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Peter E. Hilsenrath
University of the Pacific, philsenrath@pacific.edu

Thomas Pogue
University of the Pacific, tpogue@pacific.edu

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Distributed dynamic capabilities in South Africa's mineral resource-finance network

Peter Hilsenrath [a], Thomas Pogue [a, b, *]

[a] Eberhardt School of Business, University of the Pacific, 3601 Pacific Avenue, Stockton, CA 95211, USA
[b] Institute for Economic Research on Innovation, Tshwane University of Technology, 159 Nana Sita Street, Pretoria, 0001, South Africa

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1. Introduction

In this analysis, we examine dynamic capabilities in a distributed governance system. This perspective is distinct as it breaks from the dynamic capabilities' association with the firm as the primary agent. We apply this concept of distributed dynamic capabilities to three case studies on innovation in South Africa's mineral industries spanning 100 years. Our analysis shows dynamic capabilities provide an important analytical lens to understanding the role of mineral resource-based economic development. It also suggests a distributed dynamic capabilities approach may offer significant insights about technology-based competitive advantages under collectively coordinated environments.

The importance of mining-finance groups to South Africa's economic development is well established.[1] Those conglomerates brought diverse capabilities together to build a range of vertically and horizontally integrated businesses. Beginning in the 1980's, South Africa reflected on its economic development legacy as it began a transition to democratic rule [28]. In that context, there arose increasing recognition that beyond the mining-finance groups there existed a distinct coordination system built around its mineral industries, but spanning agents across the State and private sector.[2] However, those perspectives tended to focus on its features as a system of accumulation rather than a feature of higher-level organizational coherence. In this analysis, we view that network, which spans the mining-finance groups, State-owned mineral-based enterprises, and parts of the State itself as forming a unique collectively coordinated governance structure,[3] which we call South Africa's mineral resource-finance network (MRFN). Owing to the long history of mineral industries in South Africa's economic development we can explore the evolution of this network's distributed dynamic capabilities across three cases where critical new technologies and market capabilities were developed during a century.

Distributed dynamic capabilities in South Africa's MRFN thereby provides a useful context to reflect on the nature of the organization within the dynamic capabilities approach more generally. Examining a dynamic collaborative capability within a collectively governed networked organization distinguishes this analysis from others in the literature where collaboration has been viewed as means to combine resources across organizational boundaries,[4] rather than create them within the organization. Through each case study we provide evidence that the high-level collaboration generated from the MRFN meets the criteria of a dynamic capability. As such, the dynamic capabilities approach is held to provide important insights about the pattern of economic growth where resource-based sectors create opportunities for learning in production of some goods and services rather than others.[5]

The remainder of this analysis is set out as follows, after elaborating on our analytical approach we turn to the first case study which examines the emergence of distributed dynamic capabilities on the kimberlite diamond pipes at Kimberley. The paper then

* Corresponding author. Eberhardt School of Business, University of the Pacific, 3601 Pacific Avenue, Stockton, CA 95211, USA.
E-mail address: tpogue@pacific.edu (T. Pogue).

[1] See for example: [29,46].

[2] Bill Freund provides historical context for this approach [28], which includes Hobart Houghton's conceptualization of a mineral revolution akin to W.W. Rostow's modernization paradigm [43,45,80], through Martin Legassick's analysis gold mining in the labor control system [55], and on to Fine and Rustomjee's concept of the Minerals Energy Complex (MEC) [24].

[3] In this regard, we follow Walter Powell in holding collective coordination as a third dimension to the market-hierarchy continuum [74]. However, we adopt Streeck and Schmitter's andHamilton and Feenstra's perspective and assume collective governance dominates [87,31], but coexists with market and hierarchical coordination rather than excluding them.

[4] See for example [2,3,60,68,71].

[5] The distinct opportunities that certain industries afford is a focus of the product space literature, [34–37,40]. For a contemporary application of this approach in South Africa see: [33,38].

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traces how those capabilities evolved to create the technology needed to exploit the vast gold resources discovered on the Witwatersrand gold fields. The final case study describes how distributed dynamic capabilities facilitated the adaptation and transfer of technologies along with an innovative financial structure to create a uniquely South African oil-from-coal technology. Implications in terms of the dynamic capabilities approach and South Africa's mineral-resourced based economic growth are then reviewed in the conclusion.

2. Analytical approach

Dynamic capabilities is fundamentally associated with Coase's notion of the firm as the primary and efficient agent [14]. This is clear throughout most of the literature where a dynamic capability is defined as the firm's ability to integrate, build, and reconfigure internal and external competences to address rapidly changing environments [92,93,90]. Nonetheless, we contend that it is appropriately applied to a collectively governed network organization as well. These “distributed dynamic capabilities” as we call them retain the fundamental features of dynamic capabilities.

Teece et al. highlight that dynamic capabilities were conceptualized to explain what type of strategic management is needed for a firm to achieve and sustain competitive advantage [93]. Dynamic capabilities differentiate firms with the ability to survive and compete in periods of rapid and disruptive change from those firms that lose competitive advantage in those environments. As such, dynamic capabilities refer to the capacity of an organization to purposefully create, extend, or modify its resource base in the face of strong uncertainty. These are distinct from an organization's operational capabilities, which pertain to the current operations of an organization [39]. An environment of rapid and disruptive change is therefore a necessary condition for application of the dynamic capabilities approach. Therefore, each of our case studies begins with a subsection describing the rapid disruptive change, or deep uncertainty, it involves.

Organizational agility and strategy are key to the application of dynamic capabilities [90]. This combination of agility and strategy holds equally true in our analysis of the application of distributed dynamic capabilities, except that rather than residing in a firm the capabilities reside across the South African MRFN. Our case study methodology provides context that establishes the complex and systematic nature of distributed dynamic capabilities. In describing these in each case study, emphasis is given to their extraordinary nature and how they are distinct from ordinary capabilities that would perpetuate relatively static operating environments. In so doing we provide evidence that these distributed dynamic capabilities are akin to dynamic capabilities in the firm and are more than just ad hoc adjustments in the face of uncertainty with a favorable competitive outcome [21,110].

The historical structure of our case study approach also allows us to examine the socioeconomic process of these capabilities' development and change. In so doing our cases aspire to support Wadhwani and Jones' call to apply historical research to better frame understanding about the relationship between capabilities' development and the process of dynamic change [104]. Therefore, we conclude each of our case studies with a subsection devoted to an examination of the evolution of the distributed dynamic capabilities.

3. The kimberlite diamond pipes

3.1. Deep uncertainty in the Kimberley diamond fields

The pursuit of mineral wealth has been an important force in European exploration and international economic expansion over the past 500 years [65]. In southern Africa, the first significant mineral rush occurred in the 1850 s at the Namaqualand copper deposits, but the legacy of those deposits was muted [85]. It was not until the late-1860s when the Kimberley diamond fields were developed that an enduring Southern Africa's mineral-finance network emerged with distributed dynamic capabilities that facilitated broader economic development impacts. While there were an array of benefits and threats to Kimberley's establishment, the most important were associated with challenges to attract investment capital that could transform the diamond deposits' ownership structure and thereby the diamond industry's value chain.

In 1866, the ‘Eureka’ diamond was discovered on the banks of the Orange River. Despite initial skepticism about the geology of the deposits, further discoveries led to a full-scale rush for alluvial diamonds by 1869. These alluvial diggings were typically mined by a claim holder and assisted by local Africans in the digging and sorting 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 igneous diamond pipes were discovered.[6] Diamond pipes are volcanic conduits that transport geologic material from deep in the earth to the surface. The discovery of these igneous diamond deposits around Kimberly marked an entirely new era of diamond mining. By 1871 mining on the ‘dry-diggings’ centered around four diamond pipes: Kimberley, DeBeers, Bultfontein, and Dutoitspan. The diamond deposits from these four pipes varied, but together their quantity and quality dramatically increased and transformed the international supply of diamonds. Previously, diamonds had been the purview of royalty and the extremely wealthy, but with the emergent supply of diamonds from the Kimberley deposits the potential to own one of these gems expanded dramatically [12, 29,66,107].

The diamond bearing pipes were relatively small although they continued to substantial depths. In 1872, the combined area mined at the Kimberley and DeBeers pipes encompassed 12.8 hectare (ha), 6 ha at Dutoitspan and 3.2 ha at Bultfontein. Given this small area and great quantity of diamonds, it became apparent early on that if mining operations were consolidated, the diamond miners' influence over the diamond industry's value chain would be greatly strengthened. If consolidation was realized, the largest potential losers were the European diamond merchants. However, there were several challenges facing a consolidation of diamond mining on the Kimberley fields. The claim ownership structure inherited from the alluvial deposits meant that initially each claim was just 2.9 square meters, only individuals could own a claim, no individual could own more than two claims and the owner forfeited their claim if it was inactive for eight consecutive days. These restrictions and the geology of the deposits quickly led to a situation where many individuals were mining a small area to greater and greater depths [107]). 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 their collapse in places necessitated replacement by a haulage system with wires emanating in a spider like fashion to the edge of the pit which is illustrated in Fig. 1.

