Paper 42

3D Data Integration for Exploration and Mine Planning

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ABSTRACT

Over the last 10 years several mining companies within the Anglo American and related Groups have accelerated their investment in geoscience, engineering and information technologies, to continuously improve the three-dimensional understanding of their orebodies. This is an integral part of the mission to optimise the safe, cost-effective extraction of these orebodies. Geophysical orebody imaging techniques, particularly the use of 3D seismic reflection, have provided a powerful supplement to conventional orebody sampling and imaging tools, such as diamond drilling. It has become standard practice on many of the precious metal and coal mines to conduct 3D seismic surveys prior to siting new shafts or commencing major underground development. Anglo Platinum have taken this commitment several steps further and conducted second-phase, infill 3D seismic surveys and experimental Vertical Seismic Profiles in the immediate vicinity of several potential shaft sites, to further improve structural resolution and manage shaft-sinking and operational risk. The use of in-hole geophysical techniques, such as borehole radar and acoustic televiewers is growing. These techniques improve the tactical, third-phase, high- resolution imaging of orebodies, as well as assisting geotechnical engineers in characterizing the rock mass ahead of mining development and mapping potential hazards. Integration of the diverse, multi-disciplinary datasets required for improved orebody imaging and mining risk management requires a 3D GIS environment with powerful visualization and querying capabilities. Data registration and orientation challenges are enormous, especially when the range and resolution scales of imaging techniques vary from millimeters to tens of metres. The Geoscience Group of Anglo Technical Division have investigated many software solutions and the GOCAD common earth environment currently appears to be the most suitable. The success of the orebody imaging projects has reinforced our belief that there is potential for a retrospective transfer of geophysical imaging methodologies from the high resolution brownfields / mining environment to greenfields exploration. The high-resolution imaging techniques owe much of their success to rigorous basics. This includes diligent physical characterization of ore and host rocks prior to selecting a geophysical imaging methodology, appropriate survey design to meet 3D sampling requirements and, above all, a total commitment to integrating all data in 3D at each stage of the imaging process. One or more of these ingredients is occasionally missing in greenfields exploration programs. The success of on-mine geophysics may well feed back into improved exploration success.

INTRODUCTION

The last decade has seen a rapid growth in the application of geophysics to mine planning, development and risk management, particularly in the deep precious metal mines in South Africa. There are a number of good reasons for this, with the primary driver being the capital risk for inappropriate planning where high development costs exist due to deeper gold and platinum deposits being exploited. Detailed structural imaging of orebodies using geophysical techniques, primarily seismic reflection, has become an essential requirement in mining feasibility studies (Campbell, 1994; De Wet et al., 1994; Pretorius et al., 1987, 1994, 1997, 2003). Interpretation of intensely sampled 3D geophysical data requires powerful interactive workstations with the ability to integrate, query and visualize the various datasets involved in an orebody imaging and mine planning exercise. These datasets typically include: 3D seismics; gravity; magnetics; remote sensing data; surface and underground geological maps and drillhole geological data; downhole geophysical logs; assays; underground seismicity; existing and proposed underground mining development; and borehole radar.

The success of orebody imaging geophysics is attracting attention in other production areas, such as mineral resource evaluation and mine safety, with ore-sorting applications waiting in the wings. Geophysics is being applied across most of the mining lifecycle, extending from exploration, through feasibility studies, to a lesser (but growing) extent in operations, mineral processing and finally, optimization of mine closure plans (see Figure 1).

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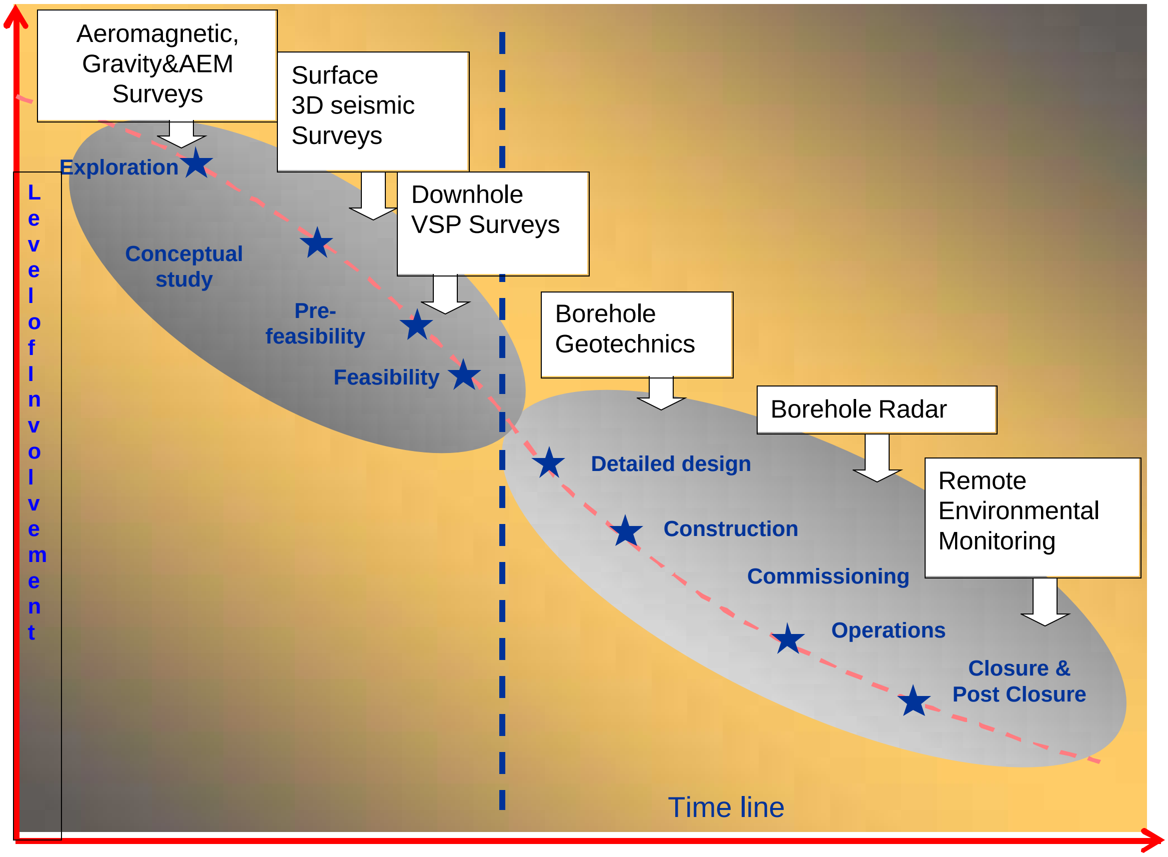


