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Development of high-resolution 3D vertical seismic profiles

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3D seismic surveys have become a well-accepted method of imaging sub-surface geology in the Bushveld Basin. Because both the seismic sources and receivers are placed at surface, most surveys are limited to imaging faults with >=7 m throw. However, some areas such as shaft infrastructure can benefit from the ability to detect smaller structures prior to shaft sinking. Borehole radar and logs such as the acoustic televiewer can identify these structures in the shaft barrel, but not within ~200 m from the shaft. Therefore, Anglo Platinum has developed the method of high-resolution 3D vertical seismic profiles (VSPs) for structural sterilization of shaft sites prior to shaft sinking. VSPs utilize a surface source and subsurface receivers deployed down a borehole. This means that seismic energy goes through the near surface only once, and therefore suffers less frequency loss than when both source and receivers are on surface. Furthermore, VSPs can record 3 component (3C) data which comprise P wave, S_h (horizontal) and S_v (vertical) wavemodes. Because S waves travel at about 0.6 of the velocity of a P wave, shorter wavelengths and therefore higher resolutions are possible using S wave data.

VSPs were first used in their 1 dimensional, zero offset, mode to correlate borehole geology with seismic stratigraphy within seismic surveys. This showed that VSPs record ~30% higher frequencies than surface seismic surveys. The program then applied 2 dimensional VSPs to the problem of imaging geological structure close to a borehole. 2D VSPs confirmed that high frequency results could be achieved, and that this enabled a more accurate image of the Merensky Reef than could be achieved by surface seismic data.

Finally, the program has achieved the successful recording and processing of 3D VSP data, with both compressional and shear wavemodes giving a high resolution structural result. While P wave data gives ~30% frequency improvement over surface seismic surveys, S wave data can give as much as 80% improvement, further improving the structural image achieved.

The high fixed costs of VSP surveys mean that they should ideally be run in multi-client batches, which can reduce the per borehole cost by up to 50%. Their application is anticipated to be on high value capital infrastructure with a geological risk from faults which are not imaged by surface seismics—generally in the sub-7 m range.

Introduction

Vertical seismic profiles (VSPs) are purely defined as measurements made in a vertical wellbore (borehole) using geophones inside the wellbore and a source at the surface near the well (Wikipedia 2010). In the more general context, VSPs vary in the well configuration, the number and location of sources and geophones, and how they are deployed. In their most basic application, standard VSPs, also known as rig-source or zero-offset VSPs (Figure 1 a), fulfil a fundamental role of tying reflectivity to stratigraphy and providing interval velocity data for time-to-depth conversion of seismic data. VSPs enjoy a natural advantage over in-hole acoustic logs because they sample reflectivity and velocity at a bulk scale, similar to the surface seismic methods. Hence their estimates of these parameters in new areas inspire confidence, particularly in new feasibility studies. However, the recently revised interest in VSPs relates to more complex offset and walkaway implementations of the technique in 2D and 3D (Figures 1: c and d). These have the potential to profile structure and stratigraphy laterally, with higher resolution at higher frequencies than surface seismics. This is mainly due to the fact that most of the downhole receivers in a VSP are placed beneath the surface weathered zone, thereby partially avoiding the attenuation of high frequencies within this zone.

In addition to recording higher frequency data, borehole seismic sensors provide a number of other advantages: borehole seismic data typically achieve a much higher signal-to-noise ratio than surface seismic data due to a combination of a quiet borehole environment and strong sensor coupling to the borehole wall. Surface geophones are generally poorly coupled in weathered rock and exposed to cultural and environmental noise at the surface. Good sensor coupling in the borehole enables acquisition of the full seismic wavetrain as well as three-component seismic data to be recorded with high vector fidelity (Paulsson *et al.*, 2004). This ultimately allows imaging of mode-converted waves and multiples. Certain of these wave modes, notably the shear or S-waves, have the potential to

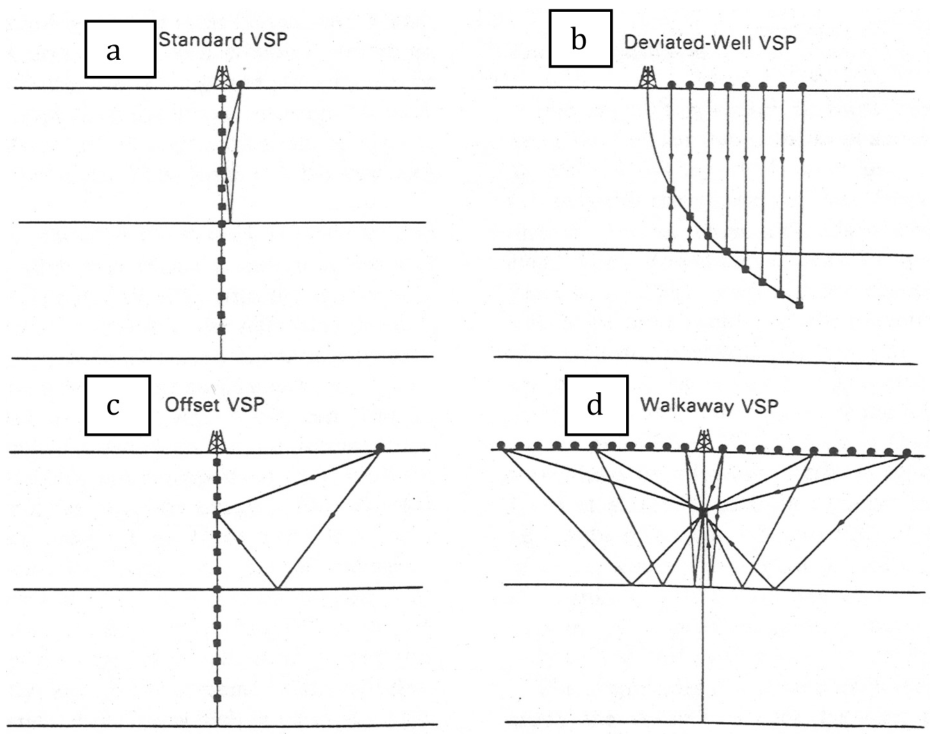

Figure 1. Different VSP acquisition geometries

further improve the imaging of geological structure, providing higher resolution than surface reflection seismics, as elaborated later.

