SAIMM

THE SOUTHERN AFRICAN INSTITUTE OF MINING AND METALLURGY

CAPACI OCCASIO

FOUNDED 1894

VOLUME 122 NO. 2 FEBRUARY 2022

SPECIAL THEMED EDITION

CALL FOR PAPERS

TOPIC:

ENLIGHTENING AFRICA – ENERGY FOR THE MINING AND METALLURGICAL INDUSTRIES

The *Journal* of the SAIMM has pleasure in inviting papers for a special edition to be published during late 2022 or early 2023. Authors are invited to submit papers that would fit into the theme '**Enlightening Africa – Energy for Future Mining and Metallurgical Industries**'.

For the foreseeable future, as the world moves towards a Just Transition, Southern Africa needs to use her abundant *indigenous coal resources* more efficiently, effectively, and cleanly, and to do so for all coal-fired power generation, metallurgical, and industrial purposes. In associated developments, coal may also be used for the creation of advanced new materials which could lead to major new industries in this country. Crucial to all the above is the need to reduce emissions in all sectors of coal-fired or coal-sourced processes.

In parallel and in the longer term, forms of *non-carbon-based* energy will be required to serve the needs of the growing mining, metallurgical, and industrial manufacturing sectors. This would require development of green energy in the form of hydrogen, solar, or wind power with battery storage capabilities. Key to this sector is the fact that renewable energy sources require the availability of backup power or battery storage of sufficient capacity to ensure continuity of service during times when such energy is unavailable.

The transition from the current coal-dominated environment to a dominantly renewable and nuclear one is anticipated to take place during the course of this century. This is likely to be a long and complex process, but it offers opportunities for *innovative and exciting mixes* in a wide range of energy production.

Of critical importance is the need to *address the energy gap* that may occur between one energy-dominated environment and the other in order to ensure continued, reliable, sustainable, and affordable power generation at all times during the course of this century.

In this regard papers covering the above scenarios are invited. The themes include, but are not limited to, the following:

- **Coal/carbon sourced energy**, with examples of high-efficiency and low-emission utilization, the reduction/elimination or utilization of CO_2 and other greenhouse gases, and the development of new alternative uses for coal, including advanced high-value products.
- **Hybrid energy sources** in cases where coal and renewables (and even nuclear) play an integrated role in clean energy production (*e.g.*, co-firing coal with biomass and waste, coal still finds application in battery storage).
- **Alternative energy sources**, such topics to include, but are not limited to, hydrogen/LNG, advanced renewables (wind and solar), geothermal, nuclear, and any other innovative energy-generating solutions that may be in the offing.
- **Projected times, techno-economic costs, availabilities, and environmental impacts** of the energy sources above.

Papers should be submitted to:

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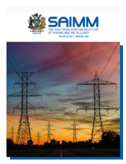


PROFESSIONAL TECHNICAL AND SCIENTIFIC PAPERS

The Ides of March and the Consequences of War

It would seem that the *Ides of March* (15 March) and the political upheavals associated with such a historic date have come upon the world this year sooner than expected. Just hours after promising the opposite, Vladimir Putin fulfilled Joe Biden's prediction by sending hundreds of thousands of Russian troops across the border to invade neighbouring Ukraine. The background to this war and the impact it may have been succinctly explained by Peter Little, from the Investment Management Department of Anchor Capital, in a recent article prepared for investors, but his thoughts could apply just as well for those in the mining and metallurgical world.

The cause of the conflict lies in the fact that Russian President Vladimir Putin is unhappy about North Atlantic Treaty Organisation (NATO) forces encroaching on Russia's western border, with Ukraine representing the last major buffer between NATO members and Russia. The Ukraine government, on the other hand, is pushing for closer ties with the West.

This conflict, however, has far broader geopolitical ramifications. China has stated that it backs Moscow in opposing the expansion of the Western military alliance to include Ukraine and other eastern European countries, all of whom were previously part of the old Russian Federation. Russia, in turn, has endorsed China's policy on Taiwan, saying it opposed Taiwan's independence and sovereignty 'in any form'. The two powers have gone on to warn of the risk of an arms race in the Asia-Pacific region. Such matters portend a situation far wider and more serious than initially may seem the case.

In terms of Russia and Ukraine's global economic significance, those countries represent about 2% of global economic activity and about 2.4% of the global population, so their economies are not particularly material in the greater scheme of things. However, should this conflict spill over into Europe and the USA, and China become heavily involved in such an armed conflict, their combined economic strength could become significantly more meaningful on a global basis.

As regards commodities, Russia is the world's third-biggest oil producer after the USA and Saudi Arabia, producing 10mn barrels per day (bbl/day) or about 10% of the global oil supply. Russia's energy commodities play a particularly meaningful role in the EU's energy needs. Namely, Russia provides about 25% of Europe's energy supply in the form of solid fuels, natural gas, and petroleum products. Russia and Ukraine are also meaningful contributors to the global food chain, representing approximately:

- 25% of the total global trade in wheat
- 20% of global corn sales
- 80% of all sunflower oil exports

What does all this foretell for the South African mining and metallurgical industry and this country's economy as a whole?

In terms of *economics and commodity prices*, once the invasion began, asset prices reacted sharply – gold jumped $40 an ounce; oil went above $100 for the first time since 2014; and share markets around the world recorded significant losses. If the conflict continues, there are predictions of well over $100 a barrel for oil and R30 per litre for petrol in Gauteng. Such costs would have considerable impact across all facets of the South African economy, pushing prices even higher than they are at present.

Furthermore, if denied the rich oil and gas energy resources from Russia, the UK and Europe would struggle to maintain sufficient power to *support the production of goods throughout all sectors* of their economies. Of particular concern are products emanating from the iron, steel, and ferro-alloy industries, all of which require, in the course of their manufacture, inordinately high heat and power inputs. The importation of iron, steel, and ferro-alloy goods from the EU and UK for use in South Africa's mining, metallurgical, transport, building, and renewable energy industries therefore could be significantly compromised.

The sanctions currently being implemented against Russian banks and other financial agencies may well prevent the importation of Russian commodities into South Africa. One such example includes speciality high-value carbon reductants for the South African metallurgical industry.

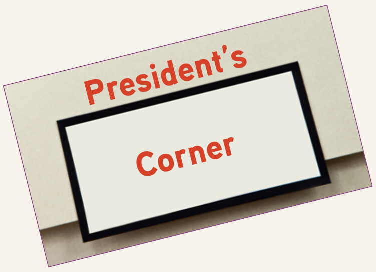
Similarly, those South African companies that derive significant profits from brownfield and greenfield mining, metallurgical, or other large industrial projects in Russia and Mongolia *may well suffer serious losses* if such projects were cancelled due to violent conflict in the region or to the consequences of sanctions.

On the other hand, should sanctions against Russia take hold, Russia's platinum and palladium production, which is currently in deficit, would suffer further, thereby leaving the *global market open to South African producers*, and at higher prices. Sasol would be a significant beneficiary of the higher *oil prices, and unprecedented opportunities could emerge for South African wheat, maize*, and other agricultural and food commodities through replacing Russian markets in Europe and the UK.

Time will tell what will happen in the next few days, weeks, and months, but of one thing we may all be certain – life as we all knew it will change, but to what extent is unknown. It would be wise to consider steps in the short to medium term that need to planned for.

Ref: Peter Little, Fund Management, Anchor Capital

R.M.S. Falcon



Dare to dream big

After two years of uncertainty, 2022 seems to be developing into something that feels more normal. Perhaps some of this normality is just us adapting to the unpredictability and the curveballs we've been given, but either way, we are daring to dream big this year. For the SAIMM, the past two years meant many changes to the status quo. With the year now in full swing, I thought it would be worthwhile to reflect on the changes and the challenges the Institute faced, and overcame, as well as the plans and projects that emanated from the hard work done by the SAIMM collective.

One of the major changes relates to the SAIMM premises in Marshalltown. For many years, we've associated the SAIMM with the offices located in the Minerals Council building, which not only hosted the staff, but also the SAIMM's rare books library, IT infrastructure, and meeting rooms. The remote working environment forced upon us by the pandemic accelerated the Minerals Council's decision to downscale their office and the SAIMM was informed that the building will be sold soon. Over the past few months, Sam Moolla and her team worked tirelessly to clear out the Marshalltown offices, downsize office furniture, and fully shift the SAIMM infrastructure to the 'cloud'. All staff members, including the Journal team, are now able to work remotely. The Institute is currently operating fully as a virtual office. The team is now meeting face-to-face on a rotational basis, with several company members graciously opening their meeting rooms to allow the team to meet and collaborate.

Even before the pandemic, the SAIMM identified the need to be able to meet virtually and opted to implement the use of Zoom to supplement committee and Council meetings. During the lockdown, this decision allowed us to rapidly deliver virtual content, primarily as webinars, and later online conferences, workshops, training courses, and schools. We've also in recent years upgraded the membership management system and all membership is now managed via the MYMEMBERSHIP platform. Members can now update their information, preferences, and pay their fees via the membership portal, eliminating the need for manually managed databases. In addition, a member-only content library is available to all members. The library is continuously growing, allowing members to view valuable content online at their leisure. These are just some of the highlights related to the positioning of the Institute to continue to be member-centric and ensuring our systems are optimized.

The flagship plans for 2022 build on the sturdy foundations laid over the past two years. In 2022, we are rebuilding, but also starting new projects and initiatives that will strengthen the Institute and thus the value to members. One of my biggest dreams is to bring back in-person events. Therefore, a key activity is to rebuild the technical events programme towards this end. A flagship event this year will be the PGM Conference. The Platinum Conference has been a feature of our technical programme since 2004, and the 8th instalment was originally planned for 2020. Without belabouring the point, we all know what happened.

I had the privilege to be involved in several of the first seven events, either as a participant, presenter, peer reviewer, or part of the organizing committee. The Platinum Conference organizing committee always tried hard to identify a topical theme for each conference in the series. The list of themes, by year, therefore, is a wonderful overview of the best of times and the worst of times for the PGM industry.

- 2004 – Platinum, Adding Value
- 2006 – Platinum Surges Ahead

President's Corner *(Continued)*

- 2008 – Platinum in Transformation
- 2010 – Platinum in Transition: Boom or Bust
- 2012 – Platinum, a Catalyst for Change
- 2014 – Platinum, a Metal for the Future
- 2017 – Platinum, a Changing Industry
- 2022 – Enabling a Cleaner World

With the long gap since 2017, the 2022 event will be of great interest to all, with many changes to reflect upon, and as PGMs again surged ahead in 2021 the 8th event is sure to deliver a full programme. The Conference will be held at Sun City from 2-3 November 2022.

Another flagship project for 2022 is the launch of a dedicated ESG-focused committee. The committee was formally constituted in January 2022 and aim to actively seek opportunities for the SAIMM to develop and implement ESG capacity for our membership. The newly formed ESG-S Committee (Environment, Social, Governance and Sustainability) is daring to dream big and will be sharing their plans and projects over the next few months with membership under the leadership of Professor Mike Solomon as the first appointed Chair, ably assisted by Professor Gordon Smith who played an integral role in defining the frame of reference for this initiative.

The Young Professionals Council (YPC) continues to inspire in 2022. On 25 February they will be launching a YPC Northwest Branch. The YPC and the various branches are synergistically working together to revitalize the activities of the SAIMM in more remote areas to maximize the value for our members, especially to support young professionals in the early part of their careers. As we integrate the YPC and Branch activities, more members can participate and network across Southern Africa.

Other plans for 2022 include optimizing our marketing campaigns and streamlining our mailers to members. Our virtual content will be streamlined as well, with webinars to be hosted on Wednesdays aiming to create an established format and build a brand for SAIMM webinars (#webinarwednesday).

There are many more activities and initiatives, some new, some renewed, and the few highlights I've touched on aim only to showcase some of the plans for 2022. If you are keen to get involved in any of the committees or projects mentioned herein or are interested in organizing a technical event of your own, please contact Sam Moolla the SAIMM Manager (sam@saimm.co.za).

Let's dare to dream big in 2022.

I.J. Geldenhuys
President, SAIMM

Rainfall-induced groundwater ridging and the Lisse effect on tailings storage facilities: A literature review

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Synopsis

The failure of tailings storage facilities (TSFs) results in the discharge of significant quantities of hazardous waste material into the natural environment. Research studies relating to slope instability have identified physical mechanisms such as rainfall-induced erosion, liquefaction, and shear failure as the main triggers. The generation of transient pressure waves and the mobilization of pre-event water in the unsaturated zone have been found to trigger shallow landslides in natural hillslopes. In this paper we review these physical mechanisms, known as groundwater ridging (GWR) and the Lisse effect (LE), from other studies. Previous researchers have explained both these phenomena through field and laboratory observations, numerical modelling, as well as conceptual discussions. These case studies demonstrate the impact of rainfall characteristics on the generation of transient pressure waves that rapidly increase the phreatic surface and change pore water suction. Reference is also made to the influence and behaviour of physical porous medium characteristics on the establishment of a continuous water phase that facilitates the transmission of an induced pressure head. However, previous studies fail to recognize the possibility that the pressure increase in pre-event water through pore air propagation could cause slope instability in tailings dams. The authors suggest that the physical properties and hydraulic behaviour of unsaturated porous tailings media make it susceptible to GWR and the LE, resulting in the creation of a potential failure plane.

Keywords

transient pressure wave mechanisms, groundwater ridging, Lisse effect.

Introduction

The global mining industry has suffered several severe tailings storage facility (TSF) failures in the last few decades, which have resulted in extensive damage, catastrophic environmental impacts, loss of life, and severe socioeconomic disruptions. According to Azam and Li (2010), trends indicate a steep increase in these failures, particularly since the 1960s. The current authors note that this timeframe coincides with a marked increase in CO_2 emissions and global temperatures, resulting in higher intensity rainfall events under the force of climate change (Schulze *et al*., 2011). The location and timeline of TSF failures are illustrated in Figures 1 and 2. Gariano and Guzzetti (2016) argue that variations in rainfall parameters could make certain areas in southern Africa especially vulnerable to the possibility of slope instability and landslides. This paper will consider alternative causes of such failures by examining the generation of groundwater ridging (GWR) and the Lisse effect (LE) in natural hillslopes and extrapolating it to TSFs.

Rainfall-induced slope instability

Lyu *et al*. (2019) found that an overwhelming majority of tailings dam failures (approx. 90%) occur with the upstream method of construction. Even though dam type, therefore, seems to contribute to the risk of failure, research results recognize rainfall-induced slope instability as the main trigger. This includes findings by *e.g*. Blight, Robinson, and Diering (1981) and Jennings (1979), who identified seepage, overtopping, shear failure, piping, and erosion as some of the most important factors causing slope failure. Blight and Fourie (2003) reported that pore water pressure and a high phreatic surface contribute to the generation of flow failure in mine waste dumps, tailings dams, and municipal solid waste landfills. This notion is supported by Yaya, Tikou, and Lizhen, (2017), who found that insufficient control of water

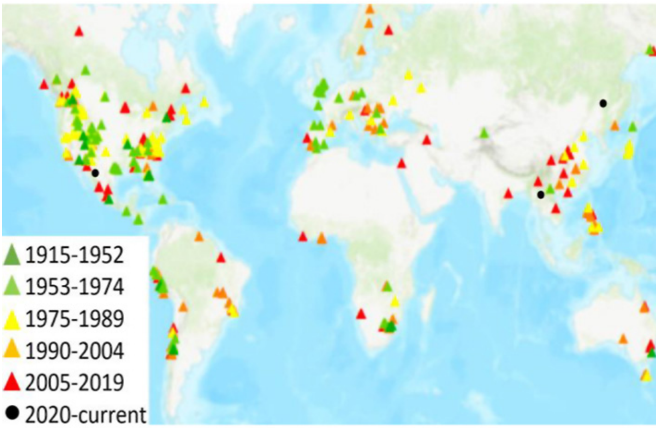

Figure 1—Tailings dam failures: location and time of occurrence (adapted from Cheng *et al.*, 2021)

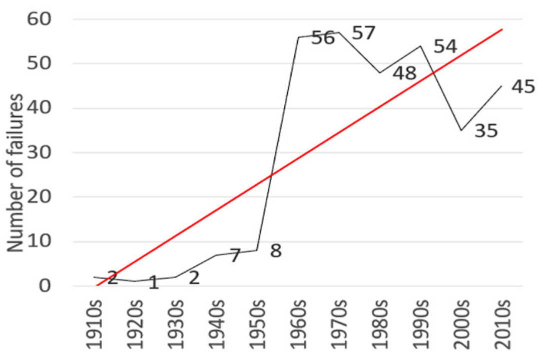

Figure 2—CO_2 emissions, temperature increases, and global TSF failures over time (adapted from Lyu *et al.*, 2019; Azam and Li, 2010

pressure can result in structural inadequacy and subsidence failure. Muñoz (2019) points out that although the increase in pore water pressure is a significant factor, the decrease in soil suction brought about by the wetting front also contributes to changes in the phreatic surface and a probable reduction in slope stability. This perception is supported by Robertson *et al.* (2019), who concluded that loss of suction in tailings was a contributing factor to the Brumadinho disaster in 2019.

Rainfall intensity and pre-event water in stream storm flow hydrograph

According to Rahardjo, Leong, and Rezaur (2008), high-intensity rainfall events cause shallow landslides in slopes with residual soils. This is believed to occur after excessive rainfall infiltration increases pore water pressure and reduces shear strength. In the case of the LE, Meyboom (1967) and Guo, Jiao, and Weeks (2008) contend that the advancing wetting front produced by a high-intensity rainfall event creates an impermeable 'lid' restricting the outflow of air. Fredlund and Stianson (2011) explain that low infiltration capacities result in ponding, which creates an additional load and higher compression values in the unsaturated zone, thereby exacerbating the magnitude of the LE. The authors of this paper argue that this would also occur if high rainfall intensities exceed infiltration capacity, regardless of soil type. In the case of GWR, Abdul and Gillham (1984) and Gilham (1984) proposed that the rapid conversion of water held in the capillary zone occurs due to the fill-meniscus hypothesis, whereby the addition of small amounts of rainwater brings about a change in suction, relieving tension in the tension-saturated capillary zone. In contrast, Waswa and Lorentz (2015) introduced the energy hypothesis whereby the intensity of a rainfall event provides additional energy, enabling the conversion of pre-event water held in the capillary fringe (CF) to water in the phreatic zone.

Guo, Jiao, and Weeks (2008) and Rahardjo *et al.* (2001) suggest that rainfall frequency impacts antecedent moisture conditions and the generation of pre-event water. Antecedent water is generated through the infiltration and percolation of precipitation and, through hydrograph separation studies, the presence of base flow water in the stream storm flow hydrograph is recognized (Kim *et al.*, 2017). Other researchers, *e.g.* Blight *et al.* (2012), Cloke *et al.* (2005), and Meyboom (1967), argue that, in the case of TSFs, this source is supplemented by vast quantities of slurry that are discarded and stored together with tailings. It is also suggested that pre-event water exists permanently in the subsurface profile, thereby establishing a tension-saturated continuous pore water phase. Cloke *et al.* (2005) found that this is caused by the uninterrupted supplementation of water sources such as rising consolidation water. The authors of this paper also suggest that, in contrast to similar studies conducted on natural hillslopes, the absence of phreatophytes exacerbates higher water content levels. Not only does this mean less moisture being removed from the soil profile, but engineered embankments would also be more prone to erosion, while the soil structure would not have the stability provided by a root system. Even though the authors of this paper postulate that GWR and the LE are significant contributors to slope instability, it is recognized that insufficient drainage causes low consolidation speeds and increases the weight of the dam, thereby reducing the shear strength and effective stress.

The significance of pre-event water in slope stability is supported by a study conducted by Rahardjo *et al.* (2001) into the causes of 20 shallow landslides on the Nanyang Technological University campus in Singapore. An investigation into similar critical rainfall events, not leading to landslides, showed similar characteristics. However, the triggering rainfall event during which slope failure occurred was found to be preceded by several non-critical rainfall events resulting in elevated levels of antecedent moisture. The notion that pre-event water, and not infiltrated water, contributes to rapid and transient increases in pore water pressure, is supported by Premchitt, Brand, and Phillipson (1986). They reported that soils in which landslides occurred in Hong Kong had an infiltration time of between 14 hours to three days. Immediate slope failure could therefore not have been attributed to infiltration, but rather to pre-event water already contained in the soil profile. Zang *et al.* (2017) also report that pre-event water contained above the phreatic surface in the CF plays an integral part in the rapid mobilization of groundwater.

Transient pressure wave mechanisms

Waswa and Lorentz (2015) state that transient pressure waves are responsible for the rapid release, mobilization, or pressure perturbation of previously stagnant antecedent moisture through the mechanisms of GWR and the LE. This enables groundwater levels, during storm events, to rise disproportionately with the amount of water infiltrating the soil profile (Waswa, 2013). Various researchers, *e.g.* Lins, Schanz, and Fredlund (2009), Rahardjo, Choon, and Tami (2004), Salas-García *et al.* (2017), and Waswa (2013), have investigated pore air propagation and transient pressure wave generation in unsaturated porous media through the use of automated columns. Waswa (2013) observed different responses depending on the depths of the water table (WT) by recognizing that GWR occurs at a shallow WT and the LE at deep WTs. Rassam and Williams (2000) conducted soil column experiments for the prediction of soil water characteristics curves (SWCC) in tailings. The set-up consisted of two tensiometers and one time-domain reflectometer (TDR). This study did not report on GWR or the LE but was able to analyse the drainage cycle and predict the behaviour of tailings in the establishment of an extended CF. Further soil column studies were presented by Yang *et al*. (2004). Similar to the above studies, the column was equipped with TDRs and tensiometer sensors placed at specific depths to measure water content and pore water pressure. Even though this study focused on water content and suction data, transient pressure waves were observed. All the abovementioned studies were able to demonstrate exaggerated WT responses after the application of a small amount of surface recharge. In agreement with Iverson (2000) and Waswa (2013), the authors hypothesise that after the application of surface recharge, rainfall-induced pore pressure rapidly propagates downward in the soil profile.

Groundwater ridging

The GWR hypothesis is described by Abdul and Gillham (1984) as a process occurring in the subsurface near the stream (and in this case near the tailings pond) that allows for the rapid rise of the WT to the surface. Figure 3 illustrates the mechanism of GWR, recognized by the rapid uneven rise in the phreatic surface after a high-intensity rainfall event. Abdul and Gilham (1984) support this view and propose that ridging is probable under high rainfall intensities under certain slope and soil conditions. In contrast, Bonell *et al*. (1998) and Elsenbeer *et al*. (1985) dismiss the notion that high-intensity rainfall events contribute to GWR and believe that event water is dominant in such environments.

According to Waswa and Lorentz (2016), a high-intensity rainfall event does not necessarily result in slope instability. Instead, a rainfall event of specific intensity and duration combined with particular antecedent moisture conditions is needed for critical conditions leading to failure. According to Cloke *et al*. (2005), rainfall intensity controls initial ridge development as well as the amount of pre-event water being discharged into the stream. It was established that low rainfall intensities (0.036 mm/h) resulted in low zones of pre-event water proportions (PEZ), while high rainfall intensities (360 mm/h) also showed low PEZ values due to event water becoming overland flow and dominating discharge. A medium-intensity rainfall event of 3.6 mm/h was found to allow ridge development and cause a significant proportion of discharge. Cloke *et al*. (2005) argue that rainfall intensity is relevant only when the CF does not extend to the ground surface and saturated hydraulic conductivity (Ks) is high enough to have rainfall-limited infiltration. Similarly, Zandarín *et al*. (2009) found that a high-intensity rainfall event is not necessarily detrimental to dam safety, but rather lower intensity events that have a longer duration (resulting in more infiltration) and which are preceded by antecedent rainfall events. Furthermore, events that have a higher intensity towards the end than at the start have a far more destabilizing effect than events with constant intensity. Rainfall events associated with shallow landslides have been found to trigger these failures after a spike in intensity during the middle or towards the end (Waswa and Lorentz, 2016).

Waswa and Lorentz (2005) argue that the extension of the CF to the ground surface is a prerequisite for GWR to occur. This notion is supported by Zang *et al*. (2017), who found that antecedent water contained above the phreatic surface plays an integral part in the GWR mechanism. Cloke *et al*. (2005) challenge this view and suggest that the role of the CF concerning the process of GWR may have been overemphasised. The hydrological model applied by Cloke *et al*. (2005) enabled the evaluation of the GWR hypothesis in different riparian environments. The study made use of a laboratory experiment from Abdul and Gillham (1984), as well as a conceptual model solving the Richards equation for matrix flow. A discrete CF was then modelled with the use of the Brooks-Corey soil moisture algorithm. These two attributes disregard any non-Darcian processes responsible for pre-event water discharge and/or pressure ridge development. It was concluded that WT height and saturated hydraulic conductivity (K_s) have the largest influence on GWR. Even though the CF regulates pressure ridge development, Cloke *et al*. (2005) suggest that it has little control over the discharge of pre-event water. They propose that the height of the WT and the CF may become significant in GWR only when combined with controlling factors such as soil hydraulic properties. This includes assumptions, *e.g*. that the fine nature of tailings would contribute to extended CF levels, establishing a continuous pore water phase and enhancing conditions facilitating the rapid mobilization of pre-event water to lower horizons (Waswa, 2013). Waswa and Lorentz (2016) report the rate of change in pressure potential to vary between soils of different grain sizes. This is illustrated by the pressure potential in fine soils measuring 15 cm-H_2O less than in coarse soils within 10 minutes after application of a simulated rainfall event. The response in pressure potential also seems to be delayed in fine soils, such as porous tailings media, which appears to be linked to the height of the CF (Waswa and Lorentz, 2016).

Waswa and Lorentz (2016) explain that the rapid rise in the phreatic surface is due to the conversion of capillary water held

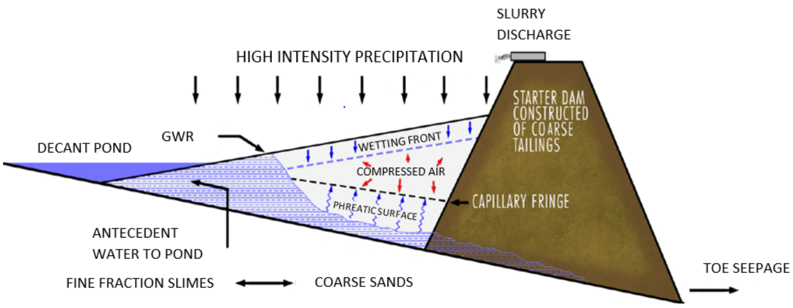

Figure 3—Schematic depiction of GWR (modified from Pacheco, 2019; Zang *et al.* 2017)

in the unsaturated zone to phreatic water in the saturated zone. Gilham (1984) and Abdul and Gillham (1984) argue that this happens according to the fill-meniscus hypothesis whereby the addition of small amounts of rainwater brings about a change in matric suction. This change relieves tension in the saturated capillary zone, resulting in vadose water converting to phreatic water with a subsequent rise in the WT. Waswa and Lorentz (2015) reject this argument and propose the energy hypothesis, whereby the intensity of a rainfall event provides additional energy that transforms kinetic energy to potential energy, enabling mobilization of pre-event water. These authors further suggest that the only difference between the CF and phreatic zone is the energy content (Waswa and Lorentz, 2019). The extension of the CF provides the contact between the kinetic energy-carrying intense raindrops and the potential energy-deficient pore water. Moisture profiles involved in the process of GWR are illustrated in Figure 4.

According to Zang *et al.* (2017), the rise in the WT is not entirely dependent on the amount of rainwater infiltrating the soil during the high-intensity event, but also on the amount of pre-event water already held in the capillary zone. The rise in the WT is therefore disproportionate to the amount of infiltrated water. According to Waswa and Lorentz (2015), seeing that a small amount of rainfall is required to fill the capillary menisci, it would result in an almost immediate and excessive rise in the WT during an event. During this process, the steep hydraulic gradient is directed towards the stream and leads to the discharge of antecedent water into the stream (Zang, 2019). This argument is supported by Cloke *et al.* (2005), who state that even a small amount of infiltrated water can rapidly convert the negative capillary pressure head in the CF to a positive pressure head, thereby changing the WT gradient and forcing the pre-event water out. GWR studies conducted on beaches support this concept and found the rapid and exaggerated WT rise to be attributed to the upper extent of the CF (sand surface). Several soil column studies confirmed that a small amount of surface recharge could result in an instant disproportionate rise of the WT, simulating GWR responses (Abdul and Gillham, 1984; Turner and Nielsen, 1997). Khaled *et al.* (2011) carried out comparable tests on Toyoura sand and Chiba LiC soils that were packed homogenously into two acrylic columns with 50 cm length and 7.5 cm ID. After the addition of only 1 mm of surface recharge, an instant fluctuation in the phreatic surface occurred, resulting in a 50 mm rise within 10 seconds. A total rise of 120 mm was observed. This upsurge is attributed to the rapid conversion of the pressure head in the vadose zone. A similar field experiment, conducted by Gillham (1984), found a significant rise of 300 mm in a shallow WT, resulting from the addition of 30 mm of water.

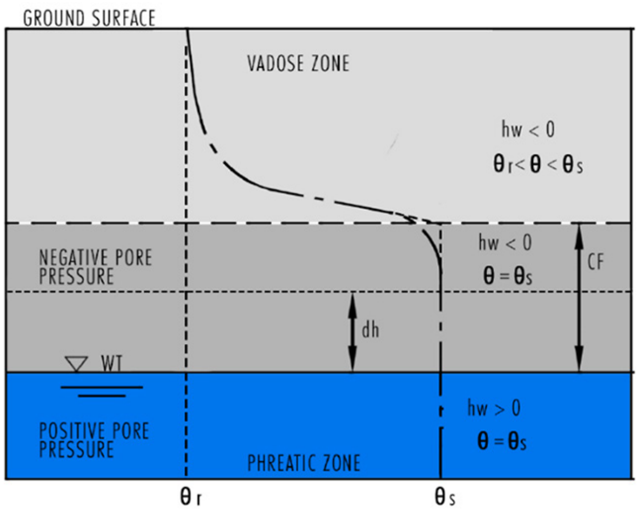

Figure 4—Moisture profiles under GWR: h_w - pore water pressure, θ_r - residual soil water content, θ_s – saturated soil water content (modified from Miyazaki, Ibrahimi, and Nishimura, 2012; Waswa, 2013)

Zang *et al.* (20179) report that as rain intensity decreases, so does pore air pressure in the vadose zone with a subsequent reduction in induced air flow and GWR. Another study by Abdul and Gilham (1984) suggests that CF GWR will not be responsible for pre-event water discharge in all environments. Cloke *et al.* (2005) also found a complex interrelationship between riparian characteristics and GWR. From their findings, it became evident that in the case of low capillary rise and low WTs, no ridge development occurred. The initial WT before the rainfall event is therefore a strong indication of the zone of pre-event water proportions reached. Rainfall intensity was found to control initial ridge development, especially if the CF did not reach the ground surface and hydraulic conductivity was high enough to allow for rainfall-limited infiltration. The magnitude of GWR would also depend on rainfall intensity, but it was further found that for rapid GWR to occur through antecedent moisture contribution from the capillary zone, a continuous water phase extending from the natural ground surface to the phreatic surface is required (Waswa and Lorentz, 2019). This agrees with observations from field studies conducted by Marui *et al.* (1993), confirming that pressure transmission through pore spaces occupied a continuous water phase enables the rapid response of pore water pressure in the deep soil profiles.

Further studies on the effect of compressed pore air on groundwater fluxes using soil columns were conducted by Marui *et al.* (1993). This study found that groundwater fluxes commence as soon as compressed pore air pressure in the unsaturated zone increases. Even though pore water pressure was monitored by tensiometers, volumetric water content and the influence of the CF were ignored. Waswa (2013) also researched the effect of compressed pore air ahead of a wetting front on the rate of infiltration using laboratory column experiments. The column was instrumented with pore air pressure probes, pore water pressure probes, volumetric water content sensors, a groundwater outflow tube, and a piezometer. It was determined that a GWR transient pressure wave mechanism arises in cases where the CF extends to the ground surface. The results also indicated that high-intensity rainfall events release tension forces in the CF, thereby discharging pre-event water. This finding supports the notion that the magnitude of GWR is proportional to the intensity of the event. Results confirmed by Waswa (2013) indicated a significant increase in pressure potential at the initial WT brought on by the advancing wetting front. It was further established that the rate of increase was directly related to the thickness of the CF and therefore proportional to, but less than, the magnitude of compressed pore air pressure.

According to Fredlund, Rahardjo, and Fredlund. (2012), transient or steady-state pore pressure changes are coupled with infiltration, particularly during heavy rainfall events. Such events cause a change in negative pore water pressures, which contributes to slope failures. The same authors state that the primary factor contributing to the unusual behaviour of residual soils is negative pore water pressure, which is related to pore air pressure. Analytical studies and laboratory experiments found that even a minor reduction in pore air pressure results in an exponential increase in slope stability (Ba-Te, 2005). Figure 5 illustrates the relationship between pore water pressure at different depths of the WT, while Figure 6 shows the relationship between pore water pressure and pore air pressures. The difference between the last two mentioned parameters also indicates matric suction.

Lisse effect

Miyazaki (2011) describes another mechanism of similar magnitude to GWR, but of different origin, that leads to the mobilization of pre-event water (a comparative summary is listed in Table I). The LE occurs due to the build-up of air pressure between the wetting front and the phreatic surface (Guo, Jiao, and Weeks, 2008). This effect is likely to occur if pore air is present in the upper boundary of the CF and the phreatic surface is located at sufficient depth. Waswa (2013) states that similar to GWR, the CF plays a pivotal role in WT response. According to Kutílek, Nielsen, and Reichardt (2007), soil that is wetted quickly, as in the case of a high-intensity rainfall event, will contain approximately 3–8% entrapped air. Fredlund, Rahardjo, and Fredlund (2012) argue that soil air content could be as much as 15% by volume. The rainfall event produces a downward moving wetting front, effectively acting as a low-permeability lid that restricts the outflow of air (Meyboom, 1967; Guo, Jiao, and Weeks., 2008). According to Li and Horne (2006), the relationship between the air and water phases is described by the Brooks and Corey relative permeability model that considers capillary pressure as a power function of the wetting phase. It is recognized that in the case of low-permeability soil, this relationship causes the two phases to undergo a phase transformation and mass transfer as pressure changes.

Weeks (2002) explained that at this point, pressure is transmitted rapidly to the top of the CF and continues to build up until the entrapped air pressure is higher than the pressure head of the infiltration profile above. Meyboom (1967) suggests that the increase in pore air pressure is accompanied by the initiation of transient pressure waves. In response, the increase in pore water pressure establishes a continuous water phase in the CF, enabling the rapid transmission of antecedent water. Meyboom (1967) found that the water level rise in the well commences before actual recharge due to rainwater percolation. Instead, the water level increase may be driven by air flow induced by an advancing wetting front at approximately 0.6-1.0 m below ground surface.

A review by Fayer and Hillel (1986) found that some entrapped air will escape vertically upward, indicating that the magnitude of the LE is governed by the air entry pressure (Guo, Jiao, and Weeks, 2008). Some entrapped air will remain in the soil profile and reduce saturation moisture content. However, the momentary increase in saturated zone pressure may be sufficient to induce slope instabilities. Figure 7 illustrates the LE whereby a rapid rise in water level in a well is observed during an event but holds little relationship to the water infiltrating the unsaturated soil profile (Bianchi and Haskell, 1966).

