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Three-dimensional reflection seismics: worth its weight in platinum

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The high-resolution three-dimensional (3-D) seismic reflection data acquired for Impala Platinum between 1998 and 2002 in the western Bushveld Igneous Complex form an integral part of Impala’s mine planning and development programme. These data are of sufficiently high quality to provide unprecedented 3-D models of the geological structure of the Merensky Reef and UG2 Chromitite Reef, from which the mine deduces the size, geometry and distribution of mineable blocks. Conversely, the seismic data details zones of un-mineable ground caused by structural disturbances in the form of potholes, fault zones and pegmatoid intrusions. Furthermore, variations in dip and strike are well imaged, allowing the mine planners to optimize the mine design and layout.

Current interpretation work is focused on enhancing the accuracy of these geological models even further through the analysis of ‘seismic trace attributes.’ Preliminary testing on the Impala Platinum 3-D seismic volume has shown that attribute analysis has the potential to illuminate a number of geological reef disturbances that are otherwise ‘invisible’ in the original seismic time volume. Potential areas of improvement include inter alia:

- Improved definition of major fault zones
- Improved definition of zones of reef depression (‘slumping’)
- Identification of reef terracing and/or reverse dip..

Keywords: 3D reflection seismics; Impala Platinum Ltd; seismic attribute analysis; Seismic Micro Technology (SMT); rock solid attributes; dip-azimuth; instantaneous phase and similarity.

Background: the seismic reflection method

The seismic reflection method was first patented in 1917 and since the 1930s, it has been the most widely used geophysical technique in global exploration. Its predominant applications are hydrocarbon exploration and research into crustal structure, with probing depths of several kilometers now being achieved routinely.

In essence, the seismic reflection method involves the measurement of the time taken for a seismic wave to travel from a source (at a known location, typically at or near the surface) through the subsurface, where it is partially reflected back to the surface and then detected at a receiver. The receiver is also at or near the surface at a known position. This time is known as the ‘two-way travel time’.

For a seismic wave to be reflected back to the surface, there has to be a rock interface (reflector) across which there is a contrast in acoustic impedance, Z, which is the product of the seismic velocity (V) and the density (ρ) of each layer (Figure 1). In reality, there are numerous such rock interfaces at which seismic energy is partially reflected and the amplitudes of a series of reflected waves are recorded by a group of receivers known as geophones (in land operations) or hydrophones (in marine operations). The resultant seismic section can give a very direct picture of the subsurface structure, but it is not a true vertical cross-section since the vertical scale is not depth, but time.

The most important problem in seismic reflection surveying is the conversion of two-way travel times (time domain) to depths (space domain). The link between time and depth is seismic velocity. While travel times are measured, the lateral and vertical variations in seismic velocity are estimated to create a ‘seismic velocity model’. Due to the major influence of this parameter on the final depth values, a great deal of research effort is devoted to improving our understanding of it.

Seismic surveying conducted along a single line (or many randomly located lines) is known as 2-D seismic reflection-profiling and allows geological interfaces to be mapped only in the plane of the resulting two-dimensional section (similar to a typical geological cross-section). Two-dimensional seismic surveys are a cost-effective means of exploration and provide vital information for the design of more detailed three-dimensional (3-D) seismic surveys.

Full three-dimensional surveys were first undertaken for hydrocarbon exploration in 1975. Since then, this mode of survey has become far more cost effective and currently constitutes in excess of 60% of the market share in the seismic industry (Reynolds, 1997). In land-based 3-D surveys, receivers occupy the points of a regular grid on the surface with seismic shots being fired from all grid points in turn.

Although 3-D surveying is far more expensive than linear 2-D surveying, it justifies itself in the increased