Vertical seismic profiles (VSPs) were extensively employed in Anglo American's Gold Division in the 1980s. In 1981/2 the decision to mobilise the first Vibroseis crew to South Africa was still pending and it was understood that this major commitment required a rigorous feasibility study to manage technical risk. A year of VSP surveying was therefore undertaken to measure the *in situ* reflectivity of the Witwatersrand Triad, basement and cover sequences before approval was granted to mobilise the first surface Vibroseis crew to South Africa. The resulting surface seismic programme was one of the most sustainable geophysical exploration campaigns in history, spanning 30 years and spreading from gold to platinum clients in the hard-rock environment. The solid foundation laid by the VSPs played a significant role in the subsequent success of the surface seismic programmes.

The potential for improved structural resolution, particularly around new shaft sites, has been the main driver for VSP research in Anglo American over the last five years. Anglo Group companies, notably Anglo Platinum and Anglo Technical, have conducted joint research with geophysical service companies such as CGG Veritas (CGGV), VSFusion, Baker Atlas, VSProwess, HiPoint and IFP to pursue these mutual technical and business goals. This paper summarizes the main findings and provides recommendations to capitalize on some exciting opportunities in the future.

Classification of nomenclature of seismic wavemodes

Figure 2 illustrates the different seismic wavemodes which will be discussed in this paper:

P waves (Figure 2 a) are compressional (pressure) waves with particle movement in line with the direction of wave propagation. S waves (Figure 2 b) are shear waves, with particle movement perpendicular to the direction of wave propagation. Vibration is in both the vertical (S_v) and horizontal (S_h) directions.

The main reflected wave-modes are:

- PPup (Figure 2 a): downgoing compressional P waves are reflected as upgoing P waves.
- PSup (Figure 2 c): downgoing P waves are mode-converted to upgoing S waves at the reflector.
- PSSup (Figure 2 d): downgoing P waves are mode-converted to S waves at the base of the near-surface weathered zone. The resultant downgoing S waves are reflected as S waves at the reflector.

Surface seismics using conventional single-component geophones can record only P wave or PSSP data (i.e. PSSup data converted back to P on return through the base of weathering). Three-component geophones used for VSP recording can record both P and S waves. S wave data can have a shorter wavelength than P wave because S wave velocity is generally 0.6 that of P wave velocity and velocity = frequency * wavelength for both modes. The ratio of P to S wave velocity can be used to calculate various geotechnical parameters such as shear modulus and Poisson's ratio.

Anglo Platinum's 1D and 2D VSP campaigns

The 2005 VSP programme

During 2005 a VSP crew comprising CGG, Baker Atlas, Reeves Wireline Services and VSFusion staff was mobilized to South Africa to conduct a test programme, coinciding with the completion of one of Anglo Platinum's surface 3D seismic surveys. Rig-source and offset 2D VSPs were conducted in 10 surface drillholes on several mining leases in the Bushveld Complex.

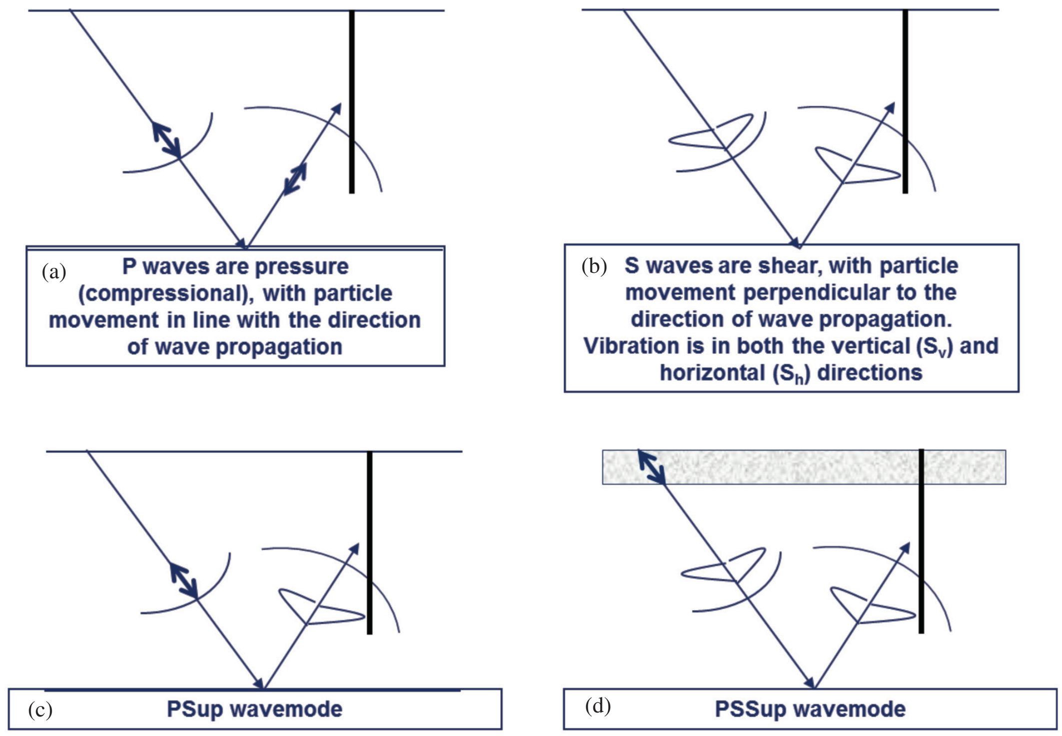

Figure 2. Useful VSP wavemodes in the hard-rock environment

As part of a shaft feasibility study, 10 Walkaway lines were recorded along surface seismic shot lines centred on a shaft geotechnical borehole. The main objective of the Walkaway VSP program was to determine whether VSPs could offer improved structural resolution over that achieved in surface 3D seismic surveys, particularly within a 100 m to 200 m radius around new shaft sites. A further objective was to determine whether VSPs would illuminate steeply dipping structures, which are not well imaged on surface seismics. The data acquisition, processing and interpretation of these data-sets are briefly discussed below, with a focus on achievement of the above objectives.

