

Exploration and Mining Geophysics and Remote Sensing in 2009 – Where have we come from and where are we going to?

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ABSTRACT

Geophysical and remote sensing (RS) techniques, integrated with the other geosciences and engineering disciplines, have made a significant contribution across the full mining lifecycle (MLC), extending from exploration to mine closure. Although much of the published data deals with the high profile contributions that geophysics and RS have made to exploration and mining feasibility studies, many of the exciting new contributions are expected in the *mining production* part of the MLC. In the future there will probably be an increasing focus on geophysical and RS contributions to mine safety, mineral resource management, geotechnical systems, hyperspectral core logging and ore sorting, as well as improved ground and airborne exploration multi-systems. A balanced portfolio across the MLC in the multi-disciplinary Geoscience / Engineering / Metallurgical environment should ensure sustainable success.

Our stock of in-house corporate geophysicists and remote sensors with an owner-manager / shareholder culture needs to be replenished. These individuals are key drivers of the macroeconomic demand for specialist geosciences. The in-house specialists should capitalise on past successes and continue to capture the methodologies in quality assurance systems, best practice manuals, procedures and guidelines in cooperation with our geological and engineering colleagues. These formalised best practices should be appropriately communicated and rolled out and will help our companies to maintain a high standard of compliance with important industry codes, for example in safety risk management and mineral resource management. Organisations such as SAGA and our tertiary education institutions can make a significant contribution to the formal compilation of best practice guidelines for the geophysical and RS geosciences.

Key Words: Geophysics, Remote Sensing, Mining Lifecycle, Anglo American, Best practice guidelines

INTRODUCTION

South Africa has a geophysical tradition that we can be proud of. Much of our contribution as geophysical and remote sensing specialists has been made at the greenfields and brownfields exploration phases of the mining Lifecycle (Figure 1). However, significant inroads are being made further along this lifecycle, extending through the production phases, up to mine closure. Indeed, it is in the production parts of the cycle where geophysics has a lot to contribute in the future, particularly in the field of mine safety. Much of a corporate mining geophysical career is spent in “catalytic” mode, striving to understand and influence the *appropriate* demand for geophysical and remote sensing services to maximise the value-add to the business. Hence, this paper will have a bias towards the *demand (stimulation)* half of the service equation, rather than the *supply* side. The supply side will be addressed when I look at R&D trends later in the paper.

The first half of this paper will briefly review geophysical achievements at several points along the mining lifecycle, focusing on the Anglo American experience, but probably emulating similar experiences in other mining groups. This is the “*where have we come from?*” part of the title. Following this, a few of the important learning experiences gained in the multi-disciplinary, geoscience / engineering production environment will be used as a platform for the trickier “*and where are we going to?*” part of the paper. Certain conclusions will be drawn which will hopefully generate discussion during the oral presentation.

WHERE HAVE WE COME FROM?

Commencing at the exploration end of the mining lifecycle, geophysics has contributed to several major discoveries within the giant ore deposits of South Africa. One of the earliest examples I was exposed to

was the use of gravity and magnetic methods to discover new goldfields and extensions to mined areas in the Witwatersrand Basin, under great thicknesses of cover rocks (Krahmann, 1936; Roux 1967). Ongoing exploration under cover in this basin in the 1970's to the 1990's eventually led to the use of 2D and 3D seismic reflection techniques, integrated with gravity and magnetic studies. This culminated in what is probably the most extensive use of reflection seismics in the hard rock mining environment globally, concentrating on gold exploration in the Witwatersrand Basin and PGM exploration in the Bushveld Complex (Pretorius *et al.*, 1989, 1994; Pretorius, 2004; Campbell, 1994; Stevenson and Durrheim, 1997).

In my personal experience, the port of relatively high-cost seismic technology from the oil industry coupled with ancillary, niche, specialised services such as borehole geophysics, hastened a fundamental shift in the role of corporate centre mining geophysicists. The in-house corporate centre geophysicist / remote sensor increasingly took on the role of outsource manager, mainly responsible for the supervision of specialised geophysical contractors and the associated quality assurance duties. The trend soon spread to airborne and ground geophysics. The outsourcing trend provided a welcome boost for mining geophysical contractors, particularly in exploration boom times, and many of my colleagues left the large corporates to pursue their scientific interests as contractors, rather than remain in corporate management positions. I perceive that this has left a shortage of hands-on geophysical skills in corporate centres and has also complicated sustainable succession planning, but this will be part of the discussion which follows below.

In Anglo American we have adopted a mixed approach where a centralised specialist division, Anglo Technical (AT), provides consulting services to all operating divisions. In addition to this, some of our production divisions and associates, notably Base Metal exploration and De Beers, have their own hub-office geophysicists, spread across several global exploration hubs. A key goal is to achieve close integration with the other geosciences and engineering disciplines. At the Centre we only maintain exploration systems that are deemed to provide a strategic advantage for the Anglo Group. One example is our Spectrem 2000 airborne electromagnetic, magnetic and gamma spectrometer system (Figure 2). This system has a number of notable discoveries to its track record and is experiencing a growing role in geological mapping, especially in heavily forested areas and in low magnetic latitudes (Figure 3). King and Le Roux (2007) summarise the reasons why we believe that this is one of the world's leading airborne multi-system geophysical platforms, which we continually strive to improve.