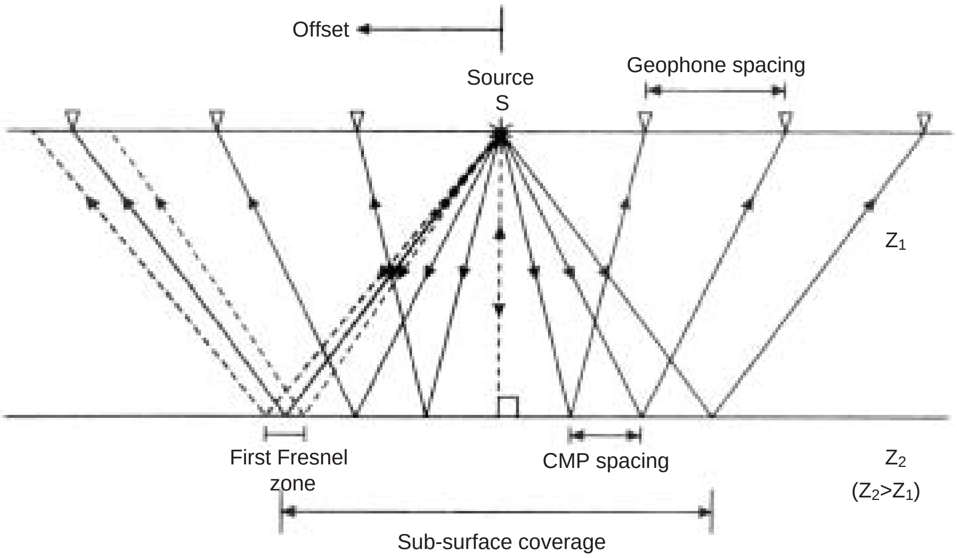

Figure 1. Schematic of reflection raypaths over a horizontal interface across which there is a contrast in acoustic impedance, Z ($Z_2 > Z_1$). In 3-D reflection seismics, more than one source location is used. In the simplest case of a flat reflecting interface, reflections arising from the same point on the interface will be detected at different geophones. This common mid point of reflection is known as the common midpoint (CMP). The reflection from an interface is generated from a finite area of the reflector surface defined by the first Fresnel Zone (Reynolds, 1997)

understanding of geological structure that it provides, and in the precision with which it permits boreholes to be drilled in geologically complex areas. As a guideline, the cost of a 3-D seismic survey in the Bushveld will typically comprise less than 1% of the total direct mine development costs.

Introduction

During the early 1980s, the South African gold mining industry began to apply 2-D reflection seismics with mixed success. At the time, the costs of 3-D seismic surveying were at least double that of conventional 2-D acquisition. However, in the late 1980s and early 1990s, global developments in the acquisition, processing and interpretation of 3-D seismic reflection data made the technique far more cost effective to the point that it became a well-established method for delineating major gold-bearing horizons in the Witwatersrand Gold Basin.

However, during the same period, only very limited 2-D seismic surveying was undertaken in the Bushveld due to financial constraints. The planning of new mines and extensions to existing mines relied on geological models based primarily on the combination of aeromagnetic and borehole data. It is only recently (in the late 1990s) with the favourable upturn in the platinum economy, and further considerable improvements in seismic instrumentation and data processing capabilities, that the potential of the 3-D seismic reflection method is being realized in the platinum environment.

Three-dimensional reflection seismics as a tool for mine planning and design

Of particular importance in ore reserve estimations and mine planning, is the identification and characterization of potholes (features unique to the platinum environment). These features are highly unpredictable, both in terms of their occurrence, shape and dimensions (varying from less than a metre to kilometers in width, length and depth). Potholes present both a significant economic loss and serious safety hazard to all platinum mines in the Bushveld.

Knowledge of sudden variations in reef dip and strike are critical in terms of mine design (very shallow dips (<7 degrees) affect the spacing of haulages and cross-cuts). Also important to a platinum mine is the detection and delineation of major fault zones and intrusive bodies that represent losses of mineable ground and potential safety hazards.

Although the aeromagnetic technique is effective in the delineation of sub-surface magnetic dykes and major fault zones, it is limited in terms of its depth of penetration. Furthermore, aeromagnetics cannot resolve potholed reef, fault geometries and pegmatoid intrusions with the accuracies required for optimal mine planning (Düweke and Trickett, 1999). On the other hand, while borehole data provides the most accurate and detailed geological information possible, the range of this information is restricted to the immediate vicinity of the borehole.

It was with these considerations in mind that Impala Platinum Ltd. (Impala) conducted the first high-resolution, surface 3-D seismic reflection surveys in the Bushveld Igneous Complex in the summers of 1998 and 1999. These surveys were followed shortly thereafter by a 3-D survey, which was conducted on behalf of Lonmin. In 2000, Impala commissioned a third, far larger 3-D survey to aid in medium-to-long term mine planning: the primary aim of these surveys was to detect and delineate the Merensky Reef and UG2 Chromitite Reef.

A general assessment of the survey results reveals that the data are of high quality, due mainly to the dense lateral and vertical sampling intervals (the lateral sample spacing (bin size) is 7.5 m and the sample time interval is 1 ms).

