled their associated mining-finance groups to access financial markets across Europe and arrange the necessary financial capital for the industry's development.[41]

7.2.5 The System of Innovation

This section describes how the open community of metallurgists developed and diffused cyanide based extraction technologies on the Witwatersrand. It begins with an overview of the southern African system of innovation during this period and its relationship to the sectoral system of innovation operating over the Witwatersrand gold mines. Attention then focuses on intra-sectoral structure of research, development, and diffusion of cyanide-based gold extraction technologies.

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introduction of increasingly large and systematic coal mining. Nonetheless, there were no aggressive efforts to horizontally integrate gold and coal mining operations during this period.

[39] For a brief list and history of the mining-finance groups during this period see Appendix Four.

[40] RMAC would subsequently be transferred to COMSA after the Second Anglo-Boer War.

[41] These ties gave the mining financiers authority and independence from shareholders, until the late-1890s when accountability increased. By that point, most mining financiers had entrenched their long-term assessments of the Witwatersrand. Over-weighting these personal judgments drove mining-finance groups to either diversify out of Witwatersrand mining or increase their presence. See: Kubicek (1979) and Webb (1980). For company histories detailing these strategic direction see: Cartwright (1965, 1967, 1968); Johnson (1987); Jones (1995); and Sander (2000).

The regional, Southern African, system of innovation considerably developed during this period. Table 7.4 hhlights some important milestones in this development. As with political and economic spheres, the growth of the Witwatersrand gold mining industry had a huge influence. The general pattern drew on earlier areas of competence and therefore tended to focus on describing and documenting the diverse natural environment found in the Southern African region.[42] Thus, even on the Witwatersrand museums were among the first scientific and technical institutions to be established.

State support of knowledge to foster economic development was most clearly demonstrated in this era in the geological surveys commissioned by the Cape Colony, the ZAR, and the Natal Colony.[43] These geological surveys built an initial local area of competency and facilitated codification of regional resource endowments. While institutions of tertiary education were largely unchanged during this period two new institutions are worth mentioning. In 1887, the Stellenbosch Agriculture School was established in the Cape Colony, marking the beginnings of sectorally focused education in Southern Africa. More important for our present focus though was the establishment of a South African School of Mines at Kimberley in 1896. While based at Kimberley, the School of Mines was focused on providing locally developed mining engineers for the Witwatersrand in order to relieve the some pressure to import these individuals from abroad.[44]

TABLE 7.4 Some Scientific, Educational, and Professional Institutions and Societies in SA: 1886-1902[45]

1887	Stellenbosch Agriculture School – 1898Elsenburg College of Agriculture
1890	The Geological Museum, Johannesburg
1891	*South African Mining and Engineering Journal (SAMEJ)**
1892	Association of Mine Managers (AMM)
	South African Institution of Engineers (SAIE)*
	COMSA – Patent Committee
	*Journal of the South African Institution of Engineers (JSAIE)**
1893	COMSA - Metallurgy sub-committee on concentration
1894	State Museum, Pretoria (now Transvaal Museum)
	Chemical, Metallurgical and Mining Society of South Africa (CMMSSA)*
	Journal of the Chemical, Metallurgical and Mining Society of South Africa (JCMMSA)
1895	Geological Society of South Africa (GSSA)
	Geological Survey of the Cape of Good Hope Colony – See GS of SA*
1896	South African School of Mines, Kimberley – See Wits*
	Proceedings of the Geological Society of South Africa (PGSSA)
1897	Medical Association of South Africa*
	South African Society of Electrical Engineers – See SAIEE*
	Zuid-Afrikaansche Republiek, ZAR, Geological Survey – See GS of SA*
	Pretoria Technical School*
1899	Natal Colony Geological Survey – See GS of SA*
1902	The South African Association for the Advancement of Science (SAAAS)

Discovery and development of the Witwatersrand created a huge shift and expansion in the intellectual capital of southern Africa. While Kimberley initiated some of these developments and supported others, this expansion of the regional knowledge system was primarily a product of the Witwatersrand gold mining industry. There was also some initial development of a sectorally focused system of innovation around the agricultural industry in the Cape Colony.

[42] See Chapter Six, Section 6.2.2 for further details.

[43] These surveys began in 1895, 1897, and 1899 respectively.

[44] See Bundavari and Philips (1996).

[45] For continuity name changes are mainly ignored. Those with changes are demarked by an astrix (*) and can be found in Appendices One, Two and Three for Journals, Associations and Institutions respectively.

Nevertheless, it was the industrial expansion of Witwatersrand mining and its associated influx of human capital that drove development of the regional system of innovation in this era.

On the Witwatersrand, the sectoral system of innovation was characterized by a concentration of Mining Professionals, in particular mining engineers and metallurgists, with frequent interactions that created a localized knowledge network. Information thereby exchanged within the community was viewed as facilitating the industry's development: "There is no doubt that the absence of trade secrets, due to the fixed price of gold, the free interchange of ideas in the numerous local technical societies and the close proximity of many workers, have all assisted in the rapid development of gold recovery methods" (Webb, 1903, p. 26).

Given the importance of this open community of practitioners, it worth looking at its structure in a bit more detail. Central to the community's open exchange of knowledge were a series of professional organizations that facilitated knowledge diffusion. During this period three professional societies were of particular importance: 1) the Association of Mine Managers (AMM),[46] 2) the South African Institution of Engineers (SAIE), [47] and 3) the Chemical, Metallurgical and Mining Society of South Africa (CMMSSA) .[48] The AMM was established in 1891, with a social, technical, and lobbying directive. As the voice of the Witwatersrand mine managers it was considered the most important professional body in southern Africa at this time (Draper, 1967, p. 10). The SAIE was established in 1892, with a core membership of mining engineers it focused on development of Witwatersrand mining techniques. Lastly, the CMMSSA was established in 1894, its membership of metallurgists was primarily responsible for development and diffusion of the cyanide-based gold extraction process that made mining of the massive Witwatersrand gold deposits economically viable.

COMSA's building was the venue for all three of these organizations' formation and initial meetings. While availability of the COMSA premises apparently indicates a general appreciation among Mining Professionals for these professional bodies to foster the industry's development, COMSA itself had a strong dependence on the Corner House mining-finance group. Therefore, support for the professional bodies might not have been as broad based as first appearance suggest.

Who ever their patrons were, the professional societies generated knowledge externalities at both an individual level as well as within the local industry. Technical papers were presented at the societies on the performance of critical competitive technologies for comparison and discussion by colleagues from other mines and mining-finance groups. Consensus would thereby develop around promising direction for further efficiencies as well as collectively developing best practices in the organization of production and associated technologies. The professional societies' journals published the technical papers while debates around these papers were published as proceedings of their respective societies. Not wanting to isolate their community of specialist, journals and proceedings were diffused to an international audience for broader comment and discussion. Thus, these institutions actively promoted both a local and international exchange of knowledge and know-how.

In generating and diffusing this knowledge, these professional societies utilized a reward structure that valued priority of discovery. This priority of discovery was supported by a selective incentive in the form of labor representation that facilitated cooperation. The CMMSSA's first

[46] See Hocking (1997) for a history of the Association of Mine Managers.

[47] See Draper (1967) for a history of the South African Institution of Engineers.

[48] See Janisch (1994) for a history of the Chemical, Metallurgical and Mining Society of South Africa.

president William Bettel mentioned this potentially excludable benefit of membership. "I maintain that it is within the scope of this Society to fix the minimum rate of payment for work done by its members, and it is for you, gentlemen, by combined and concerted action when necessary, to give force to my suggestions in such a manner as may be thought proper.... As Chemists and Metallurgists of the Rand you have before you much useful and interesting work, and it remains with you, gentlemen, by publication or diffusion of accurate scientific information, by exposure of pseudo-scientific frauds, adopting the most approved processes, and investigating problems occurring in your daily work, as well as keeping abreast of the time through acquiring the most recent knowledge in relation to your profession, and by concerted action in any matter concerning your well-being as a scientific body, to claim as a right the recognition of your proper status in relation to this community and to demand as your just due, that scientific work of value to the industry should be paid for, at *least* as well as that of skilled artisans" (Bettel, 1894, pp. 3-11).

The professional societies were not the only channels of knowledge circulation operating among the Witwatersrand Mining Professional community during this period. High intra-industry labor mobility also facilitated diffusion of best practices among the mines. Social capital within the Mining Professional community appears to have supported a convention whereby diffusion of technical information about operations was expected. In the professional societies' journals this expectation is often expressed. For example, on one occasion the CMMSSA's president noted experiments on slimes treatment at a Corner House mine by John Williams: "When Mr. J. R. Williams shall have got the fine new plant at the Crown Reef fairly in working order, I trust he will give us a paper on results obtained" (Feldtmann, 1896, p. 237). Similarly, an outgoing president of the CMMSSA noted: "The members of our Society, as well as the industry, benefit by such mutual exchange of ideas, as the experience of the past years has sufficiently shown, and it would for these reasons certainly be a great mistake to depart from the liberal policy we have hitherto adopted" (Loevy, 1899, p. 717). These features were fundamental in the establishment of an open community of practitioners developing and diffusing critical competitive technologies.

In this region with little technological infrastructure, the professional societies became a critical means to communicate experiences in the technological development of the industry. These societies were further supported by the prevailing open knowledge system that characterized the industry. Rather than attempting to capture economic rents attached to the technologies, sharing of knowledge in a timely fashion was expected. Given the large investments necessary to develop these technologies the mining-groups and their associated mines played a large role in underwriting this system of innovation. This support is further reflected in the activities of the industry's primary industrial association, the COMSA.

In addition to COMSA's supporting the professional organizations by offering its offices for their meetings, it actively sought to facilitate development of technologies to enhance the industry's competitive position. COMSA established investigative committees on specific technical challenges facing the industry and as well as promoting technology diffusion. One of the Chamber's first ventures into industrial research was its establishment of a concentration sub-committee in 1893 to address the challenges in treating the slimes generated because of cyanide based extraction. It had also established a permanent Patent Committee in 1892 to ensure technological access and diffusion of best practices to the mines by reviewing the ZAR's application of intellectual property rights.

The Structure of Innovation in the Cyanide Method of Gold Extraction

Most of the scientific knowledge diffused about these extraction technologies was developed under the auspices of productive gold mines. The CMMSSA functioned as a clearing house where information about the technical performance of various cyanide and other metallurgical processes were exchanged. Thus, performance data on various extraction practices and designs presented at the monthly meetings of the CMMSSA were essential inputs to development of cyanide extraction techniques.[49] Efficiencies in metallurgical processes were thereby developed through a process of inter-organizational search facilitated by the professional societies and their publications.

As cyanide treatment was a new and rapidly evolving technology, significant knowledge about the process was un-codified and resided in human capital. Production routines had not yet been established, nor had institutional structures been able to inculcate the process into management and learning routines. Therefore, during this period, intra-industry labor mobility also facilitated diffusion and development of cyanide-based extraction technology. Several members of the company holding the MacArthur-Forrest patents for southern Africa, the AGRS, took employment on the mines or with the principal competing metallurgical company, the RCORC. The AGRS was in a structurally weak position to limit this mobility of its employees. If it offered higher wages, it would need to raise royalty charges on its licenses or decrease the organization's own share of returns.[50] Beside the AGRS' introduction of cyanide based extraction another organization, the RCORC, played an equally important role diffusing, developing and refining it for use across the Witwatersrand (Letcher, 1936, p. 101). In these activities, the RCORC followed inter-personal and inter-organizational networks.[51] This selective nature of the technologies' diffusion and development is an important feature since, despite the existence of an open community of metallurgist willingly sharing knowledge, organizational capacity and access to that capacity influenced the impact of that community.

In the present case, the first challenge facing the nascent Witwatersrand knowledge system was demonstrating the commercial superiority of cyanide-based extraction's over chlorine-based extraction. The community of metallurgical practitioners and intra-organizational knowledge diffusion of the cyanide-based process were important in this challenge. Following a six-month demonstration at the Robinson mine in1890-1891,[52] an open community of practitioners reviewing the comparative efficiency and promise of cyanide to chlorine characterized contemporary discussions. This was supported by the AGRS, who wanted to ensure its technology was widely adopted. Therefore, the AGRS also gave demonstrations of its cyanide-based extraction technology and published its performance data. While the underlying cost structure of cyanide-based extraction favored it over chlorination, there was not a viable method of treating the slimes it generated. Since chlorination did not generate slimes and technological refinements could potentially make it more economical, cyanidation's superiority over chlorination remained uncertain for several years (Pearce, 1909, p.273). Thus in 1894, the first president of the Chemical and Metallurgical Society noted: "It is an open question whether all

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[49] As such, this case is similar to that of blast furnace development analyzed by Allen (1983).

[50] In the AGRS, a cyanide plant manager introduced its technology on an initial six month pilot basis, one mine at a time. In a mining-finance group, he could develop cyanide plants at several of the group's mines simultaneously at a much greater value to the group. Hence, AGRS staff took up work for mining-finance groups and their respective mines, promoting and improving the cyanide process while undermining the proprietary technology of the AGRS. See: Darling (1909).

[51] In particular, the RCORC had strong ties with the Corner House and played a big role in erecting cyanide plants at several of GFSA's mines.

[52] The Robinson mine was part of the Corner-House group.

gold-bearing pyritic matter of these fields can be more economically treated by cyanide than by chlorination" (Bettel, 1894, p. 7).[53]

The second challenge facing cyanide-based extraction was its treatment of slimes. A means to use the cyanide process for the treatment of slimes was realized through inter-organizational collaboration during a period of several years in the mid-1890s. In development of slime treatment three individuals, from three different organizations, made major contributions to the process that eventually proved successful: Bettel from JCI, Butters at RCORC, and Williams from the Corner House.[54]

In contemporary reflections on the development of slime treatment, and the very evolution of that process, papers and discussions from the CMMSSA dominate the historical record. This exchange and development of a technology with major economic importance to the industry is similar to the 'knowledge in the air' typically associated with Marshallian industrial districts. Beyond the forum of the professional scientific organization, the rich communication structure of the Witwatersrand was noted in a toast by a member of the press at one of the society's annual dinners: 'The first thing that strikes one after coming here is that the return, both in the matter of praise and blame, is much more immediate than [in England]. Before one has time to recover one's breath after one's morning work, the street is resounding with them. If you step into the [Rand] club to lunch you are at once met with praise or criticism of the morning labours' (Moneypenny, 1899, p. 652).

The MacArthur-Forest process from the start lacked a viable treatment of slimes, but its low-cost structure and an ever-increasing stock of unliberated gold created strong incentives for development of a process to extract gold from slime.[55] Slimes treatment evolved in large part because of individual mines and metallurgical companies building and running pilot slime treatment plants. A further, and related, force contributing to the processes' development was the exchange of information about the associated challenges and solutions from these experiences. Financial resources for the construction and operation of the pilot slime treatment plants came from business organizations, not professional societies or individuals. Yet, in the knowledge system of the district at this time, the professional societies played a critical role by providing a forum for knowledge development that had a critical mass of experience.[56] In this regard, Charles Butters notes the role played by the society in development of an economic treatment of slimes: "I am happy to say that members and associates of the [CMMSSA] are the men who have done this work" (Butters, 1898, p. 238). Each of the nine individuals Butters subsequently cites contributed papers to the society documenting their development of the slime treatment process.

The third challenge was establishing the most efficient method of gold precipitation for the cyanide process. The industrial efficiencies of competing methods of precipitation were uncertain for several years. Research collaboration in comparing operating costs and design therefore played an important role in establishing best practices. John Yates previously cited paper (1896), documents the exchange of cost and design information between mines, through

[53] The very real uncertainty of cyanide's eventual dominance is often passed over in later discussions and reflects a recurrent historical determinism in writings on technology.

[54] See Chapter Six, Section 6.3.3 for details of their respective contributions.

[55] Development of a slime treatment process during this period, and subsequently, is detailed in an article by Thurlow and Prentice (1928).

[56] It could be argued that risk diversification structurally limited dominant companies like the Corner House from seeking monopolization of gold production in the era. However paramount its position on the Witwatersrand was, there existed viable properties relatively impervious to take-over, which supported cooperation.

the metallurgical professionals of the CMMSSA. When complimentary technologies had advanced sufficiently to make precipitation with the lead-zinc couple viable, it was brought to the attention of Witwatersrand metallurgists in a paper by Lane Carter (1898) presented before the society.

The introduction of the lead-zinc precipitation process also had to overcome a vested competence in electrolysis by RCORC.[57] However, when the cost savings and efficiency of the zinc-lead precipitation method was confirmed in other plants, diffusion followed rapidly. The inter-firm communication structure among mining professionals appears a significant contributor to this rapid diffusion. The rapid diffusion was also assisted by inherent shortcomings of the electrolysis process, which previous discussions and papers presented before the CMMSSA made apparent.

7.2.6 Conclusion

The underlying structure of collaborative research in this case involved an open community of practitioners developing and diffusing a critical competitive technology. Causal conditions and effects within various theoretical approaches will provide further insights to role of collaboration in the development of this metallurgical technology that made mining of the massive Witwatersrand gold deposits economically viable. Therefore, owing to superior analytical insight given the contextual conditions of the present case the industrial district approach is applied in Section 7.3. Additional analytical insights from the other two approaches then follow with the collective action approach being considered in Section 7.4 and the distributed innovation approach in Section 7.5. Before turning to those analyses, it is worthwhile briefly reviewing how the preceding description of contextual conditions relates to structural components and relationships specified in the theoretical approaches.

Three groups of technologies needed for cyanide based extraction to become established as the dominant metallurgical process were described in Section 7.2.1 and defined the *Innovative Object* and the *Public-Collective Good* for the Distributed Innovation and Collective Action approaches respectively. The discussion of the product market in Section 7.2.2 established the supply and demand dynamics for gold during this period. This contextualized the *Market* in the Industrial District approach and highlighted the rapid growth and stable demand structure faced by Witwatersrand gold producers.

Section 7.2.3, on the social structure of production, began by distinguishing three principal groups involved in production. Internal divisions within those groups were also highlighted as the section developed a profile of *Human Resources* from the Industrial District approach. Attention then turned to describing the structure of political authority over the Witwatersrand mining district during the sixteen years of this case. The nature of the *Socio-territorial Entity* in the Industrial Districts approach was thereby delineated. Next, intra-group and inter-group ability to build social and political authority were summarized. Many important legacies from Kimberley diamond mining created an important know-who network, that helped facilitate cohesion within the Mining Professional community. The other communities were primarily united by common conditions after their day-to-day work on the mines was complete. Social cohesion, or the lack there of, on the mines and the system that translated that into stocks of social capital was thereby described. Thus, that part of the section described the *Community*, *Overlapping Activities*, and the *Mechanisms of Co-operation* in the Industrial District, Collective Action, and Distributed innovation approaches. Simultaneously, the section described how the stock of social capital leveraged

[57] This core competence of the RCORC was carried in its founding patents and the expertise of A. von Gernet.

favorable behavior supporting established group interests and deterring actions that diminished collaborative benefits. Hence, section 7.2.3 also described the *Socio-Political System,* the *Convention System* and the *Mechanism of Competition* in the Industrial District, Collective Action, and Distributed innovation approaches.

The analysis of the industrial structure in Section 7.2.4 identified evolving up-stream and down-stream relationships by the mining-finance groups. Competition for financial capital was particularly marked with significant division existing between speculative and development focused operators. Thereby, we described the structural component of *Firms and Institutions* in the Industrial District approach. The section also reviewed the role that the structure of production played in hindering or facilitating collaboration, defining in turn the *Production System* and *Product Provision* in the Industrial District and Distributed Innovation approaches.

Section 7.2.5 analyzed the structure and dynamics of the system of innovation under which cyanide-based gold extraction technologies were developed. It highlights the open community of research on the Witwatersrand and contrasted it to a very under-developed regional scientific and technical infrastructure. Hence, the Witwatersrand gold mining industry rapidly came to dominate the Southern African system of innovation. That section thereby defined *Innovation Provision* and the *Knowledge System* in the Distributed Innovation and Industrial District approaches. Lastly, with the contextual background established, the section looked at the specific structure of provision for the three principle technologies, thus describing the *Collective Supply Function* in the Collective Action approach.

7.3 CAUSES AND EFFECTS IN THE INDUSTRIAL DISTRICTS APPROACH

The presence of special factor endowments forms the causal conditions for research collaboration in our representative model of the industrial district. Once a localized externality like research collaboration exists, its size and quality depends upon the subsequent co-location of agents. Section 7.3.1 begins our analysis with an examination of the causal conditions, *i.e.* the special factor endowments, which generated agglomeration externalities. Section 7.3.2 then considers the nature of agglomeration externalities in developing the three technologies that secured cyanide based extraction. The section concludes with a review of other significant agglomeration externalities, both positive and negative that also influenced the overall structure of research collaboration.

7.3.1 Causal Conditions in the Industrial District Approach

The presence of special factor endowments forms the causal conditions for the emergence of an industrial district.[58] Although there is no clear consensus around what these special factor endowments are, they tend to include: 1) complementary human and natural resources 2) connections with external markets and 3) local entrepreneurism. Given the natural resource basis of the Witwatersrand, it is natural to view this endowment as the driving causal condition for the industrial district's emergence. Nevertheless, further analysis shows that other special factor endowments were highly important to the emergence of an industrial district on the Witwatersrand and its subsequent collaborative development of technologies for the cyanide-based method of gold extraction.

[58] See Chapter Two, Section 2.2.2 for details of the causal conditions of the industrial district approach.

In 1886, extraction began on the upper portions of the gold-bearing Witwatersrand Basin. During the initial boom period that followed, outcrop mining spread along the Central Rand.[59] The proportion of the Witwatersrand that outcropped was minute compared to the overall size of the deposits. However, the Witwatersrand gold deposits sunk rapidly to depths where the gold bearing host rock was not oxidized. As a result, despite knowing the deposits continued considerably below the surface, there were broad doubts about the economic viability of these deposits. These initial outcropping gold deposits were significant enough to attract a pool of expertise and co-location of human resources that was sufficiently competent in its collective ability that large-scale systematic development of the deeper deposits went ahead. Hence, at the outset complementarities between human and natural resources were important to the district's development.

Local entrepreneurship also contributed to the emergence of an industrial district on the Witwatersrand. In this the Witwatersrand's proximity to Kimberley was a major factor. The consolidation of claim ownership had fostered a strong entrepreneurial climate at Kimberley. The speculative nature of other gold discoveries preceding the Witwatersrand, such as Barberton and Pilgrim's Rest, also contributed to the development of local entrepreneurship. Nonetheless, it was the development focus of entrepreneurs from Kimberley who contributed the most to the emergence of the Witwatersrand district.[60]

Lastly, the structure of the international market for gold was another important contribution to the rise of the Witwatersrand district. Operating under a fixed price set by the international gold standard largely reduced uncertainty around demand for the district's output. Hence, because of the minimal associated risks and uncertainties the market for gold was favorable to the formation of an industrial district.

7.3.2 <u>Effects in the Industrial District Approach</u>

Agglomeration externalities in an industrial district influence a variety of activities, both positively and negatively. These range from benefits in labor market pooling to problems from excessive localization. Besides the technological externalities associated with development of cyanide-based extraction, the Witwatersrand enjoyed additional technological and other positive agglomeration externalities during this period. Given the economic growth and development that the Witwatersrand industrial district generated, these positive benefits from co-location significantly outweighed the negative agglomeration effects. This section reviews those positive and negative agglomeration externalities in turn.

Based upon available contemporary evidence, development of the cyanide extraction process appears to have benefited from strong and largely incidental intra-industry mobility and interaction. In this case, there was an influx and geographical concentration of metallurgical specialists on the Witwatersrand who played a major role developing cyanide-based extraction. Labor mobility and inter-organizational discussion of priority research areas, involved exchanges of information across organizational boundaries, which facilitated creation and application of location specific metallurgical knowledge. Thus, features prominent in the industrial district approach played an important role in the technological advances analyzed in this case.

Typical of a district, embodied knowledge was transferred between organizations through individual interactions. These interactions were facilitated by professional organizations like the

[59] See Map 6.2 for a representation of the Witwatersrand Basin.

[60] See Chapter Six, Section 6.2.3 for details of these mining districts' precedents, in particular that of Kimberley.

CMMSSA, corporate strategy in advanced firms like the Corner House, and through personnel mobility from key 'knowledge intensive' organizations like the AGRS and the RCORC. The open system of learning on the Witwatersrand also facilitated development of the technological infrastructure. As technological institutions in their own right and as forces for technological development, the professional organizations were paramount during this period. Some of the more forward looking mining-finance groups also promoted technical education. One result of those efforts was the 1896 establishment of a school of mines. While the industry struggled to secure its longer-term survival, technologies with immediate applications dominated research focuses and thereby integrally linked the demand and supply of technologies. Consequently, a practical focus characterized innovations and the supporting technological infrastructure on the Witwatersrand throughout these early years.

Another agglomeration externality, labor market pooling, created benefits for both employers and employees. The influx of foreign mining engineers, metallurgists and other professionals created a skills base critical for a mining financier to successfully develop a large scale mine on the Witwatersrand. Likewise, these mining professionals found a concentrated demand for their relatively specialized skills that otherwise would have been less valuable in other locales. The practical knowledge of optimal mining practices on the Witwatersrand that these individuals developed across the mines, enhanced the overall operating efficiency of Witwatersrand operations as well as the value of these local professionals to individual mines.

Urban infrastructure was also actively promoted and developed by the concentration of mining activity on the Witwatersrand. During this period the most marked impact on urban development resulted from property development undertaken by some of the mining-finance groups.[61] Intermediate markets and specialization also emerged at this time, but no where near the subsequent scale. Coal was a particularly important industry, whose development was underwritten by the industrial and urban expansion on the Witwatersrand. Specialized services within the mining industry, such as the metallurgical services of RCORC, also appeared in the district during the 1890s.

In an industrial district, the coordinated distribution of productive activities across a range of stakeholders can decrease risk and uncertainty, thereby further mobilizing local entrepreneurial resources. Establishment of the COMSA was a principal development in this regard. Through COMSA coordination of production among the mines was promoted.[62] This type of agglomeration externality may explain why a dominant mining-finance group like the Corner House did not seek complete control of gold mining operations on the Witwatersrand. Slicing the cake of Witwatersrand gold mining into relatively more pieces benefited the mining companies by reducing the capital they risked, so long as that division operations did not preclude minimum efficiencies of scale. An indication of the pursuit of these agglomeration economies were the cross holding used by the mining financiers and their emergent mining-finance groups. Further evidence that too great an exposure to the risks of mining on the Witwatersrand was undesirable is seen in the diversification of investments by prominent companies like GFSA and the Corner House outside of the Witwatersrand.[63]

Nonetheless, the co-location of mining firms on the Witwatersrand reduced the risk and entrepreneurial resources required of individual companies and thereby stimulated further

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[61] For details see Section 7.2.4.

[62] This, as previously mentioned, was mainly in the areas of political lobbying and monopsonization of African labor supply.

[63] See Cartwright (1965, 1967).

development of the district. That these concerns about the risks and uncertainties of mining operations were important to the Witwatersrand is reflected in a quote by Ralph Stokes (1913) in a comment on the district's metallurgical history: "Progress has been made and innovations have been introduced with almost unfailing caution. In the footsteps of the zealous pioneer of new ideals, treading lightly – in his reconnoitering equipment – over the treacherous quicksands of experimental metallurgy, the Rand mining industry, so ponderous in bulk and heavy-laden, has generally followed at a prudent and watchful distance with a mannerly 'After you!" (p.6).

Not all agglomeration externalities are favorable to co-location and economic growth. Because of the relative stability of the international gold standard operating in this era, two of the most important negative effects from agglomeration were avoided: limited market demand and sectoral volatility. While the third negative effect of agglomeration, excessive localization, was clearly present its deterrence to co-location seems to have been relatively minor. Congestion, pollution, and resource scarcity were a common feature of the boom towns that emerged during the resource stampedes of the late 19th and early 20th centuries. The absence of these negative externalities would have facilitated greater development of the Witwatersrand during this era. However, given the geographic specificity of the gold deposits, the real alternatives to these negative externalities are not apparent.

This section has shown that a majority of research collaboration associated with development of cyanide based extraction technology is explained by the industrial district approach. However, there are aspects of collaborative research in this case that are not described by that approach. To deal with these features requires employing the other approaches.

7.4 CAUSES AND EFFECTS IN THE COLLECTIVE ACTION APPROACH

A favorable group structure forms the causal conditions for research collaboration in our descriptive model of the collective action approach. In the present case, know-how-trading within the collective action approach deepens our understanding of why a metallurgist would want to contribute to the open community of metallurgical know-how on the Witwatersrand.[64] Participation in the open community of metallurgical practitioners is taken to form a repeated prisoners' dilemma. Exchanges of non-rival units of knowledge occur between members of the community. These exchanges occur despite competition among metallurgists for jobs at mining finance groups because there is already a community of employed metallurgists who are not active participants in the local job market. Employers' restrictions were minimal making knowledge of a large spectrum of these critical metallurgical technologies non-rival.

In this context, two features were crucial in ensuring participation in these exchanges. First,metallurgical technologies were changing rapidly so exclusion from future knowledge exchanges because of withholding valuable knowledge would incur a significant loss in the near future. Second, strong interactions within the professional societies and social connectivity of the metallurgical community on the Witwatersrand also supported conditional cooperation in knowledge exchange by fostering a convention of exchange. Thus, increases in the Witwatersrand's knowledge stock can be seen as a product of know-how-trading within the community of metallurgical practitioners.

The collective action approach focuses upon collaborative research's effects on net social welfare once it has been established. In the present case, cyanide technologies were fundamental to the establishment of large-scale deep-level gold mining operations on the Witwatersrand. According

[64] The know how trading model was discussed in Chapter Three, Section 3.2.2.

to the collective action approach, collaborative research should not be sustainable if it does not bring net social benefits to the groups in the associated system of production. However, for at least two of the three primary groups involved in the system of production it is certain that net social welfare decreased because of this technology.

Since the Mining Professional community created the technologies it predictably enjoyed predominantly positive net social benefits from their development.[65] For the European Mining community the greater depths possible with these technologies increased their exposure to an increasingly hazardous working environment, but many of these dangers such as lung disease from the dust were not understood.[66] Therefore, while employment prospects improved because of cyanide extraction, the net welfare of the existing community of European miners almost certainly declined. The 'opportunities' the technologies created were even more damaging to Africans. In addition to their exposure to an increasing hazardous working environment the mines' demand for low paid labor led to acceleration in proletarianisation of the African population and dispossession of their homelands as well as their individual liberties.

This case thereby draws attention to an important aspect inherent to the collective action approach, namely that social exclusion plays an important role in determining the actual dynamic stability and instability of research collaboration around a technology. The net social welfare benefits that the Mining Professional community realized from the technology were enough to support the collective development of the technology. In so doing the collective action approach demonstrates that research collaboration can occur in a hostile environment as long as it is supporters can insulate there efforts from these antagonists. It is therefore necessary to be as explicit as possible in discussing the nature of the net social welfare sustaining or undermining research collaboration.

7.5 CAUSES AND EFFECTS IN THE DISTRIBUTED INNOVATION APPROACH

The illustrative model of distributed innovation holds research collaboration to be a pervasive activity whose relative significance depends upon, and influences, characteristics of the technology and social capital in the associated productive and innovative systems. In the present case, the distributed innovation approach contributes to our understanding a couple of additional features of research collaboration. First, through its consideration of the value chain's structure to create incentives to innovate and collaborate, the distributed innovation approach draws our attention to the potential role played by the ZAR's monopoly concessions.[67] In part, acquiring concessions was a means to increase a mining finance groups' intra-industry authority. The groups could then bargain with the running of their concession in order to facilitate cooperation within the industry. As such, this is remarkably similar to contemporary practices in the software and semiconductor industries where firms acquire patents to facilitate trade in cross-licensing agreements.[68]

Second, between 1886 and 1902 knowledge of gold metallurgy was at an early stage of development. Although advances in cyanide technologies helped to codify a lot of information about gold metallurgy, much knowledge about the best techniques and principles governing

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[65] It is worth noting that despite these net benefits there were costs for the Mining Professional community associated with this technology. In particular, the long-term viability that cyanide extraction brought undoubtedly encouraged British Colonial authorities to seize control of the region and introduce higher taxation as well as reduced industrial development.

[66] The hazards of working underground are discussed in the next case of stoping, Chapter 8 & 9.

[67] See Section 7.2.4 for a discussion of the ZAR concessions.

[68] See Hall and Ham (2001), Jaffe (2000), and Granstrand (1999).

development of the necessary technologies were uncodified. In this regard, the CMMSSA's first president alluded to the need for that society to codify knowledge: "'Rule of thumb', a giant which has ruled the world, will have to give place to a younger rival, 'Scientific Method'...We, the representative of chemical and metallurgical science in South Africa, must, in our humble way, by disseminating scientific knowledge and applying ourselves to technical processes, help to 'scotch', if not kill this enemy of progress" (Bettel, 1894, p.2). The distributed innovation approach highlights an ability to exchange intangibles as a contextual conditions favoring research collaboration. Therefore, despite the CMMSSA's efforts, distributed innovation was favorably positioned to handle the prevalence of intangible information in this case.