Moving down the exploration lifecycle shown in Figure 1, we enter the mining feasibility stage, where 3D

seismic exploration has played a major role in risk management in mine planning and development. I believe that more hard-rock 3D seismics has been undertaken by mining companies in South Africa than anywhere else in the world. (Pretorius *et al.*, 1997, 2003, 2004, 2007; Gibson *et al.*, 2000, 2002, 2006; Rompel and Chunnnett, 2007; De Wet *et al.*, 1994). Anglo American was a leading champion of these initiatives, both in the Gold and Platinum industries. Figure 4 shows an example of a major graben imaged by 3D seismics, which had escaped detection through decades of surface drilling on this property. New structural insights, and some surprises, such as this, with major mine planning implications, have been detected on the majority of the seventeen hard-rock 3D seismic survey projects which I have managed over the last 16 years. The total value-add is difficult to quantify, but probably amounts to several billion dollars. Today, at least one phase of 3D seismic imaging would be considered mandatory on Anglo-managed mine developments in the Witwatersrand Basin and Bushveld Complex. In some cases follow-up, high-resolution, infill 3D seismics has been conducted around new shaft sites. As mentioned above, the corporate geophysicist's main role in these large seismic programs has been technical project management, quality assurance and interpretation. Credit for data acquisition and processing belongs to large external seismic service companies, notably CGG Veritas and Rockplan.

Moving still further down the mining lifecycle shown in Figure 1, we enter the production domain, where borehole geophysics is finding a significant niche. Borehole geophysical applications contribute to a range of disciplines including exploration, mine planning, metallurgy and geotechnical engineering. Trofimczyk *et al.* (2009) have produced an excellent paper on the growing use of downhole geotechnical geophysics to support conventional core studies and improve risk management at new mine shaft sites. Figure 5 shows that integrated borehole geophysical coverage, including downhole radar, extends structural imaging of the affected volume around a shaft site from .0003% (conventional core geotechnical studies alone) to almost 100% (*conventional core measurements integrated with geophysics*). This adds significant value to risk management. At least one shaft has been moved to a lower risk locality based on such integrated geotechnical assessments.

Within operating mines I am a big fan of borehole radar, particularly as a follow-up tool to *surface* 3D seismic structural imaging: Recalling Figure 4, surface 3D seismics, with a minimum fault detection limit of about 8 m throw in the hard-rock environment, is convenient for 20 to 40 year strategic life of mine planning. The technique is a particularly useful aid for optimal siting of vertical and horizontal access and transportation systems – similar to planning a metro underground railway, but at much greater depths. By comparison,

borehole radar can directly contribute to short term (3 to 6 month) *production mining optimisation*, by virtue of its higher structural resolution immediately ahead of the progressing mine-face: Figure 6 shows two borehole radargrams from a Bushveld Platinum mine, illustrating how well borehole radar images the UG2 Reef (De Vries and Du Pisani, 2005). The upper radargram shows a pothole on the reef, which would have been missed without this image or unexpectedly encountered during mining. With the additional predictive information the mining plan around the pothole can be suitably adapted. The lower radargram shows 1 to 2 m fault disruptions on the UG2 quite clearly. Equally significant is the loss of radar signal within the bad ground surrounding an iron-rich ultramafic pegmatoid (IRUP). This shows that borehole radar has a potential role in safety hazard prediction ahead of the face. This is also true of several other borehole geophysical tools, such as the full-waveform sonic sonde, acoustic and optical televiewers. In-stope radar is also being revived to assess hanging and sidewall stability issues.

For continuity following the discussion of safety applications of borehole radar, a core development concept will be introduced here. The following extract is taken from Pretorius *et al.* (2007): “An important 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, J *et al.* 2007). The concept will be briefly described and illustrated by data from a coal mine.

The concept is simple and intuitive, involving 3D 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.

Figure 7 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 7a. 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 7b shows the overall stacked hazard index projected onto a future mining plan.

WHERE ARE WE GOING TO?

In Anglo American the success and growth of integrated geophysical applications over the last two decades has been assisted by a concerted effort to balance the applications portfolio across the full mining lifecycle, with a good spread of work extending into the production / engineering / geotechnical domain. This is more than a marketing strategy. It is driven by recognition of the considerable value that high-resolution geophysics can add in this domain. For part of my career in Anglo Technical Division (2000 to 2007), I reported directly to the Engineer heading the division and found myself working more closely with engineers and metallurgists. The immersion in an engineering culture was very beneficial in terms of multi-disciplinary cross-feed. During this period our near-mine and on-mine geoscience and geotechnical workload and research interests grew substantially and often exceeded 70% by value of my department’s project work. Some of the synergies fed back into exploration improvements: for example, joint geoscience / engineering sponsorship of SQUID (Superconducting Quantum Interference Device) R&D, led to the development of what is probably the world’s best ground EM sensor. Anglo American still retains exclusive usage rights to this Low Temperature Electromagnetic SQUID technology, in the mineral exploration field. In the engineering environment we also gained important experience in rigorous project management and quality assurance. These are critical success factors as we strive to maintain and increase workload in the production part of the mining lifecycle.

It may be useful to commence the next section with a brief **SWOT** analysis:

One of the main *Strengths* of South African geophysicists and remote sensors has been their recognised world-class achievements in greenfields and brownfields exploration, and contributions to mine planning.

Our two main *Weaknesses* may be the lack of formal mandate to influence strategic exploration planning and our low presence in the geoscience complements on our mining operations. (It is a lot easier to influence change inside a system, than as a remote advisor from a distant “head office”, irrespective of the amount of marketing done).

The obvious *Opportunities* are to tackle the weaknesses with vigour. Specifically, to employ our successful track record to lobby for admission into formal management systems and procedures using all possible avenues (e.g. actively contribute to quality management systems, formal standards and guidelines, project reviews, client budgeting processes and other major events across the mining lifecycle. We can continuously lobby for admission wherever geophysics can make a meaningful contribution, even though we do not currently sit on the committees concerned. With time and persistence, we will be granted formal admission.

