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Geotechnical classification of deep and ultra-deep Witwatersrand mining areas, South Africa

Abstract As depth of mining increases, so the production costs of the aurifereous Witwatersrand deposits are continuously increasing, with some mines already mining at depths exceeding 3500 m. Health and safety aspects are, simultaneously, gaining in importance. Therefore, in order to mine deep orebodies in existing mines, as well as to develop new mining ventures safely and efficiently, novel approaches, including mining strategies, layouts and support systems have to be adopted. Geological features largely control the deformation mechanisms associated with Witwatersrand orebodies. These features are grouped into two major categories: primary and secondary features. Both impact on the rockmass behaviour associated with the excavations, and contribute to the definition of geotechnical areas. Primary geological features are defined by the various rock types, orebody geometry, and the frequency and mineralogical characteristics of sedimentary structures (e.g. various kinds of bedding planes and lithological boundaries). The primary features also control rock engineering properties, closure rates, attitude and frequency of mining-induced stress fracturing, and planes may be reactivated during seismic events. Secondary geological features are faults, dykes and veins/joints, and associated metamorphism. These cause stability problems and are often associated with seismic events. Compositional and textural characteristics of these features, and their controls on the rockmass behaviour, are ill-defined. Primary and secondary geological characteristics also play an important role in identifying the appropriate mining strategy, layout and support. Geological features can be predicted into deep unmined areas, and therefore contribute to the safest and most efficient extraction of the orebody. Witwatersrand orebodies are mined in complex geological environments, with the rockmass behaviour differing from one orebody to the other. This is approached by employing a new methodology that attempts to quantify the problems encountered when mining the major Witwatersrand orebodies.

Introduction

The gold resources of the Witwatersrand Basin (Fig. 1) are continuously depleting. For example, in 1970 some 1266 t of gold (79% of world production) were produced from this depository (Tainton 1994). In 1992 production had decreased to 614 t of gold, and some 230–300 t are forecast for the year 2025 (Sanders et al. 1994; Tainton 1994). It is due to this depletion in production that the mining companies have to consider resources at ultra-depth.

Depending on rock strength, ultra-deep mining is defined as mining at depths exceeding 3500 m. It is possible to hoist economic tonnages from 4000 m depth in a single shaft system (Stewart 1994) and the aurifereous orebodies, colloquially termed reefs, are known to extend to at least 6000 m below the surface (Tamlyn 1994). Some mines are already mining at depths exceeding 3500 m, such as Kloof and Western Deep Levels Gold Mines, East Rand Proprietary Mines (ERPM), and Driefontein Consolidated (Fig. 1).

As rockburst-related fatalities increase significantly with depth (e.g. Gurtunca and Gay 1993a, b; Roberts et al. 1994), numerous researchers stress the importance of, and requirement for, geotechnical information, especially geological features at great depths (e.g. Adams et al. 1981; Gay et al. 1984; Gay 1986; Gay and Jager 1986a, b; Roberts and Jager 1991, 1993; Kullman et al. 1994; Gay et al. 1995a, b). The geotechnical information must also be considered when proposing modifications to current mining methods (Johnson and Schweitzer 1996).

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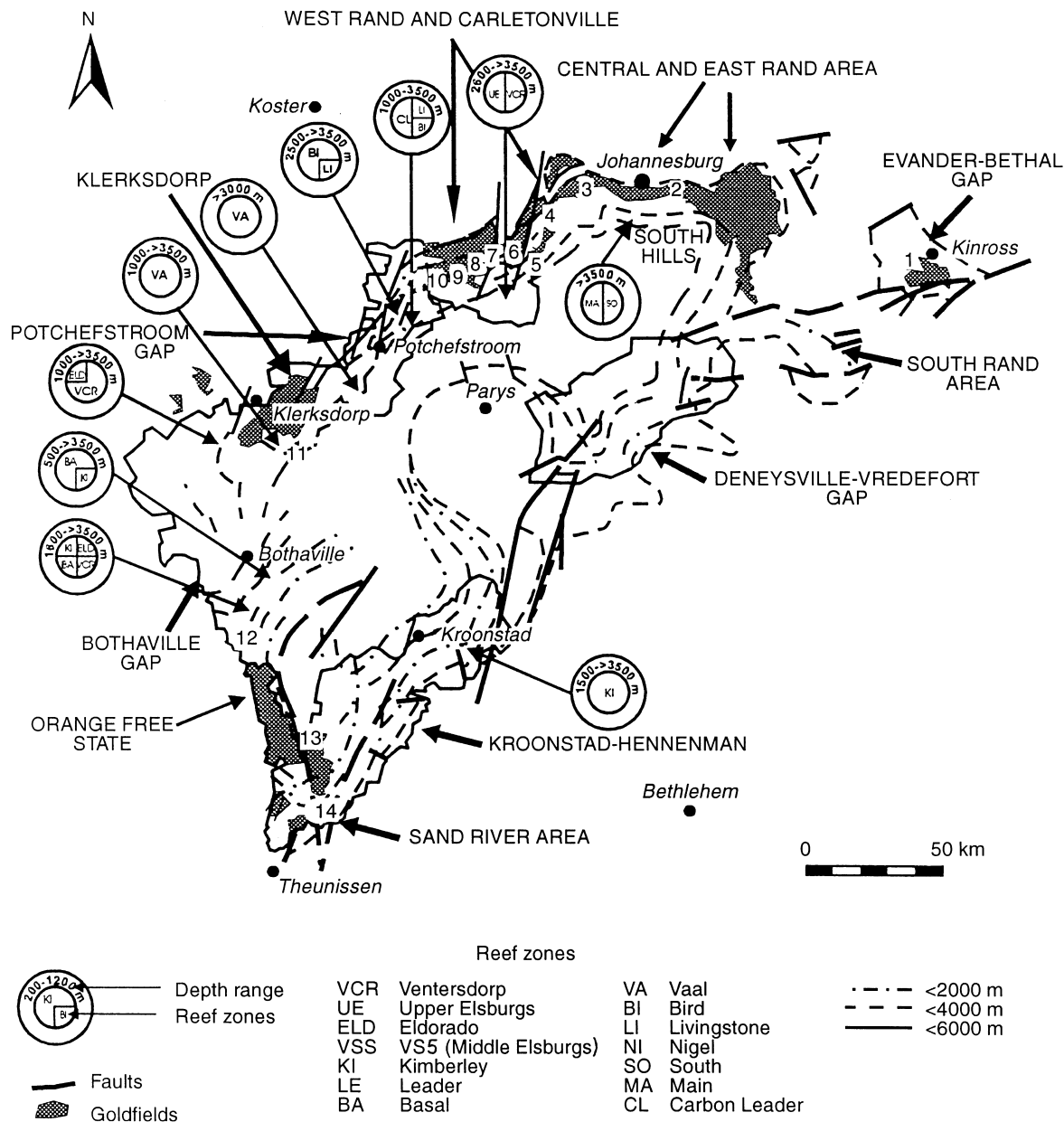Johannesburg, South Africa

Fig. 1 Outline of the Witwatersrand Basin, indicating the position of localities referred to in the text. Depth contours for the Central Rand Group, containing most of the orebodies (Fig. 2), are from The Witwatersrand Basin Map (1986). Also shown are reef-type and depth-range for potential new mining areas (modified after Tainton 1994). *Numbers* refer to the following localities: *1*, Rosespruit; *2*, East Rand Proprietary; *3*, Durban Roodepoort Deep; *4*, Randfontein Estates; *5*, South Deep; *6*, Kloof; *7*, Driefontein; *8*, Western Deep Levels; *9*, Elandsrand; *10*, Deelkraal; *11*, Eastvaal/Moab; *12*, Target/Sun; *13*, Freegold; *14*, Sand River

In this study, we will firstly review the relevance of geotechnical information for mining associated with the Witwatersrand Basin, including extensions to orebodies and potential new mining lease areas. Secondly, the orebodies and regions that are currently, and which will potentially be mined at ultra-depths, will be identified. Some of these orebodies are then categorised broadly, predominantly according to their characteristics and the frequencies of geological features. A proposed geotechnical classification scheme also aims at assisting in the prediction of the rockmass behaviour at ultra depth, as well as in the evaluation of potential mining layouts and methods for these areas.

