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Abstract

The paper illustrates the role of political and social dynamics upon technological change. Examining dynamics transforming excavation practices on South Africa's goldmines, it describes how a technology that opened up a range of social and economic opportunities became a constraint on those opportunities. This technology's development and diffusion thereby established a critical precedent in the spread of racial occupational mobility restrictions. Collaborative innovation is also a dominant feature in the analysis, highlighting both its historical importance in South Africa as well as the need for caution in its contemporary promotion.

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1. Introduction

This paper analyzes transformation of extraction practices on the Witwatersrand gold mines in South Africa between 1902 and 1933. It explores two previously discrete, but substantial research areas: collaborative research and racial occupational mobility restrictions. Collaborative research is often heralded as an important feature of the modern knowledge economy. However, collaborative research was an enduring and significant feature from the earliest days of industrial mining operations on the Witwatersrand.

While this paper forms part of a growing body of literature on the significant historical role played by collaborative research, it also highlights a neglected dimension in contemporary discussions of research collaboration. Technical and non-technical collaboration characterized the system of innovation that transformed excavation practices, but dominant social and political systems were important forces supporting collaboration. In detailing this role of social and political dynamics, the analysis highlights the need for contemporary analyses of collaborative research to examine the potential role played by broader contextual conditions in supporting or hindering alliances.

Similarly, previous research on the entrenchment of racial occupational mobility restrictions focused on social and political factors.[1] While acknowledging these factors' importance, this research demonstrates the previously neglected influence of technological dynamics. It thereby opens an original dimension to the emergence of racial occupational mobility restriction in South Africa.

Analysis begins with the close of the Second Anglo-Boer War in 1902 and concludes with South Africa's abandonment of the gold standard in 1933. Encompassing many interrelated innovations, it spans 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 extraction practices on the Witwatersrand gold mines were largely imported. However, their diffusion illustrates the innovation that occurs in adapting foreign technologies to local conditions. In changing extraction practices, innovations were effected in both traditional physical artifacts as well as work force organization.

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

The best proxy for the transformation of extraction practices on the Witwatersrand is the usage of rock drills. Figure 1 illustrates the early introduction of rock-drills on the Witwatersrand. These were not lightweight rock-drills for stoping, but heavier drills used for development of tunnels. In the figure, 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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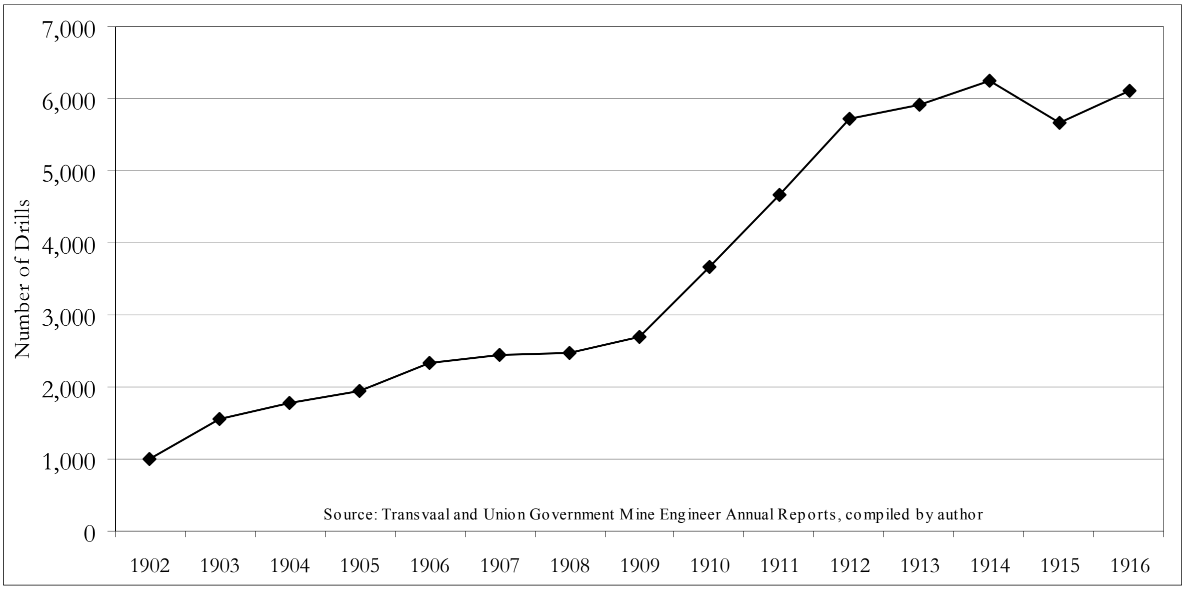
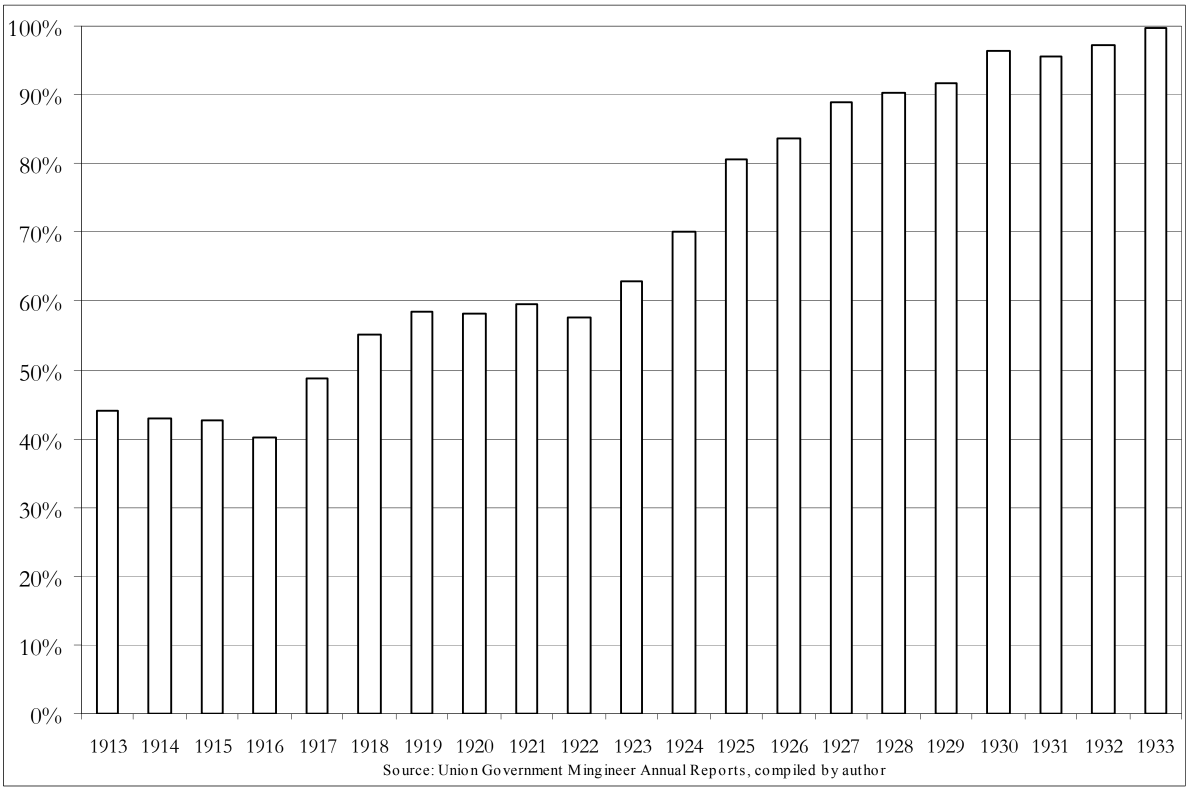
[1] Racial occupational mobility restrictions are more commonly referred to as 'the colour bar' in the South African literature.