Techno-economic success on its own is not enough. I have learned this over 30 years in a career with its fair share of successes and breakthroughs, some of these in the major league. To maintain momentum we must write our successful geophysical methodologies into recognised good practices as we go along. If we do not rigorously update formal standards and guidelines we run the risk of continuously repeating developmental marketing rather than focussing on new, leading edge improvements. In many cases we merely have to insert geophysical chapters into engineering, geological and other corporate operating manuals, standards and guidelines, with a special emphasis on risk management and safety. I see no urgent need for separate initiatives and I suspect that there is a lot of catch-up work to be done just to get up to date. Further *Opportunities* emerge from the fact that production and research work in the high-resolution fields of geophysics practised near, on- and in-mines often leads to improvements in *overall exploration* methodology and culture.

The main *Threat* is that an unbalanced portfolio could lead to a drop in momentum of applied geophysics, particularly in the production half of the mining lifecycle. Specialised outside geophysical service suppliers often do not understand mining problems from an owner-manager / shareholder perspective and sometimes struggle to suggest *appropriate*, integrated, geoscience interventions. I stress the word *appropriate* here, because it has been a key ingredient of our successful projects. We are often competing with alternative means of gathering similar information, including drilling, and must ensure that our geophysical contributions are technically and commercially competitive, with predictable deliverables on a reliable schedule. This is particularly true in the production field, where our engineering end-users have a low tolerance for failure. If geophysics is not competitive or appropriate, then we should not hesitate to recommend the alternatives. For me this is the major difference between the supply and demand domains and introduces quite a culture shock from a marketing perspective. My personal speciality is 3D seismics which has attracted a lot of interest, but I spend a lot of my time convincing keen, potential clients in our business units *not* to use this relatively costly technique if I believe that there is a

significant risk of poor results. This requires a shareholder attitude, which ensures that care for the company as a whole takes precedence over other important issues such as individual or departmental billability.

Coming from a shareholder perspective I try to discourage the use of the word “client” wherever possible in my department. I prefer to stress that we are all colleagues and co-workers with our production divisions, pursuing integrated, aligned business goals. In pursuit of these goals, we have structured our ISO9000 Quality Assurance hand books and guidelines to capture technical and economic *appropriateness* early in a project flow. The six senior managers in the department have each been given a technical consulting responsibility (their brand areas of specialist expertise) and a business relationship responsibility for a particular commodity division. It would be useful to get feedback on how many of our colleagues in the industry are following a similar route.

As part of our sustainable succession planning I also think that we need to attract young geophysicists back into the mining corporate system and develop them in the owner–manager culture. There is a significant governance function in our workload and this is expected to grow. After a considerable gap we commenced on the junior recruitment path again about five years ago. Internal geophysicists and remote sensors are champions of a powerful field in the applied geosciences and are thus important drivers of macroeconomic demand. The commercial market supply of services should continue to thrive and grow to meet this demand. This is a personal opinion, and comments on alternative strategies during the oral presentation would be welcomed.

Particular geophysical applications that I expect to expand in the future include the following:

- Improved 3D orebody imaging leading to improved mining extraction plans:

Based on solid precedents such as the South African hard-rock 3D seismic experience, I believe that there is a good case for geophysical orebody imaging to gain formal recognition in Mineral Resource classification codes. Even if the codes are not changed, company procedures and practices can be modified to recognise the contribution of geophysical techniques towards maintaining a high standard of compliance. I am not just referring to reflection seismics here, but a host of other potential techniques dictated by rigorous physical characterisation of ore bodies and host rocks, preferably through downhole geophysical logging.

- Improved geotechnical risk management and Hazard mapping (Geophysics for safety):

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The majority of geotechnical engineers we interface with are very encouraged by the additional information provided by downhole geophysics. It would not take a great effort to write geophysical requirements into standard geotechnical and SHEQ codes of practice and then roll these out. Hazard mapping and prediction ahead of mining is an important area of research. Accelerated roll-out is expected in the near future.

- Improved airborne exploration systems:

In Anglo American we have ambitious plans for our Spectrem platform and airborne SQUIDS. We strive to make our airborne multi-system capability the best in the world, to give our exploration divisions a competitive advantage. Comments from our competitors will be appreciated.

- Advanced ground geophysical systems:

In Anglo American, we are placing a lot of emphasis on ground-based LTEM SQUIDS as mentioned previously. Figure 8 compares an LTEM SQUID CDI (Figure 8b) with a competitor's AMT results (Figure 8a) beneath thick conductive cover. The superior depth of penetration and target discrimination with the SQUID system is clearly apparent.

- Hyperspectral mineralogy:

Hyperspectral core imaging is making huge strides, particularly with the development of batch processing algorithms. Fairly detailed spectral mineralogical analysis of drill cores can now be cost-effectively undertaken at almost the same pace as detailed visual logging. The mineralogical analyses feed directly into activities over much of the mining lifecycle, ranging from exploration through mining feasibility studies to metallurgical applications, including ore sorting. Figure 9 illustrates how an in-field hyperspectral core imager can rapidly add significant mineralogical value, to supplement visual core logging. We predict that on-site hyperspectral core imaging will become routine on most major drilling programs in the future.

- Geophysical sensors for ore sorting:

At Anglo Technical Geosciences we are collaborating closely with our research laboratories and outside institutions on developing improved sensors for diverse ore sorting applications. With our business focus on improved extraction economics, reduction in energy and water consumption and improved environmental management on our mines, ore sorting is a high profile area of research. Results are confidential at present, but may be the subject of future papers.