General overview of geotechnical factors in deep mining

The stability of an excavation depends on a complex interaction between mining layout and method, local and regional support, and various geological factors. Mining parameters include the extent of the unsupported spans, the rate of face advance, regional support strategies (such as pillar spacing/orientation and backfill (e.g. Arnold et al. 1994), mining method, and stoping width. Backfill, for example,

may reduce the total closure by 70% (Gay et al. 1995a), which would have a significant impact on any analysis of the rockmass behaviour. The influence of geological features on seismicity have been identified in both backfilled and unfilled stopes (Lenhardt 1989; Gurtunca and Gay 1993a). The effects of geological features are likely to increase in importance with increasing spans along longwalls (i.e. higher energy release rates, ERR; Gay 1993), a trend that is expected to be even more pronounced at great depth.

Review of the literature leads us to subdivide geological parameters into two broad categories, here termed primary and secondary geological features.

Primary geological features of rock engineering significance

Primary geological features are defined as those that formed during the deposition of the rocks of the Witwatersrand Basin, i.e. rock type, sedimentary structures, and reef geometry.

Rock type

Predominantly sedimentary and minor volcanic rocks are associated with the orebodies of the Witwatersrand Basin (Fig. 2). The major sedimentary rock types are classified as shale/siltstone,
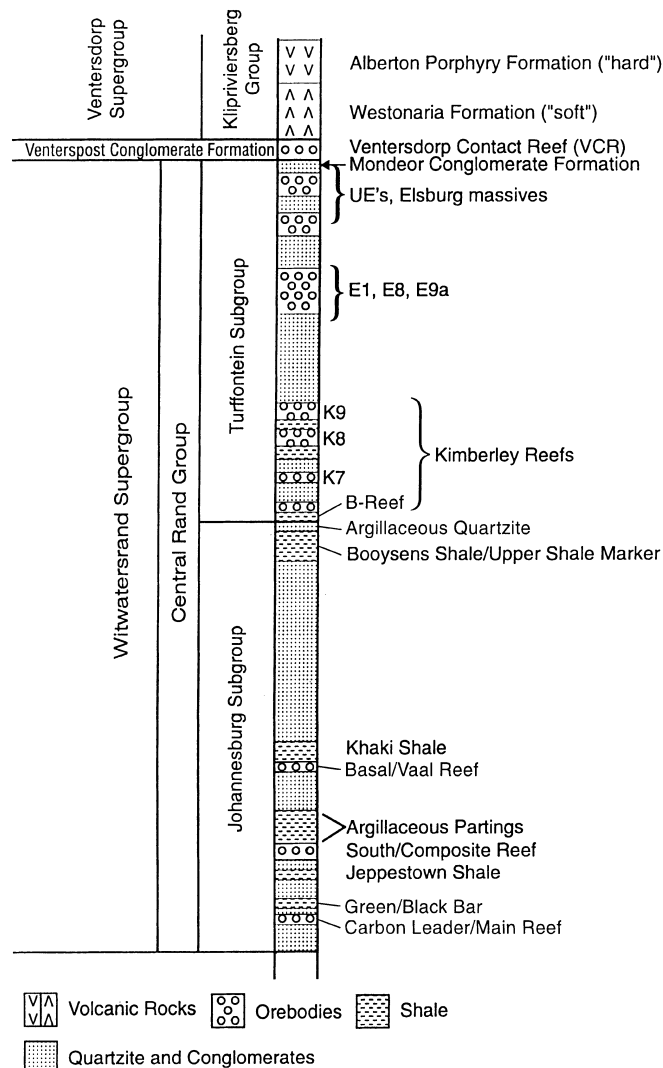

Fig. 2 Schematic stratigraphic column of the Central Rand Group delineating the orebodies that are currently and will potentially be mined at depths exceeding 3500 m

quartzite (ranging from argillaceous to siliceous quartzite; pebbly varieties do exist), and conglomerate (ranging from matrix- to clast-supported). The change of rock type along the same stratigraphic horizon, due to proximal/distal relationships (e.g. quartzite being transitional into shale) also has to be considered. The various textures and compositions of these lithologies determine whether a rock is competent or incompetent, or transitional between the two.

Tunnels, for example, should be positioned in competent strata, and require special support when positioned in shale (Gay and Jager 1986a, b). Rock type also influences total closure, and the degree of hangingwall blast damage. Ductile behaviour of strata, such as shale or argillaceous quartzites, may cause bulging of the footwall into the stope area. The distinctly different rockmass behaviour in the Klerksdorp area, compared to the Carletonville Goldfield (Fig. 1) has been attributed to the generally weaker (about 200 MPa) quartzites associated with the excavations in the Klerksdorp area. For example, weak footwall rocks can degrade the strength of support pillars, which can be further reduced by creep of shale or other laminated strata. Consequently, pillars behave differently depending on the different rock type assemblages (Leach and Lenhardt 1990), which clearly illustrates the requirement for geotechnical data during pillar design.

Volcanic rocks associated with the orebodies are predominantly basaltic and andesitic in composition, with associated pyroclastic rocks, and belong to the Ventersdorp Supergroup, which overlies the Witwatersrand beds (Fig. 2). These volcanic rocks overlie the Ventersdorp Contact Reef (VCR) and the different rockmass behaviour, especially that of the basalts when compared to the andesites, has recently been demonstrated (M. Roberts 1994 personal communication). Primary partings associated with these volcanic rocks are due to strongly amygdaloidal and brecciated, or autobrecciated horizons (mainly close to flow contacts), together with thin pyroclastic and sedimentary intercalations. These can result in horizontal mining induced movements on stope-parallel hangingwall partings, and tend to result in areas prone to fallout between face-support units.

Sedimentary structures

This group covers the various kinds of bedding, such as planar bedding, graded bedding, trough and planar cross-bedding, but also includes sharp lithological contacts. Most of these are parallel or subparallel to the reef plane and may part with variable ease, depending on their mineral composition. The frequency and characteristics of these bedding surfaces determine factors such as beam thickness, hangingwall stability, footwall lift, and pillar and tunnel stability (Atkins and Keen 1984; Gay and Jager 1986a, b; Jager and Turner 1986; Kullmann et al. 1994).

Reef geometry

Reef geometry encompasses reef thickness, and the "rolling" of the orebody. As the effects of seismicity are substantially reduced with narrow widths (e.g. Arnold et al. 1994), reef thickness and associated stoping width are significant to future mine planning. "Rolling" of the orebody results from geomorphological variations of the palaeosurface onto which the ore-bearing strata were deposited and is, to some extent, predictable, due to the close inter-relationship between footwall and hangingwall characteristics and orebody geometry (McWha 1994; Germs and Schweitzer 1994; Henning et al. 1994; Schweitzer et al. 1991, 1992, 1993, 1994). The unexpected encounter of "rolls" commonly results in mining proceeding into the hangingwall, and it is then necessary to re-negotiate mining direction after reef-loss has been encountered. The resulting excess stoping width and damaged hangingwall strata represent areas of unstable and hazardous mining conditions (J. Hamman 1993 personal communication; Durrheim et al. 1996).

Secondary geological features of rock engineering significance

The Witwatersrand basin-fill was deposited over a time period of several hundred millions of years (Armstrong et al. 1991; Robb and

Meyer 1995; Fig. 2). Regionally, the rocks exhibit comparable metamorphic grades (lower greenschist facies metamorphism), with inferred temperatures of about 350 °C (Phillips et al. 1990; Meyer et al. 1992), although temperatures of 390 °C and pressures of 3 kbar have been determined locally (Coetzee et al. 1995). The Witwatersrand rocks were faulted, and dykes intruded at several times. Dyke and fault characteristics, and associated jointing or veining, therefore vary markedly. The rockmass behaviour associated with differently aged fault and dyke populations is, at this stage, not well understood. Dyke and fault populations have not yet been related to the associated secondary mineral assemblage. Different populations are likely to be associated with varying secondary mineral assemblages. Talc-rich lithologies, for example, result in an increased slip potential along some faults and dykes, whereas silica has been observed to seal certain openings.

