Geotechnical areas associated with the Ventersdorp Contact Reef, Witwatersrand Basin, South Africa

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Synopsis

The approximately 2800 Ma old Ventersdorp Contact Reef is a unique Witwatersrand orebody, from which about 6% of the world's gold production is derived. A major portion of this production is mined at depths exceeding 2500 m and deepest levels of mining are at about 3600 m. The orebody's hangingwall consists of volcanic rocks. This differs from the older Witwatersrand orebodies, which have quartzitic hangingwalls. The thickness of the Ventersdorp Contact Reef is generally about 1.20 m, but is highly variable, at an average dip of about 18°. A pronounced unconformity beneath this orebody is also expressed by varying footwall rock type characteristics and frequent rolling of the reef plane. These rolls follow topographic variations of the palaeo-surface.

More geological than rock mechanics studies were performed on the Ventersdorp Contact Reef prior to 1992. Recently, however, a multidisciplinary team comprising various rock engineering and geological disciplines has delineated geotechnical areas by a novel technique. Geotechnical areas are defined by distinct footwall/hangingwall rock assemblages. The presence of three footwall and two hangingwall rock types results in the definition of six geotechnical areas across a distance exceeding 60 km, including about 10 gold mines. Distinct rock mass behaviour has been documented in three of the six geotechnically defined areas. Different rock mass behaviour is expressed by features such as mining-induced fracturing, closure rates, fall of ground characteristics and seismic character.

Some geological features override the rock mass behaviour as defined for the individual geotechnical areas. These are undulations of the orebody or the frequency, characteristics and attitude of major discontinuities.

It is concluded that the concept of geotechnically subdividing orebodies is not only important for facies delineation and the associated grade, but also needs to be considered for safety aspects, in determining factors such as the appropriate support to be employed.

Introduction

The approximately 2800 Ma old (Armstrong *et al.,* 1991) Ventersdorp Contact Reef (VCR) is one of the major South African gold bearing orebodies being mined along the northern and northwestern edge of the Witwatersrand Basin (Figure 1). It separates the predominantly sedimentary lithologies of the Witwatersrand from the volcanic Ventersdorp Supergroup (Figure 2a; SACS, 1980).

The VCR (Figure 3) has been identified as an exceptional orebody, differing in various aspects, especially its lava hangingwall and pronounced, undulating footwall, from the older Witwatersrand orebodies. Previous geological studies were localized in nature (e.g. Krapez, 1985), with the regional setting of the VCR only recently being considered (S. Afr. Journal of Geology, 1994, Vol. 4, Special Volume on the Ventersdorp Contact Reef; see also Regional VCR Working Group, 1992, 1993, 1994a and b). Recent findings suggest that the VCR should be included into the lowermost portion of the Ventersdorp Supergroup (Germs and Schweitzer, 1994).

The impact of geological features on the rock mass behaviour has been highlighted and documented frequently (e.g. Hepworth and Diamond, 1983; Gay, 1986; Gay and Jager, 1986a and b; Jager and Turner, 1986; Brummer, 1988; Lenhardt, 1990; Gay, 1993; Gay *et al.*, 1995a and b). The behaviour of discontinuities, such as bedding planes, faults and dykes, has also been analysed by rock engineers through computer modelling (e.g. Napier, 1991; Johnson, 1994; Napier and Peirce, 1995; Johnson and Schweitzer, 1996). The above information has especially been utilized to identify the most appropriate support (e.g. Roberts and Jager, 1993; Roberts *et al.*, 1993, 1994).

The rock engineering significance of rock type and the impact of their various assemblages on the rock mass behaviour had not been seriously considered prior to this study. However, the rock types associated with the VCR and their rock engineering properties are highly variable (Figure 2b, Figures. 4a and b). This has led to the adoption of a new approach to the delineation of geotechnical areas. A geotechnical area is defined by a specific footwall/hangingwall rock type