An 8-level, Baker Atlas, MSR600, 3-component geophone array was assembled for the 2005 program, capable of deployment in holes down to 76 mm diameter. The Walkaway surveys were a special case because they had to be zippered into a production 3D surface seismic survey and incur minimal standing time. The production constraints dictated that the receiver system could not be moved and would have to be anchored at an optimum level for all Walkaway lines. Ray-trace modelling was conducted by VSFusion to determine the optimum geophone depth position in the borehole for target illumination and was estimated to be approximately two thirds of the target depth (Figure 3). Receiver spacing was set at 12.5 m, providing 87.5 m of vertical geophone coverage in the drillhole. CGG's Nomad 65 vibrators provided the surface source. Sweep length was 16 seconds and a Log 6 db, 30 Hz to 250 Hz sweep was employed. Vibroseis source spacing was 25 m.

Following completion of the surface 3D seismic survey, the vibrators returned to resurvey one of the Walkaway lines, with a total of 48 geophone levels spaced at 6.25 m. This data-set was later incrementally decimated to provide an estimate of the minimum number of receiver positions for effective imaging, which would be an important input criterion for future equipment design and survey efficiency.

In addition to the Walkaway surveys, 38 multi-offset survey trials were conducted at the shaft site. For these trials the receiver spacing was 6.25 m over the full borehole length. This spacing prevented spatial aliasing of shear wave data. Source specifications were the same as for the Walkaway surveys.

Figure 4 shows the correlation of synthetics, PPup VSP, and surface seismics. Focusing on the UG2 event, the unfiltered corridor stack offered a promising 30% increase in useable frequencies over the surface seismics. A low pass filter of 80 Hz applied to the corridor stack displays a good match with the surface seismics on the right-hand panel. Figure 5 shows a PP Walkaway line (red) overlain on a surface seismic crossline (blue). Referring to the UG2 event the higher frequency VSP response is clear. The VSP also shows more reflectivity in the hangingwall. The net result was that the PPup VSPs demonstrated the stability of reflectors in the vicinity of the shaft hole, and further

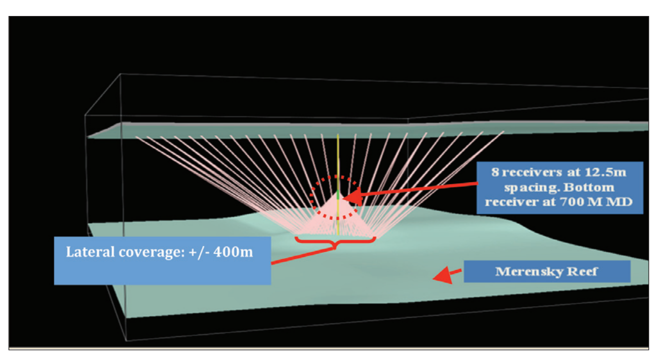

Figure 3. Simultaneous surface seismic and Walkaway VSP acquisition at a prospective shaft site (TD Approx 1 200 m). Raytracing is shown along one Walkaway line (Charles, VSFusion, 2005)