Figure 1 Rock Drills Used on the Witwatersrand 1902 to 1916



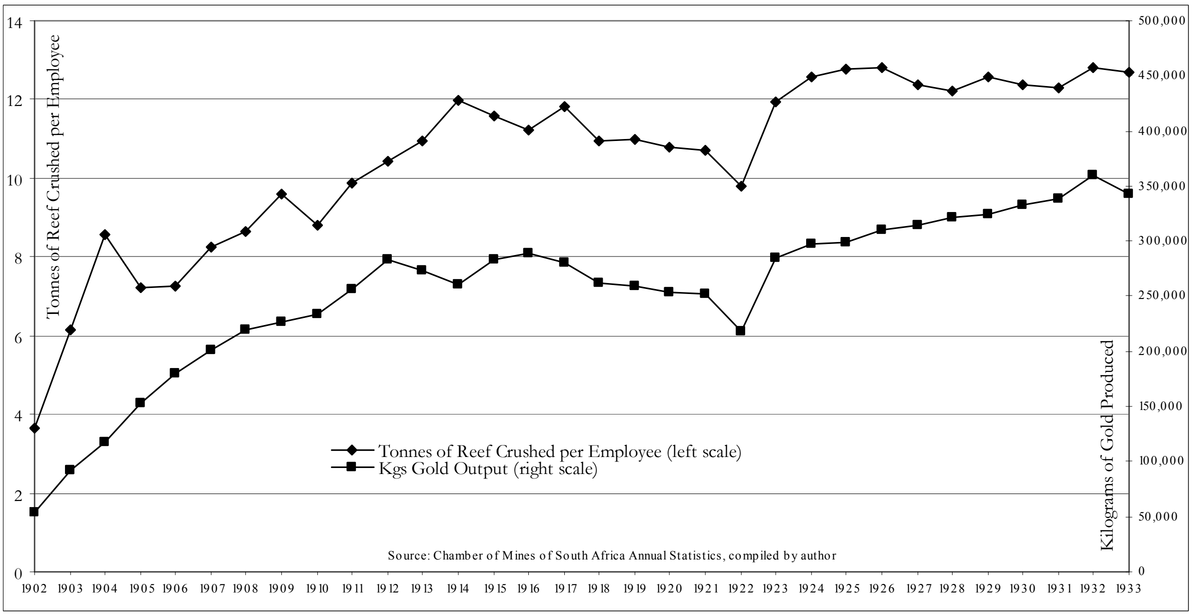
After the initial introduction of rock drills in tunneling, readily available African labor on the mines slowed further deployment. This was a short lived delay, the First World War depleted the available African workforce and led to further use of rock- drills on the mines. Amidst the war induced labor scarcity, White miners used their enhanced bargaining position to limit transformations in the organization of production. Nonetheless, the necessity for change in 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 2 shows that rock drilling quickly came to dominate excavation after 1922, with rock drilling ruling excavation by 1933.

Figure 2 Rock Excavated by a Rock Drill 1913 to 1933



Transforming excavation practices enabled the mines to realize economies in operations that made mining on the Witwatersrand a profitable endeavor for decades to follow. Figure 3 shows the increased efficiencies in production the industry realized during this period. However, developing and deploying new excavation technologies and practices was not a simple and straightforward process. It required development of original complementary technologies as well as extensive adaptation of foreign technologies.

Figure 3 Annual Output and Excavation Efficiency 1902 to 1933



This analysis begins with an examination of technical and non-technical pressures to change excavation practices. Section Three analyzes solutions to those technical challenges. The system of innovation that transformed excavation is analyzed in Section Four. The last section reviews new dimensions raised by this analysis in the literature on research collaboration as well as the literature about the emergence of South Africa's racial occupational mobility restrictions.

2. Forces for Transformation

Explosives were terrifically important to the development of rock drilling machinery. The use of black powder for underground mining in the late 1620s was a first step. Then in 1867, Alfred Nobel developed a detonator that made utilization of nitroglycerine feasible and subsequently in 1875, Nobel developed blasting gelatin (Gregory, 1980). Advances in mining explosives initiated a rapid drive for better hand and then machine drilling equipment. In 1849, J.J. Couch patented a piston-drill machine and J.W. Fowle patented another version of the piston-drill in 1851.[2] These designs marked the first generation of rock drills and the oldest predecessors of the modern rock drill (Stack, 1982). Several other innovative drills followed. In 1871, building on previous generations, Simon Ingersoll and the Rand brothers created the first rock drill widely used in commercial applications. These piston-drills were large and heavy, requiring two men to operate. It was this generation of piston-drill design that was state-of-the-art when mining of the Witwatersrand began.