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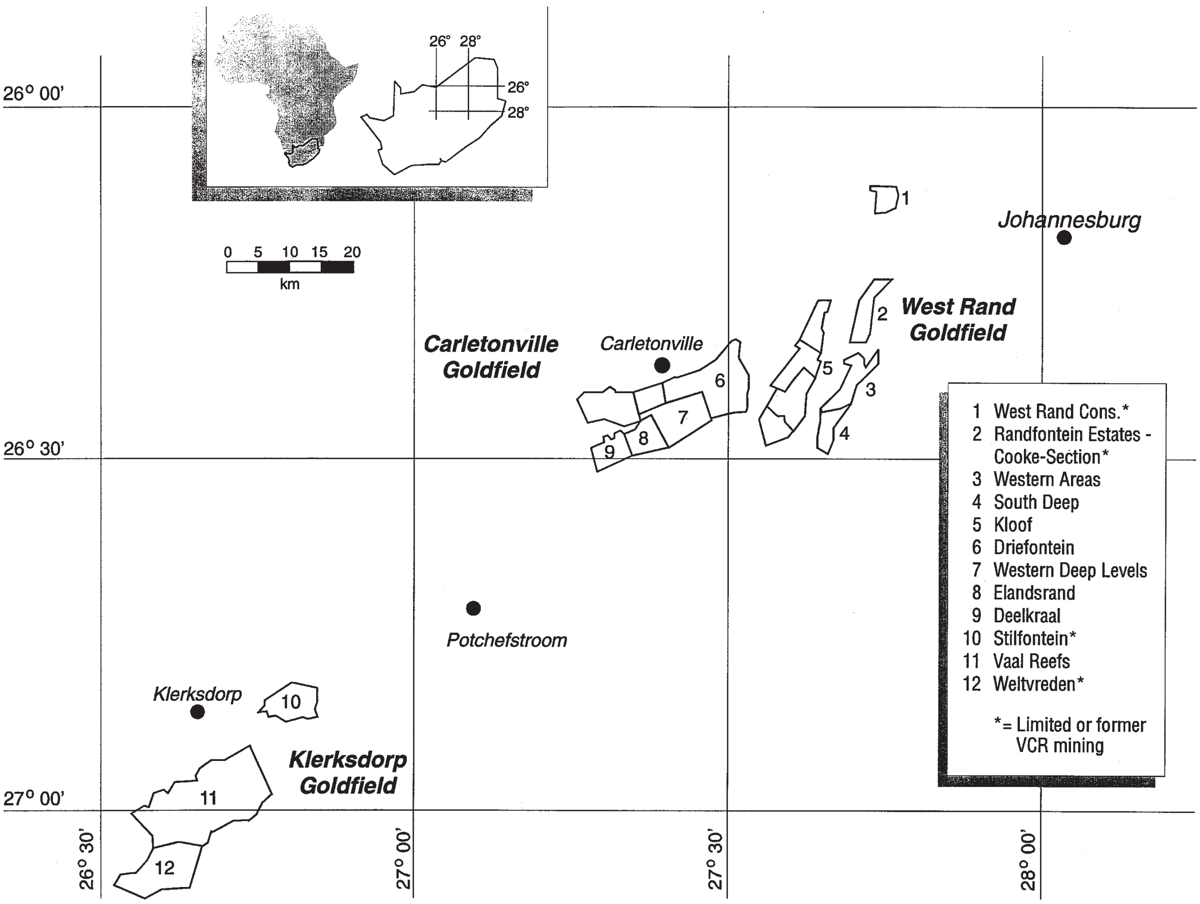
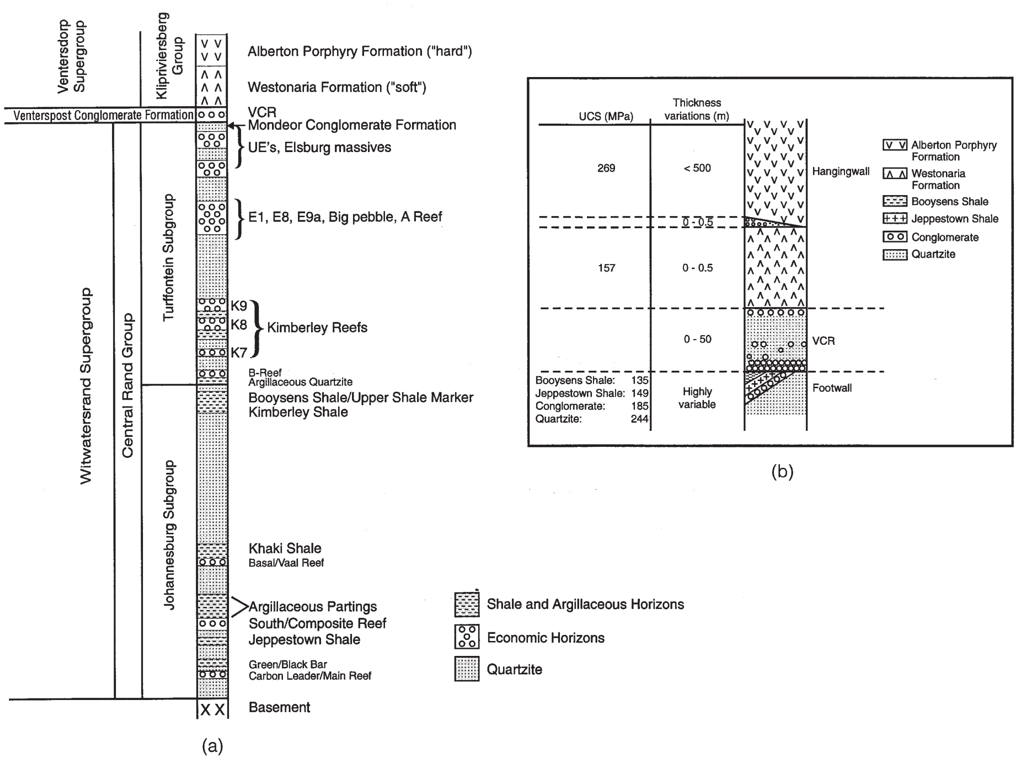


Figure 1—Location of operating and defunct Witwatersrand gold mines mining the Ventersdorp Contact Reef



Figures 2a and b—Stratigraphic position of the Ventersdorp Contact Reef (Fig 2a). An idealized stratigraphic section through the Ventersdorp Contact Reef and under- and overlying rocks, together with the thickness and uniaxial compressive strength (UCS) variations are provided in Figure 2b

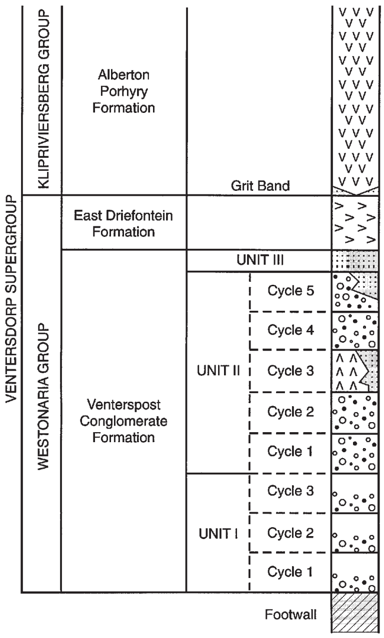
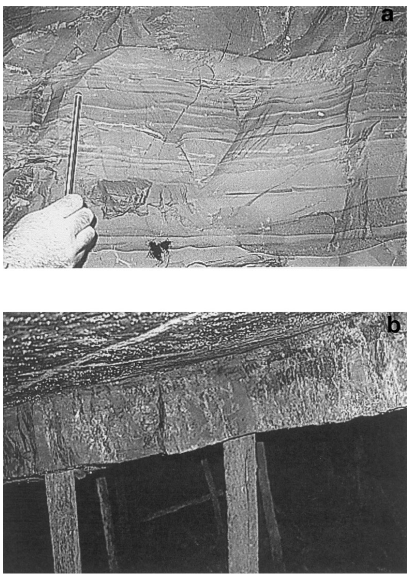


Figure 3—Stratigraphic subdivision of the VCR (after Germs and Schweitzer, 1994), showing the complexity of the VCR rock assemblages

(a)

(b)



Figures 4a and b—Densely spaced bedding planes in the Jeppestown Shale at East Driefontein Gold Mine (Figure 4a, see Figure 1 for locality). A quartzite layer is commonly present in the hangingwall of Ventersdorp Contact Reef excavations where soft lava is the hangingwall lithology. A pronounced parting is developed along the lava/quartzite contact, as documented in Figure 4b for West Rand Consolidated (see Figure 1 for locality)

assemblage. Extrapolation into unmined areas has been done where possible, using exploration information. It is anticipated that different rock mass behaviours are associated with the individual geotechnical areas. Should this concept prove valid it will be of importance for future, similar studies considering other strataform orebodies as, for example, preserved in the Witwatersrand Basin or the Bushveld Complex.