7.6 CONCLUSION

Features prominent in the industrial district approach played an important role in the technological advances analyzed in this case. Labor mobility, free exchanges of information across organizational boundaries, and definite location specificity to knowledge creation and application were major features in the technologies development and are central to the concept of research collaboration in the industrial district approach. Despite an influx and geographical concentration of metallurgical specialists, the industrial knowledge infrastructure on the Witwatersrand was emerging during this period and a considerable degree of uncertainty in political and technological arenas characterized operations. Technological developments in this case and in general at this time appear the product of the local environment.

The other approaches also furthered our understanding of research collaboration in the development and diffusion of cyanide technologies. In the collective action approach explicit motivations for an individual's participation in the exchange of knowledge within a community of peers was examined. The collective action approach also considered the effects research collaboration has on net social welfare. Through that examination research collaboration was shown to have highly skewed benefits across the three principle groups involved in production. It also demonstrated the potentially important role played by social exclusion in determining the actual dynamic stability and instability of research collaboration around a technology. Distributed innovation also deepened our understand of research collaboration in this case. It drew attention to the possible role played by the ZAR government's concession policy in facilitating cooperation within the mining-finance groups. Lastly, distributed innovation showed the inherent advantage collaborative research possessed in the presence of significant uncodified knowledge around these metallurgical technologies.

Part Three

Changing Stoping Practices, 1903-1933

"The imported European mine worker, found himself in a community whose traditional first principle was and is that the white man is an aristocrat, admitting the black to no equality in Church or State, and doing no manual labour; that the black is an inferior species of animal and must be kept so…South African racial tradition and trade union principle, therefore, invariably coalesce in demanding that the Kafir shall not be given such opportunities to improve his status…This direct dependence of the white worker's very high wages (the highest in the world) upon the very low wages of the Native labourer is the secret of the philosophy of the industrial colour bar…."

(*The Anatomy of African Misery* – S. Olivier, 1927)

Chapter Eight: Changing Work, Equipment, and Health Practices in Witwatersrand Stoping

8.1 INTRODUCTION

This chapter analyzes transformation of stoping practices on the Witwatersrand gold mines. There are two notable contextual differences in this case from the case discussed in Part Two. First, with unified government over most of southern Africa after 1910, the state was much better able to take a coordinated and strategic role. Second, the industrial organization of gold mining evolved to a point where its management control and production arrangements were embedded in established industrial structures and institutions.

While the innovations investigated had significant precedents and subsequent developments, focus is on the period from 1903 to 1933. This period encompasses a large number of technical innovations and near complete diffusion of these innovations. It begins at the close of the Second Anglo-Boer War in 1903 and ends with the 1933 South African abandonment of the gold standard.[1] The period encompasses three eras of European political rule; post Second Anglo-Boer War consolidation, which ended with the formation of the Union of South Africa in 1910; the era of Botha and Smuts administration, which held power from 1910 to 1924; and lastly, the era of Hertzog-Pact administration, governing South Africa from 1924 to 1933.

The fundamental technologies associated with the cluster of innovations in the transformation of stoping practices on the Witwatersrand gold mines were largely imported. However, their diffusion illustrates the significant innovation that occurs in adapting foreign technologies to local conditions. In changing stoping practices, innovations were effected in both technological artifacts and work force organization. This implies that we must use a broader notion of innovation, beyond the traditional physical artifact alone. It is particularly relevant given the critical role of organizational innovations in realizing productivity gains in this case.

It took three decades of innovations and concerted industry action to transform stoping practices. Three mutually dependent challenges had to be met before transformation could be realized. First, the organization of the stoping labor force needed to be restructured. Second, occupational health hazards associated with the rock-drills and depths had to be alleviated. Lastly, rock-drill design and ancillary equipment had to be developed for the Witwatersrand's conditions.

The best proxy for the transformation of stoping on the Witwatersrand is the usage of rock-drills. Figure 8.1 illustrates the early introduction of rock-drills on the Witwatersrand. However, these they were not lightweight rock-drills for stoping. One can see clearly that the repatriation of Chinese miners and the introduction of Afrikaners on the mines following the 1907 Strike marked the first substantial take-off in rock-drilling on the Witwatersrand.

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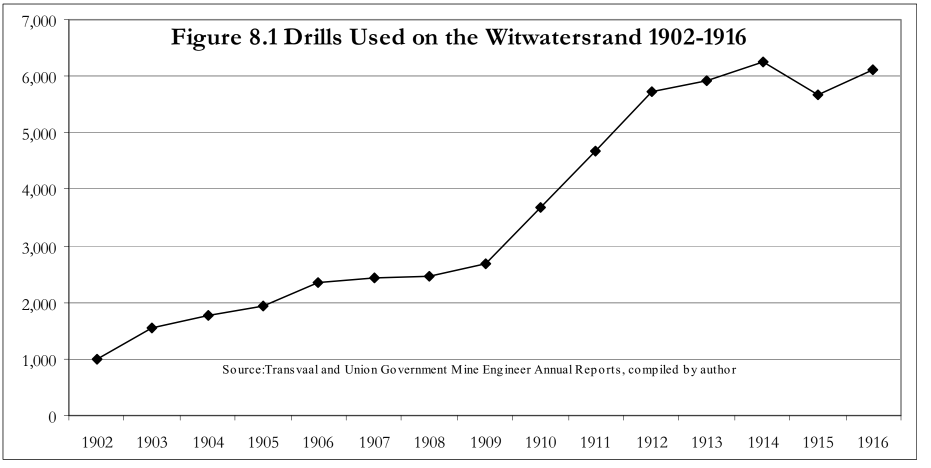
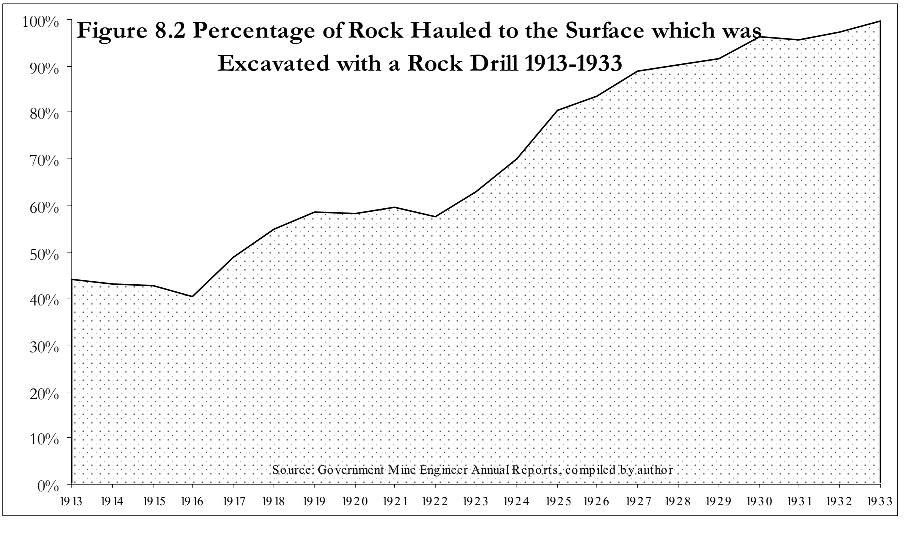
[1] Following the 1932 devaluation of the Rand, the price of gold doubled in 1933. Thus, Yudelman holds that if any date marks a watershed in 20th century South African history it is 1933 (1983, p.42).



After the initial introduction of rock-drills in tunneling, development, readily available African labor on the mines slowed further deployment. This was a short lived delay, the First World War depleted the available African workforce and led to further use of rock- drills on the mines. Amidst the war induced labor scarcity, White miners used their enhanced bargaining position to limit transformations in the organization of production. Nonetheless, the necessity for change in mining practices and in particular stoping, mounted. Securing the needed structural reform following the 1922 Rand Revolt cleared the path for deployment of the lightweight rock-drill in stoping operations. Figure 8.2 shows that rock-drilling quickly came to predominate rock excavation and by 1933 lightweight rock-drilling ruled the stopes. Hence, transformation of stoping practices on the Witwatersrand took three decades.



Transforming stoping practices enabled the mines to realize economies in operations that made mining on the Witwatersrand a profitable endeavor for decades to follow. Figure 8.3 shows the increased efficiencies in production the industry realized during this period.

However, developing and deploying this type of drill was not a simple and straightforward process. It required development of original complementary technologies as well as extensive adaptation of foreign technologies.

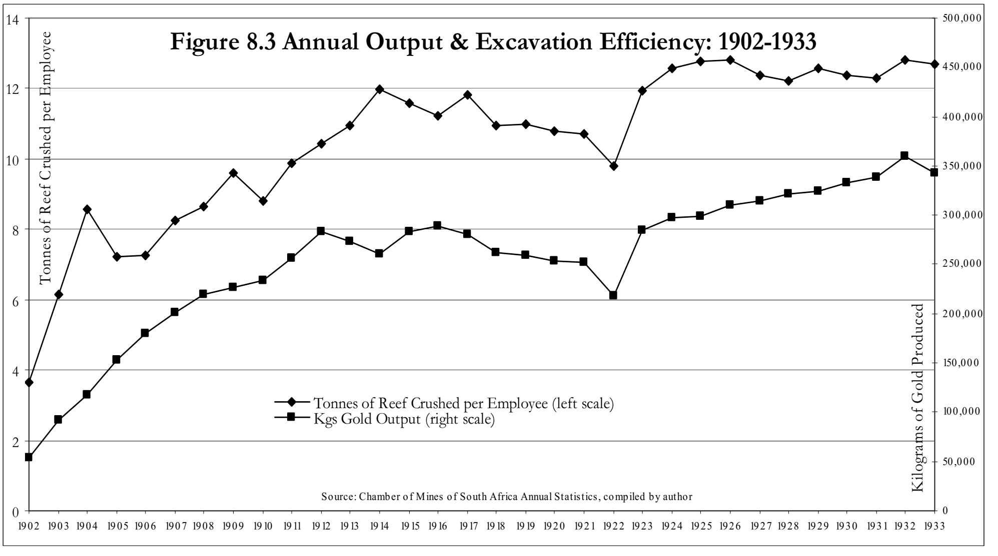


Figure 8.3 Annual Output & Excavation Efficiency: 1902-1933

This chapter reviews changes made in Witwatersrand stoping practices before turning, in the next chapter, to an analysis of collaboration in the innovative process. It begins with a general history of precedents in rock-drill development and Witwatersrand stoping practices. It then examines the identification and formation of local consensus about the technological challenge. A review of the solutions to the technological challenge, with an emphasis on collaboration, then follows. The chapter concludes with a look at subsequent technological developments.

8.2 TECHNOLOGY DEVELOPMENT OF STOPING PRACTICES

8.2.1 Previous Practices

A Brief History of Early Rock-Drill Development

Hard-rock excavation has a long and incremental history. Fire heating a rock face, cooling it rapidly with water, and then breaking it with a hammer was an early Western method of hard-rock excavation. Around the 1300s, gunpowder began to replace fire and water for the fracturing of rock. Slowly, a practice of chipping holes in the rock to insert the gunpowder was adopted. Metallurgical innovations, in particular the invention of steel, were sources of improvement in rock excavation efficiency (Vivian, 1938, p. 5671). Even greater importance to the advance of a rock-drilling machine was development of more powerful explosives. The use of black powder for underground mining in the late 1620s was the first step. In 1867, Alfred Nobel developed a detonator, which made the use of nitroglycerine feasible, and subsequently, in 1875, he developed blasting gelatin (Gregory, 1980, p. 178).

Advances in mining explosives initiated a rapid drive for better hand and then machine drilling. In 1845, a piston-drill design was invented but that model did not diffuse beyond the Prague region.[2] Then in1849, J.J. Couch patented a piston-drill machine and J.W. Fowle patented another version of the piston-drill in 1851 (Stack, 1982, p. 12). These American designs marked the first generation of rock-drills and the oldest predecessors of the modern rock-drill. They were followed by several other innovative drills, two of the more significant second generation being the 1857 Sommellier design in Europe and the 1866 Burleigh drill in the United States. In 1871, building on the previous two generations of rock-drills, Simon Ingersoll and the Rand brothers created a third generation of rock-drills, the first widely used in commercial applications. These third generation piston-drills were large and heavy, requiring two men to operate. It was this third generation piston-drill design that was state-of-the-art when development of the Witwatersrand began.

Stoping Practices on the Witwatersrand

The early Witwatersrand goldmines were called 'out-croppers' because the gold bearing host rock (reef) was harvested (extracted) from its surface exposure along the main reef. The reef(s) were then followed with trenches below the surface. With increasing depths, these open trenches became impractical and an underground system with shafts and tunnels was adopted.[3]

Underground mining uses tunnels, dug horizontally from the shafts, to access and transport the reef. The actual work area where the reef is extracted is called the stope. Rock-drills assisted with the removal of the reef underground from its host rock. The basics of shaft digging, tunneling, and stoping are similar processes; involving drilling small holes (blast holes) into the hard rock, planting and detonation of explosives in these blast holes and then clearing the blasted material.

Originally, all blast holes on the Witwatersrand were drilled by hand. Samuel J. Truscott in his 1898 book *The Witwatersrand Goldfields: Banket & Mining Practice* noted that, except near the surface, machine drills were exclusively used for tunneling, but that in stoping hand drilling remained more efficient (p. 288). Stoping was orchestrated by skilled European miners whose direction drove the single-handed manual drilling method that was adopted.[4] Anthony Hocking (1997) gives a sense of the work environment engendered by this technique.

> "Men went underground at five in the morning, equipped with four-pound [1.8 kgs] hammers and a set of freshly-sharpened drills plus candles and matches, a can of water and an old cloth swab. A single gang contained from 40 to 60 people and the positions of holes they had to drill were marked out with white paint.
>
> On starting work a man attached a candle to the rock face with wax or perhaps wired it to timber. He tackled the rock by alternatively hitting the drill with his hammer and turning it with his free hand. Every so often he pulled out the drill and squirted in a mouthful of water to turn the dust to slush, then used the drill to scoop it out. By tradition each man was required to complete a metre-deep hole per shift and was paid a bonus for anything extra." (pp. 99-100).

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[2] The piston-drill design is named because the drill steel, which drives a bit to drill the hole, was clamped directly to the piston, giving it a reciprocating action.

[3] Langlaagte Mine was the first to introduce systematic underground mining in April 1887 (Webb, 1903, p.27).

[4] See Section 8.2.2 on labor costs of European miners for details on the labor power associated to their artisanal skills before introduction of lightweight rock-drills in stoping.

8.2.2 Technological Challenge

This section discusses four prominent challenges to the efficiency of operations on the Witwatersrand gold mines between 1902 and 1933. First, a major force for changing stoping practices were economies of scale in milling that required larger throughput from the stopes. Hand drilling on the stopes was limited in its ability to meet this demand. In this context, alternative stoping practices with different work organization and rock-drilling technologies were developed. As the viability of these new technologies became apparent, resistance from threatened components of the labor force emerged. Second, an industry-wide profitability crisis further increased incentives for innovation in stoping practices. This profitability crisis manifest itself in both material and labor costs as the mines faced a static nominal and depreciating real price of gold. Third, the rock-drill design itself needed to be refined for operations on the narrow stopes of the Witwatersrand. Fourth, the use of rock-drills and the increasing depths they permitted engendered numerous occupational health hazards. Meanwhile, a variety of challenges coalesced to generate pressure for greater efficiencies in operations. Table 8.1 lists several important dates associated with these challenges. The solutions to the challenges of the period emerged gradually over the three decades studied and were multi-dimensional in approach.

Table 8.1: Important Dates of Challenges Driving Change in Witwatersrand Stoping Practices

Date	Event	Remarks
1904	Labour Importation Ordinance (LIO)	*De jure* racial occupational mobility discrimination
1904	Tube-Mill first used on Rand	Increased economies in gold extraction plants
1907	Strike	Caused by replacement of artisanal skills in tunneling
1907	Chinese Repatriation Begins	British stop further importation of Chinese, LIO is repealed
1911	Mines & Works Act/Mining Regulations	Imposes *de jure* racial mobility restrictions on skilled occupations
1912	Miners' Phthisis Act of 1912	Requires the mining corps. to pay compensation for phthisis victims
1913	Strike	Europeans & Afrikaners against ongoing changes
1913-32	SA Gov't restricts African labor recruitment	Prohibits mines from recruiting African labor north of 22° South
1914	Strike	European & Afrikaner sympathy strike with rail workers
1914-18	First World War	Industrialization and war created labor scarcity and an associated rise in labor power, delaying changes in stoping practices
1918	Status Quo Agreement	Imposes *de jure* racial mobility restrictions on semi-skilled occupations
1919-21	Profitability Crisis	With inflation and a regulated selling price the Rand mines face a perceived cost reduction imperative
1922	Rand Revolt	Caused by replacement of artisanal skills in stoping and repeal of Status Quo Agreement
1924	First death underground by heatstroke	Initiates a new era of occupational health challenges
1926	Amended Mines & Works Act	Re-imposes *de jure* racial mobility restrictions on skilled & semi-skilled occupations

Gold Extraction Plant (Mill) capacity

A major incentive for change in stoping practices came from the economies of scale realized in large gold extraction plants. In the early years, milling capacity was the constraining factor across the Witwatersrand. Indeed, lack of milling capacity on the Witwatersrand was mentioned in an early discussion as favoring hand drilling over the greater output possible with machine drilling (Niness, 1891, p. 113). However, by the mid-1890s substantial milling capacity existed because of equipment imported to the gold fields via the improved transport infrastructure. This milling capacity, created incentives to change rock-drilling practices. F.H. Hatch and J.A. Chalmers noted a contemporary need to improve the rate tunnels were developed to access the reef: "Since it is generally admitted that development [tunneling] by machine drill is more costly than by hand labor, their extensive adoption on the Rand must be attributed directly to the impossibility of developing by hand labor at the rate necessary to meet the demands of large milling plants. Large mills, again, are the result of the policy of extracting the total gold in the shortest time practicable, a policy that for deposits of the stability and permanence of the Main Reef Series is, without question, financially sound" (1895, pp. 126-127).

A later 'Survey of Rand Mining' also pointed to economies in crushing as driving the transition to mechanized stoping: "The enlargement of crushing plants very early called for greater tonnage from the stopes than the available labour could supply. Increased speed of development was called for and as transport by rail became available, steam-driven single-stage air compressors were imported and the era of mining practice, described in the modern text book was ushered in" (MIM, 1927, p. 259). With regard to economies from increased extraction plant capacity, an analysis circa 1905 showed that doubling the typical extraction plant's capacity reduced average costs by ten to fifteen percent (Browne, 1907, p. 299).

Limited numbers of shafts and tunnels constrained the number of workers deployable per shift underground for stoping. Large gangs of low paid Africans could work the reefs with hand drills, but they were not as fast as rock-drills. Therefore, while mill capacity was rising to capture economies of scale, this required ever-greater throughput and increased incentives for improving per capita labor efficiency through the introduction of rock-drills. Following the Second Anglo-Boer War, the introduction of tube-milling further heightened the need for greater throughput. Tube-mills were first used on a large-scale in Australia in 1895 where their cost efficiency was demonstrated, but concerns about the looming Second Anglo-Boer War postponed their introduction on the Witwatersrand. Thus, it was only in 1904 that the first tube-mills were imported to the Witwatersrand. With this increased crushing capacity, tube-milling raised demands on production both forward and backward.[5]

Non-Labor Resource Costs

The structure of the gold market also generated pressures for change in stoping practices that would bring, through increased efficiency, a realization of higher profitability. While labor costs are considered below, they were part of the general increased input costs that threatened profitability of the mines. Gold was sold at a fixed price under the international monetary system of the era. This meant that when the cost of inputs rose during inflationary periods, the gold mining companies had no means of passing the cost increases on except to mine higher-grade reef. Inflationary pressures then generated a fall in the Witwatersrand gold mining companies' profits and a reduction in the working life of the mines. Therefore, as inflationary pressure mounted prior to and during the First World War, a 'profitability crisis' was said to beset the industry (Richardson, 1977, p. 87).

Realizing the importance of South African gold production to the international monetary system, the Bank of England put a 'gold premium' on the market price of gold between July 1919 and March 1920.[6] Non-labor resource costs had risen by nearly forty percent between 1914 and

[5] Tube mills crushed the reef finer than the stamp mills, thereby generating more slimes. Adoption of an all-sliming process, removal of the amalgamation stage, was therefore increasingly favored with tube milling. By 1920, all-sliming with tube milling predominated gold extraction on the Witwatersrand (Janisch, 1986, p. 302).

[6] The Bank of England paid the gold premium to Witwatersrand gold producers at a variable rate above the 'market' price of gold under the pound-gold standard. During its existence, the value of the premium varied

1920.[7] This translated into a situation in late 1919, whereby without the gold premium 25 out of 35 Witwatersrand gold mines were producing at marginal or sub-profitable levels (Johnstone, 1976, pp. 95-96). The premium's phased removal began in 1920 and once again brought the profitability crisis to the fore. In this difficult environment, a strong incentive existed for the mine managers to introduce rock-drills in stoping and change the organization of stoping work in order to realize a more favorable cost structure.

<u>Labor Costs</u>

In this period, the nature of challenges from rising labor costs have different effects on three distinct groups: 1) European White Miners 2) African Black Miners and 3) Afrikaner White Miners.[8] Before the introduction of rock-drills and changing the organization of stoping work, European miners possessed an artisanal skill that was crucial to rock breaking and thereby the entire production process of Witwatersrand gold mines. This skill was knowledge of blast hole placement to remove rock effectively. With this skill, European miners held effective control over underground operations and thereby significant independence from the authority of mine management.

The reliance on these skilled European miners meant that disruptions to their availability, such as during the Second Anglo-Boer War and the First World War, caused gold production to substantially decrease. This productive knowledge and consequent authority on the part of European miners enabled them to protect their occupational exclusivity, increase their wages, and reduce their hours of work. European miners, in the traditional hand-drilling stoping structure, represented a significant component of rising labor costs per tonne of reef extracted. Johnstone (1976) examined these increases in the cost structure of 'low grade mines' between 1914 and 1918 and found costs of labor per tonne rose by 86% (p. 102). When introduction of a new stoping work organization became possible following the 1922 Rand Revolt, the European miners' skill rapidly became redundant.

African miners with low wages were another impediment to lowering stoping costs. African miners presented two difficulties for mining companies. First, African miners were limited to less skilled occupations because of *de facto* and *de jure* racial occupational mobility restrictions i.e. 'The Colour Bar'. Second, major recruitment difficulties emerged following the Second Anglo-Boer War as African miners were offered alternative work in post-war Colonial infrastructure projects (e.g. railroads, harbor and road construction) (Denoon, 1967, p. 490). This was combined with inter-colonial tensions amidst the 'Scramble for Africa' that reduced the territories from which mine recruits could be drawn. Both factors combined to reduce the number of low-cost Africans willing and able to take up work on the Witwatersrand gold mines. In this environment, mines and independent labor recruiters competed in a structurally cost inflating game for African miners.[9] This was further heightened by a 1913 South African government ban on recruitment north of 22° South and accelerated industrial development in South Africa during the First World War. Nonetheless, by the early 1920s the gold industry managed to secure a monopsony in relatively low cost African miners (Jeeves, 1985, p. 261).

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between 16 to 44%, averaging 26% (Johnstone, 1976, p.95). The conditions for the premium were established under the terms of the 'July Agreement' to offset devaluation of the Sterling because of inflation. For further details, see Ally (Chapter 3, 1994).

[7] Non-labor resources in underground operations are primarily blasting supplies, timber for stope support and mechanical equipment.

[8] Because of racial division, distinction is often necessary between the African and Non-African labor forces. Therefore, despite their various backgrounds, all Non-Africans are collectively referred to as Whites.

[9] See Chapter Four in Jeeves (1985) for a description of this escalating recruitment cost competition.

De facto racial restrictions on occupational mobility of African miners were in place before British Colonial administration of the Witwatersrand gold fields. When Chinese were imported to the Witwatersrand in 1904 to alleviate the scarcity of relatively low cost African miners, the first legal race-based occupational mobility restrictions were imposed. These restrictions in the 1904 Labour Importation Ordinance were designed to assuage European miners' fears of Chinese replacing them. They were repealed when repatriation of the Chinese began in 1907. Despite the precedent, imposition of racial restrictions on occupational mobility were not re-imposed until the Mines & Works Act of 1911 and its Mining Regulations of 1911. Even then, the Mining Regulations of 1911 restricted entry to only the most skilled jobs, those that were predominately undertaken by European miners. Semi-skilled occupations, which were increasingly undertaken by Afrikaner miners, were left only *de facto* protection from the Mining Regulations of 1911.

With increasing numbers of semi-skilled Afrikaners on the mines in the late 1910s, pressure mounted for *de jure* racial restrictions on African miners' mobility into semi-skilled occupations. Thus, in a context of severe labor shortages during the First World War, the Status Quo Agreement of 1918 imposed *de jure* racial restrictions on semi-skilled occupations. The Status Quo Agreement of 1918 effectively closed upward occupational mobility of African miners and increased incentives to remove the relatively expensive European Miner from stoping. Thereby, African miners were structurally marginalized and mine management prevented from reducing semi-skilled labor costs with lower cost labor and the efficient utilization of the entire labor force.

When in 1922, COMSA pushed forward a repeal of the Status Quo Agreement of 1918 it led to the Rand Revolt. Following this, a 1923 ruling by the South African Supreme Court overturned the authority of the racial restrictions contained in the Mining Regulations of 1911. Yet, despite these set backs to racial occupational mobility restrictions, *de jure* racial restrictions were re-imposed through the Mines & Work Act Amendment of 1926. As will be discussed further, the Witwatersrand gold mining industry tolerated the re-imposition of racial restrictions on occupational mobility. After the 1922 Rand Revolt the mines secured a critical reorganization in stoping practices that removed all immediate threats from racial occupational mobility restrictions and opened the door to develop the necessary organization change to implement the physical technology change. Thus, a profitable platform for exploitation of the reef existed for the immediate future and allowed the Witwatersrand gold mining industry to avoid incurring an 'unnecessarily costly' political conflict with the national government over the colour bar.[10]

Afrikaner miners were a crucial component in initiating the restructuring of stoping practices circa 1922.[11] However, Afrikaner miners were typically working in semi-skilled occupations that were the next progression for African miners. In the face of this occupational threat, Afrikaner miners used their increasing presence in the mine workforce and more general national political authority to secure racial mobility restrictions over semi-skilled mining occupations. While the challenges these restrictions created were not acute during this period, they would become so in succeeding decades. The attractive dinner jacket Afrikaner miners held for resolving the transformation of stoping practices, became a straight jacket for non-racial employment in the latter quarter of the century.

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[10] This 'unnecessarily costly' conflict only existed from an assumed bounded self-interested frame of reference for mine management and not that of a general long-run social optimal in which the socio-economic benefits of all members of society are considered.

[11] Chapter Two in Jeeves (1985) elaborates on the role played by Afrikaner miners in Witwatersrand gold mining.

Rock-Drill Design

As mentioned in the previous section, the piston-drill design produced relatively large and bulky drills. Given the narrow stopes of the Witwatersrand this meant that rock-drills were impractical unless one was willing to mine a significant amount of waste rock.[12] Many efforts were devoted to producing a lightweight piston-drill, but not with appreciable success.[13] One possibility was the hammer-drill design.[14] The hammer principle was used in small pneumatic tools before it was applied to rock-drills and since it did not require direct attachment to the piston, held promise as a small and powerful rock-drill. Henry C. Sergeant had invented a hammer-drill in 1884, but it used a solid drill steel that limited it to overhead drilling. In a piston-drill, the primary design still used today, the reciprocating drill steel pulled the pulverized rock out of the hole as part of the drill's action, cleaning the hole as it drilled in a manner that did not occur with a hammer-drill.

It was not until 1897, when J. George Leyner patented a drill with unique hollow drill steel that could clean the hole with air or water that a hammer-drill capable of expelling waste rock was created. The Leyner innovation allowed hammer-drills to drill in any direction and initiated a technological race with piston-drills for more reliable and efficient rock-drills. Hence, hollow drill steel would be instrumental to the design of a fast and lightweight stoping drill that could be used profitably on the Witwatersrand.

Occupational Health Imperatives

Mining is an inherently dangerous occupation with a variety of hazards. During this period, the primary occupational dangers were lung diseases and heat stroke. These two hazards were intimately linked to the use of rock-drills and the environmental challenge of stoping at depth.

It is possible to distinguish five phases of occupational health hazards.[15] The first phase began with the earliest Witwatersrand gold mining and ended with the Second Anglo-Boer War. This phase was an era of practical ignorance about the dangers of lung disease underground. The second phase, from 1903 to 1907, marked identification of the extent of silicosis (miner's phthisis) in miners' mortality and the beginning of efforts to improve ventilation. The third, from 1907 to 1916, saw increased knowledge of dust-borne lung diseases developed through systematic study and regulation of the work environment underground. It was also a period when increased attention and regulation was applied to reduce, predominately African, miners' deaths due to pneumonia and tuberculosis (Packard, 1987, p. 200). Fourth, from 1916 to 1924, systematic government and industry research initiatives began to decrease the incidence of occupational lung diseases. Finally, the fifth period from 1924 to 1934, saw the emergence of another occupational health hazard, namely heat stroke. Increased heat in the rock temperatures at ever-greater depths combined with the water used to suppress dust to make a lethal blend of heat and humidity.

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[12] As an example, on one of the Witwatersrand mines before the introduction of a lightweight rock-drill, the stope height when hand-drilled was 167cm while stopes using rock-drills were 188cm. After the introduction of lightweight rock-drills, the stope height had decreased to 117 cm (Payne, 1930, p.390). Some of this reduction in stope height corresponds to a general decrease in reef height with depth, but the waste rock around the reef decreased substantially with the use of lightweight rock-drills.

[13] See Section 8.2.3 on rock drill design below for a discussion of these attempts.

[14] The 'hammer-drill' design refers to a type of drill that imitates the manual hammering of drill steel via blows from the piston being delivered to the drill steel.

[15] It needs to be borne in mind that these phases are described from a review of the orthodox history written by the industry. See Irvine (1934) for the review from which these phases are drawn.

8.2.3 Solutions

Some challenges facing the Witwatersrand gold mining industry in areas like milling capacity, could only be met by rising to the challenge. Others, like alleviating cost pressures by increasing the market price paid for gold did not result in any enduring solution. The mines attempted to use their strategic position in gold supply to exert pressure on the Bank of England to raise the market price of gold.[16] While these efforts did result in the gold premium, which was a lifeline to the industry for a few years, it was a temporary scheme and the industry returned to troubled waters upon its removal. The three principal dimensions successfully used to transform stoping practices were: 1) changes in stoping work organization, 2) adaptation of rock-drill design for local conditions, and 3) alleviation of occupational hazards. In detailing these dimensions below, research collaboration is a recurrent and important component.

Changing the Organization of Stoping Work

The discussion of changes in organization of stoping work that follows is divided across seven eras.[17] In each of these eras, changes to the general structure of stoping work are highlighted in a summary table with details of roles/positions of the three major components of the stoping labor force. This re-organization led to a removal of the artisan's skill in rock breaking and establishment of a stoping workforce integrated into a hierarchical management structure over operations.

A. Resumption of Operations Following the Second Anglo-Boer War (1902-1904)

The major force driving change in stoping practices during the 1902 to 1904 era was a shortage of low cost African miners. Resumption of gold mining operations on the Witwatersrand in 1902 and the arrival of Chinese labor in 1904 define the era. Scarcity of European miners led to an increasing number of local, predominately Afrikaans speaking,[18] low-skilled whites taking up work on the mines. Simultaneously, shortages of low cost African miners led to examination of a variety of low cost labor solutions. The short-term solution eventually settled upon was the importation of low cost labor from China.

TABLE 8.2 THE STRUCTURE OF OPERATIONS UNDERGROUND 1902-1904

		Development	Stoping
Labor forces:	**Supervisors**	Europeans	Europeans
	Semi-Skilled	Afrikaners/Africans	Afrikaners/Africans
	Low-Skilled	Africans	Africans
Technique		Rock-Drilling	Hand-Drilling

After the Second Anglo-Boer War, European miners returned to the Witwatersrand. At the same time, there were increasing numbers of 'proletarianized' whites seeking work on the mines (Davies, 1976, p.48). Drought and war had severely limited opportunities in rural South Africa and thus, despite lacking mining skills, white males looked to the mines in their search for urban employment. These unskilled white Afrikaner miners did not replace European miners, whose mining skills were still needed, but formed a third class of labor in gold mine operations. Thereby, an important step in eroding European miners' labor power was made, since Afrikaner

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16 Ally (1994) examines these efforts.

