Application of 3-D Seismics to Mine Planning at Vaal Reefs Gold Mine, Number 10 Shaft, Republic of South Africa

Pretorius, C.C.[1], Trewick, W.F.[1], and Irons, C.[2]

1. Anglo American Corp. of South Africa Ltd., Marshalltown, South Africa
2. Irons Geophysical Consulting, Henley-on-Thames, Oxfordshire, U.K.

ABSTRACT

During 1994, a three-dimensional (3-D) seismic reflection survey was undertaken at Vaal Reefs No. 10 Shaft with the objective of mapping the detailed structure of the reflective Ventersdorp Contact 'Reef' (VCR) gold ore body. This would provide vital input into future mine planning and development. The survey benefited from 10 years of two-dimensional seismic experience and one previous 3-D mine survey, conducted in the Witwatersrand Basin by the Gold Division of Anglo American Corporation of South Africa (AAC).

The seismic survey at 10 Shaft has accurately and spectacularly delineated the 3-D structure of the VCR at depths ranging from 1000 m to 3500 m, imaging faults with throws in the 20 m to 1200 m range. The resultant structure plans have been satisfactorily validated by subsequent surface drilling and underground mining operations during the period 1994 to 1996. These plans have been merged with drill hole, underground survey and sampling data into an integrated mine modelling, gold reserve estimation and mine scheduling package.

The Geology Department now manages the planning function at 10 Shaft and 3-D seismics has played a significant role in placing this important responsibility firmly within the geologists' domain. Building on the success of the 10 Shaft survey, two further 3-D seismic surveys have been concluded over AAC group mines during 1996 and 1997.

INTRODUCTION

The Gold Division of the Anglo American Corporation of South Africa (AAC) has successfully employed seismic reflection techniques in its Witwatersrand Basin analysis programs since 1983. The emphasis during the first ten years was on reconnaissance two-dimensional (2-D) seismic surveys for subsurface structural mapping of the Witwatersrand Triad rocks, particularly the auriferous Central Rand Group, within the main Witwatersrand Basin (Figure 1). Building on the success of these 2-D surveys, AAC's first three-dimensional (3-D) seismic survey for mine planning and development took place at Western Deep Levels Gold Mine in 1993, with the second following a year later at Vaal Reefs Number 10 Shaft (Figure 1).

In many respects the 10 Shaft survey represents the mature application of seismics to detailed structural mapping in a deep AAC gold mine. Seismic structural maps of the Ventersdorp Contact Reef (VCR) gold ore body at 10 Shaft have been satisfactorily validated by subsequent drilling and mining operations between 1994 and 1996. These positive results have encouraged two more AAC mines to conduct 3-D seismic surveys in 1996–97, with the latest survey, at Western Ultra Deep Levels, being eight times the size of the motivational 10 Shaft survey and probably one of the largest mine geophysical surveys undertaken to date in the mineral industry.

This paper summarizes the 3-D seismic data acquisition, processing and interpretation methodologies which were developed at 10 Shaft, and will hopefully illustrate how this geophysical technique can make a powerful contribution to the optimization of ore body extraction in the dynamic Witwatersrand mining environment.

GEOLOGICAL SETTING AND ITS RELATIONSHIP TO SEISMIC STRATIGRAPHY

Descriptions of Witwatersrand geology and associated seismic stratigraphy appear in Pretorius *et al.* (1987, 1994), de Wet and Hall (1994) and Weder (1994). Most of the gold in the Main Witwatersrand Basin occurs

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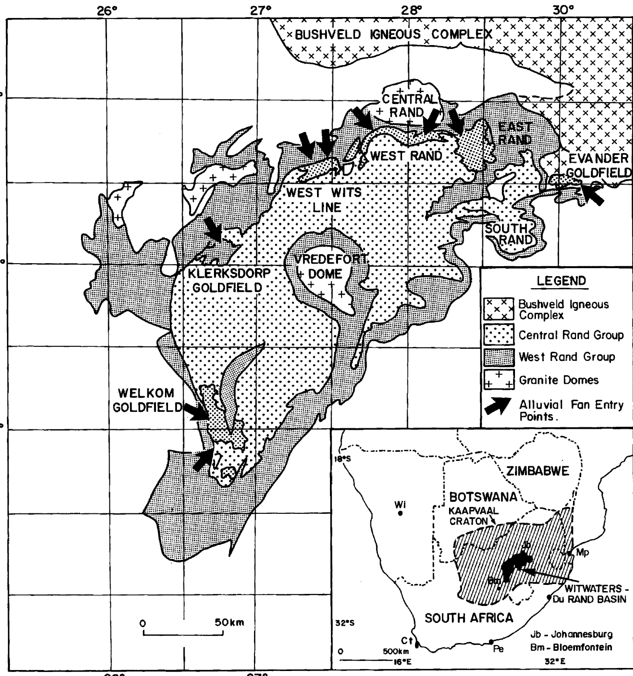

Figure 1: *Regional location, surface and sub-surface geology of the Witswatersrand Basin (after Pretorious et al. (1986) with modification).*