In addition to just accessing their claim, the small nature and

[6] This diamond bearing igneous rock is called kimberlite after the city of Kimberley, which formed in the early 1870s around the mines. Currently, kimberlite is the main source of diamonds, but only a minority of kimberlite pipes bear diamonds, and only a fraction of those are economic enough to mine.

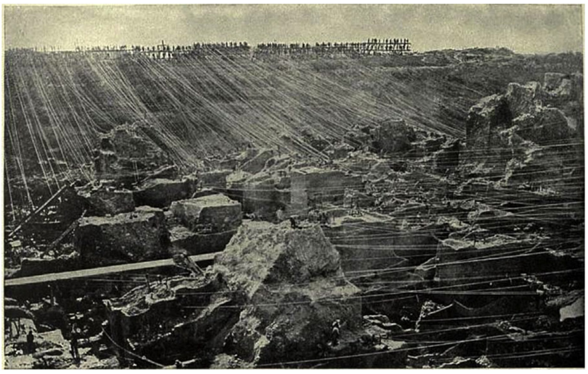


Fig. 1. Rope and Haul system at the Kimberley diamond pipe.

increasing depth of mining on the pipes created externalities that required collective action. The intercepting of groundwater and rain created an increasing need for pumping water out of the mines, but the potential to free-ride on an individual miner's water extraction was significant. Another considerable force supporting collective action came from rock falls and wall failures. As depths grew greater, and when mining of one claim progressed much more rapidly than a nearby claim, the threat and actual collapse of some part of the mine emerged. Once a fall occurred clearing the debris and potentially supporting areas to prevent further failures thereby required collective action. Mining boards were established to provide these services but they were also used to exert authority for consolidation.

Kimberley diamond mining thereby faced a tremendous challenge as coordinated mining and provision of public goods required cooperation that was difficult to achieve without consolidated ownership. The growing constraint of these technological and organizational challenges along with labor and capital shortages and conflicts over property rights ended an era individual development that was reflected in an outflow of residents. In 1872 Kimberley's population was more than 14,000, but by the end of 1874 it was only 7,000 [111]. There were strong incentives to free-ride and/or undercut actions to reduce or constrain the supply of diamonds owing to the large-scale nature of the diamond deposits. It was difficult to form coalitions with the legacy of small claims across the pipes. Adding further difficulty were several waves of speculative investments which increased uncertainty and risk to investors whose financial capital was needed to consolidate ownership. Therefore, as the deposits expanded global supply of diamonds, they simultaneously created inherent challenges for producers. While the eventual consolidation of ownership seemed inevitable, the nature of that consolidation was far from certain.[7]

3.2. Distributed dynamic capabilities in the Kimberley diamond fields

Some initial relief on these production and ownership challenges came in 1873, when the maximum number of claims an individual could own rose from two to ten, but it was only after the black flag revolt of 1875 and the significant labor and organizational change that followed when claim ownership restrictions were removed late in 1876 that significant consolidation began to occur [96]. 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. Migrant European, mainly British, miners were needed to operate and maintain this equipment and so a new class of skilled labor began work on the diamond fields. The new methods of production restored profitability to many operations, but economies in production led to a race to secure ever larger claims on all of the pipes. The further relaxation of claim ownership restrictions in 1876 led to reinstating of mining boards with a structure favorable to larger operations [67]. 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. The lack of influence over the mining boards and productive economies of scale put smaller claim holders in a position of accelerating disadvantage compared to larger operations.

Technical knowledge gained from leading producers at Kimberley created a unique distributed dynamic capability in collaborative innovation. 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 [107]. This structure of local knowledge externalities enhanced productivity across the Kimberly diamond fields, but Newbury argues that 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 entire Kimberley diamond industry [67]. The distributed ownership structure of the mines was an important precondition for this collective innovation [1]. Other prerequisites for collective innovation include risk and uncertainty regarding scientific understanding, which the unique and unprecedented nature of the kimberlite deposits certainly fulfils, as well as independent agents circulating and diffusing know-how, which autonomous mining engineers working on the Kimberley fields satisfied.

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 two pipes and monopolize global production of diamonds. Hence, an urgency characterized efforts to control both of these central pipes. While the processes of unification at the Kimberley and DeBeers pipes where unique, they had by that stage unified their commitment to a compound system to manage migrant labor and systematic exploitation of the diamond deposits.

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. Respectively, these firms were the DeBeers Diamond Corporation and the Kimberley Central Diamond Corporation. While DeBeers Diamond Corporation would eventually consolidate ownership in 1888, distributed dynamic capabilities from diamond mining at Kimberley were already being transferred to the gold mining industry on the Witwatersrand [111].

Those distributed dynamic capabilities were transferred to the Witwatersrand across what had become a coherent MRFN. The foreign capital investments that facilitated consolidation were drawn together from established networks and production relationship built primarily around the diamond industry, but unique in their focus on building sustained control over diamond mining in the Southern African interior. The mining ownership networks that were established were also unprecedented and built a productive

[7] See, for example, [67,81,96,105,111].

mineral resource industry founded on the need for collective action and coordination. Related to that familiarity of operations was simultaneous competition and coordination, such as the use of learning around diamond mining practices to facilitate consolidation of ownership. It also supported the open system of innovation in mining practices, and with its further development on the Witwatersrand goldfields it initiated a collaborative system of innovation within the mining industry that would endure for decades.

3.3. The emergence of the MRFN and its distributed dynamic capabilities at Kimberley

The MRFN's distributed dynamic capabilities that were established on the Kimberley diamond fields thereby led to notable economic development which defined the centrality of the mineral resource economy in South Africa. Many precedents were important to establishment of the MRFN at Kimberley. The diamond merchant business networks that predated the discovery of the kimberlite deposits exerted the strongest influence. The elastic nature of market demand meant that these merchants would be strongly affected if they left production of diamonds to the vagaries of speculative boom and bust production. Consolidated mining of the Kimberley deposits was necessary for them to retain the value of their processing and selling. This meant that there was an inherent interest in coordinating production early in the industry's development that was distinct from the worldwide precious metals booming mining camps with their more inelastic demand structures.

Colonial and state focused interests in development of the fiscal benefits from the mines were another established, but important influence over the development of mining activities at Kimberley [23,66]. These development focused coalitions, would be transferred via the MRFN to the Witwatersrand and entrench the centrality of the mineral resource economy in South Africa. The MRFN also created a critical foundation to support labor controls, which facilitated labor supply for the mines. While Africans had been selling labor to whites before Kimberley, the orchestrated labor power struggle facilitated by diamond producers among white-black and skilled-unskilled workers on the kimberlite diamond mines established precedents that would be followed on the Witwatersrand [47,48,84,86]. Distinct, but interrelated to these were the influence of colonial ambitions and settlers' advance into the African hinterland which impacted the racial characteristics of production. These were inherited from the early Dutch settlement of the Cape, but evolved with further European, and particularly Trekboer expansion into central Southern Africa [7].

It is significant that constraints on sovereignty of indigenous workers followed an initial considerable economic advance of African communities responding to demand for goods and services. They were central in the early development of Kimberley providing transportation services and agricultural products [7]. The state-mining partnership built on the Kimberley diamond fields and embodied in the MRFN was also instrumental to the development of the hut taxes and pass regulations to limit the mobility of labor and subjugate African societies.

Consolidation of ownership at Kimberley was also associated with decline in that community's economic importance. In essence, while ownership of the diamond fields entered final consolidation local commercial interests faced reduced market opportunities as the Kimberley mining interests: 1) constrained production of diamonds to protect their value and support demand from diamonds, 2) increase efficiencies through labor replacing capital investment in underground mining operations, and 3) creating an isolated African migrant labor force removed from local commercial interest through their accommodation in mining compounds. Using interests of the Afrikaner Bond to leverage their positions Kimberley mining interests supported the development of domestic agriculture through import duties and thereby, along with a coalition of large wholesalers and merchants who profitably supplied African labor in the mining compounds, removed opposition from the small merchants at Kimberley.[8] Hence, a slow process at Kimberley began gradually devolving the community into a company town with limited economic development impacts. Somewhat ironically, the firm that eventually consolidated the diamond field, DeBeers Consolidated, financed the railway line to Johannesburg which effectively bypassed Kimberley's commercial links with the Witwatersrand.