17 These eras are from those identified in the literature.

18 Despite heterogeneity in language as well as other attributes, reference is made to this class of miners under the umbrella term: Afrikaner miners.

miners could be used to facilitate local skills development to a degree not possible with African miners because of racial and migratory impediments.

Availability of Afrikaner miners made them a logical choice to meet the acute post-war shortage of African miners. Thus, the first wave of white labor experiments was conducted. An outspoken proponent was F.H.P. Cresswell who later joined the Hertzog administration as Labour Party leader. A related investigation by COMSA around 1902-1903 found that keeping a white family out of relative poverty required a minimum income nearly twice that of an African family (Davies, 1976, p. 49). The white labor experiments showed that Afrikaner miners could not offset their higher costs with sufficiently greater efficiencies and other alternatives for solving the labor shortage needed consideration (Denoon, 1967, p. 53). By mid-1903, consensus grew in support of the importation of low cost indentured Chinese labor (Richardson, 1982, p. 16).

Even as low cost Chinese miners alleviated the scarcity of African miners, other solutions developed. One preceded the acute post-war scarcity of African miners, the Witwatersrand mining companies attempt to establish a large, stable and low cost migratory African labor force through an extensive recruitment network.[19] This effective recruitment monopoly in low skilled African labor became the long-term solution for the Witwatersrand gold mining industry to secure a structurally low-wage labor force.

B. Chinese Labor on the Witwatersrand (1904-1907)

Chinese miners were imported to the Witwatersrand between June 1904 and January 1907 and these dates define the next era of change in stoping labor force organization. It saw the establishment of several precedents important to subsequent transformation of stoping practices. Among these, a major milestone was the first 'scientific' examination of operations and open diffusion of this analysis to the entire industry.

TABLE 8.3 THE STRUCTURE OF OPERATIONS UNDERGROUND 1904-1907

		Development	Stoping
Labor forces:	**Supervisors**	Europeans	Europeans
	Semi-Skilled	Afrikaners	Afrikaners
	Low-Skilled	Chinese	Chinese
Techniques:		Rock-Drilling/Hand-Drilling	Hand-Drilling

When Chinese arrived on the Witwatersrand, the 1904 Labour Importation Ordinance closed all skilled and semi-skilled jobs to non-white miners. Therefore, while the arrival of the Chinese caused a loss of employment among some lower skilled whites, it also made redundant semi-skilled African miners (Davies, 1976, p. 59). This closing of upward occupational mobility to relatively low cost African miners was accepted by management as a temporary measure in order to facilitate skilled (European) miners' acceptance of Chinese importation.

The Chinese provided a large stock of relatively low cost labor on the South African market. This increased supply in South Africa undermined the bargaining position of African labor and a steady decline in their remuneration ensued (Denoon, 1967, p.492). This easing of scarcity in low cost labor also reduced pressure on Mozambique's labor market, which was highly stressed by demand from South Africa (Richardson, 1977, p.90). Despite this reprieve, it was an era of intense rivalry and faction fighting in mine labor recruitment. COMSA's principle recruiting organization, the Witwatersrand Native Labour Association (WNLA), had been driven out of the

[19] Details of the efforts to establish this low-wage labor supply system are found in Jeeves (1985).

main recruiting centers in southern Africa by the various colonial governments and left with only a perilous position in Mozambique.

In the organization of stoping work, the Chinese era was notable in bringing increased productivity,[20] a higher caloric provision, and better sanitation arrangements (CMMSSA, 1934, p. 313). This era also saw the first initiative in scientific management on the Witwatersrand. Scientific management is the term used for the, principally Taylorist, innovations in work organization from 1902 to 1933 that were developed for the Witwatersrand gold mines.

Between January 1904 and September 1905, the Corner House group brought in a foreign based management expert, Ross Browne, for advice on working costs and future development of deeper mines. This analysis,[21] called for an acceleration of change in the organization of stoping work with routinization of production and increased efficiency in relatively low cost mine labor, which would decrease the proportionate number of skilled miners needed.

C. The First Round of Conflicts over a Reorganization of Stoping Work (1907-1913)

The third era begins with the first round of conflicts over reorganization of the mines' workforces, the Strike of 1907, and concludes before the 1913 Strike. Removal of the artisan from underground operations was at the center of this and the three subsequent 'rounds' of conflict, which mark the first major wave of workforce reorganization. In this era establishment of the Native Recruiting Corporation (NRC) marked an important step forward in securing a low wage African miner recruitment monopoly.

TABLE 8.4 THE STRUCTURE OF OPERATIONS UNDERGROUND 1907-1913

		Development	Stoping
Labor forces:	**Supervisors**	Afrikaners/Europeans	Europeans
	Semi-Skilled	Afrikaners	Afrikaners
	Low-Skilled	Africans	Africans
Technique		Rock-Drilling	Hand-Drilling

In 1906, following Browne's recommendations, select mines began to increase the number of rock-drills supervised in tunneling from two to three. While seemingly innocuous, this change was effectively 'deskilling' supervisory work by introducing Afrikaner miners. The increasing numbers of relatively unskilled, but politically represented proletarianized South Africans marked the beginning of a process of transformation of the non-African workforce on the Witwatersrand mines. This change met resistance from the European miners. Thus, when in May 1907 Knights Deep gold mine ordered re-organization of its tunneling operations and a simultaneous reduction in white supervisory wages, the first general strike on the Witwatersrand followed. The strike lasted a month. Mines continued limited production with non-unionized miners and took the opportunity to replace striking European miners with large numbers of Afrikaners, giving Afrikaners their first significant entry to the industry. Statistics from the Transvaal Colony Government Mine Engineer 1907 annual report in Table 8.5 indicate the change in the non-African mining workforce resulting from 1907 strike.

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[20] It is not clear from available contemporary references if this productivity resulted from a re-organization of low-wage stoping workers or greater effort. Given its perpetuation after repatriation of the Chinese, it would suggest the former was the cause.

[21] See Browne, 1907, pp. 289-354.

Table 8.5 Employment Before (April 1907) and After (June 1907) the 1907 Strike

	Before	After	Decrease	Increase
Great Britain Born	13,360	11,742	1,618	-
South African Born	3,260	4,337	-	1,077
Other U.K. Colonies Born	944	736	208	-
Non-U.K. Born	1,036	816	220	-

A political force emerged with the introduction of Afrikaner miners following the Strike of 1907. The Het Volk (Botha) and Nationalist (Smuts) parties coalition was elected to the colonial government of the Transvaal in 1907 and were more closely identified to agricultural and manufacturing interests. Meanwhile, the newly elected Liberal government in Britain had prohibited further importation of Chinese labor. Therefore, proponents of an all white mine labor force again raised calls for the industry to adopt its 'white labor policy'. To assuage emergent socio-political pressures, the Witwatersrand gold mining industry initiated another round of white labor experiments with similarly poor results as the first (Davies, 1976, p. 61). It also began to develop Taylorist methods that allowed further utilization of the relatively unskilled local Afrikaner miners to replace the artisan skill of the European miners. In this role of deskilling underground operations, from 1907 to 1922, Afrikaner miners provided a remedy for labor militancy.

Following the Strike of 1907, COMSA established the 1908 Mine Trials Committee. Its primary reasons for being was research into 'standard methods' for mining.[22] Although dissolved in 1915, the Mines Trials Committee marked the beginning of institutional cooperative research in southern Africa and industry wide support of research into scientific management. Another major initiative advancing scientific management on the Witwatersrand in this era was the 1911 establishment of the Government Mines Training Schools. These schools were initially supported by both the Union Government and COMSA, but were taken over by the Chamber completely in 1916. These schools increased the number of Afrikaner miners by teaching unskilled whites skills for occupations on the mines.[23]

While developing Taylorist methods of work organization during this era, the African labor recruitment monopoly also developed. Between 1906 and 1913, recruitment slowly improved as increasing numbers of voluntary laborers made independent recruiters redundant. This phenomenon was supported COMSA establishment of the NRC in 1912 and the Union Government's 1913 imposition of limitations on the amount of wage advances that could be paid. However, the 1913 tropical recruitment ban, imposed by the Union Government, somewhat offset these gains.

D. Round Two: The Strikes of 1913 & 1914

This relatively brief era begins in mid-1913 and concludes with the outbreak of the First World War in 1914. It marks the beginning of an effective co-optation of White labor over class and national revolutionaries opposed to state and mining interests.[24] The replacement of artisanal skills by rock-drills in tunneling preceding and following the 1907 Strike eroded the 'critical nature' of the European miners' skills and introduced a class of low skilled Afrikaner miners with

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[22] These standard methods followed from Browne's work identifying Taylorist methods of work organization on the Witwatersrand.

[23] For more information on the Government Mines Training Schools, see Chapter 52 in Letcher (1936).

[24] See Yudelman (1983, Chapter 3) for analysis of this co-optation and its legacy in South Africa's political economy.

de facto occupational protection from lower cost African miners. Thus in June 1913, a relatively minor dispute at New Klienfontein mine spiraled into an industry-wide strike by White labor, who were still predominately Europeans, over COMSA refusal to recognize unions in collective bargaining. When violent conflicts erupted in early July, the Botha-Smuts government and Witwatersrand mining industry were forced to give concessions to the strikers.

TABLE 8.6 THE STRUCTURE OF OPERATIONS UNDERGROUND 1913-1914

		Development	Stoping
Labor forces:	**Supervisors**	Afrikaners	Europeans
	Semi-Skilled	Afrikaners	Afrikaners
	Low-Skilled	Africans	Africans
Technique		Rock-Drilling	Hand-Drilling

A strike by African miners that followed shortly after the July strike illustrates the broader racial attitudes held within the industry, government, and among the miners themselves at this time. The goal of the African miners in striking was to increase their low wages (Yudelman, 1983, p.103). In contrast to the concession that the non-African miners received, the government used violent repression to send the African miners back to work with virtually no reaction by the non-Africans.

While not given a free hand, European and Afrikaner miners appear to have missed an opportunity to carry the industrial settlement into broader political initiative (Yudelman, 1983, p.100). Government lay-offs of railway workers on Christmas Eve precipitated another general strike by European and Afrikaner miners in early January 1914. This time, with better government preparation, initiative was seized back by the state and mining interests (Yudelman, 1983, p. 110).

From these conflicts, a policy of co-optation of the White mining unions began. This process of co-optation of organized White labor into an alliance with the South African state and Witwatersrand mining industry culminated with the 1922 Rand Revolt. In his book *The emergence of modern South Africa*, Yudelman (1985) argues this is an early demonstration of a process of state and capital symbiosis key to the legitimating process of modern industrial states.

E. Round Three: Labor Scarcity during the First World War

The fifth era is marked by labor scarcity and industrial expansion in the face of war-driven import scarcity. It saw increased use of Afrikaners in place of Europeans and movement up the occupational ladder by Africans. While the industry's African labor monopsony was significantly developed, increasing numbers of Afrikaner miners forced mine management to impose formal racial restrictions in semi-skilled work. Subsequently, as the labor situation improved mine management contested these restrictions.

TABLE 8.7 THE STRUCTURE OF OPERATIONS UNDERGROUND 1914-1918

		Development	Stoping
Labor forces:	**Supervisors**	Afrikaners	Europeans/Afrikaners
	Semi-Skilled	Afrikaners/Africans	Afrikaners/Africans
	Low-Skilled	Africans	Africans
Technique		Rock-Drilling	Hand-Drilling

Ensuring a reliable and adequate stock of low cost African labor was critical to the emerging industrial structure of the Witwatersrand gold mines. For nearly a quarter century, competition for African recruits between the mining groups had impeded establishment of a co-operative recruitment organization. Through the complementary South African (NRC) and southern Mozambican (WNLA) recruiting institutions, [25] this era finally saw realization of an enduring African labor recruitment co-operative. In his examination of migrant labor recruitment, Alan Jeeves (1985) highlights the 1916 take over of the large Randfontein mine by the JCI group as creating the critical industry consolidation needed for the cooperative to work (p.261). Thus, despite African labor shortages fueled by the First World War, when Randfontein finally joined the NRC in 1919 it created a powerful cooperative recruitment monopoly. [26] While challenged by a variety of socio-economic changes throughout southern Africa, these institutions under COMSA oversaw supply of low cost African labor to the Witwatersrand gold mines for decades to come.

Even though they were better able to coordinate their activities, the Witwatersrand gold mines saw falling output and excavation productivity beginning during the First World War and continuing until 1922. Three labor force conditions were the main cause: increased employment opportunities for African labor outside mining; the departure of European miners to join the military; and high labor mobility between mines. The downward trend in excavation efficiency was temporarily reversed in 1916 when amidst severe African labor shortages initial attempts were made at using lightweight rock-drills in stoping (Newhall & Pryce, 1924, p.116).

The removal of artisanal skills from underground production was an obvious priority given the scarcity of European miners. This in turn led to large-scale introduction of Afrikaner miners during the war. Even though they were typically low or semi-skilled miners, the Afrikaners rose from 40% of the non-African workforce in 1914 to 75% in 1919 (Johnstone, 1976, p. 105). In order to facilitate this increased use of low and semi-skilled labor the industry stepped up its use of 'study standard methods'.[27] The first important investigation during this era was the 1914 report by the Association of Mine Managers on time and labor saving, which highlighted the inefficiencies inherent in an artisanal dependent production system (Leger, 1992, p.43). Another investigation by the Association of Mine Managers in 1916 focused on the tight relationship between low-skilled and skilled miners in underground production bottlenecks. It identified the introduction of a lightweight rock-drill in stoping as a means of breaking this collusion (Leger, 1992, p.44). Finally, in 1916 COMSA took over the Government Mines Training Schools, which suggests a greater commitment by the industry to use the schools as a systematic means of skilling Afrikaners for work on the mines.

Besides being detrimental to European miners, replacement of artisanal skills during the war carried knock-on costs to both African miners and mine management. During the war, the simultaneous increase in the number of Afrikaner miners and the movement of African miners up the occupational ladder led Afrikaners to view the Africans as a threat to their job security. Since the Afrikaner miners had limited skills, they felt very vulnerable to movements of African miners into semi-skilled occupations even if it was done on the pretext of acute labor shortages because of the war. In January 1917, this tension manifested itself as an unofficial strike by non-African workers at Van Ryn Deep mine. Mine management had ignored the *de facto* racial occupational mobility restrictions and deployed Africans in semi-skilled work. Following this

[25] In 1932, the 22° South tropical recruitment ban was lifted and WNLA charged with all non-South African recruitment.

[26] Randfontein's movement to the NRC had to await the end of its previous recruitment contracts.

[27] 'Study Standard Methods' were Taylorist guidelines for work organization.

incident, the Mine Workers Union (MWU), with its increasingly Afrikaner membership, sought *de jure* racial mobility restriction so that Africans could not be given semi-skilled occupations. Throughout 1918, several other unions joined the MWU and fearing strike action in September *de jure* racial protection over semi-skilled occupations was granted with the Status Quo Agreement.

F. Round Four: The Rand Revolt of 1922

Following the First World War through to the 1922 Rand Revolt, the sixth era covers the conclusion of the first wave of reorganization in stoping work. While replacement of artisanal skills with Taylorist methods of stoping had been developed by the several initiatives discussed previously, during this era the Corner House group undertook a very large and important investigation. Their Rock Drill Investigations Committee (RDIC) conducted this investigation between 1919 and 1922. With a focus on rock breaking, the RDIC was critical to development of Taylorist production methods in stoping. A few of the more significant contributions made by the committee were their design of a mechanical hole director (replacing the tacit knowledge of the artisan in rock breaking), standardizing stoping work organization to maximize efficient deployment of African drillers under the supervision of Afrikaner supervisors, and establishing improved practices in drill-bit sharpening and tempering. However, resistance to a reorganization of stoping work delayed introduction of these innovations. This resistance effectively ended with mine managements' victory in the 1922 Rand Revolt.

TABLE 8.8 THE STRUCTURE OF OPERATIONS UNDERGROUND 1918-1922

		Development	Stoping
Labor forces:	**Supervisors**	Afrikaners	Europeans/Afrikaners
	Semi-Skilled	Afrikaners	Afrikaners
	Low-Skilled	Africans	Africans
Technique		Rock-Drilling	Hand-Drilling/Rock-Drilling

Imminent repeal of the gold premium and the industry's profitability crisis put cost reductions foremost among mine management's concerns after the war. Greater use of low cost African labor carried terrific potential in lowering the industry's cost structure, but this was impeded by the *de jure* racial occupational mobility restriction in the Status Quo Agreement and 1911 Mining Regulations. In this setting, the first large scale organized African miners strike took place from 17 to 24 February 1920. As before, this strike was violently dissolved resulting in the death of 11 and injury of 120 African miners (Simons and Simons, 1969, p. 232). While the African miners demanded higher wages because of rising equipment costs, which they had to buy from the mines, mine management sought to promote their own interests by emphasizing a relatively minor issue in the strike, removal of racial occupational mobility restrictions (Johnstone, 1976, p. 183). A platform was thereby established in which mine management simultaneously were pushing for re-organization of the mines' workforces and greater occupational mobility of low cost African miners.

The final *Report of the Low Grade Mines Commission* of 1920 appeared in May following the African miner strike. It summarizes the perceived situation before the 1922 Rand Revolt:

> "The question [of repeal of racial mobility restrictions] goes much deeper and involves consideration of the whole labour system on which the industries of the Union [of South Africa] have built up. In mining, as in most other industries, a more or less practicable *modus vivendi* has been arrived at, but the boundary line between the employment of black [African] and white labour is highly artificial and liable to alteration from time to time.

While the position of the supervising or highly skilled white [European miners] is a perfectly definite one as against the unskilled native [African miner] doing rough work, that of the unskilled white [Afrikaner miner] is not so obvious. He can hardly be considered to be the equal in efficiency of a native who by experience and practice has acquired proficiency in his particular class of work. The labour of such a native is therefore clearly of greater value to an employer than that of the unskilled white man, and if there were no artificial restrictions, the latter would be driven to the wall. His standard of living is higher than that of the native, and where a skilled native would be content to take 5 schilling per day, because that would enable him to live in comfort according to his standard, the inferior white man will demand a higher rate of pay for the same work, less well done, because he cannot live in decency on less.

It is on this account that the white man looks to the colour bar [racial occupational mobility] restrictions as a protection against what he considers to be unfair competition. We have on the one side a considerable body of more or less skilled and partly educated natives who clamour for opportunity to improve their pay and their situation in life, and on the other a large number of whites, through no fault of their own, have had no training in any particular trade. They claim protection against the competition of natives who are still in an inferior stage of civilization, and are strongly supported in this attitude by their more fortunate skilled fellow-workmen. Both sides have given evidence that unless their desires are given effect to, there will be struggles and explosions of a violent character, and there is already sufficient indication in recent happenings on the Witwatersrand that this is only too true" (1920, pp. 28-29).

There was an international rise in labor militancy during this time that spread to the non-African miners on the Witwatersrand. Shop stewards had come to the mines, the more revolutionary stewards forming a Council of Action. Holding racial occupational mobility restrictions high on its priorities, the Council of Action secured a broad based support. In 1921, the gold premium was ending and mine management focused on termination of *de jure* racial occupational mobility restrictions. Thus, when the MWU and COMSA entered negotiations, COMSA held repeal of the Status Quo Agreement as a non-negotiable condition. The MWU rejected this as they saw it as the first step towards complete removal of racial occupational mobility restrictions (Hocking, 1997, p. 104). Knowing the cost and efficiency gains that reorganization held, COMSA moved unilaterally. In August, they announced White African wage reductions and in December declared that from February, the mines' labor forces would be reorganized in violation of the Status Quo Agreement. In January, coal miners went on strike during a contraction of that industry and White Witwatersrand gold miners joined them.

In February, the Smuts government secured some dialogue, but following two weeks of limited work, discussions fell apart. The MWU was seeking a resolution with hostile mine management, which led members to question their leaders' resolve. In early March, the Council of Action took advantage of this situation to seize control of the union and initiated a series of violent conflicts across the Witwatersrand, in what is now called the Rand Revolt. By mid-March martial law had been declared and the Smuts government sent in troops to quell the strikers. The changes imposed by mine management stood, White wages were decreased across the board and most importantly, the mines' labor forces were reorganized.

After the 1922 Rand Revolt, the Taylorist methods of stoping were implemented, ending the first wave of reorganizations in stoping work. Jean Leger (1992) examines this transformation of Witwatersrand stoping practices and points out that Witwatersrand mines were near the international forefront of industrializing their production processes. In this three factors facilitated the development of the industry. First, the successful removal of artisanal control underground because of the 1922 Rand Revolt. Next, the weak socio-economic position of the African working class lowered productivity to some extent, but provided a racial division in labor that facilitated the introduction of Taylorist methods. Lastly, piece-rates, long established on the Witwatersrand, provided institutional momentum to the Taylorist philosophy of paying for the work done.

G. Development of Scientific Management (1922-1933)

With victory against European miners resistance to Taylorist methods underground, mine management began the 1922 to 1933 era with significant productivity gains across the industry. While diffusing the previous wave of innovations across the Witwatersrand, another wave of research and innovation began. This second wave of reorganization focused on the African miners and sought to further advance efficiencies in work organization by imposing detailed structure over their work. With its segregated focus on the mines' labor force, it advanced a uniquely South African form of Taylorism, 'scientific management'.

TABLE 8.9 THE STRUCTURE OF OPERATIONS UNDERGROUND 1922-1933

		Development	Stoping
Labor forces:	**Supervisors**	Afrikaners	Afrikaners
	Semi-Skilled	Afrikaners/Africans	Afrikaners/Africans
	Low-Skilled	Africans	Africans
Technique		Rock-Drilling	Rock-Drilling

"One of the most important aspects of scientific management in application is with respect to black [African] miners efficiency. Previously blacks were treated collectively, rationalization has led to great results from treating whites individually, we need now to translate that effort so that in the face of severe cost pressures black miners receive similar types of training and handling" (SAMEJ, 1929, p.31).

This final era concludes in 1933 following the devaluation of the South African Rand. While scientific management continued to evolve, 1933 marks an important turning point in the industry's history. The gold price effectively doubled in 1933 creating a completely different internal and external industry dynamic over subsequent developments in scientific management. As noted in the introduction, Yudelman (1983) argued that the change resulting from the increased price of gold marked a profound turning point not just for the industry, but also for the modern South African State.

The reorganization of stoping practices occurred quickly after the Rand Revolt and by 1923, working costs per ton of ore milled had fallen 24% (Yudelman, 1983, p. 27). In this advance of efficiency, contemporaries noted RDIC's new drill director as being a major source of the productivity gain.[28] The RDIC research and its associated restructuring led to an increase of 400% in the length of holes drilled per shift and an increase in the actual drilling time per shift from 3.5 hours to 5 hours (Leger, 1992, p.46). Another contribution to the general efficiency gains came from the introduction of drill sharpening machines, which also removed a class of White jobs. Despite initial use during the First World War, large-scale deployment of the drill sharpeners only occurred within the general restructuring of operations that followed the Rand Revolt (Johnstone, 1976, p. 143). Above ground, introduction of the corduroy extraction process

[28] The drill director replaced the artisans' knowledge of blast hole marking. For contemporary discussions of its importance see Simon (1927, pp. 24-25) and H.W. Adler (JCMMSSA, 1934, p. 315)

at the mills also facilitated greater efficiencies through deployment of low cost African labor, but the principal efficiency gains after 1922 originated at the stopes.[29]

Despite the victory of 1922, the political authority of White miners meant that mine management did not have a free hand to completely restructure the industry. Thus, when a court case in 1923 found in favor of management with the Hildick-Smith judgment, all racial occupational restrictions could have been removed. Mine management did not take advantage of this decision, which had been initiated before the Rand Revolt, and remained satisfied with the restructuring they had already realized. This reclaimed White labor co-optation and led to a revival of *de jure* racial occupational mobility restrictions with the Mines and Works Act Amendment of 1926, albeit over reorganized operations.

Table 8.10 Important Dates in the Reorganization of Stoping Work

Date	Event	Remarks
1902-1922	***Wave One of Reorganization***	***Replacement of Europeans' Artisanal Skills***
1904-05	R. Browne Study of the underground mining on the Witwatersrand	Corner House study, inauguration of 'study standard methods'
1908-15	Mine Trials Committee	Early collaborative research structure, with a function being to 'study standard methods'
1911	Government Mines Training Schools	Trained Afrikaner Miners to replace artisanal skills of European Miners
1912	Native Recruiting Corporation established	Facilitated domestic recruitment of African labor
1914	Association of Mine Managers Study	'Study standard methods' in semi-skilled work
1916	Association of Mine Managers Study	'Study standard methods' in low-skilled work
1918-20	African labor recruitment monopsony established	Secured supply of a low-cost class of labor
1919-22	Rock Drill Investigations Committee (RDIC)	Central Mining (Corner House) committee formulated Taylorist methods to replace artisanal skills in stoping
1922-80s	***Wave Two of Reorganization***	***Segregated Improvement of African Labor productivity***
1922	Technical Advisory Committee (TAC) established	Cooperative research organization (COMRO predecessor) for Rand gold mining practices
1929-30	Miles & Stephenson Study	Central Mining (Corner House) study, which formulated scientific management applications underground
1930	Native Training Schools established	Trained African Miners in 'standard work practices' across the Witwatersrand

Thus, the second wave of reorganization focused on the African miners. 'Study standard methods' departments were established at every mine, scientific management was advanced on a formal basis, seeking increased efficiencies by imposing prescriptive structures on the workplace. These efforts were co-operatively supported through COMSA establishment of the Technical Advisory Committee in 1923.[30] While Taylorism seeks to make implicit knowledge explicit and thereby de-skill occupations, in South Africa's variety of Taylorism, 'scientific management',

[29] For information on the corduroy extraction process, see Adamson (1972).

[30] Also, see Footnote 33.

hierarchically-imposed standardized practices were used to impart skills on migrant African miners (Leger, 1992, p. 55).[31] Belinda Bozzoli (1977) has identified four major areas where these efforts took form: 1) development of scientific selection processes, 2) acclimatization, 3) work standardization and 4) labor force control.

Aptitude tests were developed by industrial psychologists to classify and place migrant African miners according to their skills. During this era, a major initiative in this regard took place in 1929 when Rand Mines brought G.H. Miles and A. Stephenson from Britain to investigate the application of scientific management to underground work. Their 1930 report (Stephensen, 1930) focused on labor processes done by Africans underground with time and motion studies, made proposals for selection and training, and contained recommendations for individual incentives. Acclimatization arose as a complement to both occupational health imperatives and scientific management. Through these efforts, described further in the section on occupational health below, in 1932 the industry was able to get a repeal of the 1913 recruitment ban north of 22° South. An important aspect of scientific management and standardization of work was imparting these methods on the workers. This was advanced when the industry co-operatively established Native Training Schools in 1930 for the African labor force (Letcher, 1936, p. 187).

Rock-Drill Design

This section reviews the development of rock-drills and ancillary equipment suitable for stoping on the Witwatersrand, with particular attention to South African contributions. As a contemporary quote indicates, early in this period rock-drill technology was not advanced enough to replace hand drilling: "We all know of the experiments to supplant native hand drilling in narrow stopes by small light air drills, but these have not yet been entirely satisfactory" (Webb, 1903, p.34). In due course, overseas developments in rock-drill design made machine stoping technically viable. However, economic stoping with a rock-drill on the Witwatersrand required local innovations to the rock-drills, their ancillary equipment, and maintenance practices.

An efficient lightweight rock-drill did not emerge until the hammer drill design was made practical. This design came in 1897 from the American, J. George Leyner, when he patented his unique hammer drill with hollow drill steel (Hansen, 1937, p. 5295). While the Ingersoll-Rand company bought the Leyner patents in 1911 and the J.G. Leyner Company in 1912, it was only in 1914 when the Leyner patents expired that the hammer design realized dominance over the piston drill. With ever improving metallurgy, by the early 1920s the hammer-type drills predominated over lightweight rock-drills (Dana, 1927, p. 1291). The Witwatersrand gold mining industry did not sit idly by and wait for a practical design to emerge, it actively supported initiatives to advance development of a lightweight rock-drill suitable for stoping.

The principal means by which rock-drill design advances were promoted by the Witwatersrand mining industry was through rock-drill trials. There were four rounds of trials from 1902 to 1909. Hoping to advance drill design, individual mining groups, industry journals, COMSA, and the Transvaal colonial government sponsored prizes and publicized these trials. These competitions sought to identify the best available lightweight rock-drill and to stimulate innovations to make the rock-drills suitable for large-scale economic deployment on the stopes. Results of the trials and comparative performance of the drills was diffused via publication in

[31] Leger (1992) points out that this removed the tacit experience of African miners from organizational learning and knowledge, which consequently raised occupational health dangers.

local technical journals and special publications by COMSA.[32] While not producing major technical breakthroughs, they demonstrated industry support and promoted a diffused discussion of best practices to limit the dust generated by the rock-drills.

Improvements in rock-drill technologies were not left to drill manufacturers alone. COMSA collectively undertook research for the industry and the individual mining groups openly disseminated findings from their research initiatives.[33] During this period there were five large research initiatives developing rock-drill technologies, either COMSA or the Corner House conducted these. The first initiative was the 1908 to 1915 Mine Trials Committee by COMSA. Besides overseeing the previously mentioned trials, between May 1910 and February 1911 it investigated the treatment and quality of various rock-drill steels (Watermeyer and Hoffenberg, 1932, p. 55). The next significant initiative was the Chamber's establishment of a jackhammer sub-committee between 1918 and 1924. While not conducting research, the jackhammer sub-committee coordinated the transfer of information and advice about lightweight rock-drills among the mines of the Witwatersrand.

Another significant research initiative, the Corner House RDIC occurred between 1919 and 1922. Besides its analysis of labor force organization, it researched refinements in drill design, efficient drill operating parameters, maintenance procedures, drill steel and bit conditioning, rigs to hold the drill, and designed a hole-director to remove the artisan's skill from underground production. The next significant research initiative was COMSA establishment on 1 July 1922 of a Technical Advisory Committee (TAC).[34] Originally empowered to investigate issues forwarded to them by the newly formed Gold Producers Committee (GPC),[35] in 1923 the TAC received authorization to undertake independent research and fell under the leadership of COMSA Technical Advisor, F.G. A. Roberts. The TAC played a relatively minor role in advancing rock-drill technologies, but in later years, it became a major power within COMSA and an industrial force in mining research.[36]

The other large research project into rock-drill technologies of this period was Central Mining's (Corner House) Investigations Committee (CMIC) of 1925 to 1928. This committee undertook research into drill design refinements, efficient drill operating parameters, maintenance procedures, as well as drill steel and bit conditioning. As with its predecessor, the RDIC, the CMIC disseminated its research results through papers and discussions to the other mining-finance groups.[37]

Refinements in rock-drilling technologies were not isolated from similar efforts taking place around the rest of the world. South African and international experiences formed inflows and

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[32] Griffiths (1904, pp.307-311) detailed the 1902 trial, Carper et al. (1904, pp. 241-260) the 1903 trial and Orr (1907, pp. 182-232) the 1907. The drill trial of 1909 was the largest, supported by COMSA and the government, its results were published in a variety of special publications.

[33] Evidence of dissemination of research findings is found in the discussions of the professional societies journals and their reviews of the period. Analysis of this cooperative research structure follows in Chapter 9.

[34] Previously, between 1917 and 1920, a Technical Advisory Committee was established, but that committee was created solely to forward recommendations about equipment and infrastructure standards on the mines.

[35] For a history of the GPC's formation, see Lang (1986) pp. 283-284 and pp. 312-313.

[36] Its role in research was most significant through its administration of COMSA's Research Organization (COMRO). Established in 1963, COMRO was a major co-operative research organization for the South African mining industry. In 1993, it became part of the Council for Scientific and Technical Research (CSIR) and its name changed to CSIR Miningtek.

[37] See for example Meyer (1930) and Heywood (1930).

outflows of international best practices supporting both South African and non-South African mining companies.[38] Table 8.11lists some important dates in the development of a lightweight rock-drill and its directly associated technologies. [39] In development of economic rock-drills suitable for use in stoping on the Witwatersrand gold mines adaptation and incremental improvements to non-South African technologies featured significantly in the process of innovation.

Table 8.11 Important Dates in Development of a Lightweight Rock-Drill for Stoping

Date	Event	Remarks
1902	Rock Drill Trials	H.P. Griffiths' competition
1903	Rock Drill Trials	Corner House lightweight rock-drill competition
1907	Rock Drill Trials	South African Mines Journal stope drill competition
1909	Rock Drill Trials	COMSA & Government stope drill competition
1908-15	Mine Trials Committee	Early collaborative research structure, investigated mining equipment
1914	Leyner Patents Expired	Opened up manufacturing of hammer-type rock-drills
1918-24	Jack hammer sub-committee	COMSA sub-committee appointed to disseminate info about best rock-drills and drilling practices
1919-22	Rock Drill Investigations Committee (RDIC)	Central Mining (Corner House) committee. Part of mandate to identify drill design and maintenance economies in operation
1922	Technical Advisory Committee (TAC) established	Cooperative research organization (COMRO predecessor) for Rand gold mining practices
1925-28	Central Mining Investigations Committee (CMIC)	Central Mining (Corner House) committee. Focused on design and support of rock-drills within productive structure underground.

