Fast-Tracking Gold Exploration Below 300m around a mature mine complex – 3D Seismic Case History of the Darlot – Centenary Gold Mine

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SUMMARY

The Darlot-Centenary gold deposit is one of the larger known mineralised systems in the southern end of the West Australian Yandal Greenstone Belt, with an estimated 2.7 Moz having been extracted from the Darlot Centenary Mine since 1988. The area is well explored near surface but given the proven endowment there is potential for significant additional mineralisation at depth. With current proven reserves dwindling, Gold Fields recognised the need to identify a technology to fast-track target generation in order to more rapidly evaluate the nearby rock volume.

In August 2016 Gold Fields began investigating the potential for 3D reflection seismic to accelerate evaluation of the rock volume accessible via existing workings. In November 2016 a seismic crew was on ground acquiring approximately 150km3 of 3D seismic data (25km2 surface area x 6km depth). The survey coverage was designed to image the local steeply dipping geology and structures. Processing of the seismic dataset was completed in Q1 2017 and Gold Fields has completed preliminary interpretation of the 3D cube.

The seismic data has provided a rich 3D picture of the Darlot structural framework to depth, which could not be obtained by any other geophysical method. It has highlighted a number of features with similar characteristics to known mineralisation and has provided a better defined structural framework that has greatly assisted the fundamental geological understanding and further aided ranking of these targets in terms of prospectivity.

Key words: 3D, seismic, reflection, gold, structure.

INTRODUCTION

The Darlot-Centenary Gold Mine was purchased by Gold Fields Australia in, October 2013, from Barrick Gold Corporation, as part of a large regional purchase, which included the Granny Smith and Lawlers Mines. At the time, Darlot was a loss-making venture and was thought to be rapidly destined for closure. However, a management and mining refocus saw the operation return to profit soon after in 2014. Unfortunately, by Q3 2016, Life of Mine (LOM) was only guaranteed through end of Q4 2017 and as such a rethink of the conventional exploration strategy being employed was needed. As a result of this rethink, a "go big or go home" strategy was employed, with 3D Seismic being a major component of this strategy. 3D Seismic at this time was still, relatively in it's infancy in the Australian hardrock mining scene. Several 2D and a handful of 3D surveys (eg Urosevic et al 2012) had been attempted or were underway, with results limited mostly to promotional material in the public domain and so the application was still relatively unproven and compared to other geophysics an expensive technique. That said, reflection seismic is a high-resolution method, maintaining such, with depth unlike most geophysical methods and is well suited to resolving structural plays. Therefore, given the structural setting of Darlot, a decision to employ this emerging methodology was taken.

The Darlot-Centenary Gold Mine is located in the Yandal Greenstone Belt in the Eastern Goldfields Province of the Archean aged Yilgarn Craton, Western Australia (see Figure 1). The mine lies approximately, 900km northeast of Perth and has an estimated total production of 2.7Moz of gold since modern mining commenced in 1988 under the ownership of Forsyth NL. The Darlot-Centenary mineral system comprises the Darlot open-pit oxide resource and the Centenary underground primary ore-system. Current mining operations are focused on the Centenary complex, with underground development extending to some 850mBSL.

GEOLOGICAL SETTING

The Darlot-Centenary gold deposit is located at the southern end of the Yandal Greenstone belt in the Eastern Goldfields, Western Australia. The deposit is predominantly hosted in a layered dolerite sill (Mt Pickering Dolerite) and in the surrounding mafic and felsic volcano-sedimentary sequence. The sill is folded into a broad gently north-northwest-plunging syncline and a major sinistral shear (Eldorado Fault) offsets the western limb of the fold.