Delineation of geotechnical areas

Quartzite, conglomerate and shale (Figure 4a) represent the major footwall lithologies underlying the VCR (Figure 5a). Quartzites and conglomerates are assumed to possess comparable rock engineering properties and are, initially, considered as one rock type for the establishment of geotechnical regions. Jeppestown Shale at Driefontein (Figure 4a) and Booysens Shale at Leeudoorn, Kloof, Libanon and Western Deep Levels Gold Mines (Figure 1) differ with regard to their geological and rock engineering properties and are, therefore, considered individually.

Volcanic rocks of the Westonaria and Alberton Porphyry Formations (hereafter termed soft and hard lavas, respectively), associated with minor sedimentary intercalations (Figure 2b), are the major hangingwall rock types of the VCR (Figure 5b; Schweitzer and Kroener, 1985; Regional VCR Working Group, 1994a). The soft lava package is generally not thicker than 20 m whereas the thickness of the hard lava varies between 160 and 400 m. The contact between the soft and the overlying hard volcanic rocks is commonly delineated by a thin, prominent quartzite, conglomerate or shale band or a sharp flow contact. This parting is generally less than 40 m away from the VCR stope (Figure 5b). Observations indicate that an, on average, 50 cm thick hangingwall quartzite layer is frequently encountered in areas where soft lava constitutes the hangingwall of the VCR (Figure 4b), determining the beam thickness above the excavation. Soft lava flows immediately overlie the VCR over major areas of Driefontein, Leeudoorn, Kloof, Western Areas, South Deep, and West Rand Consolidated (Figure 1). The presence of the soft lava-type will become increasingly more pronounced in the deeper areas of Leeudoorn and Kloof.

Superimposing the footwall and hangingwall maps (Figures. 5a and b) results in the definition of six geotechnical areas (Figure 5c). Most prominent are areas with hard lava in the hangingwall and quartzite/conglomerate in the footwall of the VCR (Figure 6). This combination is found at almost all the mines under consideration. Areas with soft lava hangingwall and quartzite conglomerate footwall are the second-most prominent geotechnical area.

The VCR footwall plan may be further subdivided to differentiate argillaceous from siliceous quartzites and conglomerates. Competent siliceous lithologies may be associated with seismic events as opposed to argillaceous, less competent rock types. Both rock types, in addition, have been shown to impact differently on the behaviour of stabilizing pillars (e.g. Lenhardt, 1990; Lenhardt and Hagan, 1990). Distinguishing between the siliceous and argillaceous footwall quartzites and conglomerates, and superimposing the VCR hangingwall plan (Figure 5b) leads to the definition of 11 geotechnical areas (Figure 7). The approximate coverage of these areas is summarized in Table I.

Additional geological parameters influencing rock mass behaviour

The geotechnical areas are defined on the basis of rock type assemblages. The various rock types have differing grain sizes, mineral assemblages (resulting in varying competencies) and bedding plane spacings and frequencies, all of these affecting the rock mass behaviour. Varying

Table I

Approximate percentages of geotechnical areas considering siliceous and argillaceous footwall quartzites and conglomerates.

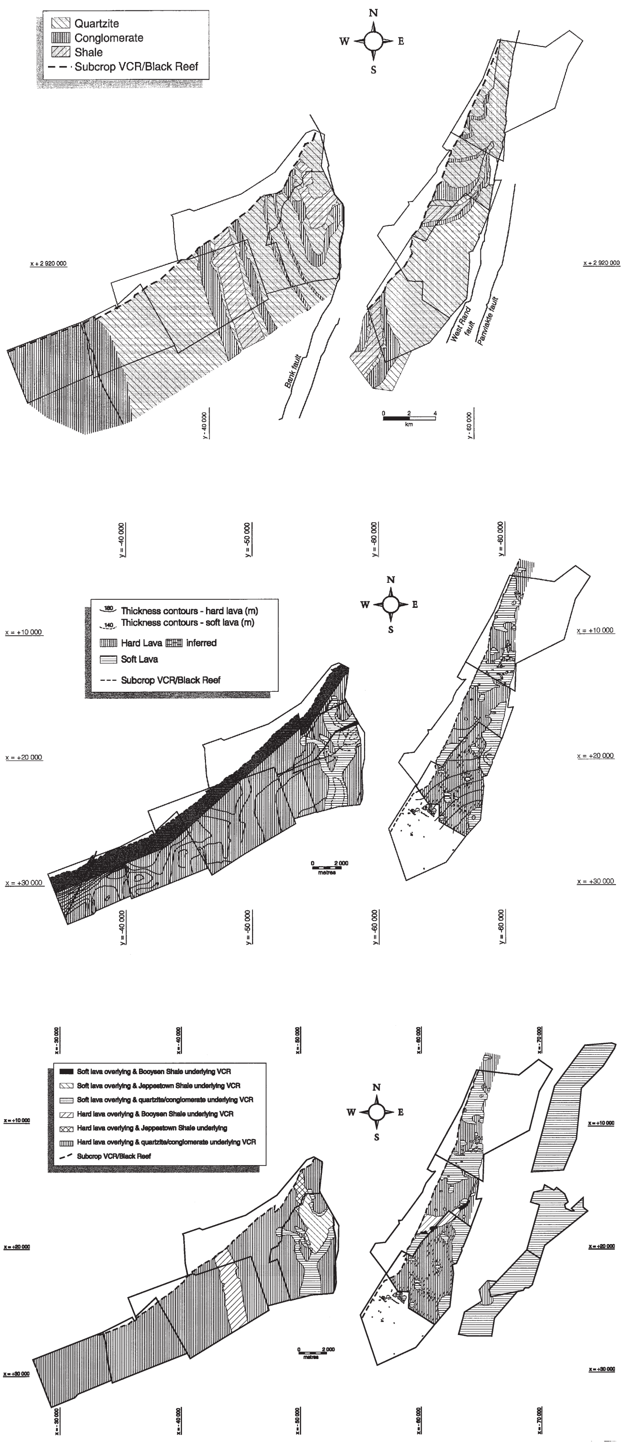
Geotechnical Area		
Footwall	**Hangingwall**	**Coverage %**
Siliceous quartzite	Hard lava	50
Argillaceous quartzite	Hard lava	20
Siliceous quartzite	Soft lava	10
Siliceous conglomerate	Hard lava	7
Booysens shale	Hard lava	5
Argillaceous quartzite	Soft lava	2
Jeppestown shale	Soft lava	2
Argillaceous conglomerate	Hard lava	1
Booysens shale	Soft lava	1
Argillaceous conglomerate	Soft lava	1
Jeppestown shale	Hard lava	1