4. The Witwatersrand goldfield

4.1. Deep uncertainty in the Witwatersrand goldfields

Surface gold deposits had been discovered by prospectors in the Southern African interior as far back as the early 1850s. However, it was not until 1873 when the region experienced its first 'gold rush'. This occurred in the Blyde River watershed and, as with many subsequent gold rushes in the region; initial small-scale alluvial mining operations gave way to more organized mining and extraction operations. During this era, after initial development gold extraction was achieved with an established technology, amalgamation, a process dating back hundreds of years and possibly back to the Roman Empire [44].

In the amalgamation process the gold bearing host rock is crushed and ground into fine sand like material. Water is then added to produce a 'pulp', which is a gold bearing muddy substance. The pulp is then passed over mercury where gold sinks into the mercury because of its higher specific gravity. Lighter minerals in the pulp cannot sink through the mercury and become waste tailings. After concentration through amalgamation, the gold amalgam enters a pyro-metallurgical stage to separate the mercury and gold. That process heats the gold laden mercury for several hours boiling and vaporizing the mercury, and leaving sponge gold. A significant, albeit incremental improvement, to the amalgamation process occurred with the California gold rush of 1849, when amalgamated copper plates were introduced facilitating greater industrialization of the gold extraction technology [11].

Mining of the Witwatersrand began in 1886 on the surface or 'outcropped' gold deposits. During this initial period of development milling facilities and amalgamation plants rapidly emerged to support the growing operations [106]. In the outcropping zone, gold recovery with the amalgamation process was around 75 to 80%, but as mining moved deeper underground recovery rates declined. Following the gold bearing host rock deeper underground, the amount of elemental gold decreased as outside of the oxidized zone it increasingly combined with sulphide. In addition, pressure at increasing depths reduced the size of the gold particles. Together, these influences reduced the efficiency of the amalgamation process. In the latter part of 1889 several of the deeper mines began to intercept the sulphide zone and with that geological transition recovery with amalgamation declined to about 60% of the gold, putting significant strain on the economic viability of mining.

As word of the declining yields at depth spread, investors in this fledgling industry began to worry that their investments would be lost and began selling their interests. This had a compounding effect and sparked a massive sell-off of mining interest on the

[8] The simultaneous growth of the Witwatersrand at this time also helped dilute opposition.

Witwatersrand. The speculative bubble burst; by early 1890, the market value of the mines plummeted 70%, and a third of Johannesburg's population departed [20]. Hence, early in 1890 the future of mining on the Witwatersrand seemed questionable unless technical breakthroughs were achieved and the settlement, Johannesburg, built to support the extraction was considered by many destined to become yet another ghost town after a mining boom [32,78]. Survival of the Witwatersrand goldfields hinged on the development of a viable metallurgical process to extract gold from the deposits in the sulphide zone.

In the later-19th century the constraint to the amalgamation process was not unique to the Witwatersrand; limits in the extractive ability of the amalgamation process limited the economic viability of gold deposits around the world. In 1890, faced with the need for an alternative extraction technology there were two principal processes: chlorine-based extraction and cyanide-based extraction. The chlorine-based process was relatively established technology at that point. The process was first developed to treat gold in 1848 by C F. Plattner at the Royal Freiberg Smelting Works in Germany [79]. By the early 1860s, the Plattner chlorine process had been applied on gold deposits at Schemnitz (Banská Štiavnica) in Slovakia, Reichenstein (Zloty Stok) in Poland, and at mines in California and Nevada in the United States [17, 53, 95]. Further adoption of the chlorination process occurred globally during the 1870s and in the mid-1880s Australian based Claude Theodore James Vautin and James Cosmo Newbery enhanced the process by introducing compressed air in the dissolution of gold and employing charcoal for its precipitation [6].

Despite adoption of chlorine based extraction there were some fundamental challenges. In the chlorination process gold is liberated from the sulphides after crushing by roasting and then using the chlorine to adhere to the gold. The effectiveness of the process varied considerably from deposit to deposit and by the chemical skill of the metallurgist. Certain elements in the deposits would also absorb chlorine and thus increase associated costs as the amount of chlorine required to extract the gold increased. Particles around the gold, particularly smaller gold at depths, would also prevent chlorination. In addition, once in solution chemical processes could cause the gold to be precipitated in the tailings before filtration was complete. Where chlorination had been established, particularly in Australia, solutions to these challenges had been developed by local metallurgists that made the process economically viable and institutionally difficult to displace with other technology [94].

Chlorine-based extraction was thereby well-positioned to address the challenges of sulphide ores found on the Witwatersrand. Hence, chlorination was employed as a solution. The first chlorination plant was built on the Witwatersrand in 1890 using the Newbery-Vautin process, then in 1891 chlorination plants were also opened at the Simmer & Jack and Robinson Mines. These plants, despite the significant investments made, could not compete with the developing cyanide-based technology and by 1902 there were no longer any chlorination plants operating on the Witwatersrand [109].

Cyanide's ability to dissolve gold had been documented in Prussia as far back as the 18th century and the solubility of gold and silver in cyanide solutions had been noted in a British patent by J.R. and H. Elkington in 1840. In commercial mining, Henry Wurtz had noted in 1866 that cyanide was being used on some goldfields as part of the amalgamation process, but not as an extraction process itself. Several processes to use cyanide for the extraction of gold were experimented with over the ensuing decades until the mid-1880s, most being laboratory experiments or niche applications [13].

In 1886, John S. MacArthur and the Forrest Brothers in Glasgow developed an industrial process of cyanide extraction. Commercialization of the technology began the same year when the Cassel gold recovery corporation was formed as a partnership of MacArthur and the Forrest Brothers [59]. In 1887, the Cassel/Forrest process was marketing itself as a gold extraction technology, but the first application of the cyanide process was in 1888 at a pilot plant in Ravenswood, Queensland Australia. Subsequently, the process was applied on a commercial basis for the first time in 1889 on a gold mine at Karangahake near Auckland, New Zealand [13,63].

4.2. Distributed dynamic capabilities in the Witwatersrand goldfields

The challenges in developing a viable metallurgical process for the massive quantity of deep level gold deposits led the Witwatersrand's system of innovation to develop critical technological leadership in cyanide-based extraction of gold. Supported by the legacy of Kimberley's open innovation precedents, incremental technological innovations and information diffusion propelled development of the cyanide process from pilot technology to a robust industrialized method of gold extraction by the end of the 1890s. Not only would cyanide-based extraction prove a durable technology, its open community of practitioners entrenched an enduring practice of collaboration in critical competitive technologies for the industry [5].

The real driver of the process' application would come in May of 1890 when the process was tested on a pilot plant at the Salisbury mine on the Witwatersrand [58]. Strong results from that experiment greatly encouraged stakeholders in the Witwatersrand mines who were desperate for a solution to sulphide layer challenges. MacArthur's Cassel Company operated the first pilot plant on the Witwatersrand in June 1890 at the Salisbury Mine. After favorable results, a local company, the African Gold Recovery Syndicate (AGRS), was granted license over process patents. At the Robinson mine in December 1890, the AGRS opened the first commercial plant to use the cyanide process. With successful operation, the Robinson mine took over the plant from AGRS when their lease expired in June 1891. Several other commercial plants would rapidly be established as the cyanide process proved itself an effective, economic, and robust technology for treating the Witwatersrand's gold [9,26].

As with other incidences of collaborative innovation, several key preconditions supported the system in the development of the cyanide-based extraction technology. The distributed ownership structure predisposed interests in a solution to the challenge. The technology was also uncertain and subject to limited scientific understanding. Collaborative innovation worked to reduce some of the uncertainty associated with those investments and thereby facilitated the financial networks to leverage further investments to develop this industrialized process for extracting the gold bearing deposits from the sulphide zone. The independent metallurgical experts were the final critical component who acted to diffuse learning and best practices about the technology as similar agents had done at Kimberley and in other instances of collective innovation.[9]

In fact, in large measure because of the mobility of these metallurgists and the open nature of their innovation system, the cyanide process rapidly spread beyond the Witwatersrand goldfields. In 1890, the process was also applied at a gold mine in Colorado [88]. In 1891 gold mines at Mercury in Utah, and Calmed in California established cyanide-based gold extraction plants. This was

[9] For descriptions of other instances of collective innovation see: [1,62,69,103].

followed by its application in Tuscarora, Nevada in 1892 and at Bodie in California in 1894 [72]. Despite this spread of the process the Witwatersrand became a critical center for the industrialization of the process and thereby its broader application.