CONCLUSIONS

Geophysical and remote sensing techniques have made a significant contribution across the full mining lifecycle, extending from exploration to mine closure. A balanced portfolio and close integration with other geosciences and engineering disciplines are key elements of success. Although much of the published data deals with the high profile contributions geophysics has made to exploration and mining feasibility studies, many of the exciting new contributions are expected in the mining production part of the mining lifecycle. There will be an increasing emphasis on geophysical contributions to mine safety. Further future contributions are expected in the fields of mineral resource management, geotechnical systems, hyperspectral core logging and ore sorting, as well as improved ground and airborne exploration multi-systems.

In Anglo Technical Division we have experienced considerable benefits from operating in the multi-disciplinary Geoscience / Engineering environment. The in-house corporate geophysicist has a significant role to play in fuelling macro-economic demand for appropriate geophysical solutions across the mining lifecycle in a multi-disciplinary environment. Within the mining industry as a whole I perceive a need to replenish our in-house stock of geophysicists and remote sensors, keeping the numbers reasonable, and developing them in the owner-manager culture". We are on this "One-Anglo" path in my company, with the assistance of executive management and hope to continue the trend in the future. Obviously this will not be an easy task in an industry that always appears under pressure to outsource services, but I believe that we have the success record and appropriate business plans to at least partially reverse this trend. A high-priority future duty of the in-house geophysicist should be to capitalise on past successes and write them into best practice manuals, procedures and guidelines in cooperation with our geoscience and engineering colleagues. These formalised best practices should be appropriately communicated and rolled out and will help our companies to maintain a high standard of compliance with important industry codes, for example in safety risk management and mineral resource management. Compilation of these best practices will probably be done in-house, but I can see potential for collaboration with organisations such as the tertiary education institutions and SAGA.

ACKNOWLEDGMENTS

I am grateful to Anglo Platinum, Anglo Coal, Anglo Exploration and Anglo American Plc for their permission to publish their data. I also wish to extend my gratitude to my colleagues in Anglo Technical and Anglo Geosciences for their contributions. Particular thanks are due to Andreas Rompel, Mark Gibson, Louis Polome, Tiaan Le Roux, Mike Buxton, Kazek Trofimczyk, Petro du Pisani, Agnes Jikelo, Phil Harris and Engel Rutherford for their contributions to the paper

and for their ongoing championing of our work mission. I also thank our consultants in MIRA Geoscience, CGG-Veritas, CSIR, Geomole, Weatherford, and Wireline Workshop who contributed to the data presented.

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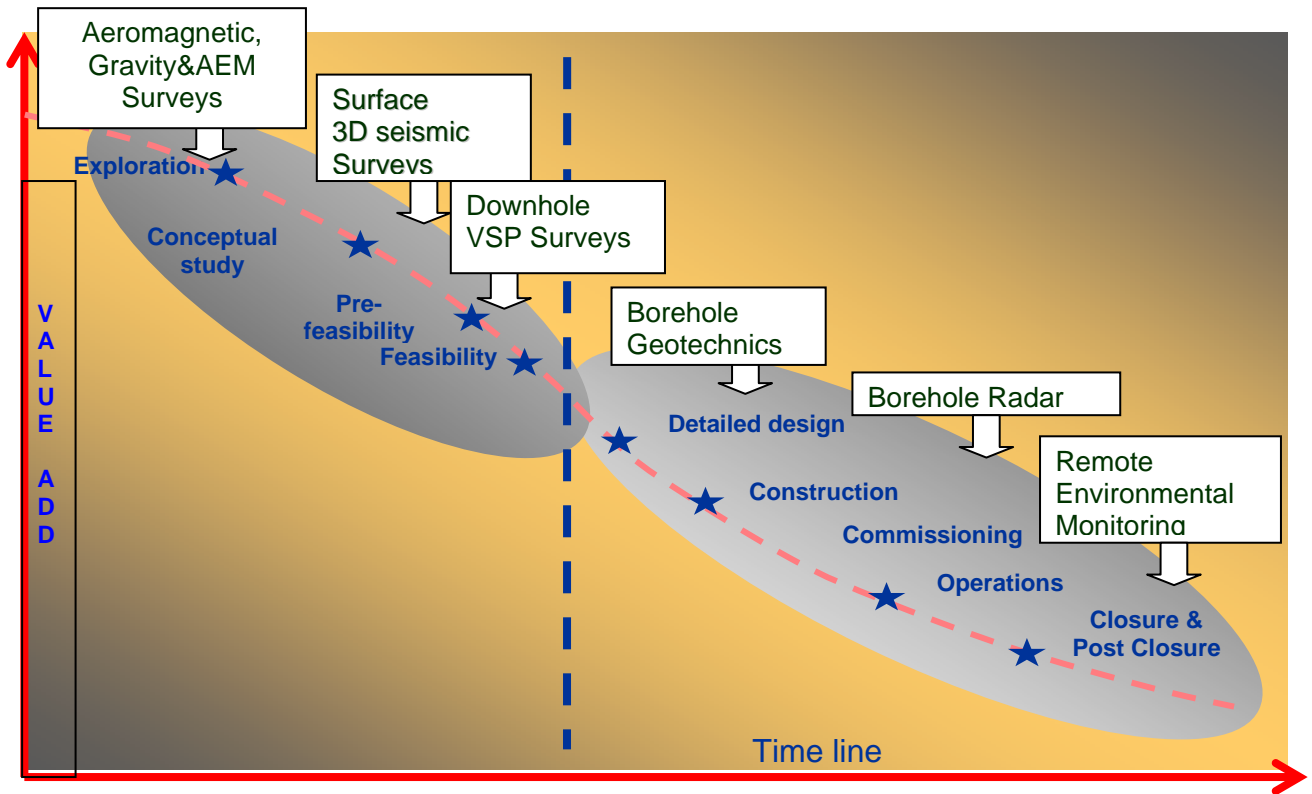


Figure 1. Application of integrated geophysical imaging across the mining lifecycle