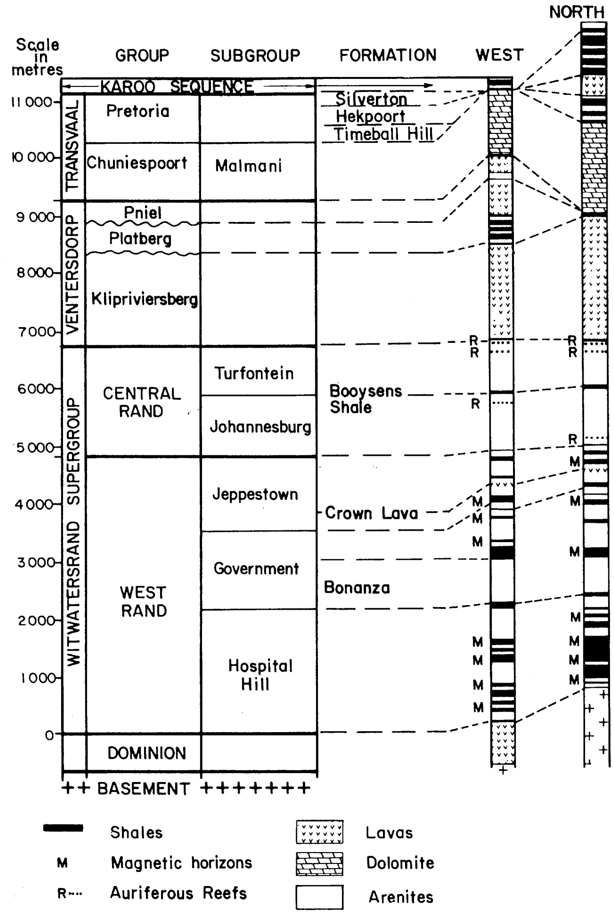

Figure 2: *Lithostratigraphic columns in the Witswatersrand Basin.*

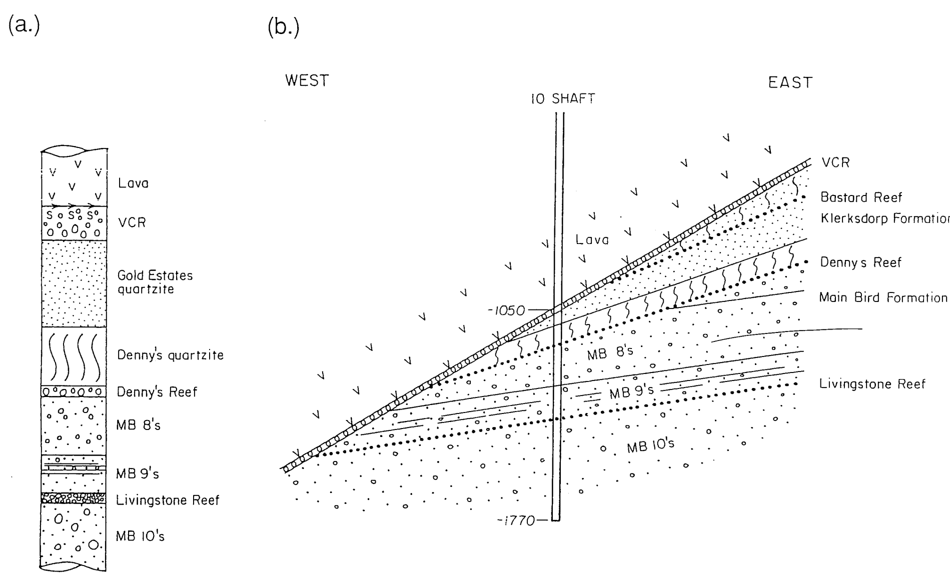

Figure 3: *(**a**) Generalized geological section No. 10 shaft.*
*(**b**) Idealized west-east section across the No. 10 Shaft Lease Area showing unconformable relationships.*
(Ref: Trewick (1994)

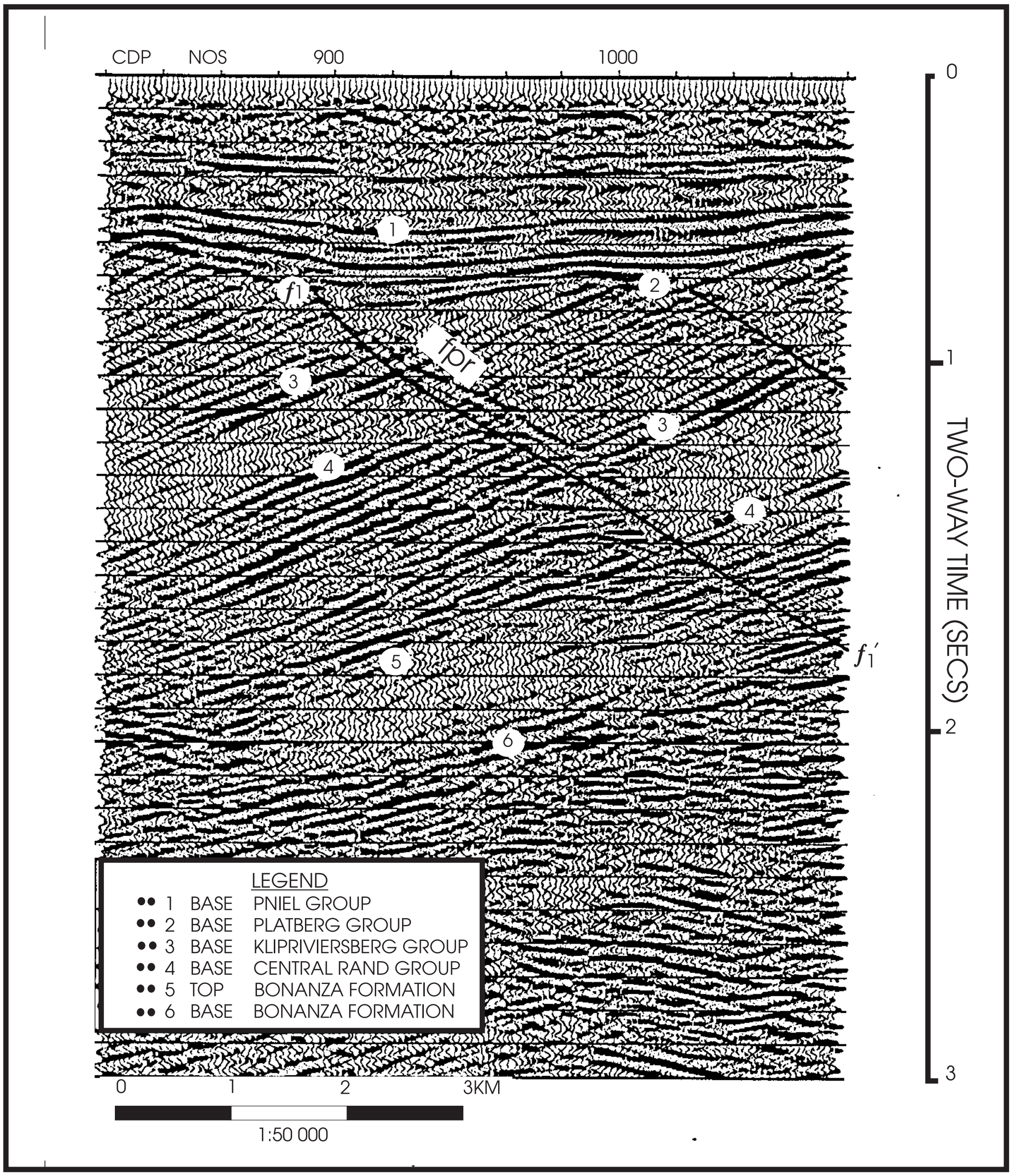

Figure 4: *A portion of 2-D seismic line OG-54 in the vicinity of 10 Shaft.*

in thin auriferous conglomerates, anomalously termed "reefs", within the predominantly arenaceous Central Rand Group (Figure 2). The principal reef mined at 10 Shaft is the VCR. The VCR is found at the base of the Klipriviersberg Group, which is the basal group of the Ventersdorp Supergroup. The VCR is conformable with the overlying lavas but unconformable on the underlying quartzites of the Witwatersrand Supergroup. Figure 3 is a generalized geological section through the 10 Shaft Lease area, showing the unconformable relationship of the various lithostratigraphic units.