Joints/veins, faults and dykes, when ahead of the face, may result in an increased rockburst frequency (i.e. peak rockburst frequency within approximately 20 m of the structure) in both longwall and scattered mining situations (Gay 1986; Gay and Jager 1986a, b; Kullmann et al. 1994), while secondary geological features are often associated with relatively large falls of ground (Gurtunca and Gay 1993a). The importance of these structures for the weakening of off-reef excavations and pillars has also been highlighted. The orientation of a structure in relation to the excavation is important, not only for the placement of bracket pillars. Joughin and Jager (1983) suggested that the effects of secondary geological features are least when at right angles to the face, and greatest when parallel to the stope. Hangingwall faults dipping towards the unmined area, and footwall faults that dip towards the mined-out area, were identified as being associated with large tremors on fault planes (Hepworth and Diamond 1983). Dykes which strike at a high angle to bedding planes have been recognised as dangerous by Gay and Jager (1986b).

Oblique and bedding-parallel quartz-filled veins (e.g. Coetzee et al. 1995) are frequently observed close to the excavation. As their presence results in hazardous hangingwall conditions, existing mining approaches have been modified to reduce the damage caused by these features (M. Handley 1995 personal communication). A great variety of fault rock types are associated with the faults of the Witwatersrand Basin (Roering et al. 1991) and these have distinctive parting potentials (Jager and Turner 1986). The rock type hosting the secondary geological features may, in addition, control fault and joint attitudes (e.g. Jager and Turner 1986), geometry, secondary mineral assemblages, and, consequently, friction angles and excess shear stresses.

Dyke composition, ranging from basaltic to rhyolitic, could be of importance in determining burst potential. Siliceous dykes, particularly, should be capable of storing significant amounts of elastic energy, therefore being most likely to fail when mining takes place near them. However, this has to be confirmed through future multidisciplinary studies.

Primary and secondary geological features: seismicity, mining induced fracturing, and computer modelling

Seismicity

A close link between seismicity, geological characteristics and mining methods is proposed (Potgieter and Roering 1984). It is predicted that, as mining proceeds to greater depths, the number and magnitude of seismic events will also increase (Lenhardt 1989; Gay et al. 1995a), resulting in a relatively higher number of rockburst-related fatalities (Gurtunca and Gay 1993b; Roberts et al. 1993, 1994). Differences in seismicity have been documented for the Carletonville and Klerksdorp Goldfields (Fig. 1), and these differences have been attributed to different mining methods, different degrees of geological disturbance, and different rock types and assemblages (Gay 1986; Gay and Jager 1986b; Gay 1993). The close inter-relationship between mining geometry, seismicity and fault properties for the Klerksdorp Goldfield has been highlighted by Spottiswoode (1986). In general, two distinct classes of seismic events are distinguished and these are related to fault slip and the unstable fracturing of intact rock (Joughin 1965; Joughin and Jager

1983; Brummer 1988). Observations suggest that large magnitude seismic events are likely to be associated with geological structures, with wave velocities and burst-proneness being different for distinct rock types, affecting both stoping and development areas (Joughin and Jager 1983; Rorke and Roering 1984; Gay 1986; Gay and Jager 1986a; Kullmann et al. 1994; Gay et al. 1995b). Seismic tremors may result from a combination of mine layout and associated geological features, also resulting in different pillar failure mechanisms and different degrees of damage to the excavation (Lenhardt 1990; Lenhardt and Hagen 1990).

Mining induced fracturing

The presence and attitude of mining induced fracturing is important when deciding on an appropriate support strategy and mine layout, and its impact on the extent of damage caused by rockbursts is recognised generally. In the absence of geological disturbances, "normal" fractures develop and ensure a stable state of mining (e.g. Brummer 1988). Rock type has been shown to control fracture attitudes. For example, siliceous rocks, when compared to relatively more argillaceous strata, tend to be more intensely fractured (e.g. Jager and Turner 1986), with fractures being displaced along the fine bedding planes of shale horizons (Adams et al. 1981). The distance of the fracturing relative to the face is controlled by the rock strength, energy release rates, excavation dimensions, presence of bedding planes and other geological discontinuities, such as joints and veins (e.g. Piper 1984). Discontinuities may result in a reduction of fracture intensity, or even their complete absence (Roering 1981; Joughin and Jaeger 1983; Gay and Jager 1986b). Different fracture intensities have even been observed on opposite sides of a fault (Adams et al. 1981). Fracturing is equally important in and around pillars, where intense fracturing results in sidewall instabilities (e.g. Yilmaz and Ozbay 1993).

Computer modelling

Various computer modelling approaches have been undertaken, to assist in an improved understanding of the rockmass behaviour under various mining conditions. The objective of the modelling is to identify the most suitable mining strategies, mine layouts and regional support designs (e.g. Napier 1991; Johnson 1994). The selection of realistic rockmass strength parameters, the length and characteristics of parting planes and multiple discontinuities (such as bedding planes, faults and joints), and the impact of textural rock properties (e.g. grain size and shape) on fracture propagation, have been identified as important (Napier and Stephansen 1987; Napier and Hildyard 1992; Snyman and Martin 1992; Sweby and Smith 1994; Napier and Kuijpers 1995; Napier and Peirce 1995). Modelling also provides insight into the energy change in the vicinity of multiple discontinuities that intersect the reef plane at any angle, slippage on fault planes, and the effects of backfill (e.g. Napier and Stephansen 1987; Napier 1991). The need for an improved understanding of the formation of mining induced fracturing has been highlighted (e.g. Adams et al. 1981) and modelling has shown, for example, that parting planes can form a barrier to fractures (Napier and Hildyard 1992).

Orebodies, mines, and project areas under consideration

A comprehensive database has been compiled which facilitates the identification of ultra-deep regions of mining. It also includes relevant reef features, such as dip and stoping width. Tonnages and depth of mining for the various goldfields have been projected into the future. When this information is linked to the corresponding mines and reefs, it is possible to identify major areas where mining at ultra-depth will take place.