The seismic reflection associated with the UG2 Chromitite is a prominent and reliable indicator of the reef’s topography. This reflection is laterally continuous throughout the survey area and of consistently high amplitude due to the strong contrast in acoustic properties between the UG2 chromitite and its host lithologies.

The seismic reflection associated with the Merensky Reef represents a combined seismic response from the Bastard Reef Pyroxenite and the Merensky Reef horizons. This reflection, although laterally continuous for the most part, is less prominent than the UG2 Chromitite reflector.

Geological deformation: clues provided by 3-D seismics

A number of general clues about the style of geological deformation in the surveyed area can be derived from a detailed analysis of the seismic time volume. Figure 2 illustrates an interpretation of the UG2 chromitite with respect to time.

- The geological structure of the Impala survey area is dominated by a large-scale NE-SW antiformal structure that divides the area between a relatively undisturbed area in the south and a structurally complex area in the north (Figure 2 and Figure 3). This feature appears to have formed simultaneously with the regional layering of the Western Bushveld stratigraphy
- Potholes associated with both the UG2 Chromitite Reef and Merensky Reef are highly variable in their location and lateral and depth extents. There is no apparent reliable correlation between the formation of the UG2 and Merensky Reef potholes
- There is a higher density of potholes associated with the UG2 Chromitite reef
- There is much evidence of normal faulting, where sets of conjugate fault pairs disrupt the reef to form grabens (Düweke and Trickett, 2001)
- A strong spatial link between faults and potholes suggests a structural control for the formation of the latter features. Typically the up-thrown flank of a pothole is steep, while the down-thrown flank dips more gradually (Düweke and Trickett, 2001).

Challenges to mining

Specific structural elements that are likely to present obstacles to mining and are imaged in the datasets include (Düweke and Trickett, 2002):

- Well-defined zones of reef ‘depression’ (or potholes) and associated reef elimination
- Less well-defined zones of slumping/depressed reef. Figure 4 illustrates typical examples of potholes or zones of reef ‘depression’ on the Merensky Reef
- Major fault zones: comprised primarily of normal faults. Many of the major faults are surrounded by a ‘halo’ of smaller faults, which are likely to translate into poor ground conditions
- Sudden variations in dip and strike
- Zones of reverse dip and/or reef terracing (continually rolling/undulating topography) (Figure 5)

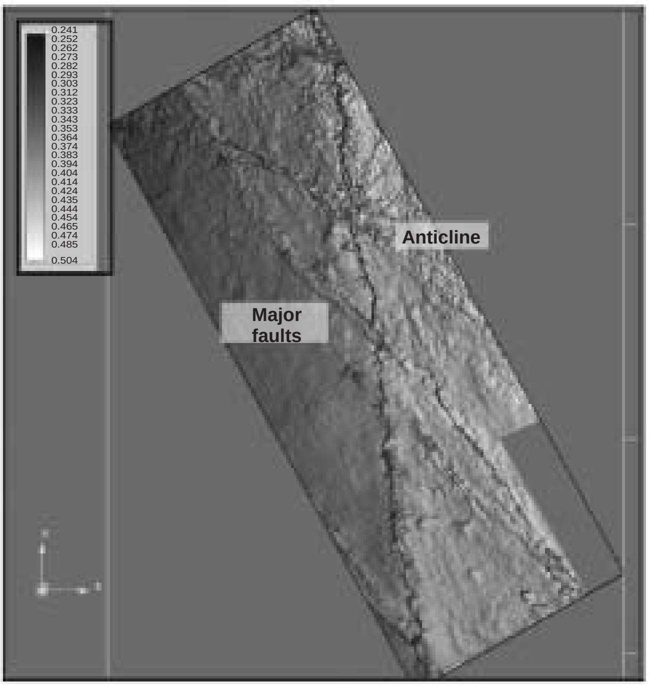

Figure 2. Plan view of a section of an interpretation of the Impala UG2 chromitite two-way travel-time horizon