orebody geometry (especially expressed by an undulating reef plane, colloquially termed rolling), pronounced partings in the footwall and hangingwall of the excavation, and faults, joints and dykes are associated with the defined geotechnical areas, and these will be discussed in the following.

Rolling of the VCR is due to the orebody's deposition on a palaeosurface with pronounced topographic variations (Figure 8; Schweitzer *et al.*, 1991, 1992, 1993, 1994; McWha, 1994; Henning *et al.*, 1994; Regional VCR Working Group, 1994a and b; Vermaakt and Chunnett, 1994). Mining across a roll is complicated, and fatal accidents are associated with these features (J. Hamman, pers. communication, 1993; Durrheim *et al.*, 1998). On-strike, down-rolls are considered as especially hazardous, and are associated with excessive stoping widths (Figure 9, insert). Across these rolls, mining proceeds into the VCR hangingwall (Figure 9a). After the excavation has been re-established on the orebody, semi-circular lava load casts (colloquially termed pilloids) cause bad hangingwall conditions, in addition (Figure 9b). Hazardous conditions are emphasised in the presence of bedding-parallel faulting, with the fault plane deviating from the reef/lava contact across a roll (Figure 9c).

The frequency of occurrence and pronouncedness of rolls is variable. Rolling is less common and pronounced at mines where distal VCR is preserved (Germs and Schweitzer, 1994). Deelkraal and Western Areas Gold Mines are mentioned as examples. Rolls may not only be predicted by employing geophysical techniques (e.g. Fenner *et al.*, 1994), but also by extrapolating lithological contacts along which rolls are known to occur into the unmined area (Figure 10). These contacts are deduced from the footwall and hangingwall maps (Figures 5a and b). Superimposing the fatal locations from 1990 to 1995 onto the roll-map for Western Deep Levels and Driefontein Gold Mines confirms that a significant number of fatalities are associated with VCR rolls (Figure 10).

Pronounced partings in the footwall and hangingwall in proximity to the VCR excavation could be seismically active (e.g. Potgieter and Roering, 1984; Rorke and Roering, 1984; Spottiswoode, 1986), overriding the rock mass behaviour normally controlled by the rock type assemblages defining the geotechnical areas. Major partings are often utilized as shear planes (Roering *et al.*, 1991). Examples are bedding-parallel faults associated with the Libanon and Deelkraal



Figures 5a–c—Ventersdorp Contact Reef footwall (considering shale and quartzite/conglomerate as the major rock types, Figure 5a), hangingwall (Figure 5b), and geotechnical area (Figure 5c) maps. Note that quartzite and conglomerate is considered as one rock-type for the delineation of these geotechnical areas. The distance of the soft lava-hard lava parting to the excavation is also delineated (Figure 5b)

Reefs, the Master Bedding Plane Fault, the strongly sheared Green Bar and Booysens Shale (Figure 11), and the contact between the soft and hard lavas (Figure 5b).

The major structures associated with the VCR that are of rock engineering relevance are faults and joints (or extension gashes). Dykes intruded on several occasions, commonly along pre-existing fault planes. A variety of faults and dykes

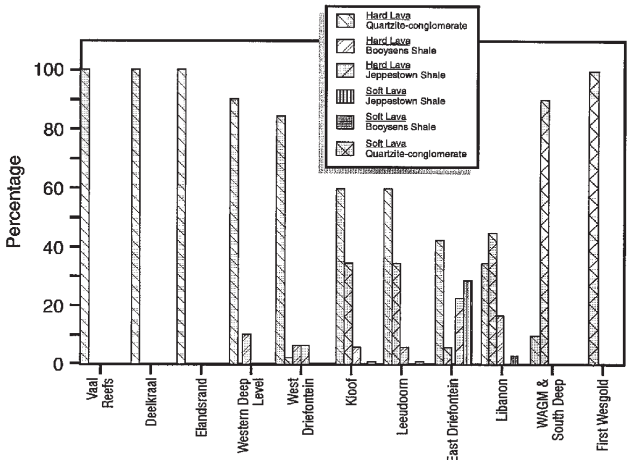


Figure 6—Estimated distribution of the various geotechnical areas as deduced for the operating mines mining the Ventersdorp Contact Reef

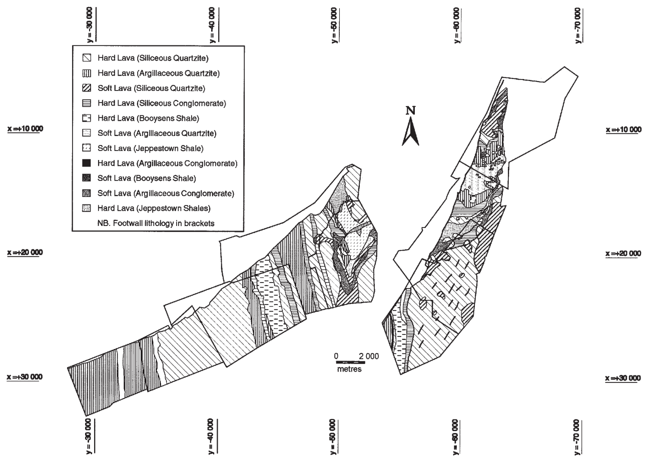


Figure 7—Geotechnical area map considering the two major hangingwall lithologies (Figure 5c) and subdivision of the footwall quartzites and conglomerates into siliceous and argillaceous lithologies