Figure 2. Spectrem 2000, with towed EM receiver

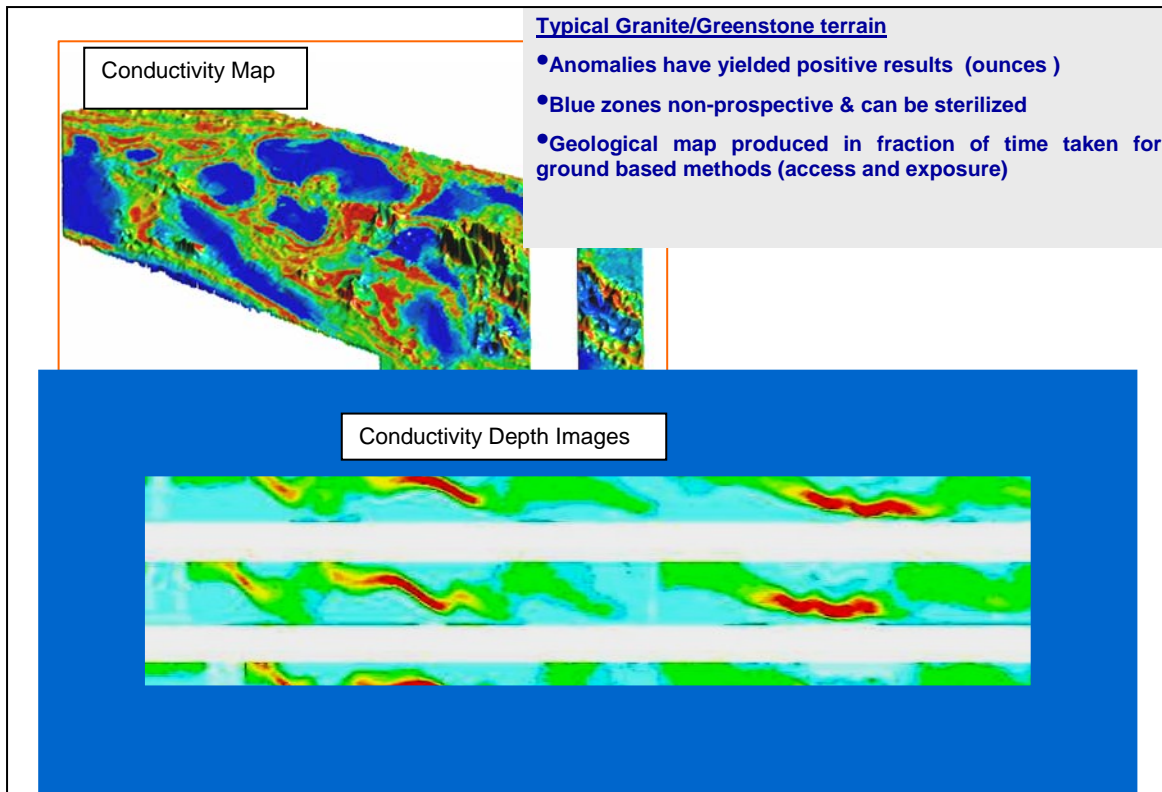


Figure 3. Spectrem 2000: 3D conductivity Depth Imaging

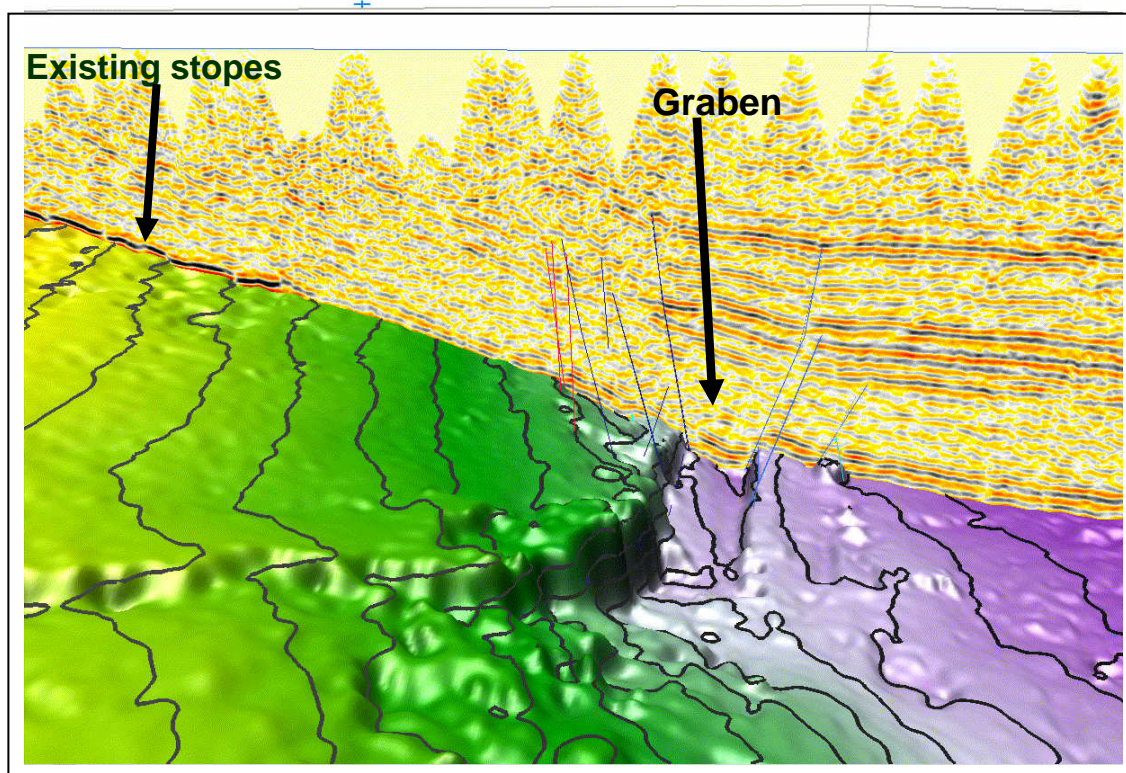
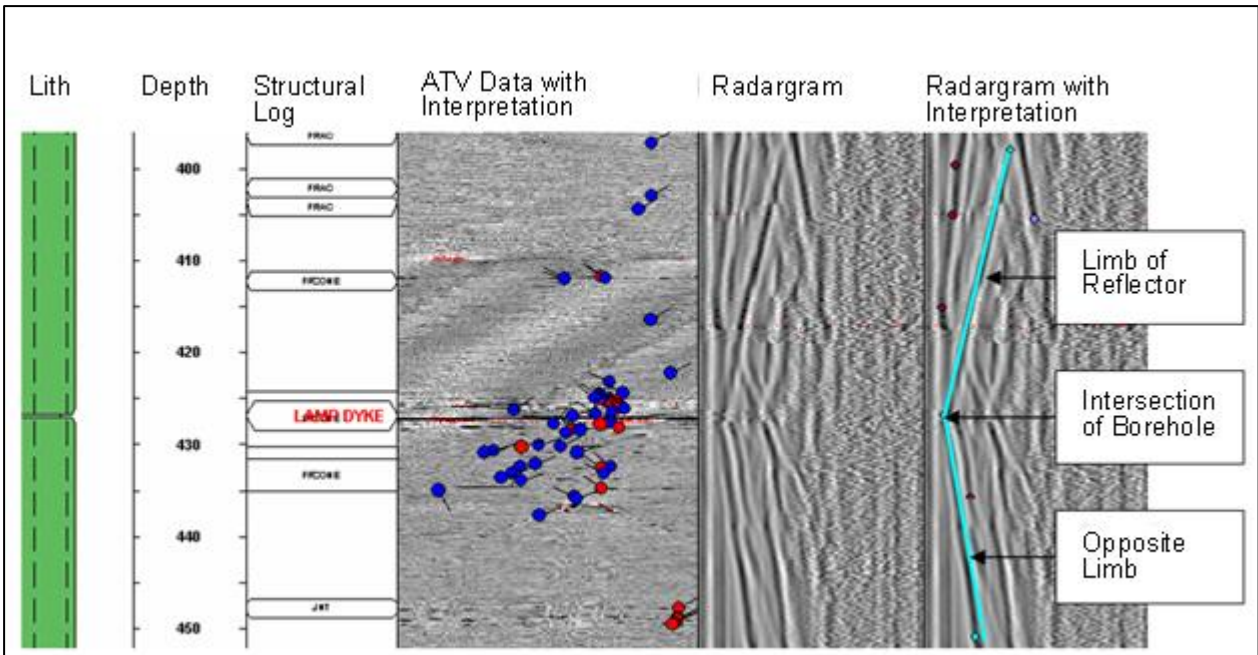


Figure 4. 3D seismic cube scrolled back to reveal the interpreted Digital Terrain Model of the target horizon. Note the central graben revealed by seismic imaging and the stope reflections on the background seismic section, revealing the current mining limit. Depths to target vary from about 700m on the left to 1800m on the right.

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0.0003% → 0.7% → 50-100%
% Sampling of the shaft barrel volume

Figure 5. Integrated geotechnical risk assessment combining downhole geophysical logs and core measurements