The cyanide process was not a South African technology; it drew on global expertise and practices. However, South Africa established technological leadership in the process globally relying on an open source approach to knowledge not so unlike open source sharing today. Using an open innovation system, the evolving challenges to the cyanide process were met with significant contributions coming from South African expertise. A method for the economic treatment of gold bearing slime material and innovations to the zinc based method of gold precipitation were two key challenges to the cyanide process' adoption in the early years that were successfully addressed with significant contributions from South Africa's nascent leadership in the technology.[10] While this does not imply that the cyanide process was a South Africa technology, the analysis demonstrates that the industrialization of the process uniquely benefited from the Witwatersrand gold mining industry.

4.3. Evolution of MRFN and its distributed dynamic capabilities on the Witwatersrand

On the Witwatersrand goldfields, the MRFN continued to evolve from its emergence at the Kimberley diamond fields. In this case, we showed its distributed dynamic capabilities led to development of an economic extractive technology to access the Witwatersrand's vast gold deposits. A distributed mining-finance group ownership/management structure continued to characterize organizations that were part of the MRFN [22,24,57,70]. Similarly, the network's broadly coordinated production among mining companies facilitated collaborative innovation like it had at Kimberley, but with more prominence in resolving the uncertainty that faced the Witwatersrand compared to that at Kimberley. Underpinning these were financial networks and social capital linkages across the enterprises which facilitated investment in the innovative extraction system like it had facilitated consolidation in ownership across the kimberlite deposits.

Perhaps one of the more important relationships built-on and developed from the Kimberley diamond fields were the MRFN's state and capital coalitions. The Kimberley diamonds fields were entering into consolidation as the Witwatersrand gold deposits were discovered. As such, leveraging state support to facilitate favorable operating conditions was important and so it was transferred directly to the Witwatersrand. Perhaps, most significant in this regard was the use of state support by industry interests to facilitate co-opting African labor. Further labor restrictions, workforce transportation infrastructure, and pecuniary charges compelled increasing numbers of Africans to work on the mines at the same time limiting alternative employment opportunities [47,48,112].

These actions, and the strength of the state-capital alliance, reduced some of the risks (known unknown) associated with the Witwatersrand gold mines and thereby made the investments in and development of the cyanide extraction technology possible, despite the lingering deep uncertainty (unknown unknowns).[11] The MRFN was also instrumental in directing broader industrial development just as it had been on the Kimberley fields [27]. As such the Witwatersrand drew-on and developed the network's social capital, colonial and ethnic identities in its influence over the structure of ownership and financial positions of mining companies [73].

In contrast to Kimberley, the certainty that the cyanide process provided for accessing the Witwatersrand's gold resources and growing confidence in the MRFN's development path combined to lead the large mining-finance groups to undertake significant investments in industrialization. These occurred in Johannesburg and other communities surrounding the Witwatersrand and ranged from the manufacture of mining equipment through, housing developments, agriculture and food processing industries, as well as electricity and water utilities. In addition to these industries, the MRFN also facilitated domestic development of ever-growing mineral resource capabilities which included production of explosives and industrial chemicals as well as iron, steel, and many others including coal and its beneficiation.

5. The South African synthetic fuels industry

5.1. Deep uncertainty in the synfuels industry

The evolution of South Africa's oil-from-coal industry was shaped by the nature of available coal deposits. South African coal is characterized by high ash content, much more so than is found in more northern deposits. This ash, or inorganic material, is mixed with hydrocarbons and complicates the process of liquefaction. Fundamentally, coal must be hydrogenated to transform to fuels and ash is generally a contaminant.

There are two primary approaches to liquefaction of coal, direct and indirect [54]. Direct liquefaction immediately converts coal to liquid fuels using high temperatures and pressures. Indirect liquefaction is a two-step process. First coal is gasified, and then hydrocarbon molecules are converted to liquid fuels; this has the advantage of first removing impurities, but is less thermally efficient than direct liquefaction. Both approaches were known in the 1930s when South Africa first became interested in oil–from-coal. South Africa selected indirect liquefaction primarily due to the high ash content of South African coal, which tends to fare poorly under direct liquefaction.

The technology of indirect liquefaction developed in Europe, especially Germany. In 1902 two French chemists, P. Sabatier and J. Senderens catalyzed carbon monoxide and carbon dioxide into methane at atmospheric pressure. About ten years later, Fritz Haber synthesized ammonia using high pressure and a catalytic technique. In 1913, the German firm of Badische Anilim and Soda Fabrik (BASF) was awarded a patent for catalytic hydrogenation of carbon monoxide. Shortly afterward, BASF developed technology for the hydrogenation of carbon monoxide into methanol with high pressures. This technology came to the attention of Franz Fischer of the Kaiser Wilhelm Institute (later to become the Max Planck Institute). Fischer and colleagues experimented with various reaction possibilities in the 1920's including use of iron shavings as a catalyst [25]. Motor fuels were first produced from hydrocarbon gases in 1931 using a cobalt catalyst. The first indirect liquefaction pilot plant was established in 1933. The technology was turned over to Ruhrchemie A. G. Oberhousen, a commercial firm. Seven normal pressure reactors were built in Germany by 1937 as part of an effort to bolster energy independence prior to World War II. The largest of these at Scwarzheide, produced 180,000 tons per year (about 3,615 barrels a day) and was the only indirect facility still operating at the end of the war [82].

Nazi Germany was more reliant on direct liquefaction, first patented in Germany by Friedrich Bergius in 1913. Bergius shared the Nobel Prize in chemistry with Carl Bosch in 1931 in large part

[10] See, for example, [8,10,76,102,108].

[11] We follow others in the dynamic capabilities literature and adopt the distinction forwarded by Frank Knight between risk (known unknowns) and uncertainty (unknown unknowns) [51].

for this work. Germany embarked on a major synfuels development program in 1936 under the direction of Herman Goering. Becker reported German plans called for a public-private partnership, with the private sector supplying half of the capital, put at 1.15 billion marks [4]. By 1943, Germany relied on synfuels for half of its petroleum needs including most aviation fuel. The remainder came primarily from Romania and domestic supplies, including oil from annexed Austria. Total production from direct and indirect liquefaction peaked in early 1944 with an estimated production of 124,000 barrels a day from twenty-five plants [97]. Later, strategic bombing destroyed much of that capacity [52].

There was considerable interest in German technology in the United States and South Africa. The United States Congress passed the Liquid Fuel Act of 1944, which allocated funds to the Bureau of Mines for pilot synfuels projects [42]. This included direct and indirect hydrogenation demonstrations in Missouri [100]. The military was also interested in this technology and formed the Technical Oil Mission, eight specialized units sent to study German methods and transfer technology as part of occupation forces. The Allied advance provided access to the petrochemical infrastructure of Germany's Ruhr Valley. American forces salvaged heat exchangers, high pressure injector pumps and other devices. They also retrieved valuable information in seized files and other records. The Truman administration favored development of a domestic oil-from-coal industry. Secretary of Defense James Forrestal recommended an 8 billion dollar synfuels industry to help assure energy independence in light of rapidly growing demand for petroleum products and rising oil prices. But the oil industry, at first ambivalent, later opposed synfuels because of high costs. The transition to the Republican Eisenhower Administration, with a reluctance to embrace nonmarket approaches, and the stability of oil prices effectively ended federal efforts to develop synfuels in the United States for twenty years.

One of the more remarkable aspects of the story of oil-from-coal development in South Africa is the transfer of state of the art German technology. Nazi views on race and ethnicity found considerable sympathy with some elements of South African white society. The German challenge to British global hegemony was very much in accord with sentiments of much of the Afrikaans population. Memories of the Second Boer War were still alive. The Ossewabrandwag, formed in the late 1930's, was a paramilitary organization allied with Germany and in active opposition to South Africa's Allied war effort [61]. Many Afrikaans leaders were important members including two future national leaders, John Vorster (1966–1978) and P.W. Botha (1978–1989). Vorster was incarcerated during World War II for his association and leadership in the Ossewabrandwag.

Pro-German sympathies may have played a role in German technology transfer to South Africa. Yet it was not an Afrikaans business interest that took possession of synfuels patents, but rather Anglovaal. Anglovaal was the parent of Satmar (South African Torbanite and Mining Company). Satmar was established in 1934 to exploit torbanite, a form of oil shale deposits in South Africa. Anglovaal was aware of developments in Germany and sought to learn more about what might be appropriate for its markets. An engineer, Oscar Feldman, was authorized to investigate German advances. In 1936, Anglovaal sought production rights from Rurhchemie and Franz Fischer. A contract was drawn between the two firms specifying and authorizing key patent transfers. Conditions for commercial operations were also spelled out, including production and marketing rights for southern Africa as far north as Northern Rhodesia (Zambia). Agreements were signed by Fredrick Martin and Heinz Waibel of Ruhrchemie and Abraham Hersov and C.H. Leon of Anglovaal. The first agreement was signed on July 25, 1936 at Oberhousen-Holten in Germany. A second agreement was signed after Anglovaal tested some of the technology. Fig. 2 shows these patent applications. They range from gasification patents in 1931 to liquid fuel synthesis technology in 1936.