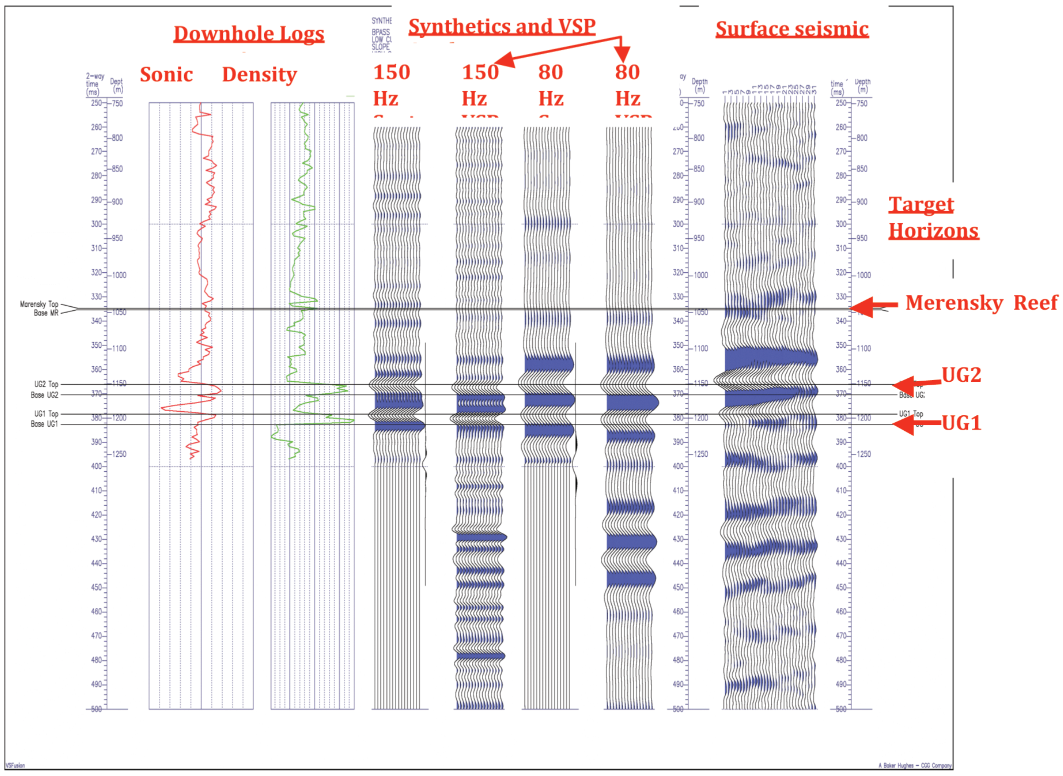

Figure 4. Synthetics, PPup VSPs and surface seismics at shaft test site

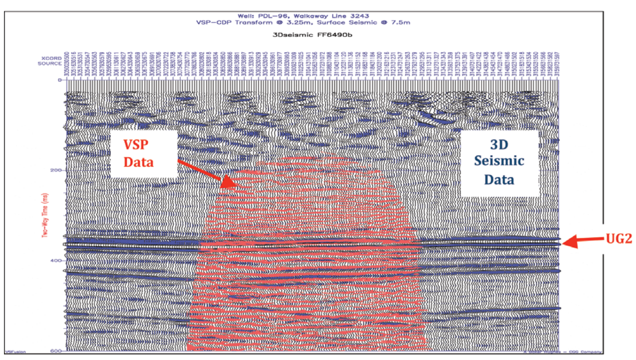

Figure 5. PPup Walkaway line at shaft test site overlaid on surface seismic crossline (Mead, VSFusion, 2005)

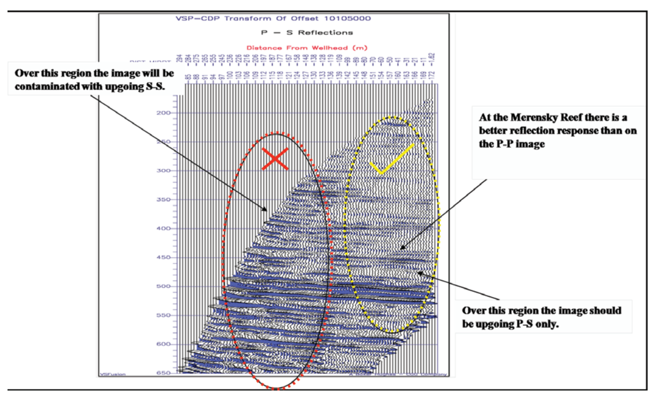

Figure 6. VSP-CDP Transform of Reflected P-S (Mead, VSFusion, 2005)

endorsed the structural suitability of this shaft site. The radial subsurface coverage at a UG2 reef depth of 1 200 m was 350 m to 400 m. Unfortunately, the VSPs did not provide a superior image of steeply dipping structures and this requires further investigation.

The main difficulty encountered in processing was the separation of PS and PSS mode-converted data. A detailed discussion of the processing challenges is beyond the scope of this paper, but the problem can be summarized as follows: between the downgoing P-wave and downgoing S-wave arrivals, S-wave reflections can be confidently separated. However, below the downgoing S arrival the SS image can contain spurious PS reflections, falsely mapped to shallower depths. Figure 6 shows reflected, offset PSup VSP data transformed to the common depth point (CDP) domain. Data in the left 'oval' are contaminated with upgoing SS, while further to the right the upgoing PSup separates nicely. What is particularly interesting on this image is that the Merensky Reef has a better reflection response than on the PPup image. This was a recurring theme in the VSP R&D programme, highlighting the need to extract value from these mode-converted wavefields.

A decimation study was undertaken along one of the Walkaway lines. Although the Walkaway quality was best with 48 levels, 24 provided an acceptable result. Below 24 levels, data quality deteriorated significantly. This information was provided to Sercel, with a recommendation to manufacture a 24 level tool, if possible. Ultimately Sercel manufactured a 12-level SlimWave tool, as an interim measure to test the mineral market in the short term. This was used on the 3D VSP survey described later.

The ongoing role of 2D VSPs

The 2D VSPs conducted during the 2005 programme, supplemented by 2D transects from the 3D VSP discussed later, have provided encouragement for a future role for 2D

VSPs in the Bushveld Complex. In fact the role for 2D VSPs could be significantly greater than for 3D VSPs, which appear to have a niche application around new shafts. The latter opportunities are usually presented only every five years or so.

2D VSPs certainly provide an improvement in structural resolution over surface 3D seismics and could therefore fulfil a high-resolution follow-up function to the former surface 3D surveys in structurally complicated areas. This would mainly be required when drill testing of the seismic structure plans continues ahead of mining. 2D Walkaway VSPs could be particularly useful close to significant faults and may help to quantify the widths of the fault damage zones. This is an important parameter for mine planners and cannot be accurately quantified on detailed infill 3D seismic surveys. It is possible to envisage a situation where deep drilling programmes could routinely include a provision for a few VSPs, to be held in reserve and used in case structural complexity is encountered or expected. This kind of advance planning will help to make 2D Walkaway VSPs economically viable. The below discussion on survey economics shows that the unit price per VSP is halved when moving from single campaigns to a group of five. Campaigns could potentially be shared between several mining companies and conducted in batch mode, thereby achieving significant mobilization synergies and shared cost savings.

The case made for the Bushveld Complex above can be generalized to cover other commodities where seismics is currently paying a significant role. In addition, 2D VSPs should continue to be important in the following niche roles:

- Seismic feasibility studies, particularly in remote areas. This may include insights on whether mode–converted energy has a role to play in surface seismics.
- As high-resolution transects linking deep drillholes to establish stratigraphic or ore continuity.
- Imaging beneath difficult surficial conditions where surface seismics fails but subsurface techniques could succeed (for example, over the Malmani Dolomites in South Africa).