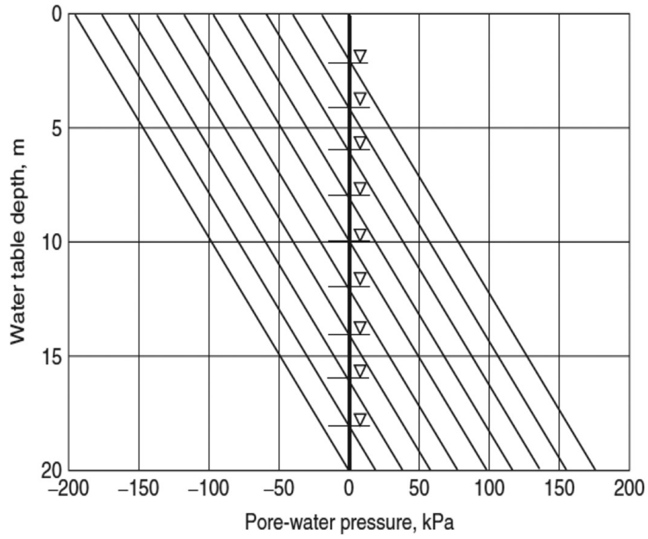

Figure 5—Equilibrium hydrostatic pore water pressures for various depths of water table (Fredlund, Rahardjo, and Fredlund, 2012)

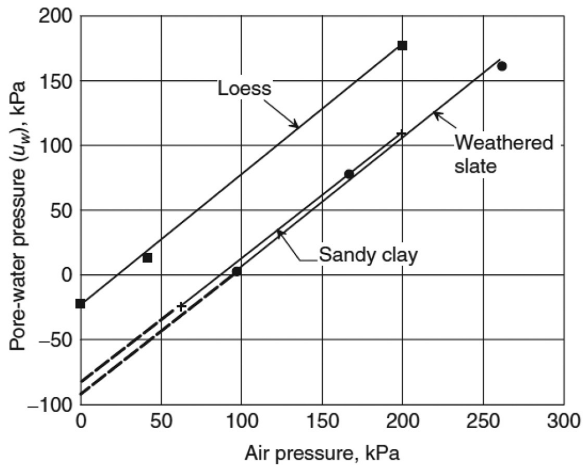

Figure 6—The relationship between pore water pressures and pore air pressures indicating matric suction (Fredlund, Rahardjo, and Fredlund, 2012)

Table I

Comparison between the LE and GWR (Miyazaki, Ibrahimi, and Nishimura, 2012)

Lisse effect	Groundwater ridging
Energy is derived from compressed air pressure in the unsaturated zone ahead of a wetting front	Energy derived from the intensity of the rainfall event
Depth to CF is less than the depth to the WT	The CF extends from the WT almost to the natural ground surface
Rapid rise in the well but slow recession	Sharp rise in WT followed by a correspondingly sharp decline
High-intensity rainfall events	Rainfall events of fluctuating intensity
WT rises in response to pressure increase	WT frequently rises to ground level
Actual WT level not affected, but the rise in the penetrating well is significant	Affects both the WT level as well as the well tapping the phreatic surface

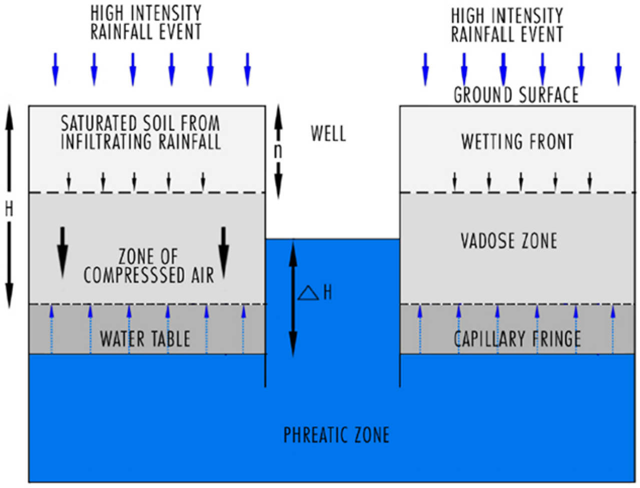

Figure 7—The conditions for LE occurrence. *n*: depth of infiltrated water following intense rain; Δ*H*: water level rise in the observation well resulting from the wetting front during intense rain trapping air and increasing soil air pressure; *H*: distance from the ground surface to the upper boundary of the CF (adapted from Meyboom, 1967; Miyazaki, Ibrahimi, M. K. and Nishimura., 2012; Weeks, 2002)

An analysis of recorded observations by Weeks (2002) indicates that if the depth of penetration of the wetting front is only a few millimetres, the water level in the well could rise by approximately 550 mm. Meyboom (1967) describes the ratio of rainfall to rise in the water level as being approximately 1:18. This value is confirmed by Hooghoudt (1947), who established a rainfall/rise ratio of 1:20 after solving for air pressure increase above the CF. Application of this calculation (Equation [1]) resulted in a rise in the observation well of 533.4 mm after a rainfall event of 25.5 mm, infiltrating the soil profile to a depth of 25.5 mm and the CF at 508 mm below ground surface.

$$H_{max} - H = \frac{n}{h-n} atm \qquad [1]$$

where (H_{max} — H) is the change in water level in the observation well, n is the depth of infiltrated water after a rainfall event, and h is the distance from the ground surface to the upper boundary of the CF. Other researchers, *e.g.* Guo, Bao, and Weeks (2008) and Weeks (2008), found that the maximum water level rise in the well would be less than the maximum air pressure induced by infiltration. Guo, Bao, and Weeks (2008) assert that the water level rise in the well is delayed relative to the rise in air pressure in the unsaturated zone. This phenomenon is described by Equation [2] (Weeks, 2008).

$$\Delta H = P_{WC}(\frac{m}{h-m}) \qquad [2]$$

where P_{WC} is the atmospheric pressure in the form of water column height, m is the depth of rain penetration and h is the distance from the natural ground level. Seeing as the entrapped air causes a decrease in the magnitude of the vertical hydraulic gradient, which restricts infiltration at the ground surface, it will also contribute to higher levels of runoff. This explains why light rainfall events often result in a disproportionate increase in runoff. Entrapped air may not only give the false impression of recharge, but may also reduce the amount of recharge that would be expected in its absence (Healy and Cook, 2002). Bear (1972) indicates that changes in volumetric water content could also occur due to swelling or consolidation of the soil profile, caused by a change in pore pressure above the air-entry value.

Guo, Bao, and Weeks (2008) suggest several variables, apart from rainfall intensity, that regulate the occurrence of the LE. For example, Fredlund and Stianson (2011) observed significant increases in the water level of the well, associated with increasing ponding depths. Simulation results compiled by Guo, Bao, and Weeks (2008) indicate an increase in ponding depth caused by the infiltration capacity of porous media being exceeded by a high-intensity rainfall event. Ponding inhibits the escape of air from the soil and, as it increases, it also results in higher compression values in the unsaturated zone, thereby intensifying the extent of the LE. Figure 8 demonstrates the effect of a 2 cm, 6 cm, and 10 cm ponding depth on the water level and air pressure (Guo, Bao, and Weeks, 2008). The characteristics of tailing material as a variable are discussed in the following section.

Tailings characteristics

Parametric studies predict how the WT will respond based on geotechnical properties such as pore size distribution (λ), permeability (k) and saturated hydraulic conductivity (K_s). These studies also enable the prediction of water retention capacities of the porous tailings medium, which becomes relevant in the establishment of a continuous pore water phase. Empirical functions, such as the van Genuchten parameters, normally present these characteristics.

Porous media conditions demonstrate intrinsic permeability parameters that play a pivotal role in generating both GWR and the LE. In keeping with Guo, Bao, and Weeks. (2008), it is believed that low-permeability formations inhibit the rate of infiltration, subsequently causing a delay in air pressure response. To our knowledge, this could result in ponding, which in fact would prohibit the escape of pore air, eventually leading to an increase in pore water pressure. This argument supports the observation of Rahardjo, Leong, and Ret (2008) that low-permeability soils, such as tailings, are more susceptible to high pore water pressures. Highly permeable soil conditions result in significant air pressure, but the response in the observation well will be diminished compared to a less permeable soil profile. For instance, soil permeability (k) of 1×10^{-12} m/s demonstrates a maximum water level rise of 0.16 m compared to only 0.08 m for soil with a permeability of 1×10^{-13} m/s (Guo, Bao, and Weeks, 2008). In contrast, higher levels of permeability do not guarantee maximum water levels in the observation well. This is due to adequate

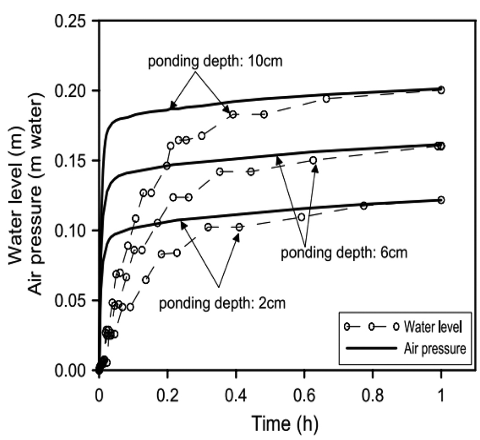

Figure 8—Effect of ponding depth of water level and air pressure (Guo, Bao, and Weeks, 2008)

hydraulic conductivity that does not allow for ponding, resulting in the release of air from the ground surface. Guo, Bao, and Weeks (2008) have shown that the magnitude of the LE is insignificant in highly permeable soils but increases as permeability decreases.

Another soil property impacting significantly on transient pressure waves is pore size distribution, which is directly related to soil uniformity. Since a high pore size distribution signifies a narrow range of particles and pore sizes, it would encourage higher levels of air pressure in the unsaturated zone and increasing water levels in the wells (Guo, Bao, and Weeks, 2008). According to Cloke *et al.* (2005), the development of a positive ridge is less dependent on the CF and relates more closely to soil type. To illustrate this belief, GWR results showed that, in the case of the CF intersecting the ground surface, a rise in the WT is enabled through the application of a small amount of water. However, if the WT is low and the CF does not intersect the ground surface, WT response is regulated by the saturated conductivity (K_s) of the porous medium. Cloke *et al.* (2005) further recognize that fine-grained soils encourage ridging by allowing for the extension of the capillary zone to the ground surface. while coarse-grained soils allow for increased infiltration capacities. The size of the CF is therefore inversely related to the K_s of the material.

The analysis of particle size distribution studies conducted by Dacosta (2017) and Blight *et al.* (2012) enabled the classification of tailings material from a platinum mine near Mokopane. Results obtained from Sample 1 (30 kg) and Sample 2 (3.9 kg) are illustrated in Figure 9 and show similar curves representing the characteristics of fine soil. Approximately 5–11% of the unconsolidated tailings sample falls within the finest clay fraction and 45– 59% in the fine to coarse silt fraction. The remaining 30–50 % was found in the finest sand fraction (Dacosta, 2017; Blight *et al.*, 2012). The fine nature of porous tailings media suggests that it is liable to retain pre-event water and establish a continuous water phase in the CF.

Discussion

This review found several studies that recognize the impact of GWR and the LE on the rapid mobilization of groundwater. Waswa and Lorentz (2016) have driven this concept further and established that critical rainfall events generating transient pressure waves contribute significantly to triggering landslides. Even though the results obtained from these studies were constrained to natural hillslopes, similar results will likely be obtained from the analysis of porous tailings media and provide insight into the cause of slope instability in tailings dams. Further research is required to determine the hydraulic mechanisms that control and transmit induced pore pressure through transient pressure waves during and after surface recharge. The authors of this paper suggest that both GWR and the LE would contribute to the failure of TSFs, and that a clear understanding of these mechanisms would facilitate better long-term design and maintenance of tailings dams, thereby reducing geohydrological risks.

We propose laboratory simulations similar to those carried out by Waswa (2013). This will be done by replicating the automated tall soil column and fitting it with seven data ports, each consisting of three probes including a time-domain reflectometry (TDR) instrument to measure volumetric water content, a 1 bar tensiometer to measure soil pore water pressure, and a 0.1 bar pore air pressure probe. The experimental design will involve infiltration experiments under controlled boundary conditions while monitoring the physical response of hydraulic state variables to simulated rainfall events. Observations and results will be used to determine phreatic surface dynamics, the soil moisture profile, pore water/air behaviour, and physical processes to facilitate the analysis of flow of water throughout saturated tailings based on short-term, one-dimensional laboratory column flow. The complexity of the physical processes occurring in the unsaturated zone necessitates automated data acquisition to accurately simulate infiltration and predict transient pressure-wave generation associated with unsaturated soil water flow. It is further intended to verify results through numerical modelling using HYDRUS software. This application simulates water flow in variably saturated soils under steady-state and transient water flow conditions. It also allows short-term, one-dimensional laboratory column flow studies, making it an invaluable resource for numerical modelling (Šimůnek, van Genuchten, and Šejna, 2012).

Summary

Both GWR and the LE have been recognized and explained by previous researchers who investigated these physical processes through conceptual discussion, numerical modelling, and field and laboratory observations. From these studies, the authors conclude that landslide responses to rainfall involve transient processes, and that these processes are linked to groundwater pressure heads that change in response to rainfall. It is further determined that critical rainfall events occurring on slope profiles containing pre-event water in the capillary zone, provide a continuous water

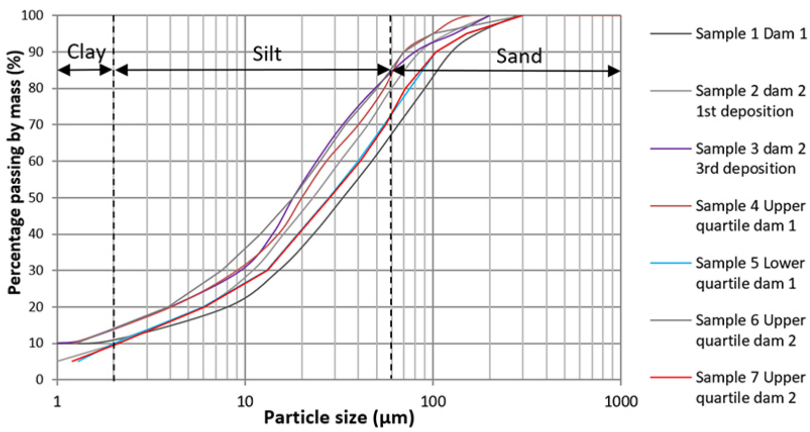

Figure 9—Particle size distribution of platinum tailings (Malvern analysis) (Dacosta, 2017; Blight *et al.*, 2012)

phase necessary for the transmission of an induced pressure head to a potential failure plane. These studies confirm that low-permeability soils are more prone to saturated conditions when combined with pre-event water, thereby enabling the formation of tension saturated or near-saturated conditions.

The authors propose that the design and operation of TSFs and the characteristics of tailings, combined with its high capacities for antecedent water, makes these engineered structures especially prone to slope instability mechanisms generated by GWR and the LE. This assumption will be addressed in future research.

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Evaluating the potential drilling success of exploration programmes using a three-dimensional geological model – A case study

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Synopsis

The technological advancements in computing power in the last 30 years have enabled the practical visualization of complex geological environments in three-dimensional (3D) space. 3D models and their application in the mining industry are becoming increasingly important, for example, to identify future exploration areas and targets, for mineral assessment and evaluation, and prediction and planning of future drill-holes. However, acquiring borehole data is an expensive practice, with drilling programmes costing mining companies up to billions of dollars each year. Tighter financial constraints on exploration budgets result in more pressure being put on three-dimensional models to accurately identify future target areas. This article aims to evaluate the potential drilling success of simulated greenfield and brownfield exploration using a 3D geological model created of Leeuwpoort tin mine. These simulations investigate the probability of intersecting a mineralized zone of economic interest and evaluate how the probability is affected when the number of drill-holes and distance from a known intersection changes. Furthermore, these simulations attempt to obtain an indication for the minimum number of drill-holes required for a successful exploration campaign at the mine. The investigation also aims to establish a first-pass attempt towards developing a 'favoured procedure' for identifying potential exploration targets for tin deposits with geological and geochemical characteristics similar to Leeuwpoort. The results for the 'favoured procedure' established are statistically tested using the 'bootstrapping' method. By simulating various exploration scenarios, the study also emphasises the importance of predicting successful drilling, which aids in budgeting for drilling programmes as the minimum number of drill-holes needed for a specific exploration project can be determined.

Keywords

three-dimensional modelling, Leeuwpoort tin mine, bootstrapping, brownfield exploration, drilling simulation, exploration simulation.

Introduction

The technological advancements in computing power in the last 30 years have allowed the practical visualization of complex geological environments in three-dimensional (3D) space (Aug *et al.*, 2005; Barnes and Gossage, 2014; Calcagno *et al.*, 2008; Chilès *et al*, 2004; Cowan 2012; 2017; Cowan *et al.*, 2002; Cowan, Spragg, and Everitt, 2011; Cowan, Lane, and Ross, 2004; Jessell, 2001; Jessell *et al.*, 2014; Lemon and Jones, 2003; Mallet, 2002; McInerney *et al.* 2005; Royse, Rutter, and Enwisle, 2009; Singer, 1993; Wang *et al.*, 2011; Wu and Xu, 2004; Wu, Xu, and Zou, 2005; Yan-lin *et al.*, 2011; Zu *et al.*, 2012). Multi-sourced attribute data such as mining, geological, ore deposit, financial, and grade-tonnage data can be used in computer software packages (Leapfrog Geo, Datamine, Minesight, GEMCOM *etc.*) to create reliable 3D models that accurately represent geological environments or settings (Bye, 2006; Wu and Xu, 2004; Zu *et al.*, 2012).

3D models and their application in the mining industry are becoming increasingly important (Bye, 2006; Jessell *et al.*, 2014), for example, to identify future exploration areas, drill-holes, and targets (Barnes and Gossage, 2014; Cowan, 2017; Jessell, 2001; Jessell *et al.* 2014; Srivastava, 2005; Wang *et al.*, 2011; Whiting and Schodde 2006; Yan-lin *et al.*, 2011). These geological models are relied on heavily for mineral assessment and evaluation (Barnes and Gossage 2014; Cowan 2012; Cowan, Spragg, and Everitt, 2011; Knight *et al.*, 2007; Renard *et al.*, 2013; Shehu and Lipo, 2016; Srivastava, 2005; Wang *et al.*, 2011). Even though the process of 3D model building has been optimized, the accuracy, certainty, and overall quality of the models created are still dependent on factors such as data quality and modeller competency

(Chilès *et al*., 2004; Cowan, 2017; Lindsay *et al*., 2013; Reid, 2017). The more complete the data used to create the 3D models, the more representative the models will be of the actual geological setting.

However, acquiring borehole data is an expensive practice (Benning, 2000) with drilling programmes costing mining companies up to billions of dollars each year (Benning, 2000; Schodde and Guj, 2012; Whiting and Schodde, 2006). Tighter financial constraints on exploration budgets result in more pressure being placed on 3D models to accurately identify future target areas.

Very recently Cowan (2017) stated that 'we still do not understand how to efficiently identify exploration targets within the near environment of a particular mineral deposit any better than we did prior to 2000'. This article aims to evaluate the potential drilling success of a simulated exploration programme using the existing 3D geological model of Leeuwpoort tin mine (Harris, 2018). These simulations investigate the probability of intersecting an economic tin lode and evaluate how the probability is affected when the number of drill-holes and distance from a known intersection point changes. Furthermore, the simulations attempt to obtain an indication of the minimum number of drill-holes required for a successful exploration campaign at the mine. The investigation also aims to establish a first-pass attempt towards developing a 'favoured procedure' for identifying potential exploration targets for tin deposits with similar geological and geochemical characteristics to Leeuwpoort. The results of the exploration simulations are statistically tested using the bootstrapping method (Rossi and Deutsch, 2013).

Leeuwpoort tin mine

Leeuwpoort tin mine is situated in the Rooiberg tinfield, which is located on the western lobe of the Bushveld Complex, 60 km from the closest town, Bela-Bela (formerly Warmbaths), in the Limpopo Province of South Africa (Figure 1). Mining took place for 87 years. The orebody can be geologically classified into two distinct groups of lodes (Falcon. 1989; Hartzer. 1995; Labuschagne. 2004; Leube and Stumpfl. 1963a; Phillips 1982; Rozendaal, Misiewicz, and Scheepers, 1995; Rozendaal, Toros, and Anderson, 1986):

1. Flat-dipping bedded lodes (vein deposits) with an approximate thickness of 10-15 cm and an average dip of 8–15°. The bedded lodes are laterally extensive and form parallel to sub-parallel to the sedimentary bedding of the quartzites in the lower Boschoffberg Member, part of the Leeuwpoort Formation (Kent and Matthews 1980).

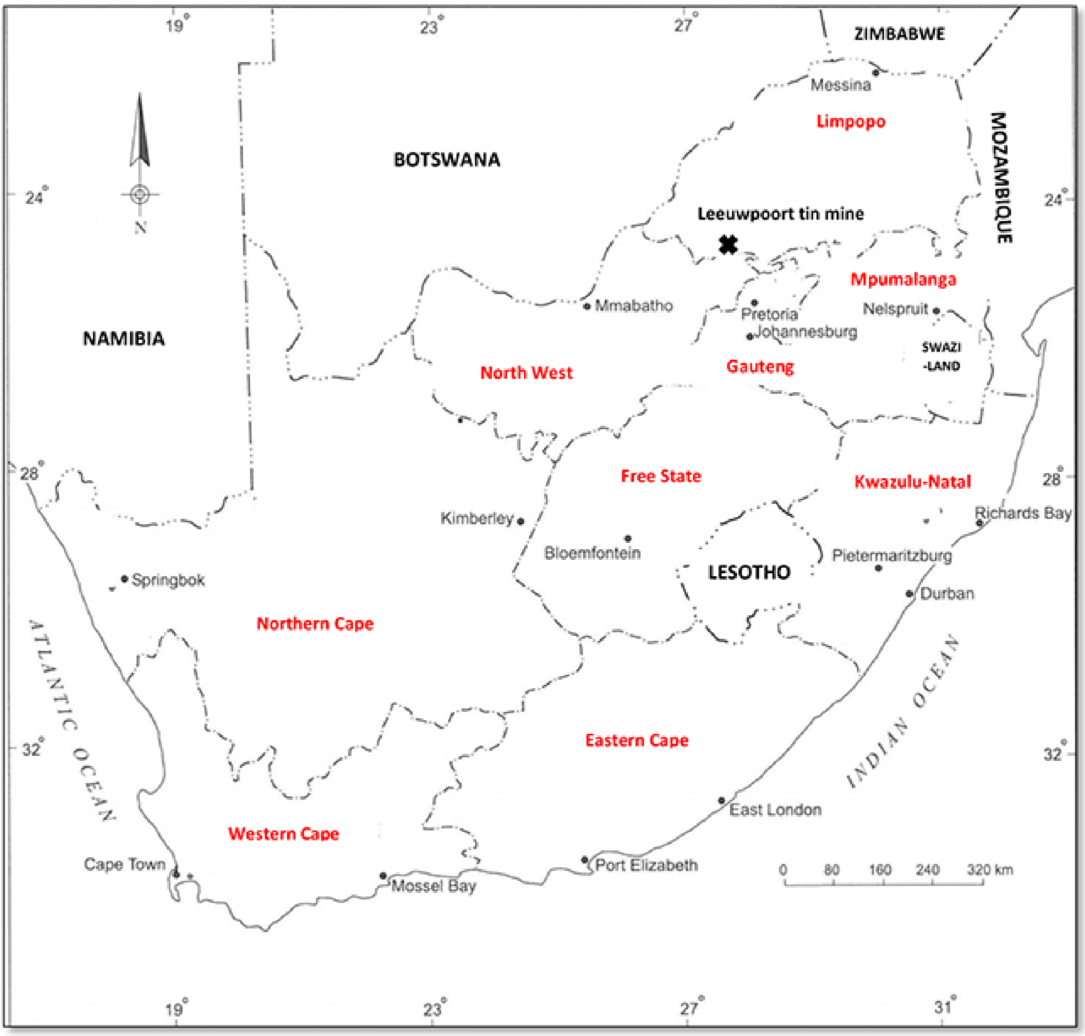

Figure 1—Locality map of Leeuwpoort tin mine in the Limpopo Province of South Africa. Modified after du Toit and Pringle (1998)

2. Steeply dipping fissure and faulted lodes (vein deposits) that have a variable thickness ranging from 1-20 cm and dips ranging from 45-90°.

These tin lodes were formed when ascending mineralized fluids moved from the underlying granites of the Lebowa Granite Suite through pre-existing fissure and faults created by the emplacement of the Bushveld Complex. At the time of mine closure in October 1993, 39 known tin lodes (22 bedded lodes and 17 fissure and faulted lodes) had been identified. Displacement of the lodes occurred due to the development of a complex faulting system after the formation of the tin deposits. Various normal and thrust faults developed omnidirectionally from the main Rooiberg thrust zone (Leube, 1960; Leube and Stumpfl, 1963b; Stumpfl and Leube, 1963).

Historical database

When the mine closed down, the only available electronic media was a 5-inch floppy disk containing the map catalogue. During the closure, some of the information was lost or misplaced, resulting in incomplete data for the exploration drill-holes such as missing survey, assay, lithological, and spatial data. The historical data consisted of:

1. Surface, underground, regional, geological, civil, and surveying maps
2. Old handwritten borehole logs stored in books and files, in some cases recorded in the imperial and/or metric systems.

During an extensive data recovery process, the data for 476 surface and 2402 underground boreholes was obtained along with all the 777 maps noted in the digital map catalogue. A digital catalogue was created for 14 106 peg positions recorded in surveyor logbooks. Extensive data validation and verification was conducted on the historical data, which was subsequently used to create a 3D geological model of the mine using Leapfrog Geo software (Harris, 2018). It is important to emphasise that the 3D geological model generated was created using limited historical data and that any estimations or simulations run from this model will introduce some uncertainty (Griffith 2007; Lindsay *et al*., 2013, 2012; Rossi and Deutsch, 2013; Thore *et al*., 2002).

Methodology

Identifying points of tin intersection

The first exploration simulation was designed to identify known points of tin intersections based on random drilling within a defined boundary of the 3D geological model. The following assumptions were made for the simulation:

1. We assume that exploration is required in a tinfield that was formed by the same geological conditions (geochemical and geophysical) as the study area – a stratigraphically and structurally controlled exogranitic hydrothermal process (Rozendaal, Misiewicz, and Scheepers, 1995; Rozendaal, Toros, and Anderson, 1986). This assumption may limit the applicability of the 'favoured procedure' established in this paper but could be used as the blueprint for further study on this topic.
2. The exploration simulation aims to identify the locations where the simulated drill-holes intersect an economic tin lode (tin lode of economic significance). This exploration test simulates greenfield exploration.
3. 500 random drill-holes (boreholes) will be simulated within a specified boundary. These simulated boreholes will be drilled vertically from the surface to a depth of 300 m and will henceforth be referred to as 'exploration phase 1'. Beyond 300 m there is no reliable geological information based on the 3D geological model.
4. The simulated drill-holes and all related information obtained are based on the 3D geological model of the mine.

Determining the confining boundary

It is necessary to confine the simulation to an area where sufficient information is available (Figure. 2). The simulation boundary encloses the historical mining area, which is also the area where the majority of the drill-holes used to create the three-dimensional geological model are located. The surface drill-holes have an average spacing of 100 m, whereas the underground drill-holes are on average 50 m apart. This means that the defined spatial boundary coincides with the drill-lhole boundaries of both the surface and underground drill-holes. Drill-holes that fall outside the central portion where the majority of the drill-holes are located were excluded because the distance between them is too large. Any correlation between these sets of drill-hole data will not lead to meaningful estimation because the data density is too low.

Generating the data for exploration phase 1

In order for the exploration simulation to be unbiased, the locations (x-, y-, and z-coordinates) of 500 drill-holes (exploration phase 1) were randomly generated using 'random functions' in Excel. The boundary limits were used as maximum and minimum coordinate values for the selected random coordinates to fall inside the boundary. Each drill-hole was given a unique name from PB1 to PB 500 (PB indicating planned borehole), a depth of 300 m, and a dip of 90°. These drill-holes were then imported into Leapfrog Geo as 'planned drill-holes' and evaluated against the existing 3D geological model in order to identify the location of known points of tin intersection (Figure. 3).

The exploration simulation indicated that of the 500 random drill-holes simulated (exploration phase 1), 83 drill-holes intersected one or more economic tin lodes. This means that if greenfield exploration was conducted based on the 500 planned drill-holes, there would be a 16% chance of any particular drill-hole intersecting an economic tin lode within the selected boundary. This leads to the next question of the simulated exploration investigation: what is the probability of intersecting an economic tin lode a certain radial distance around a known point of intersection?

Application of a 3D model to brownfield exploration predictions

The second phase of the exploration simulation evaluates the probability of intersecting an economic tin lode using the known locations of the 83 economic intersections identified in exploration phase 1 as 'central points'. These are the central drill-hole points from which the brownfield exploration simulation is conducted. The following assumptions were made:

1. We assume that brownfield exploration (Whiting and Schodde 2006) is required in a tinfield that formed under similar geological conditions (geochemical and geophysical) as the Leeuwpoort deposit.
2. The brownfield exploration simulation tests the probability of intersecting an economic tin lode, using known location

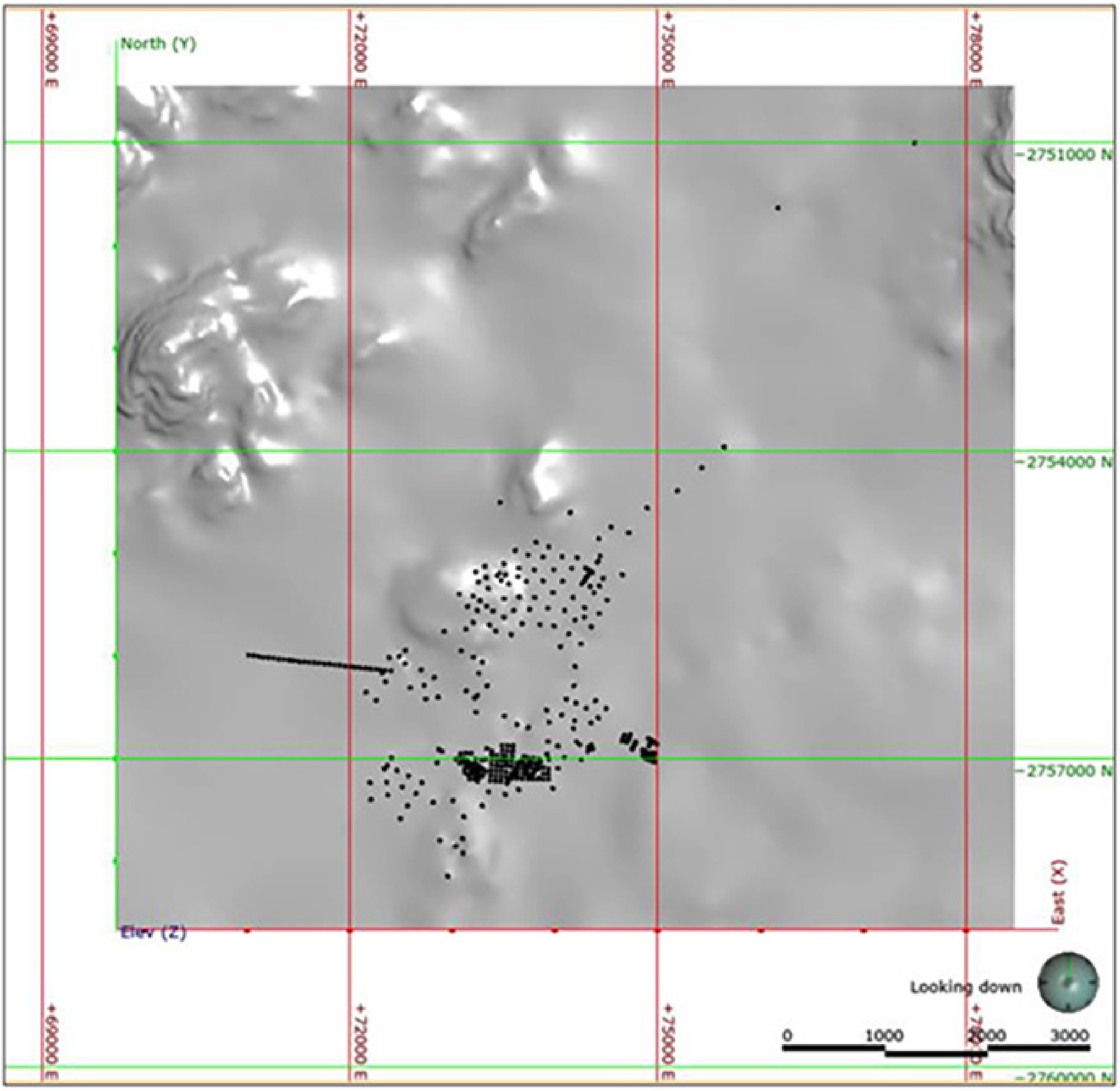

Figure 2—The confining boundary (red block) selected for exploration phase 1. The surface boreholes were used to constrain the boundary as they are the most laterally extensive. Drill-holes that are too far from the central mining area were excluded (red circle). The water drill-holes (blue circles) were not considered for the boundary because information for these boreholes is limited (program used: Leapfrog Geo)

points (identified in exploration phase 1). A constant area around each of the 83 drill-holes is used for the brownfield explorations to be consistent.

3. Five test drill-holes from exploration phase 1 (PB2, PB38, PB122, PB192, PB267) were selected randomly to establish the favoured procedure for the parameters to be applied to the rest of the identified economic drill-holes. The 'favoured procedure' thus refers to the optimal parameters based on this case study, *i.e.* the historical data and 3D geological model. The following parameters were investigated:
   (a) The effect of change in the constraining area on the probability of intersecting an economic lode was investigated by choosing areas of 1 ha, 10 ha, and 100 ha.
   (b) 50 and 100 random drill-holes within the constraining area were simulated to test the effect of the number of drill-holes per constraining area.
   (c) The number of iterations used for the bootstrapping statistical method. The effect of using different numbers of simulations during the bootstrapping analysis was evaluated for 10, 50, 100, 200, 500, 1 000, 2 000, 5 000, 7 000, 10 000, 20 000, 50 000, 100 000, and 1 000 000 iterations.
   (d) The amount of resamples selected per bootstrap analysis. The effect of changing the number of drill-holes resampled from exploration phase 2 was investigated by using 20 and 40 samples.