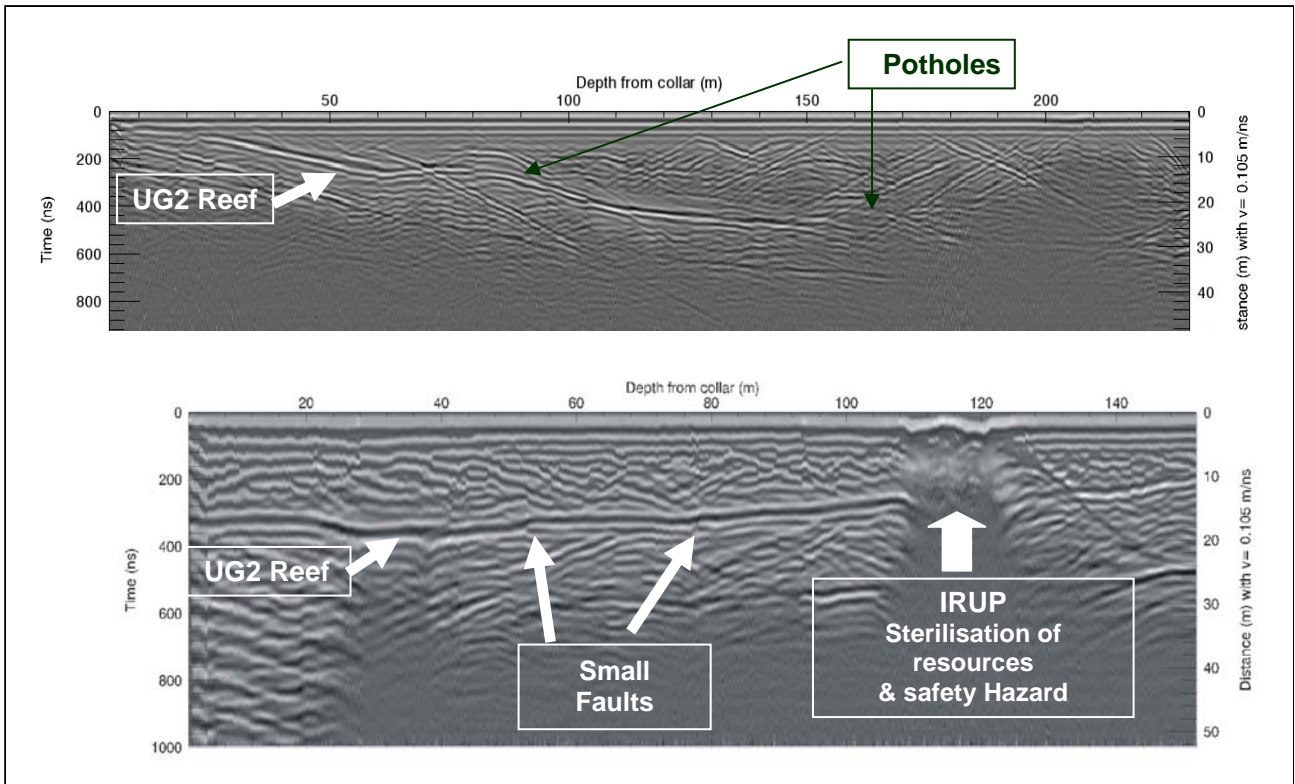


Figure 6. Structural mapping of the UG2 Platinum Reef and hazard detection using in-mine borehole radar