Although re-organizing the stoping labor force was integral, actual transformation of stoping practices required similar developments in rock-drills and occupational health hazards. Mutual dependencies among these technologies meant that developments in each dimension moved simultaneously. Thus, the final key challenges to transforming stoping practices were occupational health hazards.

Alleviation of Occupational Health Hazards

Mining is hazardous work, during this period the Witwatersrand miner, no matter his race, risked death from many sources. However, introduction of lightweight rock-drills on the Witwatersrand brought severe health hazards particularly miners' phthisis and tuberculosis. The increasing depths that the drills made economically viable also brought indirect hazards like heat stroke. Between 1902 and 1933, the strides forward in alleviating these occupational hazards were substantial, although additional health risks emerged in due course. The annual death rate of African miners from all causes was given at 58 per 1,000 in the Milner Commission Report of 1903 (Cartwright, 1971, p. 17).[40] While comparable statistics are not available towards the close of our period, a few disaggregated statistics from Leger's analysis (1990) of safety and health in South African mines indicate just how far the Witwatersrand gold mining industry progressed. From 1915 to 1925, the incidence of miners' phthisis was around 30 per 1,000 miners, and then it began a steady downward trend to around seven per 1,000 in the late-1930s where it stabilized

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[38] See Weston (1905), (1907), (1910), (1917), and Potter (1918), (1919), (1926).

[39] Among the 'associated technologies', the hole-director played a critical role in transforming stoping practices. See Simon (1927), Watermeyer and Hoffenberg (1932, p. 406), and CMMSSA (1934, p. 315).

[40] There is problem with some degree of incompleteness in all the statistics available during this period, nonetheless, they are indicative of general trends.

into the 1980s. Tuberculosis among African miners went from around seven per 1,000 in the mid-1910s to around three per 1,000 in the mid-1930s, a trend that was followed by the White labor force as well. Miner fatalities from accidents also decreased during this period, dropping from 4.25 per 1,000 in 1910 to 2.5 per 1,000 in 1920, where it remained until further slow and steady reduction began in the early 1930s.

The remainder of this section reviews how the industry went about decreasing the occupational hazards confronting its miners. The lion's share of the discussion is focused on miners' phthisis since it is most directly associated to the deployment of rock-drills. Attention then turns to a brief review of developments in tuberculosis, heat stroke, and the general safety and health of the workers.

A. Miners' Phthisis

Between 1903 and 1912, the significance of miners' phthisis was identified and a primary factor of causation, silicious dust, recognized. Understanding the hazards of silicious dust led to initiatives to reducing two primary sources of dust underground: blasting and rock-drills. Under the Mines & Works Act of 1911, blasting was regulated to minimize the miners' exposure to dust. While rock-drills were not widely used in stoping during this era, they were used in tunneling extensively and so the Mines & Works Act of 1911 required all drills to simultaneously spray water to allay the dust they generated.[41] The Miners' Phthisis Act of 1912 required the mines to pay workers compensation to their phthisis infected white work force and thus created a significant financial incentive for the mines to alleviate miners' phthisis. Because of the information it generated about the underground environment, dust sampling became integral reducing dust levels. In this area, the Goldfields group took the lead initiating systematic dust sampling in 1911. Lastly, this era saw the development of artificial ventilation on the mines. The East Rand Proprietary Mine (ERPM) was a pioneer, installing a ventilation system in 1908 that placed it at the international forefront of mine ventilation.

Between 1913 and 1923, understanding of the disease advanced through a series of government commissions and committees as well as by newly established co-operative research organizations. Robert Kotze made a huge advance in the sampling of dust with the 1916 invention of the Konimeter. In 1917, revised regulations required all mines to appoint an air-quality surveyor who would use the Konimeter to monitor dust. COMSA had already taken steps in this regard with its 1914 establishment of a dust sampling committee.

Facilitated by machine drills, ever increasing depths in the early 1920s made mine ventilation a necessity and nearly every mine had an artificial ventilation system. Further refinements were made in the rock-drills' water sprayers as part of the general efforts at increasing rock-drill performance. Towards the end of this era, a new dimension to miners' phthisis began to emerge. Joint studies by COMSA and the Mines Department in 1921 and 1923 showed that fine dust also caused the disease. The fine dust was neither visible to the naked eye nor suppressed by the water sprayed from the rock-drills.

Consequently, between 1924 and 1933 significant decreases in miners' phthisis occurred and efforts to alleviate fine dust advanced. Since spraying water was of limited use in alleviating the fine dust, artificial ventilation played an increasing role in removing the dangerous dust. As part

[41] The recognition of the hazards of silicosis dust evolved across three investigations into miners' phthisis. The first in 1901 was conducted by the Transvaal Medical Society at the request of the Association of Mine Managers. The second was a government commission, the Milner Commission of 1902 to 1903. The third was the Mining Regulation Commission of 1907 to 1910, from which the Mining Regulations of 1911 were formulated.

of the industry's general efforts to decrease respiratory diseases, miners were screened for their susceptibility and regularly checked for development. Through these efforts, progress was made in fighting miners' phthisis and despite the diffusion of lightweight rock-drills for stoping, the incidence of the disease continued to drop. While not eliminated, miners' phthisis was reduced to a socio-politically acceptable level during this period, which was critical to the transformation of stoping practices on the Witwatersrand.

B. Tuberculosis

Tuberculosis was another disease debilitating the mines' workforce in the first decade of the twentieth century. Particularly when the tropical recruitment ban took effect in 1913, the significance of the disease became apparent and remedial measures sought. Packard (1997) analyzes the racial and political economic imperatives of tuberculosis on the Witwatersrand gold mines during this period. He argues that research into the disease can be divided between two eras; the first is from 1903 to the early 1910s and second from the early 1910s to the early 1930s. Dividing the two eras is a changing political economic dynamic whereby the mines increasingly turned to the system of low-cost temporary African miners in production.

Segregated health and sanitary provision thereby evolved to 'protect' the African miners from tuberculosis and other diseases.[42] Increased screening of those miners' most physiologically susceptible to tuberculosis was the primary means of control during this period.[43] COMSA sponsored a large and internationally unprecedented study into tuberculosis among Africans between 1925 and 1932. Through these efforts and with ever-increasing knowledge of the disease, reduction in the tuberculosis rate was clearly effected.[44] This is seen in statistics from African miners at the Rand Mine Group (Corner House), which indicate that from 1916 to 1935 the incidence of tuberculosis dropped from 12.5 per 1,000 to 2.5 per 1,000 (Packard, 1987, p.206).

C. Heat-Stroke

Rising temperatures accompanied the increasingly deep stopes that the new drilling practices made practical. Thus, by the early 1920s increasing heat was becoming a major problem. This was compounded by the required spraying of water to suppress dust, which meant underground work was done in a hot and humid environment, taxing on even the fittest miners. On the older mines of the Central Witwatersrand, depths of over 1,000 meters were reached and working wet-bulb temperatures of 30° to 32° C encountered. In 1919, the Rand mines group investigated heat stresses on miners. No appreciable change resulted from that study and in 1924, the first death from heat stroke was recorded (Cartwright, 1971, p.153). Research into alleviating the hazards of heat-stroke immediately took-off and by 1926 Village Deep and City Deep mines had started a program of acclimatizing new recruits (Cartwright, 1971, p. 153). [45]

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[42] Packard highlights this health concern motivating segregation as a factor institutionalizing segregation and taking the individual African out of the policy imperative, which thereby led to an increasingly racial conception of the health problem (1987, pp. 195-196).

[43] Despite their known value, x-rays were not used to screen African miners at this time because of the cost.

[44] The theory of an underlying racial predisposition toward tuberculosis was only gradually replaced as increasing numbers of Africans became urbanized in the late 1930s and even then, the mines took decades to retreat from the facilitating paradigm of racial physiological susceptibility.

[45] These mines were part of the Corner House group.

Table 8.12: Important Dates in Alleviation of Occupational Health Hazards

Date	Event	Remarks
1901	Association of Mine Managers' Phthisis study	Transvaal Medical Society Requested to investigate mortality of rock-drillers
1902-03	Milner Commission	Highlights danger of phthisis
1906	Silicosis Regulations	First legislated occupational health laws
1908-09	ERPM installs ventilation fans	Internationally important advancement of mining work environment
1907-10	Mining Regulation (Krause) Commission	Led to mining regulations requiring dust suppression with water
1911	GFSA begins systematic dust sampling on its mines	First initiative to gather empirical data on dust underground
1912	South African Institute of Medical Research (SAIMR) established	COMSA & Gov't funded institute focused on study of diseases that miners are especially susceptible
1912-19	Miners' Medical (Phthisis) Commissions	Miners' occupational diseases, phthisis & tuberculosis (TB), investigated through various reports
1913-1914	Colonel William C. Gorgas studies Witwatersrand health conditions	Recommendations to Wits mine health practices made by Nobel Prize winning expert in preventative medicine
1913	Prevention of Accidents (Mine Safety) Committee established	COMSA committee focused on circulating best practices in mines' risk management
1914-37	Dust Sampling (Air Quality) Committee	COMSA committee focused on empirical data on and research to reduce environmental hazards on mines
1915	A.J. Orenstein appointed medical superintendent to Corner House Group	Former assistant to Gorgas, pioneer in occupational health initiatives across the Rand
1915	*The Reef* first published	COMSA mine safety magazine
1916	Konimeter invented	Important instrument in accurate measurement of air borne dust in mines
1916	Miners' Medical Bureau established	Centralized body to examine and exclude men likely prone to occupational diseases
1917	Government Air Sampling Regulations	Regulations require all mines to appoint air-quality inspector and conduct regular measurement of dust
1917	Government Tuberculosis Commission	Large in-depth study of causes and policies to reduce TB
1920	SAIMR Scurvy Investigation	First comprehensive nutritional analysis of Africa labor
1921	Association of Transvaal Mine Medical Officers established	Early professional organization for mines' medical officials
1921	Fine dust in rock-drilling investigation	Joint COMSA/Mines Dept. study on hazards of fine dust for rock-drillers
1923	Fine dust in development (tunneling) work investigated	Joint COMSA/Mines Dept. study on hazards of fine dust in development work
1924	ERPM investigates relationships between air-pressure and dust in rock-drills	Established gov't guidelines on drill air-pressures and associated dust
1924	Rescue Brigade established	Rand Mines became first to establish emergency rescue team (1946 part of COMSA)
1924-25	CMSSA Symposium on Mine Ventilation	Marks move forward from water to ventilation in alleviation of occupational health hazards
1926	Central Mining Investigation Committee (CMIC)	Part of CMIC research is into effects of drill design on dust generation
1926-32	Tuberculosis Research Committee	COMSA & Gov't study, internationally regarded as most in-depth analysis of TB among Africans
1930	Dresoti Heat Acclimatization Study	First scientific investigation in acclimatization

Despite improved acclimatization procedures and further screening of recruits according to their pre-disposition to heat stroke, by the early 1930s heat-stroke had become a major concern for the deeper mines of the Witwatersrand. It would only be in 1935 when the first artificial cooling of mine air began that an alternative to acclimatization emerged. Even then cooling of mine air continued to be complementary to acclimatization and only in the 1960s with ever increasing depths did cooling become the primary means of alleviating the occupational hazard of heat and humidity underground.

D. General Safety and Health of the Labor Force

Throughout this period, the mining companies continued to play a large role in the lives of its workforce. In securing the general health and safety of its miners, the mines had pioneered a voluntary and then statutory workers compensation scheme for White and African miners under the auspices of the Rand Mutual Assurance Company.[46] Through the compound and migratory system, the mining companies played a much larger role in the African miners' lives than the non-Africans. Again, the Corner House group attempted to lead the industry in health practices through its appointment of A.J. Orenstein as group medical officer. Because of the apparently high fixed costs this centralization of health and safety initiatives met resistance from within the group and only gradually did other groups emulate it. Bringing in the techniques Gorgas utilized in Panama, Orenstein's improvements in African miner living and working conditions confronted social and economic resistance on the Witwatersrand.[47]

In prevention of accidents on the job, COMSA led most of the initiatives during this period. The RMAC oversaw a Mine Safety committee,[48] which was established in 1913 and in 1915, COMSA began publishing a safety magazine, *The Reef*, in order to diffuse effective safety practices across the mines and miners of the Witwatersrand. COMSA was not alone in this regard and again the Corner House group made an important contribution to miner safety through its establishment of a Rescue Brigade in 1924. This general increase in safety was necessitated because of the rising hazards of work underground.

While actively adopting and refining non-local technologies to the local environment, in alleviating occupational health hazards, Witwatersrand mines were often at the forefront of international innovation. Herein, the influence of the socio-economic environment on the path of innovation is demonstrated through the direction African health initiatives followed. Nonetheless, this period saw important advances in alleviating occupational health hazards. Table 8.5 lists some important dates in development of these solutions to occupational health hazards on the Witwatersrand mines.

8.2.4 Subsequent Technological Evolution

As with the previous case these innovations were enduring. Substantial refinements in organization and technologies followed, but the basic stoping operations endured into the 1980s. These techniques built as they were around *de jure* racial occupational mobility, restricted utilization of the workforce and impeded the skills development of Africans through forced migration.[49] Thus, in the 1990s increased utilization of the entire mine workforce occurred. With depths approaching four kilometers beneath the surface, it should come as no surprise that there is also increased research into innovative equipment for rock-breaking. At depths such as these, efficiency in an individual's time spent underground is critical and the technical challenges to

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46 For a history of the Rand Mutual Assurance Company, see Lang (1986 p. 51; p. 197; p. 459).

47 Where the French had failed, Gorgas had a major role in making the U.S. digging of the Panama Canal a success. Under Gorgas, the mortality rate from all diseases dropped from 40 per 1,000 in 1906 to 6 per 1,000 in 1912 (*Cartwright,* 1971, p. 28).

48 RMAC was a pioneering workers compensation cooperative. See Chapter Seven, Section 7.2.4 for details.

49 It is important to reiterate that the segregated Taylorism promoted under scientific-management cut off a majority of its workforce's knowledge from organizational learning. Leger (1990) showed this caused increasing rock-burst dangers in stoping. Early practitioners also seemed aware of this inherent safety danger (Hildick-Smith, 1941, p. 918).

economic operations numerous. Again, solutions are sought from the three dimensions analyzed in this case, but in a very different context.

8.3 CONCLUSION

Transformation of stoping practices required the simultaneous development of several distinct technologies. The high interconnected nature of these technologies required a significant degree of coordination. Research collaboration appears to have played a significant role, but a different one from that in the case of cyanide based extraction. A recurrent feature appears to be cooperative efforts under COMSA and the collective diffusion of research from the Corner House group. The next chapter looks at these cooperative research efforts from our theoretical perspectives. Through them, the competitive dynamic that these cooperative research efforts played is analyzed.

Chapter Nine:
An Analysis of Research Collaboration in Stoping Practices

9.1 INTRODUCTION

This case describes the role of collaborative research in the evolution of three distinct, but complementary, technologies. Those technologies fundamentally transformed stoping practices and ensured the viable mining of Witwatersrand gold deposits for decades. While utilizing the open community of local mining and metallurgical practitioners, research collaboration was directed by a prominent mining-finance group acting as a cooperative research organization. As with the previous case, the structure of collaborative research is reviewed before turning to an analysis of causal conditions and effects.

9.2 STRUCTURAL FACTORS

This section examines changes and differences in the contextual conditions, beginning with a review of the technologies that transformed stoping practices. Attention then turns to the market structure and dynamics faced by producers. Next, it appraises the socio-political environment and principle social groups involved in production. Reviewing the sociology of groups engaged in production provides an indication of the moral economy governing production as well as the intra-organizational structure of production. Discussion then turns to the organizational structure of the Witwatersrand gold industry. The sector's system of innovation that developed these technologies forms the final component in this discussion of the contextual conditions. A summary of the relationship between components described in this narrative and structural components and relationships in the theoretical models concludes this section, in parallel with Chapter Seven.

9.2.1 The Technologies

Chapter Eight described the three complementary technologies that transformed underground production and ensured mining of the Witwatersrand was viable for decades. These technologies were rock drills and their associated equipment, a new organization of stoping labor, and improvement to the occupational environment. Together these technologies define the *Innovative Object* and *Public-Collective Good* in the Distributed Innovation and Collective Action approaches respectively.

The hammer-type "Leyner" drill design was a radical product innovation with two fundamental advantages over the alternative piston drill design. First, it was smaller and lighter making it easier to operate on the narrow stopes of the Witwatersrand. Second, it utilized hollow steel that could be constantly flushed with water, assisting in controlling dust, which was the major occupational health hazard of this period. Hence, when the patents protecting the "Leyner" hammer drill's innovative steel and drill design expired in 1914 an economical rock drill was at last available for stoping on the Witwatersrand. Technological change in an industry is not solely the result of radical innovations. Incremental innovations in products and processes can be even more significant, though less obvious, a driver of technological change.[1] Before rock drills could be adopted for stoping several incremental product and process innovations were required to the basic imported hammer drill design. Specifically, innovations were required in drill design, ancillary drill equipment as well as in drill maintenance and logistical practices. These were

[1] See Barañano (2003), Townsend (1976), and Hollander (1965).

needed because of the unprecedented scale and industrialized nature of Witwatersrand gold production.

Innovations in the organization of the stoping labor force can be divided into two eras. The first period, from 1903 to 1922, was directed at the removal of traditional miners' skills from stoping. The second period, from 1923 to 1933, concentrated on extracting efficiency in stoping production from African miners under perpetuated occupational mobility restrictions.

Stoping in general, but particularly with rock-drills, engendered considerable health hazards for the work force. Initially, political and economic feasibility of rock drills required a reduction in the high incidence of miners' phthisis. As progress was made here, large-scale stoping at increasing depths became possible. Additional health hazards became prevalent as stoping went deeper underground, most significant among these were tuberculosis and heat stroke. Incremental innovations to rock-drill design, ventilation, blasting practices, acclimatization and improvements to above ground living conditions all contributed to an alleviation of the primary occupational health hazards during this era.

The mining companies that led the Witwatersrand in addressing these occupational health hazards through innovations in equipment, living conditions and the underground environment predominately treated their innovations as public goods. A similar pattern occurred in the development of the other technologies. In both the first and second eras of labor force reorganization, collective diffusion and comparison of stoping practices was important to the development and refinement of a reorganization of the stoping labor force. Training of Afrikaner and African workers was also undertaken collectively, as was the establishment of a monopoly in recruitment of African workers. Collaborative structures were also critical drivers in the development of hole locators, drill design refinements, operating and maintenance practices, as well as steel treatment and sharpening procedures.

9.2.2 <u>The Product Market</u>

Throughout this period, Witwatersrand gold production remained focused on the international market. The Witwatersrand gold fields took an increasingly dominant role in the international supply of newly mined gold, which continued to be bought at a fixed price by the Bank of England. Cost pressures associated with that market structure appear to have contributed the final impetus for the Mining Professional community to push forward with the removal of artisanal skills from stoping.[2]

Table 9.1 reports the average nominal and real price of gold. Between 1903 to1932, the Bank of England fixed the international price of gold at £4.25 per troy ounce. Inflation caused by rising prices during World War One as well as rising costs from African labor shortages and White wage gains reduced the real price of gold per troy ounce from £3.97 in 1911 to £2.65 in 1919. Subsequently, a period of general deflation between 1920 and 1933 supported a rise in the real price of gold. That deflationary rise was augmented by the gold premium until 1924 and then South Africa's abandonment of the international gold standard late in 1932.

[2] For more on the role the price of gold played in the transformation of stoping. See Chapter 8, Section 8.2.2

Table 9.1 Witwatersrand Gold Mining Statistics 1903-1933[3]

	1903	**1904**	**1905**	**1906**	**1907**	**1908**	**1909**	**1910**
Gold Output (Kgs)	92,422	117,291	152,665	180,187	200,685	219,500	226,957	234,252
Avg Price (£)	4.25	4.25	4.25	4.25	4.25	4.25	4.25	4.25
Real Price (£)	N/A	N/A	N/A	N/A	N/A	N/A	N/A	4.25
	1911	**1912**	**1913**	**1914**	**1915**	**1916**	**1917**	**1918**
Gold Output (Kgs)	256,642	283,315	273,671	261,147	282,930	289,168	280,503	261,841
Avg Price (£)	4.25	4.25	4.25	4.25	4.25	4.25	4.25	4.25
Real Price (£)	3.97	3.84	3.80	3.83	3.62	3.43	3.13	2.93
	1919	**1920**	**1921**	**1922**	**1923**	**1924**	**1925**	**1926**
Gold Output (Kgs)	259,143	253,756	252,831	218,031	284,568	297,817	298,519	309,628
Avg Price (£)	4.25	5.60	5.31	4.62	4.55	4.68	4.25	4.25
Real Price (£)	2.65	2.86	2.95	3.08	3.12	3.17	2.88	2.93
	1927	**1928**	**1929**	**1930**	**1931**	**1932**	**1933**	
Gold Output (Kgs)	314,845	322,054	323,860	333,316	338,337	359,511	342,565	
Avg Price (£)	4.25	4.25	4.25	4.25	4.25	4.25	6.24	
Real Price (£)	2.91	2.91	2.92	3.05	3.15	3.26	4.95	

Note: N/A = Not Available. Prices are estimated for the years 1920-24 and 1933. Source: COMSA and Stats SA, compiled by author.

Table 9.1 also reports annual gold output from the Witwatersrand. These statistics show output rising until the labor unrest of 1913 and 1914. Output again rose in 1915 and 1916, but World War One and associated African labor shortages contributed a continual decrease in output between 1917 and 1922. That declining output was central to the 'profitability crisis' in the industry that propelled the first stage of stoping labor force reorganization in 1922. The 1922 reorganization replaced traditional skilled mine labor and was a major factor in the continuous rise in output between 1923 and 1932 despite fluctuations in the real and nominal price of gold.

Figure 9.1 South African and International Gold Production 1903-1933

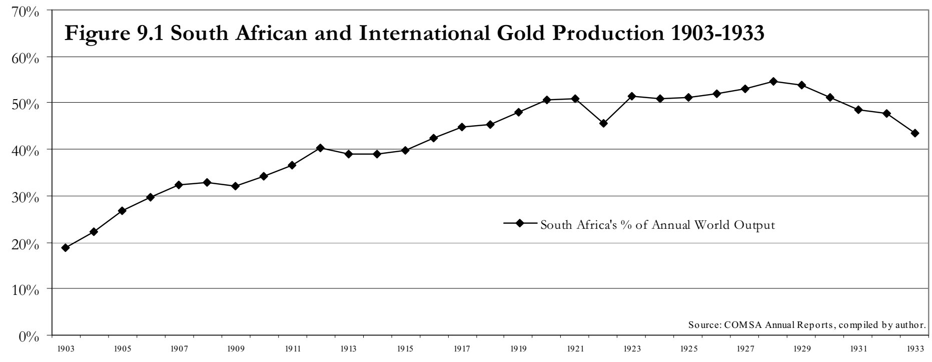


Figure 9.1 clearly illustrates the international significance of Witwatersrand gold production. Prior to a sharp rise in international gold production following the global financial and economic crisis in the early 1930s, South Africa accounted for well over half of the world's annual output of newly minted gold. In this period South Africa's gold production was vital to the international monetary system through its support of the pound-Sterling and the gold standard. South Africa

[3] During this period, 1903 to 1933 the South African Rand was pegged to the Pound Sterling at 2Rand per 1£. The real price is adjusted for inflation using the retail price index 1910-1930 and the consumer price index 1931-1933 (Union Stats, 1960). Selling prices were estimated, for the years indicated, from gold sales reported by COMSA members.

used its gold production to exert its economic independence from Great Britain, establishing a mint in 1919, a local refinery in 1920 and its own reserve bank in 1921 (Ally, 1994).

9.2.3 The Social Structure of Production

This section begins with a review of the agents directly engaged in Witwatersrand gold mining. Political authority also influences the social structure of production. Consequently, this section also describes the evolution of the group's respective political authority and its role influencing their authority over the production process. The final component of this section considers the nature of intra- and inter-group social capital and how that social capital shaped the structure of production.

Between 1903 and 1933, Africans, Afrikaners, European Miners, and Mining Professionals were the four primary groups directly involved in the production of gold on the Witwatersrand. With exception of Afrikaners these groups were the same as those in the previous case. These groups form the *Human Resources* in production from the Industrial District approach.

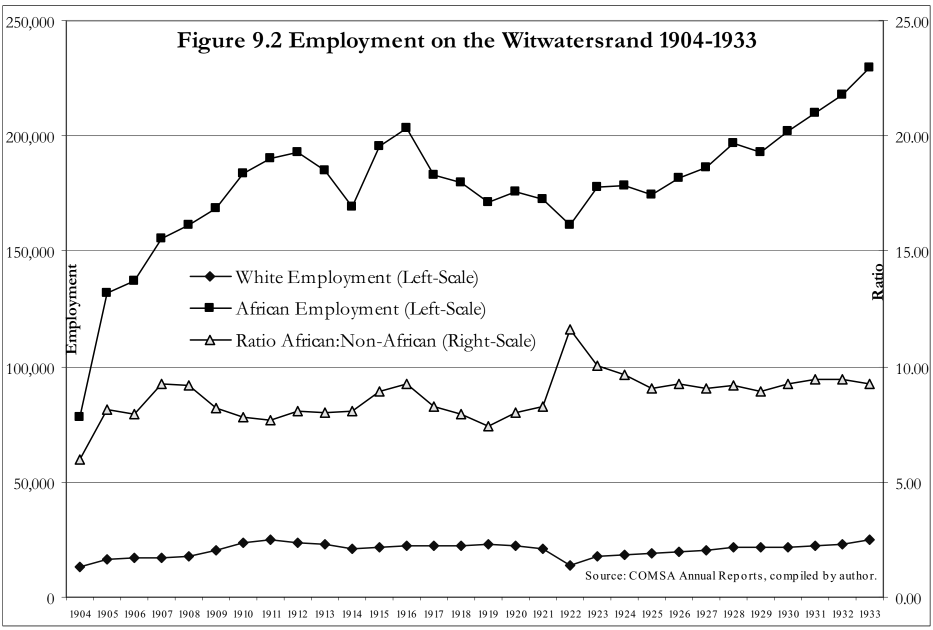


Figure 9.2 shows annual average employment of Africans and Whites on the Witwatersrand goldmines.[4] The acute shortage of African laborers immediately after the Second Anglo-Boer War is seen clearly in the African employment statistics. Between 1905 and 1933, the total labor force on the goldmines grew at a compound annual rate of 2.06%, increasing from 148,000 to 255,000. Figure 9.2 also reports the ratio of African to White employees. That ratio reveals the change in the Witwatersrand workforce associated with the re-organization of labor on the

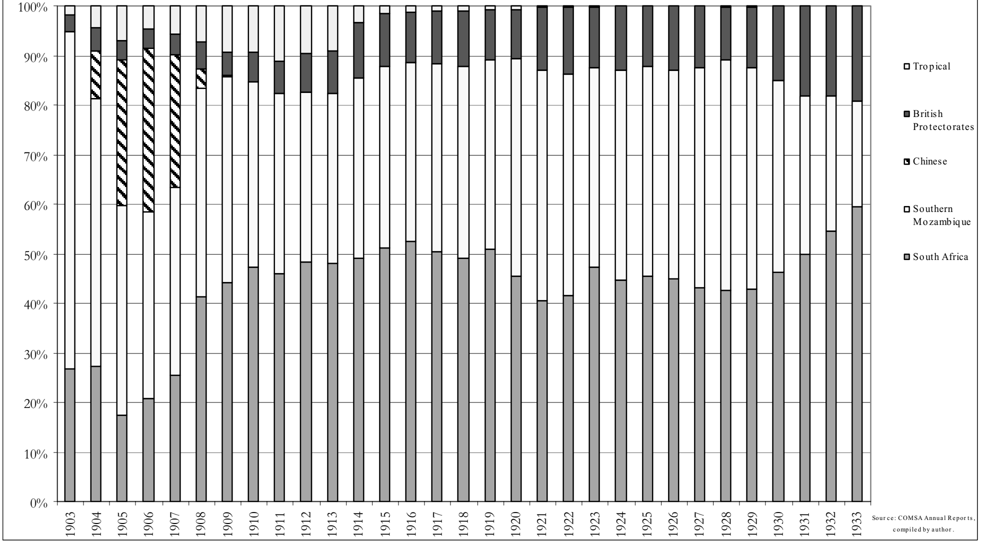
[4] The terms Africans and Whites are used in line with dominate racial classifications of this era and their associated political authority. Hence, African employment also includes Chinese nationals who worked on the Witwatersrand between 1904 and 1908. Similarly, Whites consist of Afrikaners, European Miners and Mining Professionals.

stopes after the 1922 Strike. Before 1922, the average ratio of African to White employment equaled 8.13 to 1, but after 1922, the ratio of African to White employment rose to 9.32 to 1.

Once again Mining Professionals were the primary agents involved in collaborative research, although in this case it was the mining engineers, mine managers and mining health care practitioners who formed the central communities transforming stoping practices. Continued development of the industry had brought increasing numbers of Mining Professionals to the Witwatersrand and greater specialization. One indication of this was the addition of mining health care practitioners to the mining financiers, mine managers, metallurgists and mining engineers that composed the class of Mining Professionals. The mining health care practitioners were primarily mine medical officers and associated professionals that led the research and development of technologies to alleviate the occupational health hazards on the Witwatersrand.[5]

Afrikaners were an entirely new group directly involved in Witwatersrand production during this period. They were largely given work on the mines by the Mining Professionals to facilitate replacement of European Miners. These Afrikaners were part of a predominantly dispossessed, impoverished, unskilled and urbanized division of the larger Afrikaner population.

Figure 9.3 African and Chinese Employment Composition 1903-1933



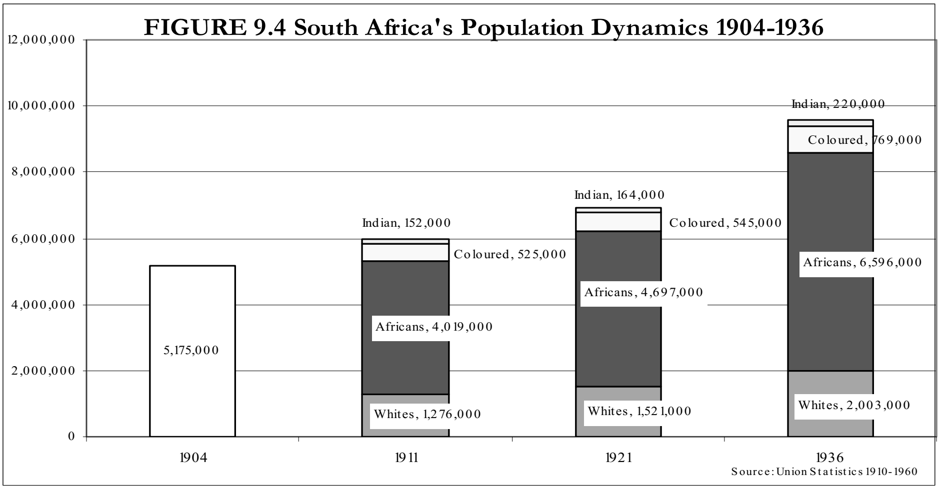
The best statistical proxy for European Miners during this era is the White workforce born outside South Africa. Katz (1994) estimated that 95% of the White workforce was born outside South African in 1905 (pp. 64-65). Table 8.2 showed that the 1907 Strike led to an outflow of over 13% of European Miners in that year alone.[6] Yudelman (1984) reports that between 1910 and 1935, the White workforce born outside South Africa declined from 72.8% to 24.9%

[5] See Chapter Seven, Section 7.2.3 for further descriptions of mining financiers, metallurgists, mine managers and mine engineers.

[6] Because of a significant number of Mining Professionals during this era were born outside South Africa, the estimated 13% is surely smaller than the actual percentage of European miners that left underground operations following the 1907 strike.

(p.132). [7] Hence, between 1903 and 1933 the White labor force, excluding Mining Professionals, transformed from being almost entirely expatriate to being local.

Figure 9.3 indicates the structure of the African labor force between 1903 and 1933. In order for the reorganization of underground operations to succeed, the low-paid African labor force had to be stabilized. That was accomplished through increased intra-industry coordination of African labor recruitment as well as exertion of the State's political authority. As a result, the composition of the African labor force changed significantly during this period. Notably the number of Africans from South Africa working on the mines rose significantly. Among non-South Africans, Southern Mozambicans continued to be important despite declining as political tensions led to the 1928 Mozambique convention decreasing recruitment. Further changes in the African labor force were also required because recruitment of Africans from tropical regions was banned after 1913.[8] To compensate for these reduced recruitment areas, the Mining Professionals increased recruitment from the British Protectorates.[9] Thereby, the changes in the African labor force reflected what effectively became a cradle to grave system of employment on the mines.