Figure 1: Typical application of integrated geophysical imaging across the mining lifecycle at Anglo American

The horizontal axis on Figure 1 is the mining lifecycle, which can vary greatly in span, depending on the mine. On a deep platinum mine in the Bushveld Complex in South Africa the total span will typically be several decades. The vertical axis is a very qualitative indication of the level of involvement (in the writers' experience) of the various geophysical techniques discussed below. Obviously geophysics has made its main inroads at the beginning of the lifecycle. With time this trend can, and probably will, change as mining production applications of geophysics grow.

This paper will discuss the benefits of 3D integrated orebody imaging, using illustrative case histories. The primary focus will be on platinum case studies, showing multi-disciplinary data integration applied to the assessment of new mining areas with a large focus on 3D seismic imaging. The suitability of the GOCAD "common earth" modeling system (McGaughey, J. 2006) for this application will be discussed in some detail. This will be followed by a further case study showing how 3D data integration in GOCAD can significantly assist hazard mapping and risk avoidance on an underground coal mine.

Anglo Platinum's commitment to ongoing 3D geological imaging as the mining lifecycle advances will be illustrated by zooming in on an area where infill, high-resolution 3D seismic surveys have been applied around new mine-shaft sites which had already been covered by reconnaissance 3D seismics. The application of vertical seismic profiling (VSP) to further improve structural resolution around the immediate shaft block will be examined.

The philosophy of applying borehole radar to strategic and tactical risk management will be briefly discussed, with supporting data. This is an important topic: although the use of surface 3D seismics has caught the attention of the mining community, borehole deployed geophysical tools such as borehole radar and seismic reflection may have a far more generic application in ore body imaging and rock-mass characterization across a broader range of commodities in future.

PLATINUM MINE PLANNING CASE STUDIES

Orebody modeling to assist mine planning and development

The following platinum case study illustrates a typical 3D data integration exercise to assist mine planning and development, prior to extending and deepening an existing platinum mine on the Bushveld Complex in South Africa. The platinum deposits in South Africa are part of a layered igneous complex: The Bushveld Complex (BC). Two of the three principle economic Platineferous horizons are narrow (1m) generally shallow dipping, largely continuous layers with relatively good seismic