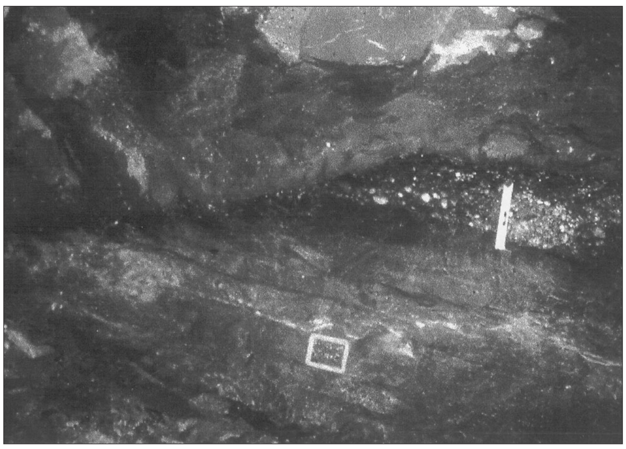


Figure 8—Terrace/slope transition as exhibited by the Ventersdorp Contact Reef at Western Deep Levels—South Mine (photograph is courtesy of M. McWha, Western Deep Levels)

is associated with the VCR (Engelbrecht *et al.*, 1986; Roering *et al.*, 1991; Killick and Roering, 1994; McCarthy, 1994; Berlenbach, 1995). Where faults occur in the hangingwall of mining areas, they are commonly characterized by weak cohesion along the fault plane and may result in rockfalls. In order to predict hazardous areas, the understanding of the spatial distribution of these faults and their direction of movement, which have a significant influence on mine safety is, therefore, important. Some features of the faults most frequently associated with the VCR are discussed here.

The complexity of faulting associated with the VCR (Figures. 12a to c) reflects the tectonic history of the Witwatersrand Basin. Several generations of extensional, compressional and strike-slip faulting affect the orebody and the mining operations. An understanding of the deformational history is essential in order to allow for the necessary precautions to be taken. In addition, the reactivation of older fault structures adds to the complexities encountered in mining operations. A detailed discussion of fault mechanisms is not considered here. However, the following examples highlight the necessity for a detailed analysis of the deformational mechanisms associated with the VCR.

Ripouts, or lensoid fault structures in the hangingwall of the VCR, can be related to a stick-slip mechanizm along the bedding-parallel fault in the contact between the VCR and its hangingwall (Berlenbach, 1995; Swanson, 1989; Figures. 12a to c).

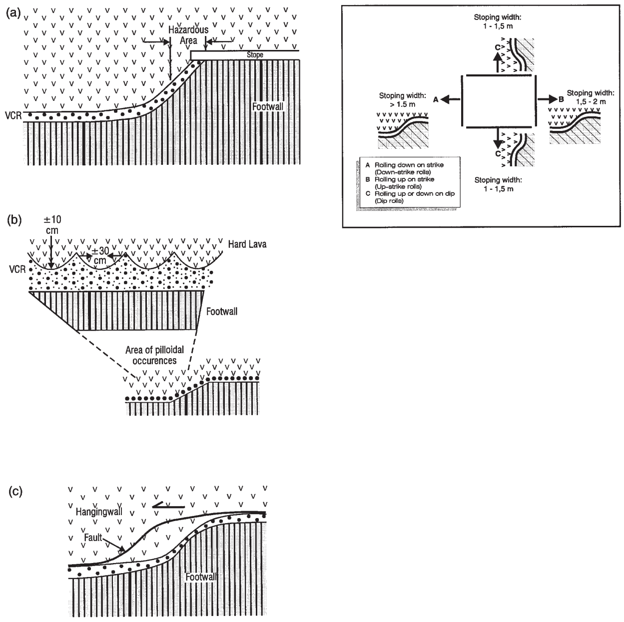
Imbricated systems (bedding-parallel faults) often splay into imbricated fans or duplex structures (Boyer and Elliot, 1982). Such imbricated systems are frequently observed where Booysens Shale is subcropping against the VCR, towards the east of the Bank Fault (Figure 5a). Where bedding-parallel faults step up in stratigraphy, forming ramp structures, or where imbricated systems develop in the hangingwall of the VCR, they result in hazardous conditions owing to the weak cohesion along the fault planes (Figure 12c).

Rock mass behaviour in different geotechnical areas

The Jeppestown Shale—soft lava and the quartzite/conglomerate—hard lava environments at East Driefontein and Deelkraal, respectively, are utilized in the following to highlight the different rock mass behaviour as observed in distinct geotechnical areas.

Fracture mapping in the geotechnical areas confirms that the mining-induced fracture pattern is controlled by the characteristics of the strata associated with the VCR. The turning point of the fractures is implied to occur in the softer strata; i.e. in areas where hard lava or soft lava comprise the hangingwall the turning point is positioned in the footwall and hangingwall, respectively. Underground examples from Driefontein (Jeppestown Shale and soft lava assemblage), and Deelkraal (quartzite/conglomerate and hard lava assemblage) are provided in Figures 13a and b, with the dominant mining-induced extension fractures being schematically represented in Figure 14.

The fallout characteristics at Deelkraal and East Driefontein Gold Mines have been analysed (Guler, 1998). Fallouts at Deelkraal, associated with the hard lava are, on average, 100 cm wide, 110 cm long and 40 cm in height. At East Driefontein, soft lava fallouts are characteristically



Figures 9a-c—Mining across a roll commonly proceeds into the hangingwall lava (Figure 9a). Pilloidal structures (load casts) are frequently encountered at the terrace/slope transition (Figure 9b). Bedding parallel faulting, if present, does not follow the reef/hangingwall contact across a roll (Figure 9c), but forms short-cuts, resulting in bad hangingwall conditions. The inset depicts different stoping widths as documented for distinct roll/mining direction associations (after M. McWha, pers. communication, 1995)