The VCR is a highly channelised reef with thicknesses varying from 20 cm to 400 cm. It can be divided into two major reef types, viz. plateau reef and channel reef, with the channel reef being further subdivided into three subfacies. There is a very strong correlation between facies type and gold grade as described by Trewick (1994).

Figure 4 shows part of a previous NW-SE 2-D seismic section traversing the 10 Shaft 3-D survey area and clearly illustrates the seismic stratigraphy of the Ventersdorp and Witwatersrand Supergroups at this locality. Note especially the strong angular unconformity (event 2) where Platberg Group sediments are draped over underlying, tilted fault blocks of Klipriviersberg Group lavas. The drop in both P-wave velocity (from 6300 m/s to 5800 m/s) and density (from 2.9 g/cm^3 to 2.67 g/cm^3) as seismic waves pass from the Klipriviersberg lavas into the underlying Central Rand Group quartzites, produces a strong reflection coefficient, which fortuitously coincides with the VCR. Reflections at

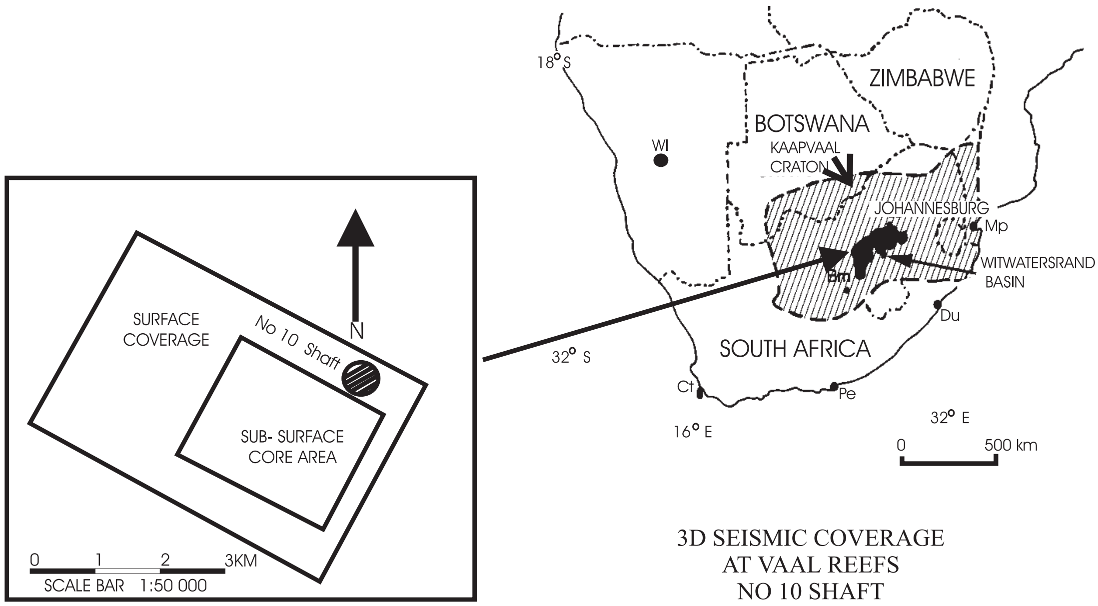

Figure 5: *3-D seismic coverage at Vaal Reefs No. 10 Shaft.*

this lava contact (event 3) can therefore be used to map the VCR ore body. The Central Rand Group between events 3 and 4 maintains a seismically transparent character in this portion of the Witwatersrand Basin. The numerous positive and negative reflections in the Jeppestown Subgroup of the West Rand Group below event 4 are caused by alternating shales and quartzites. This 'stripy' reflectivity characterizes most of the West Rand Group except for the Bonanza formation quartzites of the Government Subgroup, between events 5 and 6. These understandably have a similar seismic signature to the Central Rand Group quartzites.

Table 1: ***Vaal Reefs 10 Shaft 3-D seismic survey data acquisition parameters.***

Field crew	Geoseis
Instrument type	SN368 / CS2502
No. of channels	240
Record length	3 seconds
Sample rate	2 milliseconds
Fold	2000%
Nominal Vibroseis Source Parameters	
Vibrator type	Mertz M18 with Pelton Mk II electronics
Pattern	4 Vibs in-line 62° W of N
VP interval	40 m
Array length	30 m
Sweep length	16 seconds
Sweep frequency	10-90 Hz
Gain	6 dB/octave boost
Taper	0.3 sec
Nominal Receiver Array Parameters	
Geophone type	GCR
Geophone frequency	10 Hz
Station interval	40 m
Pattern	in-line
Spread	4 lines of 60 receivers

Note how a large, pre-Platberg normal fault such as f_1-$f_{1'}$ (2000 m throw) on Figure 4 is imaged not only where it displaces the VCR, but also where it traverses the reflective West Rand Group. However it is not easy to pick the exact position of this fault throughout the section, as certain West Rand Group reflectors still appear to pass through it undisturbed. This phenomenon is due to out-of-plane events being imaged on this section, and it illustrates a major drawback of 2-D seismics, which prevents its use as a detailed structural mapping tool. Another excellent example of such 'sideswipe' is the steeply dipping fault plane reflector, labeled "*fpr*", just above the interpreted position of f_1-$f_{1'}$. This reflector appears to originate from a strike extension of f_1-$f_{1'}$, several hundred metres north of the 2-D section line.

In order to map structure at the minimum resolution (20 m) expected by the mining clients and potentially available from the seismic data at the VCR level, it is crucial to record 3-D seismic data, followed by full 3-D depth migration at the processing phase. This will allow for the restoration of reflectors such as "fpr" to their true subsurface position in 3-D space. Further discussions on the need for 3-D seismic imaging in a structurally complex hard-rock mineral exploration environment appear in Milkereit and Eaton (1996).