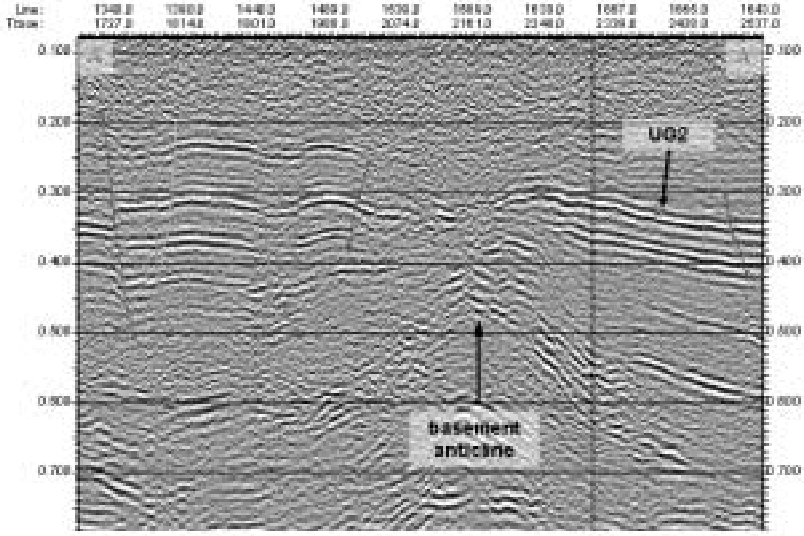

Figure 3. Vertical seismic time section showing the position of the UG2 chromitite horizon and the underlying basement anticline that separates relatively undisturbed ground in the South (A’) from structurally complex ground in the North (A). Normal faults typically divide the reef into a series of horsts and grabens

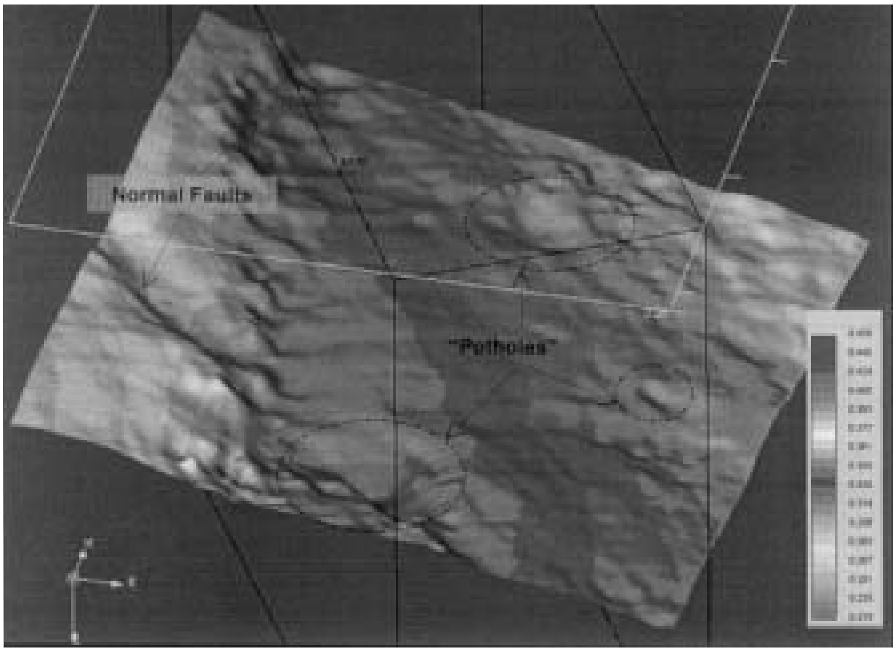

Figure 4. Normal faulting and pothole formation on the Merensky Reef. Note that the gridded horizon is scaled with respect to two-way travel-time