Determining the constraining areas around each economic drill-hole

For the simulation to be consistent for each of the planned drill-holes (exploration phase 2), a consistent area must be used to constrain the brownfield exploration simulation around the location of the economic drill-holes identified in exploration phase 1 (central points). The second step is to investigate what effect changing the area will have on the probability of intersecting an economic tin lode within the specified confining area. Areas of

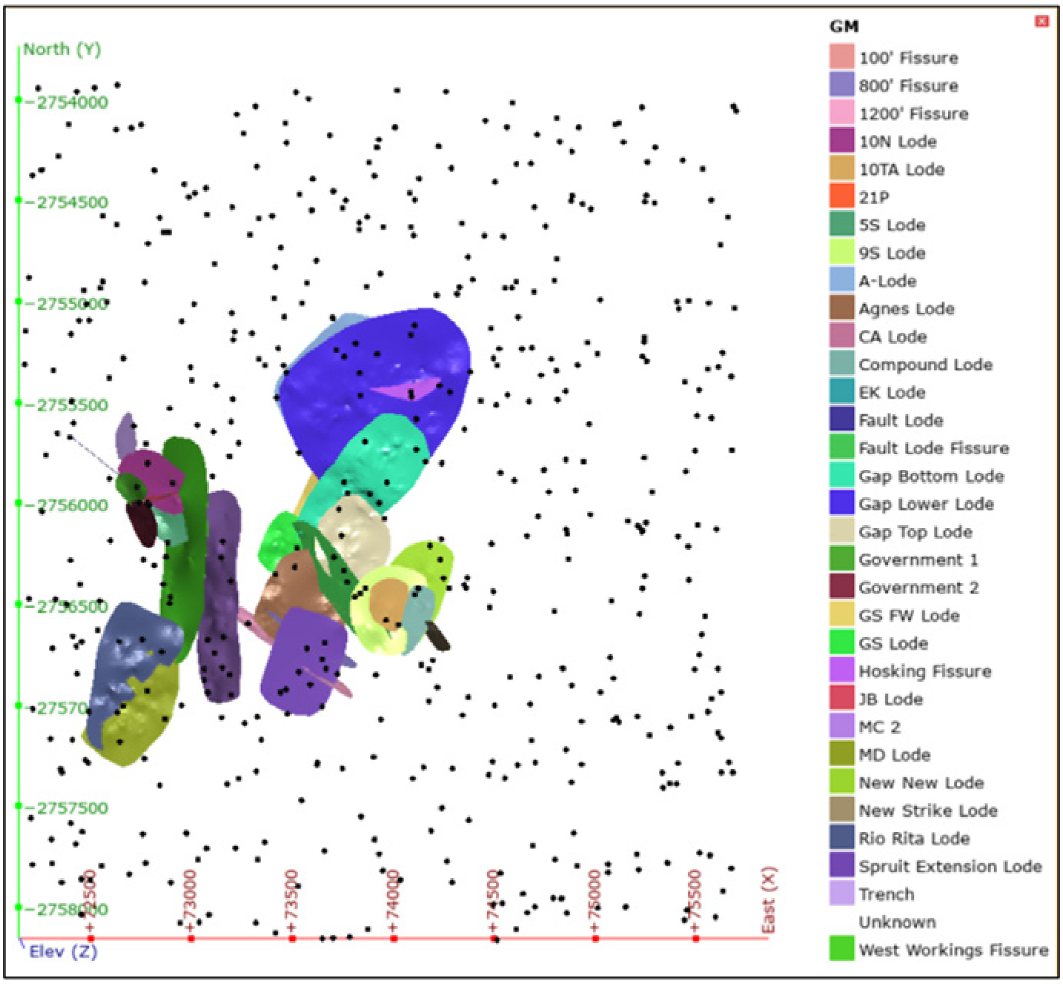

Figure 3—Plan view of the intersection between exploration phase 1 (black dots represent drill-holes) and the tin lodes modelled in Leapfrog Geo (GM)

1 ha, 10 ha, and 100 ha were chosen for this investigation and were subsequently used to calculate the respective radii around each of the 'central points' for the five test drill-holes to remain consistent in the simulation. The radial distance around each central point can be defined as the 'constraining boundary'.

Generating drill-hole data for exploration phase 2

The second parameter investigated was the effect of having 50 or 100 simulated boreholes within the constraining boundary, and how this influenced the chance of intersecting an economic tin lode. For exploration phase 2 to be comparable to exploration phase 1, the drill-holes had to be randomly generated within the constraining boundary by using 'random functions' in Excel. The radial distance around each central point of 1 ha, 10 ha, and 100 ha (Figure. 4) was set as the boundary limit, which meant that the random coordinates generated for exploration phase 2 fell within the constraining boundary.

The drill-holes were simulated from surface vertically to a depth of 300 m, as this correlated to the depth of the deepest drill-holes used to create the 3D geological model. The drill-holes for exploration phase 2 were imported into Leapfrog Geo as 'planned drill-holes' to evaluate the number of lodes intersected per drill-hole using the existing 3D geological model.

Determining the number of lodes intersected in Leapfrog Geo

Evaluations were conducted in Leapfrog Geo to determine the number of tin lodes intersected per drill-hole for exploration phase 2 within constraining areas of 1 ha, 10 ha, and 100 ha. Descriptive statistical analysis (pie charts) of the number of lodes intersected within these constraining boundaries was conducted in IBM SPSS Statistics 23 (Figure. 5).

Statistical analysis of the brownfield exploration results using bootstrapping

The bootstrapping statistical method was used to analyse the results obtained in the brownfield exploration simulation. The statistical investigation will further determine what the effect on the probability will be if (1) the samples population is changed, and (2) the number of iterations used during bootstrapping changes.

Bootstrapping and resampling

The bootstrapping method is a resampling process that is repeated thousands of times to build a distribution that will most likely be Gaussian (Efron and Tibshirani, 1994; Good, 2006; Rossi and Deutsch, 2013). By resampling the original data multiple times, statistical inferences can be made about the population from which the data came (Curran-Everett. 2009; Grunkemeier and Wu. 2004; Simon. 1997; Simon and Bruce. 1991; Wilcox. 2010; Yu. 2003). Bootstrap analysis has become increasingly popular for hypothesis testing (Davidson and MacKinnon. 2000; Efron

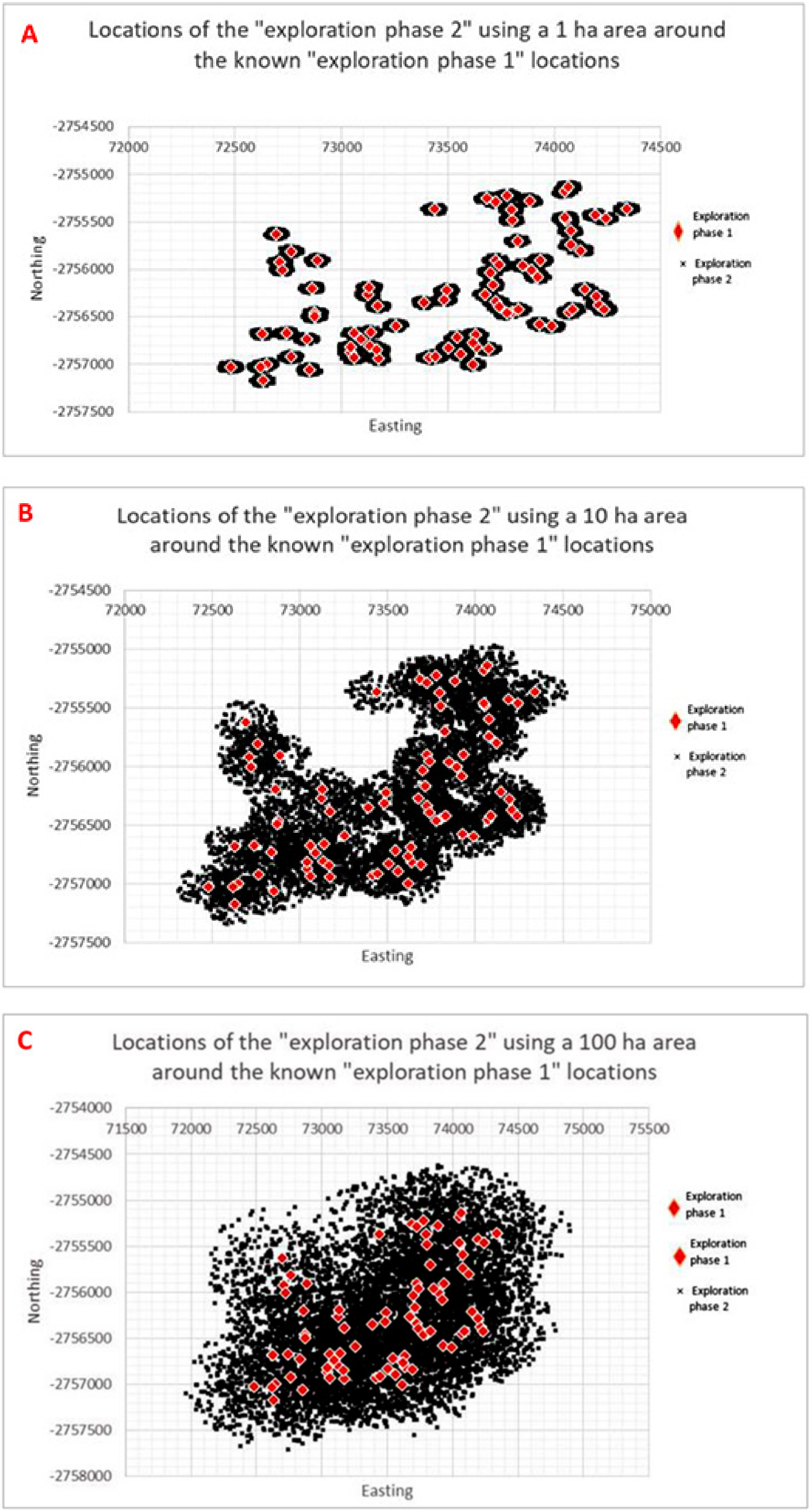

Figure 4—Visual representation of exploration phase 2 (black crosses) in (a) 1 ha,(b) 10 ha, and (c) 100 ha areas around the known locations for exploration phase 1 (red diamonds) that intersect a certain number of economic lodes of interest, using Excel

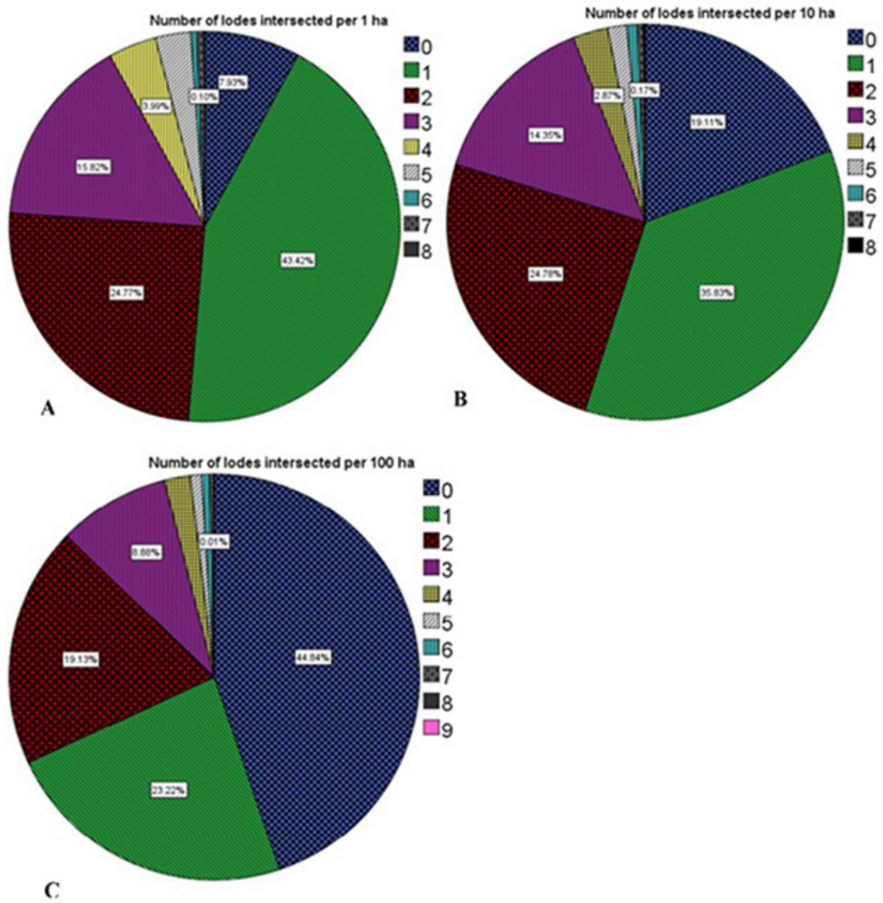

Figure 5—Probability of intersecting a certain number of lodes for a population of 100 randomly simulated drill-holes around a 'central point' in exploration phase 2 using 1 ha (A), 10 ha (B), and 100 ha (C) as the constraining boundary. The probability of intersecting one or more lodes of economic significance is 92%, 80%, and 55%

and Tibshirani. 1991) as it is considered to be a more thorough technique compared to other resampling methods such as jackknife, cross-validation, and randomization exact tests (Yu 2003). With the bootstrapping method, two types of resampling techniques are possible: sampling with replacement and sampling without replacement.

When a sample of a population has multiple chances to be selected it is referred to as sampling with replacement (Bardossy, Szabo, and Vaga, 2003; DiCiccio and Efron, 1996; Good, 2006; Grunkemeier and Wu, 2004; Olken and Rotem, 1986; Simon, 1997). However, when the sample has only one chance of being selected (zero per cent chance of reselection) from the population it is referred to as sampling without replacement (Horvitz and Thompson, 1952; Narain, 1951; Olken and Rotem 1986; Raj ,1956; Rao, Hartley, and Cochran, 1962; Sampford, 1967; Vitter, 1985; Yates and Grundy, 1953).

Sampling without replacement is used for the bootstrap analysis of the simulated brownfield exploration conducted on the 3D geological model. Because the drill-holes are randomly simulated within the constraining boundary around a central point, we assume that no hole was drilled (simulated) twice and that a drill-hole can therefore be selected only once during a resample.

Defining the parameters for the bootstrap simulation

Before the bootstrap can be scripted, the simulation criteria need to be defined. The data generated in exploration phase 2 is resampled. The bootstrap simulation was conducted on the five test drill-holes identified in exploration phase 2: PB2, PB38, PB122, PB192, and PB262. The probability and standard deviation of each resampling event are recorded and analysed to determine which parameters are considered to be the 'favoured procedure' to use based on the historical data and 3D geological model.

Setting up the bootstrap simulation

The bootstrap simulation was created using V3.6.0 of the R software environment. R is a programming language and a software environment that is freely available and is widely used for statistical analysis and visualization. For data result visualization 'ggplot2' is used in conjunction with R to create graphs, in this case, to visualize the bootstrap results. A bootstrap simulation needed to be created for each of the five test boreholes where the change in the parameters discussed above can be evaluated. The full R source code can be downloaded from https://github.com/fas-r/BoreholeBootstrap.

Results and discussion

Effect of using 50 and 100 drill-holes

Two different sets of drill-holes were generated for exploration phase 2. In each case, 50 drill-holes and 100 drill-holes (Table I) were simulated within the confining boundaries (areas) to test the effect on the probability of intersecting an economic tin lode. For both bootstrap simulations, 20 and 40 samples were investigated,

Table I

Bootstrap resampling using 1000 iterations on 50 simulated boreholes in a 1 ha area around a known borehole location modelled in exploration phase 1 that intersects a point of economic interest

Exploration phase 2 (20 samples)										
Number of drill-holes	PB2		PB38		PB122		PB192		PB267	
	Probability	Standard deviation	Probability	Standard deviation	Probability	Standard deviation	Probability	Standard deviation	Probability	Standard deviation
50	0.580	0.085	0.452	0.088	0.523	0.086	0.904	0.052	0.812	0.0662
100	0.613	0.092	0.483	0.102	0.575	0.097	0.859	0.072	0.789	0.084
Exploration phase 2 (40 samples)										
Number of drill-holes	PB2		PB38		PB122		PB192		PB267	
	Probability	Standard deviation	Probability	Standard deviation	Probability	Standard deviation	Probability	Standard deviation	Probability	Standard deviation
50	0.571	0.040	0.433	0.037	0.512	0.037	0.904	0.023	0.806	0.030
100	0.598	0.058	0.460	0.062	0.573	0.060	0.851	0.044	0.787	0.049

Table II

Bootstrap resampling using 1000 iterations on 100 simulated boreholes, for both 20 and 40 resamples, in 1 ha, 10 ha, and 100 ha areas around a known borehole location modelled in exploration phase 1 that intersects a point of economic interest

Exploration phase 2 (20 samples)										
ha	PB2		PB38		PB122		PB192		PB267	
	Probability	Standard deviation	Probability	Standard deviation	Probability	Standard deviation	Probability	Standard deviation	Probability	Standard deviation
1	0.615	0.096	0.474	0.103	0.586	0.096	0.859	0.073	0.792	0.085
10	0.320	0.090	0.468	0.098	0.551	0.097	0.715	0.089	0.630	0.095
100	0.233	0.077	0.290	0.089	0.246	0.082	0.591	0.094	0.504	0.097
Exploration phase 2 (40 samples)										
ha	PB2		PB38		PB122		PB192		PB267	
	Probability	Standard deviation	Probability	Standard deviation	Probability	Standard deviation	Probability	Standard deviation	Probability	Standard deviation
1	0.601	0.060	0.463	0.061	0.570	0.063	0.855	0.042	0.785	0.050
10	0.300	0.055	0.456	0.060	0.542	0.060	0.709	0.056	0.620	0.062
100	0.209	0.048	0.269	0.052	0.228	0.049	0.579	0.059	0.493	0.061

using 1000 iterations per bootstrap within a 1 ha confining area; the only difference is the number of drill-holes simulated. Table I indicates that the probability of intersecting an economic tin lode increases when a larger number of drill-holes are used within the confining area. In this instance, a higher chance of intersecting a tin lode can be expected when using 100 drill-holes per confining area. However, the probability of intersecting a tin lode seems to decrease for test drill-holes PB192 and PB267 when 100 simulated drill-holes are compared to 50 simulated drill-holes. This phenomenon can be ascribed to statistical noise, as these two test drill-holes are located within the sector where the majority of the tin lodes have been identified. The fluctuations of the probability and standard deviation values are due to the small number of iterations used for the bootstrap analysis.

Effect of changing the confining area

The chance of intersecting a tin lode is dependent on the size of the confining area. In order to test the effect of using 1 ha, 10 ha, and 100 ha (Table II) as a confining boundary around the central points, bootstrap simulations were conducted using 1000 iterations, 100 simulated drill-holes, with 20 samples and 40 samples per simulation. The number of iterations, sample size, and drill-holes remained constant with each bootstrap simulation; the only parameter that was changed was the confining area.

From the probability table (Table II) it becomes evident that the probability of intersecting a tin lode decreases with increasing area size (confining area) around the central points. The greater the distance around each central point, the smaller the chance of intersecting a tin lode since a larger area is now included in the confining area where tin lodes do not occur (see Figure 4 and 5).

The statistical effect of the different confining areas on the sample size selected for the bootstrap simulation (20 or 40 samples) should also be observed in the tables. One important aspect to note for this simulation is that even though the same bootstrap parameters were used (100 drill-holes, 1000 iterations, 1 ha confining area, 20 and 40 samples), a slight variation occurs for the results obtained for the probability and standard deviation. With each bootstrap simulation conducted, new samples are reselected for the simulation, which will result in a slight difference in the probability as each set of samples reselected will have different probabilities of intersecting an economic tin lode.

Effect of sample size and number of iterations in bootstrap simulations

The number of samples selected from the population and the number of iterations chosen influences the probability and, subsequently, the standard deviation. In the case of the bootstrap simulations conducted on the exploration simulation, 20 samples and 40 samples were investigated. For the bootstrap simulations, 100 drill-holes were simulated in a 1 ha confining area where 20 and 40 samples were randomly selected. The number of iterations per bootstrap simulation was changed to determine the effect on the probability of intersecting an economic tin lode. The results obtained using 10, 50, 100, 200, 500, 1 000, 2 000, 5 000, and 7 000 iterations are listed in Table III.

Bootstrap tests are dependent on a finite number of samples (Davidson and MacKinnon, 2000). In practice, thousands to tens of thousands of iterations are used during the bootstrap test as this minimizes any fluctuation in the results, generally smooths the data, and represents a more Gaussian distribution. Thus, the number of samples selected for resampling and the number of iterations used for the bootstrap simulation will depend on the data-set. When the bootstrap simulations were being set up, the general assumption was made that more samples selected from the population should yield a higher probability. However, the number of iterations used per bootstrap simulation needs to be considered as well. Consider test drill-hole PB2 (Table III). If 20 samples are selected from the population there is a 64% chance of intersecting a tin lode, whereas if 40 samples are selected the probability of intersecting a tin lode is 55%. In this instance, the probability decreased with an increase in samples selected per bootstrap analysis.

The decrease in the probability of intersecting an economic tin lode can be ascribed to more drill-holes falling outside the lode boundaries identified within the 3D geological model. In other words, more drill-holes have a higher chance of intersecting barren geology (containing no ore), especially if the random drill-hole is simulated off the modelled tin lode. It is generally expected that with an increase in the number of iterations, the fluctuations for the probability and standard deviation for the samples will smooth out. The use of fewer iterations for the bootstrap simulation will result in more variability in the data (standard deviation).

The fluctuation noted in the probability and standard deviation for the 20 and 40 samples selected indicates that an inadequate number of iterations were used. To determine the minimum number of iterations needed to minimize the variation in the data, 10 000, 20 000, 50 000, 100 000, and a million iterations were tested using 40 samples reselected from the 100 drill-holes simulated in exploration phase 2 within a 1 ha confining area around the central points for the bootstrap simulations (see Table IV). For these simulations, 40 samples were selected instead of 20 samples from the population, as the results indicated that 40 samples lowers the variability of the data, and also generally increases the probability. The study found that for a greater number of iterations, the variability decreases, as is evident by the reduction in the fluctuation of both the probability and standard deviation for the five test drill-holes.

Table III

Bootstrap resampling using 10, 50, 100, 200, 500, 1 000, 2 000, 5 000, and 7 000 iterations on 100 simulated boreholes in a 1 ha area around a known borehole location. The results for both 20 samples and 40 samples are listed

Exploration phase 2 (20 samples)										
Iterations	PB2		PB38		PB122		PB192		PB267	
	Probability	Standard deviation	Probability	Standard deviation	Probability	Standard deviation	Probability	Standard deviation	Probability	Standard deviation
10	0.645	0.072	0.465	0.088	0.535	0.111	0.895	0.050	0.745	0.112
50	0.624	0.086	0.477	0.084	0.578	0.122	0.860	0.071	0.802	0.066
100	0.603	0.117	0.492	0.104	0.579	0.094	0.845	0.073	0.787	0.073
200	0.611	0.090	0.479	0.090	0.585	0.093	0.858	0.075	0.797	0.081
500	0.605	0.101	0.474	0.093	0.579	0.097	0.855	0.071	0.794	0.083
1000	0.613	0.092	0.483	0.102	0.575	0.097	0.859	0.073	0.789	0.084
2000	0.613	0.098	0.477	0.095	0.582	0.099	0.857	0.070	0.789	0.081
5000	0.611	0.097	0.479	0.097	0.582	0.096	0.j858	0.071	0.791	0.080
7000	0.611	0.096	0.477	0.098	0.584	0.099	0.857	0.071	0.791	0.083
Exploration phase 2 (40 samples)										
Iterations	PB2		PB38		PB122		PB192		PB267	
	Probability	Standard deviation	Probability	Standard deviation	Probability	Standard deviation	Probability	Standard deviation	Probability	Standard deviation
10	0.577	0.072	0.495	0.071	0.600	0.059	0.855	0.037	0.820	0.042
50	0.598	0.055	0.464	0.059	0.563	0.060	0.849	0.043	0.794	0.044
100	0.604	0.066	0.464	0.062	0.571	0.058	0.859	0.045	0.780	0.050
200	0.603	0.063	0.467	0.056	0.579	0.060	0.853	0.044	0.789	0.053
500	0.600	0.061	0.466	0.061	0.573	0.059	0.854	0.043	0.787	0.051
1000	0.603	0.061	0.463	0.059	0.573	0.061	0.854	0.047	0.785	0.051
2000	0.599	0.060	0.463	0.060	0.571	0.060	0.6854	0.043	0.786	0.051
5000	0.600	0.061	0.464	0.061	0.571	0.061	0.854	0.043	0.786	0.051
7000	0.602	0.061	0.463	0.061	0.571	0.061	0.854	0.044	0.786	0.051

Table IV

Bootstrap resampling for 40 samples using 10 000, 20 000, 50 000, 100 000, and 1 000 000 iterations on 100 simulated boreholes in a 1 ha area around a known borehole location modelled in exploration phase 1 that intersects a point of economic interest

Exploration phase 1	Iterations (100 boreholes per 1 ha)									
	10 000		20 000		50 000		100 000		1000 000	
	Probability	Standard deviation	Probability	Standard deviation	Probability	Standard deviation	Probability	Standard deviation	Probability	Standard deviation
PB2	0.600	0.061	0.602	0.060	0.600	0.060	0.600	0.061	0.600	0.060
PB38	0.464	0.061	0.464	0.061	0.463	0.061	0.464	0.061	0.464	0.061
PB122	0.571	0.060	0.571	0.061	0.571	0.061	0.571	0.061	0.571	0.061
PB192	0.853	0.044	0.853	0.044	0.854	0.044	0.854	0.044	0.854	0.044
PB267	0.786	0.050	0.785	0.050	0.785	0.051	0.785	0.051	0.785	0.051

Table V

Summary of the bootstrap simulations conducted for exploration phase 2using 10, 50, 100, 200, 500, 1 000, 2 000, 5 000, 7 000, 10 000, 20 000, 50 000, 100 000, and 1 000 000 iterations, 40 samples selected per population, 100 drill-holes per 1 ha confining area

Iterations	log(iterations)	Exploration phase 2 (40 samples)																			
		PB2				PB38				PB122				PB192				PB267			
		Probability	Standard deviation	-2σ	2σ	Probability	Standard deviation	-2σ	2σ	Probability	Standard deviation	-2σ	2σ	Probability	Standard deviation	-2σ	2σ	Probability	Standard deviation	-2σ	2σ
10	1.000	0.558	0.072	0.414	0.701	0.495	0.071	0.352	0.638	0.600	0.059	0.482	0.718	0.855	0.037	0.781	0.929	0.820	0.042	0.736	0.904
50	1.699	0.598	0.055	0.487	0.709	0.464	0.059	0.345	0.583	0.563	0.060	0.443	0.683	0.849	0.043	0.763	0.934	0.794	0.044	0.706	0.882
100	2.000	0.604	0.066	0.472	0.736	0.464	0.062	0.340	0.588	0.571	0.058	0.455	0.687	0.859	0.045	0.770	0.948	0.780	0.050	0.680	0.880
200	2.301	0.603	0.063	0.478	0.728	0.467	0.056	0.355	0.579	0.579	0.060	0.460	0.698	0.853	0.044	0.765	0.941	0.789	0.053	0.683	0.895
500	2.699	0.600	0.061	0.478	0.722	0.466	0.061	0.344	0.588	0.573	0.059	0.455	0.691	0.854	0.043	0.768	0.940	0.787	0.051	0.685	0.889
1000	3.000	0.603	0.061	0.482	0.724	0.463	0.059	0.345	0.581	0.573	0.061	0.452	0.694	0.854	0.047	0.761	0.947	0.785	0.051	0.682	0.888
2000	3.301	0.599	0.060	0.478	0.720	0.463	0.060	0.342	0.584	0.571	0.060	0.452	0.690	0.854	0.043	0.767	0.941	0.786	0.051	0.684	0.888
5000	3.699	0.600	0.061	0.478	0.722	0.464	0.061	0.342	0.586	0.571	0.061	0.450	0.692	0.854	0.043	0.767	0.941	0.786	0.051	0.684	0.888
7000	3.845	0.602	0.061	0.480	0.724	0.463	0.061	0.341	0.585	0.571	0.061	0.449	0.693	0.854	0.044	0.766	0.942	0.786	0.051	0.684	0.888
10000	4.000	0.600	0.061	0.479	0.721	0.464	0.061	0.342	0.586	0.571	0.060	0.450	0.692	0.853	0.044	0.765	0.941	0.786	0.050	0.685	0.887
20000	4.301	0.602	0.060	0.482	0.722	0.464	0.061	0.342	0.586	0.571	0.061	0.448	0.694	0.853	0.044	0.765	0.941	0.785	0.050	0.684	0.886
50000	4.699	0.600	0.060	0.479	0.721	0.463	0.061	0.341	0.585	0.571	0.061	0.448	0.694	0.854	0.044	0.767	0.941	0.785	0.051	0.684	0.886
100000	5.000	0.600	0.060	0.480	0.720	0.464	0.061	0.342	0.586	0.571	0.061	0.449	0.693	0.854	0.044	0.767	0.941	0.785	0.051	0.684	0.886

To finally determine the minimum number of iterations needed to conduct a bootstrap simulation using the 3D model, the point where a negligible change took place in fluctuation in the variability needed to be determined. A summary of all the bootstrap simulations conducted on the five test drill-holes of exploration phase 2 is given in Table V. Variability graphs for PB2, PB38, PB122, PB192, and PB267 (Figure. 6) were constructed by plotting the probability of intersecting an economic tin lode for these samples against the number of iterations used (using a logarithmic scale). The fluctuation in the variability as a factor of the number of iterations can now be graphically viewed to help determine where the data is sufficiently smoothed to have minimal fluctuation in the bootstrap analysis. These graphs indicate that the minimum number of iterations needed to conduct a bootstrap simulation is 2000 iterations.

Defining the 'favoured procedure'

One of the main aims of these simulations was to establish a 'favoured procedure' for bootstrap simulations conducted at Leeuwpoort tin mine; in other words, the optimal parameters that are best suited for a statistical analysis applicable to the mine. From the multiple bootstrap simulations conducted, the following points were determined:

1. When choosing the number of drill-holes needed for the bootstrap simulation to determine the probability of intersecting a tin lode, a larger sample size is favourable. For this case study, 100 simulated drill-holes have a higher chance of intersecting a tin lode than 50 drill-holes.
2. The confining boundary (area) used for the bootstrap simulation conducted for each of the drill-holes identified in exploration phase 2 around the central points must be constant in order to be able to compare the results. The optimal confining area to conduct the bootstrap analysis is 1 ha rather than 10 ha and 100 ha because a 1 ha confining area results in a higher probability of intersecting a tin lode.
3. For the tested bootstrap simulations, 20 samples and 40 samples were selected from the population. The results indicate that the variability decreases with an increasing number of samples selected. For this case study, 40 samples give better probability results with less variability.
4. The extensive bootstrap tests run on exploration phase 2 indicate that a greater number of iterations reduces variation in the data for this data-set. In the case study, a million iterations was used to test the smoothing effect of bootstrapping to the extreme. The number of iterations required to reduce variation is dependent on the data used for the bootstrap analysis. The case study found that variation is reduced at 2 000 iterations for the data obtained during the bootstrap analysis. Statistically, 2 000 iterations should be considered to be the minimum amount. The recommended number of iterations is

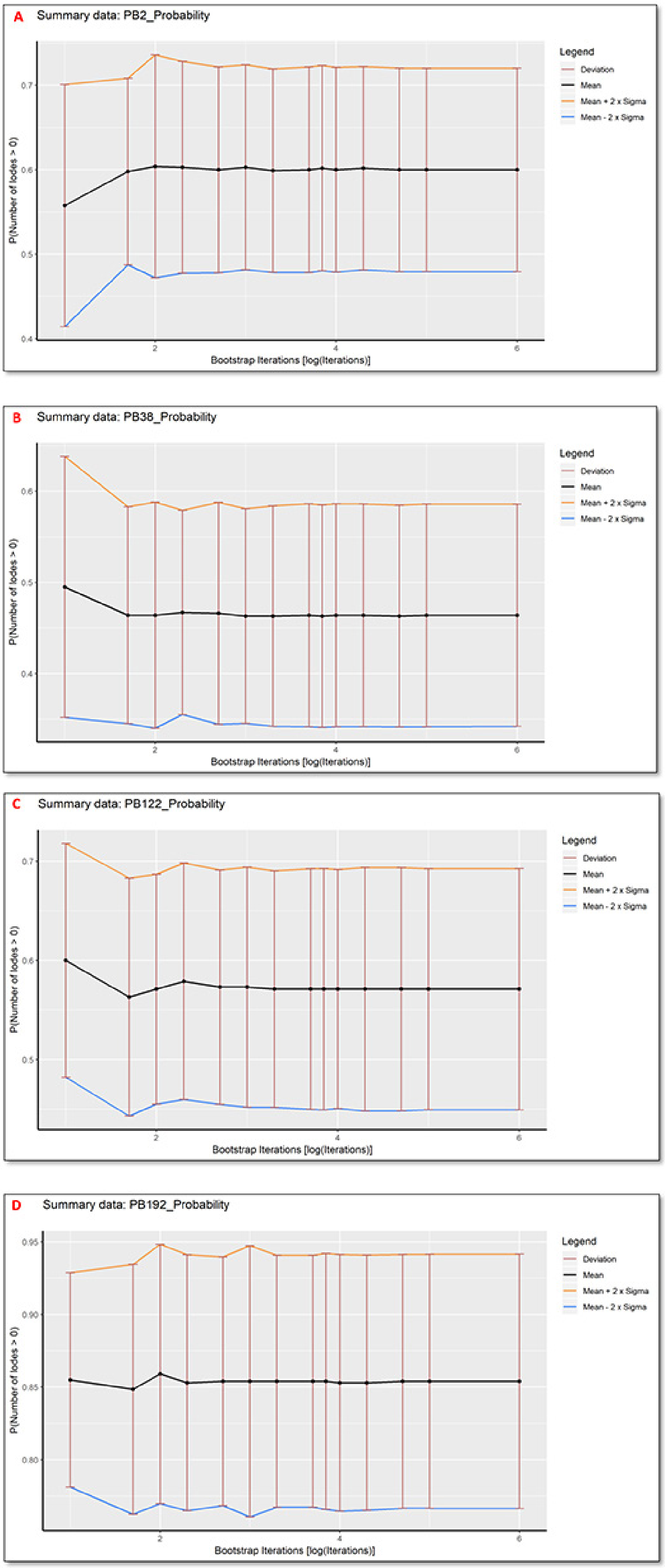

Figure 6—Variability graphs for test drill-holes. (a) PB2, (b) PB38, (c) PB122, (d) PB192, and (e) PB267, plotting probability against the number of iterations where 2 sigma is used as confidence intervals to illustrate variability. The fluctuation of the probability becomes constant at 2 000 iterations (log(2000) = 3.3 on the x-axis) indicating that this is the minimum number of iterations that should be used to conduct a bootstrap simulation at Leeuwpoort tin mine

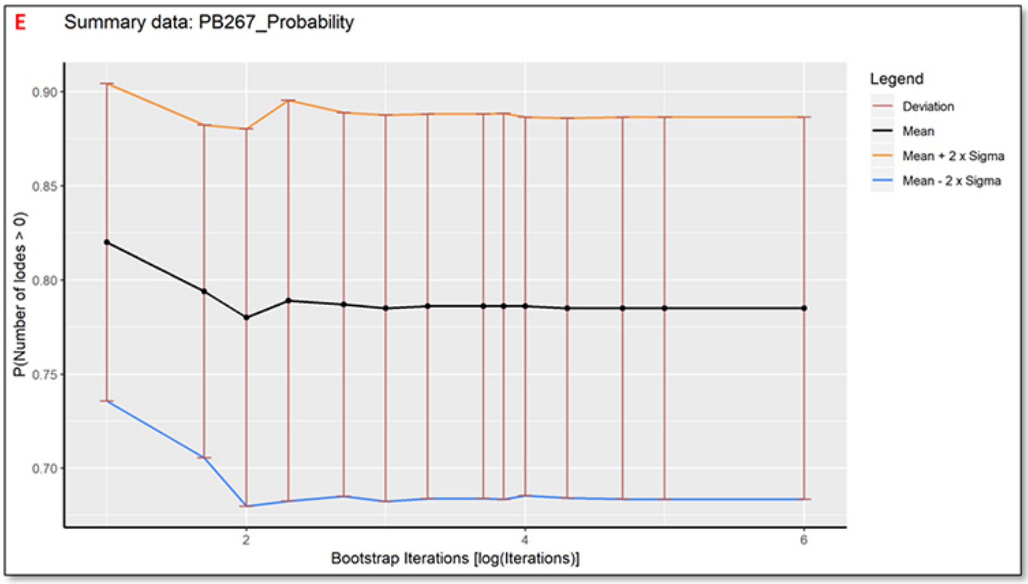

Figure 6—Continuead

100 000, just to reduce computational time, and because there is no notable statistical difference between using 100 000 and a million iterations.