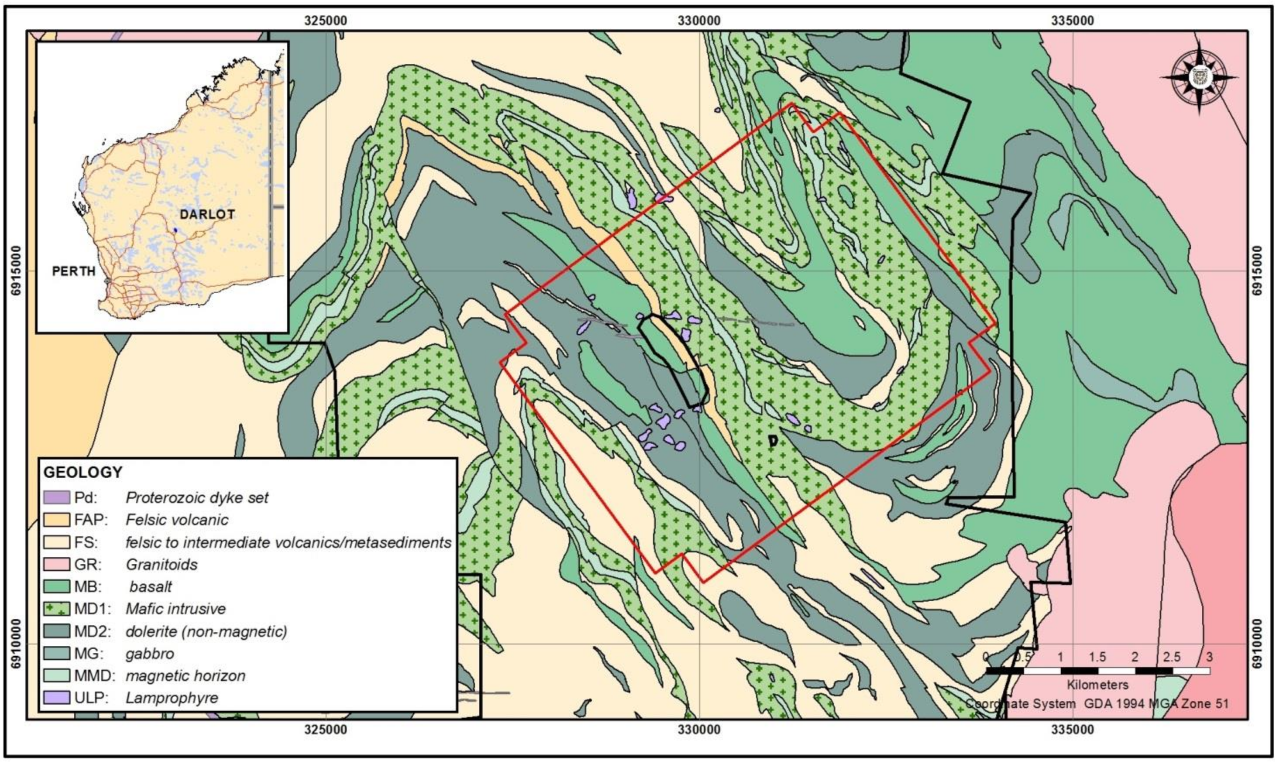

Figure 1: Location/geology map for the Darlot Gold Mine. The outline of the 3D seismic survey is shown in red. The outline of the Darlot Pit and the tenement boundaries are shown in black

Structural observations indicate that the Darlot and Centenary deposits formed during E-W to ESE-WNW compression consistent with the regional D3 event (Swager, 1997). The mineralised structures are moderately northwest- and northeast-dipping oblique-reverse faults (e.g., the Lords and Oval Faults and the Darlot Thrust). These structures likely represent second- or third-order structures adjacent to the first order Eldorado Fault, which has likely acted as conduit for the rising hydrothermal fluids. The fault system appears to form a positive 'flower' structure on the major strike-slip fault.

Gold is deposited within and around the secondary faults and in abundant narrow flat extension veins that extend off these structures. Competency contrast is important at Darlot-Centenary, with a marked increase in vein density within the magnetic-quartz dolerite horizon (MMD) near the top of the sill. This is a result of the greater silica content of this unit, making the unit more brittle than surrounding units. A similar contrast in competency is observed in the felsic intrusives (FAP) and the surrounding dolerite and basalt. Sinistral displacement along the Eldorado Fault has juxtaposed the hinge zone of the folded sill against the steeply E-dipping limb, doubling up the favourable host unit (MMD) in this area.

There is a spatial and temporal association between lamprophyre intrusions and the mineralisation. Lamprophyre intrudes prior to, during and after the gold mineralising event. Lamprophyre is predominantly located in a broad E-W trending zone that extends across the Eldorado Fault to the Oval Fault. As the lamprophyre is not offset on the Eldorado Fault, the intrusions post-date the sinistral movement on the Eldorado Fault.