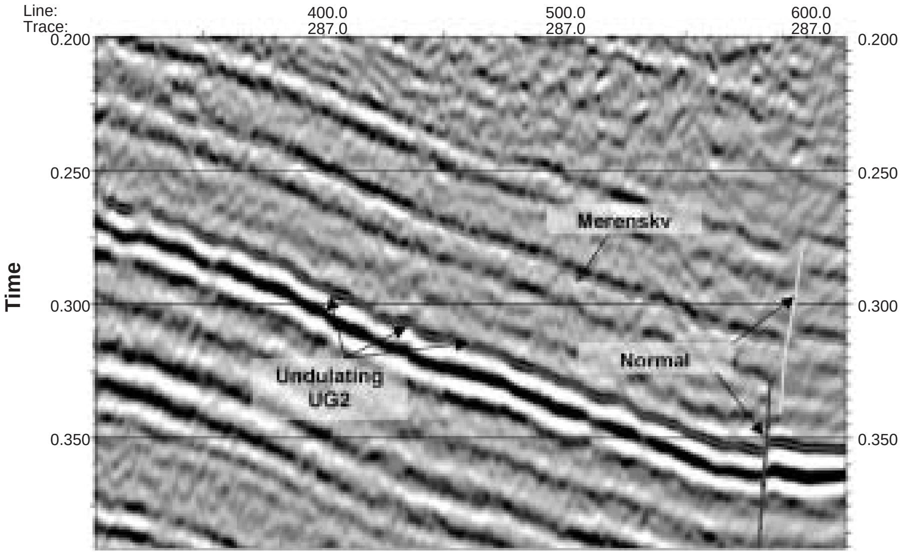

Figure 5. Vertical seismic section illustrating reef terraces (rolling/undulating topography) associated with the UG2 Chromitite horizon

- Replacement pegmatoid bodies: these features are not well resolved in the seismic data, but their presence can frequently be detected by their characteristic seismic signature (i.e. zones of relatively low amplitude seismic response).

Current focus: seismic attribute analysis

Three-dimensional seismic data provides excellent geological information ahead of mining. However, the images derived from conventional seismic amplitude data do not provide the geologist with all the information that is contained in the seismic volume. Over and above amplitude, seismic trace attributes such as phase and frequency (amongst others), may be derived from the data in order to enhance the geological model.

'Seismic trace attributes' are defined as all of the physical and geometric attributes obtainable from the seismic data and are derived from the mathematical manipulation of the three seismic wave components, namely: amplitude, frequency and phase (Rock Solid Attributes, 2003). Introduced in the early 1970s, seismic attributes have been used successfully in the oil industry to enhance the interpretability of seismic data from both the structural and stratigraphic points of view. It must be emphasized that seismic attribute analysis is purely a visualization tool: viz. the mathematical manipulation of seismic data to provide alternative means of imaging and highlighting geological features of interest.

To date, the Impala datasets were analysed in terms of two-way travel-time and amplitude variations. Impala has now reached the stage where they wish to optimize their results even further by exploring the potential of analysing other attributes of the seismic data. Their primary objective is to refine the current geological model by illuminating detailed geological features that are otherwise not immediately visible in the seismic time volume. The following discussion provides a brief overview of some preliminary volume-based attribute analysis work that is currently in progress and is being carried out using the Seismic Micro-Technology (SMT) Kingdom Suite software package*.

The process involved generating attribute volumes from the original seismic time volume. For each volume, the attribute was then extracted along the Merensky Reef and UG2 Chromitite reef horizons that were originally interpreted from the time volume. Three of the attributes that were analysed in the region of the target reefs are presented in Figures 6 to 8.

Terraced/'rolling' reef

Dip azimuth calculation (geometrical attribute): the user supplies the azimuth of the seismic survey cross-line axis (measured clockwise positive from north), which is added to the azimuth of the maximum instantaneous dip of a trace. The output is given in degrees.

Designed to highlight major structural discontinuities or 'trends', the dip azimuth attribute works well in emphasizing zones of 'terraced' or 'rolling' reef (< 10 m in amplitude) on the UG2 chromitite reef, which are otherwise not illuminated on the original time surface. This is illustrated in the comparison between Figures 2 and 6.

'Pothole' detection

Any seismic trace can be reproduced by adding together a series of waves represented mathematically by sinusoids of varying frequencies.

Instantaneous phase (measured in degrees) is generated from the seismic data using the equations of Taner *et al*. (1979). This attribute represents the phase of the resultant vector of individual simple harmonic (sinusoid) motions.

Since phase information is independent of trace amplitudes, the instantaneous phase attribute is one of the best indicators of lateral continuity. It is particularly useful as a discriminator for geometrical shape classifications and, as such, it is effective in imaging most major zones of reef depression (or 'potholes'), as is evident in Figure 7.

Lateral continuity

The similarity (semblance) over the user-defined sliding time window is computed by scanning adjacent traces in a user-defined range of dips. Higher values of similarity are indicative of a high degree of lateral similarity of depositional environment.

The similarity attribute is a good indicator of lateral continuity and illuminates detailed changes in bedding/reef dip and curvature. Figure 8 illustrates how this attribute details dip variations on the UG2 Chromitite reef horizon, particularly in the vicinity of reef 'depressions'.