SEISMIC DATA ACQUISITION

Three-dimensional seismic survey design criteria must address issues such as the subsurface area to be imaged; the required spatial resolution; bin dimensions; fold of cover and the required source and receiver configurations to achieve this; migration apertures and static control. Ashton *et al.* (1994) have published an interesting article on 3-D seismic survey design, including oil industry examples. Notes on appropriate modifications to seismic survey design criteria when addressing the hard-rock Witwatersrand environment appear in Pretorius *et al.* (1987).

From previous 2-D seismic surveys undertaken at 10 Shaft it was clear that the peak frequencies achievable at the VCR would be between 60 and 75Hz. Assuming an average velocity of 6000 m/s and quarter-wavelength vertical resolution criteria it was decided that 20 m vertical resolution was possible. It was hoped that this resolution could be further improved with the benefit of full 3-D migration and graphic workstation interpretation techniques such as 3-D visualization of horizon picks and related seismic attribute data.

The 3-D survey design was oriented towards maximizing the structural resolution on the VCR within the 5 km^2 *subsurface* core area shown on Figure 5. This area covers proposed underground development plans until the year 2012 on a complex VCR at depths ranging between 1000 m and 3500 m. The seismic acquisition parameters required to achieve the imaging are summarized in Table 1, and the required *surface* coverage is displayed in Figure 5. The data acquisition was undertaken by Geoseis (Pty.) Ltd. between December 1993 and February 1994.

While a full discussion of the acquisition methodology is beyond the scope of this paper it is pertinent to stress certain important aspects of the design:

Target bin size —The target bin size of 20 m was chosen to ensure that spatial aliasing would not occur at the typical stratigraphic dips (< 30°) and maximum frequencies (< 75 Hz) in the survey area. The spatial sampling parameters will, in theory, allow 3-D migration of dips up to 56° at frequencies up to 90 Hz .

Migration aperture —In order to migrate dips of up to 30° in the in-line (northwesterly) direction at depths of 3500 m, a migration aperture of 2000 m was selected for the core area shown in Figure 5. In contrast to this, the main concern in the cross-line direction was to ensure that diffraction hyperboloids originating at faulted contacts were sufficiently sampled to allow them to be satisfactorily collapsed during migration and provide adequate spatial resolution of the diffraction points. Experimental migration of partially sampled, computer-simulated diffractions was used to estimate a satisfactory strike migration aperture of 700 m.

The surface survey area shown in Figure 5 provides full fold coverage of the core area, and it includes the strike and dip migration apertures and the stack-on zone for both in-line and cross-line fold buildup. The total surface coverage required to satisfactorily image the 5 km^2 core area is 17 km^2.

Fold—Fold decimation exercises were undertaken on the original 48-fold 2-D seismic sections and the results were used to determine that nominal 20-fold coverage would be adequate for the 3-D survey.

Recording time—A recording time of 3 seconds was considered adequate to allow for full 3-D migration of seismic data down to the Jeppestown subgroup of the West Rand Group. This was necessary to ensure that faults affecting the VCR could be mapped at depths where they displace the upper West Rand Group reflectors (Figure 4).

Recording geometry—Figure 6 displays the acquisition geometry employed at 10 Shaft. The staggered brick wall technique generated a satisfactory range of offsets (0–1100 m) and azimuths within the bins to facilitate maximum fold at target reflection times and adequate normal moveout, and it accommodated the requirements set out above for an optimum refraction statics solution. The staggered brick pattern provided better coverage at short offsets than a rectangular checkerboard layout, but it was logistically more difficult to implement and thus incurred cost penalties. Ashton *et al.* (1994) summarize the merits of various shooting patterns.