While both African and White workforces underwent considerable changes in composition during this era, these experiences were very different in nature. Fundamentally separating these two groups was the Whites' franchise and their refusal to grant it to the Africans. Figure 9.4 illustrates South Africa's population dynamics in this period with an annual population growth rate of 1.93%. Between 1911 and 1936,[10] the racial composition of the population was reasonably steady. A small number of non-Whites were able to vote during this period, but Whites, who

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[7] Again, the fact that many Mining Professional were also expatriates means that the actual percentage of expatriates involved in underground production was far less than a quarter.

[8] The tropical region is north of 22º South and includes northern Mozambique and Northern Botswana as well as Zimbabwe, Zambia and Malawi.

[9] The British Protectorates are the modern nations of Botswana, Lesotho, and Swaziland. Between 1903 and 1933, Africans working on the mines from the British Protectorates rose from 3% of the total African labor force to 19%. Lesotho was the primary source, accounting for 52% of labor from the British Protectorates in 1903 and 76% of British Protectorate labor in 1933.

[10] Racial population data is not available for the 1904 Census.

comprised less than 20% of the nation's population, predominated the electorate.[11] Given this huge difference in socio-political power nationally, it is not surprising that exertion of the Mining Professional community's authority over the Witwatersrand gold mines followed a similar pattern

Political authority and political geography of an area defines the *Socio-territorial Entity* in the Industrial Districts approach. Conclusion of the Second Anglo-Boer War in 1902 consolidated political authority across South Africa. The State had clear political authority over the Witwatersrand, but a fundamental dependence on its tax revenue and operation. Therefore, exertion of political authority balanced promoting the interests of its constituency with ensuring viability of the Witwatersrand gold industry. Labor and industrial policies were two areas of active intervention by the State. In its labor policies the State sought to ensure the mining industry had the necessary provision of low-paid African workers, while expanding employment opportunities for its White constituency. Similarly, in industrial policy the State sought to accommodate the Witwatersrand's interests and promote broader industrialization.

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TABLE 9.2 Important Socio-Political Dates in South Africa: 1903 - 1933

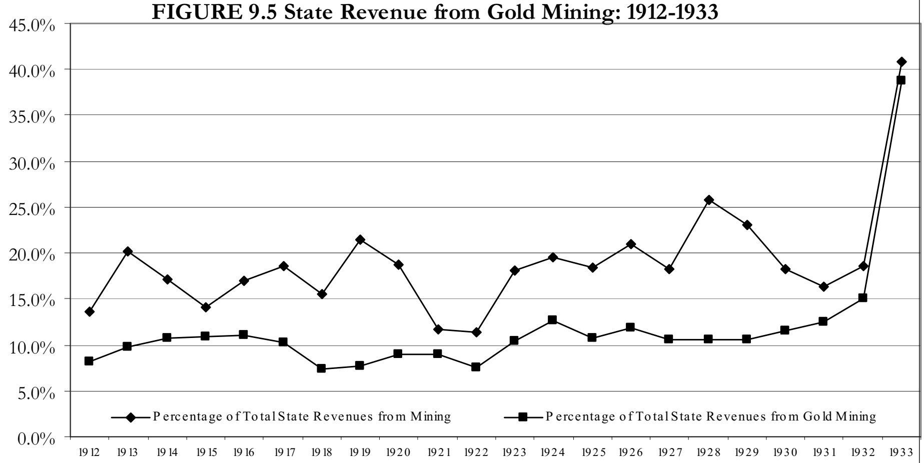
1904	Het Volk Party established in Transvaal
1905	Orangia Unie Party established in OFS
1907	L. Botha Prime Minister Transvaal Colony
1908	Railway Regulation Act
	Precious and Base Metals Act
1909	Industrial Disputes Prevention Act
1910	Union of South Africa formed
	L. Botha first South African Prime Minister
1911	Mines & Works Act
	Native Labour Regulation Act
1913	Native Land Act
1919	J. C. Smuts elected Prime Minister
1920	South African Party absorbs Unionist Party
1922	Electricity Act
1923	Natives (Urban Areas) Act
1924	J.B.M. Hertzog elected Prime Minister
	Labour Party and National Party form Pact government
1924	Industrial Conciliation Act
1925	Great Britain returns to pre-war parity with gold standard
	Customs and Tariff Act
	Wage Act
1926	Mines & Work Amendment Act
1928	Iron and Steel Industry Act
	Mozambique Convention
1929	Amendment to Native Administration Act of 1927
1931	Great Britain abandons gold standard (21 September)
1932	South Africa abandons gold standard (27 December)
1933	Fusion government between South African Party and National Party formed

[11] From 1906 all White males could vote and from 1930 women were given the franchise.

Table 9.2 highlights important socio-political dates in South Africa. Following the Second Anglo-Boer War, fractured British hegemony faced a defeated, but mobilized, Afrikaner population.[12] Thus, in 1910 an Afrikaner coalition between the Unionist party and the South African Party formed the first national government. The Unionist and South African Party coalition ruled until 1924 when discontent over the State's role in the 1922 Strike led to a coalition, between the Afrikaner National Party and the Labour Party, forming the 'PACT' government. In 1933, delays in the abandonment of the gold standard brought down the PACT government.[13] However, an alliance with the South African Party kept the National Party in power as a 'Fusion Government' until 1939. Despite these changes a remarkable consistency characterized State policies toward the Witwatersrand gold industry between 1903 and 1933.

Figure 9.5 illustrates the direct significance of gold mining to State revenues during this period. Indirectly, the Witwatersrand's demand for goods and service was also a primary engine of the economy. The Precious and Base Metals Act of 1908, popularly known as the 'Gold Law' further deepened the State's stake in the industry's fortunes. Under the Gold Law, the State leased exclusive rights to mine on land proclaimed public diggings. Governing mining rights in South Africa until 1967, the State effectively became a silent partner in the mines. Given the State's stakes, its consistency in accommodating the Witwatersrand's interests is not difficult to understand.

FIGURE 9.5 State Revenue from Gold Mining: 1912-1933



Source: COMSA Annual Reports, compiled by author. Note: The reported revenues are for the Year Ended 31 March i.e. 1912 records revenues between 1 April 1912 and 31 March 1913.

One of the most important areas of intervention by the State was its exertion of political authority to secure a stable supply of low paid African labor for the mines. The Native Regulation Act of 1911 regulated recruitment of African contract labor, but made strike action

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[12] This is reflected in the 1904 formation of the Het Volk Party by Afrikaners in the Transvaal Colony and the 1905 formation of the Orangia Unie Party by Afrikaners in the Orange River Colony.

[13] Great Britain returned to the gold standard in 1925 at pre-World War One parity. By September 1931, economic contraction led Great Britain to abandon the gold standard. However, in an effort to exert South African monetary independence Barry Hertzog, the National Party leader and South African Prime Minister, stubbornly refused to follow. Retaining the gold standard capped the price of gold and made South African exports uncompetitive. Thus, domestic pressure from mining and agriculture mounted until late in December 1932 when South Africa finally left the gold standard (Davenport and Saunders, 2000, p. 317-318).

by African workers on the mines a crime despite their exclusion from arbitration mechanisms.[14] The Native Land Act of 1913 initiated territorial separation of races, thereby facilitating the domestic supply of Africans for contract work in the mineral and agricultural industries.[15] White authoritarian control over the African population was extended with The Natives Act of 1923, popularly known as the Urban Areas Act, which required Africans to carry passes in urban 'white' areas. The Native Land Amendment Act of 1926 reduced the areas in which Africans were allowed to own land. The Native Administration Act of 1927 authorized removal and detention of Africans undertaking inflammatory action without judicial review. Then in 1929 amendment to the Native Administration Act extended the domestic recruitment pool to all non-urban areas across South Africa, thereby subjecting all African laborers to pass laws and movement control. In there entirety these acts went a long way in assisting the Witwatersrand to secure a stable supply of low paid African labor, which critical to the fundamental transformation of stoping practices.[16]

Differences in the shared identities and social capital of the groups directly involved in production on the Witwatersrand gold mines remained marked during this period. While Mining Professionals continued to foster a common identity and interests, the new Afrikaner community similarly developed a shared identity in production on the Witwatersrand that they began to use to advance their own group interests. In contrast, divisions within the European Mining community played an important role in their eventually redundancy in underground production on the Witwatersrand. Similarly, divisions continued to characterize the African community, but notable progress was seen in developing common interests compared to the previous period.

Social capital within the Mining Professional community was again key to research collaboration. However, in this period their social capital was also more important in facilitating cooperation and coordination in other aspects of production. Even with the additional division of mining health care practitioners and a new generation of mining engineers, financiers, managers, and metallurgists, Mining Professionals' cohesion remained the strongest of the groups involved in the Witwatersrand.

Social institutions, such as the Victorian all male clubs, continued to provide important opportunities for networking and informal business co-ordination. As in the previous period, many significant events on the Witwatersrand directly or indirectly involved the famous Rand Club.[17] Kimberley's diamond mining again played an important role in the connectivity of Witwatersrand's gold mining companies. Specifically among mining financiers social capital based on familial connections and the Jewish religion remained critical for inter-organizational cooperation. Lastly, the English Masonic lodges were another significant social institution for Mining Professionals on the Witwatersrand during this period.

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[14] The Master and Servants Laws from the 19th Century established an important precedent in this regard making the breach of contract by an African worker a criminal offense (Johnstone, 1976, p. 35).

[15] The Land Act, prevented Africans from purchasing land in White areas and relegated the majority African population to areas demarcated 'Native Reserves' that accounted for less than 13% of land in South Africa. See: Bundy (1988).

[16] Another important area of intervention by the State was facilitating co-optation of the White workforce. In this, the Industrial Conciliation Act of 1924 was critical. It established a system of racial labor arbitration boards and institutionalized industrial councils with binding authority over industrial relations. Thereby, organized labor was co-opted into a structure where it surrendered its political and economic authority to strike in exchange for employers surrendering their power for mass worker lock-outs, but employers retained the right to informally alter individual employee's conditions of service. See: Yudelman (1984, p. 208).

[17] The most notable examples of this involvement were attacks on the Rand Club by striking White miners in both 1913 and 1922.

The Mining Professional community used its social capital and cohesion to deepen its ideological influence over the Witwatersrand through further control of the local media.[18] However, some internal tensions required an evolution in the Mining Professional community's South African–British identity. Bozzoli (1981) describes how this tension, originating between the British Imperialist ideology and rising 'South Africanism', evolved into the Mining Professional community's co-opting national mercantile interests with their own. Hence, the Mining Professional community during this period continued to refine and exert their hegemony over the other communities involved in Witwatersrand gold production.

Authority of the Mining Professional community is clearly reflected in their ability to shape debates and history of the industry itself. Katz (1994) convincingly argues that the Mining Professional community distorted the dangers of silicosis to miners while it sought to fundamentally transform stoping practices and ensure viable mining for the near future. As a result, traditional accounts of the disease portray ignorance of its existence until after the Second Anglo-Boer war and then downplayed the fundamental understanding of the disease's causes and effects. Katz argues that little was done by the Mining Professional community because of the priority they gave to placing industrial profitability on a sounder footing.[19] Nonetheless, they did have to consider the political authority of the other White communities and this led to the adoption of industrial policies shaped mutually between the State, White labor, and the Mining Professional community.

The European Mining community did not change significantly from the previous period, but persistent internal divisions would prove critical to many of them becoming redundant on the Witwatersrand's stopes. Social institutions among the European Mining community remained less extensive than those of the Mining Professionals. Most of the European Miners continued to live out of hostels or boarding houses while their families remained in Britain.[20] However, their trade unionist backgrounds became apparent in the establishment of the Labour Party following the 1907 Strike.[21]

Division between artisans and skilled miners in the European Mining community eroded social capital and cohesion in this period. Illustrating this division was the artisans' refusal to join the skilled miners in during the 1907 Strike. The higher level of the artisans' skills facilitated this division since it was relatively easy for them to find employment in other industries. Further perpetuating this division within the European Mining community was the Mining Professionals propaganda, which portrayed the skilled miners as "privileged labourers who did very little work" (Katz, 1994, p. 69).

Initially, the European Mining community's skills gave them authority in day to day operations on the Witwatersrand gold mines. That authority was usurped by the complementary technologies the Mining Professional community developed to transform stoping practices. As a result, by 1933 Afrikaners had assumed the secondary position of authority from the European Mining community.

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[18] The most noticeable example being Abe Baily's (SA Gold Mines) purchase of the Rand Daily Mail in 1902 and the Sunday Times in 1906.

[19] Orenstein *et al.* (1921) gives a good perspective on the orthodox history of Miners' Phthisis.

[20] European Miners were from highly localized areas in Britain. See Chapter Seven, Section 7.2.3 for details.

[21] The Labour Party in coalition with the National Party ruled South Africa between 1924 and 1933 as the PACT government.

In the description of the industry's workforce, we noted the marked increase in Afrikaners. That influx of Afrikaners corresponded with a crisis in their rural existence that led to the urban percentage of the Afrikaner populace rise from 10% to 50% between 1900 and 1936 (Gelderblom and Kok, 1994, p. 74).[22] Being primarily rural agriculturalists that were part of an initial urban migration, the Afrikaner community on the Witwatersrand lacked industrial traditions and complementary institutions.[23]

While initially threatened by the greater skills of the European Miner and the less costly Africans, the Afrikaner community on the Witwatersrand, with its political authority proved critical to the Mining Professionals' transformation of stoping practices. Hence, with the technological change in stoping practices, the Afrikaner community increased its presence on the Witwatersrand both quantitatively and qualitatively. This elevated position came as the Mining Professionals technologically subverted the European Miners and all the White communities relegated the African community to the lowest ranks of the Witwatersrand's productive authority.

The migrant labor system brought African workers from rural areas with distinct cultural and linguistic backgrounds. These varied heritages and the transient nature of their engagement on the mines structurally impeded their developing social capital and cohesion. Thus, internal divisions and exclusion from political authority combined to place the African community at the bottom of the Witwatersrand hierarchy of production. In addition, structural control exerted by the Mining Professionals allowed them use the African community to dilute the White communities' resistance to the transformation of stoping practices.

Moodie (1994) identifies ethnic identities, compound room organizations, and underground work teams as primary social institutions of the African community on the Witwatersrand. Ethnic identities perpetuated differences within the African communities, but also provided communication linkages to send and receive news from home. In addition, expressions of ethnic culture through dance, poetry and song were an important means of identity translation, mobilization and self-reflection in the difficult urban working environment of the Witwatersrand.[24] The compound room was typically constituted from members of the same ethnic group and through its "Isibonda", representative, the room had a socially rooted institution expressing the interests of the African workers on a highly disaggregated level. Although partially divided along ethnic lines, underground working gangs presented important opportunities to forge inter-ethnic social linkages. Drinking was another significant social institution amongst the African community on the mines. While initially used as a means to control and labor recruitment, by 1902 excessive drinking was adversely affecting productivity on the mines. Despite attempts to constrain consumption, use (abuse) continued to characterize the lives of the single male African miners (Baker, 1992).

While ethnicity created some natural fractures, Mining Professionals perpetuated discord within the African community. One tool in this regard was the appointment of peers to supervisory positions in the compounds, Indunas, and underground, Boss Boys (Moodie, 1994, p. 19). Another tool was the ethnic segregation of African housing compounds, which provided a

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[22] Gelderblom and Kok (1994) cite five factors contributing to this urbanization: 1) Closing of the frontier, which with rapid population growth put increasing pressure on existing land 2) Roman-Dutch inheritance leading to uneconomic subdivisions of the land 3) Rinderpest epidemics which devastated cattle stocks 4) Damage from the British scorched earth policy during the Second Anglo-Boer War and 5) The drought of 1896 (p. 75).

[23] In this initial period, Afrikaners on the mines largely identified with the European Miners' Labour Party (O'Meara, 1978, p. 170).

[24] See Coplan (1994), Coplan (1986) and Tracy (1952) for further discussion of these expressions of ethnic identity.

structural basis for faction fighting within the African community (Moodie, 1992, p. 586). Lastly, the ethnic segregation of work assignments added further fuel for factional fighting.[25]

Denied political representation, the African community was brutally suppressed and manipulated. Besides real and manufactured internal conflicts, the African community faced racial occupational mobility restrictions, a legally sanctioned African labor recruitment monopoly, explicit collusion in African wage determination, and severe physical racial mobility restriction. Thus, it is not surprising that relative to the other groups directly involved in production there was very little mobilization by Africans during this period.[26]

9.2.4 The Organizational Structure of Industry[27]

Witwatersrand gold mining remained the paramount industry across Southern African during this period. However, increasingly diverse economic enterprises began to transform the context in which gold mining on the Witwatersrand occurred. This section reviews important changes to the industry's organizational structure. It thereby describes the structural component of *Firms and Institutions* in the Industrial District approach. Simultaneously, we consider how that organizational structure of production hindered or facilitated collaboration. Thus, the *Production System* and *Product Provision* from the Industrial District and Distributed Innovation approaches are defined in turn.

There are several significant changes to the organizational structure of the industry from the previous case. Among developments was establishment of a 'group system' of production that drew on all the mining-finance groups to enhance the industry's competitiveness. Another change was the emergence of the Corner House, one of the mining-finance groups, leading the industry in cooperatively addressing a spectrum of challenges that confronted the industry.[28] Those features are reviewed below within discussion of the internal and external structure of the industry between 1903 and 1933.

Mining-finance groups existed from the early days of Witwatersrand gold mining. With increasing consolidation and removal of largely speculative mining-finance groups this period saw the emergence of a group system that persisted until the last decades of the 20th century. In a 1927 speech Ernest Oppenheimer detailed essential characteristics of the group system:

> "The advantage of the system are manifold, the financing of the individual mining enterprises is facilitated thereby, the parent company provides the link between the various producing companies and promotes co-operation on matters of common interest, and perhaps most important, by engaging a staff of highly skilled experts, is able to give valuable technical assistance. In this latter regard I should like to explain that this system is specially suitable in circumstances such as obtain on the Rand, and which it would appear are likely to develop in Northern Rhodesia [Zambia]. I refer to the conduct of operations on a number of separate properties all of which, however, are located in one district and have many problems in common. In such circumstances the existence of a central organization for the supply of expert advice in various matters is obviously of incalculable value. It ensures to the individual companies great economies compared with the cost to which they would be put if each of them were called upon to maintain an equally complete staff.

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[25] See: Guy and Thabane (1987) and Guy and Thabane (1988).

[26] The first African union, the African Mine Workers Union was eventually formed in 1941.

[27] Appendix Five details the names and a brief history of the principal mining-finance groups between 1903 and 1933.

[28] As we will see in the next section, this promotion of cooperation by the Corner House included it acting as an effective cooperative research organization in research collaboration around the complementary technologies that transformed stoping practices.

> In more settled communities, or in respect of districts situated within close reach of more fully developed countries, it might be feasible to rely on the temporary engagement of someone competent to deal with a matter calling for specialized knowledge, but on the Rand, at any rate in the early days, and in [Zambia] today, it would obviously be impossible to rely on this means of obtaining the necessary advice, because the time required to secure it would cause considerable delay in the progress of the work. A central organization makes for efficiency providing a channel through which full interchange of ideas regarding mining methods and information may generally pass; it facilitates co-operation in matters such as Native labor recruitment and negotiations with the authorities and in respect of essential services such as railway facilities and power supply".[29]

Generally, business groups, like the mining-finance groups, act as alternatives to financial markets and as forces of political authority (Granovetter, 1998, pp. 94-98). A significant capital position was common among mining companies during the 20th century because of uncertainties, a relatively long duration before return on investment, and the considerable scale of fixed investments needed to get a mine started. Development of the internal financial capacity of mining-finance groups marked an important dimension in the emergence of the group system during this period.[30]

Given COMSA's origins as an industry lobby, its continued role expressing explicit political authority for the group system was natural. However, COMSA developed beyond that role into a sort of cooperative for the group system, becoming thereby an important institution of production in its own right. COMSA's movement beyond lobbying largely evolved from its efforts before 1903 to establish an African labor recruitment monopoly and repeal the patents of the cyanide treatment process.

Besides operating the African labor recruitment monopoly COMSA gave other critical support to industry. Within a decade of the Second Anglo Boer War, COMSA began administering the RMAC which provided occupational insurance for mineworkers. COMSA also financed the building to house the SAIMR in 1912 and shared SAIMR's running costs with the Union Government.[31] In 1904, it established the Mine Medical Officer's Advisory Committee, which in 1921 became the more inclusive Mine Medical Officers' Association (MMOA).[32] In 1916, it expanded the Government Miners' Training Schools and in 1930 it established the Native Training Schools.[33] Lastly, COMSA established the important Technical Advisory Committee (TAC) in 1922.

COMSA's establishment of the TAC is particularly interesting because in general COMSA was not active in the mining industry's system of innovation during this period. An explanation for this apparent incongruence is the Corner House mining-finance group. The Corner House was COMSA's principal patron as the group's chairman noted: "The policy of the Chamber of Mines is, to all intents and purposes our policy. We represent the chief interest there and, if our representative takes a strong line, he can, I think, rely upon carrying his point".[34] Thus, as research collaboration in this case was effectively driven by the Corner House acting as a cooperative research organization it would not want to duplicate its own efforts within COMSA.

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[29] Quoted in Gregory (1962, pp. 98-99).

[30] After the revaluation of gold in 1932 this internal capacity allowed the mining-finance groups to float new mines internally, thereby significantly changing the risk profile of mining investments (Frankel, 1969).

[31] See Lang (1986, p.236).

[32] See Cartwright (1971, pp. 49-52).

[33] See Lang (1986, p. 245).

[34] The quote is contained in letter #158 reproduced in Fraser and Jeeves (1977, pp. 336 - 341).

Built on the Witwatersrand, the group system came to dominate the South African economy during the 20th century.[35] Benefits from cooperation and coordination were key to the large scale adoption of the group system. Development of the platinum sector during demonstrated some of these advantages. Prior to the 1925 discovery of the Bushveld Igneous Complex (BIC) in the northern Transvaal, platinum had been mined as a by-product of nickel in Canada and Russia (Wagner, 1929, p. 23). Much like the Witwatersrand gold deposits and the Kimberley diamond deposits, the BIC was unprecedented in its scale and nature. Thus, as on Kimberley and the Witwatersrand, original methods of extraction were developed within an open community of metallurgical practitioners.[36] Mining-finance groups from the Witwatersrand had rapidly established holdings and cross-holdings along the BIC. When the platinum price collapsed in 1927, the cooperative group system facilitated amalgamation of individual platinum mines as single operation that more readily realized operating economies.

COMSA's securing an inexpensive supply of politically disenfranchised African labor broadened the scope for cooperation. However, other factor inputs appear to have played a less significant role in contrast to the previous period. While infrastructure continued to be supplied by firms associated to the mining-finance groups, several investments built around the concessions policy were expropriated and placed under State management.[37]

TABLE 9.3 Important Dates in Southern Africa's Mining Industry: 1903 -1933

COAL MINING	
1907	Transvaal Coal Owners Association formed to facilitate cooperation in marketing coal
1909	Natal Coal Owners Association formed to facilitate cooperation in marketing coal
1917	The Chamber of Mines forms a Collieries Committee to facilitate cooperation in producing coal
1922	Coal Act establishes official grading system for export and bunkering coal
1920s	Post First World War consolidation of industry leads to improved mining methods being adopted
1920s	Artificial ventilation introduced across South Africa's coal mines
1931	Fuel Research and Coal Act asserts Rail Industry and State authority over South African collieries
1932	U.K. abandonment of the gold standard destroys Natal's trade in export coal
DIAMOND MINING	
1908	Discovery of diamonds in German South West Africa (Namibia)
1912	First inter-producer agreement signed between southern African diamond producers
1914	Tripartite agreement between SA producers, Diamond Régie, and Diamond Syndicate
1924	Old Diamond Syndicate broken-up because of Anglo American and A. Dunkelsbuhler's withdrawal
1925	New Diamond Syndicate formed under the direction of Ernest Oppenheimer
1926	Alluvial diamonds discovered at Port Nolloth, Namaqualand, Northern Cape
1926	Alluvial diamonds discovered in Lichtenburg region, North-West Province
1927	Large scale diamond deposits established in Alexander Bay area, Namaqualand, Northern Cape
SUNDRY MINING	
1906	Mesina copper mining commenced
1919	Namaqualand copper mining ceases, re-opens in 1940
1922	Manganese deposits discovered near Postmasburg, Northern Cape
1923	Corner House metallurgist presents paper showing occurrence of uranium in Rand gold tailings
1923	Platinum deposits in Waterburg district discovered
1924	Platinum deposits in Lydenburg and Rustenburg districts discovered
1924	Small scale chrome mining in Lydenburg district begins
1929	Systematic mining of Postmasburg manganese deposits begins
1920s	Systematic mining of Cape Blue Asbestos begins near Kuruman, Prieska and Griquatown, Northern Cape
1931	Merging of disparate mines under Rustenburg Platinum Mining Co. leads to systematic mining of platinum
1933	Thabazimbi iron mines begin operations

[35] See: Fine and Rustomjee (1996) for an analysis of the role played by the group system in the structural development of the South African economy during the 20th century.

[36] The Corner House (Rand Mines Laboratory) developed an early chlorination based extraction method. But, it was JCI's newly established Minerals Processing Laboratory that became the general method for the industry (Sander, 2000, p. 305).

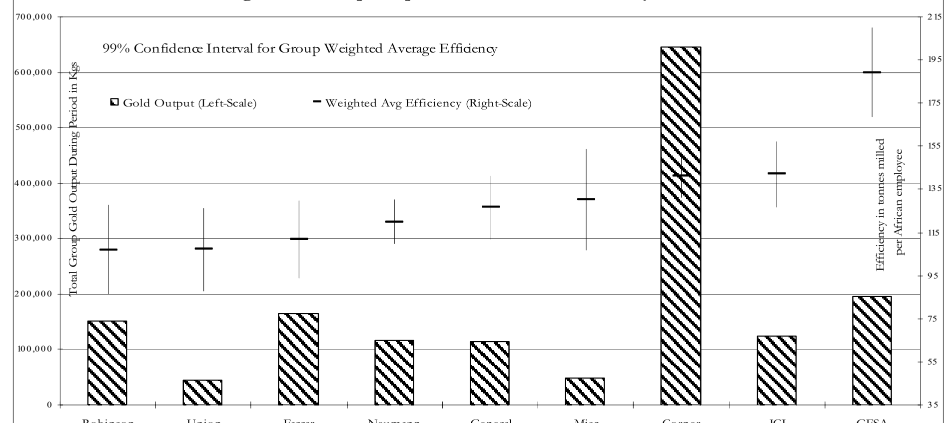
[37] The Johannesburg Waterworks became the Rand Water Board.

Table 9.3 is a summary of significant dates in southern African mining between 1903 and 1933. Development of many mineral deposits during this period drew on linkages with Witwatersrand mining-finance groups. Kimberley's diamond industry continued to hold important linkages with the Witwatersrand. However, discoveries of new diamond deposits destabilized the coordinated production of diamonds.[38] These additional deposits led to the establishment of a New Syndicate for the sale of diamonds in 1925 and transfer of control over DBMC in 1930.

On the Witwatersrand itself, the organizational structure changed as new deposits helped new mining-finance groups emerge and caused some older groups to lose a bit of their dominance. Between 1898 and 1911, the mines of the Central Rand accounted for 84% of the gold produced, with mines of the West Rand producing 10% and mines of the Far East Rand accounting for 6% (Gregory, 1962, p. 78).[39] Development of the Far East Rand took off in the late 1910s and early 1920s. In 1919, the Far East Rand accounted for 27% of tonnage milled and 58% of declared working profits. By 1924, the Far East Rand accounted for 37% of milled tonnage and 99.9% of declared profits. An important effect of Far East Rand growth was the rise of a new mining-finance group, the AAC that it facilitated.

AAC developed close productive ties with JCI that were facilitated by professional familiarity between the groups' leaders, Ernest Oppenheimer and Solly Joel.[40] The old guard of the group system, the Corner House and GFSA continued to diversify their investments. By 1918, GFSA had less than half of its investments in South Africa (Johnson, 1987, p. 40). Nonetheless, both GFSA and the Corner House still had prominent roles in the Witwatersrand gold mining industry.

Figure 9.6 Group Output and Excavation Efficiency 1908-1914



These mines account for 96% of Witwatersrand gold production in this period. Source: COMSA Annual Reports, compiled by author.

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[38] Among the more significant diamond deposits that began production during this period were the 1903 Premier Diamond mine north-east of Pretoria, the Belgium Congo deposits in 1907, the Namibian deposits around 1908, the Angolan deposits in the late 1910s, the Lichtenberg alluvial deposits of the North-West Province, South Africa, in 1926, and the Port Nolloth alluvial deposits of the Northern Cape Province, South Africa, in 1926.

[39] There is a map in Chapter Six, Map 6.2, which indicates the various goldfields along the Witwatersrand Basin.

[40] Joel and Oppenheimer led their firms into the Belgium Congo diamond fields, restructured the diamond syndicate in 1925 and installed a new leadership in DBMC in the early 1930s.

Given our present concern with the role research collaboration played in ensuring a viable stoping technique was introduced, productivity in excavation is a logical means through which to rank the mining-finance groups. Figure 9.6 reports these rankings between 1908 and 1914,[41] which is the only period in which suitable data is readily available. That figure shows GFSA, JCI and the Corner House to be the most efficient groups. Notably, those three groups were also leaders in promoting intra-industry cooperation and coordination. Figure 9.6 also reports the groups' size as measured by their cumulative output of gold during this period. In this regard the figure clearly shows the massive scale of Corner House operations compared to the other groups. There is also no apparent correlation between group size and excavating efficiency,[42] which indicates that economies of scale were not a significant determinant of productive efficiency.

9.2.5 <u>The System of Innovation</u>

This section examines development and diffusion of the three distinct, but complementary, technologies that fundamentally transformed stoping practices. It begins with a survey of the national system of innovation and its relationship to the sectoral system of innovation operating on the Witwatersrand. That survey describes *Innovation Provision* and the *Knowledge System* in the Distributed Innovation and Industrial District approaches. Focus then turns to the role of collaborative research in the technologies that transformed stoping practices, which defines the *Collective Supply Function* in the Collective Action approach.

The Witwatersrand gold mining industry again formed the majority of capacity in the South African national system of innovation during this period. Non-mining, domestic innovative capacity paralleled South Africa's industrialization experience between 1903 and 1933. Initial expansion occurred during World War One, but it was only later after World War Two that significant advance took place. Nevertheless, non-mining innovative capacity grew and some preliminary innovation policies were established. Table 9.4 lists dates in the development of the system of innovation, but it is missing the history of innovations associated with the adoption of foreign technologies. During this period chemical, electrical, and steel industries were established. Those industries utilized foreign technologies that required refinements for them to be commercially in the local environment. While the refinements were individually small, they represented a collectively large component of the national system of innovation.

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[41] The groups are ranked by their mine's average efficiency in tonnes milled per African employee during this period and weighted by each mines output.

[42] The adjusted R^2 equals zero.