Illustrative survey costs

VSPs are generally quite costly because they require scarce, expensive equipment and highly specialized technical staff. An added complication is the shortage of slimline downhole receiver systems. The main demand for these surveys is in the oil industry, where much larger holes are drilled and these can accommodate the more plentiful, larger-diameter VSP receivers. The new generations of multi-level tools are mostly being developed in larger diameter versions (i.e., HQ equivalent and larger).

A further complication is the expense of the sources. For example the mobilization, running and maintenance costs for a large Nomad-65 vibrator are the same whether the machine is being employed on a substantial 3D seismic survey or a small VSP programme. If charged at the normal market rate the mobilization overheads on their own (normally running to several million rand) would have stopped most of the VSP research programmes mentioned above. Fortunately the seismic service companies concerned were stakeholders in the R&D outcomes and appended the VSP work to take place after 3D surface seismic surveys, thereby reducing mobilization charges and other overheads. This is not a sustainable business model and a stand-alone VSP business case must be made.

The arrival of mini-vibrators on the South African scene has provided an opportunity to produce this stand-alone case. These vibrators are small enough to be transported within the region on standard container transport, rather than using the expensive and travel-restricted abnormal load systems which were required by the Nomad-65s. However, swop-out of the Nomads for mini-vibrators alone will not improve the economics sufficiently to make a good business case. Bulk work is required to reduce unit costs and this is best achieved by batching up multi-client work and conducting this seasonally, in bulk campaigns. Cooperation between mining companies on brownfield's technical campaigns is normally achievable. The cost of a typical Walkaway VSP with a 700 m target depth under a multi-company batch model, with a batch size beween 5 and 10, varies between R300 000 and R350 000. Unfortunately, the cost of a stand-alone single VSP is double this amount at close to R700 000.

3D VSPs

Background

The success of the 2D VSPs in 2005 promoted the launch of a 3D VSP survey campaign for shaft risk management in 2006. Figure 7 illustrates the main objective of 3D VSPs in this role. A tremendous amount of infrastructural planning takes place within a 100 m square area at the base of a new shaft system and the best possible structural geological resolution is required to ensure the stability of the chosen site. It was hoped that a 3D VSP would deliver this.

Combined surface 3D patch and VSP survey at a new shaft site

During 2008 a combined surface 3D seismic patch and 3D VSP survey was undertaken at a new Anglo Platinum shaft site where the UG2 occurs at a depth of 645 m. The VP source ring radius was 1 000 m (approximately 1.5 × the depth to target). Based on prior modelling a vibrator point (VP) interval of 40 m was selected, giving a total of 1963 VPs per run. Receiver spacing for the surface 3D patch was 40 m (Figure 8).

The main tool deployed in the VSP survey was Sercel's new12-level SlimWave (Figure 10) with a 10 m inter level spacing. A Sercel downhole recorder synchronized with the

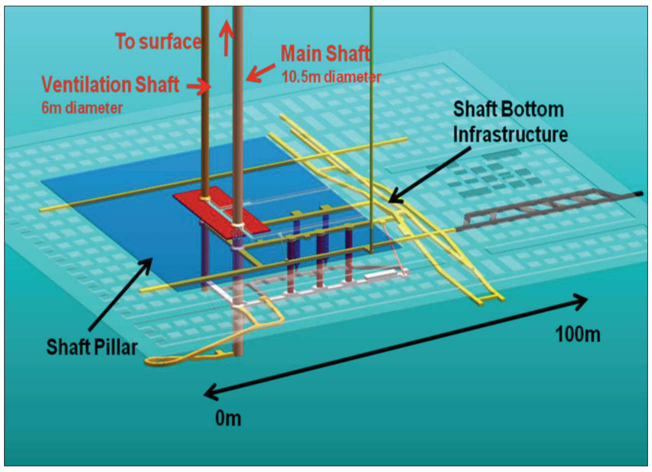

Figure 7. Detailed 3D VSP target area at the base of main and vent Shafts

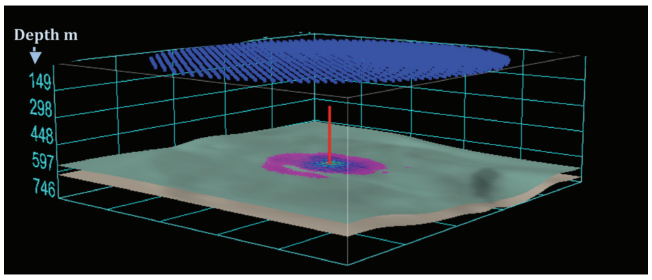

Figure 8. 3D perspective of combined 3D surface seismic patch and 3D VSP (CGGV / VSFusion)

main 408 system recorded the 36 channels of the SlimWave.

Figure 9 shows the modelled positions of the Slim-Wave tool (marked in violet) corresponding to the three different runs of the 3D acquisition, with all surface shotpoints being repeated for each run. Note that there is a one-level overlap between each run. The deepest level was positioned just above the UG2 target at 635 m and the shallowest level at 305 m. The additional blue runs in Figure 9 would be added before (deepest string) and after the 3D acquisition (2 shallow strings), using a single offset vibrator point. This gave extensive single offset VSP coverage over most of the borehole, for 2D analytical purposes and later data processing.

Data acquisition

Three runs of 1963 VPs were completed followed by the offset 2D VSPs. The sweep selected had to be adequate for both downhole measurements and high-resolution surface 3D recording. After exhaustive trials the following parameters were selected (Gilot , CGG Veritas):

- One vibrator delivering two standing sweeps per VP (two separate records)
- 16 seconds sweep length, tapers of 300–500 ms, 4 sec record length
- Frequency range from 20 Hz to 220 Hz, with negative time 20–30Hz
- 50% drive level
- Specific designed ramp applied with 0 dB at 20–90 Hz, 6 dB at 150–170 Hz and 0 dB at 200–220 Hz
- 1 ms sample rate

Figure 10 is a pictorial composite of the overall field operation.