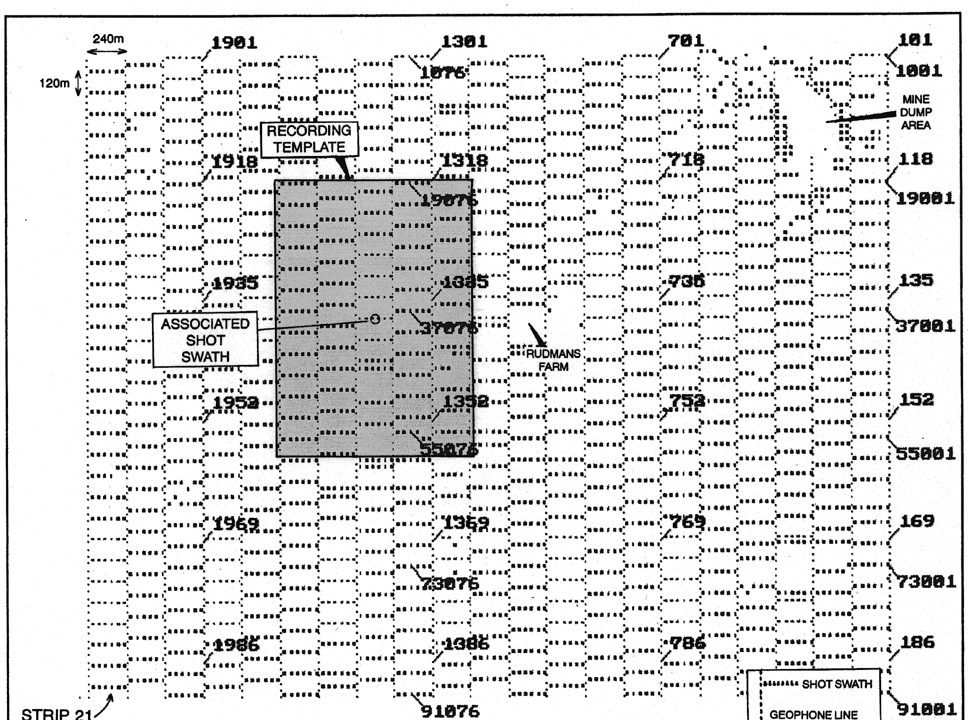

Figure 6: *Acquisition geometry employed at Vaal Reefs No. 10 Shaft.*

Table 2: *Vaal Reefs 10 Shaft 3-D seismic survey final data processing route.*

1.	Demultiplex	SEGD 6250bpi 9 track reels produced by Geoseis field crew
2.	Geometry	SEGD Reels copied to Phoenix Vector format 3480 cartridges. Line geometry and field statics appended to trace headers. Traces dropped outside 35–1064 m offset
3.	Statics	Hampson-Russell GLI statics applied
4.	Airwave	ProMAX Air Blast Attenuation 331 m/s
5.	Gain	T**1.0 Spherical Divergence correction
6.	F-k Filter	Full off 0–5200 m/s Fan Taper 5200-9360 m/s 500 ms recoverable AGC
7.	D.B.S.	Predictive 180 ms Operator 20 ms Gap
8.	Equalisation	Window Near # 300-1100 ms Far # 400-1200 ms
9.	Sort	To CMP order. 20 m bin width
10.	Autostatics	Surface Consistent Residual Statics. Derived from first round NMO corrected gathers
11.	NMO	Velocities picked from Constant Velocity Stacks after residual statics and DMO
12.	Mute	120% Stretch Mute
13.	Equalisation	500 ms sliding window 250 ms move-up
14.	Dmo	8 ms/trace dip limits
15.	Stack	Square root compensation 20-fold nominal
16.	Phase	Zero Phase Conversion
17.	Migration	One Pass Depth Migration
18.	Filter	10–20–80–90 Hz Band Pass Filter (Time Domain)

Statics — The importance of good static control in the near surface to improve structural resolution at great depths was appreciated at an early stage in AAC's 3-D seismic program. To this end a multi-line receiver template, restricted only by the number of traces available and acquisition efficiency, was adopted. This provided the capability of producing a more equal distribution of the total fold between the in-line fold and the cross-line fold, a factor important for an accurate solution of refractor based static algorithms.

Additionally, a Low Velocity Layer (LVL) seismic refraction program on a 1 km grid over the survey area was conducted together with eight uphole surveys. The data obtained from these surveys was used to optimize the final static solution derived from the GLI refraction static algorithm.

SEISMIC DATA PROCESSING

Data processing operations at 10 Shaft were divided into two phases:

1. Field QC processing conducted on site by Schlumberger/Geco-Prakla (SGP) employing its Voyager system.
2. Full 3-D processing undertaken by SGP at its Buckingham Gate (Gatwick) Processing Centre in the United Kingdom.

The emphasis in the field centre was on producing 2-D Brute-stacks for quality control purposes, within a day of completion of each swathe. This procedure ensured that potential data acquisition problems (e.g., geometry, statics) could be quickly detected and rectified in the field if necessary. GLI statics were also derived in the field from the Vibroseis records, ensuring a final check on the crucially important aspect of static control before the seismic, LVL and survey crews were demobilised.

The final processing route in the UK is summarized in Table 2. Most of the processing methods and parameters are normally accepted techniques adopted for most modern land-acquired 3-D seismic surveys. The refraction and residual statics processes, together with DMO, proved to be the critical factors in improving the signal-to-noise ratio. The main problem reported by the processing team was the elimination of air-blast and near-surface noise trains without disturbing the relative amplitudes of the shallow data. This was achieved using the Air-Blast attenuation software available within the Promax Processing System.

The means by which the velocity model for Depth Migration was constructed was, however, fundamentally different from normal accepted practices. With the restricted far offsets and the high interval velocities associated with the hard rock stratigraphy, stacking velocities are highly inaccurate when used as an approximation of the true P-wave velocity field of the subsurface. An alternative method was therefore conceived and the model constructed in a three-phase manner:

1. Based on borehole geophysical logs and prior 2-D seismic knowledge, an initial velocity approximation of 6000 m/s for the entire section was used to migrate 2-D dip lines extracted from the 3-D data set.
2. The major velocity boundaries were interpreted on these migrated sections and time-based structure maps were constructed. Local average velocities for the main geological formations were then extracted from borehole geophysical logs and a 3-D velocity and time model was constructed. Fortunately, for the 10 Shaft area only two layers and one horizon (VCR) needed construction, making this operation relatively simple. This provided the final input model for a 3-D *time* migration of the seismic data volume.
3. Contrary to the migrated time data set normally required by the oil industry (subsequently depth-converted during interpretation), the mine geologists and managers required their final data set in depth. A depth conversion was therefore carried out by an experienced interpretation geophysicist, familiar with the Witwatersrand stratigraphy, and integrated into the final migration phase of the processing.

The output data set from the 3-D time migration was first loaded onto an interpretation workstation and the major velocity boundary at the VCR was interpreted. Borehole depth control together with extracted two-way-time values from this interpretation were then used to calculate the average velocity down to the VCR at each borehole posi-