The early Witwatersrand goldmines were called 'out-croppers' because the gold bearing host rock (reef) was harvested (excavated) from surface exposures. The reef(s) were then followed with trenches below the surface. With increasing depths, these open trenches

[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.

became impractical and an underground system with shafts and tunnels was adopted. Underground mining uses tunnels dug horizontally from vertical shafts to access and transport the reef. The actual work area where the reef is extracted is called the stope. Excavation of tunnels and stopes are similar processes; involving drilling small holes (blast holes) into the hard rock, planting and detonating the explosives in these blast holes, and then clearing the blasted material. Originally, all blast holes on the Witwatersrand were drilled by hand. Skilled European miners whose direction drove the standard single-handed manual drilling method orchestrated stoping.

Several interrelated factors supported the transformation of excavation practices. Established analyses identify market structure, management control, and utilization of low-paid African labor.[3] Market pressures for transformation originated from the structure of demand for gold and the real costs of production under the international gold standard. Management concerns about control were part of a general phenomenon in many industries at this time where workplace hierarchies were developed to replace the productive authority of skilled members of the workforce. Increased utilization of low-paid African labor became particularly appealing as the industry secured a labor recruitment monopoly. Contemporary literature also mention two significant technical factors for transformation that previous analyses have neglected: processing technologies on the surface and decreasing productivity at depth.

2.1 Metallurgical Processing Technologies

A major incentive for change in stoping practices came from the economies of scale realized in large cyanide-based 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). However, by the mid-1890s substantial milling capacity existed, which created incentives to change rock-drilling practices.

Hatch and Chalmers (1895) 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".

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. Tube mills crushed the reef finer than their predecessors the stamp mills and were integral to efficiencies in the cyanide-based process of extracting gold from the reef. As a result by 1920, tube milling dominated gold extraction on the Witwatersrand (Janisch, 1986).

A contemporary 'Survey of Rand Mining' also highlighted economies in metallurgical processing as driving the transformation of excavation practices: "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

[3] For examples of these focuses see Houghton (1967), Johnstone (1976), and Jeeves (1985) respectively.

era of mining practice, described in the modern text book was ushered in" (MIM, 1927). These economies of scale from increased extraction plant capacity were quantified in a 1905 analysis that showed doubling the typical extraction plant's capacity reduced average costs by ten to fifteen percent (Browne, 1907).

2.2 Work Efficiency at Depth

The increasing depth of gold bearing reef added further pressure to transform extraction practices. The reef descended at a relatively steep angle from the surface, which required a system of shafts and tunnels for access. However, vertical shafts and tunnels are costly and until they reach the reef do not generate a productive income for the mines. With a fixed vertical transport infrastructure and an increasing depth of mining, the time to transport workers to the workface continuously rose.

While large gangs of low paid Africans could work the reefs with hand drills at lower costs than gangs using rock drills, increasing depths entailed diminishing output per shift just as technologies on the surface enhanced demand for throughput. These working efficiencies at depth required a qualitative shift in production per shift that was only possible with the mechanization of extraction practices. Hence, the reefs' geology created an increasing incentive to transform extraction practices.

2.3 Real Factor Costs and Demand

Gold's market structure also generated pressures for change. In the 1910s, material and labor costs appreciated while the nominal price of gold was static and depreciating in real terms. Under the international gold standard during this period, gold was sold at a fixed price that meant when the cost of inputs rose during inflationary periods, the gold mining companies had no means of passing on the cost increases except by mining higher-grade reef. Inflationary pressures then generated a fall in the Witwatersrand gold mining companies' margins and a reduction in the working life of the mines.

Table 1 Witwatersrand Gold Mining Statistics 1903-1933[4]

	1903	**1904**	**1905**	**1906**	**1907**	**1908**	**1909**	**1910**
Gold Output	92,422	117,29	152,66	180,18	200,68	219,50	226,95	234,25
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	256,64	283,31	273,67	261,14	282,93	289,16	280,50	261,84
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	259,14	253,75	252,83	218,03	284,56	297,81	298,51	309,62
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	314,84	322,05	323,86	333,31	338,33	359,51	342,56	
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.								

[4] 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 Statistic, 1960). Selling prices were estimated, for the years indicated, from gold sales reported by the Chamber of Mines of South Africa (COMSA) members.

Table 1 reports the average nominal and real price of gold between 1903 to1933. It indicates that inflation caused by rising prices during the First World War as well as rising costs from African labor shortages and White wage gains combined to reduce the real price of gold per troy ounce from £3.97 in 1911 to £2.65 in 1919. 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.[5] Non-labor resource costs had risen by nearly forty percent between 1914 and 1920. 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).

The premium's phased removal began in 1920 and once again brought the profitability crisis to the fore. Johnstone (1976) has described in some detail how this market environment created a strong incentive for mine managers in 1922 to push forward with an important stage of artisanal skills removal from excavation. Despite concerns over the removal of the gold premium, 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.

Table 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. This declining output was central to the 'profitability crisis' in the industry that propelled the first stage of stoping labor force reorganization in 1922. An indication of the effectiveness of the 1922 reorganization is that between 1923 and 1932 the Witwatersrand's output of gold rose continuously.

2.4 Management's Exertion of Workplace Hierarchies

Three distinct groups can be differentiated among the underground labor force: 1) European White Miners 2) African Black Miners and 3) Afrikaner White Miners.[6] Before the introduction of rock-drills and changing the organization of stoping and tunneling 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 technique, represented a significant component of rising labor costs per tonne of reef extracted. As the costs of labor per tonne rose by 86% in low grade mines between 1914 and 1918,[7] a large incentive existed to replace the European miners with workplace hierarchies.

[5] 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 between 16% to 44%, averaging 26% (Johnstone, 1976: 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 (1994).

[6] 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.

[7] Johnstone (1976: 102).