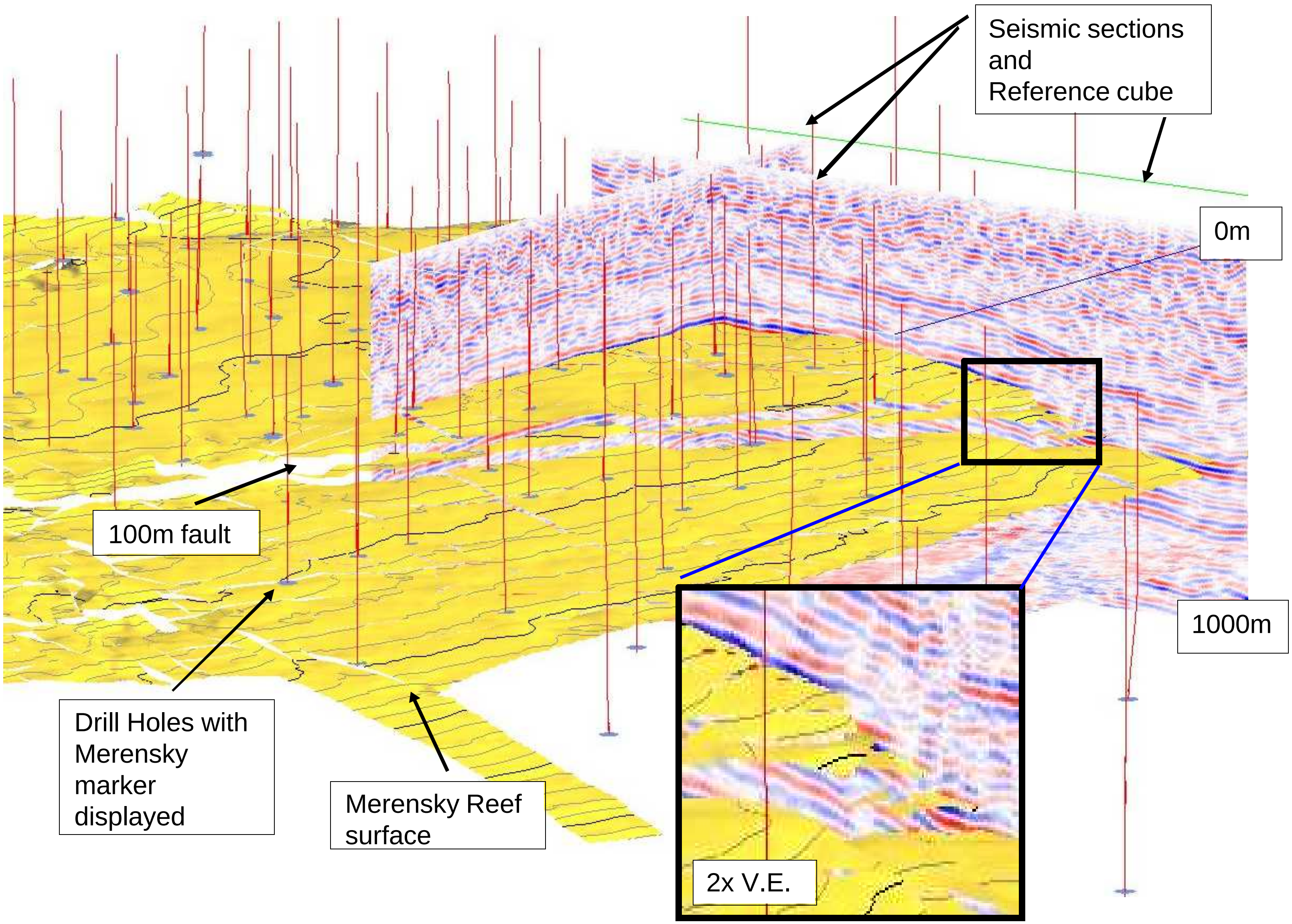


Figure 2: Unexpected 100m fault detected by 3D seismic survey in a new platinum mining area

reflectivity. These horizons are typically structurally stable, but it is the areas where structure is less stable where 3D imaging of the layers adds significant value. The third Platineferous orebody type can best be described as a thick (typically 40-100m) semi-massive rock mass with relatively poor reflectivity proximal to the mineralized zones.

In this case study historic structural mapping of the main narrow orebody, the Merensky Reef, had been conducted with the assistance of surface diamond drillholes, with an average spacing of 1500m. A 3D seismic survey conducted in 2001 showed that a very significant normal fault with a throw of up to 100m had not been detected by surface drilling (Figure 2) and this has a potential major impact on future mine planning, effectively separating the economic target into two mining regions, respectively to the north and south of the fault. The seismic structural sampling density is approximately 300 times greater than the surface drillhole coverage. Hence the structural resolution is greatly improved and the risk of spatially aliasing the structure is significantly reduced, as illustrated in Figure 2. Obviously it would be logistically and economically impractical to match the 3D seismics with equivalent drillhole coverage but the important point is not the competition between these data sources, but the optimal mix in building the integrated orebody image: drill holes provide the ore sample for mineral resource estimates, as well as calibration for the seismics, while the seismic data provide valuable input into the structural discontinuities and hence facilitate mine planning. This has an impact on the estimated cost of extracting the resource.

Anglo Platinum and Anglo Gold Ashanti conducted 3D seismic surveys over most of their future deep mines and it can be confidently stated that the structural revelation illustrated in Figure 2 is not unusual. Based on observations spanning some sixteen 3D seismic surveys over the last 10 years it is clear that many orebodies would be structurally aliased if sampled by drillhole data alone. The risk remediation offered by the geophysical imaging typically represents a twenty-fold return on investment and in certain cases has had a dramatic impact on mining economic feasibility studies. It seems likely that structural aliasing of orebodies could be a generic problem in mining economics, and is best addressed by the extrapolative power of geophysical imaging between drillholes. This does not imply the use of seismic reflection imaging alone, but can extend to other geophysical techniques such as ground penetrating radar, and electrical and seismic tomography.

Zooming into the 3D "common earth" model it is possible to see the downhole density and sonic logs (Figure 3). These logs are employed to compute the synthetic seismogram, depth-convert the 3D seismic cube and calibrate it to known geology in the drillholes. Other downhole geophysical, geological, geotechnical and geochemical data can be displayed, and graphically interrogated in GOCAD.

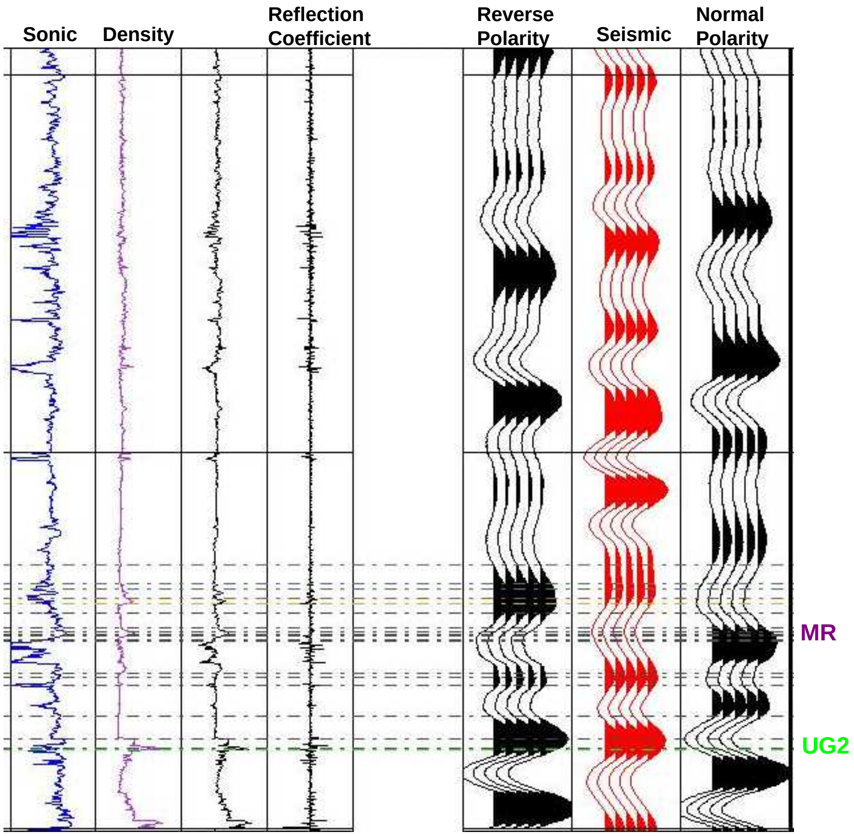


Figure 3: Tying geology to seismics via downhole geophysical logs. Note how the seismograms show that major reflectors exist close to the Merensky and UG2 platinum orebodies. These are used to map the 3D structure of these orebodies.