Conclusions

Exploration is crucial for any mining venture, whether it is greenfield exploration or brownfield exploration. This case study aimed to evaluate the potential success of greenfield and brownfield exploration drilling using the three-dimensional geological model of Leeuwpoort tin mine. For the first exploration simulation, 83 (16%) of the 500 randomly simulated drill-holes intersected an economically significant lode. These drill-holes were then used as central points, around each of which 100 drill-holes were simulated to establish 'exploration phase 2' as part of the brownfield exploration simulation.

The overall probability of intersecting a tin lode for exploration phase 2 is calculated at 92% (Figure. 5). However, the distribution of the probability is positively skewed for exploration phase 2, which gave rise to various bootstrap simulations conducted for the distribution to resemble a more Gaussian distribution. The bootstrap simulations aimed to establish a first-pass attempt at developing a 'favoured procedure' for the parameters used in this case study that would result in a small amount of variability. The favoured procedure was established by investigating the effect of changes in the number of simulated drill-holes, constraining boundary, bootstrap sample size, and number of iterations based on the probability of intersecting a tin lode determined in exploration phase 2.

From the statistical analysis of the exploration simulation, the optimal statistical parameters that should be used to identify future exploration targets in the case study area are 100 simulated drill-holes within a 1 ha constraining boundary (area) of the known location point of a drill-hole that intersects a tin lode, using 100 000 iterations for the bootstrap simulation with 40 samples selected from the population without replacement.

The exploration simulations conducted on the 3D geological model concluded that potential exploration projects could be simulated successfully and that 3D models can be used to identify future mining targets. However, it is important to note that 3D models cannot be considered to be 100% accurate; any 3D geological model created is subject to uncertainty and variability because the models are dependent on the quality of the data, and are also dependent on the interpretation by the geologist that creates the model.

The paper is intended to illustrate a first attempt on the approach to determining the probability of success in exploration drilling rather than a generalized procedure or best practice method. These parameters could potentially be used for future brownfield exploration to identify potential mining targets comprising ore deposits that have the same geological and geochemical characteristics as those of Leeuwpoort tin mine. However, these estimations cannot be accepted as accurate without knowing the geochemical and geophysical heterogeneity of the orebody. Nonetheless, this case study can be used for the prediction of successful drilling and can aid in budgeting for drilling programmes because the minimum number of drill-holes needed can be determined.

The 'favoured procedure' parameters identified for the statistical analysis of the historical data using bootstrap simulations indicate that the potential exploration success can be evaluated by simulating various parameters such as the number of drill-holes required in a confined area. However, in order to develop a generally applicable approach, or for our findings to be transferable to other mineralized areas of similar type, a broader base of similar studies is required.

Computer code availability

Name of code: BoreholeBootstrap
Developer: F.A.S. Reyneke
Contact email: stephan.reyneke7@gmail.com; zandri.harris27@gmail.com
Telephone number: +27 82 462 4311; +27 83 707 9501
Year first available: 2020
Hardware requirements: At least 2 GHz or faster processor, 4 GB RAM, and 1 GB of free hard disk space to store results. A faster machine is recommended if available to speed up bootstrap

analysis time.
Software requirements: R version 3.6.0 with the 'ggplot2' package installed. The script automatically installs this package.
Program language: R
Program size: 10.1 KB
Source code:
To access the source code, navigate to the following GitHub repository: https://github.com/fas-r/BoreholeBootstrap
Click on the 'Clone or download' button, and select 'Download ZIP'. The source code is now downloaded to your machine.
Open the README.md file in a text editor application (such as Notepad) for usage and test instruction information.

Compliance with ethical standards

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Local procurement in the mining sector: Is Ghana swimming with the tide?

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Synopsis

Since 2012, Ghana has been implementing local procurement regulations in the mining sector to broaden and deepen linkages between mining and other sectors of the economy. The regulations have been implemented in collaboration with the mining industry. This paper offers an in-depth analysis of how the local procurement regulations and related initiatives have been implemented so far. Primary data gathered with semi-structured interviews and secondary sources of data indicate a steady improvement in both in-country procurement and local manufacturing of inputs for the mining industry. There are, however, some challenges relating to tariff structure and support (financial and technical) for local suppliers and manufacturers to meet high standards and demands of the mining industry. This calls for a well-thought-out strategy and programme of activities to sustain and improve on progress made.

Keywords

local procurement, local content, mining, minerals, Ghana.

Background

In the run-up to the 2008 World Economic Crisis, global demand for and prices of minerals and metals increased rapidly, resulting in increases in production and profits of mining companies[1] (PriceWaterhouseCoopers, 2007). In most developing countries (especially in Africa) where foreign capital and multinational companies dominate ownership structure of mining companies, most of these profits did not benefit local economies where mining takes place. The marginal increases in tax revenues (the main focus of most countries) that accrued to governments in these countries and the poor linkages (backward, sideways, and forward) between mining activities and local economies meant that the mining industry's contribution to social and economic development objectives was less certain and contested in many countries (AU and UNECA, 2011). The mining industry's weak linkages to other sectors of the economy contribute to its characterization as an enclave and fuel public discontent about the sector's high environmental cost and limited developmental contributions (Bank of Ghana, 2003; Larsen, Yankson, and Fold, 2009; Akabzaa, Seyire, and Afriyie, 2007; UNECA, 2004, African Union Commission, 2008; Botchie, Dzanku, and Akabzaa 2008).

The years after the World Economic Crisis, therefore, witnessed increased calls for changes to the mining framework in ways that can enhance and optimize local developmental benefits associated with exploitation of mineral resources, culminating in 2009 in the adoption of the ECOWAS Minerals Development Policy (EMDP) in 2009 by the Economic Community of West African States (ECOWAS) and the African Mining Vision (AMV) by the African Union. The AMV aspires to fundamentally change

1PriceWaterhouseCoopers reports that between 2002 and 2007 prices of minerals and metals rose by 260% and over the same period, the average net profits of the biggest mining firms increased by more than 1400%. Average profits of these firms were up more than 64% between 2005 and 2006.

the mining regimes operative on the continent, 'integrating the [mining] sector more coherently and firmly into the continent's economy and society' among other objectives (UNECA, 2011). The adoption of the EMDP and AMV reflected, and in other cases influenced, efforts and initiatives in many African countries to optimize local returns to mining sector activities. Increasing local procurement became one of key measures resource-rich countries adopted to increase the benefits to their economies from resource extraction, beyond securing optimal rents (royalties, taxes, shares, and other revenues) (AU and UNECA, 2011; Amoako-Tuffour, Aubyn, and Atta-Quayson, 2015). Although mining laws have historically required that preference must be given to local goods and services, they were largely not enforced. Over the past decade, however, there have been further regulatory provisions to enhance local procurement of goods and services in countries such as Burkina Faso, Ghana, Mali, Guinea, Senegal, South Africa, Tanzania, Zambia, and Zimbabwe.

Ghana's local procurement regulations in the mining sector (primarily Legislative Instrument 2173) were adopted in 2012 as part of six regulations approved by the government to give further meaning and support to the enforcement of the 2006 Minerals and Mining Law (Act 703). In the 2006 mining law, and its 1986 predecessor, there are provisions that prescribe for mining companies, in the conduct of their operations, to prioritize employment of Ghanaians and utilization of local goods and services. While mining companies prioritized employment of Ghanaians[2] as prescribed by the law, the situation with utilization of local goods and services left a lot to be desired. A report published by the World Bank, it is indicated that 'despite existing capacity and the potential to create further capacity ... there is limited participation in mining supply chains by companies based in West Africa' and called on governments in the region 'to set the appropriate policy and regulatory contexts to encourage local procurement' in the mining sector' (World Bank, 2012, pp. viii-ix).

This paper is a follow-up from an earlier assessment on Ghana's approach to local content and value addition in both the mining and oil and gas sectors (Amoako Tuffour *et al*., 2015) and a more elaborate technical report on local content and value addition in Ghana's mining and oil and gas sectors by Atta-Quayson (2017) under the auspices of the African Centre for Economic Transformation's Africa-wide Local Content and Value Addition in Minerals, Oil and Gas Sectors project. Subsequent to these two reports, the author has critically followed developments in Ghana and on the continent regarding local procurement in the mining sector and engaged various stakeholders on the matter, providing the motivation for this paper. By focusing on the mineral sector alone, the paper aims at providing a more in-depth assessment of how the 2012 local procurement regulations and related initiatives have been implemented so far. With the benefit of additional implementation years, this paper seeks to assess if the country is making good progress and what measures will be needed going forward to sustain the progress made. The current work thus contributes to the literature on local content and local procurement by analysing further institutional data and interviews, leading to actionable measures and policy recommendations that can help improve Ghana's local content and procurement initiatives.

[2]This notwithstanding, the Ghana Mineworkers Union has raised concerns about the widening gap in emoluments between what is paid to local workers and expatriates, even for equal work done. The Union has also expressed misgivings about growing casualization of workers in the industry.

Research methodology

The epistemological objective of this study is to analyse the implementation of local content and local procurement regulations and related initiatives in Ghana in order to contribute to the growing literature on local content and local procurement; as well as offer novel recommendations to deepen linkages between the mining sector and other sectors of the economy. A mixed methods approach, comprising both quantitative and qualitative techniques, was therefore adopted for the study making use of both primary and secondary sources of data. Primary data was gathered using semi-structured interviews with key stakeholders in the minerals sector in person, by phone, and via email. Two rounds of interviews were conducted with representatives of mining companies, supply service providers, state regulatory agencies, NGOs, and academics. The first round took place in 2015/2016 as part of an Africa-wide eight-country project to compare local content in the minerals and oil and gas sectors undertaken by the African Centre for Economic Transformation (ACET). The other round of interviews with stakeholders was undertaken in 2019. The secondary sources of data relied on include journal articles, news articles, policy documents, laws, company reports, annual performance of mining sector reports by the Ghana Chamber of Mines (GCoM), the Minerals Commission's 2019 annual report, and institutional data among others. Following the analysis of the performance of the mining industry in relation to local procurement, the approach to local procurement in the oil and gas sector as well as successes chalked is briefly presented as a basis of identifying actionable measures and policy recommendations to improve local procurement in the mining sector.

Overview of the mining sector in Ghana

Ghana is endowed with a wide range of mineral resources such as gold, bauxite, manganese, diamonds, iron ore, clays, salt, kaolin, mica, colombite-tantalite, chromite, silica sand, gravel, stone, quartz, and feldspar (Minerals Commission, 2014; USGS, 2016). The country's focus has been on traditional minerals (gold, manganese, bauxite, and diamonds), led by gold which has accounted for over 90% of mineral revenues and over a third of export revenues for two decades since the mid-1990s. In many African countries, including Ghana, pre-colonial and post-colonial mining have been undertaken largely by foreign capital and focused on a narrow range of minerals that serve as raw materials for western countries (Organization of African Unity, 1980). Consequently, mining has historically been undertaken largely as an enclave activity with few linkages to other sectors of the economy (Bank of Ghana, 2003; Larsen, Yankson, and Fold, 2009). During the mining sector reforms in Ghana and other developing countries (as part of the ERPs/SAPs), the World Bank advised African countries to focus on 'maximizing tax revenue from mining over the long term, rather than pursuing other economic or political objectives' (World Bank 1992, p. x). Consequently, the colonially-created mining regimes that perpetrate enclave mining have largely remained in Africa (AU and UNECA, 2011). Data on mining activities in Ghana mostly concerns traditional minerals, making an assessment of the sector's role and contribution to the economy usually focused on these minerals. Furthermore, available institutional data exists only for variables such as total production, foreign exchange earnings or export receipts, government revenues obtained from the sector, employment, and broad levels of local spend (irrespective of where these goods and services are produced). In 2020 Ghana produced 4 million ounces of gold[3] (down from 4.6 million ounces in 2019), 2.4 Mt of manganese[4] (a decline by 56.2% from the 5.383 Mt produced in 2019), 25 292 carats of diamonds[5] (down from 33,789 carats in 2019), and 1.162 Mt of bauxite (up from 1.116 Mt), contributing 7.5% per cent to Ghana's GDP (Ghana Chamber of Mines 2021). The mining sector's contribution to domestic revenue (primarily through corporate income taxes, mineral royalties, and employee income tax) increased marginally from GHC4.013 billion in 2019 to GHC4.172 billion in 2020, constituting 18.1% (*ibid*.) in 2020. Proceeds from exports of minerals amounted to US$6.998 billion (up from US$6.678 billion in 2019) and accounted for 48.4% of merchandise exports in the year (*ibid*.).

According to the GCoM, the total expenditure on non-energy goods and services procured by member companies from in-country suppliers and manufacturers amounted to US$2.7 billion in 2020, while their spend on consumables directly imported by the mines, as well as capital expenditures, amounted to US$194.2 million and US$450.4 million respectively in 2020 (Ghana Chamber of Mines, 2021). While a relatively substantial amount is spent on goods and services procured locally, many of these goods and services are imported. In 2020, members of the Chamber of Mines directly employed 8760 workers (down from 10 109 in 2018 and 20 268 in 2012), most of them Ghanaians (Ghana Chamber of Mines, 2021, 2019). The fast-dwindling direct employment in the sector is a result of staff retrenchments and increasing casualization of employment occasioned by miners such as AngloGold-Ashanti, Goldfields Ghana Limited, and Golden Star Resources over the period. In 2020, producing members of the Chamber engaged 25 603 contractors or casual workers (Ghana Chamber of Mines, 2021), more than three times the number directly employed. The resort to staff retrenchment and casualization has been protested (often violently) by workers, the Ghana Mineworkers Union, and other civil society organizations. Casualization affects not only quality of work, remuneration, and security, but also government revenues.

The relatively low level of contribution by the minerals sector to the GDP (7.5% in 2020) and employment raises concerns of ordinary Ghanaians as well as the government as far as developmental benefits from the mining sector are concerned (Atta-Quayson, 2017). Even though GCoM asserts that the sector's contributions to taxes and foreign exchange are on the high side, the government differs in opinion. In May 2018, the Vice President indicated that the country obtains little benefit from its mineral wealth and called for a review of the mining fiscal regime[6], expressing surprise that the country had earned almost nothing in dividends since 2012 from its 10% stake in most mines (Dontoh, 2018). The Vice President also noted that 'we have now begun conversations about the process of making sure every single bar of gold leaving our shores is *properly weighed, tested, valued and accounted for*', adding that the government was considering a legislation that requires at least 50% of annual gold output to be refined locally within five years (emphasis added) (Kpodo, 2018). The Minister for Mines' remarks when announcing planned special audits of mining operations in the country also highlight widespread discontent among the populace and government over the benefits that accrue to the country from mining.

> '*The mining sector is an important contributor to the economy of this country but we have been short-changed for a long time now. As a government, we feel strongly that our royalties, taxes and rents have not been properly recorded and accounted for, so we are going to do an audit of all companies that engage in mining to be able to determine the real picture on the ground to be able to reverse this ugly trend*' (Ngnenbe, 2018).

The case with foreign exchange earnings is no different. Cognizant of the imperative on the part of mineral right holders to service loans, pay dividends, and procure inputs and equipment, Section 30 of the Minerals and Mining Act of 2007 (Act 703) allows mining companies to retain a percentage of their export revenues in offshore accounts to meet these exigencies, for which foreign exchange 'would otherwise not be available without the use of the earnings'. The exact percentage to be retained offshore must be negotiated, but the law requires that it should not be less than 25% and therefore can go as high as 80% (for most companies) and previously pre-negotiated 100% for companies with development agreements such as Newmont. In lieu of this, only a fraction of mineral export revenues are returned to Ghana and for the year 2020 the Chamber of Mines reported that its producing members returned 71% cent of their revenues to Ghana (Ghana Chamber of Mines, 2021). In 2013, the Public Accounts Committee of Parliament expressed shock during a public hearing that on average mining companies retain 80% of their export revenues in offshore accounts (Arku, 2013) . While the GCoM disputed the claim, concerns about the foreign exchange retention policies in the mining sector continue to linger.

Local procurement: Conceptual and analytical framework

The idea and importance of local procurement can be linked to the generalized approach to linkages theory by Hirschman, which promotes industries with strong interdependence or linkages to other sectors of the economy (Hirschman, 1958, 1977). Linkage in this context was defined as 'investment generating forces that are set in motion, through input-output relations, when productive facilities that supply inputs to that line or utilize its outputs are inadequate or non-existent' (Hirschman, 1977, p. 72). Though historically the mining sector has not had sufficient linkages to other sectors of the economy, resulting in the enclave characterization of the sector or the enclave thesis (Bloch and Owusu, 2011; Hanlin 2011), there has been strong interest in this area by resource-endowed countries over the past decade, focusing mainly on local procurement. The World Bank, in collaboration with West African governments and players in the mining industry, produced an analytical framework for assessing progress in expanding local procurement in the mining sector (World Bank, 2012).

The framework categorizes suppliers of goods and services to the mines based on four key factors: participation of citizens (in ownership, management and employment of supplying

[3]The large-scale sub-sector contributed 2.847 million ounces (representing a drop by 4.8% from the 2019 level) while the small-scale sub-sector contributed 1.175 million ounces (down from 1.588 million ounces in 2019) (Ghana Chamber of Mines, 2021)

[4]The decline was due to a directive by the government to the only firm that produces manganese to stop operations, which led to suspension in production in the first quarter of 2020 (*ibid*.).

[5]Production of diamonds by the only large-scale producer has been on suspension (*ibid*.)

[6]In 2011 the government reported in its 2012 budget statement that recent studies revealed that the country loses about US$36 million each year through transfer pricing (Government of Ghana, 2011). The GCoM disputed this claim. Transfer pricing regulations have since been passed but non-availability of regional prices of goods and services impedes implementation of the regulations. The budget statement further noted that even though gold prices reached their peak levels ever in recent times, the country did not benefit at all from the price hikes (*ibid*.).

firms), extent of value add that take place locally, proximity of the supplying firm to the mine, and the size of the supplying firm (Figure 1).

Optimizing developmental returns from mining and local procurement/content policies in Africa

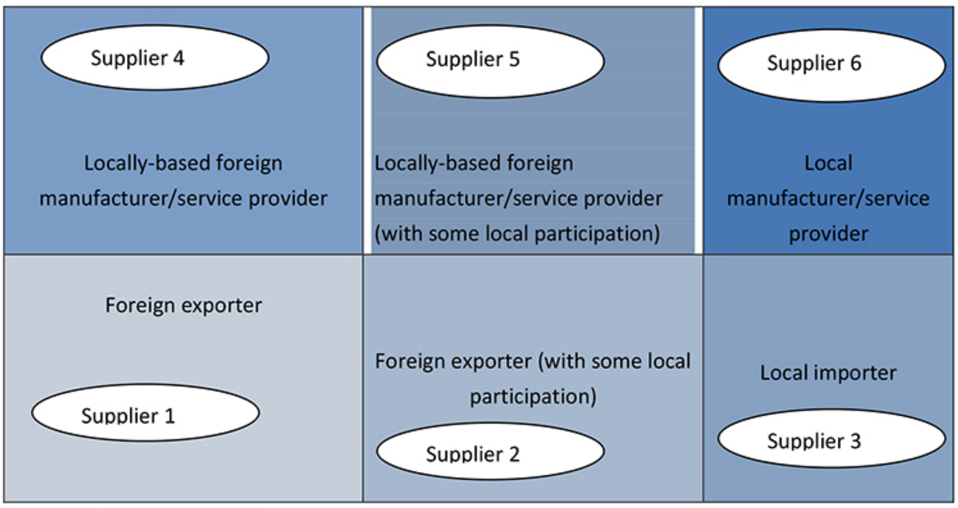
In the aftermath of the first boom in commodity prices in the 21st century (Conceicao and Marone, 2008) which eased following the World Economic Crisis in 2008, there has been a marked rise in the adoption of local procurement and local content policies and regulations in resource-dependent developing countries. Characterized as 'the greatest commodities boom in recent history' (Conceicao and Marone, 2008, p. 2), it was fuelled by strong demand by China and other emerging countries, spanning a longer period and affecting more commodities. In the process, it raised awareness among governments and citizenry on the insufficiency of developmental returns that accrue from the exploitation of their resource endowment. In Africa, the UNECA and AfDB organized what they described as the 'Big Table' in 2007[7] to discuss how to enhance the developmental benefits from the exploitation of natural resources (especially mineral resources) on the continent. This was followed by a Ministerial Conference in 2008 which adopted the Africa Mining Vision (AMV) and affirmed 'commitment to prudent, transparent and efficient development and management of Africa's mineral resources to meet the MDGs, eradicate poverty and achieve rapid and broad-based sustainable socio-economic development' (AU and UNECA, 2011, p. 5).

At the heart of the AMV, adopted by AU Heads of State and Government in February 2008, was the need to the transform the mining sector from 'colonially-created enclave features' by 'integrating the sector more coherently and firmly into the continent's economy and society' (AU and UNECA, 2011, p. 9). Among the various strategies offered by the AMV in pursuit of its objectives is the optimization of mineral-based linkages through local procurement and local content policies and regulations. Since the adoption of the AMV, regional blocs and mineral-rich countries have taken steps towards the transformation of operative mining regimes with the aim of optimizing the developmental benefits through the design and implementation of local procurement and local content policies and regulations, among others.

The Economic Community of West African States adopted the ECOWAS Minerals Development Plan (EMDP)[8] in May 2011 in line with the AMV and which sought to, among other things, support Member States to adopt local procurement and local content policies as a means of increasing local procurement of goods and services, technology transfer, and development of local entrepreneurship. About a decade prior to both the AMV and EMDP, the Southern African Development Community (SADC) had developed in 1997 a regional mining protocol which came into force in 2000 and sought, among other things, to share information among member countries and enhance the technological capacity of the mining sector. In 2006, the SADC was supported by the UNECA to develop a framework to harmonize mining policies, standards, legislative and regulatory instruments within the region.

Following the adoption of the AMV, the University of Cape Town and the Open University implemented the Making the Most of Commodities Programme (MMCP). The MMCP produced about a dozen working papers that described the state of affairs regarding linkages between the commodities sector (copper, diamonds, gold, oil and gas, mining services, and timber) and the local economies in eight African countries (Angola, Botswana, Gabon, Ghana, Nigeria, South Africa, Tanzania, and Zambia) (Kaplinsky, Morris, and Kaplan, 2011; Morris, Kaplinsky, and Kaplan, 2012). Although the MMCP sought to challenge the 'enclave thesis' and the 'negative view of the commodities sector' on the continent, most of the papers produced rather affirmed the weak linkages and poor developmental returns that accrue to African countries from the exploitation of their natural resources. One of such papers which focused on the entire continent

[7]The Big Table was a meeting of ministers and senior officials from 11 mineral-rich African countries and representatives of the African Union, among other experts.
[8]The adoption of the ECOWAS Minerals Development Policy followed an adoption of the ECOWAS Directive on the harmonization of guiding principles and policies in the mining sector in 2009, which also called on Member States with local content relevant sections.



Source: World Bank (2012)

Figure 1—Local procurement analytical framework

concluded that local suppliers are seldom used, resulting in non-development of an indigenous service and supply sector to any significant extent outside of Ghana and South Africa (Hanlin, 2011). The author cites, among other reasons, the multinational nature of extractive companies operating in Africa and the endemic systems existing in these companies that predetermine procurement routes as responsible for the situation, effectively excluding the relatively well-developed South African mining service sector from engaging in a significant proportion of the procurement process (*ibid.*).

The MMCP concluded that 'policy in both the private and public realm was a prime factor holding back the development of linkages' and in order to deal with the problem required the closing of three sets of misalignments between policy and practice: within the corporate sector, within the public sector, and between the public and other stakeholders involved in linkage development (Kaplinsky, Morris, and Kaplan 2011; Morris, Kaplinsky, and Kaplan, 2012). The authors further identify and discuss three contextual factors that influence the breadth and depth of linkages: ownership, infrastructure, and capabilities. A couple of years following the implementation of the MMCP, the African Centre for Economic Transformation undertook an eight-country (Burkina Faso, Ethiopia, Ghana, Mozambique, Namibia, Nigeria, South Africa, and Zambia) comparative study on local content in the mineral and oil and gas sectors, focusing on trends in company responses to emerging policies and regulatory frameworks (African Centre for Economic Transfromation, 2017). The study observed that among the eight countries Nigeria and South Africa had pursued with varying success local content and value addition longer than the other countries. Using a four-pillar definition for local content, it was found that while all study countries had requirements in place for local procurement and employment, only a few had requirements for local ownership (usually via the state) and use of local financial institutions.

Local procurement policies and regulations in the mining sector are not an entirely new phenomenon. The Provisional National Defence Council Law 153 of 1986 had a provision with the title 'Preference for local products and employment of Ghanaians' which require mining firms to give preference in employment of Ghanaians, materials and products made in Ghana, and service agencies located in Ghana, 'to the maximum extent possible and consistent with safety, efficiency and economy'. However, these first-generation local procurement provisions in the mining sector could not either be effectively enforced or yield the desired outcome for various reasons. For example, in Ghana, the same law which had local procurement provisions also provided exemptions from import duties and other taxes on imported products and materials required for mining operations. Coupled with a weak manufacturing sector and economy-wide challenges (relating especially to infrastructure, technology, and finance), it is understandable why first-generation local content provisions could not be enforced or produce expected outcome.

Over the past decade, a new generation (second generation) of local procurement policies and regulations has emerged as a means of optimizing developmental returns from mining by way of expanding and deepening linkages between mining and other sectors of mineral resource-rich economies. Thanks to the two main factors that have contributed to their emergence – a poor record relating to the enclave thesis of mining industry and lopsided benefit-sharing regimes in favour of largely foreign mining firms (ACET, 2017) – the second generation of local procurement policies and regulations seem to have found favour with mining companies and better prospects. The AMV, which has been influential in these policies and regulations, has been widely and openly welcomed by mining companies who have pledged their commitment to its realization. In February 2016, an African Mining Vision Compact was forged between industry and African governments on the sidelines of the 2016 'Investing in African Mining Indaba' in South Africa (Kotze, 2016) . Given that local procurement is at the heart of the AMV, the gesture illustrates favour with the industry, which is interested in improving its image. While this is welcome and necessary for the success of the second-generation of local procurement policies and regulations, it is not sufficient. What is needed is regular assessment of how the secondgeneration local procurement policies and regulations are being implemented, continuing challenges, and how best to resolve them.

In the last few years, there has been a growing interest in and focus on how these policies and regulations have been designed and implemented, bringing to the fore a number of issues and perspectives that affect their success. Kragelund (2017) offers an assessment of local content policy implementation in Zambia focusing on relevant policies at the macro-, meso-, and micro-level, noting the limited effect of these policies due to poor alignment with the broader legal practices in the sector. The study further identifies a lack of clear definition of local content, voluntarism, inclusion of a small proportion of mines and suppliers, and inadequate support of political and economic elites in the country (Kragelund, 2017). Kragelund (2020) further illustrates how efforts by the Zambian government to rank higher on the Doing Business Indicator has influenced the government policies that are inimical to broadening and deepening linkages through the implementation of local content policies in the mining sector. The study further identifies an imbalanced power relationship in favour of multinational mining companies against the Zambian state, which weakens the state's bargaining power when negotiating terms of investment agreements (Kragelund, 2020).

In a two-country case study involving Ghana and the Democratic Republic of Congo (DRC), Geenen (2019) challenges two mainstream assumptions about local content literature regarding creation of production linkages following the provision of an enabling environment by the state and the thinking that local content is beneficial for local people. The study finds that power holders use local content as political instruments to enhance accumulation of profits and control of resource rents, citing the complex political circumstances within which these policies are implemented (Geenen, 2019). In the two countries, employment opportunities and contracts were found to have been handed to political elites unfairly and largely as a means to winning local legitimacy, gaining a social license to operate, and compensating for environmental pollution. Such a phenomenon, though unfortunate, inimical to local content policies, and needing to be addressed, is not surprising as it reflects the widespread patronage and competitive clientelist political settlements that characterize many developing countries, including Ghana and the DRC.

Greenen's (2019) study further reflects the considerable potential for corrupt practices in the pursuit of local content. Similar findings have been made by Kalyuzhnova and Belitski (2019) who demonstrate, using an econometric approach, that implementation of local content policies in Kazakhstan facilitates corrupt behaviour. The dangers of corrupt behaviour in the pursuit of local content are discussed by Lima-de-Oliveira (2020) using the Petrobas scandal as a case which involved billions of dollars in kickbacks and resulted in the country's wealthiest businessmen and former politicians such as the former president, former speaker of parliament, former finance minister, and former governor of Rio de Janerio being jailed. The study finds that following the revelation of the corrupt behaviour associated with the country's implementation of local content policies, many of the local content-related programmes and requirements have either been dismantled or severely cut since 2017 (Lima-de-Oliveira, 2020).

Despite the concerns with corruption as discussed above, there is a glimmer of hope as initial findings from the implementation of local content in Ghana's oil and gas sector have been largely positive and demonstrative of the potential of local procurement initiatives. Ayanoore (2020) demonstrates that a resource nationalist government can effectively collaborate with pro-local content elites to establish strict local procurement targets and effectively enforce them to broaden and deepen linkages between the oil sector and the broader Ghanaian economy. At the heart of this feat was the institutionalization of the Local Content Committee made up of a range of stakeholders united by the need to achieve greater local content targets in the oil and gas sector (Ayanoore, 2020). By the end of 2016, just about three years from the passage of local content and local participation regulations, the government reported high local participation among the four categories of firms in the upstream value chain defined by the law: primary contractor, tier 1 subcontractor, tier 2 subcontractor, and tier 3 subcontractor. Despite the high financial and technical requirements of the primary contractor and tier 1 subcontractor categories, the government 'lobbied' IOCs to pre-finance 5% participating equities of local firms (leading to the establishment of 10 E&P equity partnerships between IOCs and Ghanaian firms) while 87 local firms were engaged in joint ventures by international service companies. The other two categories, requiring lower financial and technical capabilities, were dominated by Ghanaian companies (Ayanoore, 2020).

Overview of Ghana's local content and procurement regulations and other initiatives

Ghana's Minerals and Mining Policy calls for the promotion of 'linkages (backward, forward and side-stream) to minerals produced in the country to the maximum extent possible' (Government of Ghana, 2015). In 2012, Ghana's parliament adopted a set of six regulations 'to give meaning' to a law passed six years earlier. Among these regulations were three that are related to local content in the mining sector: Minerals and Mining (General) Regulations, 2012 (LI2173), Minerals and Mining (Support Services) Regulations, 2012 (LI2174), and Minerals and Mining (Licensing) Regulations, 2012 (LI2176). Whereas the general regulations (LI2173) remain the key local procurement regulations, the support services regulations (LI2174) and licencing regulations (LI2176) have some consequences for local content in the mining sector. The licensing regulations enforce key aspects of the general regulations on various prospective licensees, such as their proposals regarding procurement of local goods and services and the employment and training of Ghanaians in the mining industry.

The support services regulations, on the other hand, outline procedures for registering with the Minerals Commission as mine support service providers, classify mine support service providers into two categories (A and B), and stipulate benefits available to registered service providers. While class A mine support services are open to both Ghanaians and non-Ghanaians, Class B mine support services are reserved exclusively for Ghanaians. Class A support services are much broader and deeper in terms of linkages to the mining sector than Class B (Table I). The support services regulations offer different benefits or concessions to the two categories of service providers. Class A providers are eligible for concessionary (lower) import duties in respect of importation of mining inputs or items on the Mining List[9], immigration quotas in respect of expatriate personnel (this also applies to mineral right holders), and receipt of payment for services rendered in foreign

Table I

Comparison between Class A and Class B mine support services

Class A mine support services	Class B mine support services
Contract mining services: topsoil and waste removal, drilling and blasting, excavating and haulage of ore to plant on turnkey basis	Contract mining services for small-scale mining: mining and processing of ore, reclamation, revegetation, management of operations
Mining and ancillary construction services or civil works such as construction of heap leach pads, haulage roads, tailings storage facilities, and water storage facilities.	Haulage services to and from mine sites, including the transportation of personnel
Assay laboratory services	Other mining services specified by the Commission such as health care, air haulage, catering or camp management, and security services
Drilling and blasting services	
Mining consultancy services	
Mining exploration services	
Supply of mining equipment and spare parts	
Fabrication of equipment and manufacturing of components and consumables such as explosives, hydraulic components, activated carbon, sodium cyanide, and lime	
Other mining services specified by the Commission such as health care, air haulage, catering or camp management, and security services	

Source: Minerals and Mining (Support Services) Regulations, 2012 (LI2174) currency, subject to the Commission's recommendation and the central bank's approval. The only benefit or concession available to Class B providers is the receipt of payment in foreign currency, subject to the Commission's recommendation and the central bank's approval.

The general mining regulations represent the main local content requirements in the mining sector. The relevant sections of the regulations are contained in the first two sub-regulations and focus on recruitment of expatriates and employment and training of Ghanaians as well as local procurement of mining inputs. Among other prescriptions related to employment of Ghanaians, mineral right holders, support service providers, and licensees to export or deal in minerals are required by the regulations to develop a 5-year renewable plan to be approved by the Commission that spells out recruitment of expatriates and employment and training of Ghanaians to replace expatriates. The second sub-regulation of the general regulations deals with procurement of goods and services with Ghanaian content to the maximum extent possible subject to efficiency, safety, and economy. This requires that the 5-year procurement plan, renewable annually (to deal with possible changes in the procurement list, if any), is submitted within a year of passage of the regulations or commencement of operations for approval by the Commission.

The procurement plan must address the following three things: the targets for local procurement of items on the procurement list, prospects for local procurement, and specific measures or support to providers or suppliers to 'develop the supply of local goods and services'. The Commission shall make available a procurement list with goods and services with Ghanaian content that must be procured in Ghana. There is no definition of Ghanaian content in the regulations and the goods and services on the procurement list need not be locally produced. However, the sub-regulation mandates that in assessing tenders for items on the procurement list, bids with the highest level of Ghanaian participation (based on ownership and management) shall be selected where bids are within 2% of each other by price. There are reporting requirements and sanctions involving payment of full customs import duty to the Commission for items on the procurement list that are directly imported. Further, there is a fine of US$10 000 for each month of the first two months of non-compliance in terms of obtaining approval of the procurement plan, and subsequently the same amount per day that the breach continues.