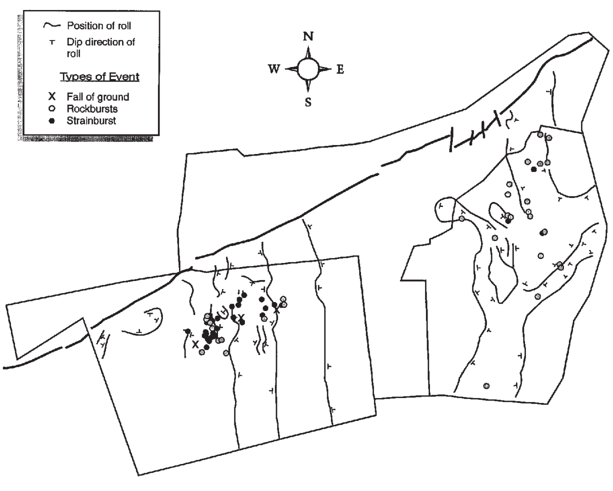


Figure 10—The occurrence of rolls at Western Deep Levels and Driefontein Gold Mines related to the occurrence of fatalities for the 1991 to 1995 time period. The classification of 'Types of Event' are those used by the Department of Minerals and Energy

smaller when compared to Deelkraal: 25 cm wide, 30 cm long and 20 cm in height. The sizes of the fallouts at both mines are determined by the fracture and joint frequency and orientation.

Extensometer measurements from East Driefontein and Deelkraal (Guler, 1998) reveal that the footwall in these areas contributes distinctly to the total closure. Bedding planes in the Jeppestown Shale at East Driefontein are frequent, spaced at an average of 1 mm (Figure 4a). The hangingwall is the major contributor to the total closure at

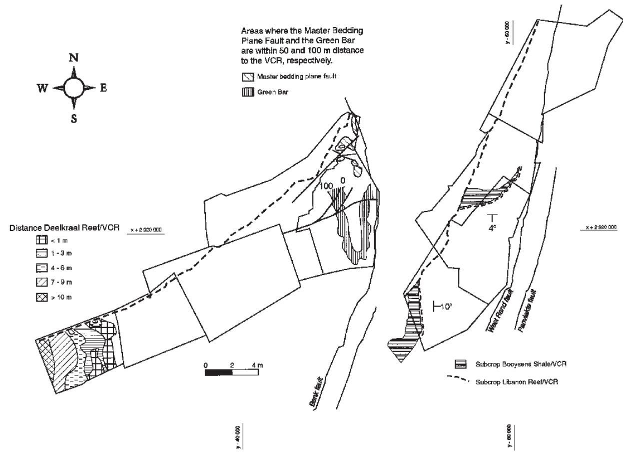
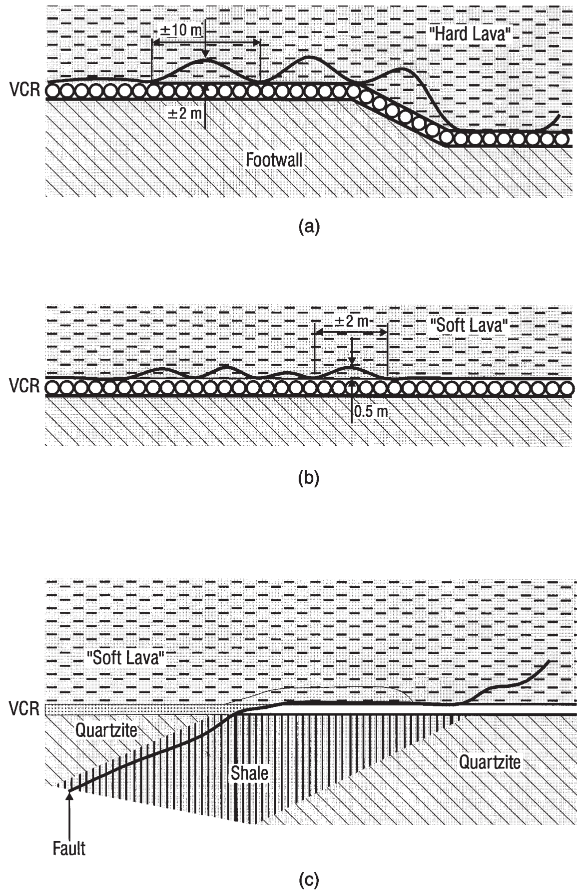
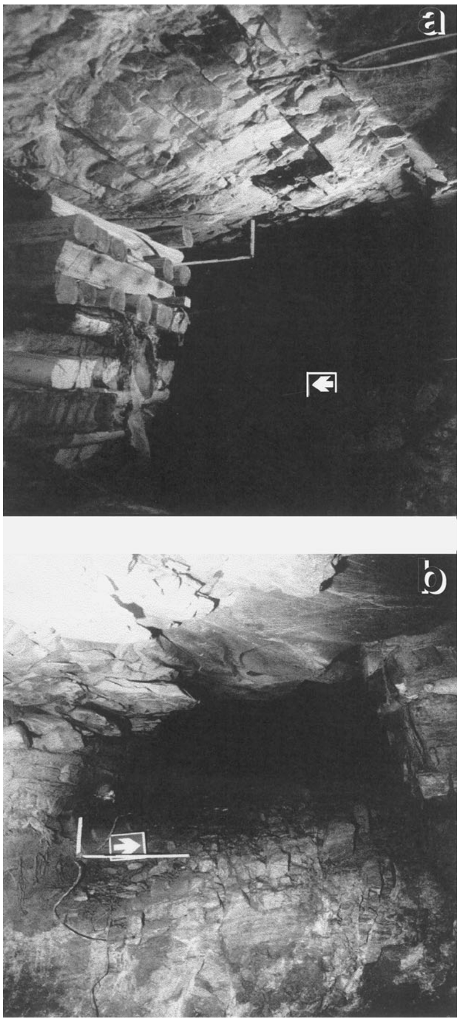


Figure 11—Pronounced partings as developed in the footwall of the Ventersdorp Contact Reef for some mines of the West Rand and Carletonville goldfields