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*Seismic Micro Technology Inc: http://www.seismicmicro.com

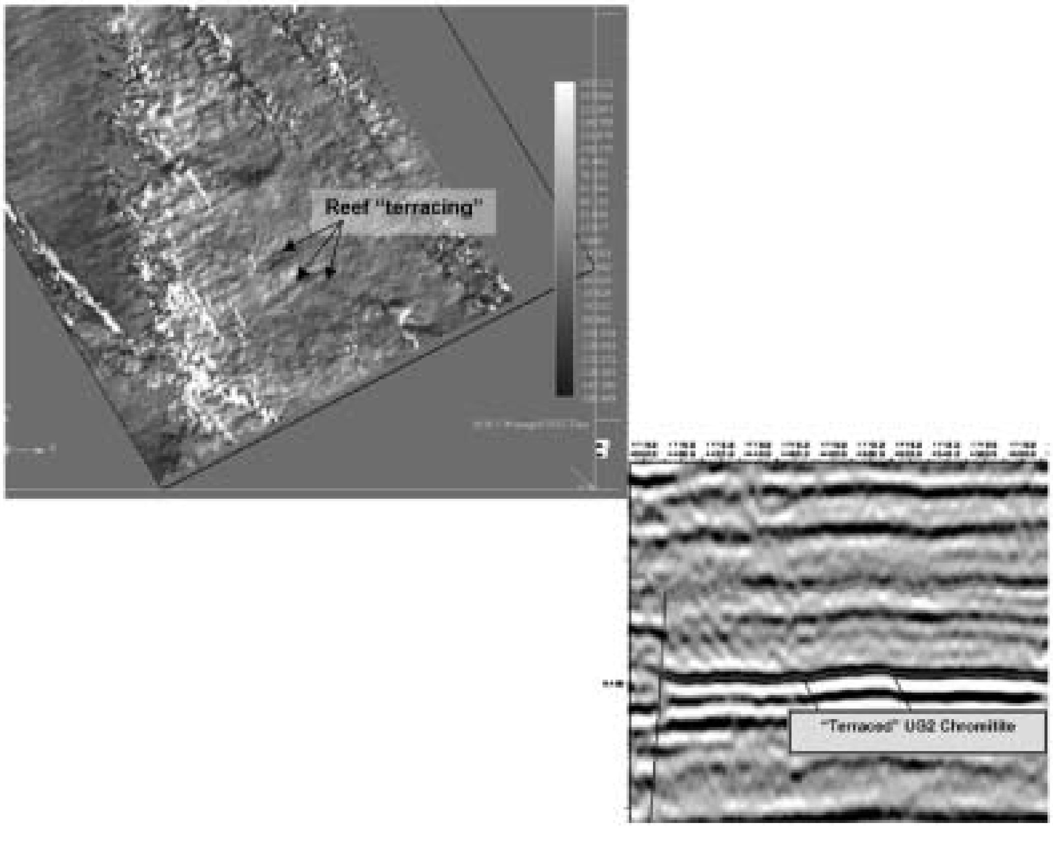

Figure 6. Plan view of the dip azimuth surface showing a zone of 'trolling' or 'terraced' reef, not visible on the time surface in Figure 2. The vertical section shows Merensky Reef and UG2 chromitite interpretations with respect to time