In 2011, the International Finance Corporation (IFC), Minerals Commission (MC), and GCoM entered into an MoU to develop a NSDP. Three years thereafter, the NSDP was designed as a three-year intervention programme aimed at building the management and technical capacity of 35 local suppliers in the mining supply chain in order to increase their participation in the mining industry. It is, however, unclear if the NSDP was implemented. In November 2017 the Africa Minerals Development Centre (AMDC), ACET, and Hanover-based German Institute for Geosciences and Natural Resources (BGR) jointly held a two-day workshop in Accra during which another National Suppliers Development Programme was launched by the Vice President of Ghana. Led by the AMDC, this NSDP seemed different from what had been contemplated earlier by the IFC, MC, and GCoM. Again, it is unclear if this NSDP is being implemented. Despite the GCoM's involvement in these efforts, on 3 July 2020 it put out a call for proposal seeking to recruit a consultant to develop a framework and strategy for positioning Ghana as a hub of mining support services in the sub-region by exploring means of supporting firms in Ghana to provide competitive and quality goods and services to the mining industry. This raised questions about the two versions the NSDP earlier contemplated in the country.

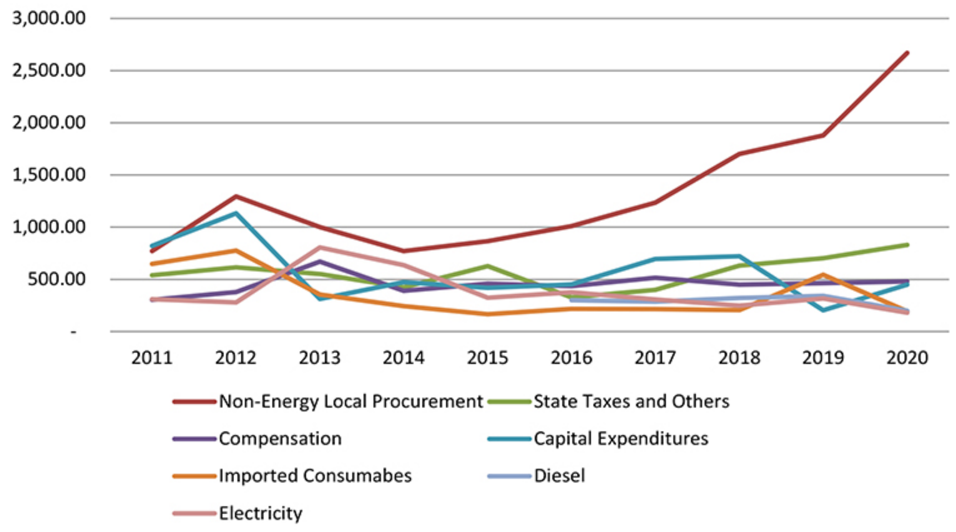
Influenced largely by the need to compensate for negative externalities, create a positive image in the eyes of catchment communities, and obtain a social license to operate (Atienza, Arias-Loyola, and Lufin 2020; Nwapi 2015) rather than a deep-seated motive to broaden and deepen linkages, almost all mining companies operating in Ghana have created programmes or initiatives that seek to ensure that catchment communities are given preference in employment and procurement of goods and services. As signature programmes or initiatives of mining companies, they differ from one company to the other in terms of scope and depth.

Local procurement in the mining sector: Is Ghana swimming with the tide?

This section presents and analyses trends in local procurement of goods and service by the mining industry in Ghana following the 2012 adoption of the general regulations, that were updated with the local content and local participation regulations in 2020. Arguably, local procurement of goods and services (especially those produced in-country and largely by the citizenry) holds the largest potential for broadening and deepening linkages between the mining sector and other sectors of the economy in Ghana and therefore enhancing the contributions of mining to inclusive growth and development. In 2020, producing members of GCoM spent $2.67 billion (about 51.93% of mining revenues) on local procurement of goods and services. Out of this amount, $198.95 million and $180.40 million were spent on diesel and electricity respectively while expenditures on imported consumables and capex stood at $194.18 and $450.39 respectively (Ghana Chamber of Mines 2021). This compares with $830.2 million and $479.7 million spent on statutory payments to the state (taxes and workers' pension payments) and workers' salaries in 2020, respectively (*ibid*.).

In relation to emoluments, there is deep-seated concern about wide disparities and inequalities in the mining industry as the top 10% of the staff population was recently reported to be earning about half of overall basis salary while a few expatriates and management staff earn about two-thirds of mining industry's wealth (Ankrah *et al*., 2017). An earlier report citing a study by the Ghana Mineworkers Union also indicated that 90% of mineworkers' share of wage income is less than 10% of that of the highest paid staff (Ghana News Agency, 2015). It is, however, generally believed (and flowing from Hirschman's linkages theory) that spending on locally produced goods and services tends to create greater multiplier effects than spending on statutory payments and salaries. In light of this, the analysis that follows will focus mainly on procurement of goods and services by mining companies. Figure 2 shows the trend in the major categories of expenditure that mining companies make in the course of their operations.

[9] The Mining and Minerals Law offers exemptions to mineral right holders from payment of import duties in relation to importation of plant, equipment, and mining consumables that are provided on the Mining List. The regulations extend similar concessions to Class A providers, but not to Class B.



Source: Ghana Chamber of Mines

Figure 2—Trends in major expenditures by mining companies (thousand US$)

Table II

Data on procurement of items on the procurement list, 2014

Product	2014			2015		
	Total procurement (US$)	% locally procured	% locally produced	Total procurement (US$)	% locally produced	% locally produced
Grinding media	67 947 404.46	49.46	44.19	62 283 571.00	45.16	28.73
Electrical cables	2 292 580.52	60.55	7.53	1 350 579.89	70.30	36.13
HDPE/PVC pipes	5 010 304.67	100.00	98.50	9 767 869.65	99.82	99.57
General lubricants	12 641 802.22	97.30	97.30	11 221 521.45	97.40	97.40
Quick/hydrated lime	30 236 784.40	100.00	100.00	21 812 497.94	100.00	100.00
Tyre retreading	1 441 519.40	100.00	100.00	751 665.99	100.00	100.00
Explosives	60 668 569.92	100.00	100.00	63 289 945.58	100.00	100.00
Cement	3 585 735.09	100.00	100.00	769 572.00	100.00	100.00
Total	183824700.7	80.64	77.99	171 247 223.50	79.64	73.38

Author's compilation based on Minerals Commission data (Minerals Commission 2020)

For Ghana, the vision is to ensure that as much as possible of the $2.67 billion spending on locally procured inputs in 2020 is actually made on goods and services (excluding diesel and electricity) that are produced locally and meet some level of 'Ghanaian content' as far as ownership, management, and general staffing of the producing firms are concerned. This was the vision of the government of Ghana when, in 2012 and 2020, relevant regulations were passed to promote job creation through the use of local expertise and products (local goods and services) in the mining industry value chain (Government of Ghana, 2012, 2020). In accordance with the general regulations, the Minerals Commission published the first procurement list with eight items in 2013. The performance of the industry regarding these items in 2014 and 2015 is presented in Table II. Out of the almost US$184 million total spend on items on the procurement list in 2014 (this is less than a quarter of total expenditures incurred by mining companies on local procurement of non-energy goods and services, which amounted to about US$771 million), US$148 million worth of those items was obtained from in-country suppliers and manufacturers, with US$143 million (78% of total spend) on locally manufactured goods. And out of US$171 million total spend on items on the procurement list in 2015 (which is less than a fifth of total spend by miners on local procurement of non-energy goods and services which amounted to US$866 million), about US$136 million of items were procured locally, out of which US$126 million worth of items (representing 73% of total spend) were locally produced.

The data on grinding media and electrical cables deserves some comment. In 2015, the country's installed capacity for producing grinding media could meet about half of industry demand. One of the three local manufacturers was in the process of adding a third plant in order to double installed capacity and be able to manufacture other sizes and specifications of grinding media to meet the requirements of other miners. With that expansion, local manufacturers could meet all the demand in the sector. In interviews two producers expressed concern about power (not regularly available and expensive) and payment of import duties and other taxes on importation of steel bars used in producing grinding media, whereas mining companies are exempt from paying import duties and related taxes when directly importing grinding media. They called for incentives (such as export subsidies) to enable them to maintain the local market and increase exports (which had been started by those local producers on a small scale).

Regarding electrical cables, the country has world-class producers – Tropical Cables and Conductors Limited and Nexans

Cables and Metals Limited. Yet mining companies have been very reluctant to source their electrical cables from these producers for various reasons. Electrical cables are very critical inputs, and engineering firms that construct mining plants often recommend particular specifications and brands. This makes it difficult for mining firms to ignore the advice of consulting firms with respect to electrical cables. Furthermore, even when mining companies want to try locally produced electrical cables the classifications (and specifications) make it difficult to buy from producers. For example, an electrical product with a particular specification can be classified differently by different producers in Ghana. This also presents a challenge to the mining companies when considering procuring electrical cables from local sources. The challenge regarding the use of local electrical cables by mining companies reflects lack of urgency and weak coordination among key state agencies (such as the Minerals Commission and Standards Authority). However, the GCoM has since taken steps to address the challenge by facilitating various meetings involving local producers of electrical cables, mining companies, and other state agencies such as the Standards Authority to address pertinent concerns including development of related standards.

In 2015 the procurement list was revised to include an additional 11 items, bringing the total to 19. The 2015 edition also stipulated penalties (5% for all items except electrical cables, which attracted 10% penalty) to be paid by mining companies who import these products. Instead of the penalty, some of the local producers interviewed suggested that those items should be removed entirely from the mining list. The list contains items that are exempted from import duties and related levies and charges. This has been identified as a major impediment to the expansion of local production for the mining sector. The performance of the industry is presented in Table III. In the year 2018, the total spend on procurement list items amounted to $426 million, which was about a quarter of the industry's total in-country purchases of goods and services (excluding diesel and power), which amounted to $1.702 billion in that year. Out of the total spend of $426 million on the items on the procurement list, $394 million (representing 92.4%) was procured in-country while $252 million (representing 59%) was spent on locally manufactured inputs.

The inclusion of 11 additional items reduced the proportion of inputs locally produced on the procurement list for the mining industry from 80% and 73% in 2014 and 2015 respectively to 52%, 64%, and 59% in 2016, 2017, and 2018 respectively. In terms of value, six items are very important and make up about 97% of the total spend on procurement list items. These are grinding media, general lubricants, quick/hydrated lime, explosives, haulage services, and catering services. As regards haulage services, for example, the industry spends an average of US$185 million, almost entirely on local services, though less than half of that is offered by local firms while the remaining half represent 'imported' services. With respect to grinding media, local producers met between a third and half of industry demand over the same period. The performance as regards the other four items is excellent, with many of them meeting industry demand fully for most of the years. .

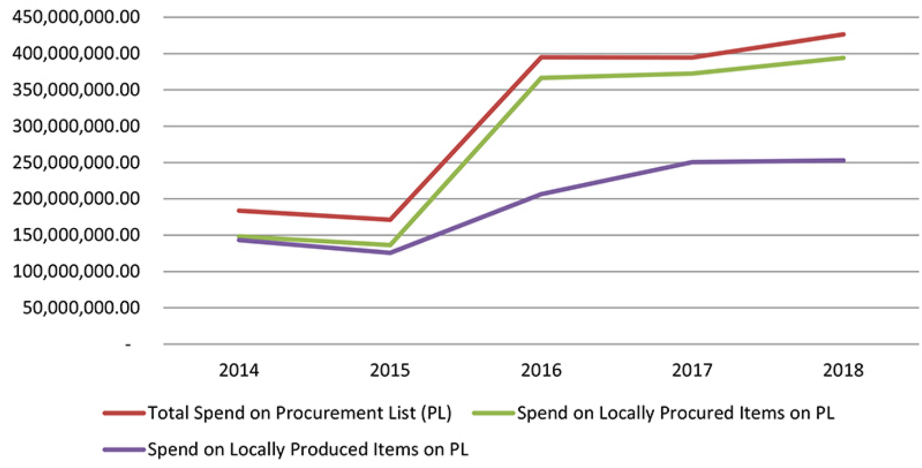
Over the period, it can be observed that the mining industry has acted contrary to the regulations by directly importing items that appear on the mining procurement list. In 2014, for example, $35.6 million worth of items on the list (falling to US$32.4 million in 2018) which should have been procured in-country were imported directly by the mining companies themselves. From Figure 3, it is clear that the mining industry has consistently been directly importing items on the tune of between US$30 million and US$35 million. This notwithstanding, the value of non-energy goods and services procured locally has been growing markedly. While the value of the first eight items hovered around US$180

Table III

Data on procurement of items on the procurement list, 2016-2018

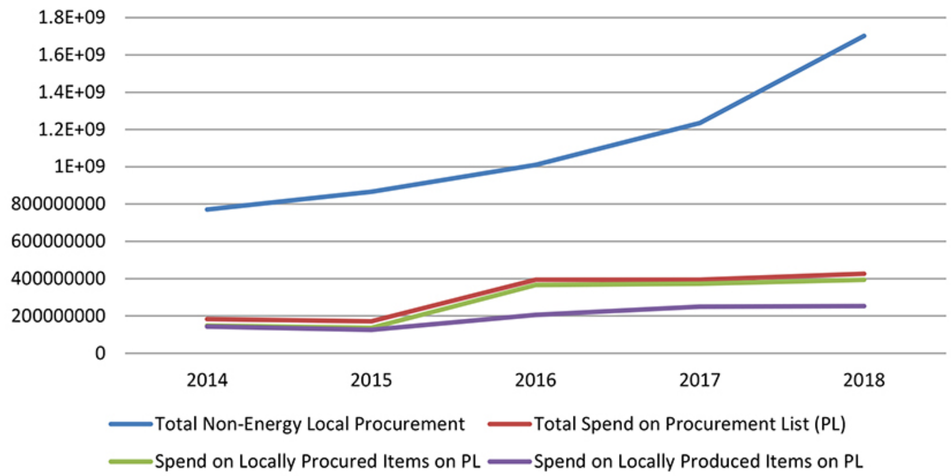
Product	2016	2017	2018						
	Total procurement (US$)	% locally produced	% locally produced	Total procurement (US$)	% locally produced	% locally produced	Total procurement	% locally produced	% locally produced
Grinding media	60 595 146.96	54.30	42.24	63 081 057.10	65.95	43.64	83 058 867.33	61.55	38.50
Electrical cables	1 451 848.79	90.35	73.39	1 778 316.14	91.51	34.42	2 971 025.99	98.63	56.20
HDPE/PVC pipes	5 727 456.35	100.00	99.74	6 593 008.95	100.00	67.80	5 630 022.36	100.00	99.38
General lubricants	13 817 800.04	99.98	99.98	15 473 514.09	100.00	99.73	11 654 523.87	100.00	66.40
Quick/hydrated lime	17 292 271.37	100.00	87.82	15 239 921.16	100.00	86.67	14 838 937.59	100.00	82.62
Tyre retreading	707 735.50	100.00	100.00	678 900.64	100.00	100.00	179 014.23	100.00	100.00
Explosives	79 960 882.70	100.00	100.00	73 890 992.84	100.00	100.00	94 025 915.37	100.00	100.00
Cement	437 340.17	100.00	100.00	445 784.21	100.00	100.00	432 223.71	100.00	100.00
Bolts and nuts	786 676.74	97.32	7.12	874 261.41	97.51	3.24	589 419.18	95.91	0.00
Crucibles	208 570.95	49.38	5.66	230 013.89	39.38	0.04	223 586.93	62.42	20.50
Plastic sample bags	644 404.85	100.00	100.00	565 790.45	100.00	97.62	718 086.44	100.00	100.00
Calico bags	216 769.63	100.00	100.00	194 953.05	100.00	100.00	141 820.68	99.96	99.96
Bullion boxes	7 632.38	73.21	73.21	38 607.57	95.35	95.35	25 361.66	84.34	0.00
Chain link fencing	206 133.83	33.88	6.83	66 187.25	93.35	57.03	169 376.33	33.74	2.27
Conveyor rollers	535 481.62	63.67	61.25	651 712.31	61.10	43.34	748 590.90	78.55	65.03
Metal/PVC core trays	675 687.01	100.00	0.00	846 501.33	92.48	0.00	1 131 392.39	100.00	0.00
Overalls and work clothes	1 021 486.37	99.74	91.02	1,338,148.68	100.00	80.41	972,059.09	100.00	81.61
Haulage services	188 521 099.84	100.00	25.58	190,420,636.74	100.00	50.27	185,943,114.38	100.00	39.72
Catering services	22 026 737.84	100.00	61.85	22,277,883.73	100.00	73.58	23,002,592.62	100.00	100.00
Total	394 841 162.94	92.83	52.31	394,686,191.54	94.40	63.49	426,455,931.05	92.41	59.31

Source: Author's compilation based on Minerals Commission data (Minerals Commission 2020)



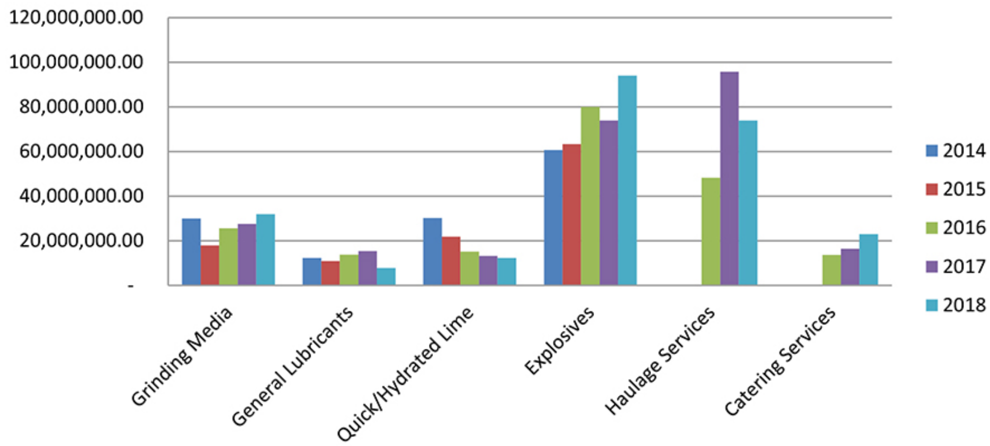
Source: Minerals Commission

Figure 3—Trends in expenditures on procurement list items (US$)



Source: Minerals Commission and Chamber of Mines

Figure 4—Mining industry's total spend on non-energy local procurement and trends in expenditures on procurement list items (US$) Source: Minerals Commission



Source: Minerals Commission

Figure 5—Performance in terms of supply of top six items on procurement list by local manufacturers (US$)

million, increasing to about US$400 million when 11 other items were added to the list, the total spend on non-energy goods and services procured locally by the mining industry has increased from less than US$800 million in 2014 to over US$1.7 billion in 2018 (it reached over US$2.7 billion in 2020), see Figure 4. This raises some concerns and questions about the extent to which Ghana is swimming with the tide of local procurement in the mining sector.

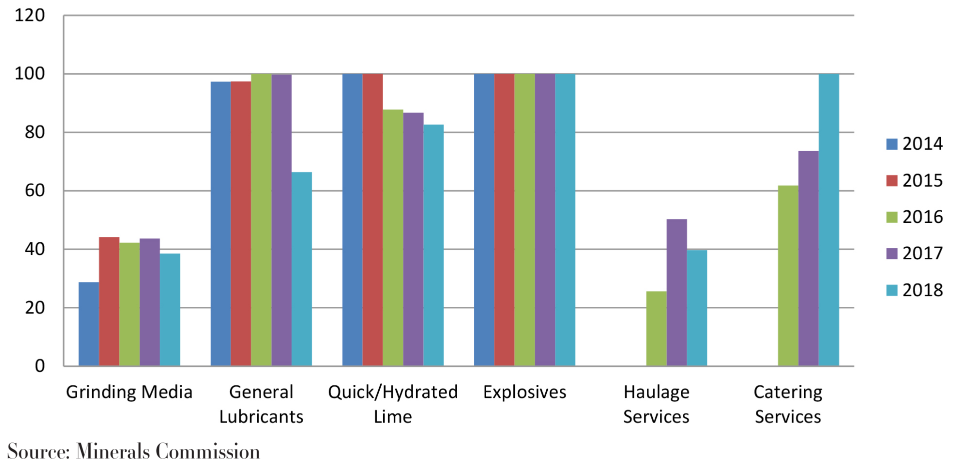


Figure 6—Performance in terms of supply of top six items on procurement list by local producers as percentage of total spend on those items

It is worthy of note that the items on the procurement list are inputs that the country is supposed to have the potential to produce locally, yet locally produced goods and services met less than 60% of the total spend on those items between 2016 and 2018 (and less than 80% in 2014 and 2015). While this does not look bad in general, as grinding media, general lubricants, explosives, and catering services showed an overall increasing trend (Figures 5 and 6), there is some concern with quick/hydrated lime and haulage services. While locally produced quick/hydrated lime supply to the mines showed a decreasing trend (falling from US$30 million in 2014 to US$ 12 million in 2018), supply of haulage services by Ghanaian businesses increased from US$48 million in 2016 to US$96 million in 2017 (nearly double) but reduced to US$74 million in 2018. Similar mixed performance can be observed for the other items on the list. This requires a tailored supply chain development programme to carry local producers along.

While there is currently no supply chain development programme being implemented by the government to facilitate expansion in local production of items on the procurement list on a sustainable basis , there are questions surrounding the level of 'Ghanaian content' for those items that are locally produced. The dominance of international firms exclusively owned by non-Ghanaians in the mining suppliers' sector, such as Lycopodium, Atlas Copco, Boart Longyear, Sandvik, Liebherr, Mantrac/Caterpillar, African Explosives, Maxam, Carmeuse Lime Products, and Castrol, among others, is well noted (Bloch and Owusu 2011). To what extent are Ghanaians participating in firms producing these goods and services, in terms of ownership, management, and employment? Similar questions can be posed with respect to the other locally produced goods and services outside the procurement list. Responding to this question will require the Minerals Commission and GCoM to collate and share relevant data. Unfortunately, after collaborating with the World Bank (2012) to produce a relevant framework for measuring local procurement as elaborated in section 2, these agencies have yet to apply this template and publish the findings. On the issue of supply chain development, some attempts have been made in the past (as previewed under the overview of Ghana's local content and procurement regulations and other initiatives) but they have largely remained on the drawing board.

Ghana's approach to local procurement in the mining sector differs markedly from what pertains in the oil and gas sector, with implications for how far and how quickly gains can be realized. In the oil and gas sector, three categories of subcontractors or service providers have been recognized on the basis of capital (see Table IV). In contrast, the approach in the mining sector recognizes two classes of service providers as described above: class A for servicing large-scale mines and class B for servicing small-scale mines. The approach in the oil and gas sector allowed for greater participation of Ghanaians, especially in the tier 2 and tier 3 subcontractor categories. The Petroleum Commission intervened to implement high levels of joint venture equities benefiting 87 local companies at the tier 1 subcontractor level, while at the primary contractor level, international oil companies were lobbied to pre-finance 5% participating equities of local firms (Ayanoore, 2020). Another area of difference relates to the specification of local content levels for ten service categories over a period of time (see Table V). The mining sector approach has a 2% margin on bids with the highest level of Ghanaian participation based on ownership, management, and employment.

Table IV
Different categories of operators in the oil and gas industry

Category	Scope of work	Financing threshold
Primary contractor	Engages in exploration and production activities	$5 million or more
Tier 1 subcontractor	Provides direct services to primary contractors	$1 million - $5 million
Tier 2 subcontractor	Renders services to tier1 subcontractors and primary contractors	$0.5 million - $ 1 million
Tier 3 subcontractor	Renders indirect or support services to oil companies	Less than $0.5 million

Source: Ayanoore (2020)

Table V

Goods and services categories and specified minimum local content levels

Goods and services (there are other subservices under each category)		Minimum local content levels		
		Start (%)	5 years (%)	10 years (%)
1	FEED, detailed engineering, and other engineering services	10 – 20	30 – 50	60 – 80
2	Fabrication and construction	10 – 20	30 – 50	50 – 100
3	Materials and procurement	20 – 60	40 – 80	60 – 100
4	Well drilling services	10 – 40	20 – 70	70 – 95
5	Research and development relating to in-country services	20 – 40	30 – 70	60 – 90
6	Exploration, subsurface, petroleum engineering, and seismic services	10 – 40	30 – 70	55 – 90
7	Transportation, supply, and disposal services	30 – 80	60 – 90	80 – 100
8	Health, safety, and environment services	20 – 100	30 – 100	45 – 100
9	Information systems, information technology, and communication Services	20 – 80	50 – 90	70 – 100
10	Marine operations and logistics services	10 – 80	30 – 90	45 – 100

Source: Ayanoore (2020)

The third edition of the local procurement list, published in 2018, departed from the previous editions by reserving certain services exclusively to Ghanaians. This suggests that in future, mining companies may be compelled to procure other goods and services from firms that are exclusively or majority owned by Ghanaians and with some specified level of Ghanaian participation in terms of employment and management. The new items added to the list are as follows: security services (exclusive Ghanaian directors and shareholders), legal services (exclusive Ghanaians), insurance services (strictly incorporated in Ghana), and financial services (strictly incorporated in Ghana). The rest are, contract mining (strictly incorporated in Ghana), fuel (exclusive Ghanaian directors and shareholders), activated carbon, cable bolt and accessories, split setts, rebars, mining mesh and cupels (Ministry of Lands and Natural Resources, 2018).

Notwithstanding the evolution in the local procurement policy, some local suppliers interviewed complained that they are unable to obtain contracts with mining companies despite recent efforts by the government to increase local content. This is largely a result of the high standards demanded of local suppliers by mining companies. Some local suppliers contend that meeting these standards requires time as well as support from the both the government and mining companies. An official of one of the local supplier firms added that 'the first-class supplier firms that mining companies are used to dealing with were not built overnight'. Further to these concerns is the recent increment in fees paid by local suppliers to obtain and renew permits. In July 2020, local mining contractors accused the Minerals Commission of collapsing their businesses with outrageous charges, following an increment about 500% in annual fees paid to the Commission (Tijnani, 2020).

Some local companies questioned the wisdom behind the local procurement and local content policy, describing the approach as narrow. In an interview with a local mining support services provider (and a member of the GCoM), one official questioned why the government wouldn't rather channel efforts being made to enhance local content into growing local mining companies to become multinational entities. He reasoned that once there are multinational mining firms that originate from the country, they will naturally deal more with local suppliers than is the case with the foreign multinationals that dominate the industry. As such, the challenges of enclave mining that local content policies and laws have been designed to address would be better dealt with if efforts are rather geared towards developing local mining giants. In this regard, the state may consider the case of Botswana where an active state involvement in the mining sector (particularly diamonds) was leveraged for the growth of local SMEs in the sector. Furthermore, recent moves by the Minerals Commission to establish a medium-scale mining sector where current small-scale mining companies will be allowed to enter into joint ventures with foreign partners may also be explored .

Conclusions

Ghana's approach to local content in the mining sector has taken off in a collaborative spirit between regulatory authorities and mining companies. Since the general regulations were passed in 2012, in-country procurement by the mining industry has increased significantly (though most of the products are imported by third parties) along with a reduction in inputs directly imported by mining companies. Over the same period, locally manufactured inputs for the mining industry have steadily grown and in some cases meet the entire demand of the mining industry. However, local production of mining inputs as well as Ghanaian participation in both suppliers and manufacturers in terms of ownership is still on the low side. Evolution in the local procurement list, which allows for some inputs to be reserved exclusively for Ghanaian or meet some minimum 'Ghanaian content' requirements, as is the case in the oil and gas sector, has potential for improving the situation. Furthermore, there is need for a well-thought-out strategy and programme of activities to offer local manufacturers and suppliers needed support and guidance so they are able to meet the high standards and demands of the industry. Despite concerns about local procurement and local content initiatives in broadening and deepening linkages between mining and other sectors of the economy (see Geenen, 2019), the findings of this study support the view that local procurement and local content initiatives remain relevant.
In light of this, the following actionable measures and policy recommendations are offered to expand and deepen local procurement in the Ghana mining sector:

(i) Revision and implementation of the National Suppliers Development Programme collaboratively developed by the IFC, the Chamber of Mines, and the Minerals Commission.
(ii) Removal of all goods and services that are on the mining procurement list from the mining list (list of products that are exempted from payment of import duties and related levies).

(iii) The Minerals Commission must be more proactive in sharing information and analysis pertaining to local procurement in the mining sector and collaborating with other state agencies to seek redress to critical challenges that local suppliers face.
(iv) The Minerals Commission must engage the Minerals Income and Investment Fund towards provision of cheaper finance (both in terms of debt and equity) for local suppliers with discipline and in ways that facilitate greater Ghanaian content in these firms.

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CUT-OFF GRADES AND GRADE TONNAGE CURVES
Short Course

19-21 April 2022

Online *via* Zoom

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Not every portion of mineralized rock removed from an ore body can be turned to profit. Some portions simply contain insufficient metal to pay for the costs of mining, milling, and marketing the product. The grade and tonnages of rock containing the mineral or metal to be recovered must firstly have sufficient tonnage to support a long-term mining operation, and secondly must contain sufficient metal when sold at the current price to cover the cost of extraction and processing, as well as making a profit for the mining company. Establishing a cut-off grade for a mining operation, a delicate balance between maximizing the life of the mine while at the same time making as much money out of it as possible, is strongly linked to internal and external forces which shape company policy and procedure. While this might be an overarching principle, establishing an appropriate cut-off grade will also affect the mine design, mining layout and economic performance of the operation. For the majority of mineral deposits, the inverse relationship between tonnes available for mining and extraction, and the average grade of the contained metal, is shown in a grade-tonnage curve as a function of the cut-off grade.

One should be reminded that grade tonnage curves provide a global and statistical appreciation of what the ore deposit could deliver in an ideal circumstance. It has been applied in financial analysis of the ore bodies providing an indication of the proportions (tonnages) and the grade at a range of different cut-off grades. It is always a best or optimistic estimation of what could be mined at a given cut-off assuming of course that the ore body is continuous, and every block is accessible for mining. It provides an estimation of global grade and tonnes and how they are related in the perfectly accessible and minable ore body. It takes no account of the spatial distribution of the actual SMU's or panels that will be mined, and tells nothing about spatial continuity or about the location of specific blocks, it tells you nothing about scheduling or rates of extraction. It tells one nothing about the problems to be encountered in accessing the ore body or the mining layout or scheduling – it simply assumes all these are perfectly and easily manageable.

There is a big difference between the minable reserves and *in-situ* reserves at any cut-off grade. The grade tonnage curve captures none of the uncertainty associated with an actual mining operation or the extractability of the ore. One thing we should consider is that once a cut-off grade is established it imposes a certain degree of continuity between blocks in the ore body. As the cut-off grade is increased this continuity between mining blocks breaks up, becoming less and less, to the point where there may be quite a number of payable blocks, but because they are surrounded by waste material, they are isolated and will never be mined. Nevertheless, an appropriate cut-off grade will ensure that the rate of production, the Life of Mine, and mass of metal delivered to the market from the deposit, will make appropriate returns to investment after costs, revenues, and profits, measured by NPV, IRR and Pay back periods, have been considered.

Brief Bio

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Dick Minnitt is a geologist who completed an MSc in the Murchison Range and a PhD in the Richtersveld regions of southern Namibia. He joined Anglo American and worked on Western Deep Levels gold mine. He later joined Spectral Africa, a subsidiary of JCI dedicated to remote sensing, after which he spent 14 years doing contract and consulting work. He completed an MSc in Mining and joined the School of Mining Engineering at Wits in 1995 where he taught courses in Mineral Economics and Geostatistics. His interest in statistical valuation, geostatistics and sampling of particulate materials arose from the numerous visiting lecturers to Wits University amongst whom were Isobel Clark, Peter Dowd, Clayton Deutsch, Roussos Dimitrakopoulos, Dominique Francois Bongarçon, Francis Pitard, Geoff Lyman, and Kim Esbensen. Dick retired from Wits in 2017 but continues to consult for international mining companies and research in his fields of interest. He holds a position as a Visiting Emeritus professor where he continues to teach postgraduate classes and supervises masters and doctoral students.

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Quantified Value-created Process (QVP) – A value-based process for mine design and operating decisions

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Synopsis

This paper introduces the Quantified Value-created Process (QVP), a decision-making process for use in mine design and operation. The implementation of the QVP is founded on a ten-step rock engineering design process and a ten-step strategic planning process. The potential of this approach is demonstrated by examples of value created as a result of good research, design, and planning. The QVP is divided into two parts, namely, a 'planning the process' section and an 'implementing the process' section, and can be considered to be an extension of the risk approach. All costs, direct and indirect, associated with a significant mining decision (design, operational, investment) must be quantified in advance of committing to that decision, to determine the value that will be created in the short, medium, and long terms. Ethical values, associated with health, safety, the environment, public perception, and social aspects, may be difficult to quantify in economic terms, but must nevertheless also be considered. In contrast with a traditional risk approach, the QVP will identify the upside, and allow executives to make more informed strategic decisions. In this context it is essential to actively engage upper management in the decision process.

Keywords

Quantified Value-created Process, decision-making, value creation.

Introduction

Mining is recognized as a risky business, which is why risk assessment is a routine activity in many mining processes. Financial risk is associated with any mining investment, with the possibility that the actual return on an investment will be different from that expected. Hadjigeorgiou (2020) noted that in addition to traditional financial risks, which include credit, liquidity, market, foreign exchange, interest, and commodity prices, mining companies have to tackle environmental, community, political, and reputational risks in an interconnected global economy. Mining companies are therefore faced with the task of developing winning strategies for a business unit, a particular asset, or a specific project. Ilbury and Sunter (2005) recognized that different people within an organization have different wishes, opinions, strengths, and weaknesses, and consequently perceptions of what 'winning' is. They postulated that the objective should not be 'seeking alignment of everyone's meaning of winning, but a balance between their meanings'. The case is made in this paper that traditional, narrowly focused risk analyses may miss the opportunity to provide a winning strategy or increased value that balances various objectives. This is brought to perspective with reference to environmental, social, and governance issues.

Environmental, social, and governance (ESG) compliance is now an integral requirement for all mining companies. ESG in effect represents risks and opportunities that will impact a company's ability to create long-term value. This includes traditional environmental issues, social issues like labour practices such as health and safety, and governance matters. The issues covered by ESG are not new and arguably are what was understood as being a good corporate citizen. The major change, however, is that failure to demonstrate compliance with ESG requirements could potentially harm a company's valuation, access to capital, or its brand reputation in the market. In fact, many institutional investors will shun any company that does not comply with ESG best practices (Glass Lewis, 2021).

Geotechnical engineering provides several examples of focused risk analysis approaches. For example, evaluation of the risk associated with the stability of open pit mine slopes is frequently undertaken (Terbrugge *et al.*, 2006; Contreras, 2015; Read and Stacey, 2009). Furthermore, risk has been proposed as a criterion for design in rock engineering (Stacey, Terbrugge, and Wesseloo, 2007). However, such risk evaluations are usually associated with the downside, and ignore the upside potential. Experience at many mine sites suggests that decisions are often made based on short-term considerations, often cost-cutting exercises, which may result in 'quick fixes'. The short-term consequences may provide immediate value, but the longer-term consequences of these actions may often lead to much greater value destruction. The practical implication is that frequently experienced problems, such as rehabilitation of rock support, clearing blockages of orepasses, clearing slope failure material from haul roads and pit bottom, *etc*., will often be the subject of provisions in the operating budget of a mine. Once such a budget has been established, mine management will usually be satisfied if the operation meets its budget forecasts and see these problems as the cost of doing business. However, this approach ignores the potential upside, which is the additional value that could have been realized in the longer term if these problems could have been prevented. Furthermore, budget provisions usually only cover the direct costs of the consequences, and do not take into account what is frequently the most important cost, that of the loss of production.