Images produced by VSProwess

A detailed discussion of data processing is beyond the scope of the current report. VSProwess produced three main 3D images: PPup, PSup and PSSup, as defined in the introduction. All of these were considered to provide higher resolution than the surface seismics. The comparisons between synthetic seismograms and all VSP images were good. The PSup mode was probably the most coherent VSP image and will be discussed in detail before considering the relative advantages of all three modes:

Figure 11 shows a PSup migrated VSP spliced into the corresponding surface seismic in-line at the new shaft site. The PSup data have been squeezed into equivalent PPup two-way travel times before the merge. Note the improved resolution of the Merensky Reef (MR) on the VSP compared to the surface seismics. Figure 12 shows a power spectral comparison of the two data-sets. It indicates that the VSP recovers significantly higher frequency data and offers about 60% greater vertical resolution than the surface seismics. Figure 13 is a zoom into the composite data-set, showing auto picks on the UG1 horizon on a seismic interpretation workstation, extending from the surface cube through the VSP. A 7 m fault resolution should be comfortably achieved and image processing should offer even higher resolution. Imaging of fault damage zones should also be improved, due to the closer proximity of the downhole receivers to fault displacements on the target

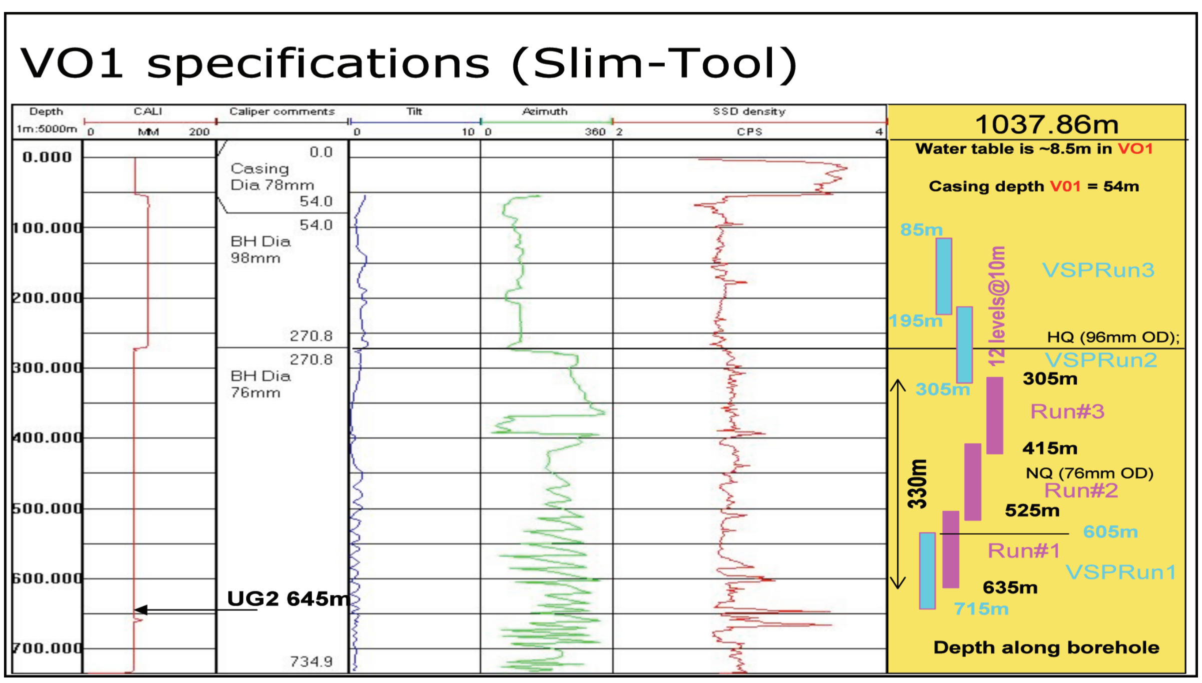

Figure 9. Slim-Wave tool positions in shaft hole for 3D runs (violet) and 2D supplements (blue) (Gilot, CGGV, 2008)

Figure 10. (a) CGGV seismic recording truck (foreground), Weatherford borehole geophysical logging truck (middle) and crane for VSP tool deployment (background); (b) CGGV Nomad 65 vibrator; (c) 6 levels of CGGV/Sercel SlimWave tool ready for deployment; (d) sidewall calliper brace on SlimWave element in open position; (e) Engineer inside CGGV seismic recording truck; (f) Survey simulation and design using 3D raytracing (VSFusion)

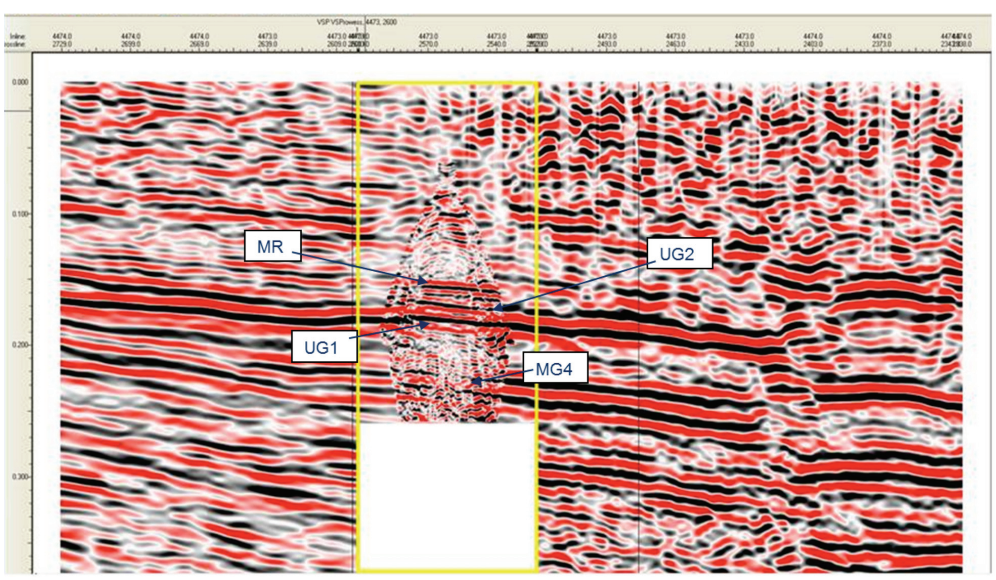

Figure 11. Migrated PSup VSP section spliced into surface 3D seismic line through new shaft site (Humphries, VSProwess, 2010)