TABLE 9.4 Some Scientific, Educational, and Professional Institutions and Societies in SA: 1903- 1933

1903	National Herbarium, Pretoria	1913	Botanical Society of South Africa
	South African Institute of Civil Engineers		National Botanical Gardens, Kirstenbosch
	Institute of Mine Surveyors of SA (IMSSA)*	1915	South African Sugar Association (SASA)*
	University of the Witwatersrand*	1916	Industrial Research Committee (IRC)
	*South African Medical Journal**		University of Ft. Hare*
	*South African Journal of Science**	1917	South African Geographical Society
1904	Natal Museum, Pietermaritzburg		Sci. & Tech. Comm. on Indstl. Research (STCIR)
	Transvaal Museum, Pretoria		*South African Sugar Journal*
1905	*Journal of the Institute of Mine Surveyors of SA**		*South African Geographical Journal*
1906	University of Pretoria (UoP)*	1919	Sci. and Techn. Advisor to the South African Govt
	University of the Free State (UFS)*		South African Veterinary Association (SAVA)
1907	South African Biological Society		Glen (OFS) College of Agriculture
	Technikon Natal (TN)*		Potchefstroom University (PUK)*
1908	Onderstepoort Vet. Research Institute	1920	Assoc. Sci. and Tech. Soc. of S. Africa (AS & TS)
	COMSA Mine Trials Committee (MTC)		Cape Technikon (CT)*
	Bulletin – Department of Agriculture	1922	COMSA Technical Advisory Committee (TAC)*
1909	Potchefstroom College of Agriculture		Dental Association of South Africa (DASA)
	SA Institute of Electrical Engineers (SAIEE)*	1923	*Entomology Memoir – Department of Agriculture*
	S. A. Branch British Stnds Inst. (SABBSI)*	1925	Sugar Experiment Station, Mt. Edgcombe
1910	University of Natal (UoN)*		First Public Radio Broadcast
	Transactions -SA Institute of Electrical Engineers		Technikon Witwatersrand (TWR)*
	Science Bulletin – Department of Agriculture	1926	National Parks Board
1911	Grootfontein (E. Cape) College of Agr.	1929	Division of Sea Fisheries
	Journal of the Department of Agriculture		ML Sultan Technikon*
1912	Geological Survey of SA (GS of SA)*	1930	Fuel Research Institute
	SA Institute of Medical Research (SAIMR)		SAIEE Lightening Investigation Committee
	Meteorological Office (now Weather Bureau)		Empire Mining and Metallurgical Congress
1912	South African Chemical Institute*	1931	*Assc. of Mine Managers of S.A.: Papers and Discussion*

While the majority of collaborative research seems to have occurred in the mining industry, there were exceptions. For example, the South African Sugar Association (SASA) was established in 1915. Driven by disease which threatened the sugar cane industry in Kwa-Zulu Natal, SASA established a scientific journal in 1917 and a research institute in 1925.[43] Other areas of cooperation in the system of innovation drew on linkages with the mining sector. An example of this was establishment of the South African Branch of the British Standards Institute (SABBSI). In 1909, a professional association with close ties to the Witwatersrand, the South African Institute of Engineers (SAIE) established a Committee for Standardization of South African Material.[44] Aware of the need for a nationally recognized body to coordinate initiatives to standardize engineering and industrial materials, in 1918 the SAIE allowed its committee to reform as the SABBSI.[45]

[43] These were known as the South African Sugar Journal and the Sugar Experiment Station respectively.

[44] Preceding this, COMSA appointed a standards committee in 1905 with eight subcommittees covering a range of machinery and materials after discussions with the SAIE in 1904. By 1909 COMSA's efforts to promote these standards had shifted to lobbying and supporting the efforts of the professional societies. In its efforts to improve the extraction process the CMMSSA published standards in assaying and established a committee in 1906 which worked with the COMSA's subcommittee to establish standards for the stamp screens.

[45] SAIE's Committee for Standardization of South African Material was renamed the South Africa Engineering Standards Committee in 1911. After the industrial expansion associated with the World War Two, the 1945 Standards Act replaced the voluntary structure of SABBSI with full-time technical personnel. See Appendix Three for a chronology of the names associated with the SABBSI.

The community of professionals and their associated professional societies that had emerged around the Witwatersrand were also responsible for developing a broader scientific community that supported the emergent industrial and agricultural sectors. One of the best examples of this was the 1920 formation of the Associated Scientific and Technical Societies of South Africa (AS & TS) in 1920.[46] The AS & TS provided a venue to host professional associations' secretariats and meetings. As a supporting institution, AS & TS facilitated the establishment and sustainability of professional societies in a variety of fields as the need for increasing numbers of specialists grew with development of the domestic economy.

Collaboration amongst the professional associations also facilitated development of initial South African scientific and technical policy. In 1916, an industrial research committee (IRC) composed of members from the professional associations reported to the Minister of Mines and Industries on ways to promote South African industrial research and development in support of the war effort (Draper, 1967, p. 34). Among its recommendations, the IRC proposed establishing a separate Department of Industries and Commerce with an explicit function to advance industrial research and setting up a Technical Board, composed of scientific and technical individuals (AS & TS, 1963, p. 3). In response, the State established a Scientific and Technology Committee on Industrial Research (STCIR) in 1917. An important legacy of the STCIR was South Africa's appointment of a scientific and technical advisor who began building support for the establishment of the Council for Scientific and Industrial Research (CSIR) and Mintek.[47] In later years, both the CSIR and Mintek would become important components of the national system of innovation, with direct and indirect roles in mining's sectoral system of innovation.

This period also saw establishment of several new institutions of higher education. The 1916 University Act led to independence from the University of South Africa (UNISA) for the University of Cape Town and the University of Stellenbosch in 1918. The University of the Witwatersrand and the University of Pretoria also achieved independent status during this period, but UNISA retained examining and degree granting authority over most tertiary institutions in South Africa.[48] As the mining industry underwrote increasingly broad industrialization, technical education became a critical component for further industrial development. In recognition of the need for technical training the SAIE requested a 1919 government assessment of apprenticeships (Draper, 1967, p. 233). As a result, the 1923 Higher Education Act provided for establishment of technical colleges.[49] Additionally, training of underground miners occurred in the Government Training Schools and Native Training Schools. The State also made significant efforts in this period to foster scientific and technical infrastructure for the agricultural sector. In part, this support appears to have arisen because of the need for foodstuff on the ever growing Witwatersrand, but it is also important to remember that agriculture was an important political constituency. After World War One efforts to export South African agricultural products increased with State investments in the scientific and technical infrastructure supporting these initiatives.[50] Nonetheless, South African agriculture did

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[46] The original societies that established the AS & TS were: AMM, CMSSA, GSSA, IMS, MASA, SACI, SAIE, SAIEE, and the Transvaal Association of Architects (TAA).

[47] South Africa would eventually establish these government industrial research institutes, but only after the Second World War. See Kingwill (1990) and Basson (1995).

[48] Among the university colleges falling under UNISA were Rhodes University, established as a university college in 1904; University of the Free State, established as a university college in 1906; University of Natal in 1910; University of Fort Hare in 1916; and Potchefstroom University in 1919.

[49] The technical colleges established during this period included Technikon Natal in 1907, Cape Technikon in 1919, Technikon Witwatersrand in 1925, and M.L. Sultan Technikon in 1929.

[50] Examples include selective breeding began in the 1910s, Oenological and Viticulture research at the University of Stellenbosch in the 1920s, and citrus and sub-tropical fruit research in the 1920s. See Joubert (1977).

not seize the opportunity to significantly develop. Despite progress in both industrial and agricultural sectors, mining continued to dominate innovative activities between 1903 and 1933.

On the Witwatersrand, the sectoral system of innovation evolved with the private sector, an open community of practitioners, cooperative research, and even the State contributing. The State did not undertake research for the established gold and diamond industries, but it encouraged development of international markets for its coal resources by establishing a Fuel Research Institute (FRI) in 1930. The FRI helped develop technologies for the preparation of coal for sale on the international market and in coal carbonization and coke production, but it was formed within legislation that gave Railways the right to compel collieries to deliver a proportion of the coal they produced and gave the government the right to suspend international sales of coal for bunkers and exports if it feared a scarcity of supplies for the domestic market (Lang, 1995, p. 115). As such, the FRI typifies a general pattern of State support for science and technology during this period driven by interest group political lobbies within the white communities.

In terms of the open community of mining and metallurgical practitioners, increased specialization accompanied growth of the Witwatersrand gold mining industry leading to the establishment of several additional associations and journals.[51] While several non-mining professional associations emerged,[52] professional associations linked to mining remained the largest in scale and scope. Examples of their impacts have already been mentioned with respect to national standards and State innovation policy. In general cooperation between the professional associations also deepened. An illustration of this was the joint hosting of the Third Triennial Empire Mining and Metallurgical Conference (EMMC) in 1930 by the SAIE and the CMMSA. The EMMC itself being an initiative to foster cooperation and diffuse best practices in mining across the British Empire.

The relatively conscribed role of COMSA in the sectoral system of innovation has already been noted.[53] Again, in large part COMSA's limited role appears to be related to the Corner House acting as an effect cooperative research organization for the industry. Since, that is central to research collaboration in the technologies that transformed stoping practices, further discussion is postponed to the next sub-section.

In terms of the private sector, Figure 9.9 showed that the industry's technical leaders were JCI, GFSA and the Corner House. JCI's 1919 take-over and subsequent turn-around of Randfontein clearly reflects their technical competence.[54] JCI also established a metallurgical laboratory in 1926 that later pioneered the predominant method of platinum extraction from the BIC deposits (Sander, 2000, pp. 304-305). GFSA established its own metallurgical laboratory in 1905 and through its commitments to Rudolph Krahmann's geophysical research in the 1930s opened development of the FWR and OFS goldfields.[55] In 1902, GFSA also began sponsoring an annual

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[51] Amongst the new mining professional associations established during this period were the South African Institute of Civil Engineers (SAICE) in 1903, the Institute of Mine Surveyors of SA (IMSSA) in 1904, and the SA Institute of Electrical Engineers (SAIEE) in 1909. Several journals were also launched during this period; they include the *SA Medical Journal* (SAMJ) in 1903, the *Journal of the IMSSA* (1905), *Transaction of the SAIEE* (1910), and *Association of Mine Managers of South Africa: Papers and Discussions* (1931).

[52] Some non-mining professional associations established during this period include: Transvaal Biology Society, South African Ornithology Society, the Botanical Society, Dental Association of South Africa, and the South African Veterinary Association.

[53] See Section 9.2.4 above.

[54] See Chapter 9 in Sander (2000).

[55] See Chapter 14 in Cartwright (1967) and Chapter 28 in Lang (1986).

award for the best paper presented to the CMMSSA in order to foster research in deep-level mining (Cartwright, 1967, pp.97-98). The Corner House continued developing its metallurgical competencies with its establishment of a metallurgical laboratory in 1913. Its centrally managed health services, established in 1915, became a model emulated across the industry.[56] In addition to their individual competencies, the mining-finance groups expanded their support of the open community of mining and metallurgical practitioners by funding their associations' publication costs (Draper, 1967, p.16). Lastly, a great contribution toward the vibrancy of the professional associations was the groups' expanding employment of scientists and engineers.

The Structure of Innovation in the Transformation of Stoping Practices

Fundamental transformation of Witwatersrand stoping practices depended on the coordinated adoption of three distinct, but complementary groups of technologies. In contrast to the previous case where knowledge exchanges were critical, development of these technologies were driven by a single mining-finance group, the Corner House. Nonetheless, research collaboration continued to play a central role. First, co-operative organizations like COMSA and SAIMR directly and indirectly contributed to research in many areas as well as laterally supporting adoption through establishment of training and monitoring functions. Second, working largely through professional associations, the open community of practitioners, developed, exchanged, and diffused crucial know-how. Finally, the Corner House acted as if it were a co-operative research organization diffusing its proprietary research to the other groups.

As a co-operative research institute funded jointly by the State and industry, SAIMR focused on solutions to the occupational health hazards associated with transformation of stoping practices.[57] Directly, COMSA undertook the collection of dust samples as well as establishing research committees on rock drills. Indirectly, COMSA supported research initiatives by funding the MMOA and the SAIMR. Laterally, COMSA also supported the technologies' adoption through institutes that fostered complementary skill development and by establishing an African labor recruitment monopoly.[58] Another increasingly active role for COMSA was industry-wide research coordination with the TAC.

An open community of local practitioners instituted across professional associations similarly made significant contributions. The associations' journals played a role in developing and diffusing the technologies that transformed stoping practices.[59] The associations also sponsored symposiums around specific research challenges. The associations also initiated research into labor force organization, occupational health hazards, and rock drills.

While the mining-finance groups were involved with both the open community of practitioners and the cooperative institutes, they played an enormous role directly developing the new stoping practices. The Corner House led the groups by sponsoring research that it readily diffused across the industry. Although dominant, the Corner House was not alone in its efforts with other

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[56] See Cartwright (1971, pp. 28-44) for details on the centralization of health services at the Corner Houses and its relationship to health practices across the Witwatersrand.

[57] In particular SAIMR conducted research identifying the danger and threat of fine dust in spreading phthisis as well as collecting evidence on health costs associated with poor nutrition in the African labor forces' diet.

[58] In skills development Government Mine Training Schools and Native Training Schools were two particularly significant institutes. In the African labor recruitment monopoly, the NRC and WNLA were at least as important.

[59] For instance, the JSAIE published numerous articles on best practices in systematically deploying the rock-drills on a large scale industrially. The JCMMSA published several papers on mine ventilation and health, while the SAMEJ and PAMM published articles on productive efficiencies in workforce organization with the rock-drills. Many issues in understanding and alleviating health concerns were published in the SAMJ and working papers of the SAIMR.

groups acting similarly.[60] This cooperative approach over the technologies' diffusion was central to realizing the fundamental transformation of stoping practices that ensured the viable mining of the Witwatersrand for decades.

Changing the organization of stoping work into a Taylorist structure was one of the marked research focuses. In this regard, the mining-finance groups in general and the Corner House in particular drove the research that first replaced the skilled European miners and then began to maximize the functions of inexpensive African labor within racial occupational mobility restrictions. The Corner House commissioned Ross Browne's 1904-1905 study, which was the first study into the transformation of underground operations. It also funded the Miles and Stevenson's 1929-1930 study, which identified organizational efficiencies from labor force reorganization under racial occupational mobility restrictions.[61] These changes in the structure of underground work met resistance by constituents of the underground labor force and limited the scope for the Corner House to go it alone in these transformations. As a result the Corner House utilized the professional associations to diffuse these changes in the organization of the underground workforce across the mines of the Witwatersrand.[62]

Alleviating occupational health hazards associated with the transformation of stoping was another discrete area of research. In this the groups' efforts, while still important, were less central than in other areas. Co-operative organizations like COMSA and SAIMR both commissioned and undertook research that made important contributions toward solving the challenges of occupational health hazards.[63] The horrific incidence of health diseases led to State involvement in research around the health hazards. While the efficacy of the State's involvement appears questionable,[64] it enacted several important pieces of legislation and commissions as well as developing an instrument to accurately measure the amount of dust under ground.[65] However, the open community of professional practitioners was the most important element in developing solutions to the occupational health hazards.[66] In contrast to the intra-industry mobility described in the previous case, the exchange of information about the various hazards within and between the professional societies was central to the open community's operations during this period.

The other distinct group of technology was in the rock-drilling equipment as well as operating procedures to deploy and maintain that equipment underground. In this, the State did not take a proactive role: "In other British Colonies the Government usually gave assistance in matters of this kind, and it was due to the present Transvaal Government to show more material interest in

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60 Goldfields and JCI's contribution were mainly in dust investigations during the 1910s.

61 During this period, the Corner House also developed the 'Langlagte Manual' which was effectively a guide to Taylorization of underground operations on a Witwatersrand goldmine.

62 The AMM also undertook research in Taylorization of the stopes through investigations in 1914 and 1916.

63 COMSA funded Gorgas' 1913-1914 study of health practice on the mines and a dust sampling committee between 1914 and 1937. COMSA also funded SAIMR research on scurvy in 1920 and the MMOA 1927 pneumonia survey. COMSA worked cooperatively with the State supporting the 1903 ventilation commission, the 1921 and 1923 dust studies and in the tuberculosis research committee between 1926 and 1932.

64 See Katz (1994) and Kennedy (1984).

65 Among activities in this regard were the 1902 Milner Commission, the Mining Regulation Commission between 1907 and 1910, the Medical Commission of 1911, The Miners Phthisis Commission between 1912 and 1914, and the Government Tuberculosis Commission of 1914. The Government Mine Engineer invented the instrument that measured the level of dust underground.

66 The Association of Mine Managers (AMM) jointly conducted the 1902 Phthisis study with the Medical Association of South Africa (MASA).The CMMSA sponsored a symposium on phthisis in 1921 as well as three symposiums on mine ventilation in 1924, 1925 and 1930. In addition, the mine medical officers association (MMOA) sponsored a 1928 study and a 1930 symposium on of phthisis. The MMOA also championed a 1922 conference on mine hygiene and a 1927 study of pneumonia.

this important matter [of developing a rock drill for stoping]" (Orr, 1907, p. 231). COMSA undertook some research into rock-drills,[67] but the most important initiatives were again by the Corner House who actively diffused the research through the open community of practitioners.[68]

9.2.6 Conclusion

Research collaboration in this case involved a leading agent actively releasing proprietary technologies. The Corner House drove development of the technologies necessary to transform stoping practices. In understanding why the Corner House acted this way it is apparent from the contextual description above that inventing the technologies was not the only challenge to transforming stoping practices. It was critical that power be exerted across and along the production chain in order for the technologies' adoption. Therefore, assessing the causes and effects of research collaboration in this case begins in Section 9.3 with the distributed innovation approach, which gives those dynamics a central role. Additional analytical insights from the other approaches then follow in turn with collective action in Section 9.4 and industrial district in Section 9.5. Before turning to that aspect of the analysis, it is again worthwhile to briefly review how the preceding description of the structural factors relates to structural components and relationships in the theoretical approaches.[69]

The three inter-dependent technologies that transformed stoping practices were described in Section 9.2.1 and defined the *Innovative Object* and the *Public-Collective Good* for the Distributed Innovation and Collective Action approaches respectively. The discussion of the product market in Section 9.2.2 established the supply and demand dynamics for gold during this period. This contextualized the *Market* in the Industrial District approach and highlighted the increasing significance of Witwatersrand gold in the international monetary system and the effects of Britain's abandoning the gold standard.

Section 9.2.3, on the social structure of production, began by distinguishing a few of the principal groups involved in production and the dynamics of their population groups in the Witwatersrand workforce. After a static and dynamic profile of *Human Resources* from the Industrial District approach, attention turned to describing thirty years of State authority over the Witwatersrand and the rest of South Africa. We thereby sketched the nature of the *Socio-territorial Entity* in the Industrial Districts approach. Next, the section described intra-group and inter-group ability to build social and political authority. For some groups this history was one of leveraging their influence to increasing their authority. The African population in contrast experienced an era of concerted fragmentation by other groups and a perpetuation of their exclusion from the ruling political authority. Social cohesion, or the lack there of, on the mines and the system that translated that into stocks of social capital was thereby described. Thus, that

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67 COMSA commissioned a mine trials committee between 1908 and 1915 as well as a jack-hammer committee between 1918 and 1924. COMSA worked cooperatively with the State supporting the 1909 rock drill trials.
68 Examples of this system include the 1913 Corner House investigations into the necessary design and operating efficiency for compressed air plants and distribution system to power the rock drills were published in the JSAIE. See: Izod and Laschinger (1913). Similarly a series of papers were presented on the research of the rock-drill investigations committee (RDIC) between 1919 and 1922. The RDIC developed a hole director, a drill rig, and established work practices (routines) that facilitated the Taylorization of stoping. Between 1925 and 1928, the Central Mining Investigations Committee (CMIC) of the Corner House developed numerous logistical and operating practices for the use and maintenance of rock-drills underground. In 1931 the Corner House conducted additional research refining the equipment for development that facilitated Taylorization. That research was diffused to industry through publication in the professional associations' journals. See Heywood (1931) and Heywood (1936).

69 What follows parallels the review concluding Chapter 7, Section 7.2.6.

part of the section described the *Community*, *Overlapping Activities*, and the *Mechanisms of Co-operation* in the Industrial District, Collective Action, and Distributed innovation approaches. Lastly, the section described how the stock of social capital could leverage favorable behavior supporting established group interests and simultaneously deterring actions that diminished collaborative benefits. Hence, the final part of Section 9.2.3 described the *Socio-Political System,* the *Convention System* and the *Mechanism of Competition* in the Industrial District, Collective Action, and Distributed innovation approaches.

The analysis of the industrial structure in Section 9.2.4 identified changing up-stream and down-stream relationships by the mining-finance groups as well as the clear predominance of the Corner House in production. As a result, we described the structural component of *Firms and Institutions* in the Industrial District approach. The section also reviewed the role that the structure of production played in hindering or facilitating collaboration, defining in turn the *Production System* and *Product Provision* in the Industrial District and Distributed Innovation approaches.

Section 9.2.5 analyzed the structure and dynamics of the system of innovation under which these innovations to stoping practices were made. It reviewed the political landscape's influence on the development of the national system of innovation. Overall, the national system of innovation remained vested in the Witwatersrand gold mining industry. The sectoral system of innovation that transformed stoping practices remained strongly collaborative, but in contrast to the previous case a dominant organization rather than a community of practitioners drove it. The section thereby defined *Innovation Provision* and the *Knowledge System* in the Distributed Innovation and Industrial District approaches. Lastly, with the contextual background established, the section looked at the specific structure of provision for the three principle technologies, defining the *Collective Supply Function* in the Collective Action approach.

9.3 CAUSES AND EFFECTS IN THE DISTRIBUTED INNOVATION APPROACH

Distributed innovation considers features of the contextual environment, pull-factors, and the agents themselves, push-factors, which form causal condition favoring a predominantly distributed governance structure. The stability or instability of the predominantly distributed equilibrium gets explicit consideration under the constraining circumstances. These three factors leading to research collaboration are considered in Section 9.3.1. Research collaboration's distinct influences on both the technologies and broader distributed relationships are then deliberated in Section 9.3.2.

9.3.1 Causal Conditions in the Distributed Innovation Approach

Push Factors

In Section 9.2.5, analysis of innovations transforming stoping practices highlighted the existence of a common class interest among Mining Professionals and their mining-finance groups. That common cause was simply the need to economically extract the gold bearing ore at increasing depths. Thus, as understanding about the technologies' complementarities developed it was shared within the open community of practitioners. Contemporary discussions recognized the need to co-operatively develop understanding of these inter-relationships: 'It is then with the hope that a brief description of the methods followed, a discussion of the information obtained on a particular subject which has reached a definitive stage of development, and a statement of the improvements resulting, may prove of service to the others, that this paper is presented' (Newhall and Pryce, 1924, p. 115).

Inter-class cooperation also proved a significant element supporting distributed innovation. The Mining Professionals faced resistance from the European Miners and required a perpetuation and institutionalization of low-cost African mine labor. Hence, Sections 9.2.3 and 9.2.4 described how Afrikaners were brought into the structure of production and the indirect interests of agriculture and manufacturing were coordinated with those of mining to secure the necessary State interventions. An example of the real influence the State had in underground operating efficiencies was noted in a discussion of stoping practices. In that discussion, adjustment in the Mining Regulations that facilitated a Talyorization of stoping operations late in 1921 were claimed to have generated a 40% increase in drilling efficiency (Newhall and Pryce, 1924, p. 135).

Pull Factors

Both the rapid processing and application of information about a technology as well as the exchange of intangible knowledge did not play as significant a role in this case as it did in development of cyanide based gold extraction. Nonetheless, building understanding of intangibles was significant in both occupational health hazards and associated industrialization of rock-drill maintenance. In reviewing progress in reducing the incidence of phthisis, the CMMSSA sited four early papers and associated discussions that codified understanding of the phthisis problem (CMMSSA, 1934). Similarly, a host of papers around drill maintenance and operating practices identified key efficiency parameters. Potter (1926) called upon the Mining Professional community for greater participation in the exchange of these intangibles: '…I hope Members, and those who have been carrying out experimental research work in connection with the forging and hardening of drill steel, will come forward and present to this Institution, in the form of discussion, the data they have obtained, and the conclusions they have come to with regard to the various matters they have been investigating' (p. 164).[70]

A highly significant force supporting a predominantly distributed structure in this case was the necessity to establish a standard of practice in Taylorized stoping operations. The coordinated replacement of the European Miners and institutionalizing a low-cost supply of African labor strongly depended upon a standard transformation of stoping practices across the Witwatersrand that inherently limited unilateral action. Economies in deploying the physical equipment also supported standard practices across the mines.[71] More generally, the adoption of a Taylorist organization of stoping facilitated cooperation through an increased understanding of interactions between various stages of production.

Constraining Circumstances

The entry of Afrikaner miners and the removal of European Miners fundamentally transformed underground operations. In realizing this transformation, the Mining Professionals had to secure an alliance with the relatively less-skilled Afrikaner miners. As a result the Mining Professionals traded away full deployment of low-cost African labor in production. The necessity to access deeper deposits drove this unfortunate alliance that held sway for several decades to follow.

Market conditions were another factor supporting distributed governance in this case. Section 9.2.2 described how the declining real price of gold created a profitability crisis in the industry. This cost pressure added further critical impetus to a collaborative transformation of underground operations.

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[70] Also see: Meyer (1930) Heywood (1930) and Heywood (1931).
[71] See: Potter (1918) Potter (1919) and CMMSSA (1934).

9.3.2 Effects in the Distributed Innovation Approach

Innovations Generated

In assessing the impact of the transformation of stoping practices it is crucial to realize that a legacy of cooperation in innovation supported distributedness. Particularly, collaborative innovation in the first case built momentum towards collaboration in the transformation of stoping practices. The Taylorization of stoping practices was a major transformation of the production system generating a radical change in productive authority. The technologies were not particularly complex in themselves and solutions to most of the challenges were reasonably well understood, even if important details required further development. Quite a number of rapid simultaneous technological transformations occurred, but once these were realized there was limited subsequent evolution. In part, this limited further evolution resulted from the racial occupational mobility restrictions imposed on the majority African workforce.

If the Corner House had unilaterally transformed stoping practices under a predominantly hierarchical structure, alternative technologies to transform stoping practices might have developed in other mines that would have created a very different industry dynamic. The necessity for coordinated action as well as rapid transformation fundamentally augured against alternative governance structures. In the end, the technologies that transformed stoping practices left an indelible legacy on the mining industry as well as broader South African economic development.

Distributed Relationships

The transformation of stoping practices ensured the structural exclusion of Africans from the primary system of production. They were effectively relegated to a role of physical capital. In removing the importance of European miners' skills they were also effectively excluded from the system of production. Again it was the African community that suffered the most from this exclusion, not only within the mining industry, but also across the socio-political system.

Collaboration in this case was apparently associated with increased cooperation in other areas. Judging by that extension of cooperation, social capital seems to have deepened. Impetus for part of that collaboration relates to the greater homogeneity of agents. By adopting similar operating practices underground, the groups were linked in common interests concerning the State, other industries, and other agents of production. Specifically, that common interest was rooted in low paid African labor and a structurally advantaged Afrikaner workforce. This enforced homogeneity of agents facilitated a remarkably unified productive dynamic over the industry and its broader role in the South African economy.

Lastly, the distributed structure played an important role in decreasing the risks that the Corner House would have faced through unilateral action. Leveraging State interventions and international recruitment of low-cost African labor was difficult enough in coalition. Adding to the pressures for distributed transformation was Corner Houses' internal diversification out of its predominantly South African investments. Hence, the Corner House did not want to risk achieving too dominant an industrial position. As a result, the diffusion and distributed investments in the technologies to transform stoping practices by the Corner House lowered the innovative hurdle for the other groups. Thereby a fundamental transformation of stoping practices was achieved as the Corner House, acting as a cooperative research organization, drove research collaboration.

9.4 CAUSES AND EFFECTS IN THE COLLECTIVE ACTION APPROACH

In the collective action approach four structural features determined whether the causal conditions were sufficient for research collaboration. If the collective supply function (CSF) and the collective goods did not create a privileged situation, then collaborative research depended upon the additional support of the convention system and overlapping activities. Once research collaboration occurs, its sustainability depends on its improving net social welfare.

The three technologies were non-rival and excludable *e.g.* club-goods. Although occupational health hazards were slightly different, both labor force reorganization and rock-drills primarily resulted from proprietary research by the Corner House. This case then demonstrated collective research occurred because the technologies were privileged goods.[72]

Even more dramatically than the first case, the collective action approach highlights the incongruence of net social benefits on the stability of research collaboration.[73] The transformation of stoping decreased social welfare of both European Miners and African Miners. Social exclusion of these negatively affected communities was again central to defining the net benefits such thatcooperation was stable. In addition, in this period the non-excluded Afrikaner community significantly increased its incidence of benefits from the technologies adding thereby to the stability of cooperation. In later years, as the African miners and their broader population gradually increased their socio-political authority the interest group coalition that allowed the successful transformation of stoping practices was no longer tenable. Therefore, the collective action approach draws attention to the fact that an evolutionary stable strategy in one period can become unstable as contextual conditions evolve.

9.5 CAUSES AND EFFECTS IN THE INDUSTRIAL DISTRICT APPROACH

Complementary human and natural resources, connections with external markets and local entrepreneurism form the causal conditions of an industrial district and collaborative research in the industrial district approach. In this case, an industrial district and associated research collaboration were driven by beneficial agglomeration externalities that enhanced its competitiveness. Nonetheless, negative agglomeration externalities like sectoral volatility and excessive localization existed. The net benefits or cost of these externalities make an industrial district favorable or unfavorable to local firms' competitiveness.

In this period complementarities between human and natural resources further augmented development of the district. An open community of practitioners was again important in developing the technologies that transformed stoping practices and ensured viable mining of the Witwatersrand for decades. The role of the open community was mentioned in a contemporary comment about the Corner House's diffusion of rock-drill technology: "The industry had to be congratulated on having this wealth of information put in front of it. It was a very good thing that is was not a competitive industry, and that the mines here were going to benefit by the hard work which the engineers of the Corner House and Mr. Calder had put into this job" (Vaughan, 1913, p. 94). However, the biggest role played by the open community of practitioners was in occupational health technologies. For example, experiences with different ventilation and drill equipment were circulated among the professional societies developing understanding and

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[72] Collective action gives useful insightful around motivation for know-how trading by practitioners on occupational health hazards as it did around the similar activities in the previous case.

[73] See also Chapter Seven, Section 7.4.

interventions that alleviated phthisis. Labor market pooling considerably expanded as the African labor recruitment monopoly was established and a traditionally low-skilled Afrikaner community came to the Witwatersrand gold mines. Training externalities also developed directly through Afrikaner and African training schools, but also through the increased promulgation of universities and technical colleges. Lastly, a significant feature of all of these externalities was an increasing incidence among other local productive activities.

On the other hand, negative agglomeration externalities also rose. Limited market demand became much more pronounced. Inflation in the face of a fixed nominal price drove down the real price of gold during the 1910s. Sectoral volatility in-turn became more pronounced as decreasing profitability of gold mining operations depressed government revenues and the general economy of the region until the removal of the gold standard in 1932. Despite these negatives, net agglomeration externalities remained significantly beneficial throughout this period and as such the industrial district approach demonstrates why research collaboration continued to be a significant force.

9.6 CONCLUSION

This analysis further demonstrated unique and complementary analytical insights from the alternative approaches to collaborative research. The complex orchestration of diverse interest groups and their associated socio-political power were clearly reflected in both the collective action and distribute innovation approaches. The underlying structure of collaboration itself was revealed best in both the industrial district and distributed innovation approaches. Comparative advantages and aggregate benefits were explicitly considered in the collective action approach. Distributed innovation highlighted the confluence of events that led to the establishment of these uniquely distributed innovative technologies. Systemic effects from collaborative technology were also examined across the approaches, but especially in the Industrial District approach.

Chapter Ten: Conclusion

10.1 INTRODUCTION

This dissertation has taken an original track in its examination of research collaboration and South African history. While breaking with tradition, it draws on previous research to illuminate its direction. Deconstructing methodologies that centrally place collaborative research showed similarities in their structures, causal conditions and effects. However, each approach emphasized different aspects of the phenomenon. By applying these methodologies on two sequential cases, the dissertation indicates some of their relative strengths and weaknesses in analyzing collaborative research. Its analysis also showed that the socio-economic environment and underlying features of the technology interact, thereby influencing the nature of an innovation's development, its diffusion, and the extent and role of research collaboration in its development. Because of the central role given collaborative research in contemporary policies aimed at developing modern 'knowledge-based' economies, there is an urgency to improve our understanding of collaborative research. Through its application of these methodologies to century old cases, this analysis has demonstrated that research collaboration is not just an important modern force, but also a complex and enduring component in the innovation process.

In the case studies, placing the socio-economic environment behind the innovative dynamics reversed conventional emphasis in South African historiography. Developing this narrative led to novel insights about industry dynamics and the legacy of the Witwatersrand gold mining industry on South African history. In the case of cyanide-based gold extraction, this reversal brought attention to the legacy of Kimberley diamond mining on the Witwatersrand's early innovative system. Examining technology dynamics in the second case on the transformation of stoping practices highlighted alternative motivations for the industry's actions towards racial occupational mobility restrictions. In particular, this case showed that demand on the surface for higher mill inputs depended on mechanizing underground operations. Therefore, the industry searched for the shortest route to Taylorization of stoping practices, a route that added critical momentum to the broader social advance of racial occupational mobility restrictions.

10.2 CASE STUDIES

These cases covered a 50-year period, showing the evolution of an emergent industry, its technologies of production and system of innovation. In both instances, collaborative research played a critical role in the technologies development. Examining the details of these cases showed collaboration to be multi-dimensional and co-existent with competition. This section reviews lessons from the comparative analysis of research collaboration with the synthesized methodologies. In reviewing each case, there is also a brief description of the relationship between the case's innovation system and broader systems of innovation operating during the years of these two cases, between 1886 and 1933. Finally, there is a discussion of neglected features in South African historiography, which application of these methodologies highlighted.

10.2.1 Cyanide-Based Extraction of Gold

Preceded by several other mining rushes across southern Africa, this case began in the early 'boom' era of Witwatersrand gold mining. The basic challenge driving technological development was an inability of existing extraction technologies to economically remove gold from the deeper zone of non-oxidized host-rock. Since the vast majority of the Witwatersrand's deposits were in the non-oxidized zone, the Witwatersrand's industrial future hinged on an economic method of extracting gold from the non-oxidized host rock.