The proposed Quantified Value-created Process (QVP) can be considered an extension of the risk approach. All costs, direct and indirect, associated with a significant mining decision (design, operational, investment) must be quantified in advance of committing to that decision, to determine the value that will be created in the short, medium, and long terms. Ethical values, associated with health, safety, the environment, public perception, and social aspects, may be difficult to quantify in economic terms, but cannot be ignored. Thus, in contrast with a risk approach, the QVP approach will identify the upside, and allow executives to make appropriate strategic decisions. For example, it might be shown that a proposed decision will result in short-term value destruction, but that medium and longer term value will be substantial, thus promoting a positive decision. Value created in the short term, but not in the longer term, should result in a negative executive decision. To implement the process, executives need to demand quantification of all relevant direct and indirect costs from their mine management and operational staff to assist in making their decision. Mining company executives have managerial and financial expertise, but may be non-technical, which means that they are unlikely to understand fully all the technical issues associated with proposed mining developments. This phenomenon has been described as an 'asymmetry in knowledge' between the different levels of management within a mining company (Hadjigeorgiou, 2020). Traditionally, executives have to base their decisions on the confidence they have in the information supplied to them by mine management. In contrast, with this approach, using the QVP, executives will have a comprehensive involvement in the overall development and thus be able to make the most meaningful decisions for the short, medium, and long terms with knowledge and confidence.

In the following sections, examples will be given of value creation achieved in numerous mining projects. This will be followed by a suggested ten-step QVP, which is aimed at ensuring a logical implementation of the process.

Examples of value creation in mining

In this section, information extracted from published material is presented to illustrate that all significant mine design and operational decisions should be based on the quantified value that will be created by those decisions, taking into account the short, medium, and long term. Although the selected examples are mostly geotechnical in nature, the same concepts can be applied to other fields. The published information generally relates to after-the-event evaluations, to illustrate the magnitude of the value that can be created. However, the thesis of the paper is that such value should be quantified in advance so that appropriate decisions can be taken to realize optimum value in line with the company's goals.

Health and safety

Safety is of prime importance in mining, and a safe mine represents great ethical value for the mining company. Poor design and operation, leading to unsafe situations and accidents, often have serious economic consequences. It is possible to quantify the financial implications of accidents or potential accidents, although this does not appear to be commonplace. Preis and Webber-Youngman (2021) suggest that financial costs relating to mining incidents can be split into direct and indirect costs, with indirect costs being substantially greater. Quantifying health and safety costs is complex and in many cases made more difficult as the costs are incurred at different time periods following a mining incident.

Mine policy in preventing health and safety incidents is usually very bland and although the overarching objective is zero harm, in practice rules or guidelines are often arguably bent, against policy, so that short-term production targets can be met. This highlights the need for both accountability and responsibility repercussions of full enforcement of safety guidelines.

Design and operation of orepasses

Design decisions regarding orepasses involve the definition of pass location (including proximity to production excavations, shafts, crusher chambers, *etc*.), orientation (inclination and orientation relative to geological strata), size, shape, length, method of excavation, lining and installed support, system geometry, and operating principles. Storage capacity and required operating life may also be important. In high-stress environments, pass cross-sections may 'grow' during use due to stress-induced failure of the rock and/or the geological structure. From an operating point of view, it is most efficient to locate passes as close as possible to the sources of ore and shafts so as to optimize the load-haul-dump or other transfer efficiencies. However, in a deeper sub-level caving environment, for example, stress concentration in the solid around the base of the caved area, which is where passes are located, may lead to rock failure in the pass if it is too close to the orebody. Thus a 'close' pass would provide short-term operational benefits, but in the medium to longer term a 'more distant' pass may avoid such rock failure and associated loss of production and rehabilitation costs, and therefore contribute much greater economic value to the mine. In a deep-level gold mining environment. passes with an initial diameter of 2.4 m have been reported to have opened up under stress to a span of up to ten times the original diameter. Minney (1990) describes a case in a deep-level gold mine in which pass breakout failure occurred to such an extent that the 'extended' pass affected the stability of the shaft with which it was associated. The impact on the efficiency of the pass would have been significant, indicating the longer term economic benefit and value that could have been realized with improved orepass design.

Because orepasses rarely involve safety risks, it appears that they are usually given no more than scant detailed design considerations (Hadjigeorgiou and Stacey, 2013), and there rarely appears to be any strategy in planning, designing, and operating orepass systems. A likely explanation is that the comprehensive costs of the absence of strategies have not been apparent. Mines can usually quantify satisfactorily the routine construction, operational, and maintenance costs, but they commonly do not have cost data on hangup clearance, blast damage repair, and rehabilitation. All of these unexpected occurrences impact on production and can result in major costs of loss of production, which is often the single most important economic factor for a mine. A review of orepass design practice in the deep gold mining industry, involving 200 individual passes in eight mines (Joughin and Stacey, 2004) revealed minimal quantitative information: what information there was, was often undocumented, but communicated by word of mouth from shaft personnel; and very few cases existed in which geological information, such as from borehole logs, was available for passes. This confirms the widespread absence of strategy associated with planning, design, and operation of orepasses (Hadjigeorgiou and Stacey, 2013). The practical implication of not collecting adequate geotechnical data has been demonstrated in a benchmarking study of ten Canadian mines. There was no incidence of uncontrolled failure in any orepass section developed in competent rock mass conditions (*i.e.* Q value greater than 5, see Table I).

In massive mining operations, from an operational efficiency point of view, it is an advantage to locate orepasses as close to the orebody as possible such that tramming times are minimized and production rates maximized. However, as mining progresses, the stresses around the orebody will change and this might lead to stress concentrations in the orepass and resulting instability. As a result, the orepass may become inoperable, and therefore it will be necessary to transport ore to adjacent orepasses, at much lower efficiencies and greater costs. In such cases value is destroyed. Therefore, such potential occurrences should be taken into account in the design location of the passes to optimize value.

Blasting in open pit mines

The quality of blasting determines the amount of damage induced in the rock mass. The extent of this damage effectively determines the stable slope angles that can be adopted in open pit mines. In addition, the fragmentation is determined by the blasting, and the particle size distribution has a major influence on the efficiency of loading, hauling, and milling. Research conducted by Bye (2003) established the desired particle size distributions in both ore and waste rock at an open pit mine. The research involved over 200 trial blasts to define those blast designs that would deliver the required fragmentation. The result was a significant improvement of 18% in the average plant milling rate, 16% in the autogenous milling rate, 13% in the average instantaneous loading rate for ore and waste, and 11% in the average instantaneous loading rate for ore. An additional revenue of over $2 million a month was realized in the plant alone (Little, Bye, and Stacey, 2007).

Further blasting research was carried out to investigate the value of implementing electronic delay detonators (EDDs). This demonstrated that EDDs would consistently provide uniform fragmentation. The implementation of EDDs involved an extra blasting cost, but the fragmentation surpassed expectations and therefore the blast patterns could be expanded, reducing the overall drilling and explosive costs. The result was then in fact not a cost, but a cost benefit attributable to the EDDs.

While conventional mine thinking might have argued that the costs of trial blasts would not be justified, that EDDs would be too costly, and that blasting costs should be minimized, the research and subsequent implementation resulted in substantial value creation for the mine. This demonstrated the importance of a focus on longer term value creation rather than on short-term costs. In addition to the blasting benefits, EDDs also play an important part in the management of slope stability. EDDs improve the quality of wall control blasting, thus providing the indirect benefit of enhanced wall stability and hence steeper slopes that result in further economic benefits. Slope optimization is dealt with in a later section.

Good blast design and practice is also relevant in underground excavations. In tunnels, for example, poor quality blasting causes damage and instability in the rock mass, which then requires more support to ensure stability. Spending more on good blast designs is likely to improve safety and save substantially on rock support costs, thus creating value for the operation.

Preconditioning of stope faces in gold mines

Preconditioning of deep-level gold mine stope faces is now common practice in South Africa to reduce, and in most cases prevent, the occurrence of stope face rockbursts. Research carried out by Toper (2003) demonstrated very considerable safety benefits as a result of preconditioning: the area mined per accident increased by 347% for updip mining, 260% for diagonal mining, and 254% for combined mining.

In addition, despite the additional amount of drilling, with the expectation of increased direct costs as well as higher costs of labour for the additional drilling, blast-hole drilling penetration rates actually increased, and total drilling time reduced. An increase of up to 50% in the stope face advance per blast was achieved, and there was a significant improvement in the condition and stability of the hangingwall. With the finer fragmentation – about 30% smaller particles and more uniform particle size distribution (Toper *et al.*, 2000) – the result was greater efficiency in ore handling.

This research proved that preconditioning of gold mine stope faces contributes to improved safety, productivity, and profit, creating huge safety and economic value for the mines, amounting to many millions of dollars. However, this value would have been even greater, and the safety record better, had a QVP been contemplated 50 years earlier. In-mine trials in the 1950s (Roux, Leeman, and Denkhaus, 1957) indicated the potential of preconditioning to reduce rockbursts. These trials demonstrated that the number of severe rockbursts was reduced by 73%, and occurrences of on-shift rockbursts were rare. Unfortunately, despite the success of the trials, preconditioning became a routine operation only some 40 years later, in the late 1990s.

Table I

Performance of orepass sections in ten underground mines (after Lessard and Hadjigeorgiou, 2006)

Q rating	No. of sections	Non-supported	
		Total	Failed
> 5 (fair)	47	4	0
< 5 (poor)	53	3	3
Total	100	7	3

Open pit slope optimization

In addition to the blasting investigations by Bye (2003), described above, further research was carried out into the design of open pit slopes, evaluation of slope stability, and slope optimization, monitoring, and management. The required geotechnical information for slope design includes properties of the rock types present, information on geological structures and their properties, details of the groundwater status, and the boundary conditions (*in-situ* stress conditions). The geometry of the orebody dictates the design configuration of the open pit. Consequently, the extent and shape of the orebody must be well defined and captured in a block model. Bye (2003, 2005a) developed a geotechnical block model of the mine in Datamine. Each 15 m^3 block was assigned appropriate information on the rock type, its compressive strength, the RQD, and Laubscher's Mining Rock Mass Rating (Laubscher, 1990). Interpolation involved geostatistical evaluation of borehole and face mapping information. Using this block model, predictions of blasting costs were made using the blastability index (Lilly, 1986) and the modified Cunningham (1986) fragmentation equation. Inter-ramp slope angles were also determined in the block model using a rock mass classification approach (Haines and Terbrugge, 1991). This allowed the possibility of steepening of planned slopes to be ascertained, and where slope flattening was required. Comprehensive numerical slope stability analyses were carried out. The result of the process was a steepening of the overall slope angle. The strategic and tactical value created was assessed by Bye, Little, and Mossop (2005). The following is a quote from the conclusions to Bye's research (Bye, 2003).

> '*The development of the slope design model provided the opportunity to move away from one design process for the entire pit, and customization of slope design and configurations were developed to cater for local variations in the rock mass conditions. The availability of the geotechnical information in 3D and the improved level of confidence of that data resulted in a slope optimization of the final pit ... the final walls were optimized by three degrees, resulting in revenue increase for the mine in excess of [$120 million] ...*'

It is also worth mentioning the value to the mine of databasing geotechnical and monitoring information (Little, 2006a, 2006b) – this meant that good design information was readily available when required.

Slope optimization initiatives at Sishen mine in South Africa have unlocked significant value. The research carried out for this project involved the development of synthetic rock mass (SRM) models for banded iron formation and shale units, on which the economics of the large iron ore mine depend (Bester, 2019; Bester *et al.*, 2019). The research introduced a 'concept level' SRM for early-stage projects wherein certain informed assumptions may be made based on existing knowledge. SRM models rely on geotechnical data, which can be provided by quality structural mapping of benches. This information is not commonly available in the early stages of a project but can be gathered during the mining process by physical mapping and, when physical access is not available, by remote methods such as laser mapping (Russell and Stacey, 2019). This allows models to be iteratively tested and improved as new geotechnical data becomes available. The slope optimization methodology applied utilized input from SRM modelling to identify the spatial variation in parameters, by highlighting possible areas (of any size or shape) that show unfavourable interactions with slope geometries in early-stage projects, current operations, and future pushbacks. This approach exploited the integration of modern, smooth, implicitly built, radial basis function-derived surfaces and solids in geological/structural geological modelling as critical inputs to slope design, based on maps that show the continuous variation of certain parameters throughout the volume of interest. This slope design methodology can be accommodated from early-stage projects through to revised planning cycles in operating mines. A risk-based approach is followed, which includes focused data acquisition, rigorous stability analysis, and risk assessment in areas of concern, and risk mitigation from early project stages to operating mines. The approach therefore deals with the common fact that slope instability is one of the major sources of risk in open pit mining. This is mainly due to data uncertainties. The development of a geotechnical block model as the main output of the geotechnical engineering function is essential to support the iterative process that will facilitate a dynamic model that can be continuously updated with new information.

The value that was created in the slope optimization process was reported in the company's 2018 Annual Report (Anglo American, 2019):

> '*Reserve life increased to 14 years (from 13 years in 2017), as a result of the optimised pit slope designs built into the updated LoM [Life of Mine] plan life and productivity improvements.*
> '*Most of the annual increase can be attributed to a steepening of the pit slopes of the Sishen pit design resulting in a 50.8Mt increase in Ore Reserves, based on advances made in the spatial geotechnical modelling field enabling a better spatial understanding of pit slope failure mechanisms, allowing for optimisation of pit slope designs.*
> '*Sishen – in 2018 a slope optimisation project was completed which resulted in a reduction in the LoM stripping ratio from 3.89:1 in 2017 to 3.4:1 in 2018.*)

The increase in NPV achieved, mainly due to the slope optimization, was approximately $700 million.

Ground support

The process for selection of ground support for underground mines is well established and follows engineering guidelines. It is relatively straightforward to determine the unit costs and installation costs for ground support. When these are combined with time studies then the decision-makers can make informed choices that meet the technical requirements and are cost-effective. In order to quantify the true value of these choices, however, it is necessary to address the long-term performance of ground support. In practice a significant degradation of ground support over time may require rehabilitation, *i.e.*, additional ground support or replacement of existing support. In this context, what originally may have been considered as both meeting the technical requirements and reducing costs may not be appropriate.

In the mining environment, rock engineering has significant safety implications, but it is often regarded as a cost. Mercier-Langevin (2019) reports that ground support, depending on the prevailing ground conditions, can make up a sizeable portion of the operating budget of an underground mine. For example, ground support material costs at the LaRonde mine, which manages severe squeezing ground and significant seismic risk, were triple those at Goldex mine, which did not have to cope with the same level of geotechnical problems. If one also considers the related development costs it can be seen that the choice of ground support has a significant impact on the profitability of an operation. A further challenge is defining the success of any ground support strategies based on the objectives. For example, in squeezing ground, the objective of ground support is to manage deformation and keep the excavation safe for workers for its service life (Mercier-Langevin and Hadjigeorgiou, 2011). In seismically active ground, the objective of support is to withstand the amount of energy that an event of a given magnitude is expected to generate in order to contain rock ejection. It is now standard practice to use yielding or energy-absorbing ground support elements for both extreme squeezing and seismically active or rockburst-prone conditions.

It is remarkable that, although rockbursts are recognized as major safety hazards, which may result in significant disruptions, and consequent negative effects on the economics of mining and tunnelling, the industry was slow to introduce yielding support. Ortlepp (Cook and Ortlepp, 1968; Ortlepp, 1969) was probably the first to develop a yielding rockbolt for rockburst-prone ground. Testing of this bolt under dynamic loading conditions showed that it had great potential for containing rockburst damage, but it was never commercialized. The conebolt, developed in South Africa in the 1990s (Jager, 1992), was proven to be very effective in dynamic loading conditions (Ortlepp, 1994) but was not installed in South African mines in large numbers, probably due to short-term economic considerations. Modified conebolts were used extensively in Canada and have been successful in limiting rockburst damage (Simser, Joughin, and Otlepp, 2002). Most seismically active mines now use dynamic or enhanced ground support. For example, Creighton mine in Canada has demonstrated that modifications to its ground control strategies and the use of yielding support had a significant impact the evolution of the frequency and severity of rockbursts (Figure 1).

In retrospect, the reluctance to introduce what is arguably a more effective ground support strategy for extreme conditions is surprising. The reason is probably that yielding bolts are somewhat more expensive than conventional bolts. However, using mine costing data for all aspects of bolt installation (bolt, grout, drilling, labour), it was shown that by increasing conebolt spacing by only 5 cm, the overall cost of the installed yielding support was identical to that of conventional rockbolt support (Ortlepp and Stacey, 1995). The most important aspect of this comparison was, however, that the energy absorption capacities of the yielding bolts were approximately 15 times greater than those of the conventional bolts. If rockburst-resistant support had been implemented substantially, it is probable that much of the rockburst damage, associated direct and indirect costs, and accidents could have been reduced. The resulting value to the mines would have been very significant (Stacey, 2016). Recent research has been carried out (Moganedi, 2018) to estimate the economic value that could have been created by the use of rockburst-resistant support. In this research, 13 rockburst case studies were analysed. Two of these case studies were evaluated to demonstrate the value that could be created by installing appropriate rockburst support systems (Moganedi and Stacey, 2019). This indicated that such dynamic support of an access tunnel could obviate a $20 850 daily loss in revenue, as well as prevent negative consequences such as accidents, injuries, and equipment damage. The installed rock support consisted of rigid elements, as was the case in all except one of the rockbursts evaluated. In contrast, value will be created by energy-absorbing support, which will prevent, or at least reduce, damage. Many yielding support systems are now available in the market, including rockbolts, very strong mesh, and tendon straps.

An example of increased value from the selection of ground support has been observed at the LaRonde mine in Canada. Owing to a combination of high stresses and foliation in the rock mass, the mine is subject to some of the more challenging squeezing ground conditions and high convergence rates. In cases when wall stability is compromised, or if equipment clearance is insufficient, an 8-yard scoop-tram is used to 'purge' the walls, *i.e.* to remove excess material. The resulting drift dimensions require the installation of secondary back support, such as cable bolts, in order to stabilize the greater spans created by scaling of the sidewalls. LaRonde demonstrated that introducing a relatively more expensive rockbolt (the hybrid bolt) in the support system resulted in a significant reduction of 'purging' of drifts that display excessive squeezing (Figure 2). This is another example of increased value following a greater investment in ground support.

Value creation in a deep level open stoping mining environment

This case deals with gold mining at a depth of greater than 2000m, using an open stoping mining method. Instability in the stopes caused equipment damage, as well as ore dilution (le Roux, 2015). There were no safety concerns, since remotely operated LHDs were used for extraction of ore. Owing to dilution resulting from the instability, the recovered ore grade reduced from 5.5 to 4.5 g/t, and the associated loss was some $1.8 million per month

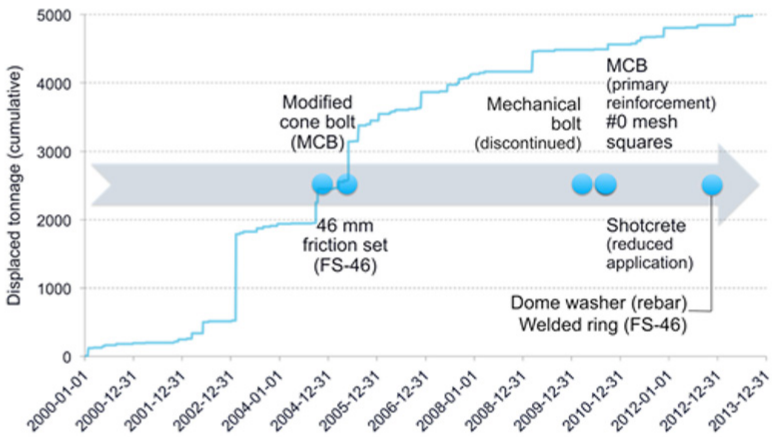

Figure 1—Correlation between the evolution of ground support systems and the frequency and severity of rockbursts at Creighton mine (**after Morissette *et al.*,** 2017)

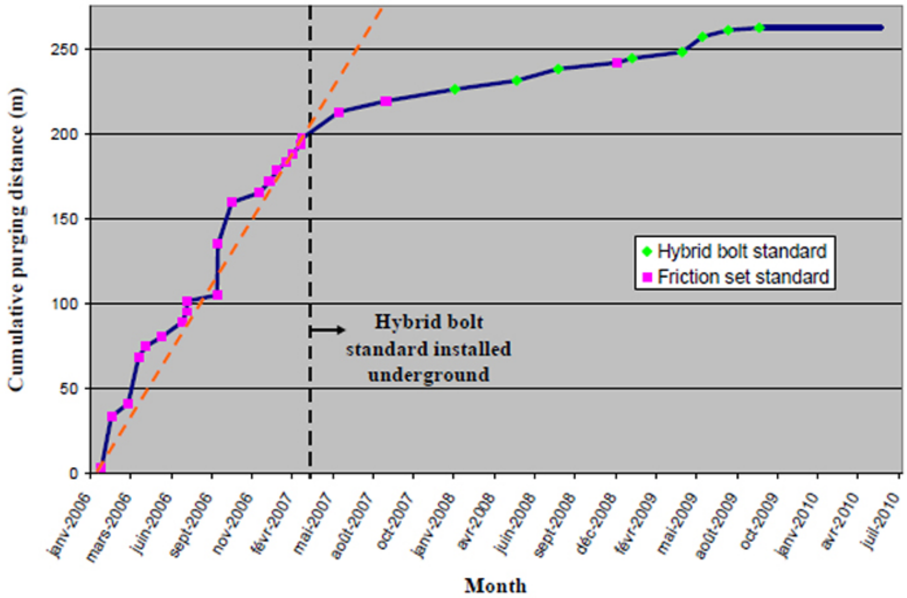

Figure 2—Reduction in cumulative distance purged under the 215 level, related to the introduction of the hybrid bolt as part of the ground support standard for squeezing rock conditions at LaRonde (after Turcotte, 2010)

(based on a gold price of $20 000 per kg). The cost of damage to trackless equipment (illustrated in Figure 3) was also significant, and in addition there were costs for standing time. A $40 million cost was estimated for a 10-year period at the mine. Other costs, associated with milling and plant treatment, secondary blasting, transport, and hoisting amounted to about $24 million. The calculated total opportunity loss was $65 million over a 10 year period. These costs indicate the significance of 'accurate' open stope design that will prevent, or at least reduce, costs due to falls of ground.

Le Roux (2015) carried out back-analyses of records of stope instability, which showed that commonly used rock mass failure criteria and empirical approaches were not applicable. Instead, he implemented a strain-based design criterion, which resulted in reliable prediction of stability of the open stopes. Very significant reductions in equipment damage and dilution (Figure 4) resulted from the revised stope designs. It was estimated that the loss of income would probably have been greater than $250 million without the strain-based design criterion, confirming the value created for the mining operation (le Roux and Stacey, 2016).

Figure 3—Equipment damage due to rockfalls in open stopes (after le Roux, 2015)

Improved design confidence due to collection of additional geotechnical data

In the early stages of mining there is commonly a deficit in the geotechnical data available for mine design. The result is likely

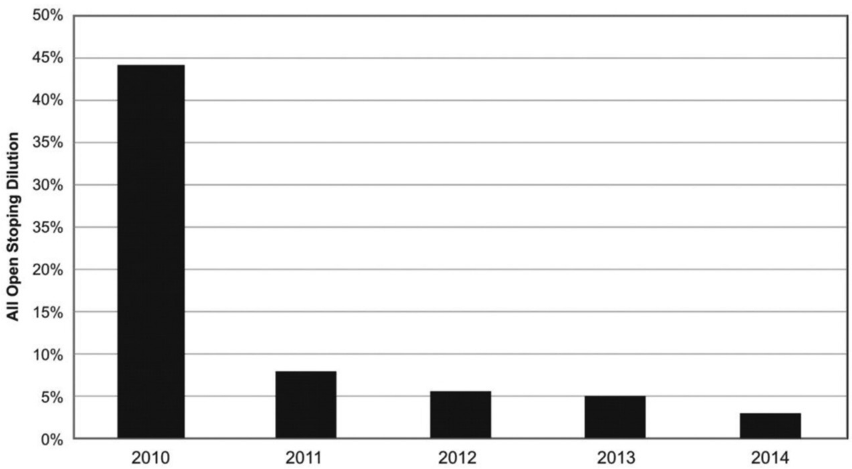

Figure 4—Annual dilution associated with deep level open stope mining (after le Roux, 2015)

to be a more conservative design to allow for the ’unknown’ conditions. As mining progresses and more rock surfaces are exposed, there is the possibility of obtaining additional geotechnical information and thus improving the design. There is also the possibility, due to the creation of the mining excavations, of new locations for borehole drilling, also to gain more information on the rock mass. However, such additional work involves extra costs which mining companies are often loath to incur. It is not unusual to find that preliminary or incomplete data from the feasibility stage is still the basis of important decisions.

To address the value of additional investigations, Fillion and Hadjigeorgiou (2016, 2017; 2019) carried out research to quantify the improvement in confidence in geotechnical data This work demonstrated that committing funds to additional geotechnical investigations and rock testing provided value through the increased confidence in the data that could then be used for design revisions. Although this research did not quantify actual financial values created, it did clearly show, for example, that the new information would allow open pit slopes to be steepened. In a deep open pit, the value created by steepening of slopes by as little as 1° or 2° could run to hundreds of thousands of dollars. This would clearly justify the additional expenditure on further geotechnical investigations and revised mine design work.

Having established that there is value in additional information, it is possible to establish an informed strategy. Figure 5 illustrates the resulting confidence intervals for uniaxial compressive strength tests for different tock types at the same mining operation. It clearly demonstrates that the number of tests required to attain the same confidence interval differs according to rock type. As the sampling and laboratory costs are independent of rock type it is possible to quantify the increased value, *i.e.*, greater confidence in the design parameters, of additional tests for each rock type.

Suggested QVP implementation

In this section, a logical process for the implementation of the QVP will be described. This work is inspired by the engineering design process developed by Bieniawski (1988, 1992, 1993), whereby ‘mine design is a process based on empiricism and practical experience that does not qualify as engineering design’. The lack of a thorough engineering design process in mining is sometimes attributed to significant variability and geological complexity in the rock masses that host the mining. However, a more likely explanation is the attitude of many mining personnel, for example – ‘Our mine is different, and therefore what applies elsewhere, does not apply here.’ This is further compromised by a perception that the economics of the project do not justify the additional costs. Such attitudes do not facilitate the implementation of a thorough design process and are difficult to justify.

Bieniawski (1992) defined six design principles, which expanded into a ten-step design methodology or process. Owing to the close correspondence between this process and a circular ten-step strategic planning process (Ilbury and Sunter, 2005), Bieniawski’s process was cast into a circular format, referred to as the ‘wheel of design’ (Stacey, 2009). This circular format has been adopted for the proposed QVP. Basing the QVP on an engineering design process and a strategic planning process are considered to be completely justified, since it is essential that a decision-making process in mining must take into account both engineering design issues as well as short-, medium-, and long-term strategic planning issues. Figure 6 shows a recommended QVP wheel, with its ten steps: the different colours indicate the different levels of responsibility for carrying out the step. There is significant responsibility indicated for the executive level (directors) since they determine the policies and expectations for the company. Lower level personnel will be required to supply the quantified information that is essential to enable senior personnel to make appropriate, well-informed decisions. The following are the suggested ten steps of the QVP.

1. *Clear definition of the objectives of the decision process*
   This is an extremely important step in which directors and senior management must define the overall aims, for example ‘world-class block caving operation’, ‘safe mine’; ‘no long-term environmental damage’, ‘company policies’ or acceptable risk.
2. *Constraints: restrictions that may affect the decision process*
   Constraints may be related to the mining company itself, for example, accommodation and availability of personnel, equipment maintenance facilities, *etc*., and/or the country, for example, the country’s laws, rail capacity, harbour capacity, electricity supply, water supply.

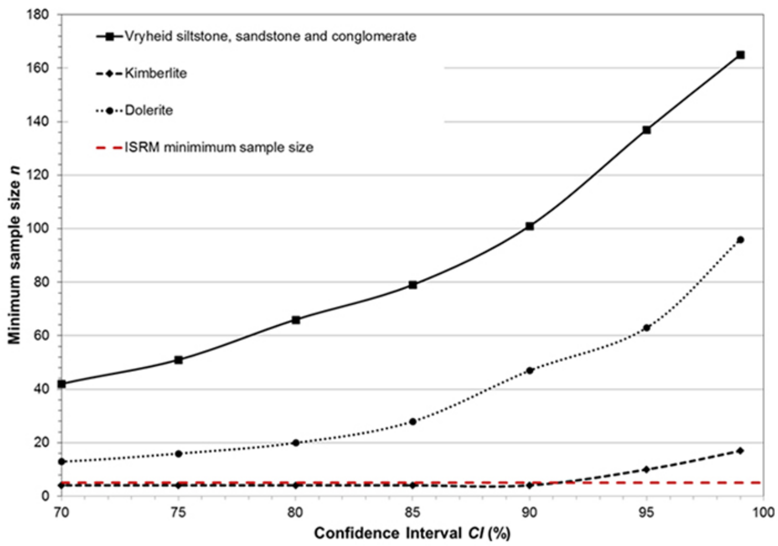

Figure 5—Minimum number of specimens required for a given confidence interval for UCS (**after Fillion and Hadjigeorgiou, 2017**)

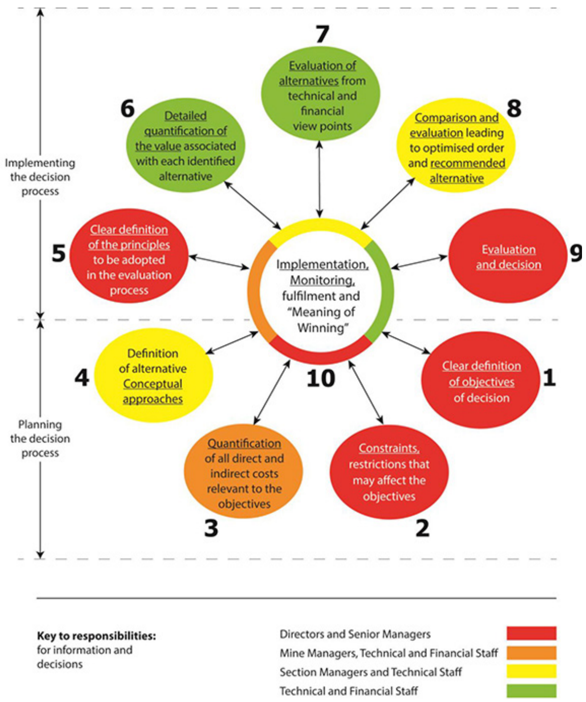

Figure 6—Quantified Value-created Process wheel. The arrows on the spokes of the wheel indicate that, at each step, the requirements of previous steps must continue to be met; in particular, that the objectives defined in step 1 of the process are being addressed

3. *Quantification of all direct and indirect costs relevant to the objectives*
   In this step, a catalogue of costs would be compiled, for example, drilling costs, blasting costs, rock support costs, loading and hauling costs, *etc*., and indirect costs such as costs of falls of ground, costs of rehabilitation of support, costs of accidents, costs of damage to equipment, and (probably most significantly) costs of loss of production due to any of the factors listed (and others). Costs associated with past occurrences on the mine or experienced by the mining company, such as collapses, equipment damage, orepass blockages, shaft instability, *etc.* would be sources of information in compiling the catalogue, which is then available for reference in the considerations in step 4, and is essential for step 6.
4. *Definition of alternative conceptual approaches* (*to achieve the objectives*)
   In this step, alternative mining methods and layouts that would potentially achieve the objectives would be considered (including excavation methods, excavation sizes, rock support methods, *etc*.), ideally allowing the alternatives to be listed in preferential order for quantification in step 6.

The first four steps of the process involve the planning of the decision process. This stage is extremely important, requiring very clear thinking and definition of objectives, culminating in alternative conceptual approaches to be considered. Significant director-level input is required in this first stage, and in the definition of the principles to be adopted in the evaluation process (step 5).

The following six steps involve the more routine or 'number-crunching' part of the process, to provide the quantification of value on which the ultimate decision will be based. Directors and senior managers will make the final decision in step 9, followed by the actual implementation in step 10.

5. *Clear definition of the principles to be adopted in the evaluation process*
   Non-negotiable company policies will be stated, essentially defining the company's ideals and standards to be used in the evaluation process.
6. *Detailed quantification of value associated with each identified alternative*
   Using the catalogue of costs developed (step 3), the value created in each step 4 alternative must be quantified. Importantly, this should be aimed at avoiding losses rather than minimizing costs. The example referred to in the section 'Design and operation of orepasses' is relevant: locating an orepass close to an open stope may minimize tramming costs, but the pass may become unstable as the stope is mined due to stress concentrations in its vicinity. Costs will then increase substantially owing to loss of production due to non-availability of the pass, or to much greater tramming costs if an alternative, distant orepass has to be used. A second example is the choice of rock support – limiting the amount, type, and capability of the support may apparently reduce costs, but will result in greater potential for instability, rockfalls, possible accidents, and equipment damage, leading to loss of production and the requirement for rehabilitation and re-supporting. The importance of taking into account indirect costs cannot be overemphasized.
7. *Evaluation of value created for each alternative from technical, financial, health and safety, ethical, social, and environmental viewpoints*
   In addition to the quantified value determined in the step above, this step will take into account further aspects such as health and safety, ethical, social, and environmental effects, which may not be fully quantifiable, but which may influence the ultimate decisions.
8. *Comparison and evaluation, leading to optimized order and recommended alternative*

The outputs from steps 6 and 7 must be carefully considered and presented in optimized order of value created, for thorough evaluation by the executives and senior management.

9. *Executive evaluation and decision*
   This is the final executive step of the process, in which the final decision on the method of execution of the project is made.
10. *Implementation, monitoring, fulfilment, and the 'meaning of winning'*
   The decision is implemented, and the progress must be monitored to check that the project is performing as predicted. If there is any deviation from the predicted performance, it may be necessary to intervene in the process (*i.e.*, reconsider appropriate earlier steps) to bring the project back to the desired performance. The ultimate aim is to achieve fulfilment and, as indicated by Ilbury and Sunter (2005) in their strategic planning process, the 'meaning of winning'.

A critical element in the implementation of the QVP is recognizing the role of personnel within the organization in the cession and implementation process. Although there are inherent variations within each organization, it is important that the levels of responsibilities are well defined and well understood. In a discussion on managing risk, Hadjigeorgiou (2020) suggested that the purpose of risk management is the creation and protection of value. In a mining company, risk management responsibilities are shared or assigned to different players. A similar template that would address the QVP could be as follows.