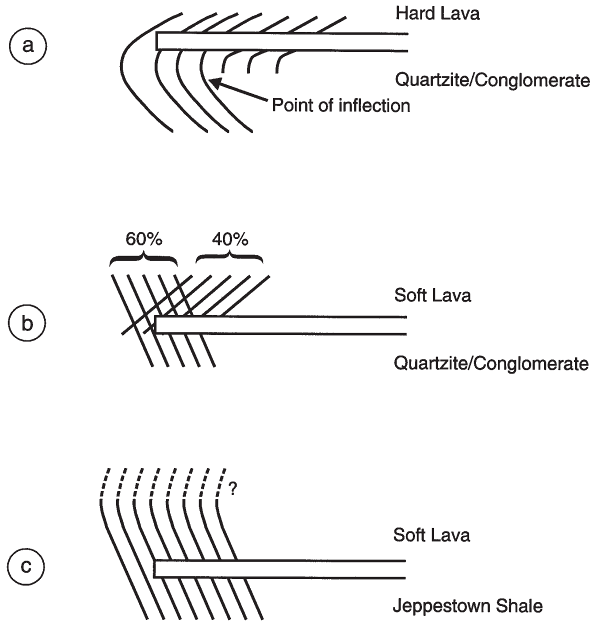


Figures 12a-c—Attitudes of ripouts associated with faulting in soft and hard hangingwall lavas are schematically shown (Figs. 12a and b). Duplex structures and ramps may result in weak hangingwall conditions (Figure 12c)

East Driefontein, despite the presence of pronounced footwall partings. Sliding along the Jeppestown Shale bedding planes is, therefore, not pronounced. The predominant contribution of the hangingwall to the total closure could be due to the presence of flat, almost reef-parallel joints. At Deelkraal, where hard lava overlies and quartzite/conglomerate



Figures 13a and b—Mining-induced extension fracturing as observed at East Driefontein Gold Mine (Figure 13a). The geotechnical area consists of Jeppestown Shale footwall and soft lava hangingwall. The arrow points towards the face. Note that the fracturing is dipping away from the face, which is opposed to the conventional fracturing observed in Witwatersrand ore bodies having quartzitic footwalls and hangingwalls. Mining-induced fracturing in the hard lava-quartzite/conglomerate footwall geotechnical area (Figure 13b) is typically characterized by flat-dipping (on average 45°) extension fractures, dipping towards the face (note arrow)



Figures 14a-c—Summary of mining-induced extension fracturing for the following geotechnical areas: quartzite/conglomerate and hard lava (Figure 14a), quartzite/conglomerate and soft lava (Figure 14b), and Jeppestown Shale and soft lava (Figure 14c)

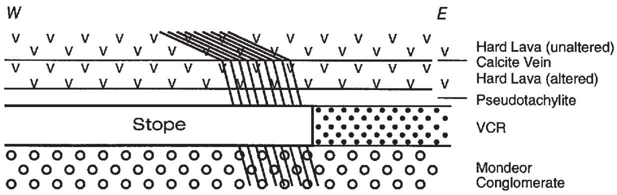


Figure 15—Steeper mining-induced fractures are observed where fault rock is present in the hangingwall of the excavation, as also observed at Deelkraal Gold Mine. The fractures are flatter in the hard lava

underlies the VCR, it is deduced that the hanging- and footwalls contribute equally to the total closure (Guler, 1998).

A joint database (D. Vermaakt, pers. communication, 1994) indicates that joint characteristics differ from one geotechnical area to the other. Joints, in addition, closely interact with the mining induced-fracture pattern, and are commonly fault and dyke parallel. The orientation of these joints relative to the mining-induced fracturing and the face is responsible for the different degrees of difficulty encountered when mining the VCR in different directions.

Variations in lava strength have been examined petrographically with special reference to the lava properties in the vicinity of geological structures (Figure 15). The hard lava adjacent to the fault rock (pseudotachylite, Figure 15) is strongly altered. This is made obvious by the presence of abundant secondary minerals. Amygdales are filled with secondary quartz and epidote. The proportion of phenocrysts to matrix to amygdales is 30:60:10. Plagioclase phenocrysts are the majority (80%) of the phenocryst assemblage and are replaced by sericite, confirming the severe alteration this rock has undergone. Alteration obviously reduced the competency of the rock, which is also expressed by steep mining-induced fracturing (Figure 15). The relatively unaltered hard lava is strongly porphyritic, with a ratio of phenocrysts to matrix of about 80% to 20%. Phenocrysts consist of plagioclase (80%) and quartz (15%) with accessory (5%) calcite, magnetite and epidote. The extension fractures in this hangingwall are relatively flat (Figure 15). The different types of lava exhibit distinct attitudes of mining-induced fracturing and differ mainly with regard to their degree of alteration. The above is only presented as a case study, and similar observations have been made in the vicinity of faults and dykes.

In summary, it is concluded that geotechnical area-specific rock mass behaviour is observed. This is also expressed by area-specific mining-induced fracturing, specific fall of ground sizes and shapes, different contributions of the footwall and hangingwall to the overall closure rate, and distinct joint characteristics. The attitude of mining-

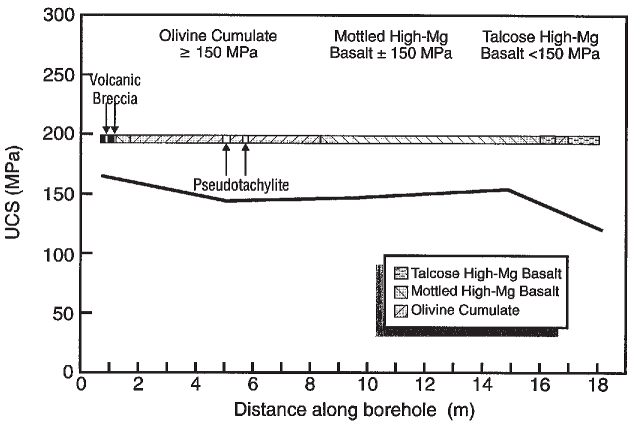


Figure 16—Point load test results for three distinct soft lava types, i.e. olivine cumulate, mottled high-Mg basalt, and talcose high-Mg basalt. Point load tests were performed every 5 cm

induced fracturing changes within altered rock, in proximity to major discontinuities. This confirms that hydrothermal fluids penetrating along geological discontinuities altered the abutting host rock (Henckel *et al*., 1990; Phillips *et al*., 1990; Meyer *et al*., 1992; Henckel and Schweitzer, 1994).