The onset of the war halted construction, agreements were suspended and afterward Anglovaal allowed its rights to expire. At this point, most of the technology was held by American and British interests and there was little expectation that Ruhrchemie could provide exclusive production and marketing rights.

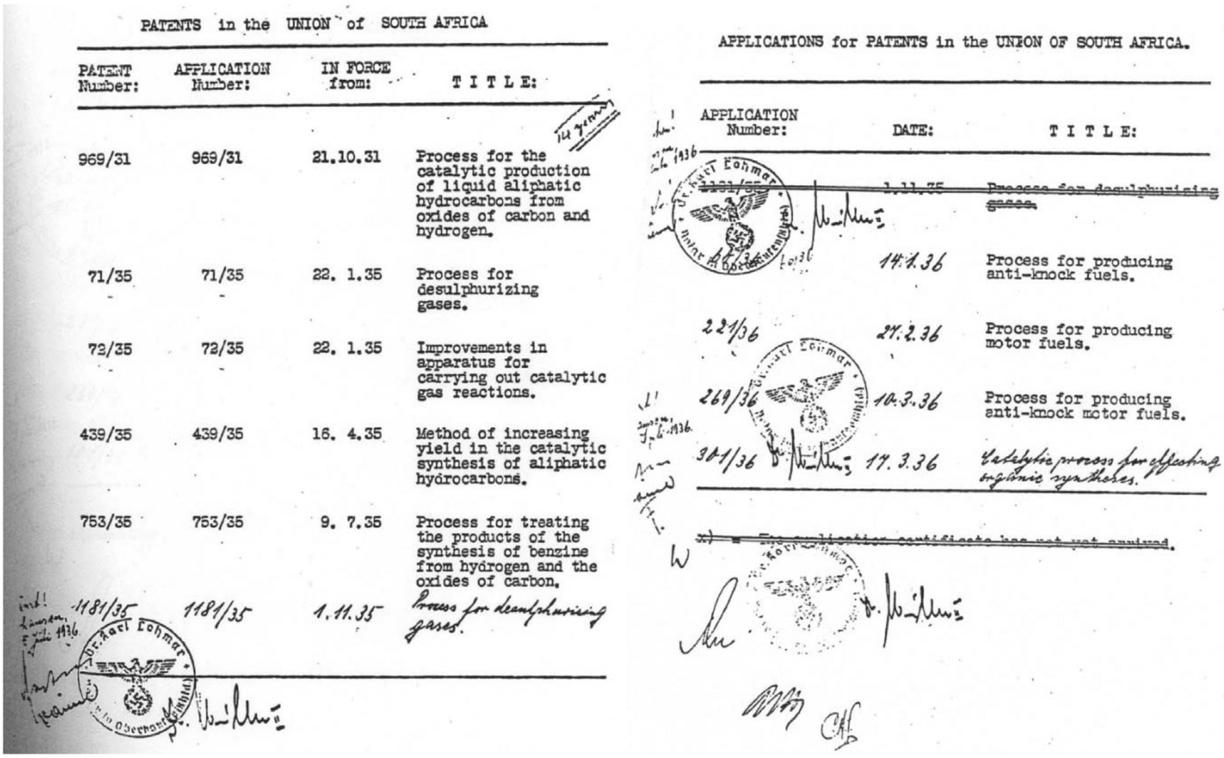
There remained inherent uncertainty about the economic viability of the oil-from-coal technology despite advances during the war. There was no clarity about the extent of the capital cost, the effectiveness of existing indirect liquefaction technologies with South African coal, and other concerns. Moreover, post-war decolonization and growing cold war tensions heightened South Africa's sense of impending isolation. A national security externality regarding oil vulnerability was imminent, but there was much uncertainty about its magnitude and timing. These issues were beyond Anglovaal's purview and alternative means of developing the technology were necessary.

5.2. Distributed dynamic capabilities in the synfuels industry

In guiding the South African MRFN's distributed dynamic capabilities, the experience of German industrial development efforts provided a new model embracing private production with large-scale government support. Public concern about international isolation in the anticolonial post war period was another factor driving support for establishment of a parastatal organization responsible for synfuels development. The Liquid Fuel and Oil Act was passed in 1947. But at this point, South Africa was not isolated and the internationally respected Boer War veteran, Jan Smuts was still Prime Minister. The National Party, known for advancing apartheid, was elected in 1948.

The Liquid Fuel and Oil Act effectively gave Anglovaal what it would have had with the German agreement, exclusive rights for synfuels production and marketing. A license for production was granted in 1949. Provisions of the license stipulated that no coal of less than 30% ash content could be rejected unless necessary for mine roof support. This helped assure use of indirect liquefaction. A new organization, wholly owned by the government's Industrial Development Corporation took the lead. In 1950 the South African Coal, Oil and Gas Company, known as South African Synthetic Oil Limited (Sasol) was established. The first plant, known as Sasol I along the Vaal River, was constructed at what is now Sasolburg in the Free State province. The facility employed gasifiers manufactured by Lurgi of Germany and Ruhrchemie was brought back into the fold as supplier of reactor and catalyst technologies [99]. Additional reactor technology was obtained from the United States including some for production of motor fuels. American technology also afforded relatively easier enlargement. Sasol integrated German and American approaches into the construction of Sasol I, which began operations in 1955. Financing was provided by the state's Industrial Development Corporation. Teething problems plagued production until 1960 [64].

Sasol was developed in the post-World War II era of decolonization and was a lynchpin in South Africa's “laager” of isolation and white minority rule. Supported by the MRFN, South Africa was confident it could establish synfuel production. But this large industrial undertaking was only possible because of South Africa's well-established infrastructure and expertise in coal mining and geo-chemical engineering. The distributed dynamic capabilities established in Kimberly and developed on the Witwatersrand were essential building blocks in establishment of this new resource-



PATENTS in the UNION of SOUTH AFRICA

PATENT Number:	APPLICATION Number:	IN FORCE from:	TITLE:
969/31	969/31	21.10.31	Process for the catalytic production of liquid aliphatic hydrocarbons from oxides of carbon and hydrogen.
71/35	71/35	22. 1.35	Process for desulphurizing gases.
72/35	72/35	22. 1.35	Improvements in apparatus for carrying out catalytic gas reactions.
439/35	439/35	16. 4.35	Method of increasing yield in the catalytic synthesis of aliphatic hydrocarbons.
753/35	753/35	9. 7.35	Process for treating the products of the synthesis of benzine from hydrogen and the oxides of carbon.
1181/35	1181/35	1.11.35	Process for desulphurizing gases.

APPLICATIONS for PATENTS in the UNION OF SOUTH AFRICA.

APPLICATION Number:	DATE:	TITLE:
~~1181/35~~	~~1.11.35~~	~~Process for desulphurizing gases.~~
	14.1.36	Process for producing anti-knock fuels.
221/36	27.2.36	Process for producing motor fuels.
269/36	10.3.36	Process for producing anti-knock motor fuels.
301/36	17.3.36	Catalytic process for effecting organic syntheses.

~~x) = The application certificate has not yet arrived.~~

Fig. 2. Applications for patents in the Union of South Africa.

based industry. This legacy included the model of labor relations, which was later embedded in Sasol's very large underground coal mines. The heavy-handed role of the public sector, significantly more so than in diamond or gold mining, providing equity and debt capital on favorable terms, was a critical and the key subsidy. Other subsidies were also important including export credits, customs advantages and an internal subsidy per liter of gasoline sold. Moreover, transportation barriers favor Sasol's inland market. Johannesburg is at 1,750 m in elevation. There are significant transportation costs associated with bringing imported fuel to market. Sasol production on the high veld affords "natural protection" that augments economic viability.

While economists commonly argue that coal-based synfuels are inefficient because costs exceed the opportunity cost of imported fuels. In the South African case those results are more ambiguous for several reasons.[12] South Africa's purposeful approach to synfuels established an industry with tens of thousands of employees and an expertise that is part of the global petrol-chemical industry with Africa as its primary market. Therefore, even if the initial opportunity costs where not clear, it became an enterprise with an established competitive advantage.[13]

5.3. Evolution of the MRFN and its distributed dynamic capabilities with synfuels

South African MRFN and its various capabilities were well-developed by the mid-20th century. The progression from diamonds in Kimberly to gold on the Witwatersrand provided infrastructure for mining and related industries. A critical mass of mining engineers, chemical engineers as well as other professional and skilled workers provided a technical foundation and confidence for establishment of an oil-from-coal industry. The well-developed financial sector that evolved with exploitation of diamond and gold resources was another key element in this path dependent story. Financial institutions were on hand to provide both debt and equity finance for large-scale industrial undertakings. Most importantly, the post Second Anglo-Boer War era facilitated South Africa's development of a more centralized and modern state. The MRFN's distributed dynamic capabilities leveraged that centralized and modern state to provide the resources and leadership necessary to see the synfuel project through to completion.