➤ The Board of Directors is generally assigned a risk oversight role. Atkins and Ritchie (2019) further suggest that there is need for mining expertise in a board and upper management in order to be able to request the appropriate assurance of mining-specific technical and operational risk.
➤ Senior management designs and implements processes that respect the Board's corporate risk strategy and that function as directed. It is the responsibility of senior management to instil a culture of risk-adjusted decision-making throughout the organization and provide guidelines to technical personnel. Finally, senior management informs the Board on the company's most material risks, how these risks interrelate, how they affect the company, and how management addresses them.
➤ Mine management is responsible for the day-to-day operation. In a single-asset company there is an overlap between responsibilities of senior corporate and mine management.
➤ The main responsibility of the technical engineering group is to design and construct engineering structures and provide oversight to operations. They employ risk analysis tools to identify and quantify geomechanical risk. Finally, they provide input to the company risk policy/strategy.
➤ The main emphasis of operations is to implement good practice to ensure the safety of personnel and equipment, and to limit or mitigate risk.

This terminology has been used in the QVP wheel in Figure 6.

Discussion and conclusions

Examples have been illustrated of the major value that can be created in projects by careful attention to engineering design and implementation. The values created in these examples were determined after the event, but they do indicate the enormous value that could be used for justification of planning and design decisions. In most of these cases, although the value created has been quoted in financial terms, it must be recognized that much non-financial value will often be created as well. Examples are health and safety, and social aspects such as extended employment periods, which are of benefit to the employees as well as their dependents and the community. Social value will also be created by careful management of environmental matters.

In contrast with conventional risk evaluation processes, which tend to focus on negative aspects such as costs and potential losses as the basis for decisions, the proposed decision-making process, based on quantitative evaluation of the value that can be created, focuses on the upside or positive aspects. This proposed process is firmly rooted in well-established engineering design and strategic planning principles, which are essential components of mine planning, design, and operation. The logical QVP presented requires significant input from executives, particularly in the early stages, and this will ensure that ethical and responsible decisions are made, and that short-, medium-, and long-term strategic considerations are taken into account. Quantification of the inputs to the process, as required by the executives, will be supplied by mine management personnel and mine technical specialists, who have access to the appropriate costing information and to records of past performance on the mine, including accidents, damage, collapses, dilution, loss of production *etc*., and associated costs. This will allow the benefits of additional investment to be quantified. For example, the value created by installing better, but more costly, rock support; the value of improved monitoring for advanced indication of any instability, with the potential of then avoiding the instability, and with the associated safety value; and of course ensuring that any loss of production is minimized. The ultimate decision on the implementation of chosen option is again the responsibility of the executives, based on the quantified value-created data. All steps involved in the process should be monitored to ensure that the objectives defined in step 1 of the QVP are met. Any deviation from these objectives may require intervention (such as returning to an earlier step) to bring the process back on track.

It is suggested that the proposed QVP is a logical decision-making system that will result in decisions that will be of great benefit in the planning and operation of mines.

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Effect of silica concentration on degree of sintering of chromite-silica ladle well filler sand based on South African raw materials

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Synopsis

During steelmaking, one important factor for production efficiency is the free opening of the ladle nozzle during continuous casting. Free opening occurs when the well filler sand and the steel flow freely when the slide gate is opened. Well filler sands are used for the slide gate of a ladle to separate the slide gate refractory and the molten steel. The well filler sand is partially sintered by the heat of the molten metal, which can result in the ladle nozzle failing to open if the sand is not sintered to an appropriate extent. It is therefore of great importance that the sintering behaviour of well filler sand is understood.

We studied the effect of the well filler sand chemistry on its sintering properties. Samples of well filler sand with various chemical compositions were sintered in a high-temperature chamber furnace. Quantitative X-ray diffraction (XRD), inductively coupled plasma optical emission spectrometry (ICP-OES), and wavelength dispersive spectrometry (WDS) by electron microprobe analysis (EMPA) were used to analyse the various well filler sand mixes. Points of analysis were indicated on backscattered electron (BSE) micrographs. Quantitative element mapping was undertaken by energy dispersive spectrometry (EDS). Thermodynamic calculations in FactSage predicted the percentage liquid phase present for the various well filler sand compositions at equilibrium conditions.

The results of this work show that the degree of sintering of chromite-silica well filler sand depends strongly on the silica content. The amount of liquid phase formed increases with increasing silica content.

Keywords

well filler sand, sintering, ladle free opening, continuous casting, ladle nozzle.

Introduction

Iron- and steelmaking are mature processes consisting of various unit operations, as indicated in Figure 1.

After the process of continuous casting, the remaining slag must be removed from the refractory-lined ladle after every heat using a construction machine. The sliding gate at the bottom of the ladle is then cleaned. This is done manually using an oxygen lance. Any damaged ladle well parts are then replaced and damage to the top part of the ladle repaired. The ladle is then transported to the reheating station where it is heated with a mixture of natural gas and air to the desired temperature. Just before the molten metal is poured into the ladle, a standard amount of well filler sand is poured through a tube into the slide gate (Kovacic, Jurjovec, and Krajnc, 2014). The slide gate (or sliding gate) consists of two plates: an upper and a lower plate. When the openings in the plates align, the liquid steel flows into the tundish via the shroud. When the two parts are misaligned, the flow of liquid steel is prevented (Figure 2).

Well filler sand is poured on top of the tap-hole in the slide gate to prevent liquid metal from entering the ladle nozzle (Figure 2), which requires that the sand is sintered to an appropriate extent during preheating.

The aim is for the sand to break due to the pressure of the liquid metal when the slide gate in the nozzle is opened, allowing the ladle to freely open. The most likely issues that can be experienced are:

- An excessive degree of sintering prevents the slide gate from opening in order to pour the molten steel
- An inadequate degree of sintering can cause leakage of the molten steel.

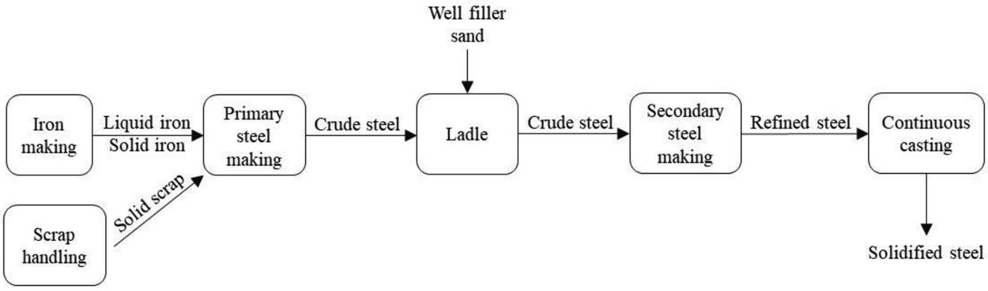

Figure 1— Simplified schematic of the iron- and steelmaking process

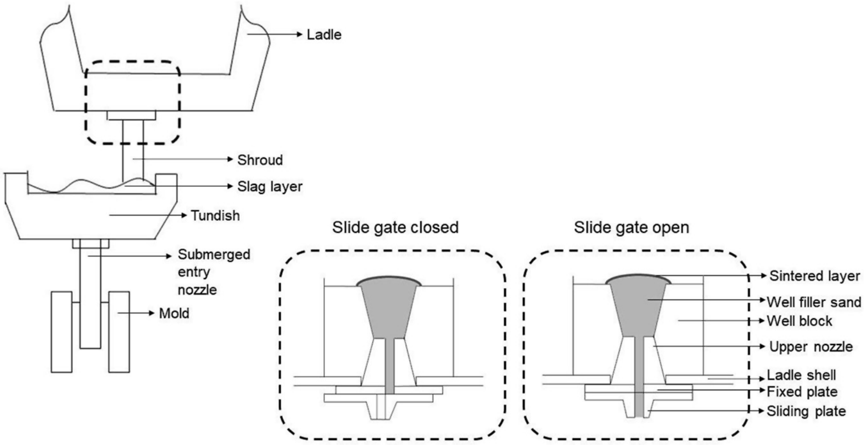

Figure 2—Schematic of the ladle sliding gate system

Table I

Typical chemical compositions of well filler sand bulk (weight %)

Cr_2O_3	SiO_2	ZrO_2	C	Al_2O_3	Fe_2O_3	MgO	HfO_2	K_2O	Na_2O	Total	Reference
30-40	15-30	–	1.0	<21	<20	–	–	–	–	±100	Farshidfar and Ghassemi Kakroudi, 2012
>20	45-50	–	1.5	<15	<30	–	–	–	–	±100	Farshidfar and Ghassemi Kakroudi, 2012
>23	30-35	–	1.0	<15	<30	–	–	–	–	±100	Farshidfar and Ghassemi Kakroudi, 2012
±42	<20	–	–	±10	±23	±6	–	–	–	±100	Deng *et al*., 2015
27.0	38.3	–	0.22	11.3	17.6	4.0	–	–	–	98.4	Cruz *et al*., 2016
27.5	39.3	–	0.55	11.8	15.5	4.2	–	–	–	98.9	Cruz *et al*., 2016
–	93.0	–	–	4.6	–	–	–	2.0	0.4	100	Kobayashi *et al*., 2014
–	32.8	66.0	–	–	–	–	1.4	–	–	100.2	Cox and Engel, 1990
20.0	21.5	35.5	–	7.1	11.5	3.7	–	–	–	99.3	Cox and Engel, 1990

Various raw materials, such as chromite sand, quartz, zircon sand, carbon black, graphite, or coke, can be used to produce well filler sand (Table I). The oxide phases form the aggregate and matrix phases of the well filler sand (Cruz *et al*., 2016). Carbon hinders the sintering speed and lubricates the particles, thus improving the well filler sand flow. It prevents direct contact between the particles, which assists in the formation of weaker sintered material (Seixas, 2008; Cruz *et al*., 2016).

In the event of the ladle not opening freely, oxygen lancing is used to open the nozzle, reducing the cleanliness of the steel (Deng *et al*., 2016). The quality of steel, specifically high-grade clean steel, has been given more attention in recent years (Pistorius, 2019). Producing clean steel requires extensive control of the nonmetallic inclusions (Verma *et al*., 2011). Previous research (Wunnenberg, 2005; Zhang *et al*., 2007) demonstrated that the presence of contaminants and inclusions escalates the internal deformities and diminishes the fatigue and erosion resistance of steel. Since well filler sand can indirectly be a source of these inclusions due to lancing, it is important that the sintering behaviour of well filler sands is well understood (Kobayashi *et al*., 2014).

One example of such an investigation is the work done by Cruz *et al*., (2016), who studied the free opening performance of a steel ladle as a function of filler sand properties. In their study, four chromite- and silica-based well filler sands were fired in an electric furnace at 1600°C and analysed using scanning electron microscopy (SEM). Energy dispersive spectroscopy (EDS) was used to assist with phase identification. From the microstructures of the sintered sand obtained, it was observed that:

➤ All aggregates were chromium oxide. It was stated that a good dispersal of aggregates in the sintered well filler sand enhances its performance.

- Aggregates were surrounded by a matrix of higher silica content, with a lower melting point. It was stated that the correct amounts of aggregate and matrix phases are important for optimal performance of the well filler sand.
- The fraction of liquid in the well filler sand aids the formation of a sintered surface layer, which stops infiltration of the molten metal into the nozzle.

Another example is Deng *et al.*, 2015 who studied the effect of temperature and holding time on the sintering of ladle filler sand by liquid steel. They used commercial ladle filler sand, based on chromite and quartz, sourced from Germany. Their main findings were that:

- The reaction between the silica phase and the chromite phase is the main mechanism for sintering of well filler sand.
- The reaction results in a liquid oxide phase, which becomes the binding phase between the solid oxide grains.
- The amount and grain size of silica have a great impact on the formation of the liquid phase.
- Faster formation of the liquid phase leads to more sintering.
- The sand becomes denser – *i.e.* agglomeration increases – with increased sintering time.
- Changes in the composition of chromite before and after sintering occurred.
- Changes in the bulk modal composition of filler sand samples occurred.

Although there have been numerous studies on the sintering of well filler sand (Cox and Engel, 1990; Cruz *et al.*, 2016; Deng *et al.*, 2015; Deng, 2016; Kobayashi *et al.*, 2014; Kovacic *et al.*, 2014; Tajik, Nugin, and Holke, 2018), few studies report on the systematic development of well filler sands and none deal with the systematic development of well filler sands based on South African raw materials. This work therefore forms part of a larger study aimed at filling the gap by focusing on the systematic development of well filler sands based on South African raw materials, specifically chromite and quartz.

Background

Sintering of well filler sand

According to Deng (2016), the primary mechanism for sintering well filler sand is the reaction between silica and chromite grains that leads to liquid formation. Different variables such as the chemistry of the liquid steel in contact with the well filler sand, sintering time, sintering temperature, and particle size distribution and chemistry of the well filler sand constituents have a great impact on sintering (Deng, 2016; Kovacic *et al.*, 2014; Cruz *et al.*, 2016; Tajik, Nugin, and Holke, 2018). All well filler sands used for the ladle tap-hole nozzle are powders of various chemical compositions in different weight ratios and particle sizes. At least one composition is needed to react favourably with liquid metal and to form viscous glass at high temperatures capable of preventing the metal from penetrating the well. Moreover, a highly refractory aggregate phase is necessary to keep the well filler in shape throughout the process of refining before casting takes place (Tseng *et al.*, 2012). In a study by Deng (2016), where two different chromite-based well filler sands were used for laboratory sintering experiments, the sand with smaller size and higher silica content formed more liquid phase and was much denser. It was demonstrated that liquid phase formation is related to dissolution of the silica phase in the well filler sand. It was noted that silica plays a significant role in the degree of well filler sand sintering.

Aim of this investigation

In this work, the effect of silica concentration on the degree of sintering of chromite-silica well filler sand is investigated to understand:

- The main sintering mechanism of well filler sand based on South African raw materials
- The effect of the silica content on the extent of sintering of the well filler sand.

Experimental procedure

Five different chromite-based well filler sands were used. These sands all consisted of three raw materials, namely silica sand, chromite sand, and carbon black powder. The characteristics of the raw materials, as obtained from the supplier's data-sheets, are summarized in Table II.

The well filler sand chemistry was varied according to Table III, by varying the SiO_2 and Cr_2O_3 content while keeping the C content constant. Weighing was accomplished with the use of a laboratory scale (Mettler Toledo, SB32001-F Delta Range). The weighed raw materials were blended using a Turbula Shaker Mixer T2F at a rotational speed of 101 r/min for one hour.

Thirty grams of each mix of well filler sand was poured into 27 mm diameter alumina crucibles. The crucibles were charged into a high-temperature chamber furnace (Lenton, B-type, England) heated at a rate of 10°C/min, and sintered at 1600°C for one hour in air. At the end of the sintering time, the furnace was switched off and the samples left overnight to cool to room temperature. The cooled, solid sintered samples were removed from the furnace and sectioned for analysis.

The bulk phase chemical compositions of each unsintered and sintered sample, as well as the as-received raw materials, were determined by X-ray diffraction (XRD) analysis using a Bruker D8 Advance powder diffractometer, with Linxeye detector and variable divergence and fixed receiving slits with Fe-filtered Co-Kα radiation. The instrument was run from 0 to 80° 2Θ. Phases were initially identified using Bruker Eva software. Quantitative XRD was performed using the DIFFRAC.SUITE TOPAS software package, based on Rietveld refinement and the fundamental parameters approach (FPA).

Table II

Characteristics of raw materials (from suppliers' data-sheets)

Materials	Particle size (µm)	Purity (%)	Supplier
Silica sand	<1180	99.75	Consol
Chromite sand	<850	46.16	Intocast SA
Carbon black	0.049 - 0.060	99.0	Orion Engineered Carbon

Table III

Compositions of the various well filler sand samples (weight %)

Mix ID	Silica sand	Chromite sand	Carbon black
Sample 1	40	60	0.5
Sample 2	35	65	0.5
Sample 3	30	70	0.5
Sample 4	25	75	0.5
Sample 5	20	80	0.5

The unsintered and sintered samples, as well as the as-received raw materials, were prepared into polished sections for analysis to determine the specific phase chemistry. Selected phases were analysed for major elements as well as selected trace elements. Analyses were carried out using wavelength dispersive spectrometry (WDS) by electron microprobe analysis (EMPA) using a Jeol JXA-8230 Superprobe. Oxygen was assigned stoichiometrically. Typically, counting times of 20 seconds on peak and 5 seconds on each of two background positions adjacent to the peak were employed at an accelerating voltage of 20 kV, and a beam current of 30 nA with a beam defocused to a diameter of 5 µm, except where noted otherwise. A defocused beam of 10 µm diameter was used on sinter material that comprised a fine intergrown matrix of Si, Al, Cr, Fe, and Ti phases. The intergrown phases in the matrix were nanometric in scale and it was not possible to target individual phases within the sinter with the beam resolution of 1 µm. In certain points a reduced beam of 3 µm was used with an increased count time to ensure a reasonable total was achieved. The system was calibrated using pure elemental oxide and sulphide standards. BSE images of points of interest were captured indicating the point of analysis.

Major elements were determined on the pulverized portion of the unsintered and sintered samples, as well as the as-received raw materials, using inductively coupled plasma optical emission spectroscopy (ICP-OES) (Thermo Scientific, iCAP7600 Radial). These elements were Mg, Al, Si, Ca, Ti, V, Cr, Mn, Fe, Co, and Ni. This method has a detection limit of 0.05% on Mg, Al, and Ca, 0.01% on Ti, V, Mn, Co, and Ni, 0.2% on Si, 1% on Cr, and 0.5% on Fe. The results from the chemical analysis were used for mineral-chemical reconciliation of XRD data.

FactSage 7.2 thermodynamic software (Bale *et al*., 2002) was employed to predict, as a function of temperature, the different phases present for the various well filler sand compositions as well as the percentage liquid phase present in each. The calculations were based on the mixtures defined in Table III and the bulk chemical compositions of each raw material. The liquid phase formed at equilibrium as a function of temperature was plotted.

Results and discussion

Bulk phase compositions

Quantitative bulk phase chemical analysis by XRD revealed that the chromite does not have a typical end-member composition but rather one more like those found in the Bushveld Complex, with appreciable Mg and Al. Further to the chromite, inclusions, attached gangue and veins of gangue minerals were identified. The gangue phases included feldspar, pyroxene, quartz, and talc as identified by EMPA.

For the sintered samples, four crystalline phases were identified by XRD analysis. Chrome-bearing phases identified were chromite and the sesquioxide, eskolaite (Cr_2O_3). Further, quartz and cristobalite (both with end-member chemical formula SiO_2) were noted. Each diffractogram between 3 and 15° 2Θ was shaped as a broad hump, suggested the presence of a liquid phase (Bhagath Singh and Subramaniam, 2016). The presence of a liquid phase was expected from the thermodynamic calculations to follow, but phase chemical analyses indicated that not all the quartz reported to the liquid – some was unaffected, while other converted to cristobalite.

The X-ray diffractograms for sample 1, sintered and unsintered, are shown in Figure 3 and Figure 4 respectively. The bulk composition of each sintered sample is shown in Table IV and the proportion of quartz and cristobalite in each sintered sample relative to their starting proportions in Table V. Melted SiO2-rich liquid can recrystallize when slow-cooled and would not necessarily report as an amorphous liquid phase under XRD. The use of the XRD amorphous phase quantification would be more justifiable if the samples were water-quenched.

Main sintering mechanism for well filler sand based on South African raw materials

The main sintering mechanism of well filler sand based on South African raw materials is the reaction between the silica and chromite sand grains that leads to liquid formation. This

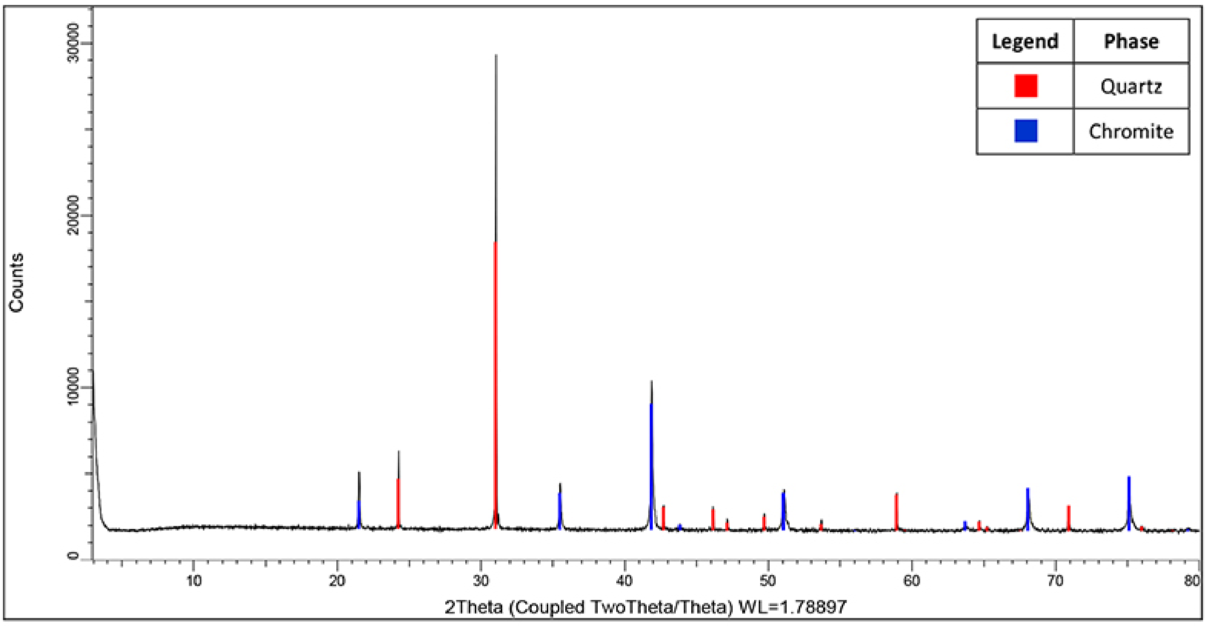

Figure 3—X-ray diffractogram for unsintered sample 1

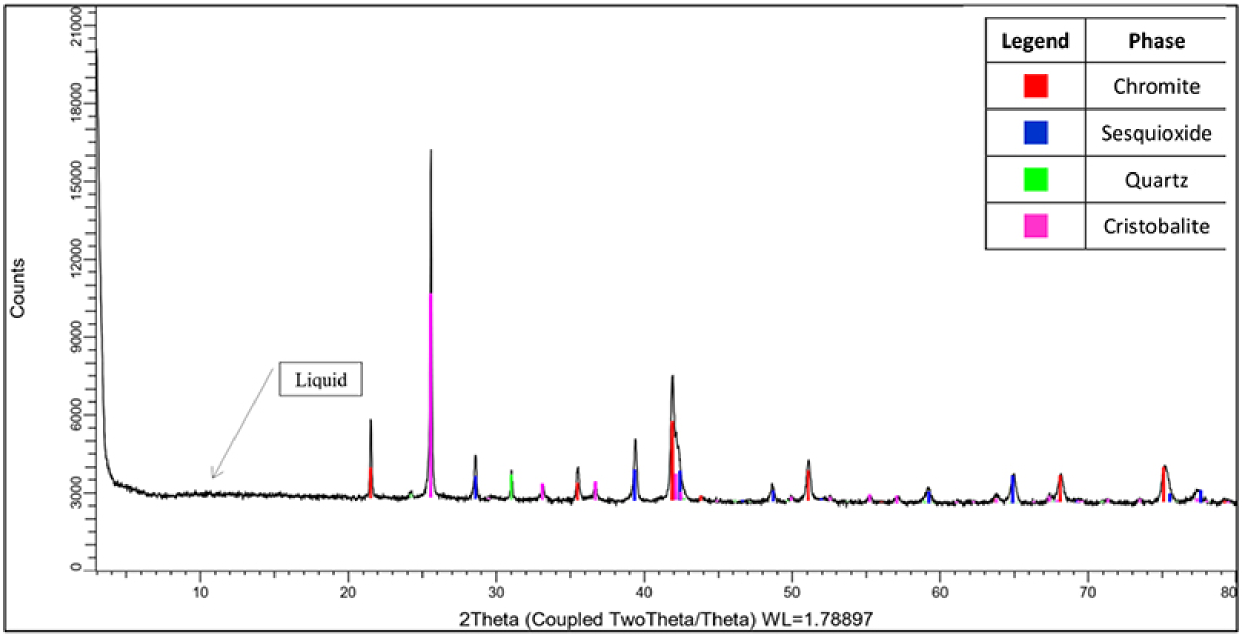

Figure 4—X-ray diffractogram for sintered sample 1

Table IV

Bulk phase composition of each sintered sample determined by quantitative XRD (mass %)

Crystalline phase	Sample				
	Sintered S1	Sintered S2	Sintered S3	Sintered S4	Sintered S5
Chromite	33.6	33.7	36.4	35.0	38.3
Sesquioxide	23.1	24.4	24.9	24.8	27.6
Quartz	7.4	5.9	7.6	6.7	7.0
Cristobalite	19.9	20.7	17.9	14.8	11.8
Liquid	16.0	15.3	13.2	18.8	15.3
Total	100	100	100	100	100

Table V

Proportions of quartz and cristobalite in each sintered sample relative to their starting proportions, determined by quantitative XRD (mass %)

Quartz + cristobalite	Sample				
	Sintered S1	Sintered S2	Sintered S3	Sintered S4	Sintered S5
Starting proportion	40	35	30	25	20
XRD	27.3	26.6	25.5	21.5	18.8
XRD ÷ Starting proportion × 100	68.3	76	85	86	94

observation is supported by the bulk phase chemical analysis, which detected only chromite and quartz in the unsintered samples, while in the sintered samples, sesquioxide, cristobalite and a liquid phase were also noted (Table IV). Examination by electron microprobe confirmed the presence of chromite, silica, sesquioxide, and the liquid phase. The liquid phase between the chromite and quartz grains, responsible for sintering, comprised Si, Al, Mg, and Fe (Table VI). These elements mobilized from the quartz and chromite (Table VII). This observation is in agreement with that of Deng (2016), the main difference between the two sands being the silica size and content. SEM images of Deng's (2016) sintered sand at various sintering times demonstrated three phases: liquid; chromite, and silica. Deng (2016) also analysed the boundary between chromite and silica in order to investigate the sintering mechanism and demonstrated that a thin layer of liquid formed between the silica and chromite phases. Cations such as Fe^{3+}, Mg^{2+}, and Al^{3+} in chromite diffused to the boundary and reacted with silica to form a liquid phase, while Cr^{3+} remained in the chromite phase (van Orman and Crispin, 2010; Vogt, Dohmen, and Chakraborty, 2015; Suzuki, Yasuda, and Ozawa, 2008). In a study by Cruz *et al.* (2016), from SEM images and EDS analysis of four different chromite-based well filler sands sintered at 1600°C, it was also observed that all aggregates were chromium oxide and that the aggregates were surrounded by a matrix of higher silica content that had an aspect of a fully fused material (liquid phase).

Table VI

Calculated average quantitative phase compositions (wt. %) of phases identified by EMPA in sintered sample 1-5. '-'indicates not detected and 'n' indicates the number of analyses used to calculate the average and standard deviation for each component in each mineral phase

Phase	Chromite				Sesquioxide						Silica					Liquid				
	S1	S2	S3	S4	S5	S1	S2	S3	S4	S5	S1	S2	S3	S4	S5	S1	S2	S3	S4	S5
n	6	9	7	12	11	4	16	9	12	8	11	7	4	8	9	8	4	9	13	13
MgO	12.3	13.6	14.0	12.2	10.7	0.5	1.1	1.7	0.7	1.1	0.3	0.1	0.7	0.0	0.2	8.9	4.7	7.0	6.2	7.2
Stdev	2.5	1.9	2.3	3.4	2.0	0.2	1.1	1.7	0.5	0.8	0.5	0.1	0.8	0.02	0.2	3.9	2.7	4.0	2.5	2.6
Al_2O_3	12.4	13.9	13.3	13.1	12.3	11.5	13.6	15.0	13.2	12.7	0.7	0.6	2.0	0.4	0.7	20.3	14.6	20.7	17.1	20.9
Stdev	1.9	1.8	1.9	1.9	2.2	1.9	2.0	2.9	3.6	3.2	1.4	0.3	2.1	0.3	0.7	5.6	10.6	8.5	7.1	5.3
SiO_2	0.1	0.1	0.1	0.2	0.1	0.3	0.9	0.1	0.1	0.1	97.7	98.9	93.7	96.5	97.5	42.1	52.3	39.2	48.4	47.5
Stdev	0.01	0.1	0.03	0.5	0.01	0.3	2.3	0.03	0.1	0.04	2.5	1.5	3.2	2.2	2.8	17.7	10.8	21.6	26.7	15.0
CaO	-	0.1	-	-	-	-	0.0	-	-	-	-	0.1	0.0	0.1	0.4	0.1	0.2	1.4	0.2	0.1
Stdev	-	-	-	-	-	-	-	-	-	-	-	0.02	0.01	0.1	0.8	0.04	0.3	2.4	0.3	0.1
Cr_2O_3	47.6	46.7	44.9	46.2	47.7	58.7	52.6	52.2	58.6	59.3	0.2	0.3	0.1	1.1	0.1	0.9	0.6	0.4	0.7	0.7
Stdev	3.5	2.2	5.0	4.4	1.8	8.8	8.4	6.8	7.3	6.7	0.14	0.4	0.1	1.5	0.1	1.8	0.5	0.4	0.7	0.8
TiO_2	0.3	0.2	0.2	0.3	0.4	0.9	1.6	3.1	1.2	2.0	0.1	0.6	0.2	0.3	0.2	1.0	4.8	5.6	3.6	1.4
Stdev	0.18	0.1	0.1	0.2	0.3	0.56	1.4	2.4	0.7	1.2	0.07	0.1	0.1	0.2	0.2	1.8	4.2	7.0	6.1	1.5
MnO	0.3	0.4	0.4	0.3	0.3	-	-	-	-	0.1	-	-	-	-	0.1	0.3	0.2	0.4	0.2	0.2
Stdev	0.07	0.1	0.1	0.1	0.1	-	0.02	0.03	0.02	0.02	-	-	-	-	0.1	0.17	0.1	0.4	0.2	0.1
Fe_2O_3	27.3	26.9	27.5	28.1	29.4	26.2	29.9	25.7	25.1	23.2	0.5	0.3	1.8	0.5	0.6	25.1	22.5	22.5	23.2	22.2
Stdev	0.4	0.5	0.8	0.7	0.2	5.5	3.1	5.3	4.5	3.7	0.14	0.04	0.3	0.1	0.1	2.4	2.2	2.6	3.4	3.0
Total	100.3	101.9	100.4	100.4	100.9	98.2	99.7	97.8	98.9	98.5	99.5	100.9	98.5	98.9	99.8	99.0	99.9	97.2	99.6	100.2

Table VII

Compositional variation of selected oxides in the liquid phase from sintered sample 4 (defined in Table IV) compared to the compositions of the as-received chromite and quartz. n (number of analysis used to calculate average) = 13

Oxide	Min. (wt. %)	Max. (wt. %)	Average (wt. %)	Standard deviation	As-received chromite	As-received quartz	* Calculated wt. %
MgO	2.1	9.4	6.2	2.5	8.3	-	6.23
Al_2O_3	5.5	26.1	17.1	7.1	15.5	-	11.63
SiO_2	4.6	81.9	48.4	26.7	-	99.9	24.98
Cr_2O_3	0.1	2.4	0.7	0.7	45.6	-	34.20
FeO	4.3	63.7	20.9	19.5	28.0	-	21.00

* For sample 4 with blend ratio: 75% chromite, 25% quartz:
Calculated wt. % = (As-received chromite * 0.75) + (As-received quartz * 0.25)

Quantitative phase analysis

The specific chemical compositions of the phases were quantified by EMPA analysis: the two Cr-bearing phases (chromite and sesquioxide), the Si-bearing phases lumped together (quartz and cristobalite), and the liquid phase located in the welds between chromite and silica particles. The average phase compositions, determined by EMPA, are presented in Table VI. Due to the oxidizing atmosphere in which the samples were sintered for this study, Fe^{2+} ions oxidized to Fe^{3+} and generated vacancies which resulted in separation of a Fe-rich phase, sesquioxide (Tathavadkar, Antony, and Animesh Jha, 2005). During oxidation of chromite ore, the Fe^{2+} is known to preferentially report to the sesquioxide lamellae that form (Biswas *et al.*, 2018). To maintain charge in the spinel matrix, Mg^{2+} counter-diffusion is needed, which results in Mg depletion of the sesquioxide phase (Tathavadkar, Antony, and Animesh Jha, 2005). The distinction between chromite and sesquioxide was determined in this study by XRD analysis (Figure 3 and Figure 4). The distinction was further made by the Mg content. The range of Mg in chromite was identified as 'high' (>10 wt. % MgO), while in sesquioxide Mg was 'low/ (<2 wt. %).

Cation recalculation was carried out for both the chromite and sesquioxide phases. For phases assigned as 'chromite', stoichiometry generally conforms to expected ratios for this structure ($FeCr_2O_4$), further supporting this assignment in most cases. For phases assigned as 'sesquioxide' the cation ratios do not conform to a sesquioxide structure (Cr_2O_3), but, however, neither can they be assigned to a chromite structure ($Fe_2Cr_2O_4$). The assignment as 'sesquioxide' is therefore based on XRD analyses – this conclusion is valid since good XRD reconciliation/validation was achieved using EPMA compositional data on 'sesquioxide' phases.

A BSE image from a selected area in sintered sample 1 is presented in Figure 5. The Cr-bearing particles display a breakdown along their boundaries, evidenced by the lenticular, blocky grains with higher BSE intensities. EMPA showed that the lenticular to have higher concentrations of Cr than chromite centres, and these are classified as sesquioxide. Chromite in the sintered samples also displays typical exsolution lamellae,

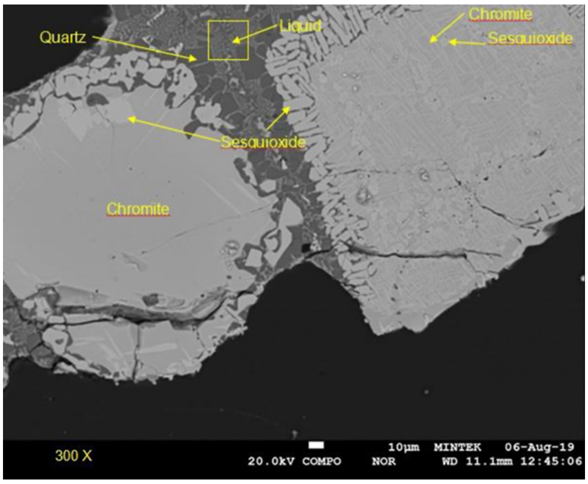

Figure 5—BSE micrograph of selected area from sintered sample 1 (defined in Table III)

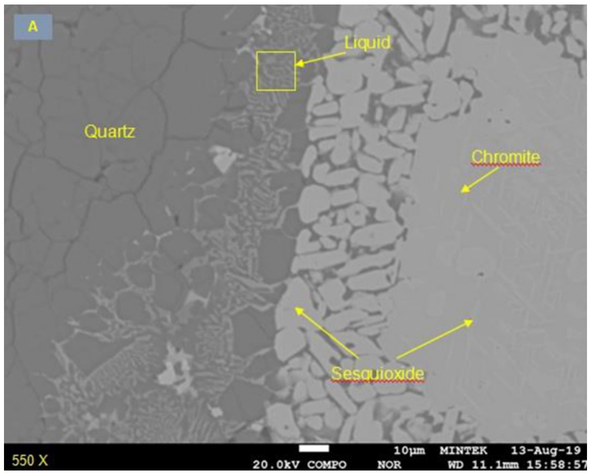

Figure 6—BSE micrograph of selected area from sintered sample 4 (defined in Table III)

noted by the higher BSE intensity and cross-hatched form. EMPA revealed that the bright phases have a lower Mg content and are therefore considered to be sesquioxide, while the areas with the lower BSE intensity revealed higher concentrations of Mg and are therefore considered to be chromite.

