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3D VSP in a Mining Context

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SUMMARY

VSPs have an application across the mining lifecycle. The main advantage of VSP over surface seismic is the increase in resolution achieved by placing the downhole receiver below the highly attenuating weathered zone and recording the full seismic wave-train, including mode-converted shear waves. This presentation looks at a 3D VSP shot in conjunction with a surface seismic, specifically the improved resolution gained from mode-converted shear waves.

Introduction

Vertical Seismic Profiles (VSP's) are high-resolution seismic imaging tools that have an application across the mining lifecycle, ranging from exploration feasibility studies to advanced risk management applications in mine planning and development. The advantage of a conventional VSP over surface seismic is that the down-hole receivers are placed below the surface weathered zone, thereby partially avoiding the attenuation of high frequencies in this zone and improving structural resolution on the seismograms. 3-component VSP's also measure the full seismic wave-train in the subsurface domain, including mode-converted waves which have the potential to complement surface seismic and further improve the imaging of geological structure in localised areas around the recording drill-holes. Anglo American, in partnership with Anglo Platinum have, conducted five years of VSP Research to investigate and quantify this potential. This paper looks at some of the results from one of the most recent 3D VSP's shot in conjunction with a patch of 3D surface seismic, specifically the improved resolution gained from analysis of mode-converted waves.

Setting

The 2.06 Ga Bushveld Igneous Complex in South Africa is the largest layered intrusion in the world and probably contains over half of the planet's Platinum Group Mineral (PGM) resources (Cawthorn, 1999). Situated just north of Johannesburg, it has an east-west extent of about 400km, a north-south extent of about 300km and a maximum thickness of about 8km. Surface seismic exploration in the Bushveld Complex commenced in the 1980's and the most intensive 3D seismic campaigns took place in the late 1990's and 2000's. Seismic reflectivity is driven primarily by the density contrast between norite or anorthosite and pyroxenite units. These host the PGM - bearing reefs and chromitite layers, notably the Merensky and UG2 Reefs. The main VSP survey was shot into shaft geotechnical boreholes around 600m deep. Recent experience has shown that VSP's offer significantly improved structural resolution compared to surface seismics.

Acquisition and Processing

The 3D VSP was shot simultaneously with a 3D surface seismic patch. The source was a Nomad 65 Vibrator sweeping from 20 Hz to 220 Hz, with a specifically designed ramp. VSP and seismic patch source positions described a 40m regular grid within a circle of radius of approximately 1000m. Receiver spacing for the surface 3D patch was 40 m. Record length was 4 seconds, with a 1ms sample rate. The main tool deployed in the VSP survey was Sercel's 12-level SlimWave, with a 10 m inter-tool spacing. A Sercel WavLab recorder synchronized with the main 408 system recorded the 36 channels of the SlimWave. The VSP survey was recorded in three different runs, with all surface shotpoints being repeated for each run. There was a 1-level overlap between each run. The deepest level was positioned just above the UG2 Reef at 635 m and the shallowest level at 305 m.

Processing was conducted in a sensitive way to retain small structures. Down-wave separation was simplified by using polarisation techniques as described by Ahmed [1987]. Up-wave separation was model-based and applied to each source and receiver pair in turn. The same model was used to derive trace-by-trace NMO corrections and migration sample-stacking maps, in a similar way to Dillon [1984]. Major trace editing, stacking and multi-channel smoothing was only applied during the migration process. Three migrations were performed: P-down reflecting as P-up (PP-up), P-down mode-converted on reflection to S-up (PS-up) and P-down, mode-converted on transmission, to S-down and reflected as S-up (PSS-up), resulting in three separate 3D VSP images.

Because shear-waves travel with slower velocity than P-waves, the hope was that PS-up and PSS-up images might display significantly improved resolution. To aid interpretation, migrated images are produced at PP-up two-way time hence the shear-wave images have an apparently wider band-width.

Velocity and density logs from the borehole that contained the VSP receivers and also from nearby geotechnical boreholes, were carefully edited and used to generate synthetic seismograms at a range of frequency band-widths for comparison with the surface seismic and VSP images.