Fig. 3a, b Past, current and projected tonnages mined for the Witwatersrand orebodies at depths exceeding 3000 m, related to **a** various stoping widths and **b** dips. Data have been modified after P. Willis (1995 personal communication)
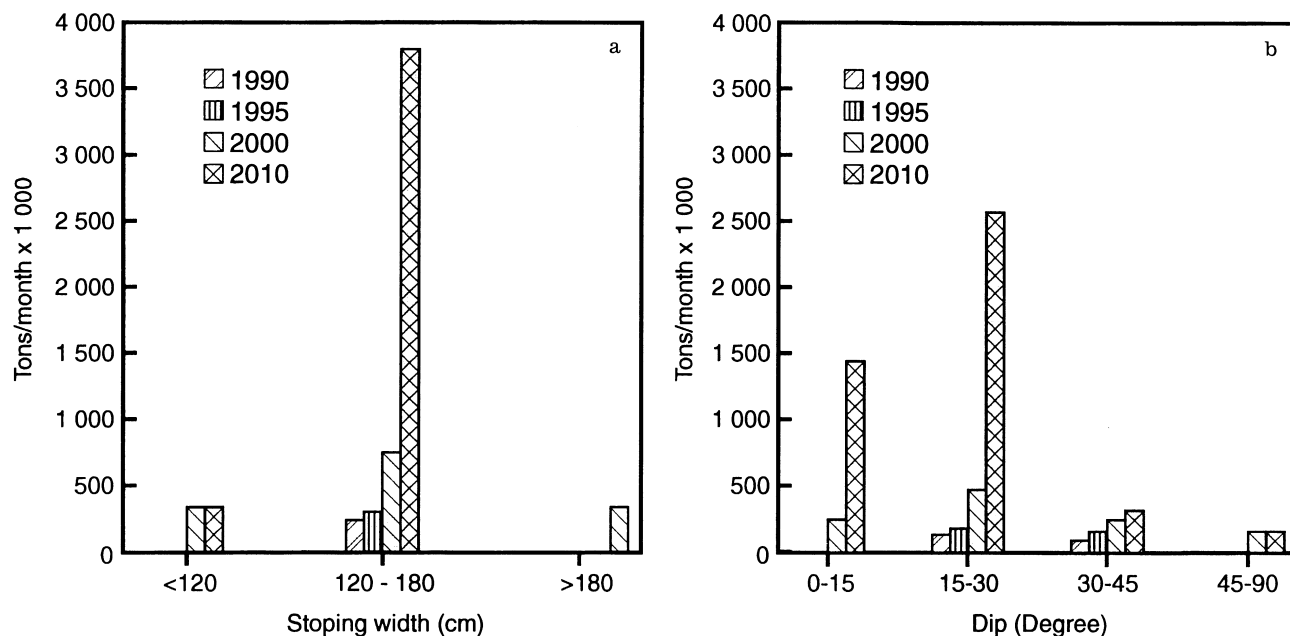
Figure 3a, b, prepared from this data-base, shows the percentage of Witwatersrand production at depths exceeding 3000 m for the years 1990, 2000 and 2010, for various stoping widths and dips. It is inferred that the majority of orebodies mined in the future will have dips ranging between 0° and 30° and will be extracted at stoping widths of 120–180 cm. A shift towards deeper mining is projected for the future (Fig. 4), with some 15% of the total tonnage being forecast to be derived from depths exceeding 3500 m by the year 2010.

Information deduced from the database suggests that ultra-deep mining will not occur in the Evander and Free State Goldfields (Fig. 1), although limited mining at depths of about 3000 m does take place in localised areas of the Orange Free State, where the Basal Reef is extracted. Ultra-deep mining in several other areas has been proposed, or is being developed, i.e. Target, Sun, South Deep, and Moab or East Vaal (Fig. 1, Table 1). In addition, exploration has identified other deep level ore reserves which could be developed in the longer term (e.g. Potchefstroom Gap). These examples represent the
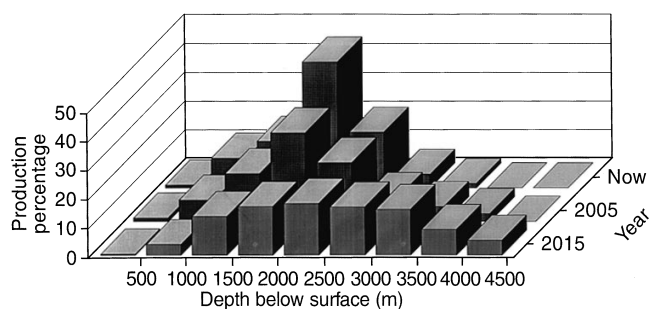
interests of all major South African mining companies and cover all current mining districts.

Most of the orebodies presently being mined will also be mined at ultra-depth (Figs. 1 and 2). One of these is the exceptional Ventersdorp Contact Reef (VCR, e.g. Germs and Schweitzer 1994), which is overlain by the volcanic rocks of the Ventersdorp Supergroup. Inspec-

Table 1 Summary of mines/project areas and reef types that are currently, and will potentially be mined at ultra-depth. The majority of the reef types are currently also mined at shallow depths

Goldfield	Mine/project area	Reef
Evander	Rosespruit	Kimberley
Central Rand	East Rand Proprietary	Composite Reef
	Southern Central Rand	Main Reef
	Durban Roodepoort Deep	Main Reef, Kimberley
West Rand	Randfontein Estates	South Reef
	South Deep	VCR, Elsburg
	Kloof	VCR, Main Reef
Carleton- ville	East Driefontein	VCR, Carbon Leader
	West Driefontein	VCR, Carbon Leader
	Western Deep Levels-North	Carbon Leader
	Western Deep Levels-South	VCR, Carbon Leader
	Elandsrand	VCR
	Deelkraal	VCR
Klerks- dorp	Buffelsfontein	Vaal Reef
	East Vaal (Moab)	Vaal Reef
Bothaville	Sun/Target	Basal Reef, B-Reef A-Reef, Elsburgs, Kimberley, VCR
Orange Free State	Freegold Sand River	Basal Reef Kimberley, Leader Reef

Fig. 4 Percent production versus time and depth below surface as determined and projected for the gold production from the Witwatersrand Basin. Data are courtesy of P. Willis (1995 personal communication)

tion of Fig. 2 also reveals that the majority of orebodies currently exploited, or potentially to be mined at ultra-depth (Table 1), are associated with shale horizons. These horizons are characterised by frequent, closely spaced bedding planes.

Our approach is to correlate, regionally, stratigraphically corresponding orebodies (employing the stratigraphic correlation scheme of the Witwatersrand Task Group of the South African Committee of Stratigraphy, SACS; T. McCarthy 1994 personal communication), assuming that similar geological processes occurred throughout the Witwatersrand Basin at the same time. For example, the Basal Reef is taken as the Orange Free State equivalent of the Vaal Reef in the Klerksdorp area, while the Carbon Leader (Carletonville Goldfield) is inferred to be the time equivalent of the Main Reef in the Central Rand (Fig. 1).

In the following sections, some of the geotechnical information is detailed for the different goldfields, located along the margin of the Witwatersrand Basin (Fig. 1) and presented in an anti-clockwise order, from east to west. Strata characteristics about 100 m beneath and above the orebody are considered, in order to facilitate consideration of the geotechnical environment in development areas. Some of the following information, where of rock engineering significance, is summarised in Table 2.

East Rand Goldfield

East Rand Proprietary Mine (ERPM) mines the Main Reef at a depth of about 3500 m and mining is expected to approach 4000 m. The orebody is characterised by a quartzitic footwall and hangingwall (Fig. 5a), while the rock engineering properties of the footwall and hangingwall quartzites vary laterally, with the quartzites being less competent in the eastern portion of ERPM (Fig. 5a). Argillaceous partings and shale horizons are also present in the footwall and hangingwall at various distances from the orebody, with the footwall shales, especially, causing tunnel support problems.

The majority of seismic foci at ERPM have been located in the hangingwall strata (McGarr et al. 1975), as it is able to store more strain energy than the footwall. This is due to the hangingwall having a significantly higher Young's modulus (86 GPa) than the footwall (75 GPa) (Gay and Jager 1986b). Our information, however, implies that these rock engineering properties are comparable for the footwall and hangingwall quartzites (Fig. 5a). A possible explanation is that reef-parallel sills, such as aplite sills (rhyolitic in composition), in the hangingwall at ERPM have sharp contacts with the sedimentary host rocks and tend to burst or collapse, resulting in roof damage (Gay and Jager 1986b).

Central Rand Goldfield

Future, deep mining could occur towards the south of the Central Rand (Table 1, Fig. 1), with the Main (Fig. 5a) and South Reefs being potentially mineable. It has previously been noted that most Central Rand tunnels are developed in undisturbed quartzite with uniaxial compressive strengths of 250 MPa (Gay and Jager 1986b), contributing to tunnel stability in this area.