A magnified portion of the liquid phase from sintered sample 4 is depicted in Figure 6. Here the chromite and exsolution lamellae and broken-down grain boundaries of sesquioxide are evident in conjunction with quartz. Utilizing a defocused beam, the composition of the liquid phase was determined. The compositional variation of the liquid phase from sintered sample 4 is shown in Table VII. While the composition is highly variable, it is clear that these elements were mobile and diffused from the surrounding quartz and chromite upon sintering. According to Scowen, Roeder, and Helz (1991) the compositional changes are the result of the re-equilibration of chromite with the residual melt by cationic diffusion.

Mineral-chemical reconciliation

The results from the chemical analysis were used for mineral-chemical reconciliation of XRD data (Table VIII). The standard deviations for all the elements in the liquid phase were below 5% and the averages were hence considered to be acceptable. Overall, the mineral-chemical reconciliation is good, the slight differences noted are due to variation in the composition of all phases (results are stated for the liquid phase only, but we do see variation in the chromite and sesquioxide as well. For example, the SiO_2 in the amorphous phase ranges from 48-58% and Cr_2O_3 in chromite from 44-50%.

Quantitative mineral mapping

Quantitative mineral maps for sintered samples, at various magnifications, are presented in Figures 7–11 for the major components of the samples: Si, Cr, Al, and Fe. The elemental map of selected area in sintered sample 1 (Figure 7) highlights the dissolution of the silica phase and the presence thereof in the liquid phase. Cr is not present in the liquid phase. Al and Fe are present in the chromite phase as well as the liquid phase; this further confirms the mobilization of Si, Al, and Fe from the starting material grains to the liquid phase in-between.

The elemental map of the selected area in sintered sample 2 (Figure 8) indicates the presence of a chromite-bearing phase with higher Al and Mg contents at the boundary of the chromite and liquid phase. Higher Si concentration is also noted at the boundary between the chromite and liquid phase, demonstrating the dissolution of the silica phase.

In Figure 9, the chromite particles display a breakdown along their boundaries. The Al and Mg concentrations are higher along the boundaries of the chromite particles. Figure 9 also demonstrates the presence of liquid phase (which contains a significant amount of Si), surrounding the chromite grains.

Table VIII

Mineral-chemical reconciliation of each sintered sample (elemental %). Min; = mineral contribution (XRD), Che. = chemical contribution (ICP-OES) Δ = Mineral contribution % - Chemical contribution %

Oxide	Sample														
	Sample 1			Sample 2			Sample 3			Sample 4			Sample 5		
	Min.	Che.	Δ	Min.	Che.	Δ	Min.	Che.	Δ	Min.	Che.	Δ	Min.	Che.	Δ
SiO_2	33.5	33.3	0.2	34.5	32.1	2.4	30.8	26.5	4.3	29.9	24.0	5.9	25.6	19.4	6.2
MgO	5.8	6.2	0.4	5.6	6.3	0.7	6.3	6.8	0.5	5.6	7.1	1.5	5.6	7.4	1.8
CaO	-	0.1	0.1	0.1	0.1	0	-	0.1	0.1	0.1	0.2	0.1	0.1	0.1	0
Al_2O_3	10.3	10.1	0.2	10.4	10.2	0.2	11.0	11.2	0.2	11.1	11.6	0.5	11.5	12.4	0.9
FeO	17.4	18.6	1.2	17.9	18.7	0.8	17.9	20.3	2.4	18.5	21.1	2.6	19.1	22.6	3.5
Cr_2O_3	29.7	30.7	1	28.7	30.0	1.3	29.4	31.4	2	31.0	32.9	1.9	34.8	38.1	3.3

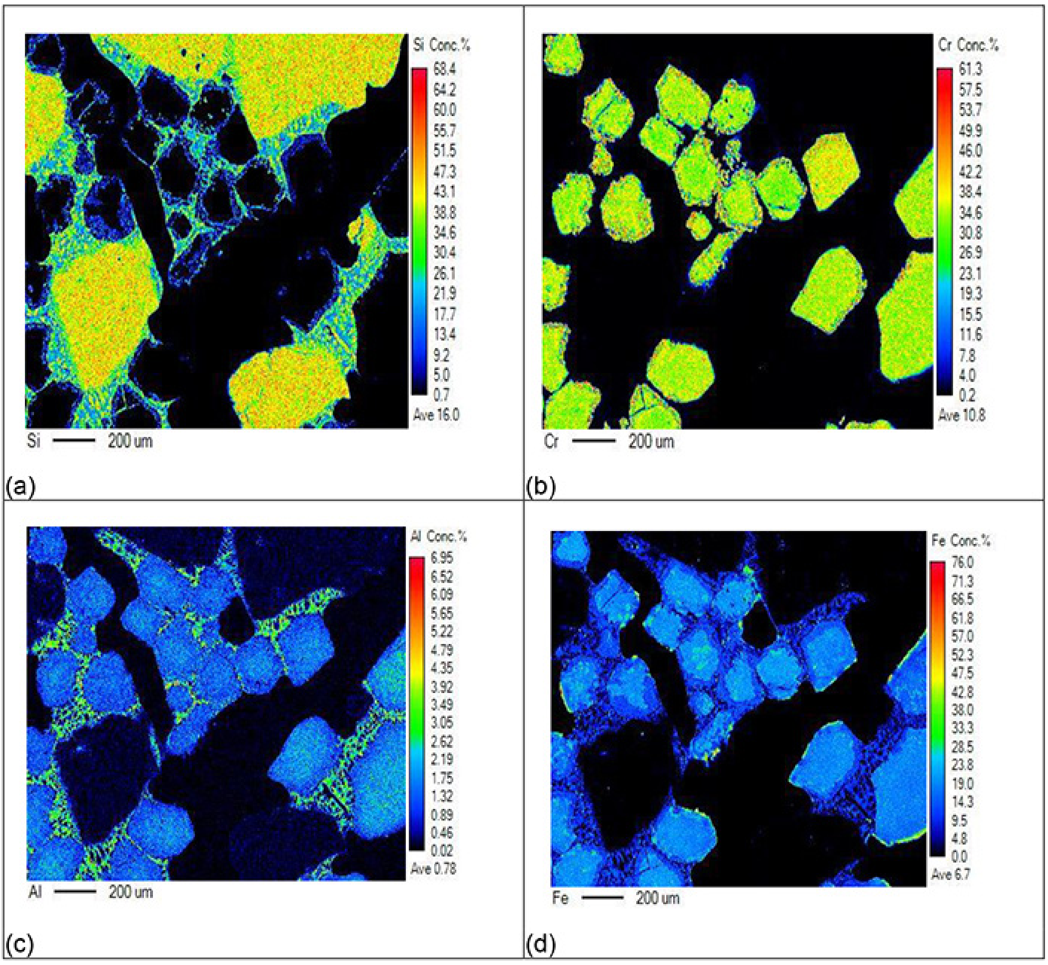

Figure 7—Quantitative elemental maps for Si (a); Cr (b); Al (c), and Fe (d) for a selected area in sintered sample 1

The breakdown of chromite particles and Fe depletion at the boundaries of the chromite particles (Demir and Eric, 2015) is evident in Figure 10. The silica phase in contact with the chromite phase is displayed with the liquid phase forming in-between the silica and chromite phases. Again, the Al concentration is higher in the liquid phase than in the chromite phase, indicating mobilization of the Al from the chromite phase to the liquid phase.

Figure 11 shows the interface between various chromite grains. Here the silica phase is no longer visible and the Si is now contained in the liquid phase between the chromite grains. Breakdown of the chromite grains is visible, with lower Fe concentrations at the chromite grain boundary and significant amounts of Al and Fe present in the liquid phase.

The quantitative elemental maps further demonstrate the mobilization of Si, Al, and Fe from the starting material grains to the liquid phase in-between (Figures 7–11). Elemental maps from silica well filler sand sintering experiments by Kobayashi *et al*. (2014) similarly demonstrated the presence of Al and Si in the liquid phase. A study by Demir and Eric (2015) on the dissolution of chromite in liquid slags demonstrated that the chromium and iron concentrations in the chromite decreased from the centre of the chromite grains towards the periphery. Magnesium and aluminium concentrations increased at the edges of the chromite grains.

The quantitative elemental maps highlight the dissolution of the silica phase and the presence thereof in the liquid phase. They also indicate the silica phase in contact with the chromite phase, and that a liquid phase is forming between the silica and chromite phases. This demonstrates that the main mechanism for sintering of well filler sand based on South African raw materials is the reaction between the silica and chromite sand grains, and that the silica and chromite phases react to form a liquid phase responsible for sintering.

Effect of the silica content on the extent of sintering

We further found that the silica content in well filler sand has a strong influence on its degree of sintering, with the amount of liquid phase forming increasing with increasing silica content. This observation is supported by XRD analysis. Table V indicates the quantity of quartz in each sintered sample compared to that of the starting proportions. The comparison indicates that sintered samples 1 and 2 (defined in Table III) containing the highest percentage of quartz pre-sintering contained the least amount of quarts post-sintering (68.3% and 76% of starting proportion respectively), while sintered sample 5 (defined in Table III), with the least amount of quartz pre-sintering, contains the most (94% of starting proportion) quartz after sintering. It is important to note, however, that slow cooling of the samples most likely influenced the crystallization sequence of the samples. Kobayashi *et al*. (2014) similarly concluded that the liquid proportion increased as a result of the dissolution of the silica phase into the liquid phase.

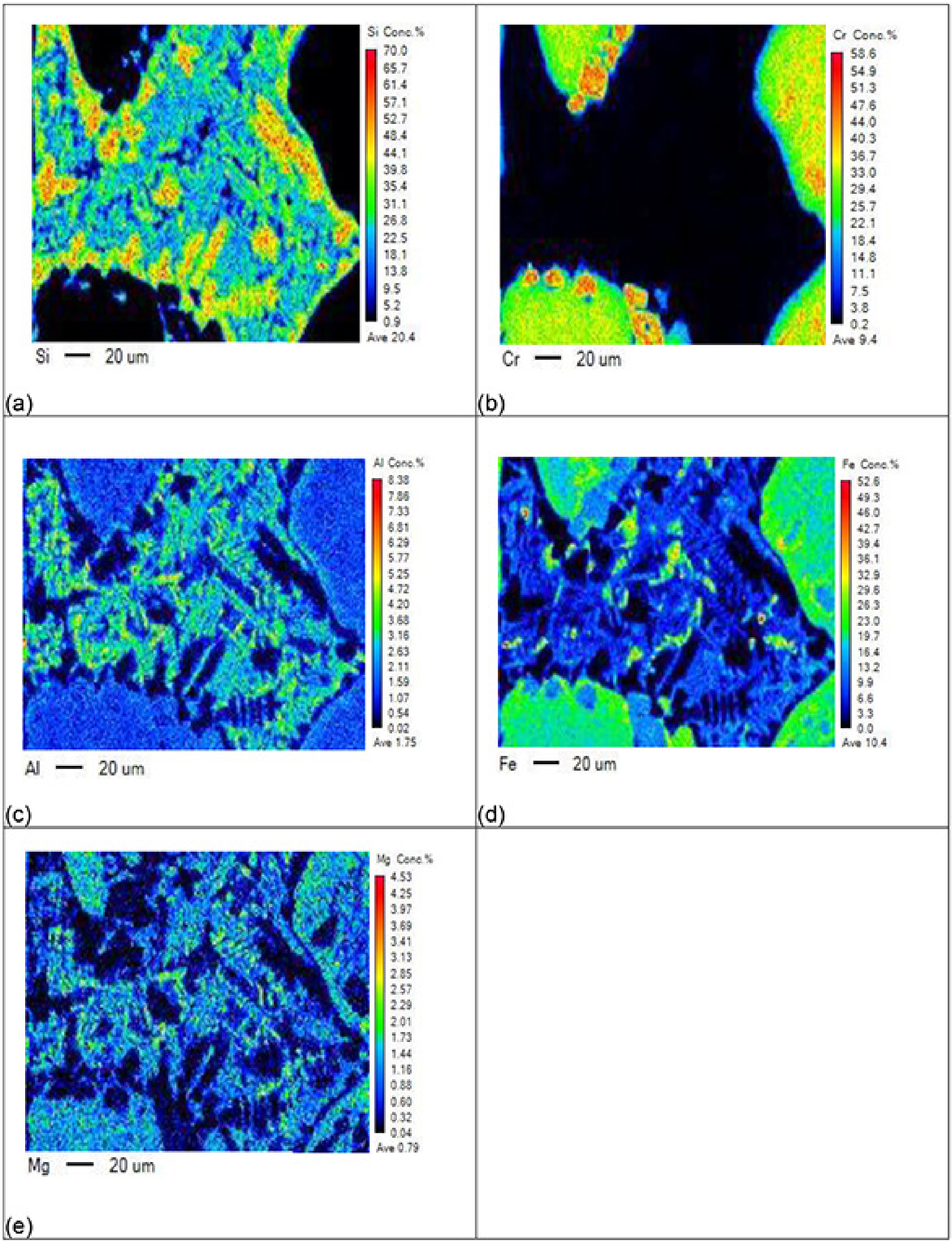

Figure 8—Quantitative elemental maps for Si (a); Cr (b); Al (c); Fe (d). and Mg (e) for a selected area in sintered sample 2

From the quantitative phase analysis (Table VI), the liquid phase in all of the sintered samples consisted of significant amounts of SiO_2. This is further illustrated by the quantitative mineral mapping; which illustrates the high concentration of Si in the liquid phase (Figures 7–11). Again, this observation is in agreement with Deng (2016), where SEM images indicated a larger amount of liquid phase in the sample which contained more silica. Cox and Engel (1990) sintered a zircon well filler sand containing silica, at 1600°C, and similarly, observed from SEM images that the zircon grains were chained together by thin glassy bridges comprised of silica.

The degree of sintering is, however, only quantified by the amount of liquid phase formation in our study. Iron ore pelletizing studies by Nellros *et al*. (2015) and Kumar *et al*. (2018) demonstrated that there is typically an optimum amount of liquid phase required for each combination of particle shapes, sizes, and surface chemistry to give an optimum sintering strength. Excessive liquid formation is typically detrimental to sintering strength. Nellros *et al.* (2015) and Kumar *et al.* (2018) presented methods to quantify the degree of sintering through automatic image analysis based on the geometry and structure of particle joins.

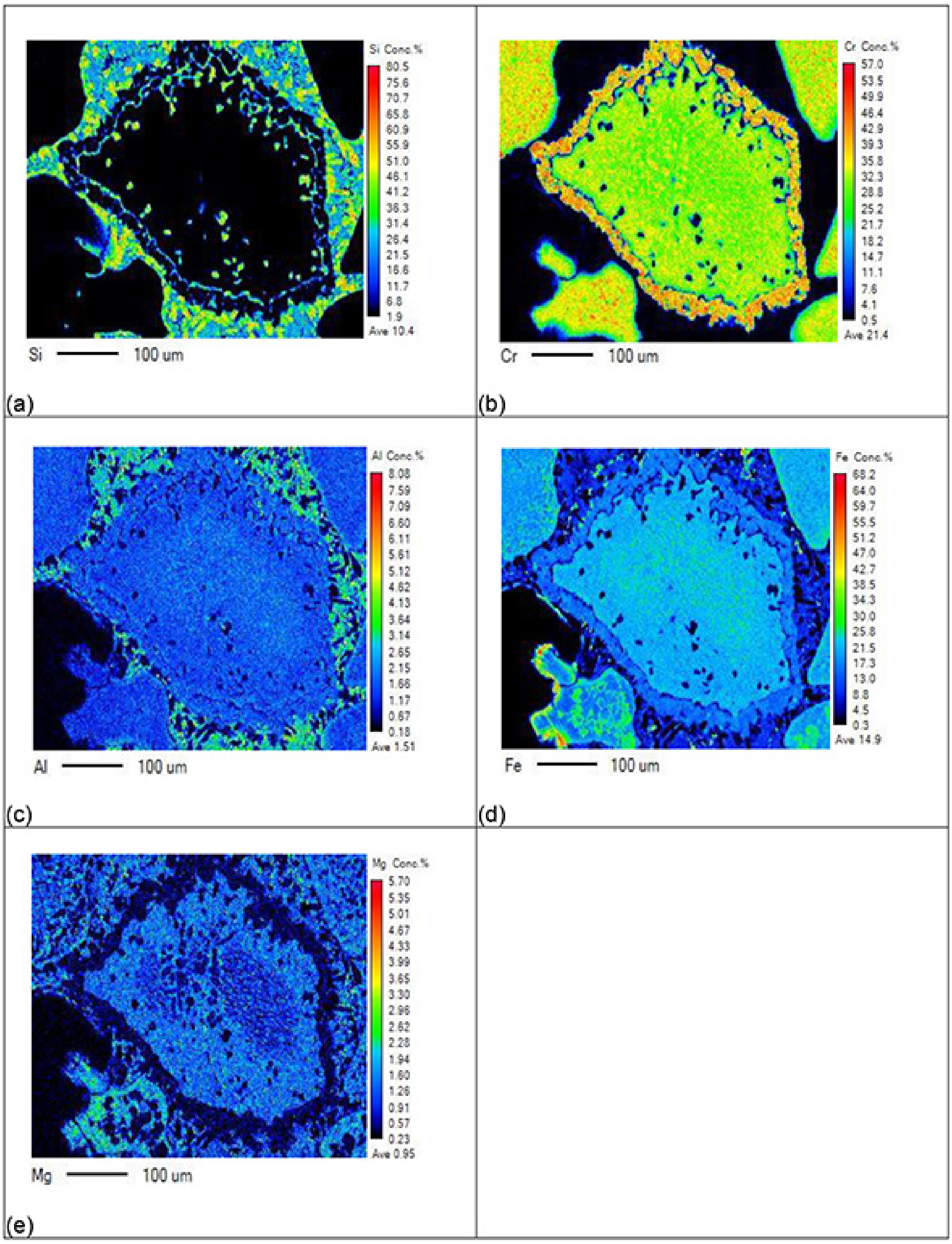

Figure 9—Quantitative elemental maps for Si (a); Cr (b); Al (c); Fe (d) and Mg (e) for a selected area in sintered sample 3

FactSage calculations

FactSage 8.0 thermodynamic software was employed to predict, as a function of temperature, the percentage liquid phase present in each sample at equilibrium conditions. The ratios were defined in Table III and the raw material compositions are presented in Table IX. Furthermore, the optimal ratio (sample 3) were repeated on chromite compositions from other parts of the world, more specifically chromite with different Al_2O_3 and MgO contents . All as-received chemical compositions were normalized prior to calculations.

The Equilib module was utilized and the FToxid, FSstel, and FactPS databases applied. Of the compound species, only gas and solids were selected. For the solids, duplication was suppressed with the order of preference FToxid, FSstel, and FactPS. All solution species were selected, except in cases where multiple options were available and then the A-phase only was selected. The temperature range 1200–1700°C was considered at intervals of 100°C. Pressure was set at 1 atmosphere. Both normal equilibrium and transitions were calculated. The results are presented in Figure 12 for the South African chromite mixed at various ratios with silica, and in Figure 13 for chromites from all over the world mixed at a ratio of 70/30, chromite/silica.

For the South African chromite, the calculated percentage liquid at 1600°C increased with increased silica content in the

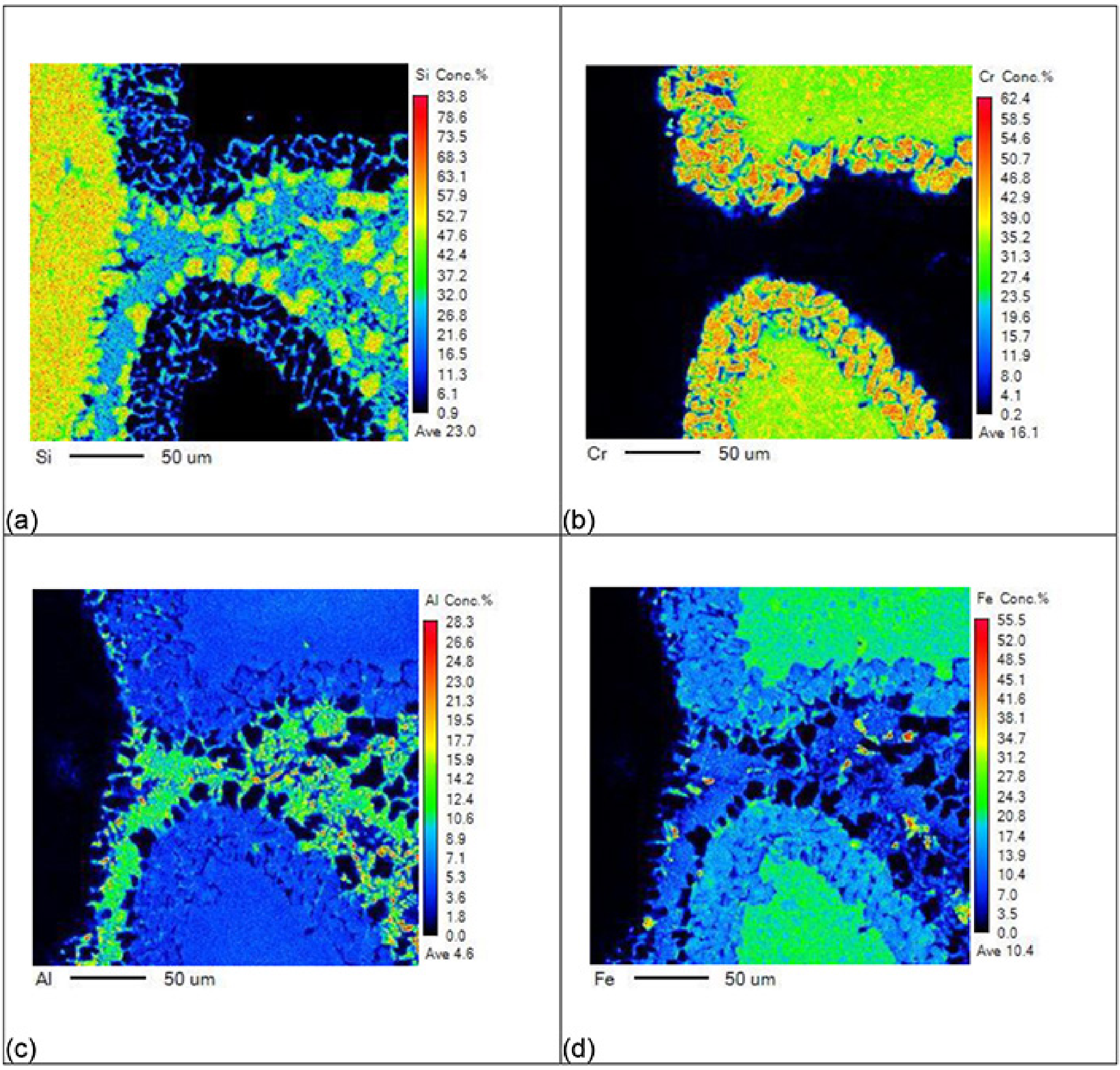

Figure 10—Quantitative elemental maps for Si (a); Cr (b); Al (c) and Fe (d) for a selected area in sintered sample 4

well filler sample (Figure 11), as seen from samples 1 and 2 where the percentage liquid formed was 80% and 77% respectively. With lower silica content, as seen from sample 3, 4, and 5, the percentage liquid decreased, to 75, 72, and 69% respectively. The fact that the actual liquid phase formed after sintering (Table IV) is significantly less than the predicted liquid phase formation at equilibrium, indicates that equilibrium conditions were not reached during the experimental work. The difference in results can therefore be attributed to heat and/or mass transfer phenomena (if the samples are left long enough at temperature, more liquid phase could form). The variances may also be due to inaccuracies in the XRD method applied.

For chromites from other parts of the world, slightly less liquid phase will form at 1600°C compared to the South African chromite (Figure 12). The biggest differences lies at the lower temperatures where the liquid phase would start to form: for the South African chromite, liquid starts to form at 1238°C. For the chromites from India the temperature is 1256°C, from Kazakhstan 1289°C, Zimbabwe 1290°C, and North America 1300°C. This would probably give the South African chromite a competitive advantage.

Conclusions

The aim of this research was to study the effect of silica concentration on the degree of sintering of chromite-silica well filler sand produced from South African raw materials. Laboratory sintering experiments were conducted at constant temperature, time, and atmosphere. The effect of various SiO_2 concentrations on the microstructural phase evolution and amount of liquid phase formation was studied using SEM, EMPA, and XRD. Phase evolution was also simulated using FactSage thermodynamic software.

It can be concluded from this study that:

- ➤ The main mechanism for sintering of well filler sand based on South African raw materials is the reaction between the silica and chromite sand grains.
- ➤ The silica and chromite phases react to form a liquid phase responsible for sintering.
- ➤ An increase in silica content in the well filler sand resulted in the formation of a liquid phase and was observed to also improve sintering. However, the silica and chromite contents were both responsible for sintering.

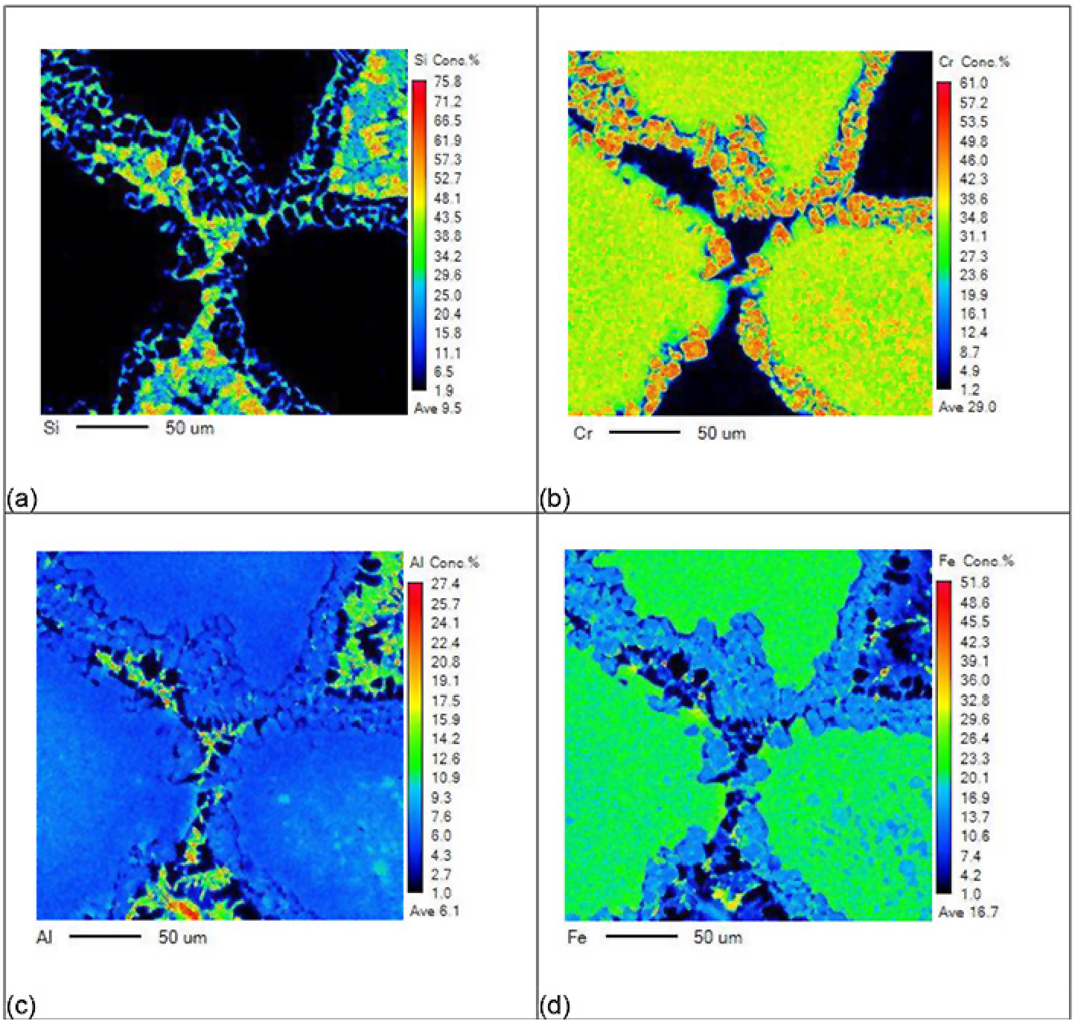

Figure 11—Quantitative elemental maps for Si (a); Cr (b); Al (c); and Fe (d) for a selected area in sintered sample 5

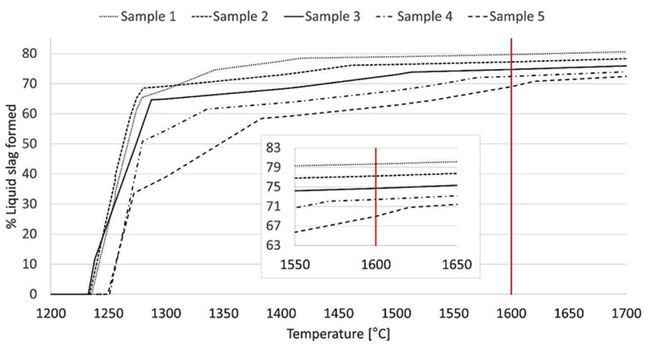

Figure 12 – Results of the FactSage calculation, showing the liquid fraction that forms at equilibrium as a function of temperature for sample 1–5 (defined in Table III and Table IX). The insert indicates a higher resolution version of the results at 1600°C

- ➤ Sintering of the chromite-based well filler sand, which initially consists of only chromite and silica, will result in formation of a second chrome-bearing phase (sesquioxide) and cristobalite with end-member chemical formula SiO2.
- ➤ Previous well filler sand studies (Cox and Engel, 1990; Cruz *et al.*, 2016; Deng *et al.*, 2015; Deng, 2016; Kobayashi *et al.*, 2014; Kovacic *et al.*, 2014; Tajik, Nugin, and Holke, 2018) performed in an inert atmosphere did not report formation of a second chrome-bearing phase (sesquioxide). Due to the oxidizing atmosphere in which the samples were sintered for this study (an oxidative environment is more representative of the application of well filler sand in industry), Fe^{2+} ions oxidized to Fe^{3+} and generated vacancies which resulted in separation of an Fe-rich phase, sesquioxide (Tathavadkar, Antony, and Animesh Jha, 2005).

Future work, addressing the following aspects, will be useful.

- ➤ Further studies on the laboratory-scale, using the methods developed in this investigation, to quantify the effect of carbon addition, particle size distribution, and variations in temperature and holding time on the extent of sintering.
- ➤ Investigation on the laboratory scale into the effect of steel grade on the extent of sintering.
- ➤ Investigation, through a combination of heat transfer modelling and industrial trials, into the temperature profile of the well filler sand during ladle preheating and transportation of liquid steel.
- ➤ Industrial trials to study the effect of the various parameters mentioned on the ladle free opening rate.
- ➤ Further studies into the effect of compaction of the well filler sand due to ferrostatic pressure of liquid steel in the ladle.

Table IX

Chemical compositions for raw materials utilized in FactSage calculations. Compositions for chromites from other parts of the world were obtained from Geldenhuys (2013)

	SiO_2	Al_2O_3	FeO	Cr_2O_3	MgO	C	CaO	Total
Silica no. 1 HP	97.7	0.1	0.0	0.0	2.0	0.0	0.0	100
Normalized	97.9	0.1	0.0	0.0	2.0	0.0	0.0	100.0
Chromite sand AFS 50	1.1	15.6	24.2	44.3	12.2	0.0	0.0	97.31
Normalized	1.1	16.0	24.8	45.5	12.5	0.0	0.0	100.0
Chromite sand Kazakh	6.9	6.5	11.9	51.2	19.8	0.0	0.0	96.30
Normalized	7.2	6.7	12.4	53.2	20.6	0.0	0.0	100.0
Chromite sand Zimbabwe	3.9	12.7	13.3	50.8	17.9	0.0	0.0	98.60
Normalized	4.0	12.9	13.5	51.5	18.2	0.0	0.0	100.0
Chromite sand India A	1.3	11.4	16.9	53.5	11.4	0.0	0.0	94.50
Normalized	1.4	12.1	17.9	56.6	12.1	0.0	0.0	100.0
Chromite sand India B	1.2	12.7	17.9	50.9	10.9	0.0	0.0	93.60
Normalized	1.3	13.6	19.1	54.4	11.6	0.0	0.0	100.0
Chromite sand N. America	5.9	5.9	18.2	44.0	12.8	0.0	0.0	86.80
Normalized	6.8	6.8	21.0	50.7	14.7	0.0	0.0	100.0
Carbon black	0.3	0.1	0.2	0.0	0.1	98.8	0.4	99.99
Normalized	0.3	0.1	0.2	0.0	0.1	98.8	0.4	100.0

➤ Further studies to investigate the effect of pO2 - atmosphere in the laboratory furnace compared to under liquid steel in the ladle.

➤ Investigation of the use of automated measurement of the degree of sintering using optical microscopy through image analysis of particle joins.

Acknowledgements

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Time Mining and Processing (Pty) Ltd
Timrite Pty Ltd
Tomra (Pty) Ltd
Traka Africa (Pty) Ltd
Ukwazi Mining Solutions (Pty) Ltd
Umgeni Water
Webber Wentzel
Weir Minerals Africa
Welding Alloys South Africa
Worley

BATTERY MATERIALS CONFERENCE 2022

24-25 AUGUST 2022

MISTY HILLS CONFERENCE CENTRE,
MULDERSDRIFT, JOHANNESBURG

The intensified search over the past decade for alternatives to fossil-fuels as stores of energy has led to an exponential growth in the demand for batteries and research into battery technologies. The largest application by far has been in transportation, followed by electrical distribution grids.

Of the raw materials required for battery manufacture, metals such as cobalt, manganese and vanadium are highly concentrated in southern Africa. The supply of lithium, on the other hand, is concentrated in Australia, Chile and Argentine.

These activities have created both opportunities and challenges. Opportunities such as new value chains for the associated raw materials, with several production companies with battery-material metals in their plant feedstocks undertaking research towards producing battery-grade products.

And challenges such as the means for recycling these batteries once they reach the end of their (first) life.

The aim of this conference is to provide the opportunity for thought leaders in the global battery value chain to exchange ideas on recent developments in the fields of:

- Materials and high-purity intermediates for battery components
- Flow-battery electrolytes
- Processes for the recycling of batteries
- Market outlook and legislative implications
- Related case studies.

KEYNOTE SPEAKERS

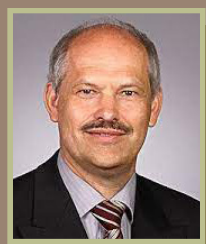
Dr Nils Backeberg
Cape Geo

Prof Jacques Eksteen
Cooperative Research Centre

Prof. Donald Sadoway
Massachusetts Institute of Technology

Prof Justin Barnes
B&M Analysts

Dr Joost Kessels
Volkswagen



Prof Bernd Friedrich
RWTH Aachen University

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