Figure 4 shows a revised ore-block model which combines the structural model from the 3D seismics (on the left) with block model data from the Mineral resource model (on the right). This facilitates assessment of resource properties in reference to identified fault blocks. This greatly increases the confidence in the estimated ore reserves, particularly with regard to quantifying geological loss factors (e.g. along the central fault traversing diagonally across the structural model).

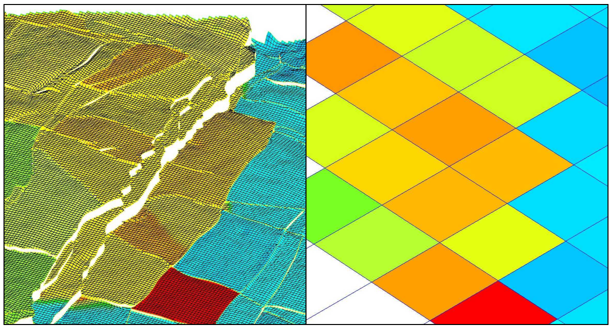


Figure 4: Integration of resource blocks with the structural model

Detailed helicopter-borne aeromagnetic gradiometer surveys have been conducted over most of Anglo Platinum's current and future mining areas. The complementary nature of 3D seismics and aeromagnetics in integrated structural imaging is illustrated in Figure 5: the aeromagnetic image is superimposed on the seismic interpretation of the Merensky reef surface. 3D seismics works best in mapping horizons with lower dip, as well as fault displacement of these surfaces. These same faults are often not detected by the detailed aeromagnetics, which is more effective in mapping steeply-dipping magnetic discontinuities. Note how well the magnetic method delineates the steeply dipping dykes and IRUPS (Iron-rich Ultramafic Pegmatoids), which are not detected by the 3D seismics. The latter structures are important because they represent areas of geological loss or sterilisation on the platinum orebody.

Other datasets incorporated in the assembly of the detailed 3D structural model of the orebody include airborne gravity gradiometry (detailed geological sub-crop mapping), magnetic SQUID gradiometry (better definition of IRUPS and hence improved quantification of geological loss), digital elevation models, satellite imagery and surface and underground mining infrastructure. The confidence in the orebody model and mine plan have been significantly improved and the new shafts to exploit the deeper orebody can be confidently sited in relatively structurally sterile areas.

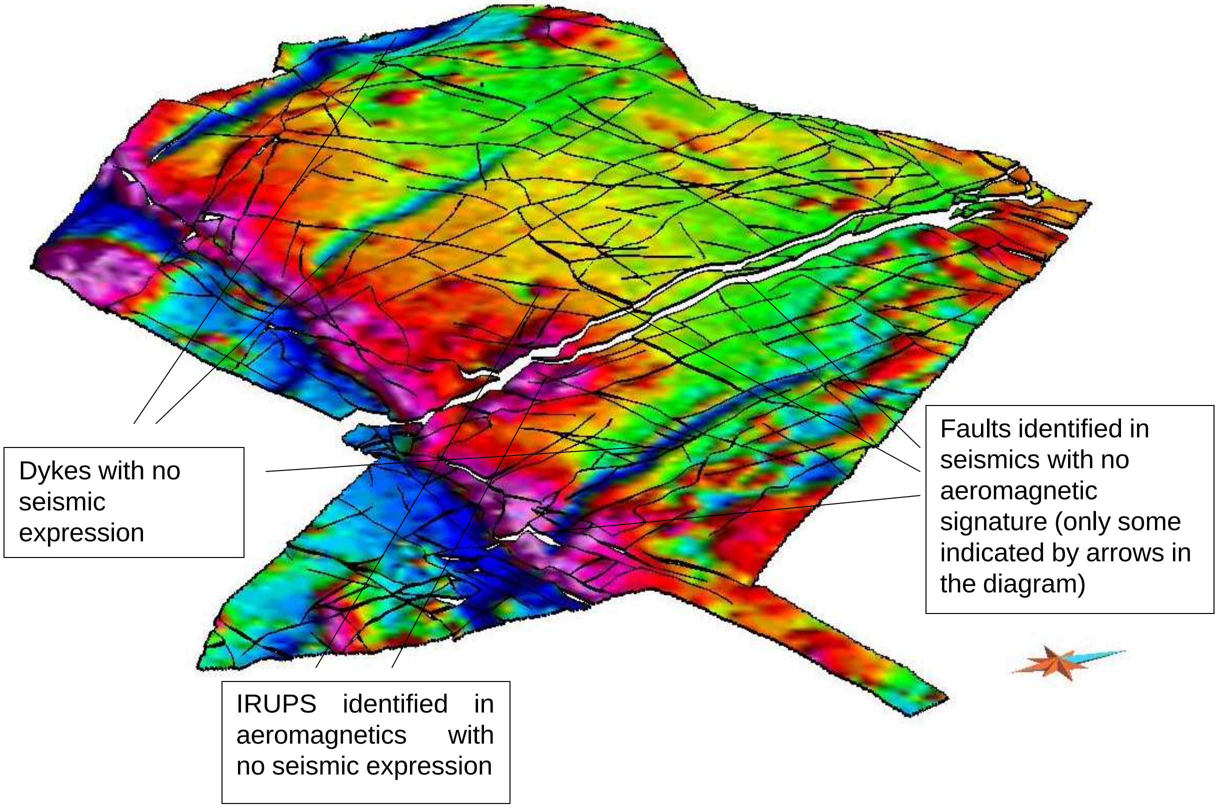
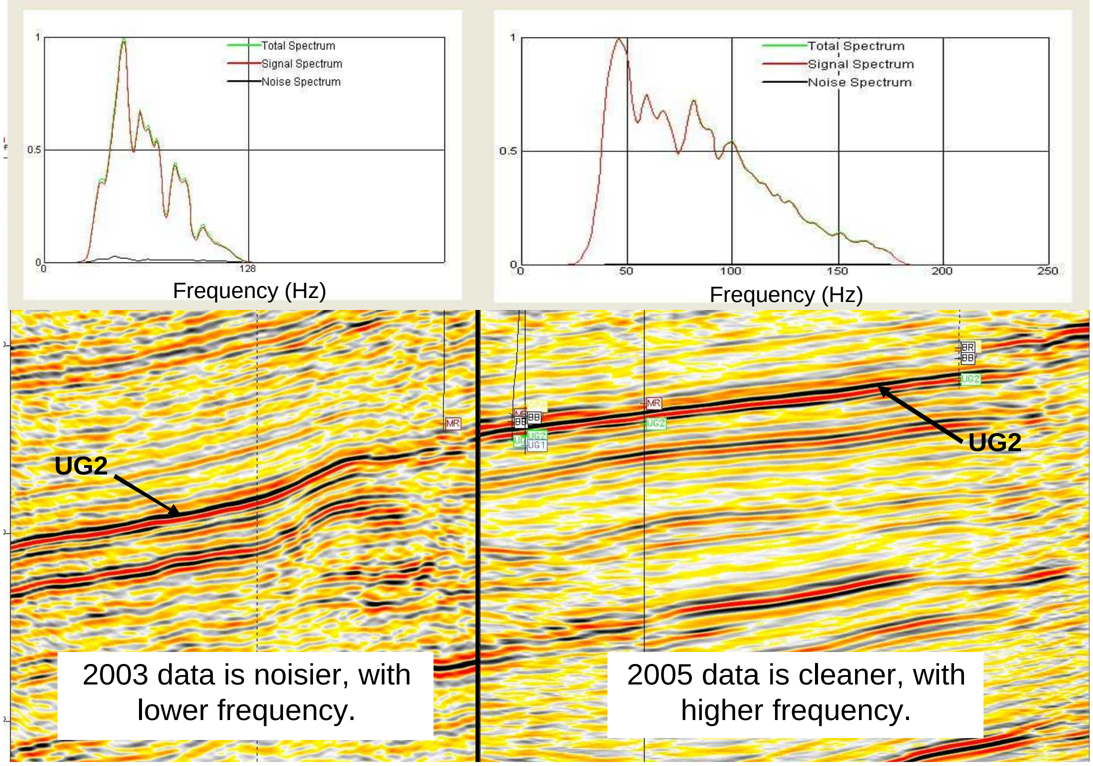