West Rand Goldfield

Reefs to be mined at depth are the VCR (Fig. 5b), the Upper Elsburg's and probably the South Reef (Table 1). The VCR is currently mined at ultra-depth at Kloof Gold Mine. In this area, it is underlain predominantly by synformally folded, competent quartzites, and minor conglomerates and shales, of the Elsburg Quartzite and Booysens Shale Formations (Fig. 5b). The hangingwall

Table 2 General characteristics of the orebodies and associated strata under consideration

Orebody	Region	Footwall	Hangingwall	Channel width	Grade	Dip (degrees)
VCR/ (Kruidfontein)	Carletonville Klerksdorp Bothaville	Highly variable Shale-conglomerate	Westonaria Formation (0–40 m thickness) Alberton Porphyry Formation (< 500 m thickness)	0–2.00 m	Erratic	15–35
Upper Elsburg's/ Massives	West Rand	Quartzite, conglomerate	Quartzite, conglomerate	1.20–1.80 m >1.80 m	Erratic	0–15
Elsburg's-UEIA BP,A	West Rand	Quartzite, conglomerate	Shales above grey hangingwall quartzite	1.20–1.80 m >1.80 m	Erratic	0–15
Kimberley	Bothaville West Rand Evander	Shale, quartzite, conglomerate	Quartzite, conglomerate ± argillaceous partings	1.20–1.80 m	Erratic	15–45
Steyn/Basal/Vaal	Klerksdorp Orange Free State	Quartzite, conglomerate	Argillaceous quartzite Shale	(< 1.20) 1.20–1.80 m	± Even	15–30 (OFS) 15 (Klerksdorp)
Main	Central Rand	Quartzite (± Shale)	Quartzite, conglomerate	1.20–1.80 m	± Even	30–45
Carbon Leader/Main	Carletonville	Quartzite, conglomerate	Quartzite (Bedding planes) Shale (1–2 m thick)	1.20 m	± Even	15–30

a

Main Reef ±2 m

UCS (MPa)		E(GPA)	δ
West	285-292	83-87	0.15
East	172	66	0.17
	292	87	0.16
West	221	83	0.20
East	160	83	0.19

b

m

Alberton Porphyry

Westernoria

Ventersdorp Contact Reef

Booysen Shale

Cobble/Bird Reef

Johnston Reefs

UCS (MPa)	E(GPA)	δ
200	75 - 80	0.17 - 0.21
100 - 150	63 - 74	0.22
146	52	
263	76	
167	87	
142(37)	73(5)	0.20(0.02)
180	55	0.23(0.06)

c

Carbon Leader

Middelvlei Reef

Green Bar

M-SPQ

L-SPQ

Jeppestown Shale

1 m
5 m

UCS (MPa)	E(GPA)	δ
218(56)	87(15)	0.20(0.03)
222(85)	87(5)	0.24(0.05)
260(106)	87(6)	0.17(0.01)
265(107)	78(11)	0.20(0.04)
219(25)	71(7)	0.23(0.04)
260(8)	71(2)	0.23(0.06)

d

Vaal Reef

Kimberley Shale
MB1
MB2
MB3
MB4
Quartzite
MB5
MB6

UCS (MPa)	E(GPA)	δ
218(34)	73(6)	0.23(0.03)
209(39)	74(4)	0.17(0.03)
184(44)	70(7)	0.20(0.04)
203(60)	78(8)	0.19(0.05)
268(66)	81(8)	0.19(0.06)
180(53)	74(6)	0.18(0.03)

Legend: Dyke/Sill · Volcanic Rocks · Argillaceous Partings/Shale · Conglomerate · Orebody · Quartzite
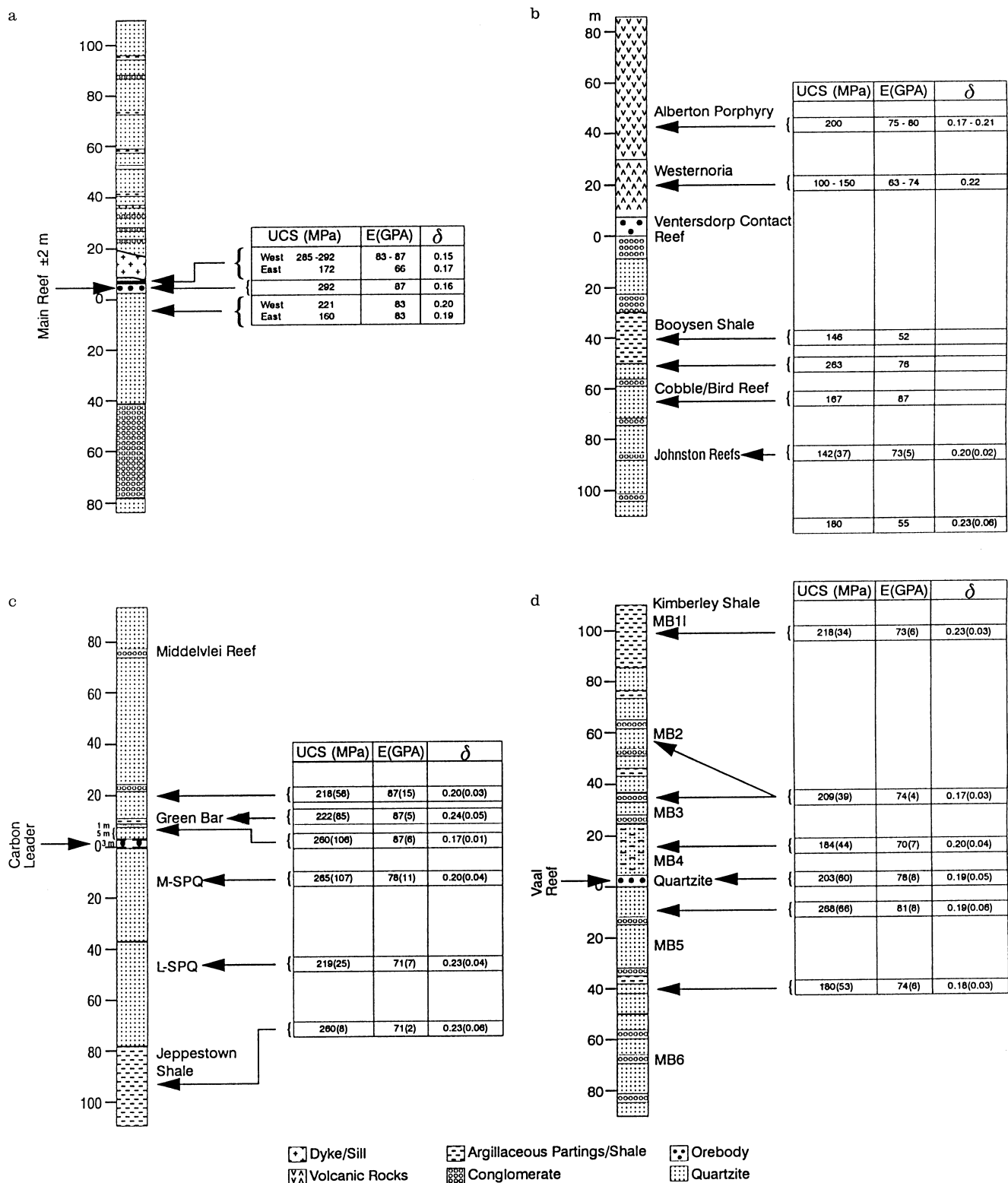
Fig. 5a–d Stratigraphic profiles delineating the various rock types associated with the **a** Main, **b** Ventersdorp Contact Reef, **c** Carbon Leader and the **d** Vaal Reef. Also provided are some rock engineering property analyses (*numbers in brackets* represent standard deviations) for the orebodies and some of the footwall and hangingwall strata. *UCS*, uniaxial compressive strength; *E*, Young's Modulus; δ, Poisson's Ratio

consists predominantly of Westonaria Formation lavas (colloquially termed "soft" lava), with a distinct parting separating the "soft" rocks from the overlying lavas of the Alberton Porphyry Formation (colloquially termed "hard" lava). This parting is situated some < 1–40 m into the hangingwall. The presence of the "soft" lava results in highly fragmented hangingwall conditions and impacts on the performance of stabilising pillars (M. Maccelari 1995 personal communication). The average stoping width is about 120 cm, and selected cut extraction is practised in areas where the uppermost portion of the VCR consists of unpayable quartzite.