2.5 Utilization of Low Paid African Labor

Lastly, an incentive for transformation of excavation practices came from the industry's establishment of an African labor recruitment monopoly that ensured an adequate supply of low paid African labor. The mines had faced major recruitment difficulties 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).[8] 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.

3. The Transformation of Excavation Practices

Three distinct groups of innovations were necessary to transform excavation on the Witwatersrand's gold mines. First, organizational routines were needed that could replace the artisanal skills of the European miners in excavation. These techniques development preceded the Second Anglo-Boer War and continued after 1933,[10] but this period corresponds to their greatest change. Second, rock drilling equipment had to be adapted for local conditions and refinements in the technology needed to be effected before rock drills could be adopted on a large scale. Lastly, there were occupational health hazards that raised serious doubts about the utility of rock drills despite substantial evidence of the severe discounting of the miners' lives.[11] The primary occupational health hazards were lung diseases and heat stroke. These hazards were intimately linked to the use of rock drills and the environmental challenge of stoping at depth.

3.1 Changing the Organization of Excavation Work

Transformation of excavation work led to a removal of artisanal skills in excavation and establishment of an underground workforce integrated into a hierarchical management structure. While these innovations to the organization of production coincided with the impositions of workplace hierarchies internationally, they encompassed much more than just the development of appropriate techniques to replace the artisanal skills of the miners. In particular, these changes were integral to the codification of racial occupational mobility restrictions in the industry and more generally in South Africa's formal economy.

Traditional analyses of these organizational changes focus on socio-political influences over the technology's development such as the utilization of Afrikaners by mine management as an instrument of socio-political control.[12] Largely forgotten in the literature is role played by the technical development of these organizational practices in their implementation.

When gold mining operations resumed after the Second Anglo-Boer War a scarcity of European miners led to an increasing number of local, predominately Afrikaans speaking, low-skilled whites taking up work on the mines.[13] Drought and war had severely limited opportunities in rural South Africa and thus, despite lacking mining skills, white males

[8] See Denoon (1967).
[9] See Jeeves (1985).
[10] See Leger (1992).
[11] See Katz (1994).
[12] See Yudleman (1983).
[13] See: Davies (1976).

looked to the mines in their search for urban employment. As Table Two details, these 'proletarianized' 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 miners could be used to facilitate local skills development to a degree not possible with African miners because of racial and migratory impediments.

Table 2 The Structure of Excavation Operations 1902-1904

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

Availability of Afrikaner miners also led to their being considered as substitutes for African miners in the acute post-war shortage. This created a wave of white labor experiments. One of these early investigations by the Chamber of Mines of South Africa (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. Other alternatives for solving the acute labor shortage were also investigated and around 1903 consensus developed in support of the importation of low cost indentured Chinese labor.

When Chinese arrived on the Witwatersrand in 1904, the 1904 Labour Importation Ordinance closed all skilled and semi-skilled jobs to non-white miners. Designed to assuage European miners' fears of replacement by the Chinese, the ordinance marked the first *de jure* race-based occupational mobility restrictions by the British Colonial administration on the Witwatersrand. Management as a temporary measure accepted this closing of upward occupational mobility to relatively low cost African miners in order to facilitate skilled (European) miners' acceptance of Chinese labor.

Table Three presents the structure of excavation operations on the Witwatersrand during this era of imported Chinese labor. The large stock of relatively low cost Chinese labor undermined the bargaining position of African labor and reduced pressure on Mozambique's African labor market, which was highly stressed by demand from South Africa.[14] Nevertheless, 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 several important recruiting centers across southern Africa by a variety of colonial governments and retained only a perilous position in Mozambique.

Table 3 The Structure of Excavation Operations 1904-1907

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

[14] See Richardson (1977).

The era was notable in bringing increased productivity,[15] a higher caloric provision, and better sanitation arrangements (CMMSSA, 1934). Between January 1904 and September 1905, the Corner House mining-finance group brought in a foreign based management expert, Ross Browne, for advice on working costs and future development of deeper mines. That analysis called for changes in the organization of excavation work with routinization of production and increased efficiencies in relatively low cost mine labor, which would decrease the proportionate number of skilled miners needed.[16] Browne's examination of operations initiated development of 'scientific management' or workplace hierarchies over excavation practices on the Witwatersrand.

Following Browne's recommendations, in 1906 some 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 White workforce on the Witwatersrand mines.

These changes met resistance from the European miners and in May 1907 when Knights Deep gold mine re-organized its tunneling operations and reduced White supervisory wages, the first general strike on the Witwatersrand followed. The mines continued limited production during the month long strike and took the opportunity to replace striking European miners with large numbers of Afrikaners, giving Afrikaners their first significant entry to the industry. Table Four indicates the scale of change in White mining workforce resulting from 1907 strike.

Table 4 Employment Before (April 1907) and After (June 1907) the 1907 Strike[17]

	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. The Het Volk (Botha) and Nationalist (Smuts) parties coalition elected to the Transvaal colonial government in 1907 was closely identified to agricultural and manufacturing interests. Meanwhile, the newly elected Liberal government in Britain had prohibited further importation of Chinese labor. This created a second wave of white labor experiments with similarly poor results to the first (Davies, 1976).

Following the strike COMSA established a Mine Trials Committee in 1908. Its primary task was development workplace hierarchies for mining. 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 workplace hierarchies on the Witwatersrand was establishment of the Government Mines Training Schools in 1911 (Letcher, 1936). These schools increased the number of Afrikaner miners and facilitated replacement of the European miners to effectively remediate labor militancy. Nonetheless, despite Afrikaners' threat to the European

[15] 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.
[16] See Browne (1907: 289-354).
[17] Source: 1907 Annual Report Transvaal Colony Government Mine Engineer.

miners' structural authority direct conflicts between European and Afrikaner miners did not emerge.

Table 5 The Structure of Excavation Operations 1907-1913

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

European miners did realize the threat to their job security, as indicated in Table Five, and reacted accordingly. Between 1907, when the 1904 Labour Importation Ordinance was repealed with Chinese repatriation, and 1910 there were no *de jure* racial occupational mobility restrictions. In 1911, *de jure* racial occupational mobility restrictions returned with the mining regulations of the Mines & Works Act of 1911. Significantly, these restrictions only applied to highly skilled jobs primarily undertaken by European miners. Semi-skilled occupations, which were increasingly done by Afrikaners, remained under *de facto* protection.