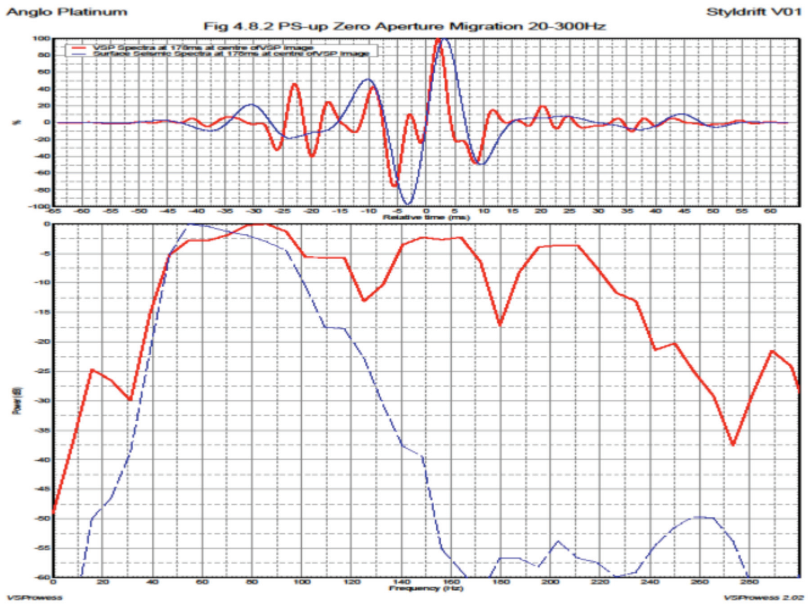

Figure 12. Waveforms (top) and power spectra (bottom) of the PSup VSP (Red) and surface seismic data (blue) shown in figure 11 (Humphries, VSProwess, 2010)

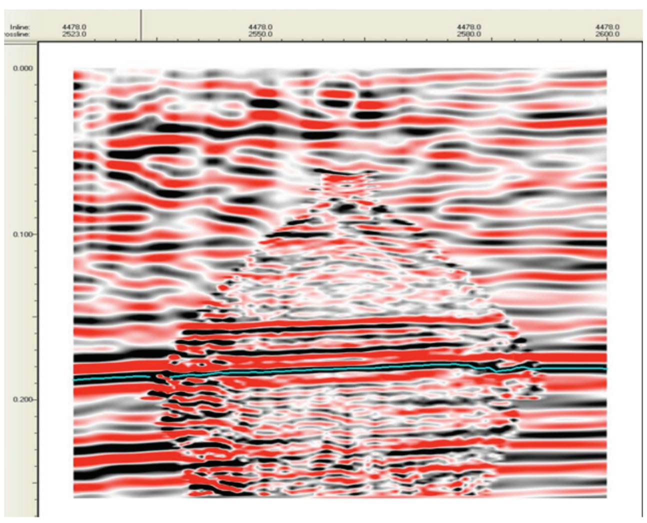

Figure 13. Top-UG1 picks in section through surface seismic patch and PSup VSP

horizons. Fortunately, no significant faults appear close to the shaft site (centre of image). This upgrades the structural suitability of this site. The signal to noise ratios deteriorate visibly on the extreme flanks of the VSP volume and autopicks in this zone should not be trusted. Further editing of input records would probably improve the coherency and this will be the subject of future research.

Figure 14 shows a composite of merged PPup, PSup and PSSup data with surface seismic backdrops, indicating the incremental increases in structural resolution moving from P wave data to the two mode-converted shear wave images. Clearly, the first prize in the structural resolution stakes should be the PSSup data-set. Unfortunately, the signal to noise ratio for this mode was significantly lower than PSup, the deterioration on the image flanks was greater and the map image showed more gaps. Improvement in acquisition and processing of PSSup data will be the subject of future R&D.

Illustrative survey costs

Unlike the 2D VSP case, it is difficult to arrive at a generic cost for a 3D VSP survey. As a rough estimate, it is likely that a typical VSP plus 3D surface seismic patch, imaging a primary target between 700 m and 1 000 m, would cost about R10 million to acquire process and interpret in 2010.

Conclusions

During 2009/2010 a number of breakthroughs were achieved in the reprocessing of 3D VSP data. Most of these were achieved by Mary Humphries of VSProwess. Her results complement the 2D VSP achievements of the CGG/Baker Hughes/VSFusion consortium in 2005 and both have provided a basis for drafting good practice guidelines for the future. P wave and mode-converted S wave VSP images returned higher structural resolution than surface seismics in localized apertures around the drillholes. Future surface seismic programmes should take this into account and design for S as well as P wave recording. Significant progress was also made with innovative processing approaches by HiPoint Reservoir Imaging (Fuller *et al*, 2008) and IFP. These may be discussed at some stage in the future.