Results

The surface seismic and VSP were processed to 3D images. All the VSP images display significantly greater 3D resolution than the surface seismic. Figure 1 shows a vertical slice of the surface seismic and PP-up VSP.

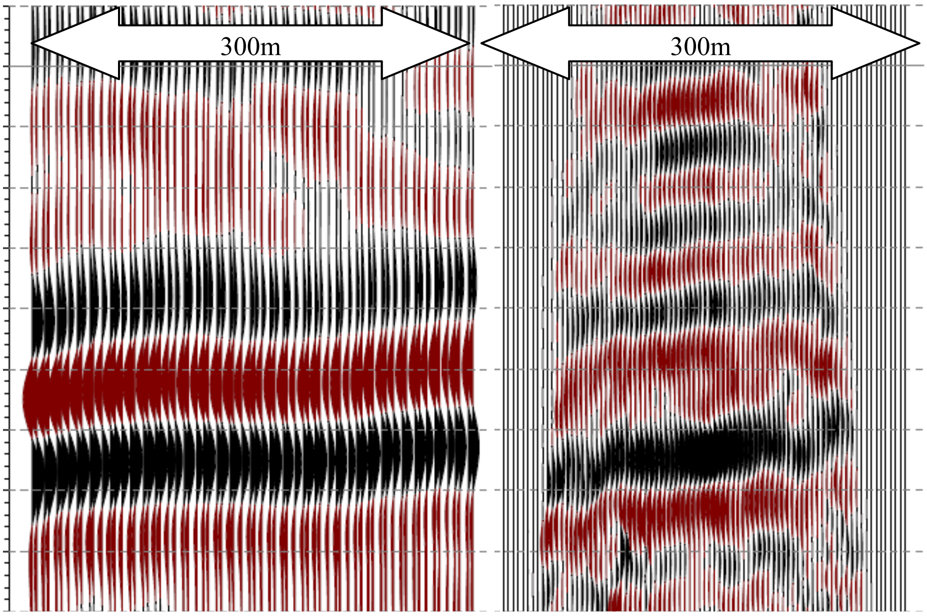

Figure 1 *Surface seismic (left), VSP PP-up (right), 50ms of each image is displayed.*

There are a number of geotechnical boreholes within the zone of the VSP image, three of which lie in a line through the borehole containing the VSP receivers, approximately 40m apart. It was therefore possible to test the veracity of the VSP images.

Figure 2 shows a synthetic seismogram from one of the geotechnical boreholes. Reflection coefficients have been filtered with zero-phase band-pass filters to match the various images, starting with 120Hz for the surface seismic. Figure 2 illustrates the problems in resolving the thin reefs.

Figure 3 shows synthetic seismograms from four geotechnical boreholes along the line of the 2D slice of figure 1, filtered at 10-160Hz and spliced into the PP-up VSP. Synthetic seismograms filtered at 10-200Hz have been spliced into the VSP PS-up image. It may be seen that the PS-up VSP starts to separate the reef complexes.

There is a good tie between the VSP images and their respective synthetic seismograms, proving the resolution seen by the VSP wave-modes. The results of this comparison and a perpendicular line containing a further borehole, give confidence in extrapolating the high-resolution VSP images out into the 3D volume. Continuity seen in the 2D slice extends to 3D in the surface seismic, PP-up, PS-up and PSS-up images.