This period also saw development of the African labor recruitment monopoly. African recruitment slowly improved as increasing numbers of voluntary laborers made independent recruiters redundant. This phenomenon was supported by COMSA's establishment of the Native Recruiting Corporation (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.

In 1913, conflicts with the White workforce led by European miners forced the Botha-Smuts government and Witwatersrand mining industry to give considerable concessions to the strikers.[18] Table Six denotes that Afrikaners continued to play a larger role in excavation, but in early January 1914, when lay-offs of railway workers on Christmas Eve precipitated another general strike of White miners a better prepared government and industry seized initiative back from the White labor force. From these conflicts a policy of co-optation of White mining unions began that culminated with the 1922 Rand Revolt in an alliance between organized White labor, the South African state, and Witwatersrand mining industry (Yudelman, 1985).

Table 6 The Structure of Excavation Operations 1913-1914

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

[18] In contrast, when African miners went on strike later in 1913 for an increase in their low wages the government and industry used violent repression to send the African miners back to work.

The First World War saw an enduring African labor recruitment monopoly established that ensured a reliable and adequate stock of low cost African labor for the Witwatersrand gold mines. That recruitment monopoly was affected through the complementary South African (NRC) and southern Mozambican (WNLA) co-operative recruiting institutions. The 1916 take over of the large Randfontein mine by the JCI mining-finance group created critical industry consolidation for the cooperative to work (Jeeves, 1985).

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). However, at this time the industry had not yet developed adequate workplace hierarchies for stoping, so the opportunities for significant transformation of excavation practices were severely constrained.

Given war related European miners scarcity, removal of artisanal skills from underground production became a great priority. As indicated in Table Seven, Afrikaner miners became the greater part of the White workforce during the war even though they were typically low or semi-skilled miners. The Afrikaners rose from 40% of the white workforce in 1914 to 75% in 1919.[19] In order to facilitate this increased use of low and semi-skilled labor the industry stepped up its development of workplace hierarchies (Leger, 1992).

Table 7 The Structure of Excavation Operations 1914-1918

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

The simultaneous increase in the number of Afrikaner miners and scarcity induced 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. In January 1917, this tension manifested itself in an unofficial strike by White 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 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.

After the First World War, the Corner House mining-finance group undertook a very large and important investigation with its Rock Drill Investigations Committee (RDIC). Focused on excavation practices, the RDIC marked critical development of workplace hierarchies for stoping. A few of the more significant contributions made by the RDIC to

[19] Johnstone (1976: 105).

workplace hierarchies 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. Table Eight shows that a limited transformation of stoping practices occurred. However, resistance to a reorganization of stoping work delayed introduction of these innovations until mine managements' victory in the 1922 Rand Revolt.

Table 8 The Structure of Excavation Operations 1918-1922

		Tunneling	Stoping
Labor forces:	**Supervisors**	Afrikaners	Europeans/Afrikaners
	Semi-Skilled	Afrikaners/Africans	Afrikaners/Africans
	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, mine management used the first large scale organized African miners strike in 1920 to form a platform that simultaneously pushed for re-organization of the mines' workforces and greater occupational mobility of low cost African miners.

By 1921, with the gold premium ending 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. Fearing the complete removal of racial occupational mobility restrictions, the MWU rejected this condition. Nonetheless, COMSA moved unilaterally announcing White miner wage reductions in August and in December declared that from February 1922, the mines' labor forces would be reorganized in violation of the Status Quo Agreement. While those actions resulted in a general White miner strike between January and March 1922,[20] the industry with government assistance broke the strike and the changes imposed by mine management were entrenched. The reorganization of excavation occurred quickly after the Rand Revolt and by 1923 working costs per ton of ore milled had fallen 24 percent.[21]

Table 9 The Structure of Excavation Operations 1922-1933

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

Table Nine specifies the structure of excavation practices once workplace hierarchies were effected in tunneling and stoping. Despite the victory of 1922, the broader social and

[20] This strike is known as the '1922 Rand Revolt'.
[21] Yudelman (1983: 27).

political systems constrained mine management's ability to restructure the industry. A court case in 1923 allowed for the removal of all racial occupational restrictions,[22] but mine management did not take advantage of that decision. Instead, mine management maintained the restructuring effected after the Rand Revolt. That maintenance of the new status quo 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.

While mine management continued research and development in to the reorganization of excavation practices, they focused on further utilization of African miners within a social and political environment that would not tolerate removal of racial occupational mobility restrictions. Socio-political dynamics were constraining technological change within a system of entrenched racial occupational mobility restrictions. Hence, after 1922 workplace hierarchies sought to use standardized practices to impart skills on migrant African miners rather than making implicit knowledge explicit and thereby de-skill occupations as was the traditional role played by workplace hierarchies.[23] These efforts were co-operatively supported through COMSA establishment of the Technical Advisory Committee (TAC) in 1922.

A major initiative in furthering racially designed workplace hierarchies took place in 1929 when the Corner House mining-finance group brought G.H. Miles and A. Stephenson from Britain. Their 1930 report focused on labor processes done by Africans underground with time and motion studies as well aptitude tests to classify and place African miners according to their skills (See: Stephenson, 1930). An important aspect of this second wave of workplace hierarchies was imparting these methods on the African miners. Therefore, in 1930 the industry co-operatively established Native Training Schools to standardize training and expertise of the African labor force.

3.2 Rock Drilling Equipment

The heavy piston-drill design that was used initially in tunneling on the Witwatersrand were relatively large and bulky drills. Given the narrow reefs of the Witwatersrand, these drills were impractical for stoping. Efforts were devoted to producing a lightweight piston-drill, but not with appreciable success until the hammer-drill design.[24]

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 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.

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. However, the American Ingersoll-Rand company bought the Leyner patents in 1911 and the J.G. Leyner Company in 1912. As a result, it was only when the patents protecting the Leyner's innovative steel and

[22] The 1923 decision is known as the Hildick-Smith judgment.