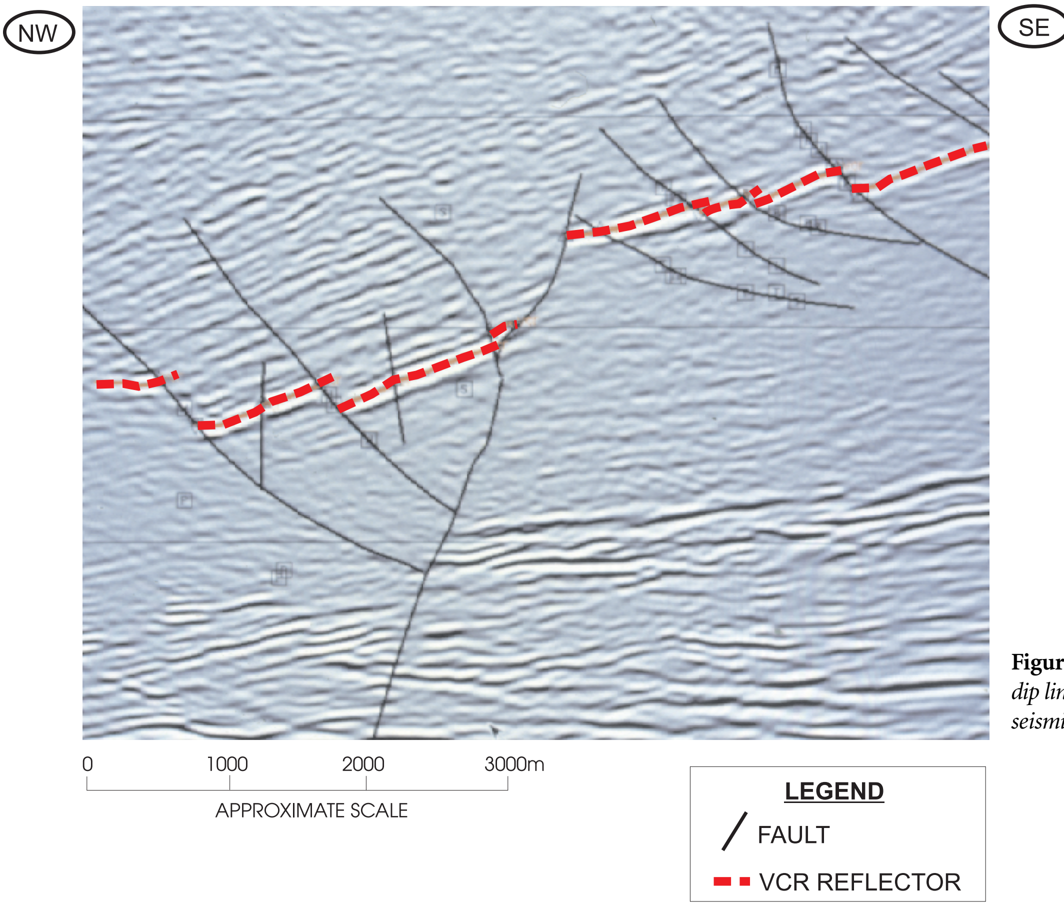

Figure 7: *Portion of an interpreted dip line through the center of the 3-D seismic data cube.*

tion. These values were contoured to produce a velocity map for the Klipriviersberg Lava which, together with the time interpretation of the VCR, was used as an input model to the *Depth* Migration of the data set. The quartzites and shales of the Witwatersrand Supergroup underlying the lava were given a constant velocity of 5800 m/s.

The final *Depth* Migrated data set was output in depth for detailed interpretation on the mine. The accuracy of this final velocity model for migration is borne out by the accuracy of the predicted depth and position of the faults intersected to date on the mine, as discussed below.

INTERPRETATION

Interpretation of the 10 Shaft seismic data commenced on the depth-migrated data cube using Schlumberger-Geoquest's IESX software with the GEOVIZ geovisualisation module. On the basis of this interpretation the mine design has been completed for the entire life of the mine.

It must be appreciated that the data cube will still contain some processing artifacts and depth mismatches. The interpretation is therefore expected to require minor updates throughout the life of the mine. The important principle is to apply these updates dynamically to maintain the required predictive capability ahead of development ends (200–300 m).

Figure 7 is an interpreted in-line (dip-line) through the centre of the data cube, showing the VCR horizon and associated faulting. The stratigraphy will not be described in detail as this has already been done for the 2-D type section in Figure 4. Clearly, the VCR is well imaged and there are no indications of residual 'sideswipe' such as feature "fpr" in Figure 4. Figure 8 is a 3-D representation of the VCR and fault surfaces after computer-assisted tracking of the horizon and faults has taken place through approximately half of the data volume. For illustrative purposes, the seismic cube has been peeled back to the current in-line section, revealing the ore body surface, displayed in light gray, with fault planes shown in dark gray. Surface drill hole G40, to which the interpretation has been tied, is displayed in the northwest. Note how grid-shading of the topographic surface in GEOVIZ, using a shallow sun angle from the north, helps to highlight smaller faults such as f2 (throw of approximately 20 m) by casting a significant shadow across the discrete change in topography.

In Figure 9 the seismic data cube has been completely rolled back to reveal the interpreted VCR surface within the 5 km^2 core area. As shown by the reference cube, the VCR depths range from 1000 m to about 3500 m within this area. The survey has accurately and spectacularly delineated faults with throws in the 20 m (f2) to 1200 m (f3) range, with a lateral positioning accuracy of better than 40 m. Note that the surface drill hole control has done little to define the fairly complex faulting in the subsurface, particularly the smaller faults with throws in the range of 20 m to 100 m (e.g., 100 m fault f4). Few, if any, of these faults could be interpreted from surface drilling and most will have a bearing on short-