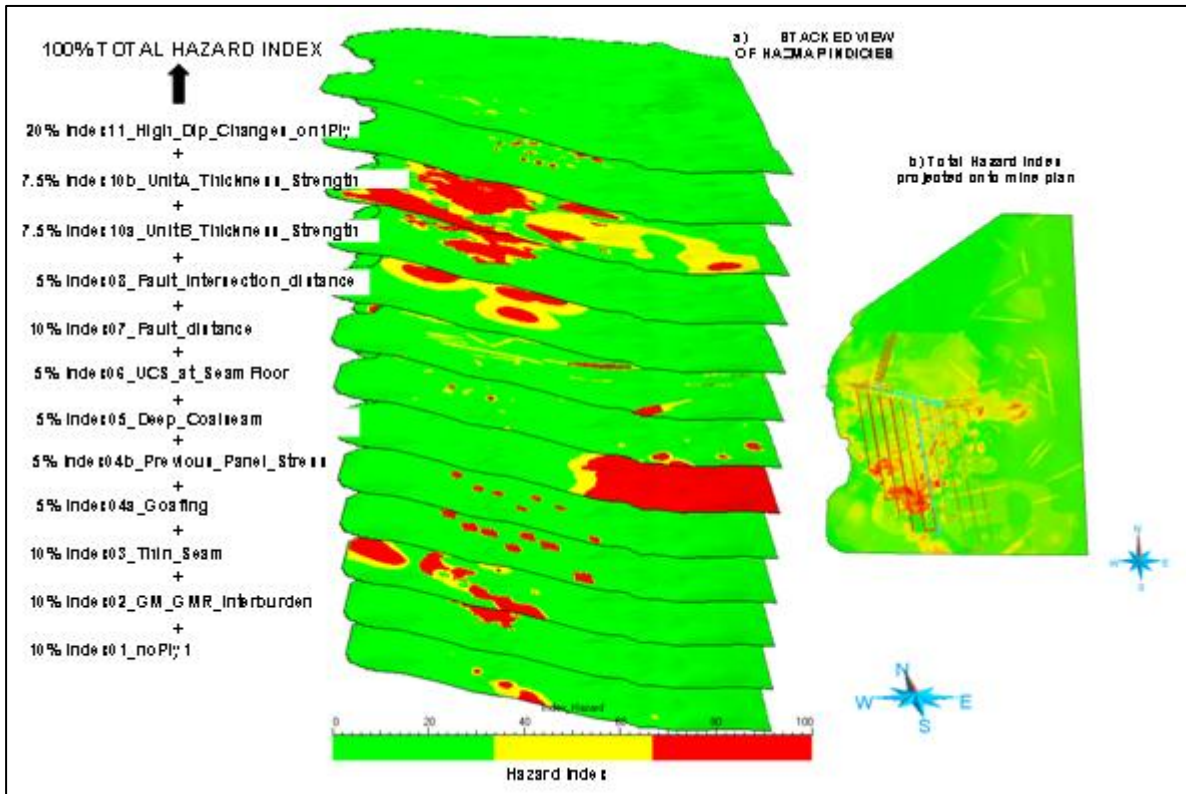


Figure 7. Underground coal mine HAZMAP study

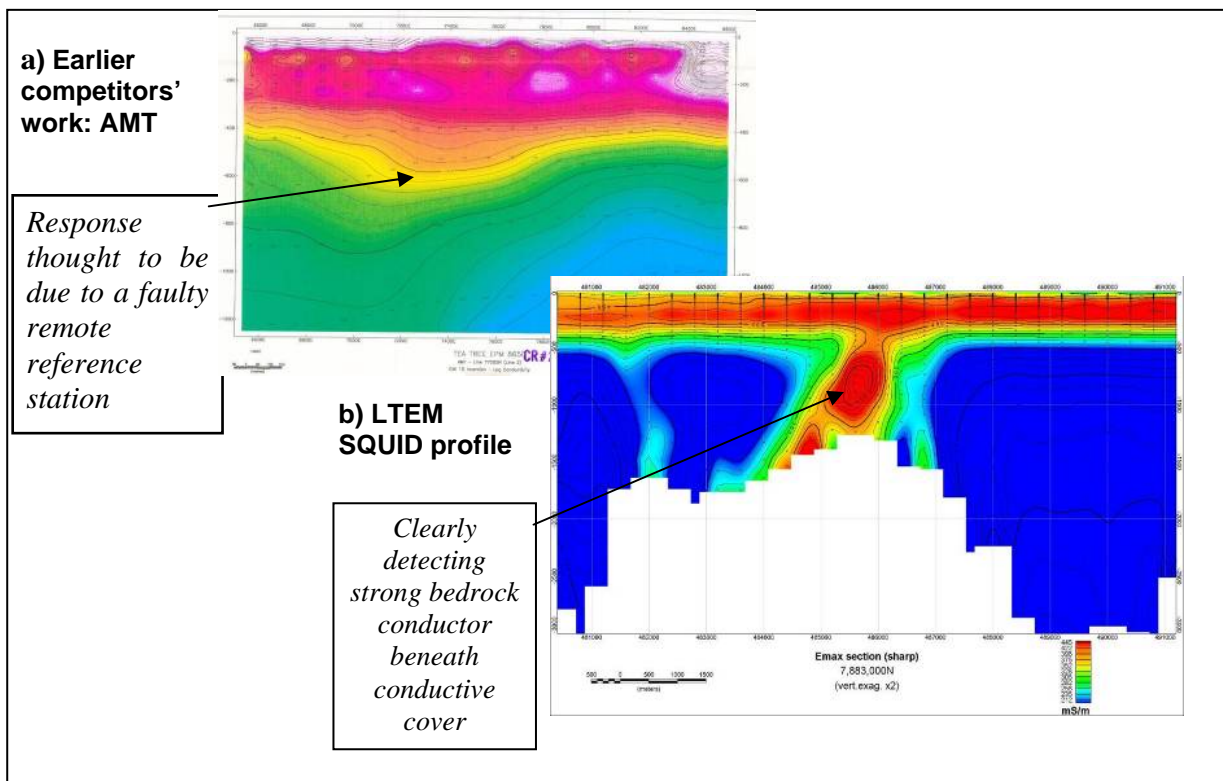


Figure 8. Low Temperature EM SQUID CDI (b) versus previous AMT (a), showing the superior depth of penetration and target discrimination of