[23] See Leger (1992).

[24] 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.

drill design expired in 1914 that an economical rock drill was available for stoping on the Witwatersrand. Thus, the technological constraint of those intellectual property rights formed a critical influence on other technologies' development as well as the scope for meaningful socio-political transformation of racial occupational mobility restrictions.

Nonetheless, the Witwatersrand gold mining industry did not sit idly by and wait for a viable design to emerge, it actively supported initiatives to develop a lightweight rock-drill suitable for stoping. Rock drill trials were the principal means that the Witwatersrand mining industry promoted advances in rock drill design. There were four major trials between 1902 and 1909. Individual mining-finance 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 stimulate innovations that would make rock drills suitable for stoping. Results of the trials and comparative performance of the drills was diffused via publication in local technical journals and special publications by COMSA.[25] 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.

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.[26] These were needed because of the unprecedented scale and industrialized nature of Witwatersrand gold production. COMSA collectively undertook some of this research for the industry and individual mining-finance groups openly disseminated findings from their research initiatives.[27] During this period there were five large research and development initiatives on rock drilling equipment. 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).

The next significant initiative was COMSA'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. The Corner House RDIC between 1919 and 1922 carried out another significant research initiative. 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 drill-director to remove the artisan's skill from underground production. The drill director was noted in contemporary writings as being a particularly significant source of productivity gains.[28] Leger (1992) estimated that the combination of RDIC equipment and workplace hierarchies contributed to a 400 percent increase 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.[29]

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[25] Griffiths (1904) detailed the 1902 trial, Carper et al. (1904) the 1903 trial and Orr (1907) 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.

[26] Among the 'associated technologies', the hole-director played a critical role in transforming stoping practices. See Simon (1927), Watermeyer and Hoffenberg (1932: 406), and CMMSSA (1934: 315).

[27] Evidence of dissemination of research findings is found in the discussions of the professional societies journals during this period.

[28] See Simon (1927) and CMMSSA (1934).

[29] Leger (1992: 46).

COMSA's establishment in 1922 of the TAC was the next significant initiative.[30] Originally empowered to investigate issues forwarded by the newly formed Gold Producers Committee (GPC), 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 advanced rock-drill technologies by diffusing equipment practices along with the previously mentioned workplace hierarchies. The other large research initiative in rock drilling equipment was Central Mining's (Corner House) Investigations Committee (CMIC) of 1925 to 1928. CMIC carried out 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.[31] However, CMIC undertook its development of rock drilling equipment in an environment of socio-political constraints on further transformation of racial occupational mobility restrictions. Therefore, CMIC's technologies were designed to further efficiencies through increased standardization that augmented the skills low-paid African miners.

Despite its unique influences, the Witwatersrand's development of rock drilling equipment was integrated with other international efforts. Supported by South African and non-South African mining companies these efforts circulated international best practices.[32] Technological challenges in rock drilling equipment influenced the transformation of excavation practices and associated opportunities to influence racial occupational mobility restrictions. Conversely, after replacement of European miners' skills in stoping, racial occupational mobility restrictions influenced the design of rock drilling equipment as standardization was used to impart skills on African miners.

3.3 Alleviation of Occupational Health Hazards

Mining is hazardous work and during this period Witwatersrand miners, no matter his race, risked death from many sources. The transformation of excavation practices increased these health hazards, most notably because of miners' phthisis and tuberculosis. The increasing depths that the other changes made economically viable also brought indirect hazards like heat stroke. Between 1902 and 1933, the strides forward in alleviating these occupational hazards were substantial.

The annual death rate of African miners from all causes was given at 58 per 1,000 in the Milner Commission Report of 1903. While comparable statistics are not available towards the close of our period, a few disaggregated statistics 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 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 (Leger, 1990).

Miners' Phthisis

Between 1903 and 1912, the significance of miners' phthisis was identified and a primary factor of causation, silicious dust, was 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

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[30] 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.
[31] See Meyer (1930) and Heywood (1930).
[32] See Weston (1905), (1907), (1910), (1917), and Potter (1918), (1919), (1926).

the miners' exposure to dust. While rock drills were not widely used in stoping during this era, they were extensively used in tunneling resulting in the Mines & Works Act of 1911 requiring all drills to simultaneously spray water to allay the dust they generated. 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 1911, the Goldfields mining-finance group took the lead by initiating systematic dust sampling. Lastly, artificial ventilation systems were developed 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. By the early 1920s increasing depths 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 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.

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' African miners from tuberculosis and other diseases. Health concerns were thereby used to motivate and institutionalize segregation and remove individual Africans from policy imperatives. Increased screening of those miners' most physiologically susceptible to tuberculosis was the primary means of control during this period.[33] COMSA sponsored a large and internationally

[33] Despite their known value, x-rays were not used to screen African miners at this time because of the cost.

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. 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.[34] However, socio-political bias had encouraged a racial conception of the industry's health problems. As a result, the theory of underlying racial predispositions 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 (Packard, 1987).

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).[35]

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.

4. The Organizational Structure of Innovation

Transformation of Witwatersrand excavation practices depended on the coordinated adoption of three distinct, but complementary groups of technologies. These consisted of workplace hierarchies, rock drilling equipment, and alleviation of occupational health hazards. A single mining-finance group, the Corner House, drove these technologies. Nonetheless, development and diffusion was a systemic process involving most of the industry. The Corner House itself acted as if it were a co-operative research organization diffusing proprietary research to across the mining-finance groups. Co-operative organizations like COMSA and the South African Institute of Medical Research (SAIMR) directly and indirectly contributed to research in many areas as well as laterally supporting adoption through establishment of training and monitoring functions. In addition, the open community of practitioners working largely through professional associations, developed, exchanged, and diffused crucial know-how.

4.1 The Mining-Finance Group System

Witwatersrand gold mining remained the paramount industry across Southern African between 1902 and 1933. However, a significant development during this period was establishment of a 'group system' of production that drew on all the mining-finance groups to

[34] Packard (1987: 206).