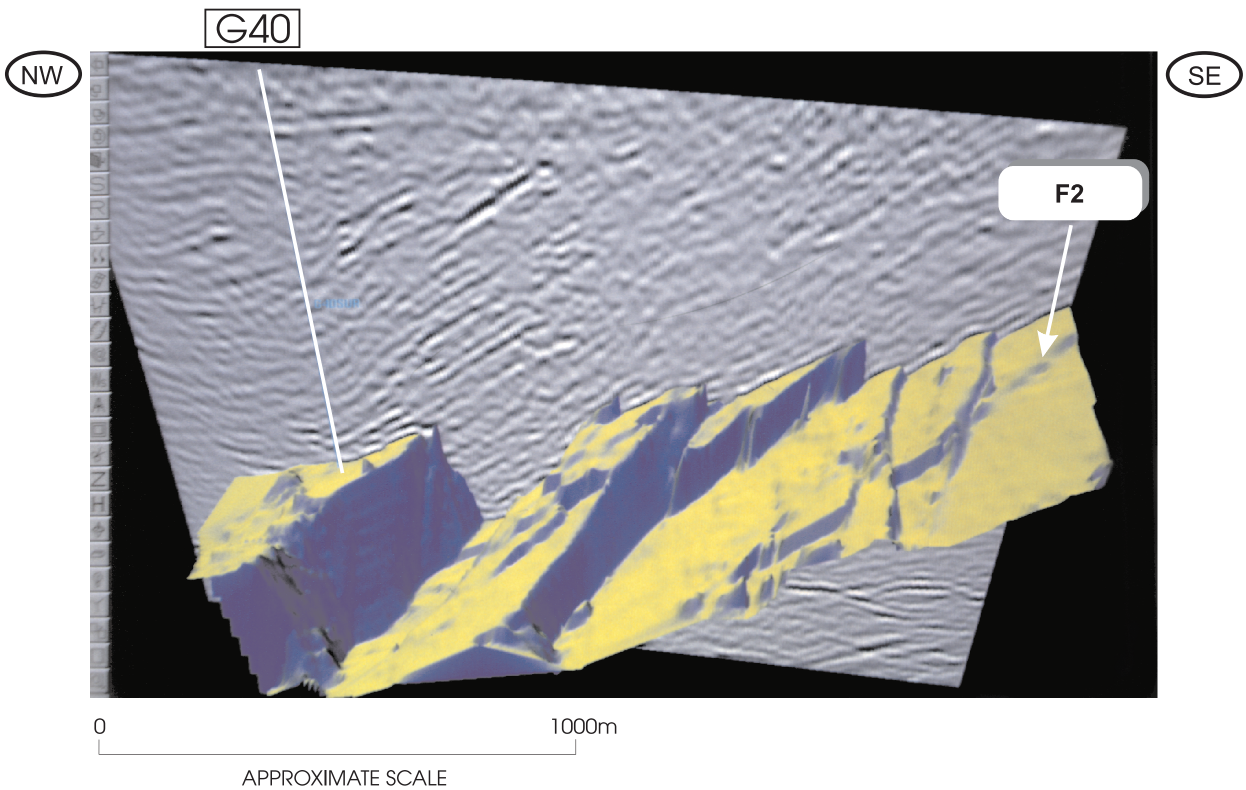

Figure 8: *Interpreted VCR surface approximately mid-way through the 3-D cube.*

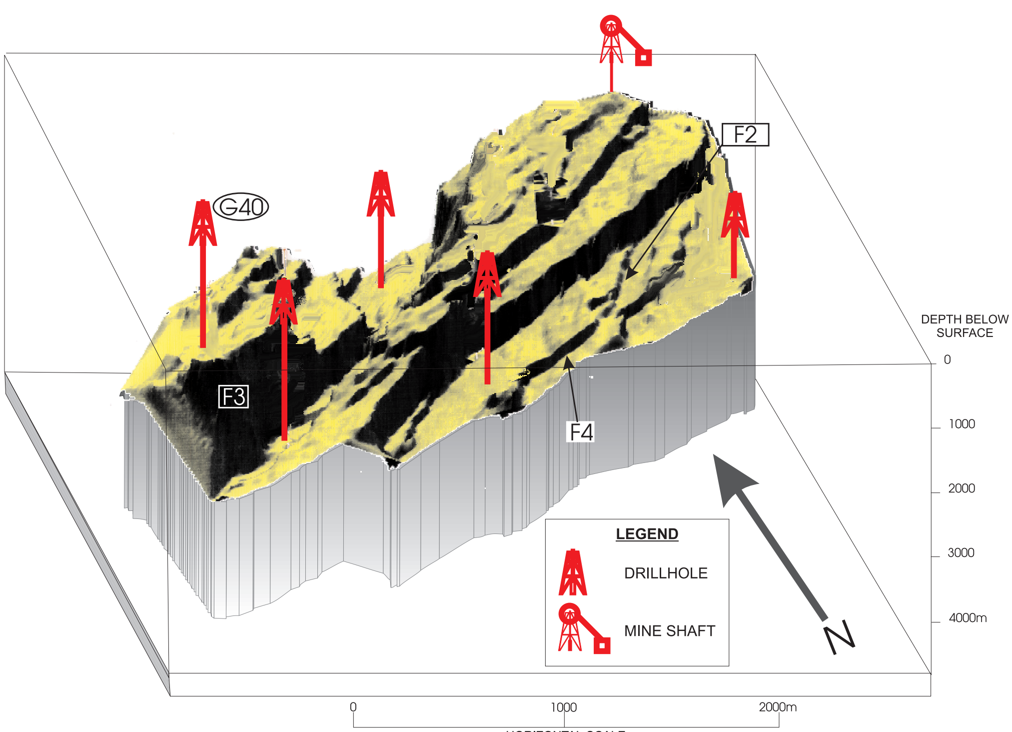

Figure 9: *Grid shaded 3-D perspective display of the VCR at Vaal Reefs No. 10 Shaft.*

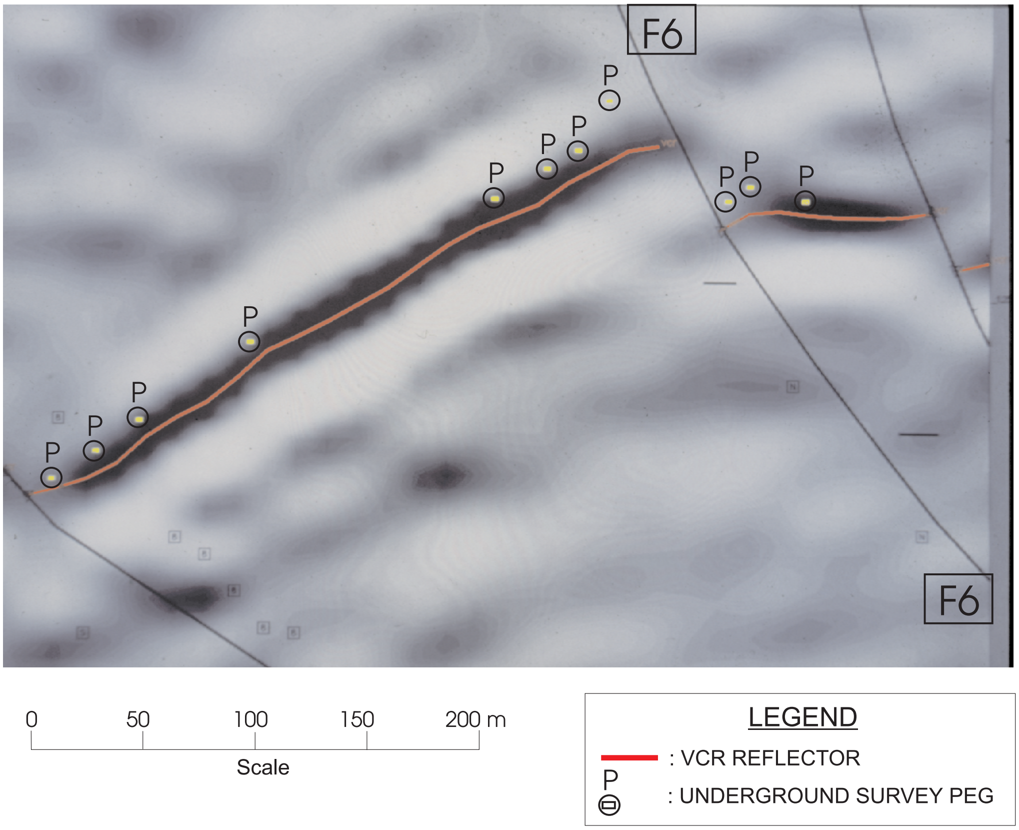

Figure 10: *Mining confirmation of VCR seismic structure plan at Vaal Reefs No. 10 Shaft.*

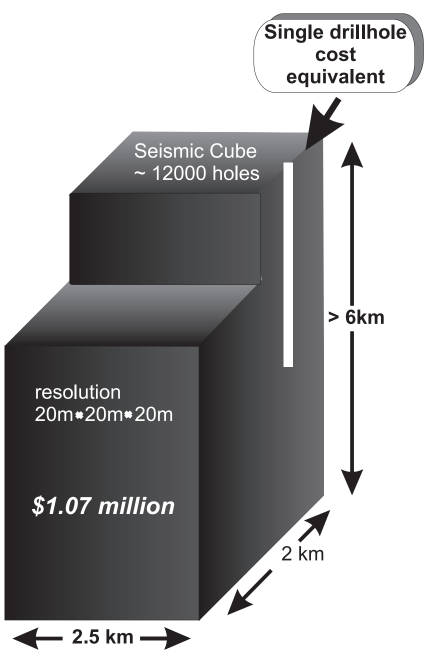

Figure 11: *Information economics at Vaal Reefs No. 10 shaft.*

to medium-term mine planning. The 3-D imaging of structures is very satisfying. As should be expected the fault planes are generally non-linear. Fault throws vary along strike and there is evidence for transfer structures displacing faults such as f4.