Figure 5: 3D perspective view of aeromagnetics draped onto faulted Merensky Reef from 3D seismics. The draping highlights the complementary structural data from these two datasets. Regions are evident where aeromagentics identifies dykes and IRUPS not identified in the seismics, while conversely the 3D seismics identifies faults not evident in the aeromagnetics.



2003 data is noisier, with lower frequency.

2005 data is cleaner, with higher frequency.

Figure 6: Comparison of low resolution 3D seismic data and power spectrem (left), with a high resolution infill 3D seismic survey recorded around a shaft site (right). Note the position of the UG2 platinum orebody.

High-resolution infill imaging to further improve the orebody model over shaft sites

A new deep (1000m) vertical shaft to exploit deeper portions of a platinum orebody in the BC represents an investment of about US$ 500 million before underground development commences. Anglo Platinum were sufficiently concerned about structural sterilisation in the immediate shaft sites to conduct infill 3D seismic surveys over two of these sites in 2005 and 2006, effectively quadrupling the lateral resolution and achieving significant improvements in the vertical resolution compared to the original, regional 3D seismic surveys. Figure 6 illustrates these resolution improvements at one shaft site. Whereas the regional survey had a generic vertical structural resolution of about 15m the infill survey approaches about 8m resolution in the vicinity of the shaft.

In an attempt to further improve the structural resolution an experimental, walkaway VSP was conducted in the shaft pre-collar hole. The improvement in received frequencies recorded downhole led to a further increase of about 30% in vertical structural resolution. This is illustrated in Figure 7, where the walkaway VSP section (red data) has been spliced into a 3D seismic strike section at this locality (blue data). The VSP results added value to the shaft risk assessment by confirming the absence of significant structural geological discontinuities around the immediate shaft site.

Ultra-high resolution structural imaging and geotechnical investigations

Stepping still further up the structural resolution scale, additional value can be added to structural risk assessments at shaft sites by conducting borehole radar surveys and downhole geophysical logs in shaft pre-collar holes and then integrating these data with more conventional geotechnical measurements conducted on drill core. Although borehole radar lacks the penetrative range of surface and borehole seismic techniques, structural resolution is greatly improved and geological discontinuities as small as 1m can be resolved with the borehole radar systems currently deployed. Radar range is still adequate in the electrically resistive rocks of the BC, allowing features up to 30m from the shaft hole to be effectively imaged. Radar offers significant advantages in putting the finishing touches on a shaft risk assessment: it is deployed vertically and therefore able to image steep structures which could have escaped detection with surface 3D seismics and the VSP technique, provided, of course, that the above-mentioned structures are radar reflective. Fortunately this is often the case. Secondly, in transmission mode borehole radar can potentially provide an early warning of bad ground conditions if there is an anomalous drop in expected penetration. Borehole radar is an important addition to the conventional suite of in-hole geotechnical tools.