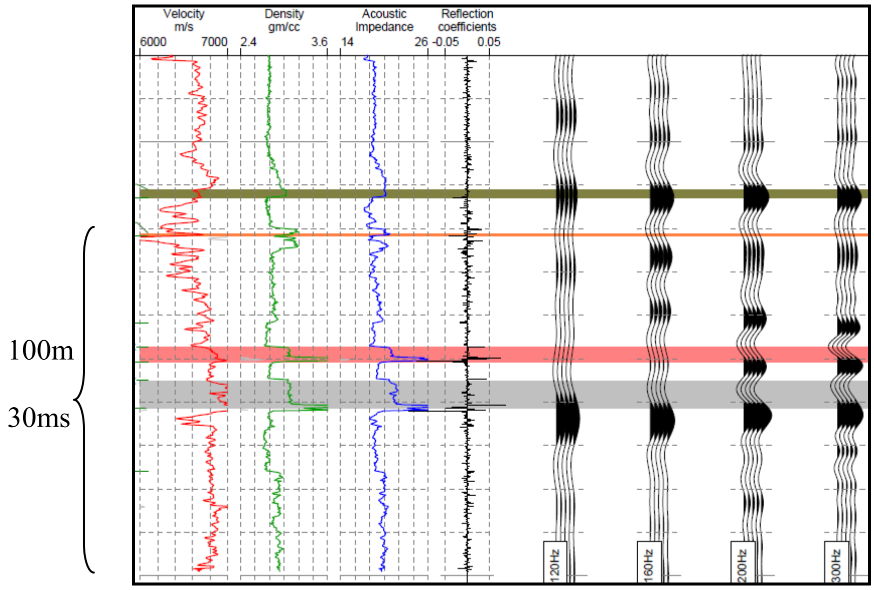

Figure 2 *Synthetic seismograms with reef interpretation.*

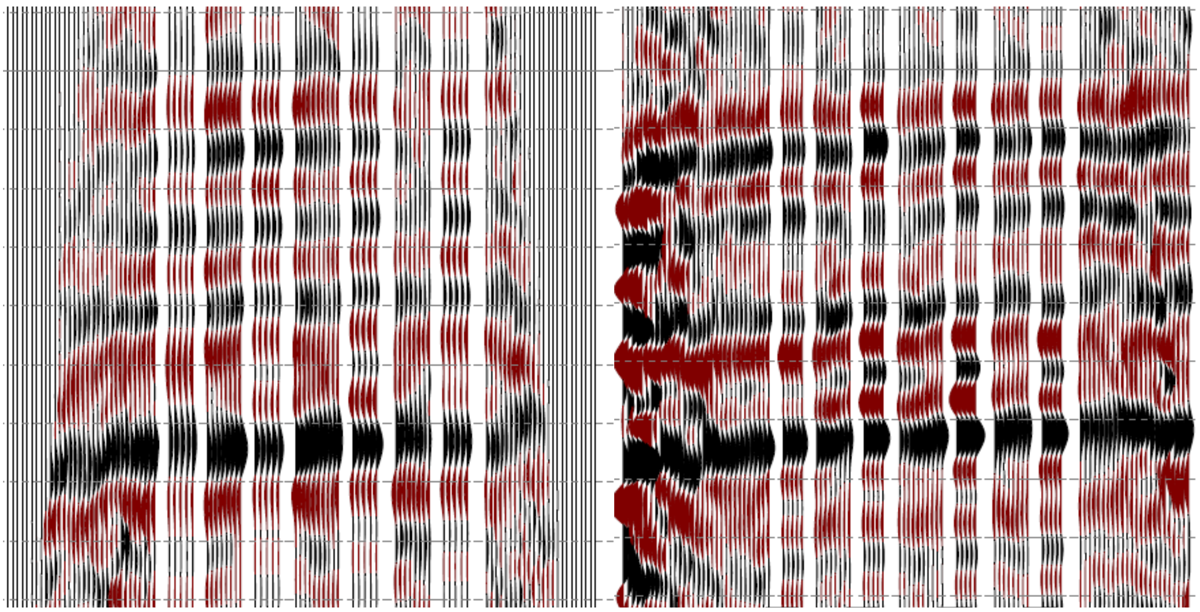

Figure 3 *PP-up VSP and 10-160Hz synthetics (left), PS-up VSP and 10-200Hz synthetics (right).*

VSP results were loaded into a seismic interpretation package and interpreted. The PS-up image is probably the most coherent of the three modes under discussion. The PSup volume offered a 60% to 80% improvement in vertical resolution compared to the surface cube (Figure 4). An 8 m fault resolution is expected to be comfortably achieved. Imaging of fault damage zones should also be improved, due to the closer proximity of the downhole receivers to fault displacements on the target horizons.