In meeting this challenge, research collaboration within the Witwatersrand gold mining industry was central to development of the large-scale cyanide-based gold extraction process. In transforming cyanide extraction from a laboratory technology to a technology suitable for the factory floor, its developers faced two major hurdles, the effective treatment of slime, and the efficient precipitation of gold from solution. Through a predominately collaborative structure, these problems were resolved and a fundamental technology for deep level mining rapidly diffused.

Development of the Technology

Chapter Six described the context of the technology's development. A general process of initial industrial development and innovation with colonial incursion into an 'un-developed frontier' set the backdrop for the case. Establishing dominion over natural resources was fundamental to European colonization for centuries, but the associated degree of local industrialization varied considerably. In this instance, the primary direct and indirect colonial influence was British.

The Witwatersrand was part of a global 19th century boom and bust phenomenon driven by the international gold standard raising the price of gold. While the legacy of individual mineral deposits varied greatly, in aggregate they generated economic and infrastructure development, even if the geographic impact only loosely followed the location of the deposits. Typically, amidst fierce competition for mineral rights there was also a strong sense of community, common cause, and identity in these settings.

An important influence shaping the social, political, and economic structure of the Witwatersrand was the community at the Kimberley diamond deposits. Kimberley transferred an emergent class of Mining Professionals to the Witwatersrand. Any metallurgical technology that would allow the large-scale economic extraction of the massive gold deposits from the non-oxidized layer was an imperative for the nascent Witwatersrand mining community. Given this necessity, the frontier setting of pioneer industrialization, and a close network with the Kimberley community, cooperation emerged over many aspects of production. Nonetheless, competition persisted for ownership of mineral rights and in securing finance, but the borders of co-operation and competition were rapidly established.

Role of Collaboration in the Technology's Development

In the examination of the role of collaborative research in development of the cyanide technology in Chapter Seven, the industrial district was the most descriptive methodology. This 'cyanide valley' focused on finding a commercial solution to a challenge whose basic scientific principles were uncertain. No codified textbook solution existed and as such, alternative extraction technologies required comparison through a learning-by-doing process. This favored and supported a geographical centralization of innovators, which did in fact occur.

Given these circumstances, research collaboration was supported by the initial variety of contending technologies that might solve the common problem of mining in the non-oxidized zone. Proprietary ownership of any of these unproven technologies would not appreciably enhance the competitiveness of a mining firm. In contrast, allowing and facilitating company metallurgists' interactions with colleagues at other companies enhanced the competitiveness of their operations through a process of comparative learning and information sharing that accelerated development of a critical technology.

Research collaboration among Witwatersrand metallurgical practitioners thereby became an important feature in development of the cyanide-based gold extraction technology. The industrial district approach captured many dimension in this process of research collaboration. Professional societies and less formal interactions, such as occupational mobility, were crucial to developing and diffusion of the cyanide process. There was no established technology for this type of metallurgical extraction anywhere in the world. In development of the technology there was no ex-ante certainty that cyanide would be the best or indeed if any viable technology existed. As the translation of the technology from the laboratory to production occurred many significant obstacles and doubts emerged around its viability. In evaluating the technology's development therefore the free exchange of information at the individual level was crucial. As we also expected from the industrial district approach, intra-industry mobility of individuals played a large part in development of knowledge about the cyanide process.

Kimberley diamond mining's legacy on the Witwatersrand went beyond merely fostering a social identity and extended to instilling a distinctive economic process. To the extent that this instituted process was a significant influence on research collaboration in development of the cyanide-based method of gold extraction, the collective action methodology was insightful. In this case, there appeared to be some explicit and/or strategic release of information occurring from the Corner House mining-finance group. Also during this period an important and enduring industrial cooperative was established, COMSA. While COMSA was primarily a lobbying organization during this period, its mission was expanding, even if its success in some of these new areas was limited. Looking at the operation of the innovative system, 'know-how' trading provided some interesting insights. Metallurgists competed for jobs in an international market place, but once employed there was a large potential for cooperation. Nonetheless, it is difficult to argue that this was part of an explicit strategy as it seems coincident with externalities from other activities.

As already noted, competition in this era primarily took place in acquiring mineral rights and in securing financial investment. Cooperation in other areas was not universal, but it was extensive. Besides mining techniques to exploit the relatively low-grade and deep-level gold deposits, cooperation by Witwatersrand mining firms also occurred in securing favorable tax policies from the ZAR, reducing the burden of the ZAR's monopoly concessions policy and in reducing African labor recruitment costs. The distributed innovation approach was particularly useful in capturing the inter-relationships between these different aspects of cooperation and competition. Another perspective on the Kimberley legacy emerges through this approach because of unification of diamond operations, but it goes beyond just Kimberley as worldwide at this time competition was not typically in technologies. The cyanide-based extraction technologies were associated with substantial learning by doing in this instance. Therefore, cooperation and individual mobility supported this type of learning. External shareholders' demands played a minor, but real role which limited the independence of mine financiers and managers to a variable but ever present extent. During this period, mining know-how (know-who) networks developed on the Witwatersrand that were supported by organizational behavior. Finally, an important industrial feature in the organization of innovation in the industry at this time were the consulting corporations that interacted and transferred best practices across mining-finance groups on the Witwatersrand.

Relationship to the Innovation System

There was an obvious effort to use the regional mineral wealth to finance colonial economic expansion into the African interior. Nonetheless, particularly in the early years, there was no sober indication that the Witwatersrand gold field would be a corner stone to the industrial development of the Southern African region. Education and research capacity was in agriculture and generally fragmented preceding the Kimberley and Witwatersrand discoveries. Kimberley began the process of transformation and through the course of this period it was the leading force behind increased regional innovative capacity with a focus around natural resource extraction technology.

Extraction of the non-oxidized deposits was a critical concern eliciting both financial capital and human capital investment. The Witwatersrand mining-finance groups brought a critical mass of specialized knowledge to the area through their hiring of chemists and engineers. These individuals were critical to the industrialization of cyanide-based gold extraction technology. Their impact was more profound than just resolving one technical challenge though. These pioneering metallurgists and engineers' initiative and their employers support, led to establishment of local institutions to retain and develop that knowledge. That legacy was clearly demonstrated in this case through the establishment of a multitude of professional societies. Thus, this technology's early development on the Witwatersrand influenced the emergent South African system of innovation. However, while a regional industrial knowledge system was forming around the mineral activities in Southern Africa at this time, it arose across a politically fractured region.

The British colonial government contributed to the region's development, following a global policy of promoting infrastructure and finance favorable to its own domestic competitiveness. Despite this, local industrial priorities drove development of the regional system of innovation. These were primarily linked to the principal mining enclaves of Barberton, Kimberley, and Johannesburg. The Witwatersrand and its system of innovation were part of the international fortune seeking phenomenon, but it rapidly developed its own political economic dynamics. Nevertheless, an industrialized production process of cyanide-based gold extraction is best placed within an international system of innovation than in a regional or national system. This outward orientation is clear in the contemporary discussions used to trace the development of the technology, as are the diverse geographic origins of its pioneers.

Implications for South African Historiography

Development of an innovative system in a dynamic frontier community is a core dimension to the story portrayed in this case study. Previous analyses of this era on the Witwatersrand did not examine this process. Relationships between the local, and broader colonial and international systems of innovation, carried important direction in the evolution and structure of the innovative system that developed cyanide- based gold extraction technology. In demonstrating this, the case is an historic example of a previously neglected aspect of industrial development in a frontier economy.

During this period, Kimberley played a significant role in the formation and direction of the Witwatersrand's innovative system. Previous historical research on the relationship between the two communities only gives indirect attention to Kimberley's innovative legacy on the Witwatersrand. In considering the influence Kimberley had on the Witwatersrand this case also indicates areas in which Kimberley carried an important influence in the development of what would eventual become South Africa's national system of innovation.

Another neglected feature of South African history emerging from this case is the contrasting dynamics technologies implemented in this case compared to those in the transformation of stoping practices.[1] In their respective eras, both sets of technologies were crucial to efficient mining of the Witwatersrand. However, in labor force impacts, the scale of the two technologies was very different. In considering why the resistance to this technological change was much less dramatic than that of changing stoping practices, this case indicates the socio-economic power of agents affected by the technology are an important force in shaping the actual dynamics of a technology's application and can yield as much an influence as engineering imperatives. This influential power of group interests' is not always integrated in considerations of labor force dynamics and the pursuit of production efficiencies.

10.2.2 Changing Stoping Practices

The changes in stoping practices realized in this case removed the last significant layer of artisanal skills from production on Witwatersrand gold mines. This second case described the nearly thirty years it took to achieve Taylorization of stoping practices. Truly industrial mining of the Witwatersrand gold deposits therefore dates from the predominant diffusion of these stoping practices at the end of this case study. Witwatersrand mining generated economic impacts across southern Africa throughout this period. It was a major force in local and regional industrial development, and a crucial source of revenue to the South African government. Changing stoping practices carried significant political economic consequences as they transformed the structure and organization of the racially segregated labor force. The individual efficiencies of these technologies had to contend with this political economic power, which in turn required special adaptations of the technologies, just as they exerted pressure for change in the labor force. These internal and external forces were critical aspects influencing the local development and diffusion of these stoping technologies.

The three distinct technologies that eventually transformed stoping practices were strong complements. Reorganization of stoping work involved removing the independent authority of the artisan from production and forming a stoping workforce integrated into a comprehensive hierarchical management structure. Development of the actual equipment of production primarily involved designing a durable lightweight rock-drill, but also included other equipment like the compressors to run the drills and the tools to maintain them. Finally, while mechanization made mining at increasing depths economically viable, it also created a host of severe occupational health hazards. A host of innovations were necessary to resolve these occupational health hazards, but it is important to remember that the work environment on the stopes remained harsh and dangerous.

Development of the Technology

The review of the case's innovative dynamics in Chapter Eight illustrated technology specific factors, such as innovations in rock-drill design, and industry needs, such as scale economies realized in milling capacity, which provided significant stimulus for an alternative stoping practice. Between these technology-push and market-pull forces for innovation, the pull of milling capacity and increasing depths of ore extraction were critical. Given the high cost of developing a deep level mine shaft, there was a strong constraint on the numbers of workers that could be brought underground in any given shift. Despite the relatively low cost of manual African drillers, with deeper mines the productive efficiency of each individual underground

[1] Part Three, Chapters Eight and Nine.

increased. While a labor force of 5,000 manual-drillers might be able to break the same amount of reef at a lower cost than a force of 500 rock-drillers, if the depths of the mines prohibited transport of such a large number of drillers to the stopes, the comparison was meaningless. Meanwhile, continued innovations in gold extraction technology led to creation of metallurgical plants requiring increasing throughput on the surface. Thus, further pressure mounted for higher productivity of the underground labor force.

Supporting, and in some instances driving, change in the Witwatersrand's stoping practices were foreign technological precedents. These overseas technologies did not provide out-of-the-box solutions, but access to them and knowledge of their existence provided major insights to changing the stoping practices on the Witwatersrand. As a result, a significant portion of the innovation occurring in this case involved adaptation of foreign technologies to the local operating environment. However, this was not a one-way flow, the adaptations on the Witwatersrand became international benchmarks and precedents in themselves guiding thereby the drive for an industrialized mining industry.[2] Given the geographic dispersion of the innovative system that operated in this case, as well as the important local political economic influences on the technologies development, widespread collaboration was crucial to access available technical knowledge and secure consensus over the choice of technologies that would valorize stoping operations.

Role of Collaboration in the Technology's Development

Chapter Nine analyzed the role of collaborative research in creating the necessary technologies to change stoping practices. It showed a high degree of overlap between inter-organizational relationships in production and the relationships under which these technologies were cooperatively developed. These inter-relationships are important features that unfortunately often end up as un-integrated background in innovation studies. Innovation depends on commercial viability as well as technical capability, ignoring either leads to a misleading understanding of what drives innovation.

The inter-organizational relationships in productive and innovative collaborations from this case were not limited to economic dimensions, but encompassed political dimensions as well. 1910 marked the establishment of the South African nation, accompanying it was a greater coordination of regional political economic concerns. Generally, these concerns of the South African state centered on the predominantly rural white population, the emergent agricultural sector, and the mining industry. Implementation of these changes in stoping practices materialized from this critical state support. Thus, there is clear call from this analysis for remembering the basics of a classical political economic approach.

Distributed innovation best described the power exerted across and along the production chain in order for the cluster of technologies transforming stoping practices to be adopted. Those technologies covered areas from managerial inventions to mechanical and medical technologies with major implication both within and outside the Witwatersrand gold mining industry. As a result, the transformation of stoping practices were of tremendous significance in terms of both its contemporary impacts and its broader socio-economic legacy. Distributed innovation captured these effects through unique attention to both supply and demand dynamics. On the supply-side, cosideration was given to the interactions between the technologies development and the broader production environment. On the demand-side, the industry's rising global

[2] See the chapter on the Witwatersrand in Morrel (1940) for a description of the industrial precedents it established in mining.

significance in production and the associated political and economic authority that position entailed was analyzed.

In its analysis of the dynamics of collaboration, the collective action approach showed why with clear dominance, the Corner House would allow free riding on its innovative efforts. Namely that the technology required broad industry acceptance if it was to surmount the resistance of the labor force to its reorganization. Thus, the Witwatersrand mining industry was a privileged group, benefiting from the large and relatively efficient operations of the industry leader. It is also worth noting that previous analyses did not discuss this fundamental role played by the Corner House group in development of these technologies that critically changed stoping practices.

The industry matured and research and development functions, within and between the mining-finance groups, were increasingly routinized. Thus, the local system of innovation was again clearly important to the successful development of these technologies. Though not capturing the central forces propelling research collaboration, the industrial district approach again provided critical insights to understanding the associated local and individual dynamics of knowledge creation and innovation. Across the Witwatersrand, other mining-finance groups followed the efforts from the Corner House to develop these new technologies, providing evidence thereby of an internalization of technological externalities within the local industry.

Relationship to the Innovation System

As with the development of cyanide-based extraction, adaptation of foreign technologies was prominent in this case. The ability to make these adaptations is a notable characteristic of South Africa's innovative capacity. In their text on industrial innovation Freeman and Soete (1997) noted a similar ability by firms in the United States during the later decades of the 19th century: "Firms in the United States were able to take advantage of a rich endowment in natural resources and large domestic market to develop and exploit new technologies in these industries. American firms were particularly successful in scaling up new techniques of production and marketing and became world leaders in many industries despite the fact that many of the original innovations and most of the related scientific work had been performed in Europe" (p. 85).

The adaptation of foreign technologies to local conditions is a large quantity of the innovation that occurs in international technology transfers, particularly when the transfers occur between relatively more developed economies to less developed economies. It is interesting to note therefore that South African firms in these early decades of the 20th century were following a similar pattern to a nation like the United States, which was subsequently able to develop its own leading edge capacity in technology creation.

In the development of new stoping practices, the active dissemination of innovative resources by the Corner House supported the development of broader national innovative capacity in mining technologies. In addition, the growth of Witwatersrand gold mining created industrial demand that encouraged further development of local technical infrastructure. Besides the growth of mining related technical institutions like the University of Pretoria and the University of the Witwatersrand, other tertiary institutions began to emerge. In fields like medicine, agriculture, and manufacturing local innovative capacity advanced through associated institutes like SAIMR, 1912; the Onderstepoort Veterinary Research Institute, 1908; and SABBSI in 1918. The formation of the Union of South Africa in 1910 also added a more coherent government coordinating capacity over research as is evidenced by the 1916 formation of the Industrial

Research Committee. A truly South African national system of innovation emerged during this period, which would be of regional and international significance.

Implications for South African Historiography

Since these changes in stoping practices led to the establishment of the first large industry in South Africa, they influenced not only their own industry's dynamics, but established a precedent for the general pattern of industrial development in South Africa. This case of changing stoping practices on the Witwatersrand has carried great historical significance in the political economic history of South Africa; through it the 'colour bar' or racially based occupational mobility restrictions became entrenched in South Africa[3].

Through its reservation of the highest paid jobs for whites and the lowest paid jobs for blacks, the colour bar facilitated the entrenchment of racially based inequality in South Africa. This policy structurally limited the number of skilled employees in South Africa and began to generate particularly acute skilled labor shortages as South African manufacturing grew in the 1960s. The scarcity led to a gradual liberalization of the colour bar restrictions in the 1970s and by the 1980s black trade union representation was actively pushing for the complete repeal of these racial occupational mobility restrictions (Davenport and Saunders, 2000, p. 642). In the drive to remove these occupational restrictions, entrenched since the 1922 reorganization of stoping practices on the Witwatersrand, the black trade unions became de facto political voices for the banned black political parties. This political role was reflected in the ruling alliance between the African National Congress, the South African Communist Party, and the Congress of South African Trade Unions elected in South Africa's first democratic elections in 1994 and which continues to govern today.

Recent analyses acknowledge the complexity of the mining-finance groups' role with regard to the advancement of the colour bar. This study of the actual technologies and occupational changes in stoping practices demonstrates the important role that technological dynamics played in the shaping of broader political economic forces. The replacement of artisanal skills in underground stoping was a primary goal of the mines' changing stoping practices. When this reorganization was possible following the 1922 Rand Revolt, the efficiency gains were such that retention of racial occupational mobility restrictions were tolerated because the productivity gains at that time from a complete relaxation of occupational mobility restriction would not offset the political costs of a more extensive white labor displacement.

The mounting cost pressures throughout the 1920s meant that the mines wanted to finish developing and diffusing the improved stoping practices as quickly as possible. Therefore when the Hildick-Smith decision of 1923 offered further legal opportunities for non-racial underground labor force reorganization they were not acted upon because of potential delays from white, now predominantly Afrikaner, labor resistance. The legacy of prior racial division therefore did not outweigh the non-racial technological operating efficiencies. Racial occupational mobility restrictions persisted in the Witwatersrand, thereby supporting their broader industrial imposition and adding momentum to an industrial policy that would discriminate and suppress the majority of South Africa's population for most of the rest of the century.

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[3] Two particularly informative and detailed descriptions of this entrenchment of the 'colour bar' can be found in Johnstone (1976) and Yudelman (1984).

The importance of this case for South African historiography is not just in its contribution to understanding the colour bar. It also presents an important snap-shot of the early development of the national system of innovation and the role played by collaboration in its development. This is critical to understanding the development of subsequent features of South Africa's national innovative capacity and its current structure. For instance, COMSA subsequently created an important cooperative research organization that is now an operating division within the national Council for Scientific and Industrial Research. Mining has underwriten most of South Africa's economic history and had a major influence on the national innovative system. Thus, this investigation marks an important contribution to understanding the current dynamics and comparative strengths in South Africa's national system of innovation.

The causes of South Africa's economic growth experience and its future prospects require a better understanding of the broader impacts from extraction of South Africa's mineral resources. While many less economically developed nations hail natural resources as a curse, this need not be the case. David and Wright (1997) have shown that a major factor in the economic development of the United States was associated with productivity improvements in its natural resource sector and not just a passive comparative endowment. Compared with many other nations and its regional counter parts South Africa has exhibited a similar pattern of dynamic growth in its mineral economy. Unpacking this aspect of its political economy therefore contributes to improved policies for national economic development.

10.2.3 Select Issues from the Case Studies for Further Analysis

Together these case studies indicate the early emergence and evolution of South Africa's national system of innovation. Given the Witwatersrand's long held position as the engine of South Africa's economy, its historical dynamics at the sectoral level are important to expand our contemporary understanding of both the national and sectoral systems of innovation. The rich historical record holds a tremendous amount of information for further investigations of this early evolution. Further detailed systems of innovation analysis would advance understanding of South Africa's core innovative competences. Mining is a logical first choice for an analysis of innovative competence during the years of these two case studies, 1886 to 1933. However, in both cases solutions to their respective challenges came from a diversity of disciplines. Chemistry, medicine and physics developed locally as distinct research fields because of the Witwatersrand's mining industry. These histories need recording if the legacy of the past innovative system is to guide contemporary innovation policies. Analyses of this sort, utilizing a rich historical record of the innovative system, would also contribute to the systems of innovation approach, adding an emphasis on dynamics within innovative systems and breaking from its tendency to focus upon narrow science-based activities (Lundvall *et al.* 2002, p. 216).

Both cases were in the same narrow industry and productive location, Witwatersrand gold mining. Contemporary importance and the significance of collaborative research in their development motivated their selection. With these cases as benchmarks, there are numerous directions to develop further case studies and comparative analyses. In the same period as these cases, cooperation occurred in other aspects of innovation and production. An analysis that compared these experiences with other collaborative experiences in African labor recruitment, electricity generation, and shaft design would further develop understanding about the complexities of simultaneous cooperation and competition.

Witwatersrand gold mining dominated, but co-existed with gold mining in other parts of southern African during this period. Kimberley diamond mining preceded and persisted during these cases, and other diamond producing districts emerged. Coal mining materialized as another significant mineral industry in South Africa by 1933. Because there was significant overlap in the ownership structures of these activities, comparing the collaborative research experience of these commodities would highlight the role downstream market structure plays in facilitating or hindering cooperation.

During most of the 20th century, enduring collaboration in production and associated research activities characterized gold mining in South Africa. Particularly in the 1990s, research collaboration within the industry decreased substantially. International reintegration and the imposition of market discipline on the large South African mining-finance groups was a partial cause for this decline in collaborative research. The implications and permanency of this transformation are not yet clear. One way to assess the costs and benefits of this decrease in research collaboration is through the lessons of these cases, and further analyses of other innovations significantly developed by a process of collaboration in the decades between the 1930s and 1980s.

Though mining dominated the South African economy for most of its history, significant industrial development also occurred. The large mining-finance groups were large players in the financing and management of South Africa's industrial development. Investigating research collaborations in other sectors of South Africa's economy would broaden the comparison. Because of the limited analysis of technological dynamics in South Africa, the list of other intra-sectoral, inter-sectoral, inter-temporal, and inter-regional combinations for further analysis is massive. It is not just within South Africa that further development of our knowledge is need. International comparisons are critical future analytical developments both for the South African context and for our general understanding of collaborative research.

10.3 ANALYTIC APPROACHES

Chapter Five previously reviewed and compared the analytical approaches in considerable detail. Therefore, this section briefly reviews a comparative summary of the theoretical approaches before considering their respective insights across the two case studies. We conclude with a discussion of some select issues for further research.

TABLE 10.1 A SUMMARY AND COMPARISON OF THE ANALYTICAL MODELS

Industrial District Approach			
Structure: Components	Structure: Relationships	Causal Conditions	Effects
1) Socio-territorial Entity 2) Community 3) Firms & Institutions 4) Human Resources 5) Markets	I) *Production System* II) *Knowledge System* III) *Socio-Political System*	1) Spcl. Factor Endowments	1) Agglomeration Extrn.
Collective Action Approach			
Structure: Components	Structure: Relationships	Causal Conditions	Effects
1) Public – Collective Goods 2) Overlapping Activities	I) *Convention System* II) *Collective Supply Function*	1) Favorable Group Structure	1) Net Social Welfare
Distributed Innovation Approach			
Structure: Components	Structure: Relationships	Causal Conditions	Effects
1) Innovative Object 2) Mechanisms of Coordination 3) Mechanisms of Competition	I) *Product Provision* II) *Innovation Provision*	1) Push Factors 2) Pull Factors 3) Constr. Circumstances	1) Distributed Relationships 2) Innovations Generated

In terms of structure, all three approaches allow for some means by which trust is developed and subsequently used to facilitate a collaborative research endeavor. Community in the industrial district approach, overlapping activities in the collective action approach, and mechanisms of competition in the distributed innovation approach all act to develop a stock of trust or social capital. In all three approaches, this stock of social capital is used to encourage cooperation that facilitates research collaboration. The distributed innovation approach refers to these powers against defection from cooperation as mechanisms of coordination, while the collective action approach refers to them as the convention system, and the industrial district approach calls them the socio-political system.

While sharing a fundamental means to support collaborative research endeavors, the analytical approaches vary in their structural analysis of research collaboration. Both the industrial district approach, through the productive system, and the distributed innovation approach, through product provision, directly consider the role played by production of some good or service in the collaborative provision of a technology for that good or service. Similarly, the industrial district approach, through the knowledge system, and the distributed innovation approach, through innovation provision, directly consider the role played by the innovative system in collaborative provision of a technology for that good or service. In contrast, these are only indirectly considered in the collective action approach through their effect on the collective supply function. However, the technology created by the research collaboration is not directly considered in the industrial district approach, its concern being upon the underlying conditions in which a technology is collaboratively developed, *i.e.* the agglomeration externalities in the district. Both the collective action approach and the distributed innovation approach provide direct analysis of the collaboratively created technology, respectively as the collective good provided and the innovative object of analysis.

The causal conditions for research collaboration further vary and differentiate each of the approaches. A diversity of causal conditions is captured by these three approaches. In the industrial district approach, the presence of special factor endowments creates the causal conditions for research collaboration. Agglomeration externalities are a fundamental characteristic of an industrial district, which support the collaborative development of a technology. The collective action approach regards a favorable group structure as the causal conditions for collaborative research. The potential scale and scope of collectively providing a technology is determined by the group structure. Lastly, the distributed innovation approach considers push factors, pull factors, and constraining circumstances associated with the technology as forming the causal conditions for research collaboration and its subsequent growth or decline.

Because of their selection of causal conditions, each approach distinctly examines the relationship between the resulting technology, the collaborative system, the broader innovative system, and the socio-economic system. Hence, once technologies are being collaboratively developed, the distributed innovation approach focuses on the influence those technologies have on subsequent research collaborations and their effect on the associated dynamics of the productive and innovative systems. In contrast, the collective action approach focuses on whether the structure through which the technology was collectively provided would be supported or undermined by the technologies. Lastly, the industrial district approach considers whether the agglomeration externalities, generated as a result of favorable initial factor endowments, are sustained or damaged by the collaboratively developed technologies. All of the approaches consider the broader effects of the collaboratively developed technology. In each, the degree of cooperation and the boundaries of competition are influenced by the innovations generated in the cooperative initiatives.

In conclusion, while the industrial district approach focuses on the circumstances in which research collaborations occur, the collective action approach concentrates on the collaborative vehicle through which technologies are developed, and the distributed innovation approach highlights the influence that the technology itself carries over the political-economic environment. Each approach thereby enhances our understanding of certain aspects of research collaboration and the associated technologies generated from them. Research collaborations are complex phenomenon that the simple analytical clarity of any one approach does not adequately capture. We have shown that employing all three methodologies led to a more thorough understanding of collaborative research and its associated technologies.

10.3.1 Industrial District Approach and the Cases

The localized focus of the industrial district approach was particularly informative in the case of development of cyanide-based gold extraction. In that period, local industrial development was paramount. Precedents at Kimberley's diamond mines facilitated establishment of a community that saw mutual benefits in pooling resources to solve pressing technical challenges. With a concentration of international metallurgical expertise and an open policy of technical performance release by the mines, the industrial district approach appeared to explain many features of research collaboration in this case.

The subsequent case analyzed the transformation of stoping practices. While some of the district's features continued to have important explanatory powers, the approach missed a significant portion of technological dynamics that characterized the research collaboration. Managerial innovations were an important component in changing stoping practices and these involved re-designing the organization of the stoping labor force. Racially differentiated political power of the mines' labor force strongly determined the structure of this reorganization. Not only is there a tendency to assume homogeneity of actors in the industrial district approach, but there is also a limited focus on the incremental iterative dynamics of technology development. Given the importance of these two features in the changing of stoping practices, the limited explanatory power of the industrial district approach was expected.

Another interesting facet of the industrial district approach in these cases is the productive system. The modern popularity of the industrial district approach stems largely from its ability to explain the competitiveness of relatively small and localized firms. In both of these cases, the research collaboration occurring in the district generated technologies that increased the scale of efficient operations. Thus, the Witwatersrand district became increasingly competitive as its firms became increasingly large.

The analysis of research collaboration through the industrial district approach highlighted the important interaction between production and knowledge systems. The local nature of information flows and knowledge creation are thereby linked to the broader product market and division of production. Given the competitive focus of the approach, it is unfortunately lacking in translating these characteristics into systematic implication over the district's dynamic competitiveness.

10.3.2 Collective Action Approach and the Cases

Collective action forces an explicit consideration of economic motivations supporting research collaboration. In the case of changing stoping technologies, this provided considerable explanatory power over the asymmetric contribution of mining-finance groups to development of the technology. Its analysis of the effects from those changes in stoping practices enabled us to differentiate the group benefits from the innovation and the broader social costs from the adopted organizational structure.

Its application to the case of cyanide-based extraction highlighted the role of local interactions to the formal and informal information exchanges among the mines. The case of cyanide-based extraction also generated some analytical difficulties in separating the unintentional from the intentional causes of collective action. The case also highlighted an important tendency in consideration of the impacts of research collaboration. Our analysis focused on considering the direct and indirect benefits research collaboration to those groups that were directly involved in production. However, both British Colonial and Afrikaner interests were directly related to the success or failure of the resulting technology. Incorporating these broader institutional relations adds further coherence to the picture of net social welfare than the narrower focus on agents directly involved in production alone.

10.3.3 Distributed Innovation Approach and the Cases

Distributed innovation is similar to the industrial district approach in its explicit examination of productive and innovative systems. However, in its greater focus on the structure of power and the resultant interactions between these systems, the distributed innovation approach captures important nuances in these relationships. The case of changing stoping practices demonstrated this. In that case, the structure of agent power played a crucial role influencing the features of the distributedly developed technology.

The approach also highlighted the subtle, but important differences in the co-existence of competition and co-operation between cases. In the first case, it illustrated an industry with aggressive competition for scarce international finance, both speculative and developmental, but a simultaneous realization among mining operations that cooperation in production technologies was in their self-interest. By the second case, industrial consolidation had slowed the pace of financial competition, but mounting cost pressures placed a strong emphasis on producer cooperation to realize the necessary technological changes in production.

In the frontier and emergent mining enclave setting that characterized the first case study there was a significant role played by social conventions. While these are captured in the distributed innovation approach through its description of allocative relationships, the distinct inter-agent colonial and international mining rush influences are rather washed-out in such a placement. Therefore, the distributed innovation approach is somewhat restricted in its ability to distinguishing between the types of extra-local and local social influences seen the case of cyanide-based extraction of gold.

10.3.4 Select Issues from the Analytical Approaches for Further Analysis

Through its comparative application of methodologies that consider both informal and formal dimensions of research and productive collaborations, this analysis marked an important step in advancing theoretical and empirical understanding over these complex phenomenon. Tracing two sequential cases of innovation where research collaboration played an important role, this analysis highlighted critical dynamic features. In particular, it showed that as the industry and technological methods become more established and the technologies' characteristics changed, the structural relationships and causative forces in research collaboration evolved. Associated with this, the explanatory power of the respective methodologies varied. None of the approaches, not even the relatively comprehensive Distributed Innovation, was superior for analyzing all aspects of collaborative research.

In the first case, the Industrial District approach captured a large extent of the research collaboration, but as the industry and its technology became more codified in the second case the industrial district approach lost some of its explanatory scope. Until we derive a better understanding of the complex nuances of innovation and its inter-relationship to productive activities, a comprehensive methodology awaits. As such, given our current knowledge the best way to analyze existing research collaborations, their creation, growth, and destruction, as well as to formulate policies to enhance their positive benefits is through a process of appreciative theorizing at a level close to the empirical subject matter.

In the second case, the Distributed Innovation approach provided the greatest insights into the role played by the broader contextual conditions in facilitating a collaborative research structure. The Collective Action approach also explicitly raised the issue of effects on net social welfare from collaboratively developed technologies and the associated weight which exclusive political authority places on that calculation. This brought up a fundamental issue that needs to be further analyzed and developed in the analytical approaches. Collaborative research definitely has an important role to play in enhancing the efficiency of innovation, but that is not a universal role. Collaboration carries its own disadvantages as well as advantages, which this analysis has illustrated. A critical area of further research needs to deepen our understanding in what conditions collaborative development carry the greatest net social benefits as well as developing our understanding of where, despite initial appearances alternative structures might be more beneficial.

10.4 CONCLUSION

In an increasingly globalized world, collaboration can be central to an industry's international competitiveness. Modern South Africa is abundant in examples where a lack of collaboration contributes to a sector's underdevelopment. Therefore, in contrast to the historic instances of collaboration discussed at length so far, a brief example from contemporary South Africa is useful to demonstrate why it is important for competitiveness.

Owing to sanctions and isolation of the previous regime, South Africa emerged in 1994 as a democratic nation with an inwardly focused industrial structure. Increased liberalization of the economy after 1994 occurred within a setting of strong intra-national competition. Evidence that the legacy of internal competition inhibits South Africa from leveraging its existing capacity to its full competitive potential can be gleamed from a brief appraisal of plastic converting firms in Ekurhuleni.