The MRFN continued to contribute to the subsequent development of the synfuels industry. When the OPEC oil embargo of 1973-74 singled out Israel, South Africa, the United States and the Netherlands for oil supply disruptions, the MRFN facilitated the flow of resources to substantially increase Sasol production. The first step in this regard was the development of Sasol II, which began construction in 1974, with the support of financial institutions, both public and private, and the guarantee of state price support through retail motor fuel taxes, grants and export credits. There was a second oil shock in 1979 with the Islamic Revolution in Iran, which led to the development of Sasol III. It was financed much the same way as Sasol II, and it again involved the Industrial Development Corporation, but Sasol III also included equity capital

[12] U.S. Dollar pricing of oil and South African Rand weakness is one such reason [41]. In addition, assumptions of full employment of labor which support the opportunity costs of capital argument are questionable in South Africa with its high, and historically orchestrated, unemployment. Lastly, periods of high liquidity in South Africa also led to an environment of negative real interest rates raising further questions about the opportunity costs of capital in this very capital-intensive endeavor.

[13] It is significant that South Africa's competitiveness in resource-based intermediate products, like oil-from-coal, also have large economies of scale which can insulate them from competition. In South Africa this was particularly true during its increasing international isolation prior to democratization.

raised on the Johannesburg stock exchange. The MRFN's distributed dynamic capabilities were critical to this development of the larger indirect coal liquefaction facilities. Both second-generation facilities were constructed to produce 50,000 barrels a day, approximately ten times the size of the Sasol I facility. Numerous improvements over Sasol I were also incorporated, including electronic instrumentation, improved cooling systems and better catalytic techniques. These facilities were also much more efficient in water consumption [83]. The impact of Sasol on South African liquid fuel production has been substantial but it is also important to note that Sasol generates substantial nonfuel by-products including feedstock for plastics and high quality industrial waxes. As a result, the MRFN development path perpetuated with establishment of Sasol was also important to broader economic development. Sasol emerged as the primary producer of gasoline for most of South Africa's large inland area and diversified into other branches of chemical production. These other areas included synthetic ammonia and petro-chemical raw materials. The mineral resource based economy in South Africa was not a sector of limited knowledge intensity and growth constrained by finite mineral deposits. In contrast, it was much more in line with the description of knowledge-based development.[14]

6. Conclusion

This analysis demonstrates that the concept of ‘distributed dynamic capabilities’ facilitates the examination of a host of path dependent social and economic factors on a distributed organization's development. This reconceptualization of the dynamic capabilities framework from its focus on the firm as the primary agent to include a network of agents creates a unique analytical tool to explore the evolution of an economy overtime.[15] We explore some implications in terms of South Africa's historiography in the remainder of this conclusion, but we also believe it holds significant promise in managerial science and economic development applications that are beyond the scope of the present analysis.

Recognizing that a distributed organization is more than the firms which compose it raises a range of issues regarding the strategic management of networks that should be explored further. In addition, distributed dynamic capabilities suggests a useful approach to examine the organizational structure of economic development and the features driving the evolution of an economy's product space and comparative advantage. Exploring these insights, we believe will advance understanding of the process of technological change in society and society in technological change.

This analysis shows that the microfoundations of a dynamic path dependent trajectory were established at Kimberley like those described in the dynamic capabilities approach [91]. There on the kimberlite diamond fields the MRFN emerged with distributed dynamic capabilities that directed development of the diamond industry and facilitated broader economic development across the Southern African interior.[16] We then showed the distributed dynamic capabilities of the MRFN were applied to develop an industrial cyanide based extraction method through a collaborative effort of mining-finance groups. That technology led to the large-scale development of the Witwatersrand goldfields and another round of much broader industrial development across the Southern African interior. Lastly, we described how the MRFN's distributed dynamic capabilities led to the development of a domestic oil-from-coal technology through a partnership between a mining-finance group and the government. That collaboration led to the creation of state-owned enterprise and a South African synfuels industry with further industrial development impacts. While counterfactuals are by nature speculative, it is reasonable to believe that a very different domestic mineral industry and economic history would have developed if the MRFN had not emerged on the Kimberley diamond deposits without the network's distributed dynamic capabilities. We believe that our analysis shows that without the MRFN, the Southern African interior would likely have been considerably less economically developed. That is not to say that development of the region's mineral resources would not have occurred, but that eventual development would have depended more on foreign technology and not been characterized by leveraged industrialization, development of additional mineral resources, and the emergence of other resource-based intermediate products.

We described how this development path led by the MRFN involved processes of political and cultural dimensions in the process of capabilities development. While those were important to establishing broader South African capabilities in finance, engineering, and chemistry which became features of the South African economy in their own right, they also created legacies South Africa's industrial and labor relations systems that institutionalized racial discrimination. Those racial labor policies were part of the MRFN's distributed dynamic capabilities that helped solve the deep uncertainty at one point in time, but overtime they would become a fundamental challenge to the MRFN's further operation. As such, our analysis suggests that it is necessary to reassess the assumption put forward by Protogerou et al. that dynamic capabilities are positive on performance [75].

Deepening our understanding about the origins and evolution of the MRFN's distributed dynamic capabilities through historical analysis is therefore an important processes of rediscovering South Africa's mineral resource history. It is also a necessary part of building informed policy that addresses the MRFN’s institutional legacy. However, many issues regarding the MRFN’s legacy were beyond the scope of this analysis. These include whether there is evidence the network's resources and capabilities became immobile and thereby location specific [19]. While our cases covered development across distinct mineral deposits, the geographic structure of the network was not explored. We describe the network's emergence and development across what now corresponds to the boarders of modern South Africa, but its influence was felt across southern Africa and globally. Similarly, the influence of overseas forces, such as the dynamics of the international gold standard, foreign financial networks and colonial ambitions were all issues beyond the critical technology focus of this analysis. The downstream users of the intermediate goods produced by the MRFN, such as petro-chemicals, and steel, are also significantly impacted indirectly by the MRFN but those implications, despite needing to be considered in a comprehensive analysis of distributed dynamic capabilities, were also beyond the scope of the present analysis.

Nonetheless, this analysis is an important contribution to the reconceptualization of dynamic capabilities to analyze issues of economic development and the management of networks. It also raises a new perspective to better understand South Africa's historiography. It demonstrates that distributed dynamic capabilities accumulate through socially embedded and contingent historical processes [49]. Research is clear that long run economic growth is

[14] See, for example, [15,98,101].

[15] We believe the conceptualization of the networked organization and distributed dynamic capabilities is an original contribution of this analysis, but it is related to the issue of the location of organizational links being diffused and distributed that were raised by Neil Kay that he referred to as “diffused dynamic capabilities” [50].

[16] This kind of change in economic and social contexts is described within the distributed capabilities framework as a dialectical process that transforms the structural environment faced by the firm [104].

driven foremost by the ability to absorb new technology and having an educated labor force capable of implementing and exploiting it [16,30]. We show that a synergistic accumulation of dynamic capabilities can catalyze these factors and foster economic development. Therefore, we believe the distributed dynamic capabilities framework holds considerable promise for analysis of a range issues beyond the strategic management focus of its namesake.