Conclusions

It has been shown that 3D VSPs have the potential to significantly improve resolution over surface-seismic images, especially with the use of mode-converted waves. Simultaneous recording of VSP and surface seismic reduces the cost over shooting the VSP alone, while minimising the differences between VSP and surface seismic images associated with the acquisition environment.

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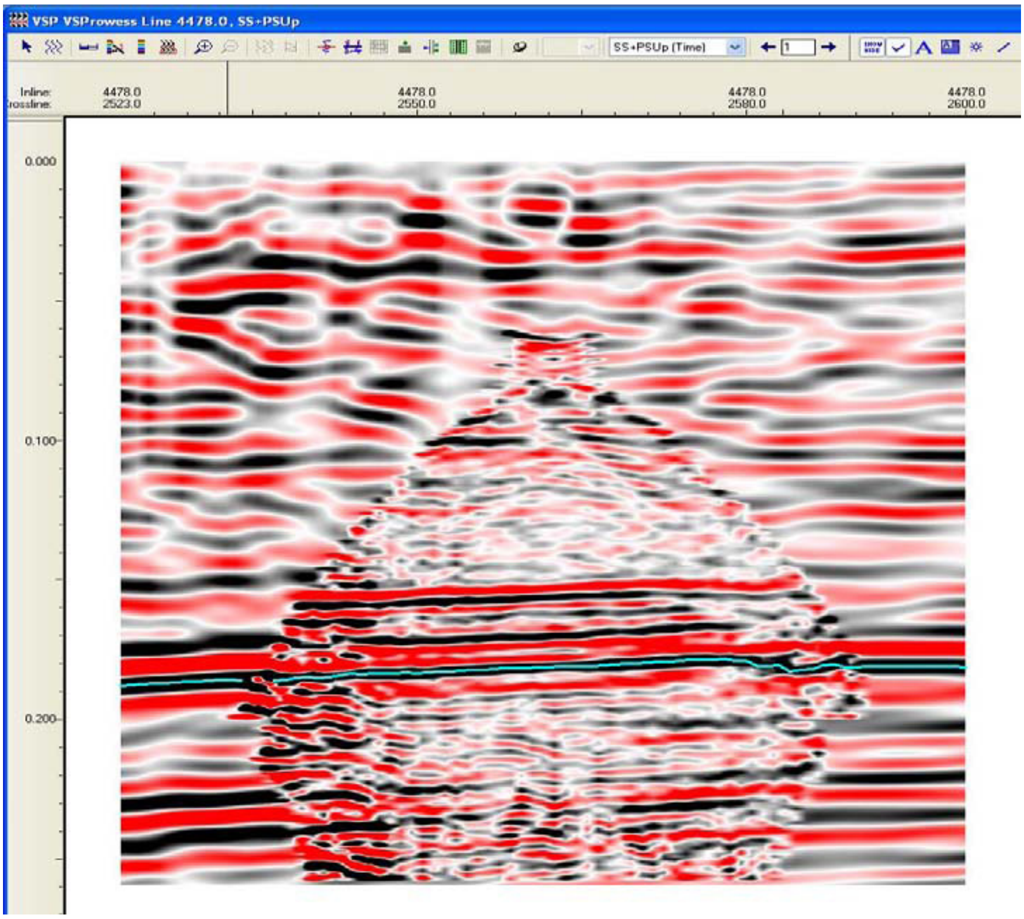

Figure 4 *Seismic workstation auto-picks on UG1 marker in profile extending from surface cube (backdrop) through PSup VSP volume along shaft line.*

Outside mining applications, P-wave images from on-shore VSPs shot in tandem with surface seismic are often constrained by vibroseis sweep parameters designed for the surface seismic. The potential for VSPs to see reservoir-scale structure close to the bore-hole may thus be squandered. This is especially important when trying to find small-scale, 4D time-lapse differences.

Acknowledgements

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