Ekurhuleni is a municipality immediately to the east of Johannesburg. Ekurhuleni's plastic converters are the largest concentration of plastic converters in South Africa, accounting for nearly a third of all domestic plastic manufacturing (Dobreva et al. 2005). The agglomeration is primarily composed of numerous small firms engaged in semiskilled or unskilled labor intensive production.

Polymers account for the majority of input costs incurred by Ekurhuleni plastic converters (Dobreva et al. 2005). In contrast to many countries, South African manufactured polymers are derived from coal rather than oil. Despite liberalization of the economy, a ten percent tariff continues to be imposed on all imported polymers that can be produced locally from coal. While the tariff was created to foster a domestic polymer manufacturing industry, today it is a burden on labor intensive plastic converts as capital intensive domestic polymer manufacturers add the tariff in their import parity pricing of polymers.[4]

There are no plastic converter associations based in Ekurhuleni, but there are national associations.[5] Notably, both of the primary national associations are directly or indirectly supported by Sasol, the largest domestic manufacturer of polymers. Structured interviews with plastic converters in Ekurhuleni also identified a shortage of technically skilled personnel as being a competitive concern. However, the majority of firms also expressed an unwillingness to invest in localized skill training due to concerns about potential losses to other Ekurhuleni plastic converters (Dobreva et al. 2005).

Recent manufacturing surveys in Ekurhuleni showed that plastic converters remain focused on local markets.[6] In general, these plastic converters are competing for established local market share rather than broadening local markets and looking for their international comparative advantage. While there are no associated public or tertiary research institutes in Ekurhuleni, national institutes were identified as being far removed from the needs of domestic plastic converters (Dobreva et al. 2005).

Sasol dominates local technical services by offering free technical services to its customers. Some active in the industry have suggested that Sasol uses this service to perpetuate a dependence on its inputs. Other domestic technical and research service capacity in the private sector appears to be under utilized because of its diffused nature, the lack of a network linking it to domestic plastic converters, and the existence of Sasol's tariff supported technical services (Dobreva et al. 2005).

This brief sketch of Ekurhuleni plastic converters highlights a few areas where greater collaboration could enhance local competitiveness. These include formation of a local skills training initiative, coordinating and consolidating local research and technical service capabilities, and lobbying for concessions on domestic polymer tariffs. In fact, faced with increasing trade liberalization, the continued growth and development of the sector seemingly depends on greater collaboration in a range of areas across the production and innovation systems.[7]

The situation of Ekurhuleni plastic converters is not unique. International economic integration has generated competitive challenges in many areas of the South African economy as well as other economies around the world. Collaboration in general and research collaboration in particular are important means to enhance local competitiveness in an integrated world economy. However, collaboration is not a panacea for globalization. The histories of research collaboration in this analysis have shown several negative social externalities associated with collaboration.

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[4] For further details on the domestic pricing of polymers see Dobreva et al. (2005).

[5] The two largest associations are the Plastics Federation of South Africa and the Plastics Converters Association.

[6] These surveys have been conducted for the Ekurhuleni Municipality by the Corporate Strategy and Industrial Development Research Unit in the School of Economics and Business Sciences at the University of the Witwatersrand.

[7] See: Pogue (2005).

A particular problem with collaboration is that the networks along which collaboration occurs can form a basis for exclusion. In an increasingly integrated world this exclusion endangers expanding the gap between the economically advantaged and disadvantaged. The case study on the transformation of stoping practices clearly illustrated that potential, where exclusion of low-wage African workers led to the growth and institutionalization of racial occupational mobility restrictions.

Today, poverty and inequality are major challenges to international development. Collaboration can be a powerful tool to facilitate economic development, but its structure and dynamics must be monitored on a systematic basis to avoid perpetuating undesirable divisions. Through its assessment of theoretical approaches and historical instance of collaborative research this analysis sought to increase understanding about the nature of research collaboration and its potential role in facilitating contemporary inclusive economic development.

Appendix One: Names of Select Journal

Journal of the Chemical, Metallurgical and Mining Society of South Africa (JCMMSA)
Proceedings of the Chemical and Metallurgical Society of South Africa (1894-1902)
Journal of the Chemical, Metallurgical and Mining Society of South Africa (1903-1956)
Journal of the South African Institute of Mining and Metallurgy (1956 - Present)

Journal of the Insitute of Mine Surveyors of South Africa (JIMSSA)
Proceedings / Institute of Mine Surveyors of the Transvaal (1905-1923)
Journal / Insitute of Mine Surveyors of South Africa (1923-1951)
Journal of the Insitute of Mine Surveyors of South Africa (1951-1981)
Insitute of Mine Surveyors of South Africa Journal (1981-Present)

Journal of the South African Institution of Engineers (JSAIE)
Proceeding of South African Association of Engineers and Architects (1892-1898)
Proceeding of South African Association of Engineers (1899-1910)
Journal of the Mechanical Engineers Association of the Witwatersrand (1902-1906)
Journal of the Transvaal Institute of Mechanical Engineers (1906-1911)
Transactions of the South African Institution of Engineers (1912-1950)
Journal of the South African Institution of Engineers (1912-1950)
Journal of the South African Institution of Mechanical Engineers (1950-1955)
South African Mechanical Engineer (1955-Present)

Proceedings of the Geological Society of South Africa (PGSSA)
Transactions and Proceedings / Geological Society of South Africa (1896-1903)
Transactions / Geological Society of South Africa (1904-1945)
Proceedings / Geological Society of South Africa (1904-1945)
Transactions and Proceedings / Geological Society of South Africa (1946-1970)
Proceedings / Geological Society of South Africa (1970-1987)
GeoBulletin (1984-Present)
South African Journal of Geology (1987-Present)

South African Journal of Science (SAJS)
South African Association for the Advancement of Science Annual Report (1903-1909)
South African Journal of Science (1909-Present)

South African Mining and Engineering Journal (SAMEJ)
South African Mining Journal and Financial News (1891-1903)
South African Mines, Commerce and Industries (1903-1908)
South African Mining Journal (1908-1918)
South African Mining Journal and Engineering Record (1918-1919)
South African Mining and Engineering Journal (1919-1984)
South African Mining, Coal, Gold and Base Minerals (1985- Present)

South African Medical Journal (SAMJ)
South African Medical Record (1903-1926)
Transvaal Medical Journal (1905-1913)
Medical Journal of South Africa (1913-1926)
Journal of the Medical Association of South Africa (1926-1931)
South African Medical Journal (1932-Present)

Transactions of the Royal Society of South Africa (TRSSA)
South African Quarterly Journal (1829-1836)
Cape Monthly Magazine (1857-1881)
Transactions of the South African Philosophical Society (1877-1909)
Transactions of the Royal Society of South Africa (1909-Present)

Appendix Two: Names of Select Associations

Chamber of Mines of South Africa (COMSA)
Witwatersrand Chamber of Mines (1889-1896)
Chamber of Mines of the South African Republic (1897-1901)
Transvaal Chamber of Mines (1902-1952)
Transvaal and Orange Free State Chamber of Mines (1953-1967)
Chamber of Mines of South Africa (1968-Present)

Chemical, Metallurgical and Mining Society of South Africa (CMMSSA)
Chemical and Metallurgical Society of South Africa (1894-1902)
Chemical, Metallurgical and Mining Society of South Africa (1903-1956)
South African Institute of Mining and Metallurgy (1956 - Present)

Institute of Mine Surveyors of South Africa (IMSSA)
Institute of Mine Surveyors of the Transvaal (1903-1923)
Institute of Mine Surveyors of South Africa (1923-Present)

Medical Association of South Africa (MASA)
Cape Province Medical Council (1903?-1926)
Transvaal Medical Society (1895-1905)
British Medical Association, Witwatersrand Branch (1905-1925)
Medical Association of South Africa (1926-1998)
South African Medical Association (1998-Present)

Royal Society of South Africa (RSSA)
South African Institution (1829-1832)
South African Literary Society (1829-1832)
South African Literary and Scientific Instsitution (1832-1857)
South African Philosophical Society (1877-1909)
Royal Society of South Africa (1909-Present)

South African Chemical Institute (SACI)
South African Association of Analytical Chemists (1912-1921)
South African Institute of Assayers and Analysts (1922-1993)
South African Chemical Institute (1921-Present)

South African Institution of Engineers (SAIE)
South African Association of Engineers and Architects (1892-1898)
Mechanical Engineers' Association of the Witwatersrand (1898-1905)
Transvaal Institute of Mechanical Engineers (1905-1910)
South African Association of Engineers (1898-1910)
South African Institution of Engineers (1910-1950)
South African Institution of Mechanical Engineers (1950-Present)

South African Institution of Electrical Engineers (SAIEE)
South African Society of Electrical Engineers (1897-1904?)
South African Institution of Electrical Engineers (1909-Present)

South African Sugar Association (SASA)
South African Sugar Technologists Association (1922-1951)
South African Sugar Association (1915?-Present)

Appendix Three: Names of Select Institutions

Cape Technikon (CT)
Cape Technical College (1920-1968)
Cape College of Advanced Technical Education (1969-1978)
Cape Technikon (1979-2004)
Cape Peninusla University of Technology (2005-Present)

Fuel Research Institute (FRI)
Fuel Research Institute (1930-1983)
CSIR National Institute for Coal Research (1984-?)

Geological Survey of South Africa (GS of SA)
Geological Survey of the Cape of Good Hope Colony (1895-1912)
Zuid-Afrikaansche Republiek, ZAR, Geological Survey (1897-1899)
Natal Colony Geological Survey (1899-1905)
Geological Survey of the Transvaal (1903-1912)
Geological Survey of South Africa (1912-1993)
Councial for Geosciences (1993-Present)

ML Sultan Technikon (MLST)
Indian School (1929-1946)
Hindu Tamil Institute (1929-1946)
Malukmahomed Lappa (ML) Sultan Technical College (1946-1969)
ML Sultan College of Advanced Technical Education (1969-1978)
ML Sultan Technikon (1979-2004)
Durban Institute of Technology (2004-Present)

PE Technikon (PET)
Port Elizabeth (PE) Art School (1882-1923?)
PE Technical College? (1923?-1969)
PE College of Advanced Technical Education (1969-1978)
PE Technikon (1979-2004)
Nelson Mandela Metropolitan University (2004-Present)

Potchefstroom University (PUK)
Theological School of the N.G. Kerk (1869-1919)
Theological School transferred from Burgersdorp to Potchefstroom (1904)
Het Potchefstroom Universiteitskollege voor Christelike Hooger Onderwijs (1919-1921)
Potchefstroom University College (1921-1933)
Potchefstroom University College for Christian Higher Education (1933-1951)
Potchefstroom University for Christian Higher Education (1951-2004)
University of the North-West (2004-Present)

Pretoria Technikon (PT)
Pretoria Technical School? (1897-1906)
Pretoria Polytechnic School (1906-1908)
Pretoria Trades School and Polytechnic (1909-1925)
Pretoria Technical College (1926-1968)
Pretoria College for Advanced Technical Education (1969-1978)
Pretoria Technikon (1979-2003)
Tshwane University of Technology (2004-Present)

Appendix Three (Cont.) Names of Select Institutions

Research Grant Board (RGB)
Research Grant Board (1917-1938)
National Research Board (1938-1946)
CSIR Research/University Grants Division (1946-1984)
CSIR Co-operative Scientific Programmes (1975-1984)
HSCR Center for Science Development (1970s?-1999)
Foundation for Research Development (1984-1999)
National Research Foundation (2001-Present)

Rhodes University (Rhodes)
St Andrew's College (1855-1904)
Rhodes University College (1904-1951)
Rhodes University (1951-Present)

South African Branch of the British Standards Institute (SABBSI)
Committee for Standardisation of South African Material (1909)
South African Engineering Standards Committee (1910-1918)
South African Branch of the British Engineering Standards Association (1918-1931)
South African Branch of the British Standards Institute (1931-1934)
South African Standards Institute (1934-1945)
South African Bureau of Standards (1945-Present)

Technical Advisory Committee (TAC)
COMSA Technical Advisory Committee (1922-1986?)
Chamber of Mines Research Organisation (1964-1993)
CSIR Mining Technnology (1993-Present)

Technikon Natal (TN)
Durban Technical Institute (1907-1915)
Durban Technical College (1915-1923)
Natal Technical College (1923-1969)
Natal College of Advanced Technical Education (1969-1978)
Technikon Natal (1979-2004)
Durban Institute of Technology (2004-Present)

Technikon Witwatersrand (TWR)
Witwatersrand Technical Institute (1925-1930)
Witwatersrand Technical College (1930-1969)
Witwatersrand College of Advanced Technical Education (1969-1978)
Technikon Witwatersrand (1979-2004)
University of Johannesburg (2005-Present)

University of Cape Town (UCT)
South African College (1829-1918)
University of Cape Town (1918-Present)

University of Fort Hare (UFH)
South African Native College (1916-1951)
University of Fort Hare (1951-Present)

University of Kwa-Zulu Natal (UoN)
Natal University College (1910-1951)
University of Natal (1951-2004)
University of Kwa-Zulu Natal (2004-Present)

Appendix Three (Cont.) Names of Select Institutions

University of South Africa (UNISA)
University of the Cape of Good Hope (1873-1918)
University of South Africa (1918-Present)

University of the Free State (UFS)
Grey College School (1855-1906)
Grey University College (1906-1918)
University College of the Orange Free State (1918-1951)
University of the Orange Free State (1951-2001)
University of the Free State (2001-Present)

University of Pretoria (UoP)
Transvaal University College in Johannesburg (Wits) establishes Pretoria Campus (1906-1910)
Transvaal University College (Wits) transfers Arts & Sciences to Pretoria Campus (1908)
Transvaal University College transferred from Johannesburg to Pretoria (1910)
Transvaal University College (1910-1930)
University of Pretoria (1930-Present)

University of Stellenbosch (UoS)
Stellenbosch Gymnasium established (1866-1881)
Stellenbosch College (1881-1887)
Victoria College of Stellenbosch (1887-1918)
University of Stellenbosch (1918-Present)

University of the Witwatersrand (Wits)
South African School of Mines (1894-1904)
South African School of Mines tranferred from Kimberely to Johannesburg (1904)
Transvaal Technical Institute (1904-1906)
Transvaal University College (1906-1910)
South African School of Mines and Technology (1910-1920)
University College of Johannesburg (1920-1922)
University of the Witwatersrand (1922-Present)

Appendix Four: Select Mining-Finance Group Histories: 1886 to 1902

A. Goerz & Co. Group namesake (Adolf Goerz) arrived on Witwatersrand 1888 forming group in 1897 to develop Far East Rand properties.

Anglo-French This group was formed by George Farrar in 1889. Under his guidance he formed the largest blocks of mines on the Witwatersrand, The East Rand Proprietary Mine (ERPM) in 1893.

Barnarto Brothers See: *JCI*.

Corner House This group was led by many individuals but most prominently Alfred Beit and Julius Wernher. Interlinked with *L. Breitmeyer & Co.* who held group diamond interests. During this period, *Wernher, Beit & Co.* operated two sub-groups *H. Eckstein & Co.* built on holdings acquired since 1887 and *Rand Mines Ltd.* established in 1893.

Farrar See: *Anglo-French*.

General Mining and Finance Corp. Formed by George Albu in 1895 on interests acquired since 1888.

Gold Fields Established in 1887 under the reputation and to a lesser extent guidance of Cecil John Rhodes until his death in 1902.

H. Eckstein & Co. See: *Corner House*.

Johannesburg Consolidated Investment Co. *Johannesburg Consolidated Investment Co.* (JCI) was established in 1889 under Barney Barnato's guidance. Interlinked with *Barnato Brothers* who held group diamond interests while *JCI* held gold interests. After Barnato's death in 1896 Solly Joel took charge of both companies.

L. Breitmeyer & Co. See: *Corner House*.

Robinson This group was formed on two large mines, Langlaagte and Randfontein, by Joseph B. Robinson following establishing his independence from the *Corner House* in 1895.

Sigismond Neuman Group is namesake of entrepreneur from Kimberley who founded and held several mines on the Witwatersrand.

South African Gold Mines Established by Abe Bailey in 1897. Under his guidance the group specialized in acquiring shares in deep level mines that *Gold Fields* and the *Corner House* were slow to move on.

Wernher, Beit & Co. See: *Corner House*.

Appendix Five: Select Mining-Finance Group Histories: 1903 to 1933

A. Dunkelsbuhler & Co. See: *AAC.*

African & European Investment Corporation See: *Lewis & Marks.*

A. Goerz & Co. After death of A. Goerz in 1900, Henry Strakosch appointed Managing Director in London. In 1918, during the First World War, the name was changed from *A. Goerz & Co.* to the *Union Corporation Ltd.* Control of the *Union Corp.* was acquired by *Federale Mynbou* in 1975 and in 1980 it was merged with *Federale Mynbou*'s *General Mining Corp* to form *Gencor* and now forms part of *GoldFields.*

Anglo American Corporation Formed by Ernest Oppenheimer in 1917 to develop gold-bearing reserves on the Far East Rand held by the *Consolidated Mines Selection Company* (CMSC). *CMSC* was formed in 1897 on holdings in the Far East Rand. *A. Dunkelsbuhler & Co.* acquired control of *CMSC* in 1905 and under Ernest Oppenheimer's direction became foundation stone of the *Anglo American Corporation* (AAC) launch in 1917. *AAC* controlled non-diamond mining interests while *A. Dunkelsbuhler & Co.* held group diamond interests until control of *De Beers Mining Corporation* secured in 1931.Today, *AAC* remains one of the world's largest mining companies with its gold operations falling under its *AngloGold Ashanti* subsidiary.

Anglo-French Farrar's group, with its foundation on The East Rand Proprietary Mine (ERPM), was effectively absorbed into the *Corner House* in 1912.

Barnarto Brothers See: *JCI.*

Consolidated Mines Selection Company See: *AAC.*

Corner House Alfred Beit 1906 death was followed by Julius Wernher's in 1912. During this period, *Central Mining and Investment Corp.* was created to replace *Wernher, Beit & Co.* By 1910 *Central Mining* provided essential financial and technical services to *Rand Mines Ltd. Rand Mines* supplied secretarial services to the group's South African operations. Consolidation under *Central Mining* also corresponded to *Rand Mines* controlling all *H. Eckstein & Co.* interests. Structurally, *Central Mining* based in London had central control while *Rand Mines* in Johannesburg was *Central Mining*'s operating agent in South Africa. *Central Mining* was interlinked with *L. Breitmeyer & Co.* who held group diamond interests. *AAC* took control of *Central Mining* in 1958, which led to *Central*'s South African operations being vested with *Rand Mines*. *AAC* merged *Rand Mines* with *Barlow and Sons* in 1971 to form *Barlow Rand Ltd.* In 1992, unbundling of *Barlow Rand* led to formation of *Randgold & Exploration Ltd*. Today, the *Randgold* group continues gold mining and exploration activities across Africa.

Dunkelsbuhler & Co. See: *AAC.*

Farrar See: *Anglo-French.*

General Mining and Finance Corp. After George Albu's death in 1935, *AAC* facilitated *General Mining*'s acquisition by *Federale Mynbou*, an Afrikaner mining group built on coal, in 1965. In 1980, *General Mining* acquired control of the *Union Corp.* (*A. Goerz & Co.*) and the merged company became known as *Gencor*. In 1998, the gold assets of *Gencor* and *GFSA* were merged to form the modern *Gold Fields Corporation*, which today is in merger discussions with *Harmony*.

Appendix Five (Continued): Select Mining-Finance Group Histories

Gold Fields During this period *GoldFields* (GFSA) sustained its position as one of largest groups. In the 1990s, after several changes in its ownership structure *GFSA* was re-launched with a focus on gold mining. In 1998, the gold assets of *Gencor* and *GFSA* were merged to form the modern *Gold Fields* mining company.

H. Eckstein & Co. See: *Corner House.*

Johannesburg Consolidated Investment Co. Solly Joel led *JCI* during this period until his death in 1931. Interlinked with *Barnato Brothers* who held group diamond interests. The group was effectively controlled by the *AAC* from 1963. In 1998, it was unbundled from *AAC* as *JCI Gold* - a black empowerment mining company. With *Consolidated Mines Selection Company* acquiring *JCI Gold* in 2002, it was reformed as new empowerment mining company JCI.

L. Breitmeyer & Co. See: *Corner House.*

Lewis & Marks Named after cousins Issac Lewis and Sammy Marks who besides mining held diverse industrial and property interests across the Witwatersrand and Transvaal. After Sammy Marks death in 1920, Lewis Marks headed the diverse industrial interests of this company. Its mining interests were held principally by its *African & European Investment Corporation*, which was established in 1904. Holdings in the OFS goldfields under *African &European* led to the group's acquisition by *AAC* in 1945.

Robinson J.B. Robinson headed this group, whose principal holdings were Randfontein and Langlaagte until it was eventually taken over by JCI in 1917.

Sigismond Neuman S. Neuman died in 1916 having last visited South Africa in 1910. By 1914 he had largely divested his gold mining interests on Witwatersrand to the *Corner House.*

South African Gold Mine See: *South African Townships, Mining & Finance Corporation.*

South African Townships, Mining & Finance Corporation Abe Bailey formed this group by amalgamating *South African Gold Mines* with his property company *Witwatersrand Townships.* He headed this group until his death in 1940. *South Africa Townships* in turn floated *Western Holdings* in 1937 with significant mineral rights in the Orange Free State (OFS). Acquisition of *Western Holdings* and *South African Townships* by AAC after Bailey's death was critical to establishing AAC in the OFS goldfields.

Union Corp. See: *A. Goerz & Co.*

Wernher, Beit & Co. See: *Corner House.*

Western Holdings See: *South African Townships, Mining & Finance Corporation.*

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Nederlandse Samenvatting (Summary in Dutch)

Deze dissertatie bestudeert de ontwikkeling van samenwerking op het gebied van onderzoek in de goudmijn industrie in Zuid-Afrika tussen 1886 en 1993. Het onderzoek laat het belang zien van collaboratief onderzoek voor innovatie en economische groei. Er zijn drie verschillende methodologische benaderingen gebruikt om meer inzicht te verkrijgen in collaboratief onderzoek. In de dissertatie wordt niet een benadering boven de andere te verkozen of een hele nieuwe benadering voorgesteld; in plaats daarvan laat de dissertatie zien dat de methodes complementair zijn en dat deze complementariteit kan bijdragen tot dieper inzicht van het fenomeen van collaboratief onderzoek. Twee case studies over de gezamelijke ontwikkeling van sleuteltechnologieën illustreren zowel de rol van collaboratief onderzoek in een innovatiesysteem als de ontwikkeling van collaboratief onderzoek en haar relatie met bredere socio-economische omstandigheden.

Een meerderheid van de hedendaagse analyses over collaboratief onderzoek beschouwt collaboratief onderzoek als een fundamenteel kenmerk van het ontstaan van de moderne kenniseconomie. De analyse van de cases in deze studie illustreert verschillende eigenschappen die in de recente theoretische literatuur over collaboratief onderzoek worden beschreven: de coördinatie van agenten middels niet-marktgebonden en niet-hiërarchische mechanismen, het belang van samenwerking bij de ontwikkeling van een internationaal competitieve technologie, en het vaak cruciale gelijktijdige bestaan van competitie en samenwerking. Er wordt tegenwoordig veel gesproken over collaboratief onderzoek, maar het is geen nieuw fenomeen. Deze analyse laat zien dat collaboratief onderzoek een lange geschiedenis heeft die onze moderne begripsvorming kan sturen.

Het is algemeen aanvaard dat technologische verandering een cruciaal drijver van economische groei is. Deze dissertatie gebruikt casestudy materiaal voor het bespreken van drie verschillende theoretische benaderingen met betrekking tot de coördinatie gezamenlijk onderzoek in het innovatieproces. De dissertatie onderscheidt drie perspectieven op onderzoekssamenwerking: industriële districten, collectieve actie en gespreide innovatie. Deze benaderingen verschillen in hun keuze van gebeurtenissen die de aanleiding vormen tot collaboratief onderzoek. Op basis van deze benaderingen kunnen drie analytische modellen worden geformuleerd. Deel 1 introduceert de verschillende analytische benaderingen, met per benadering een hoofdstuk waarin de empirische en theoretische onderbouwing van de benadering besproken wordt, en waarin gestileerde modellen voor de analyse worden gespecificeerd. Deel 1 eindigt met een hoofdstuk waarin de verbanden tussen benaderingen worden besproken en hoe ze zich verhouden tot de analyse van het fenomeen van collaboratief onderzoek. Gezien de uitgebreide literatuur waar de benaderingen op voortbouwen – onder meer de literatuur op het gebied van agglomeratie, externaliteiten, collectieve actie, en de economie van de technologische verandering – is er niet gestreefd naar volledigheid. De focus is op die aspecten van de literatuur die te maken hadden met collaboratief onderzoek.

Elk perspectief is beschreven in termen van zijn structuur, causale voorwaarden, en effecten. Statische en dynamische componenten in de benaderingen zijn beschreven in de sectie over structuur. De sectie over causale voorwaarden specificeert hoe elementen beschreven in de structuur, leiden tot gebeurtenissen die samenwerking en mogelijk andere activiteiten genereren. De sectie over effecten beschrijft de relaties die ontstaan binnen en tussen samenwerkingssystemen, het bredere innovatie systeem en het socio-economische systeem. Het onderscheid tussen de benaderingen in termen van de causale voorwaarden voor het genereren van onderzoekssamenwerking leidt tot een meer omvattende analyse van de case studies dan zou mogelijk geweest zijn bij eenzijdige benadering.

De case studies beslaan de periode voor (case 1) en na (case 2) het ontstaan van de Zuid Afrikaanse Natie. Hoewel slechts een deel van het sectorale en nationale systeem van innovatie wordt geanalyseerd, geeft deze studie toch inzicht in de complexe structuur die een innovatiesysteem is. De goudmijnbouw van Witwatersrand[1] heeft een centrale rol gespeeld in de economische ontwikkeling van Zuid Afrika, en is een belangrijke kracht geweest in de vorming van het politiek-economische milieu. In deze hoedanigheid heeft het een dominante stijl aangebracht in het nationale innovatiesysteem. Door het analyseren van de centrale invloed van technologische verandering op de industriële dynamiek richt deze studie daarnaast de aandacht op een verwaarloosde dimensie van de Zuid-Afrikaanse geschiedschrijving.

Iedere case study illustreert de algemene evolutie van onderzoekssamenwerking die in de industrie te zien was tijdens de respectievelijke periodes. Beide cases bestaan uit twee hoofstukken. Het eerste hoofdstuk geeft een beschrijving van de technologie en van de relatie van de technologie met de structuur van productie en de socio-economische context waarbinnen de technologie werd geïnitieerd. Het tweede hoofdstuk analyseert de case met behulp van de gestileerde modellen. In beide cases worden alle benaderingen toegepast. De analyse van de cases is gestructureerd middels de verschillende analytische inzichten van de verschillende complementaire benaderingen. In de eerste case study wordt de industriële districten-aanpak grondig doorgenomen, waarna aanvullende inzichten van kenmerken van de collectieve actie en de en gespreide innovatie benadering worden betrokken. Op dezelfde wijze wordt in de tweede case study de gespreide innovatie aanpak gebruikt, waarna aanvullende inzichten uit de collectieve actie en industriële districten-aanpak worden ingebracht.

De eerste casus, over de aanpassing en verfijning van een technologisch proces dat de extractie van goud uit erts mogelijk maakt door gebruik van cyanide, wordt beschreven in deel twee. Dit vond plaats in de aanvangsperiode van de ontwikkeling van mijnbouw in Zuid-Afrika, tussen 1850 en 1902. Deze ontwikkeling was deels onderdeel van een internationaal fenomeen, en had deels te maken met de geologische eigenschappen van de Zuid Afrikaanse mineralen. De bestudeerde onderzoekssamenwerking beslaat een periode van 10 jaar van 1892 tot 1902. Gedurende die tijd werden technologieën ontwikkeld die het mogelijk maakten om het delven van goud met behulp van cyanide op grote schaal toe te passen in de industrie. Er was veel lokale industriële ontwikkeling, met precendent zoals de Kimberley diamant mijnen, waardoor de oprichting van een gemeenschap mogelijk werd gemaakt van partijen die wederzijds voordeel zagen in het gebruik maken van elkaars middelen om uitdagende technische knelpunten op te lossen. Daarom was de industriële district aanpak bijzonder bruikbaar voor het beschrijven van onderzoekssamenwerking in dit geval , met een concentratie van internationale mettallurgische expertise en een open beleid inzake het publiceren van technische prestaties door de mijnen.

De tweede casus, in deel 3, gaat over de transformatie van stapsgewijze ontginning (ondergrondse productie) bij mijnexploitatie. Het beslaat een periode van 30 jaar: van 1903, toen de Tweede Boerenoorlog voorbij was, tot 1993, toen de prijs van goud omhoog ging wegens het opschorten van de goud standaard. Stapsgewijze ontginning was een nieuwe mijlpaal in de technologische ontwikkeling van de industrie, die de gecoördineerde ontwikkeling van een groot aantal onderling afhankelijke technologieën vereiste. Het leidde tot een geïnstitutionaliseerd economisch proces dat van de goudmijnen doordrong tot de hele economie, waarbij de potentiële economische mogelijkheden voor een meerderheid van de bevolking van Zuid Afrika werden beperkt. De onderzoekssamenwerking was anders in de situatie van industriële consolidatie die deze tijd na de initiële ontwikkelingsfase karakteriseerde. Onderzoekssamenwerking was sterk verweven met macht en controle over het productie-systeem vanwege de dominante mijnbouw financiering. Dit maakte de gespreide innovatie benadering geschikt om veel van de belangrijke dimensies van onderzoekssamenwerking te beschrijven.

Dit proefschrift draagt bij aan twee gebieden van onderzoek, theoretisch en experimenteel. Door toepassing van een combinatie van drie verschillende, maar complementaire benaderingen voor de analyse van onderzoekssamenwerking, ontstaat een samengesteld beeld . In de economische wetenschap kenmerkt zich door de aanname dat markt of hiërarchie het gedrag van mensen stuurt. Deze vergelijkende analyse van onderzoekssamenwerking toont aan dat een derde vorm van sturing, namelijk collectief bestuur, eveneens belangrijk kan zijn. Hoewel de huidige analyse zich richt op onderzoekssamenwerking, is duidelijk geworden dat ook verschillende andere economische activiteiten eveneens via dit coördinatie-mechanisme gestuurd worden. Dit wijst op een groot en opwindend gebied voor verder onderzoek.
In onze moderne economie waar communicatie meer en meer onafhankelijk is van fysieke afstand, is inzicht in de werking van collectief bestuur belangrijk. Door onderzoek kunnen waardevolle inzichten gecreëerd in anders schijnbaar onduidelijk fenomenen. Bijvoorbeeld, collectief bestuur heeft de ontwikkeling gekenmerkt van Apache, de meest populaire webserver gedurende de laatste 10 jaar, waarbij programmeurs vrijwillig hun werk inbrengen om de software samen aan te passen en te verbeteren.

Deze analyse van de vroege goudmijnindustrie in Witwatersrand is substantieel verschillend van de voorgaande studies. Door technologische veranderingen en hun relatie tot de socio-economische omgeving als uitgangspunt te nemen, is deze studie uniek in de Zuid Afrikaanse geschiedschrijving. Deze twee case studies zijn enkel een voorbeeld van de wijde reeks van onderzoek die uitgevoerd kan worden door gebruik te maken van de rijke empirische data die de industrie bezit. We spreken dan ook de hoop uit dat de huidige analyse een aanzet levert tot verder onderzoek van de technologische veranderingen in deze industrie, omdat het veel belangrijke aanknopingspunten bevat om de huidige dynamiek te begrijpen en een belangrijke sleutel kan zijn tot verdere bijdragen aan tot de literatuur over economie en technologische ontwikkeling.

Curriculum vitae

Thomas E. Pogue was born in 1970 in Carson City, Nevada in the United States. In 1989, he began studies at the University of Nevada, Reno where in 1993 he received a Bachelor of Arts degree in Economics. In 1995, he graduated from the University of Nevada, Reno with a Master's degree in Economics. His Master's thesis focused on regional economic impacts of Nevada's open-cast mining in the 1970s and 1980s. Between 1997 and 1999, he worked as a researcher at the University of Cape Town's Development Policy Research Unit (DPRU) in South Africa. However, in 1998 he moved to Johannesburg where he was based at the University of Witwatersrand's Sociology of Work Unit (SWOP). From 1999 to 2001, he started his Ph.D. studies at United Nations University - Maastricht Economic and social Research and training centre on Innovation and Technology (UNU-MERIT), which is based at the Economics Faculty of Maastricht University, the Netherlands. Between 2002 and 2004, he worked as a researcher at the Council for Scientific and Industrial Research's (CSIR) Corporate Policy Group in Tshwane (Pretoria) South Africa. Since 2004, he has been a research associate with Tshwane University of Technology's Institute for Economic Research on Innovation (IERI).