SEISMIC BASICS

Reflection seismic operates by transmitting vibrational waves into the ground (Figure 2). These waves propagate until there is a change in the elastic properties (e.g. lithological boundaries, alteration zones, faults and shears). At each boundary a small portion of the energy is reflected whilst the majority of the energy is transmitted down to the next boundary where the process is repeated - and so forth. The reflected signals are measured by an array of sensors on the surface and can be used to provide a detailed image of the subsurface. In a 3D seismic survey, sensors are typically laid out at constant intervals along a series of parallel lines and energy is transmitted into the ground at constant intervals along orthogonal lines. The resulting vast number of raypaths between source and receiver combinations assists with the creation of high resolution 3D images of the subsurface. The source and receiver lines do not need to be perfectly straight and in the presence of obstacles small areas can be skipped. The effect of missing source and receiver positions is to reduce the fidelity of near surface imaging but experience indicates the 3D image heals at a depth approximately half diameter of a circular exclusion zone. Beneath this depth there are limited effects of the reduced coverage.

The key parameter that determines the strength of reflections is the acoustic impedance (AI). This is equal to the product of density and seismic velocity. Seismic velocity is broadly correlated with rock strength. Geological features are imaged both directly by reflections off specific boundaries and by interruptions to the reflections and changes in texture of the reflections.

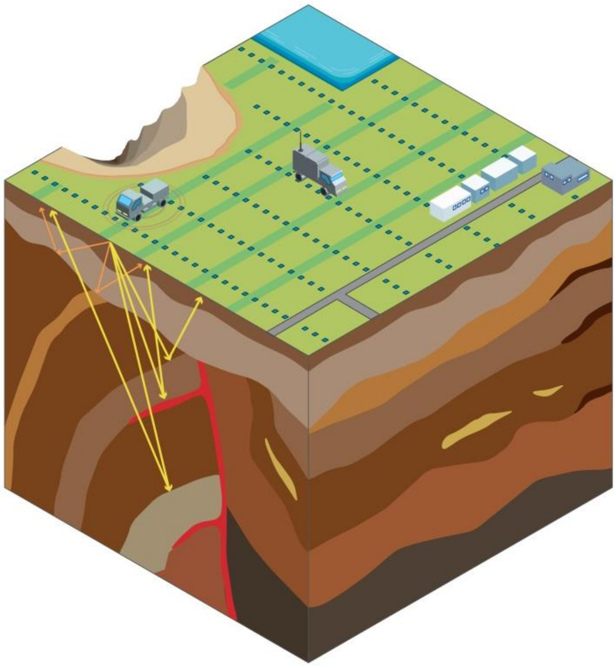

Figure 2: Diagram illustrating 3D seismic survey layout. Sensors (grey dots) are placed at constant intervals along parallel lines. Source locations are at similar constant spacings along orthogonal lines (shown here by darker green stripes)

PETROPHYSICS

In September 2013, the move towards a seismic survey was gathering momentum. Prior to a commitment being made to proceed, two phases of petrophysical sampling were completed between 14-16th September and 3rd-7th October, 2016. Measurements of seismic P-wave velocity (Vp) and density (SG) and were made on 979 samples of core from nine holes. These measurements were mostly made at approximately 5m intervals to provide a coarse log of the variations along the length of the hole. While this may sound like a lot of measurements, it is important to keep in mind that the sample covers only a relatively small portion of a complex mineral system.

The purpose of this work was to investigate if key geological elements exhibited sufficient "seismic contrast" in core, which could be extrapolated to synthetic modelling and ultimately real world measurements. The measurements broadly showed that structures together with accompanying alteration, felsics and lamprophyres had low AIs compared to the surrounding rock types and dolerites had high AIs, relative to surrounding rocks. However, clustering and/or overlap of the majority of the Acoustic Impedance populations, as evident in lithology attributed cross-plots was not as diagnostic or distinctive as hoped for given the wide range of lithologies present at Darlot. Therefore, the resulting synthetic seismogram was at best in some respects circumstantial evidence in supporting the 3D seismic approach.