[35] These mines were part of the Corner House group.

enhance the industry's competitiveness. This group system dominated the South African economy throughout most of the 20th century.[36]

Business groups typically act as alternatives to financial markets and as forces of political authority (Granovetter, 1998). This was also true the individual mining-finance groups on the Witwatersrand with a significant financial capital position being common because of uncertainties associated with mining, a relatively long duration before return on investment, and the considerable scale of fixed investments needed to get a mine started.[37] Mining-finance groups existed from the early days of Witwatersrand gold mining in the 1880s. During this period, increasing consolidation and removal of largely speculative mining-finance groups led to a marked development of their internal financial capacity. That development of the individual groups contributed to a common interest and identity, which supported cooperation and coordination among the groups. It was in the context of this group system that the Corner House acted as a cooperative research organization developing and actively diffusing several technologies central to effecting a transformation of excavation practices.

Figure 4 Group Output and Excavation Efficiency 1908 to 1914

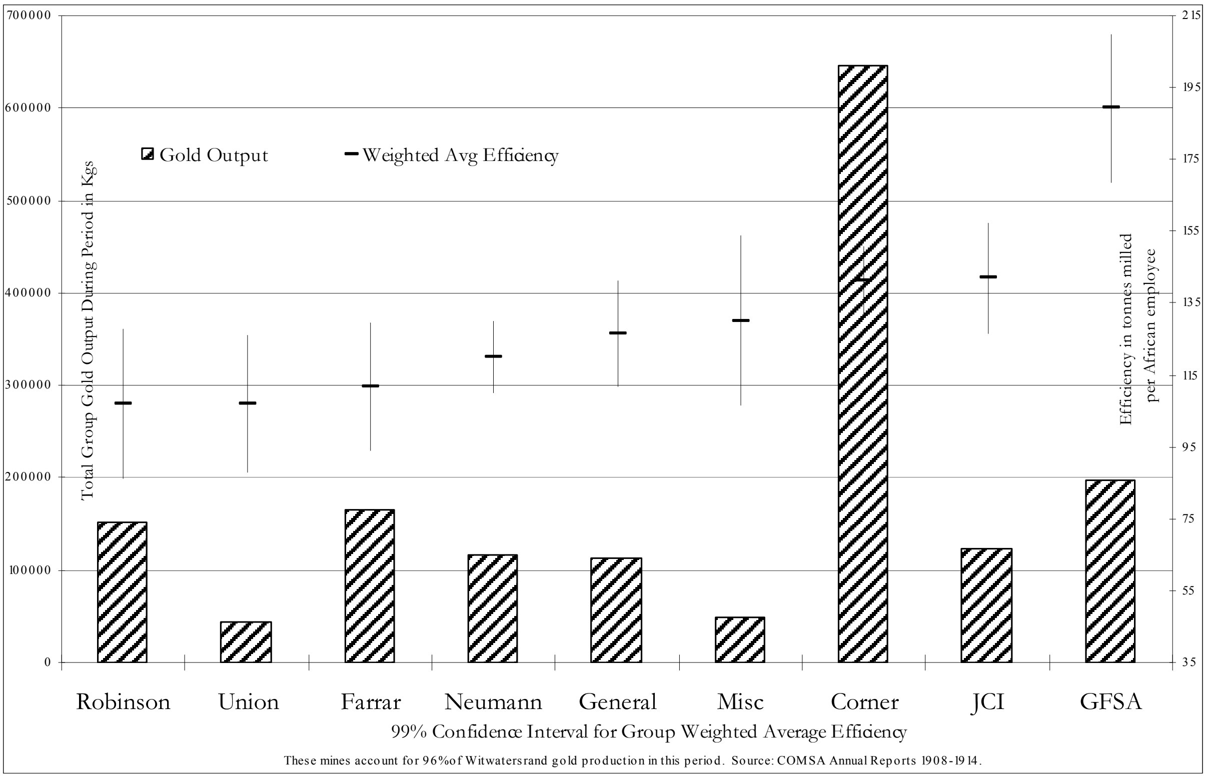

Figure Four reports the groups' size as measured by their cumulative output of gold during the period 1908 to 1914. It illustrates the tremendous prominence of both Gold Fields South Africa (GFSA) and the Corner House before the development of the Far East Rand.[38] While mining-finance groups shifted somewhat in their importance later in the period between 1902 and 1933, the Corner House's output gave it an unparallel dominance of production during most of this period. Figure Four also reports the excavating efficiency of

[36] See Fine and Rustomjee (1996).
[37] See Frankel (1969).
[38] The Far East Rand is a as a part of the Witwatersrand basin east of Johannesburg. It became an increasingly important source of gold from the late 1910s and formed the basis of Anglo American Corporation's emergence as a mining-finance group.

the groups between 1908 and 1914.[39] It shows GFSA, Johannesburg Consolidated Investments (JCI) and the Corner House to be the most efficient groups. These three groups were also leaders in promoting intra-industry cooperation and coordination.

It is also worth noting that there is also no apparent correlation between group size and excavating efficiency,[40] which indicates that economies of scale were not a significant determinant of productive efficiency at the level of the mining-finance group. While the mining-finance groups, and the Corner House in particular, drove development of the technologies necessary to transform extraction practices it was complemented by an open community of practitioners as well as co-operative research and industrial associations.

4.2 Open Community of Practioners

Professional associations were critical institutions of the open community of professionals. The associations' journals facilitated development and diffusion of the technologies that transformed stoping practices. For instance, the Journal of the South African Institution of Engineers published numerous articles on best practices in systematically deploying the rock-drills on a large scale industrially. The Journal of the Chemical, Metallurgical and Mining Society of South Africa published several papers on mine ventilation and health, while the South African Mining and Engineering Journal and the Proceedings of the Association of Mine Managers published articles on productive efficiencies in workplace hierarchies combined with the rock-drills. Many issues in understanding and alleviating health concerns were published in both the South African Medical Journal and working papers of the SAIMR. These journals publication costs were supported by the mining-finance groups (Draper, 1967, p.16).