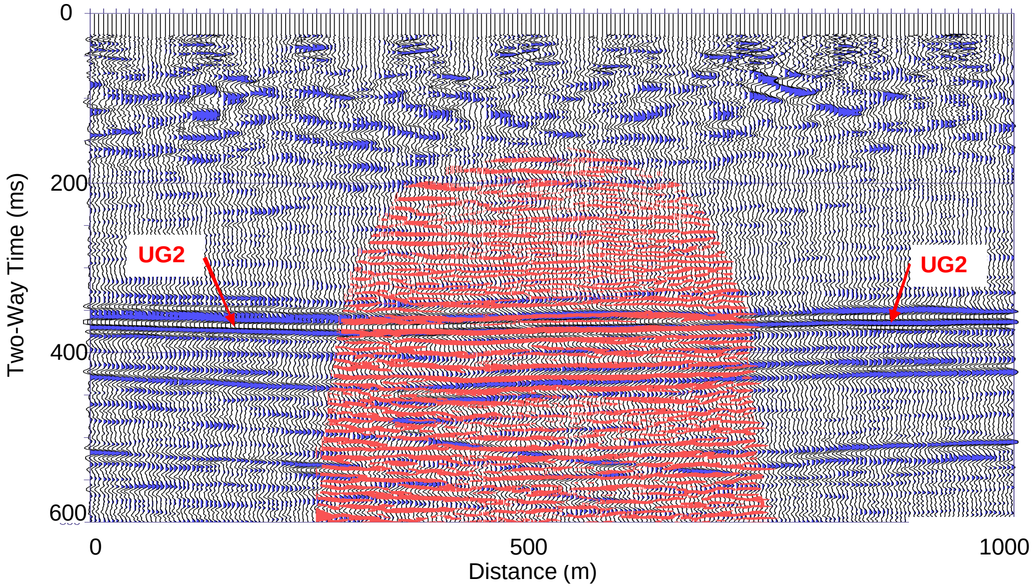


Figure 7: Walkaway VSP (red data) spliced into 3D seismic section (blue data). The VSP shows a 30% improvement in vertical structural resolution over 3D seismics at this deep mine shaft site. Note the slimmer red reflector on the VSP overlaid on the broader reflector in the 3D seismic volume used to map the UG2 platinum orebody.

The two right-hand panels in Figure 8 show a borehole radargram measured in a shaft pre-collar geotechnical hole. The panels to the left display the lithology and structural logs, followed by an acoustic televiewer (ATV) image with over-laid, interpreted dip “tadpoles”. Vertical structural resolution on this image is about 1mm. Dipping horizons intersecting a cylindrical drillhole have a sinusoidal geometry when the cylinder is unwrapped to provide a flat projection. The amplitude and phase of these sinusoids on the ATV image respectively provide the dip and azimuth of these features.

The sinusoidal nature is not clear on this image, owing to the compressed vertical scale, but will be better illustrated on an expanded image in Figure 9. The position of the body of each “tadpole” on the ATV image shows dip magnitude (higher to the right), while the tail of each tadpole provides the dip direction (e.g. the upper three blue dip tadpoles on the ATV image show steep north-easterly dips. The next two below these, at a depth of about 410m, show lower dips to the northwest). Note the strong radar reflection at depth 427m, showing fractures flanking a lamprophyre dyke. It indicates that this is a very significant fracture system which penetrates up to 10m away from the shaft hole. Without the radargram and ATV image this fracture system could well have been allocated a lower risk rating, based on the core log alone. By analyzing the televiewer data at the intersection with the radar reflection, the probable dip and strike of the associated fracture system can be estimated. This is a powerful benefit of integrating these datasets because the slimline borehole radars available for this work are currently non-directional.

Figure 9 shows how integrated, downhole geophysical log interpretations can be further utilized to characterize fracture systems. The ATV amplitude image, similar to Figure 8, is supplemented by an ATV travel time image. Compared to Figure 8 the sinusoids can now be clearly seen on the expanded vertical scale, particularly on the amplitude image. The ATV travel time image adds an important dimension because it shows which of these systems are potentially open and hence more hazardous. Two additional logs are added to the right to further assist in characterizing the fractures. These are the downhole 3-arm caliper log and water flow meter. Increased water-flow, combined with a caliper image anomaly would usually confirm a televiewer interpretation of an open fracture system. However, the water flow meter should take precedence in the overall hazard rating because of the dynamic nature of the measurement. Referring to Figure 9 it is apparent that fracture systems F1 and especially F3 would be characterized as open, based on ATV and caliper data. However, neither of these have significant flowmeter anomalies. By comparison, F2 appears to be a more innocuous system based on the ATV and caliper data, but significant water flow takes place in this system and it must be characterized as potentially the most hazardous in this depth range. Figures 8 and 9 together indicate the power of 3D data integration and querying at different sampling scales when classifying potential geotechnical hazards.

The growing use of downhole geophysical data to supplement traditional geotechnical core measurements is important because it characterizes the structures in-situ and provides improved volumetric sampling statistics when compared to core measurements alone. K. Trofimczyk, a co-worker in this field has provided a few thought-provoking (unpublished) statistics as follows: in a shaft of 3m radius to a depth of 200m the total volume of excavation is 5, 656 m^3. The effective volume of the disturbed zone surrounding the shaft is 22,622 m^3, assuming a further 3m radius of influence. A geotechnical borehole with 50mm core diameter samples a volume of 0.39 m^3 within the shaft or 0.0017% of the volume of influence. 30 samples selected for UCS measurements represent 0.0074 m^3, or 0.00033% of the volume of influence. By comparison, multi-parameter downhole geophysical logs sample up to 157 m^3, or 0.69% of the volume of influence over the full