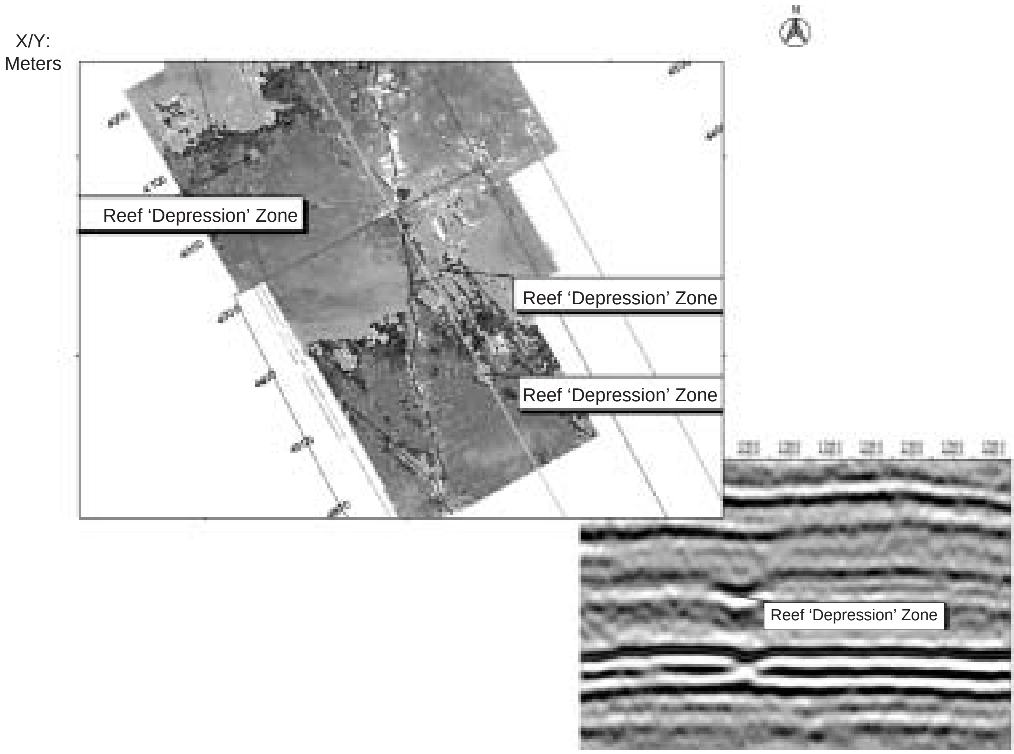

Figure 7. Plan view of the instantaneous phase Merensky Reef surface showing zones of ‘depressed’ or ‘potholed’ reef. The vertical section shows one of the corresponding potholes on the Merenky Reef

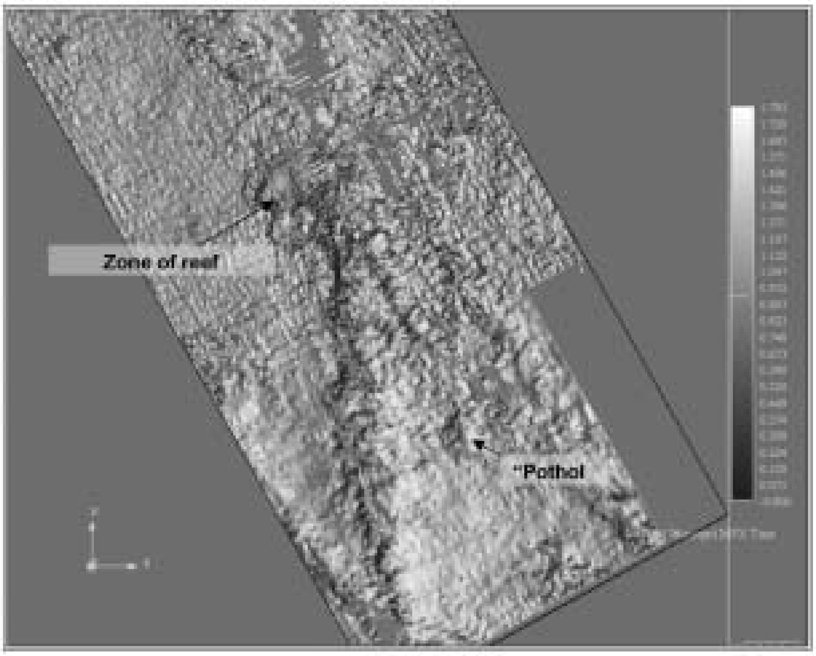

Figure 8. Plan view of the similarity attribute extracted along the Merensky Reef Horizon showing two prominent zones of reef ‘depression’

Conclusions

The seismic data is of high quality, providing vertical resolutions of approximately 10 m. In essence, the 3-D seismic reflection method has proven itself as a very effective tool in imaging macro-geological structure in the region of Impala’s target reef horizons, namely: the Merensky Reef and UG2 chromitite reef. As such, the geological model derived from the seismic data, in conjunction with a well-populated borehole database, has produced unprecedented detail of both mineable and unmineable areas. This model forms a dynamic and integral part of Impala’s ongoing mine design and planning processes.

The aforementioned examples are just three of many that prove the potential of ‘seismic attribute analysis’ to significantly enhance the interpretability of 3-D seismic reflection data to ulitmately reduce the risks of 'surprise mining'. Two important caveats apply to attribute generation, namely: the necessity for high quality data and the environment-specific nature of attribute applicability. Furthermore, it should be emphasized that there is no single attribute that will highlight the full spectrum of geological features that may pose obstacles to mining. Rather, an integration of complimentary attributes is proposed.

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