Thicknesses of the VCR at South Deep (Fig. 1) are highly variable, averaging 150 cm, with the reef dipping at 29° towards the east (Haslett 1994). The VCR at South Deep is mined conventionally, similar to exploitation of the VCR at Kloof Gold Mine (Circular to Members of Western Areas and South Deep 1995). The Upper Elsburgs' (UE's, Fig. 2) at South Deep will be mined differently along their extent, due to lateral lithological variations. Trackless mining will be used to mine the proximal, thick, conglomeratic portion of this orebody in the west, whereas conventional mining methods will be applied in the distal, deep eastern portion, highlighting the importance of lateral facies variations. In the eastern portion, individual gold-bearing conglomerate horizons are separated by unpaying quartzites (Circular to Members of Western Areas and South Deep 1995). Up to 15 mineable orebodies are contained in the Upper Elsburgs' and the thicknesses of these conglomerate horizons vary between 50–1200 cm. Pillars are strategically placed along the N/S-trending faults and dykes to limit spans and ERR. Dykes are ultrabasic and syenitic and trend N/S and E/W. Three phases of faulting are associated with the VCR, characterised respectively by cataclasite, pseudotachylite, and slickensides.

Carletonville Goldfield. Deep-level reserves of the Carletonville Goldfield comprise the Carbon Leader (Fig. 5c) at Driefontein Consolidated Mines Ltd. and Western Deep Levels, and the VCR (Fig. 5b) at Western Deep Levels, Elandsrand, Deelkraal, and to a lesser extent at Driefontein Gold Mine. In deep areas at Driefontein, provision has been made for 18% geological loss and 12% loss due to stabilising pillars (Tamlyn 1994). Faults strike NE/SW and N/S and exhibit displacements of several hundred metres.

The Carbon Leader is generally characterised by a competent quartzite footwall, with a complex succession of rock types overlying this orebody (Fig. 5c). Bedded, siliceous quartzite (0–3 m in thickness), the Rice Pebble Marker (0.5 to 1 m in thickness) and the shaly Green Bar (1 to 5 m in thickness) are the hangingwall to the

Fig. 6 Variations in footwall rock types subcropping against the Ventersdorp Contact Reef at depths ranging between 3000 m and 4500 m, as observed at Western Deep Levels Gold Mine (modified after Regional VCR Working Group 1994)
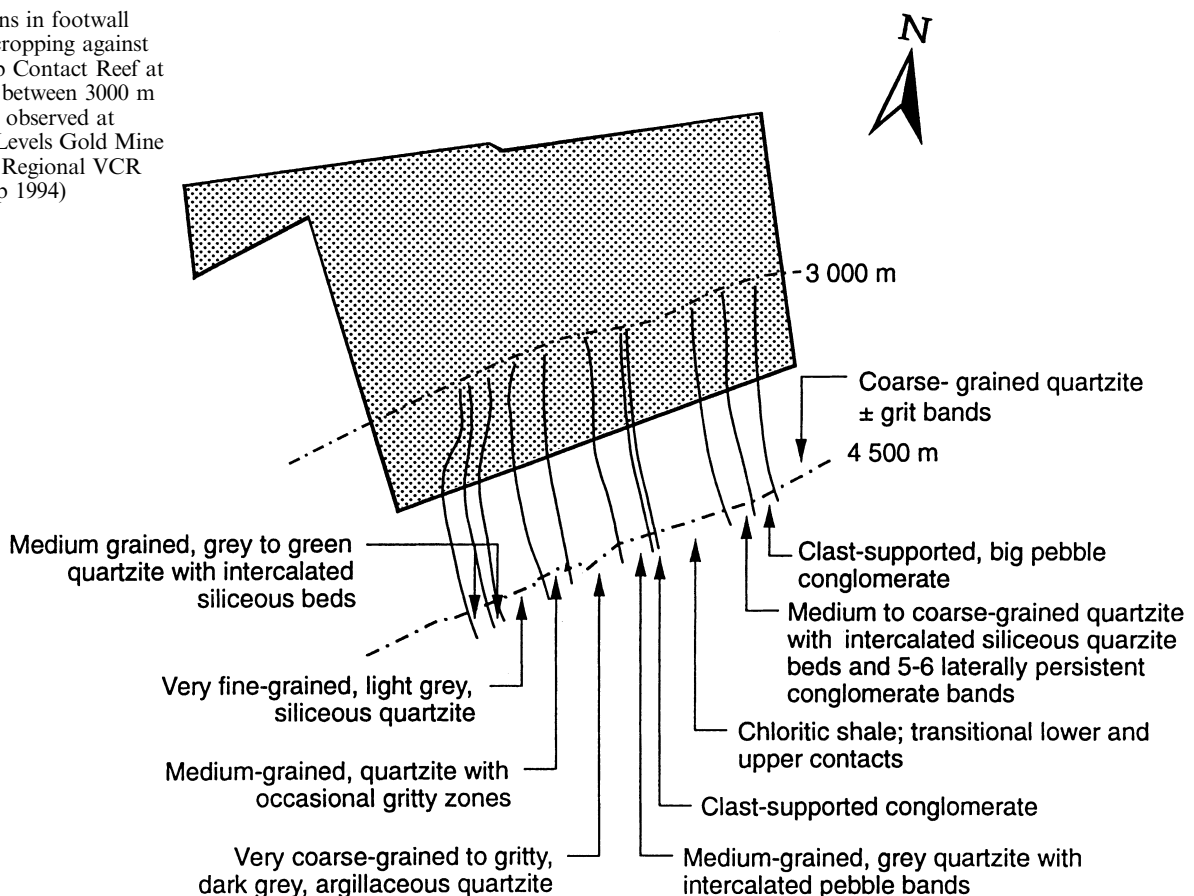
Carbon Leader. Pronounced partings are developed along the contacts of these lithologies, and in the lower portion of the Green Bar, which are also characterised by quartz veining and slickensides.

The VCR depth contours and associated footwall lithologies at depth between 3000 and 4500 m for Western Deep Levels are shown in Fig. 6. A great variety in the features of footwall quartzites is noted, ranging from siliceous to argillaceous. Varying chlorite contents are indicated by the variations in colour of the rocks. Conglomeratic footwall horizons are less frequent and shaly footwall is encountered in the eastern portion of Western Deep Levels (Fig. 6), with the Alberton Porphyry Formation lava ("hard" lava) only being present in the hangingwall of the VCR towards the west of Driefontein (Fig. 1).

Klerksdorp Goldfield. Future mining at depth will largely concentrate on the Vaal Reef (Fig. 5d) in the eastern portion of Vaal Reefs Gold Mine (Fig. 1, Moab extension). Production at Moab, where the sub-vertical shaft extends to depths of about 3700 m, is expected to commence in the shallow areas towards the end of 1996 (Gilroy et al. 1994). Channel widths are about 83 cm, with the dips varying between 22° and 30°.

The footwall of the Vaal Reef consists of the MB5, a sequence of quartzites and conglomerates of varying characteristics (Fig. 5d). The variations in footwall and hangingwall rock types are also reflected in varying rock strength parameters, affecting rockmass behaviour around footwall developments. The Zandpan Marker is an approximately 0.5 m thick, argillaceous quartzite layer in the hangingwall of the Vaal Reef, characterised by relatively low uniaxial compressive strength values (Fig. 5d).

The fault pattern in the Klerksdorp Goldfield is complex, and three major stages of faulting are observed, with northeast-southwest trending faults being the most dominant. Generally displacements are in the region of several hundreds of meters, with some even exceeding 1000 m. Bedding parallel faulting is common and may add to the complexities encountered, while dykes exhibit similar orientations to the faults. The Ventersdorp Supergroup-aged dykes are known for their burst potential (Gay and Jager 1986b).