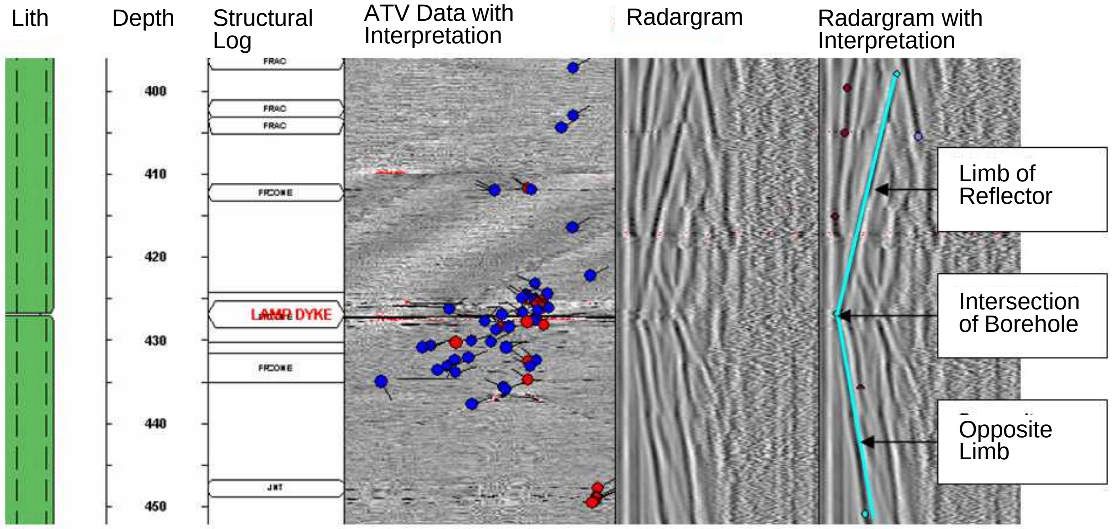


Figure 8: Integrated geotechnical risk assessment combining downhole geophysical logs and core measurements.

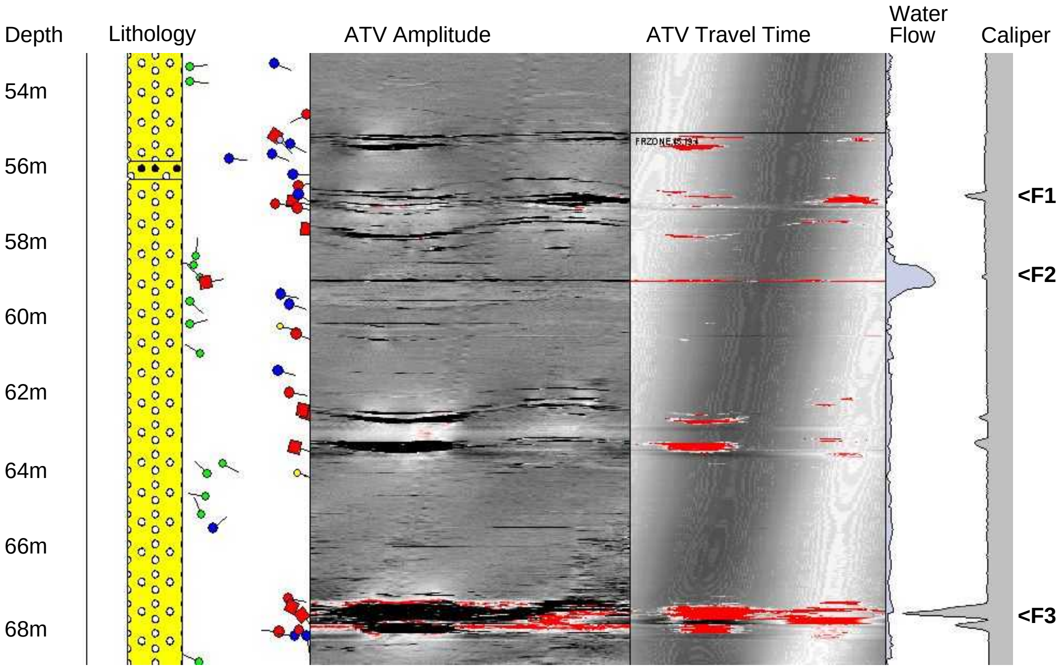


Figure 9: Integration of ATV, water flow and downhole caliper to characterise fracture systems

length of the borehole. This is a significant improvement over core sampling alone. When these logs are combined with lower resolution, off-hole measurements such as borehole radar, the sampling can extend to 100% of the volume of interest. These sampling statistics are not intended to downplay the importance of any one of the techniques, but rather to illustrate the improved coverage of risk assessment bases when using the 3D, integrated, multi-disciplinary approach to characterize the rock mass surrounding a proposed shaft.

In summary, 3D data integration incorporating various geological and geophysical imaging techniques, is applied across much of the mining lifecycle at Anglo Platinum. The applications extend from seismic structural imaging to assist long range mine planning, through to borehole radar imaging in shaft and cover drillholes holes to assist long and short term risk management and culminating in innovative, high resolution borehole geophysical supplements to conventional geotechnical data. Structural resolution ranges are enormous, extending from tens of metres down to millimeters and integrated interpretation is best undertaken in a 3D "common earth" modeling environment with powerful visualization and querying capabilities. GOCAD fulfils this requirement very well in terms of its ease of use and ability to integrate a broad variety of geological, geophysical and mining datasets.

3D DATA INTEGRATION APPLIED TO MINE SAFETY AND PRODUCTIVITY

The HAZMAP concept

Another experimental application of 3D data integration on operating mines is the mapping and prediction of potential mining safety and productivity hazards, with the option of semi-automated hazard updates and alerts. Several applications have been launched by MIRA Geoscience in conjunction with mine staff on ‘Anglo Group’ mines under the brand name HAZMAP (McGaughey et al., 2007). The concept will be briefly described in this section and illustrated by data from a coal mine.

The concept is simple and intuitive, involving 3-D spatial and temporal analyses of mining and geological features (e.g. geological faults) which can contribute to a potentially hazardous condition. The hazard data are spatially quantified utilising 3D topology GIS functions and can be projected onto a 2-D surface, normally the current and future mining plane, to provide a map of each hazard index. This index is colour-coded according to a semi-quantitative “percentage” risk estimate as illustrated in the following case history.