Recommendations

2D Walkaway VSPs should fulfil an important role in high resolution follow-up of surface seismic surveys, particularly when structurally complex areas are drill-tested ahead of mining. They may be particularly useful for quantifying the potential width of fault damage zones. In such complex areas, provision should be made in drilling budgets for Walkaway VSP surveys to be conducted in strategically important drillholes. 2D VSPs are also recommended in seismic feasibility studies, particularly in remote areas. 2D Walkaway VSPs are also potentially useful for imaging beneath difficult surficial conditions, where surface seismics fails, but subsurface techniques could succeed. 3D VSPs are most appropriate for risk management at new

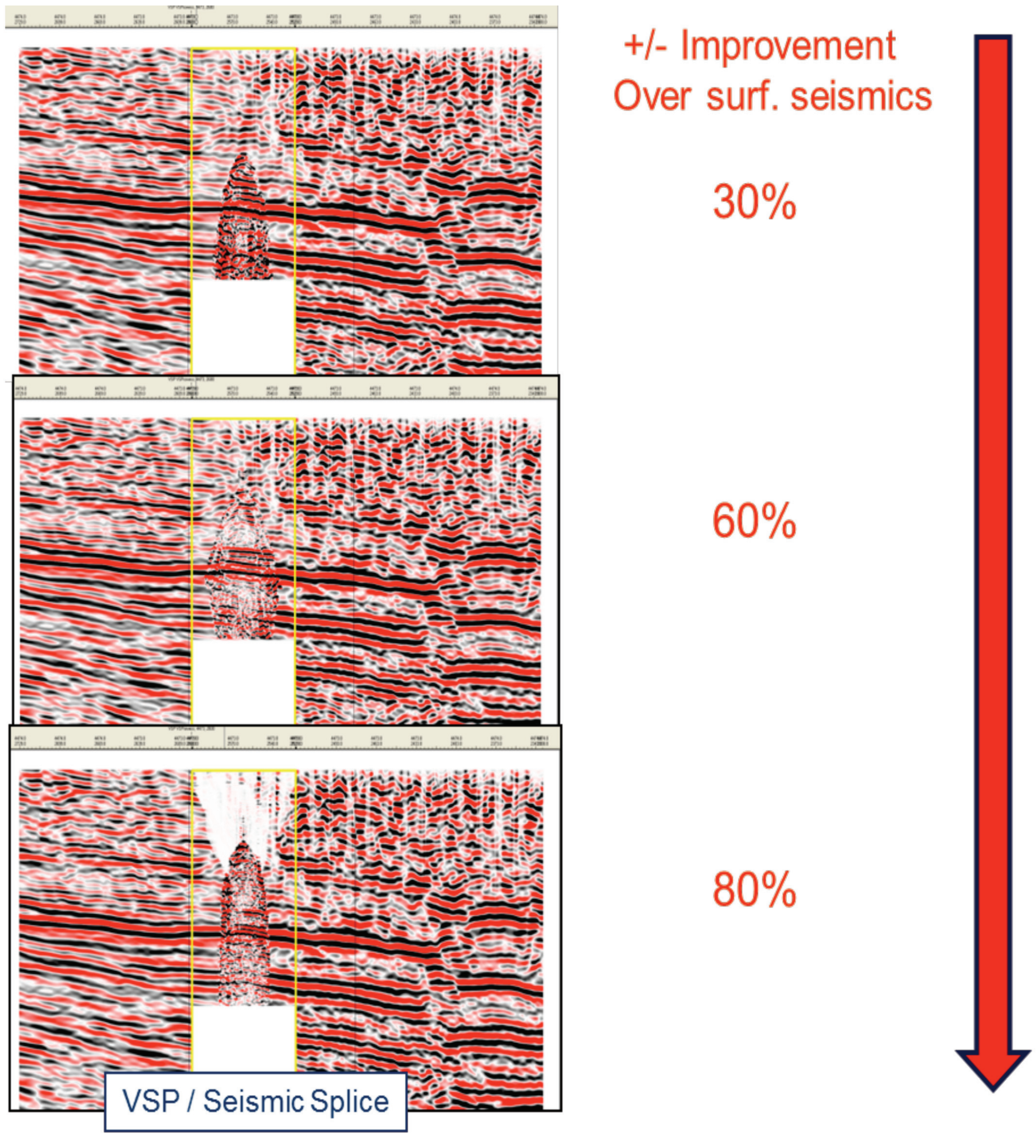

Figure 14. Structural resolution improvements over surface 3D seismics offered by PPup, PSup and PSSup VSPs (Humphries, VSProwess, 2010)

shaft sites, where they should be conducted with a coincident, high-resolution, surface 3D seismic patch. An important requirement for all VSP surveys is that the drillhole diameter must be at least 76 mm.

In order to reduce costs, it is recommended that 2D VSPs should be conducted in multi-client, collaborative batch campaigns. An optimal 2D VSP batch size is about five surveys, which would halve the unit cost of a typical Bushveld Walkaway VSP from about R700 000 to approximately R350 000. The typical cost of a combined 3D surface seismic patch and VSP would be about R10 million, and this approach is recommended only at new shaft sites.

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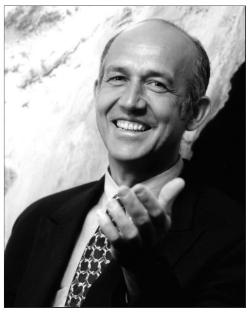

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- 1983–1993:Sectional to Senior Divisional Geophysicist AAC Gold Division. Particular responsibility for Witwatersrand Vibroseis surveys: Exploring for buried gold orebodies in and around one of the world's giant gold deposits.
- 1978–1983: Senior Geophysicist Anglo American Prospecting Services Namibia: Prospecting for gold, uranium, base metals (including zinc at Skorpion), diamonds, coal, tin, tungsten, using a wide variety of ground and airborne geophysical techniques.
- 1977–1978: Contract Geophysicist, General Mining Corporation and Loxton Hunting. Mainly Uranium prospecting and test mining in the Namib Desert, Namibia.

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