The associations also sponsored symposiums around specific research challenges. The associations also directly contributed to the transformation of excavation by initiating research into labor force organization, occupational health hazards, and rock drills. The need to economically extract gold bearing ore at increasing depths created common cause for these associations as it did for their members and the mining-finance groups. That common cause facilitated a deepening of cooperation among the professional associations. This characteristic of the industry was mentioned in a contemporary comment about the 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).

As a means to build and diffuse a complex systemic technology the open community had comparative advantage in its ability to building understanding of intangibles. This was particularly 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

[39] 1908 to 1914 was focused upon because data was not readily available for other years. 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.

[40] The adjusted R^2 equals zero.

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).[41]

Lastly, the open community of practitioners was able to facilitate understanding about technologies' complementarities and rapidly diffuse that understanding. Contemporary discussions recognized the ability of the open community of professions to 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).

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.[42] 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.[43] 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.

4.3 Co-operative Organizations

In this period, the COMSA also developed beyond its origins as an industry lobby to become a sort of cooperative for the group system and an important institution of production in its own right. This transformation of COMSA evolved from its efforts before 1903 to establish an African labor recruitment monopoly and repeal the patents of the cyanide treatment process. In this period, besides operating the African labor recruitment monopoly, COMSA began administering the Rand Mutual Assurance Company (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.[44] In 1904, it established the Mine Medical Officer's Advisory Committee, which in 1921

[41] Also see: Meyer (1930) Heywood (1930) and Heywood (1931).
[42] The original societies that established the AS & TS were: the Association of Mine Managers (AMM), the Chemical, Metallurgical and Mining Society of South Africa (CMSSA), the Geological Society of South Africa (GSSA), the Institute of Mine Surveyors of South Africa IMSSA, the Medical Association of South Africa (MASA), the South African Chemical Institute (SACI), the South African Institution of Engineers (SAIE), the South African Institution of Electrical Engineers (SAIEE), and the Transvaal Association of Architects (TAA).
[43] South Africa would eventually establish these government industrial research institutes, but only after the Second World War. See Kingwill (1990) and Basson (1995).
[44] See Lang (1986: 236).

became the more inclusive Mine Medical Officers' Association (MMOA).[45] In 1916, it expanded the Government Miners' Training Schools and in 1930 it established the Native Training Schools.[46] Lastly, as previously mentioned COMSA established the TAC in 1922.

COMSA's establishment of the TAC is interesting because it was not particularly 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".[47] With many research efforts in this case effectively driven by the Corner House, COMSA's limited involvement therefore appears to reflect the coordinating authority of the Corner House rather than its own strategic development.[48]

Alleviating occupational health hazards associated with the transformation of stoping was yet 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.[49] 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,[50] it enacted several important pieces of legislation and commissions as well as developing an instrument to accurately measure the amount of dust under ground.[51] However, the open community of professional practitioners was the most important element in developing solutions to the occupational health hazards.[52] 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.

A significant role was also played by co-operative organizations. The SAIMR was one such co-operative research institute. It focused on solutions to the occupational health hazards associated with transformation of stoping practices.[53] 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

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45 See Cartwright (1971: 49-52).
46 See Lang (1986:. 245).
47 The quote is contained in letter #158 reproduced in Fraser and Jeeves (1977: 336 - 341).
48 Further evidence of this can be found in the subsequent development of research capacity within COMSA. See: Pogue (2006).
49 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.
50 See Katz (1994) and Kennedy (1984).
51 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.
52 The AMM jointly conducted the 1902 Phthisis study with the 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 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.
53 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.

complementary skill development and by establishing an African labor recruitment monopoly.[54]

The transformation of excavation practices was a radical change in productive authority. 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. 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. Thus, the distributed structure played an important role in decreasing the risks that the Corner House would have faced through unilateral action. As we have seen leveraging State interventions and international recruitment of low-cost African labor was difficult enough in coalition.

5. Conclusion

This analysis demonstrated the important role technological dynamics played in the development of racial occupational mobility restrictions on the South African gold mines. If these technologies had not been able to adapt to socio-political demands, it is certain that South Africa's history of racial discrimination would have followed a very different course. Mounting cost pressures throughout the 1920s increased the incentive for the mines to finish developing and diffusing the new excavation 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. At that stage, further transformation would almost certainly have met resistance from white labor, which by then was predominantly Afrikaner and only offered marginal gains in efficiency. Consequently, benefits from non-racial technological operating efficiencies did not outweigh the costs of overturning social and politically entrenched racism. 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.

Traditionally, analyses focused on three factors driving transformation of excavation: structural pressures associated with the market for gold, management concerns about control of the underground workforce, and increased utilization of low-paid African labor. In this analysis, two additional factors directly linked to technological dynamics were identified as being critical causes for change. First, scale economies realized in milling capacity provided significant stimulus for transforming excavation practices. Second, the high cost of developing a mine shaft meant that there was a strong constraint on the number of workers that could be brought underground in any given shift. While a labor force of 5,000 low paid Africans manually drilling 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.

With this analysis drawing critical attention to the effects of technology on socio-political dynamic an entirely new dimension was added to our understanding of the development of racial occupational mobility restrictions. As a result, the analysis clarified the

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[54] 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.

timing, nature and scope of excavation practice's transformation. For example, when tunneling practices were changed in 1907 a large portion of the underground workforce was engaged in stoping and they would seem to have been a logical target for simultaneous transformation. However, the analysis showed that a suitable drill did not exist for stoping until the mid-1910s and even then the mines still had to develop techniques and equipment to replaces the skilled European Miners on the stopes. Therefore, it was only in the early 1920s that mine management could consider transforming stoping practices and by then the social and political context for transformation had considerably changed from what they faced in 1907.

This analysis also contributes to the literature on the economics of technological change, especially research collaboration where the contextual influence of social and political systems on distributed innovation is not adequately examined in contemporary literature focused on leveraging capabilities. 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. 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. This analysis of the transformation of excavation practices clearly illustrated that potential, where exclusion of low-paid African workers led to the growth and institutionalization of racial occupational mobility restrictions.

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[55] Abbreviation: AS & TS - Associated Scientific and Technical Societies of South Africa; CMMSSA - Chemical, Metallurgical and Mining Society of South Africa; MIM - Mining and Industrial Magazine.

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