An unexpected result of this survey was the definition of the large upthrown block of VCR to the northwest of the 1200 m Mariendal fault, f3. This structure has since been tested by drillhole G40, which was drilled 2 km west of current mine workings and sited to intersect the block within an extrapolated VCR channel facies with good grade potential. This hole intersected the VCR within 20 m of the interpreted depth at 1800 m.

Several of the smaller faults were intersected by mining operations between 1994 and 1996, generally confirming the predicted structure. One example is illustrated in the enlarged dip section displayed in Figure 10. On this section the VCR pick is displaced by a 45 m fault (f6). Subsequent mining operations have confirmed the presence and throw of the fault, as shown by the underground survey pegs (p). Recent underground survey control indicates that fault throws as small as 15 m can be resolved at shallower VCR depths within the 3-D data cube. These results are a remarkable confirmation of the seismic method and the velocity model when one considers a regional dip of up to 30° resulting in VCR event migration of over 500 m.

DYNAMIC MINE PLANNING AND DEVELOPMENT

Development of a reliable facies plan has greatly assisted with the evaluation of Vaal Reefs 10 Shaft. Together with the accurate structural information provided by the 3-D seismic survey, this has enabled shaft geologists to develop a robust geological model. Availability of the geological model, together with the necessary computer technology in the form of GEOQUEST, MICROSTATION and CADS-MINE, enabled merging of seismic, drill hole, underground survey and sampling data into an *integrated* mine modelling, reserve estimation, and mine scheduling package. The new system is being used to generate an upgraded, accurate and comprehensive planning database which is sufficiently flexible to facilitate dynamic re-planning in response to new information.

The planning database is currently being used to optimise the positioning of the sub-shaft system, which will allow access to the deeper portions of the VCR ore body in the west and will hopefully extend the life of the mine to the year 2012. This sub-shaft must be optimally sited within VCR fault loss, to minimise the sterilisation of resources, while at the same time avoiding complex fault intersections that could compromise safety. The structure plan displayed in Figure 9 will greatly assist the planners in achieving this objective.

CONCLUSIONS

The 3-D seismic method has proven to be a very cost-effective technique for mapping structure on the VCR at 10 Shaft, delivering adequate resolution for short-, medium-, and long-term mine planning and development. Figure 11 illustrates, in a schematic form, just how cost effective the survey has been, compared to surface drill holes, as a means of providing *structural* information *on a reflective geological horizon*. If each binned seismic trace is considered to be the equivalent of a structural drill hole, the survey has arguably delivered spatial information equivalent to 12 000 surface drillholes, on a 20 m × 20 m grid, extending to VCR depths within the core area. Cross-sections within the seismic cube can be viewed and interpreted in any orientation, including horizontal time slices, as displayed in Figure 11. The total survey cost of USD $1.07 million, in 1994 money, would fund only one 3000 m deep drill hole, including deflections.

The ability of 3-D seismics to predict structure well ahead of the current stope faces and development ends has been admirably demonstrated over the last three years. The seismic data set is expected to play a key role not only in the modeling and design phases of mining operations, but also in the auditing phase, where compliance with the extraction plan is audited. In essence, the Geology Department now manages the planning function at 10 Shaft, and 3-D seismics has played a significant role in placing this responsibility firmly within the geologists' domain.

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REFERENCES

Ashton, C.P., Bacon, B., Déplanté, C., Ireson, D., and Redekop, G., 1994: 3-D Seismic Survey Design, p. 19-32 *in* Schlumberger Oilfield Review, Volume 6. Number 2 April 1994, edited by Henry N. Edmundson.

de Wet, J.A.J., and Hall, D.A., 1994: Interpretation of the Oryx 3-D Seismic Survey; p. 259-270 in 15th CMMI Congress, 4-9 September 1994, Geology Vol. 3, Edited by C.R. Anhaeusser.

Milkereit, B., and Eaton, W. D., 1996: Towards 3-D Seismic Exploration Technology for the Crystalline Crust: p. 17-36 in Trends, Technologies and Case Histories for the Modern Explorationest, Lawton, S.E. (ed.), Prospectors and Developers Association of Canada, Short Course notes.

Pretorius, C.C., 1986: Compilation of the Geological Map of the Witwatersrand Basin; p.1019-1020 in Mineral Deposits of Southern Africa, edited by C.R. Anhaeusser and S. Maske, Volume 1, 1020p.

Pretorius, C.C., Jamison, A.A., and Irons, C., 1987: Seismic Exploration in the Witwatersrand Basin, Republic of South Africa; p. 241-253 in Proceedings of Exploration 87, Ontario Geological Survey, Special Volume 3 (1989).

Pretorius, C.C., Steenkamp, W.H., and Smith, R.G., 1994: Developments in Data Acquisition, Processing and Interpretation over Ten Years of Deep Vibroseismic Surveying in South Africa; p. 249-258 in 15th CMMI Congress, 4-9 September 1994, Geology Volume 3, Edited by C.R. Anhaeusser.

Trewick, W.S.F., 1994: Exploration History and Mining Strategy for the Ventersdorp Contact Reef at Vaal Reefs No. 10 Shaft-Klerksdorp Goldfield; p. 67-70 in 15th CMMI Congress, 4-9 September 1994, Geology Volume 3, Edited by C.R. Anhaeusser.

Weder, E.E.W., 1994: Structure of the Area South of the Central Rand Gold Mines as Derived from Gravity and Vibroseis Surveys; p. 271-282 in 15th CMMI Congress, 4-9 September 1994, Geology Volume 3, C.R. Anhaeusser, editor.