Bothaville Goldfield. Several, economically important reef horizons have been identified at Sun and Target (e.g. Gray et al. 1994; Tucker et al. 1994), which generally occur at depths exceeding 3500 m. The reef horizons are the Basal Reef, reefs of the Kimberley succession, Elsburg Reefs, and the Kruidfontein Reef (VCR equivalent). Borehole MA1, for example, intersected the Basal Reef, and shows encouraging values, at a depth of 3975 m. The regionally developed "Khaki" shale and the argillaceous quartzite in the hangingwall and footwall of the B-reef, respectively, are known to affect mining conditions negatively, while additional shale horizons are present in the overlying Kimberley succession.

Geotechnical classification of the major Witwatersrand orebodies

The orebodies under consideration are characterised by distinct geotechnical conditions, also expressed by orebody-specific rockmass behaviour. The following, preliminary methodology assesses the geotechnical environment associated with Witwatersrand excavations. It considers four geological categories (a to d), as defined in the previous sections, and one mining parameter (e):

a. Frequency and features of secondary geological parameters
b. Variations in reef characteristics and geometry
c. Frequency and characteristics of sedimentary and volcanic partings
d. Rock type assemblage (e.g. soft/hard or hard/hard, rock strength environment)
e. Stoping width

Weighting factors for (a) to (e) are deduced by evaluating the importance of the individual categories, using the information from the literature and our own data. A hazard rating may then be assigned to selected Witwatersrand orebodies, which, when combined with the weighting factors, results in an overall rating of problems associated with individual orebodies (Table 3a, b). This rating is considered for dynamic and static mining conditions at, for example, depths of mining of 1500 m and 4500 m.

The methodology proposed here must be improved through future studies, which may also consider a detailed seismic comparison of the various orebodies, and computer modelling. It must be emphasised, therefore, that the preliminary methodology given here, serves as an example, which should be subject to changes in the future. Further scope also exists to further subdivide individual orebodies, according to rock-type assemblage and other parameters. This is exemplified by separating the areas where the Westonaria lavas ("soft") form the hangingwall of the VCR from those where the Alberton Porphyry Formation lavas ("hard") are preserved (Table 3).

Consideration of the individual reef ratings (Table 3) suggest that rockburst problems are most prominent for the VCR and the Carbon Leader (Fig. 7a). Seismic activity may increase with depth for all the orebodies under consideration, with strata control problems significant for the same orebodies, as well as for those contained within the Elsburg succession (Fig. 7b), due to high stoping widths (Table 3).

The combined rockburst/strata control problem rating again identifies the VCR and the Carbon Leader as the orebodies imposing the most problems during mining, followed by the Elsburg reefs (Fig. 8), while less problems may be encountered while mining the Vaal and the Main Reefs. The Kimberley and Basal Reefs will most likely encounter the least problems during mining.

The proposed classification methodology may be considered when evaluating different mining and sup-

Table 3 Seismic and strata control problem ratings for the major gold-producing Witwatersrand orebodies. The weighting factors and hazard ratings have been deduced considering data available from the literature, combined with our own observations. Note that the table has been compiled to demonstrate a format that quantitatively assesses the problems associated with individual orebodies, and that the methodology is subject to modifications. The seismic and strata control problem rating is graphically summarised in Fig. 7a, b, respectively. The combined problem rating is provided in Fig. 8

	Rockburst problem											
	Frequency and features of secondary geological parameters		Variability in reef geometry and other reef features		Frequency and characteristics of sedimentary and volcanic partings		Rock type assemblage (e.g. soft/hard)		Stoping width		Total	
Depth (m)	1500	4500	1500	4500	1500	4500	1500	4500	1500	4500	1500	4500
Weighting	0.30	0.40	0.15	0.05	0.20	0.30	0.20	0.05	0.15	0.20		
VCR (hard)	8 (2.40)	10 (4.00)	8 (1.20)	10 (0.50)	8 (1.60)	9 (2.70)	8 (1.60)	10 (0.50)	3 (0.45)	3 (0.60)	7.25	8.30
VCR (soft)	7 (2.10)	9 (3.60)	8 (1.20)	10 (0.50)	7 (1.40)	8 (2.40)	6 (1.20)	7 (0.35)	3 (0.45)	3 (0.60)	6.35	7.45
Carbon Leader	7 (2.10)	9 (3.60)	5 (0.75)	6 (0.30)	9 (1.80)	10 (3.00)	7 (1.40)	8 (0.40)	2 (0.30)	2 (0.40)	6.35	7.70
Vaal Reef	6 (1.80)	9 (3.60)	2 (0.30)	3 (0.15)	4 (0.80)	6 (1.80)	4 (0.80)	6 (0.30)	2 (0.30)	2 (0.40)	4.00	6.25
Main Reef	5 (1.50)	8 (3.20)	2 (0.30)	3 (0.15)	5 (1.00)	7 (2.10)	3 (0.60)	4 (0.20)	1 (0.15)	2 (0.40)	3.55	6.05
Elsburg Reefs	3 (0.90)	4 (1.60)	2 (0.30)	3 (0.15)	4 (0.80)	5 (1.50)	6 (1.20)	7 (0.35)	8 (1.20)	9 (1.80)	4.40	5.40
Kimberley	2 (0.60)	3 (1.20)	2 (0.30)	3 (0.15)	3 (0.60)	4 (1.20)	3 (0.60)	4 (0.20)	3 (0.45)	4 (0.80)	2.55	3.55
Basal Reef	4 (1.20)	5 (2.00)	2 (0.30)	13 (0.15)	3 (0.60)	4 (1.20)	4 (0.80)	5 (0.25)	2 (0.30)	2 (0.40)	3.20	4.00

HAZARD RATING

1	2	3	4	5	6	7	8	9	10
LOW					MODERATE				HIGH

	Strata control problem											
	Frequency and features of secondary geological parameters		Variability in reef geometry and other reef features		Frequency and characteristics of sedimentary and volcanic partings		Rock type assemblage (e.g. soft/hard)		Stoping Width		Total	
Depth (m)	1500	4500	1500	4500	1500	4500	1500	4500	1500	4500	1500	4500
Weighting	0.30	0.35	0.10	0.05	0.25	0.30	0.15	0.05	0.20	0.25		
VCR (hard)	6 (1.80)	7 (2.45)	7 (0.70)	8 (0.40)	8 (2.00)	10 (3.00)	1 (0.15)	3 (0.15)	2 (0.40)	2 (0.50)	5.05	6.50
VCR (soft)	9 (2.70)	10 (3.50)	5 (0.50)	7 (0.35)	8 (2.00)	10 (3.00)	7 (1.05)	8 (0.40)	2 (0.40)	2 (0.50)	6.65	7.75
Carbon Leader	7 (2.10)	8 (2.80)	4 (0.40)	5 (0.25)	8 (2.00)	10 (3.00)	4 (0.60)	5 (0.25)	2 (0.40)	2 (0.50)	5.50	6.80
Vaal Reef	6 (1.80)	7 (2.45)	3 (0.30)	4 (0.20)	7 (1.75)	8 (2.40)	3 (0.45)	4 (0.20)	2 (0.40)	2 (0.50)	4.70	5.75
Main Reef	6 (1.80)	7 (2.45)	2 (0.20)	3 (0.15)	7 (1.75)	8 (2.40)	4 (0.60)	5 (0.25)	2 (0.40)	2 (0.50)	4.75	5.75
Elsburg Reefs	5 (1.50)	6 (2.10)	2 (0.20)	3 (0.15)	6 (1.50)	7 (2.10)	5 (0.75)	6 (0.30)	9 (1.80)	10 (2.50)	5.75	7.15
Kimberley	3 (0.90)	4 (1.40)	2 (0.20)	3 (0.15)	5 (1.25)	6 (1.80)	2 (0.30)	3 (0.15)	5 (1.0)	6 (1.50)	3.65	5.00
Basal Reef	5 (1.50)	6 (2.10)	3 (0.30)	4 (0.20)	3 (0.75)	4 (1.20)	3 (0.45)	4 (0.20)	2 (0.4)	2 (0.50)	3.40	4.20

HAZARD RATING

1	2	3	4	5	6	7	8	9	10
LOW					MODERATE				HIGH

port techniques for specific orebodies. The classification undoubtedly requires refinement, especially to account for regional variations associated with a particular orebody, but is presented as an initial approach for continuing development.