References

[1] Robert C. Allen, Collective invention, J. Econ. Behav. Organ. 4 (1983) 1–24.
[2] Chad R. Allred, E. Fawcett Stanley, Wallin Cynthia, M. Magnan Gregory, A dynamic collaborative capability as a source of competitive advantage, Decis. Sci. 41 (1) (2011) 129–161.
[3] M. Barratt, Unveiling enablers and inhibitors of collaborative planning, Int. J. Logist. Manag. 15 (1) (2004) 73–91.
[4] P.W. Becker, The role of synthetic fuels in World War II Germany, Air Univ. Review (July-August) (1981).
[5] J. Bessant, A. Alexander, G. Tsekouras, H. Rush, R. Lamming, Developing innovation capability through learning networks, J. Econ. Geogr. 12 (5) (2012) 1087–1112.
[6] Ralph Winter Birrell, Development of Mining Technology in Australia: 1801–1945, PhD dissertation, University of Melbourne, 2005.
[7] Colin Bundy, The Rise & Fall of the South African Peasantry, University of California Press, Berkeley, 1988.
[8] W.A. Caldecott, The solution of gold in accumulated and other slimes, Proc. Chem. Metallurgical Soc. S. Afr. 2 (1897) 98–103.
[9] W.A. Caldecott, Discussion: reminiscences of the early Rand, J. Chem. Metallurgical Min. Soc. S. Afr. 9 (125) (1908).
[10] T. Lane Carter, A zinc process for precipitating gold from weak solutions, Proc. Chem. Metallurgical Soc. S. Afr. 2 (22) (1898) 440–446.
[11] Chemical, Metallurgical and Mining Society of South Africa (CMMSSA), 'A review of the progress in chemistry, metallurgy and mining", including miners' phthisis as reflected in the journal of the society', journal of the chemical, Metallurgical Min. Soc. S. Afr. 34 (1934) 280–316.
[12] Hedley Chilvers, The Story of De Beers, Cassell and Company, London, 1939.
[13] John Edward Clennell, The Cyanide Handbook, McGraw-Hill, New York, 1910.
[14] Ronald H. Coase, The nature of the firm, Economica 4 (1937) 386–405.
[15] D. De Ferranti, G.E. Perry, D. Lederman, W.F. Maloney, From natural resource to the knowledge economy, IBRD, Washington D.C., 2002.
[16] Edward Dennison, Accounting for United States Economic Growth: 1929-1969, The Brookings Institution, Washington DC, 1974.
[17] W.A. Dixon, On a method of extracting gold, silver, and other metals from pyrites, J. Proc. R. Soc. N. S. W. 10 (1877) 96.
[19] John H. Dunning, Sarianna M. Lundan, The institutional origins of dynamic capabilities in multinational enterprises, Industrial Corp. Change 19 (4) (2010) 1225–1246.
[20] Aiden M. Edwards, The role of technology in development of South Africa's mining industries, in: 15th CMMI Congress, Johannesburg, SAIMM 2, 1994, pp. 251–254.
[21] K. Eisenhardt, J. Martin, Dynamic capabilities: what are they? Strategic Manag. J. 21 (10–11) (2000) 1105–1121.
[22] Paul H. Emden, Randlords, Hodder & Stoughton, London, 1935.
[23] Charles Feinstein, An Economic History of South Africa: Conquest, Discrimination, and Development, Cambridge University Press, Cambridge, 2005.
[24] Ben Fine, Z. Rustomjee, The Political Economy of South Africa: from Minerals-energy Complex to Industrialisation, Hurst & Co, London, 1996.
[25] Franz Fischer, Lecture on coal research, J. Assoc. Sci. Tech. Soc. S. Afr. (February) (1938).
[26] C.E. Fivaz, Presidential Address: how the MacArthur-Forrest cyanidation process ensured South Africa's golden future, J. South Afr. Min. Metallurgical Assoc. 88 (9) (1988) 309–318.
[27] Stanley H. Frankel, Capital Investment in Africa: its Course and Effects, Oxford University Press, London, 1938.
[28] Bill Freund, The significance of the minerals-energy complex in the light of South African economic historiography, Transformation Crit. Perspect. South. Afr. 71 (2010) 3–25.
[29] Theodore Gregory, Ernest Oppenheimer and the Economic Development of Southern Africa, Oxford University Press, Cape Town, 1962.
[30] Zvi Griliches, Productivity, R&D, and the data constraint, Am. Econ. Rev. 84 (1) (1994) 1–23.
[31] Gary G. Hamilton, Robert C. Feenstra, Varieties of hierarchies and markets: an introduction, in: Dosi, et al. (Eds.), Technology, Organization, and Competitiveness: Perspectives on Industrial and Corporate Change, Oxford University Press, Oxford, 1998, pp. 105–145.
[32] Frederick H. Hatch, J.A. Chalmers, The Gold Mines of the Rand: Being a Description of the Mining Industry of Witwatersrand South African Republic, MacMillan, London, 1895.
[33] Ricardo Hausmann, Bailey Klinger, South Africa's export predicament, Econ. Transition 16 (4) (2008) 609–637.
[34] Ricardo Hausmann, Bailey Klinger, The Structure of the Product Space and the Evolution of Comparative Advantage, 2007 (CID Working Paper Series).
[35] Ricardo Hausmann, César A. Hidalgo, The network structure of economic output, J. Econ. Growth 16 (2011) 309–342.
[36] Ricardo Hausmann, César A. Hidalgo, Sebastián Bustos, Michele Coscia, Sarah Chung, Juan Jímenez, Alexander Simoes, Muhammed A. Yildirim, The Atlas of Economic Complexity: Mapping Paths to Prosperity, The MIT Press, Cambridge, MA, 2011.
[37] Ricardo Hausmann, Hwang Jason, Rodrik Dani, What You Export Matters, 2005 (CID Working Paper Series).
[38] Ricardo Hausmann, Final Recommendations of the International Panel on ASGISA, 2008 (CID Working Paper Series).
[39] C.E. Helfat, S. Finkelstein, W. Mitchell, M. Peteraf, H. Singh, S.G. Winter, Dynamic Capabilities: Understanding Strategic Change in Organizations, Blackwell Publishing, Malden, MA, 2007.
[40] César A. Hidalgo, Bailey Klinger, A.L.- Barabási, Ricardo Hausmann, The product space conditions the development of nations, Science 317 (5837) (2007) 482–487.
[41] Peter Hilsenrath, Coal-based Synthetic Fuels: the South African Experience, PhD dissertation, University of Texas, 1985.
[42] Peter Hilsenrath, The development of synthetic fuels in South Africa, J. Energy Dev. 14 (2) (1989) 269–283.
[43] Peter Hilsenrath, Stages of growth revisited, Dev. South. Afr. 10 (1) (1993) 101–110.
[44] Herbert C. Hoover, Lou H. Hoover, De Re Metallica New York: Trans. Of De Re Metallica (1556), trans, Dover Publications, New York, 1912.
[45] Hobart Houghton, The South African Economy, Oxford University Press, Oxford, 1967.
[46] Duncan Innes, Anglo American and the Rise of Modern South Africa, Raven Press, , Johannesburg, 1983.
[47] Alan H. Jeeves, Migrant Labour in South Africa's Mining Economy: the Struggle for the Gold Mines' Labour Supply, 1890-1920, McGill-Queens University Press, Montreal:, 1985.
[48] Frederick A. Johnstone, Class, Race, and Gold: a Study of Class Relations and Racial Discrimination in South Africa, University Press of America, Lanham, MD, 1976.
[49] Steven J. Kahl, Associations, jurisdictional battles, and the development of dual-purpose capabilities, Acad. Manag. Perspect. 28 (4) (2014) 381–394.
[50] Neil M. Kay, Dynamic capabilities as context: the role of decision, system and structure, Industrial Corp. Change 19 (4) (2010) 1205–1223.
[51] Frank H. Knight, Risk, Uncertainty, and Profit, Harper, New York, 1921.
[52] A. Krammer, Fueling the third reich, Technol. Cult. 19 (3) (1978).
[53] Küstel, Guido (1863) Nevada and California processes of silver and gold extraction: for general use, and especially for the mining public of California and Nevada, with full explanations and directions for all metallurgical operations connected with silver and gold from a preliminary examination of the ore to the final casting of the ingot. Also, a description of the general metallurgy of silver ores. San Francisco.
[54] Eric Larson, Robert Williams, A comparison of direct and indirect liquefaction technologies for making fluid fuels from coal, Energy Sustain. Dev. 7 (2003) 103–129.
[55] Martin Legassick, Gold, agriculture and secondary industry in South Africa: from periphery to sub-metropole as a force labour system, in: R. Palmer, N. Parsons (Eds.), The Roots of Rural Poverty in Central and Southern Africa, University of California Press, Berkeley, 1977.
[57] A.J. Limebeer, The group system of administration in the gold mining industry, Optima 1 (1) (1951) 26–30.
[58] John S. MacArthur, Discussion: reminiscences of the early Rand, J. Chem. Metallurgical Min. Soc. S. Afr. 9 (1908) 204–206.
[59] John S. MacArthur, Gold extraction by cyanide: a retrospect, J. Soc. Chem. Industry 24 (1905) 311–315.
[60] A. Madhok, S.B. Tallman, Resources, transactions and rents: managing value through interfirm collaborative relationships, Organ. Sci. 9 (3) (1998) 326–339.
[61] Christoph Marx, The Ossewabrandwag as a mass movement, 1939-1941', J. South Afr. Stud. 20 (2) (1994) 195–221.
[62] Judith A. McGaw, Most Wonderful Machine: Mechanization and Social Change in Berkshire Paper Making, 1801–1885, Princeton University Press, Princeton, N.J., 1987.
[63] Kenneth G. McQueen, Early developments in treating pyritic gold ores: the Australian perspective, J. Australas. Min. Hist. 10 (2012) 88–102.
[64] J. Meintjes, Sasol: 1950-1975, Tafelberg, Cape Town, 1975.
[65] William P. Morrell, The Gold Rushes, Frank Cass, London, 1940.
[66] Colin Newbury, The Diamond Ring: Business, Politics, and Precious Stones in South Africa, 1867-1947, Oxford University Press, Oxford, 1989.
[67] Collin Newbury, Technology, capital, and consolidation: the performance of DeBeers mining company limited, 1880-1889, Bus. Hist. Rev. 61 (1987) 1–42.
[68] S.G. Nicovich, C.C. Dibrell, P.S. Davis, Integration of value chain position and Porter's (1980) competitive strategies into the market orientation conversation: an examination of upstream and downstream activities, J. Bus. Econ. Stud. 13 (2) (2007) 91–106.
[69] Alessandro Nuvolari, Collective invention during the british industrial revolution: the case of the cornish pumping engine, Camb. J. Econ. 28 (3) (2004) 347–363.
[70] Harry F. Oppenheimer, Union's group mining system, Min. Industrial Mag.