SURVEY DESIGN

A common practise in the current hard rock seismic workflow is to carry out 2D "derisking" surveys prior to committing to an expensive 3D shoot and given the results of the derisk study one might conclude the logical next step in process. However, support for the "go big or go home" mantra was gaining significant traction and, given that going down the 2D route would incur a "time penalty", something Darlot couldn't really afford, the technical recommendation, to go for the 3D survey was accepted. Typical timelines to enact a 3D survey from a decision point, post the AI and Synthetic work is not uncommon to be of the order of 3 to 6 months, again a potential time penalty for Darlot. So with this in mind and a desire from upper management to proceed as aggressively as possible, funding was made available in late October for the survey. HiSeis duly supported an all hands on deck approach being embraced by the Darlot site teams, geology, mining and engineering, with the shoot kicking off on December 5th, only five weeks from formal approval! A key element in this process, apart from the pointy end of potential closure was continual site engagement meetings, held townhall style in the wet mess each week. The teams had to own this process for it be achieved and thus be given the time to impact Darlot's LOM.

And so the real work of designing the survey, permitting it, getting a crew of 25+ on site and all the associated vehicles and equipment, inducted and inspected respectively, getting earthworks done and then mobilising and shooting the survey, began!

A key design aspect of the survey was to image and ultimately generate targets within 12 months "development" of existing underground infrastructure. The development timeframe, equated to a distance of approximately 700-1000m from the current workings, laterally and in some cases vertically. To meet this requirement and to maximise bang for the buck, a high fold survey was designed, to “illuminate” a cube from 400m-1200mBSL (below surface level) over a lateral footprint of some 3.0 km x 3.5 km. The base of the current mine infrastructure was at ~900m BSL. The survey layout is shown in Figure 3 whilst Table 1, contains a listing of significant parameters and statistics from the survey.

One of the key challenges with respect to undertaking 3D seismic around an operating mine is the potential for large areas of limited to no access, creating “data voids” in the final data volume. The voids, typically extend from areas of “no-go” for the Vibes. One way to counter this is to utilise additional receiver lines or stub lines. Such lines were used extensively at Darlot, in and around the historic, Darlot open-pit as well as around tailings dams, waste dumps and within the Mill area. Additional efforts were also made to get the Vibes into as many “no go” or limited access areas as possible, including within the historic pit. This was achieved through open engagement of the respective jurisdictions at the mine. Figure 3 illustrates this point well.

Shoot Footprint	5.6 x 4.5km
Line Spacing	90m
Shoot Spacing (Crossline)	30m
Receiver Spacing (Inline)	15m
Planned Fold	90
Shots Fired	12960
Source	2 X Inova 60,000lb AH IV Vibroseis Units Operating in flip-flop sequencing array With a sweep frequency range of 8-120Hz
Sensors	10HZ Sensor SM25 Geophones
Acquisition System	Aram Aries II, 1080 channel
Start Date	December 5th, 2017
Completion Date	January 12, 2017 (25 acquisition days , straddling Christmas-New Year Period)
Final Data	March 16th, 2017