Discussion and recommendations for future work

Geotechnical areas delineate regions with distinct rock mass behaviour. Distribution of these areas is extrapolated into the unmined, facilitating the prediction of hazardous regions. Further scope exists to characterize the geotechnical areas in more detail. Bedding planes, for example, appear to part more easily in the siliceous quartzites, as opposed to their argillaceous counterparts. Also, little is known about the lava flow thicknesses considering individual flows of the soft and hard lava types. It is implied that flow thicknesses associated with the soft lava are less than those of the hard lava, because soft lavas represent low-viscosity flows.

More than 1000 point-load tests on cores containing soft lava from Western Areas Gold Mine have been related to the lithological/geochemical variations in the soft lavas (Figure 16; Guler, 1998). Three soft lava types are distinguished (Coetzer and Lambert, 1993; Killick, pers. communication, 1994): Talcose high-Mg basalt, mottled high-Mg basalt, and olivine cumulate. Talcose high-Mg basalts have uniaxial compressive strengths (UCS) of generally < 150 MPa. Olivine cumulate and mottled high-Mg basalt have values generally exceeding 150 MPa (Figure 16). The soft lava may, therefore, be further subdivided in future studies, possibly into two broad categories. It is noted that the fault rock (pseudo-tachylite) possesses UCS values of just less than 150 MPa (Figure 16), reinforcing the view that steep mining-induced fractures form in incompetent strata (Figures 14 and 15).

In mining operations, an understanding of the geometry and distribution of faults, especially in unmined areas, is of great significance, especially with mining operations taking place at increasingly greater depths (e.g. Schweitzer and Johnson, 1997). Future work could also consider the detailed documentation and modelling of structural features. This would facilitate a better understanding of the deformation mechanisms and the interrelationships between the pre-mining state of stress (as the result of paleo-tectonic forces) and mining-induced stresses, and the prediction of these features. These studies could be combined with modern geophysical methods (Ground Penetrating Radar or Radiowave Tomography) to map mining-induced fracturing and geological structures ahead of mining. Detailed documentation of the frequency and amplitude of bedding-parallel faulting will also assist in the identification of the approximate support spacing. Evaluation of the above features also needs to consider the different behaviour of faults and dykes with varying orientations to the excavation and compositions.

Limited VCR mining also occurs at West Rand Consolidated and at Cooke Gold Mine (Figure 1). Although these mines are not considered on the geotechnical area maps, it is noted that quartzite and soft lava comprise the VCR footwall and hangingwall assemblage. Vaal Reefs is the only mine currently mining the VCR in the Klerksdorp Goldfield (Figure 1), where it is mined at the Number 10 Shaft, situated in the western portion of the lease. Volcanic rocks of the Orkney Formation overlie the VCR at this mine and the rock engineering properties of this lava type are expected to be similar to the hard lava of the Alberton Porphyry Formation. The footwall is comprised of quartzites and conglomerates, resulting in the definition of one geotechnical area.

Future studies may also investigate the behaviour of the delineated footwall and hangingwall partings and the rock mass behaviour in areas of VCR mining with siliceous and argillaceous footwalls. However, the major outcome of this study is that the rock mass behaviour is strongly controlled by the rock types and their assemblages. The different assemblages respond distinctively to the mining-induced stresses. The concept of geotechnically subdividing excavations associated with strataform ore deposits is therefore valid.

Summary

The VCR differs markedly from the underlying Witwatersrand orebodies. A hangingwall consisting of two lava types with vastly different rock engineering properties, pronounced undulations of the surface onto which the VCR deposited, and the great variety of footwall rock types are the unique features that are of special importance for the understanding of the rock mass behaviour.

Considering three major footwall and two hangingwall rock types results in the definition of six geotechnical areas. In three of these, minor or no mining occurs. The three most important areas have been investigated in detail and each of these possess a characteristic rock mass behaviour. This is expressed by different attitudes and frequencies of mining-induced fracturing, closure rates, seismic character, and sizes and shapes of fall of ground. It is therefore concluded that the rock mass behaves differently from one geotechnical area to another. The geotechnical area approach may therefore be adopted to delineate regions of differing rock mass behaviour associated with the older Witwatersrand orebodies and other, planar mineral deposits.

The distinction between siliceous and argillaceous footwall quartzites and conglomerates facilitates further

subdivision of the geotechnical environments associated with the VCR into 11 areas. Further investigations may consider the rock mass behaviour associated with the additional regions.

Some geological features override the influence of the rock types within individual geotechnical environments. These are especially the rolling of the VCR and potentially seismically active stratigraphical discontinuities in proximity to the excavation. Faulting also impacts significantly on rock mass behaviour. Detailed studies may be required to investigate the relationships between structural deformation and faulting.

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Strong growth in demand for tantalum

New report analyses supply and demand worldwide

Over the past few decades tantalum has been transformed from a minor by-product of tin mining to a valuable resource. A new report from international market analyst Roskill points to the strong growth in consumption behind this transformation: their new report, *The Economics of Tantalum (7th edition, 1999)* says that the development of tantalum capacitors, initially for military applications and more recently for small portable electronics, has led to growth averaging over 10% per year since 1992.

Mobile phones boost demand

The surge in popularity of mobile phones, laptops and video cameras has helped to boost consumption of tantalum capacitors from 5Bn units in 1988 to 15Bn units in 1997. Roskill expects the growth in demand to continue to boom over the next two years, reaching 25Bn units by 2000. The Asian crisis has had little effect on the market for tantalum capacitors, and while it is likely to slow growth in the region, it is unlikely to cause a downturn. In the longer term, demand for tantalum in capacitors will be limited as the components get smaller and require less tantalum metal per unit, and the market will also come under pressure from other capacitor technologies such as ceramic capacitors and electrolytic aluminium capacitors. However, Roskill says that there are a number of new markets for tantalum capacitors which will maintain demand. The most important is in under-hood applications in automobiles, such as engine-management systems, ABS controllers and air bag systems

Tantalum has become an important addition to superalloys, particularly those used for casting single-crystal turbine blades for aero-engines. Improvements in engine performance have demanded new alloy technologies, and many new alloys contain substantial quantities of tantalum. Roskill estimates that this application accounts for around 100t of Ta_2O_5 each year. Despite record production of aircraft in 1998, continued through 1999, the expected downturn in the commercial aircraft industry will limit short-term growth in the use of tantalum in this sector.

For further information please contact Mark Seddon. ◆

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