South. Afr. 44 (9) (1954) 323–327.
[71] T. Pehrsson, N. Ghannad, A. Pehrsson, T. Abt, S. Chen, F. Erath, Dynamic capabilities in foreign markets: developments within international new ventures, J. Int. Entrepreneursh. 13 (1) (2015) 28–48.
[72] Michael H. Piatt, "The Mines Are Looking Well…": the History of the Bodie Mining District, Mono County. California. North Bay, 2003.
[73] Thomas E. Pogue, The Evolution of Research Collaboration in South African Gold Mining: 1886–1933, PhD dissertation, Maastricht University, 2006.
[74] Walter W. Powell, Neither market nor hierarchy: network forms of organization, Res. Organ. Behav. 12 (1990) 295–336.
[75] Aimilia Protogerou, Yannis Caloghirou, Spyros Lioukas, Dynamic capabilities and their indirect impact on firm performance, Industrial Corp. Change 21 (3) (2011) 615–647.
[76] Ernest T. Rand, A continuous process of slimes treatment, Proc. Chem. Metallurgical Soc. S. Afr. 2 (1899) 686–696.
[78] Theodore Reunert, Inaugural presidential address: the progress of engineering in South Africa during the last thirty years, Proc. South Afr. Assoc. Eng. Archit. 4 (1898) 188–196.
[79] Thomas K. Rose, The Metallurgy of Gold, 1898 (London).
[80] Walt W. Rostow, Stages of Economic Growth: a Non-communist Manifesto, third ed., 1990 (Cambridge).
[81] Robert I. Rotberg, The Founder: Cecil Rhodes and the Pursuit of Power (With Miles F. Shore), Southern Book Publishers, Johannesburg, 1988.
[82] D. Sauter, The development of the fabulous fischer-tropsch process', industrial review of Africa, 1958.
[83] Manny Singh, Economics of biofuels for the transport sector in South Africa, Energy Sustain. Dev. 10 (2006).
[84] John Smalberger, I.D.B. And the mining compound system in the 1880s, South Afr. J. Econ. 42 (4) (1974) 398–414.
[85] John Smalberger, Aspects of the History of Copper Mining in Namaqualand 1846-1931, 1975 (Cape Town).
[86] John Smalberger, The role of the diamond-mining industry in the development of the pass-law system in South Africa, Int. J. Afr. Hist. Stud. 9 (3) (1976) 419–434.
[87] Wolfgang Streeck, Philippe C. Schmitter (Eds.), Private Interest Government: beyond Market and State, Sage, London, 1985.
[88] Wilbur Fisk Stone, The Beginnings of Mining History in Colorado, History of Colorado, Chicago, 1918, pp. 228–262.
[90] David J. Teece, A dynamic capabilities-based entrepreneurial theory of the multinational enterprise, J. Int. Bus. Stud. 45 (2014) 8–37.
[91] David J. Teece, Explicating dynamic capabilities: the nature and microfoundations of (sustainable) enterprise performance, Strategic Manag. J. 28 (13) (2007) 1319–1350.
[92] David J. Teece, Gary Pisano, The dynamic capabilities of firms: an introduction, Industrial Corp. Change 3 (3) (1994) 537–595.
[93] David J. Teece, Gary Pisano, Amy Shuen, Dynamic capabilities and strategic management, Strategic Manag. J. 18 (7) (1997), 537–533.
[94] Jan Todd, Colonial Technology: Science and the Transfer of Innovation to Australia, 1995 (Hong Kong).
[95] C.H. Gustave Troost, Extraction of gold, J. Gold Min. Operations 10 (1858) 329–330.
[96] Robert Vicat Turrell, Capital and Labour on the Kimberley Diamond Fields 1871-1890, Cambridge University Press, Cambridge, 1987.
[97] US Department of Energy, Early Days of Coal Researchavailable at:http://energy.gov/fe/early-days-coal-research, accessed July 14, 2014.
[98] F. Van Der Ploeg, Natural resources: curse or blessing? J. Econ. Literature 49 (2) (2011) 366–420.
[99] J.C. Van Dyk, M.J. Keyser, M. Coertzen, Syngas production from South African coal sources using Sasol-Lurgi gasifier, Int. J. Coal Geol. 65 (3) (2006) 243–253.
[100] R.H.K. Vietor, The synthetic liquid fuels program in the Truman era, Bus. Hist. Rev. 54 (1) (1980) 1–34.
[101] S. Ville, O. Wicken, The dynamics of resource-based economic development: evidence from Australia and Norway, Industrial Corp. Change 22 (5) (2012) 1341–1371.
[102] Andries Von Gernet, 'The Electrical Precipitation of gold from cyanide solutions, in: Proceedings of the Chemical and Metallurgical Society of South Africa 1, 1894, pp. 28–34.
[103] Eric Von Hippel, Cooperation between rivals: informal know–how trading, Res. Policy 16 (6) (1987) 291–302.
[104] R. Daniel Wadhwani, Jones Geoffrey, Historical change and the competitive advantage of firms: explicating the "dynamics" in the dynamic capabilities framework, in: David Teece, Sohvi Leih (Eds.), The Oxford Handbook of Dynamic Capabilities, Oxford University Press, New York, 2017, p. 18.
[105] Percy A. Wagner, The Diamond Fields of Southern Africa, The Transvaal leader, Johannesburg, 1914.
[106] H.H. Webb, Valedictory presidential address: discovery and history of the Witwatersrand gold fields, Proc. South Afr. Assoc. Eng. 8 (1903) 3–39.
[107] Gardner F. Williams, The Diamond Mines of South Africa, B.F. Buck, New York, 1905.
[108] John R. Williams, The treatment of battery slimes, Proc. Chem. Metallurgical Soc. S. Afr. 2 (1897) 92–97.
[109] John R. Williams, Inaugural presidential address, in: Proceedings of the Chemical and Metallurgical Society of South Africa, 2, 1899, pp. 726–730.
[110] Sydney G. Winter, Understanding dynamic capabilities, Strategic Manag. J. 24 (10) (2003) 991–995.
[111] William H. Worger, South Africa's City of Diamonds, Yale University Press, New Haven, Connecticut, 1987.
[112] David Yudelman, The Emergence of Modern South Africa: State, Capital and Incorporation of Organized Labour on the South African Gold Fields, 1902-1939, David Philip, Cape Town, 1983.

Peter Hilsenrath is Joseph M. Long Chair of Healthcare Management and Professor of Economics. He received his B.A. from the University of California at Santa Cruz and Ph.D. from the University of Texas at Austin. Professor Hilsenrath has published over 70 peer-reviewed articles and reports. They include publications in medical, management and economics journals such as the American Journal of Public Health, Inquiry, the Journal of Rural Health, and Defence and Peace Economics. Many of his papers have addressed issues of efficiency in the health sector. Some have had an international focus, especially concerning South Africa and China.

Thomas Pogue is Associate Director of the Center for Business and Policy Research and Visiting Research Fellow with the Institute for Economic Research. He received his B.A. from the University of Nevada, Reno and Ph.D. from Maastricht University in the Netherlands. His research focuses on three inter-related themes: regional economic development, human resource mobility, and systems of innovation. Dr. Pogue has worked at several research institutes. In that work an initial concern with sustainable regional economic development in rural mineral dependent communities evolved into an interest in the economics of technological change and its relationship to development.