Coal Mine HAZMAP case study

Figure 10 summarises the HAZMAP exercise on an underground coal mine. In this case the main goal is to avoid mining roof collapses which would introduce interruptions in normal mining operations, as well as posing safety hazards. Several geological and mining factors have a bearing on the potential collapse of the mining roof. The hazard components and weightings are illustrated alongside the stacked layers on Figure 10a). Note that in this case high dip changes on the main coal seam (Index 11) carry the highest weighting. Other hazard indices carrying a high weighting are seam thickness and interburden thickness. It is clear that a lot of thought has gone into this complex HAZMAP model, indicating the commitment of the multidisciplinary geoscience and engineering team responsible for the project. A simple traffic light colour coding scheme has been used here (red most hazardous, green least hazardous). Figure 10b) shows the overall stacked hazard index projected onto a future mining plan.

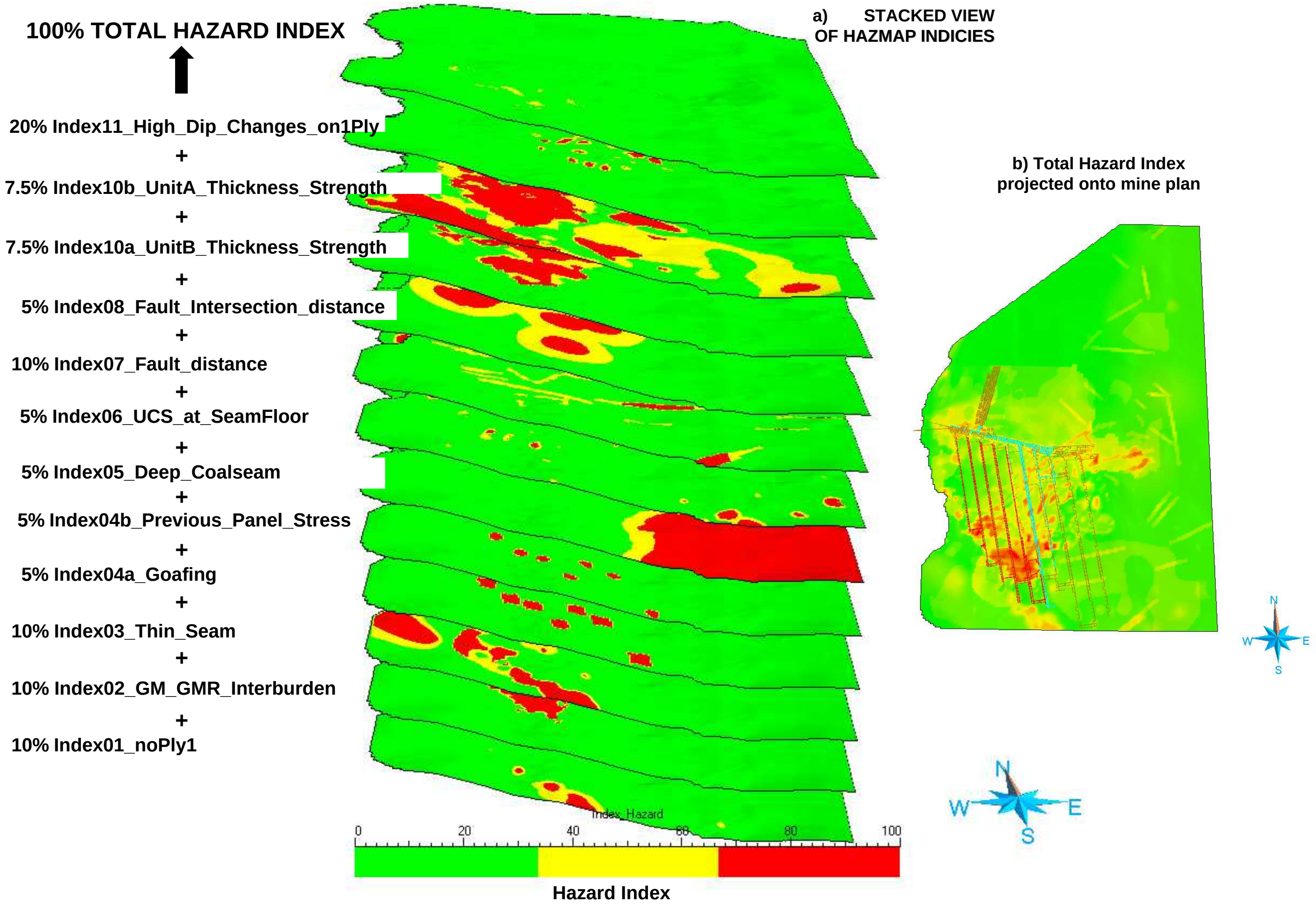


Figure 10: Shallow coal mine HAZMAP study.

CONCLUSIONS

Integrated 3D “common earth” modeling adds considerable value to exploration and mining across much of the mining lifecycle. Important opportunities for technology/methodology transfer are emerging from the new, high-resolution applications of geophysics. The cost effectiveness and success of bold, integrated 3D orebody imaging methodologies in the precious metal and coal mines seems to have caught the attention of mining practitioners in other commodities such as base and ferrous metals. There is an increasing interest in similar applications from mining and exploration staff in these divisions, albeit with a different mixture of techniques. Perhaps the most satisfying outcome is the potential for a retrospective transfer of orebody imaging methodologies from the high resolution brownfields and mining environment to greenfields exploration. The high-resolution imaging techniques owe much of their success to rigorous basics. This includes diligent physical characterization of ore and host rocks prior to selecting a geophysical imaging methodology, appropriate survey design to meet 3D sampling requirements and, above all, a total commitment to integrating all data in 3D at every stage of the imaging process. One or more of these ingredients is occasionally missing in greenfields exploration programs. The success of on-mine geophysics may well feed back into improved exploration success if the same adherence to QA fundamentals is encouraged.

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