Discussion

Many of the current deep level mine-layouts and strategies will need to be modified or replaced for mining at ultra-depth (e.g. Johnson and Schweitzer 1996). To achieve this, a better understanding of the geotechnical
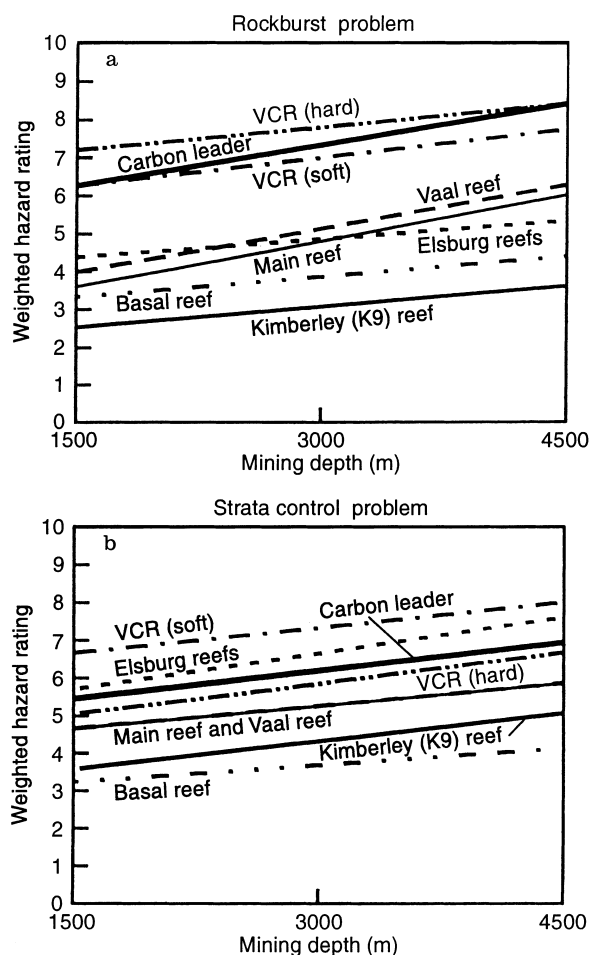
Fig. 7a, b Classification of reefs indicating geotechnical variability for selected orebodies, with **a** rockburst and **b** strata control problems determined by employing the weighted hazard rating listed in Table 3
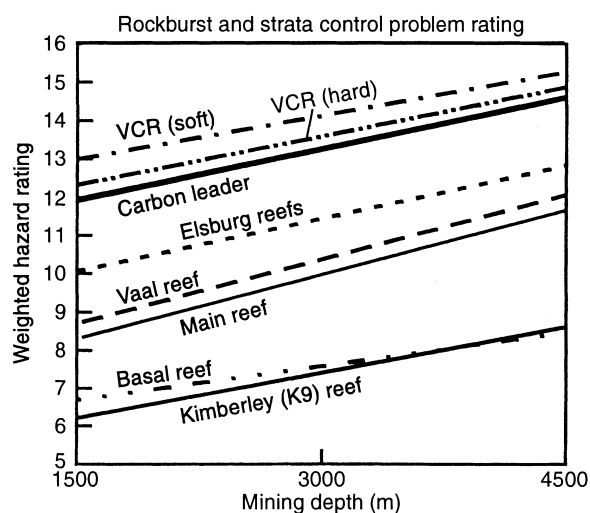

Fig. 8 Combined rockburst and strata control problems associated with, and potentially associated with the major Witwatersrand orebodies. The problem ratings have been deduced using the information summarised in Table 3

environment at ultra-depth is essential in assessing the effectiveness of such mining methods.

Recently, it has been confirmed that geological characteristics, such as rock type influence the rockmass behaviour around excavations (M. Roberts 1994 personal communication). However, our review reveals that the quantification of the impact of the primary and secondary geological features on the rockmass behaviour has only commenced.

A detailed review of the various fault and dyke populations, and associated joint characteristics, as observed in the regions to be mined at ultra-depth, is beyond the scope of this study. However, examination of the literature (Antrobus 1986; Antrobus et al. 1986; Engelbrecht et al. 1986; Minter et al. 1986; Tucker and Viljoen 1986; Tweedie 1986; Killick and Roering 1994; McCarthy 1994; Vermaakt and Chunnett 1994; Berlenbach 1995) reveals that fault and dyke characteristics and attitudes differ within the various goldfields, with the frequency and extent of faulting impacting on mine layout. Scattered mining is, therefore, practised in heavily faulted terrains, with longwall mining being performed in structurally less disturbed areas. Jointing/veining is closely linked to the various fault and dyke populations and it is anticipated that joint characteristics and attitudes will also differ from one goldfield to another. However, this needs to be confirmed through future investigations. The interpretation of the various structural settings is complicated due to the frequent reactivation of the various fault and dyke planes (e.g. Berlenbach 1995), therefore resulting in a structurally complex environment. The rock engineering significance of different fault rock types (e.g. Roering et al. 1991) also needs further attention, especially as different fault rock types could possess distinct slip potentials.

The Witwatersrand rocks were, on a number of occasions, intruded by dykes with varying textures and compositions, which vary from basaltic to rhyolitic, and this is also reflected in varying competencies. Future work could consider the potential link between the texture/composition of the dykes and their rock-engineering properties, while the establishment of such a link would enhance the prediction of dyke behaviour at ultra depth.

It has previously been stated that rock engineering problems arise from unpredictable discontinuities when mining activities proceed into unfamiliar geological terrains (e.g. Atkins and Keen 1984; Piper 1985). This statement is questioned here, in that a combination of the various geological disciplines, in conjunction with rock engineering, will enable the projection of the various rock types, and their associated features (such as "rolls" and rock engineering properties) into the unknown. Proximal/distal relationships of the orebody, as well as associated hangingwall and footwall strata are, similarly, predictable into the unmined areas (van Niekerk et al. 1990, 1994). Seismic surveys and other geophysical techniques, in addition, enable the prediction of geological discontinuities on a local and regional scale

(Fenner et al. 1994; Circular to Members of Western Areas and South Deep 1995).

A variety of studies have been carried out on the textural and compositional characteristics of Witwatersrand strata (e.g. Henckel and Schweitzer 1990, 1994; Henckel et al. 1990a and b; Hallbauer and Schweitzer 1992), and to date, no attempt has been made to investigate the potential rock engineering significance of these studies. Combining all the evidence, it is suggested that multidisciplinary approaches must be implemented during current and potential mining of ultra-deep Witwatersrand orebodies.

Various geotechnical environments are associated with the major orebodies. It has been attempted to quantify the complexities associated with the individual orebodies, considering multi-disciplinary findings, which results in a preliminary, geotechnical classification scheme, to be employed during the assessment of deep mining environments. The scheme is subject to future improvements. Future findings may, for example, support the proposal that seismic risk could be reduced in ultra-deep mining environments (Ryder 1988; Kirsten 1994; Kuijpers 1994), which will change the proposed hazard ratings (Table 3, Fig. 7a,b, Fig. 8).

Conclusion

About 20 mines and project areas that are mining, or will potentially mine at great depth have been identified. The VCR, Carbon Leader, Main Reef, reefs of the Elsburg and Kimberley successions, Vaal Reef, and the Basal Reef are the major targets.

Evaluation of the data reveals that geological parameters significantly control rockmass behaviour. A variety of rock types, having distinct rock engineering properties, are located in close proximity to the excavations, with primary and secondary partings also being prominent. The auriferous orebodies are, therefore, located in complex geological environments. The quantitative assessment of the complexities associated with these environments has been attempted, and the resulting preliminary methodology, assigning different degrees of difficulty to be encountered while mining individual orebodies, may be developed further. However, it is intended to serve as a guideline while identifying different mining conditions at ultra-depth, impacting on the mining strategy and the mine design.

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