the SQUID system beneath 400m of 2 Ohm-metre conductive cover.

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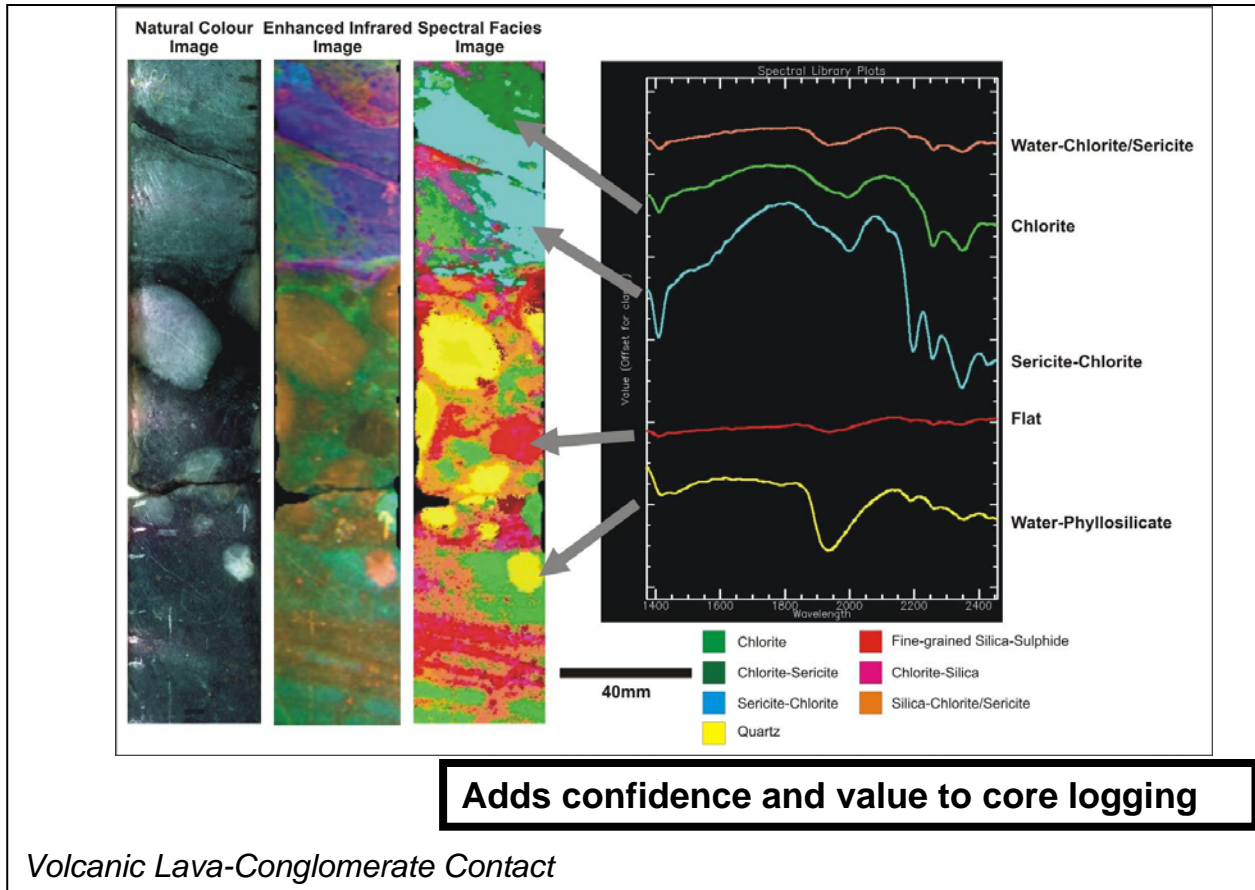


Figure 9. An example of the mineralogical information that can be added in the field by a Hyperspectral Core Imager