Table 1: Details of Darlot 3D seismic survey

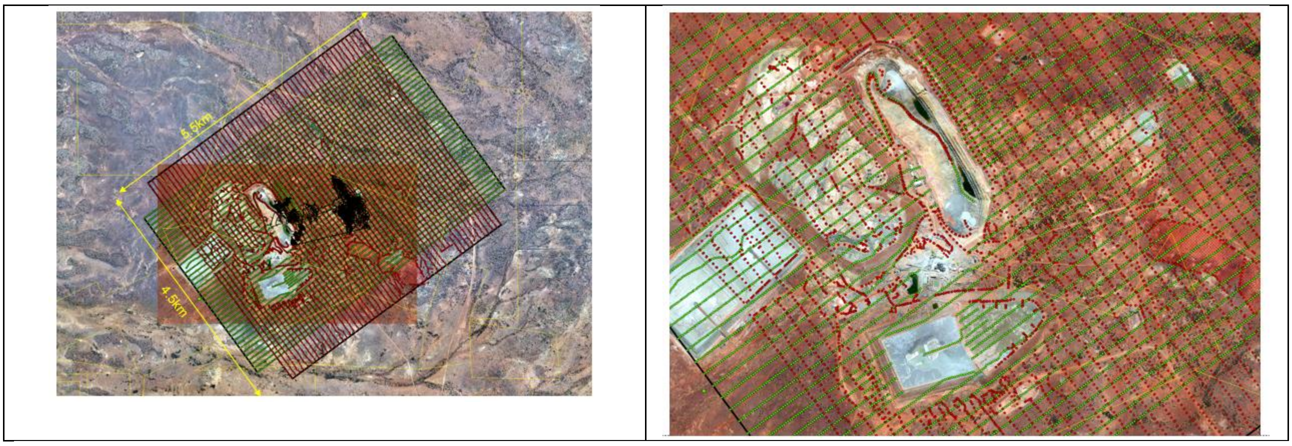

Figure 3: The image on the left shows the full 3D seismic survey layout around the mine, including actual shot and receiver points achieved. The image on the right shows how infrastructure was handled. The potential holes in coverage caused by access restrictions were reduced by the use of stub lines.

DATA

Preliminary data cubes were supplied at regular intervals during the processing sequence with the “final” PSTM (Pre-Stack time migration) cube delivered on March 16th. Data quality is excellent, being perhaps one of the best datasets seen by the authors. A 3D cut away of the data cube generated in GOCAD software is shown in Figure 4. A key element of the seismic processing workflow is depth conversion process, which in this case was based on DMO corrected velocity picks, coupled with the rock property and VSP data.

One of the challenges of 3D seismic is handling the data, particularly in terms of getting the seismic volume into the hands of the site geological team. GOCAD software was used because it handles the SEG-Y format of the seismic cube generically, however, many of the mine packages typically used by the geological teams do not handle this format natively and so workarounds have to be designed to get the data into the hands of those that will use the data on a day-to-day basis. At Darlot, the exploration and mine teams tended to work inside the Leapfrog Geo package for the exploration modelling and in order to get the data into the team’s hands, manual extraction of sections and fliches was done on site. An example of the “Leapfrog” cube is shown below (see Figure 5). Although, useful at the practical level, this process of discretisation, does lose some of the inherent power and value of the cube and so efforts must be made for the team to also work with the cube in a native environment as well as their day to day work environment. This has been achieved at Darlot through internal use and training in GOCAD with access to it being routinely utilised.

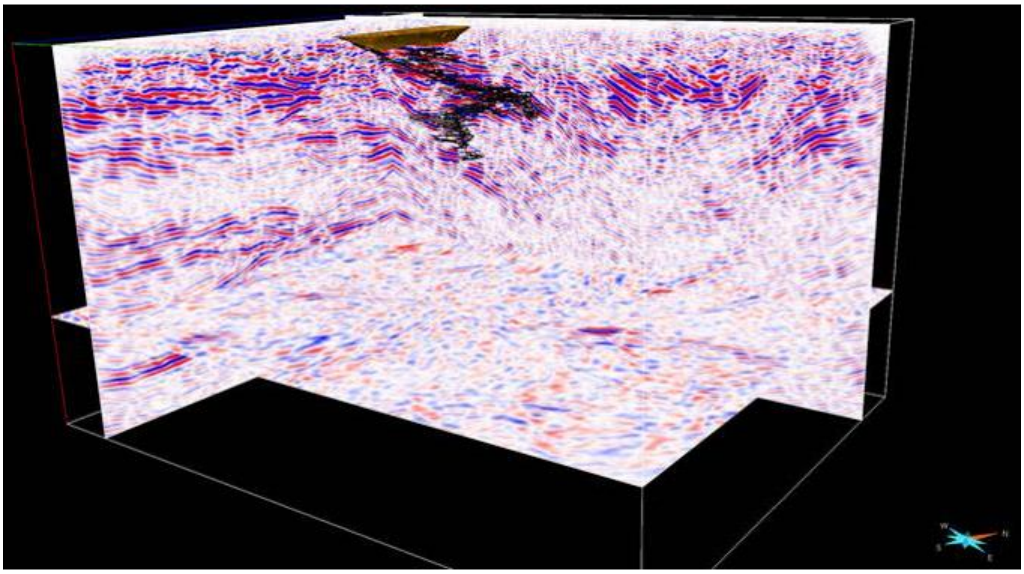

Figure 4 A 3D Gocad cut away of the 3D seismic data cube showing the location of the pit and the underground workings

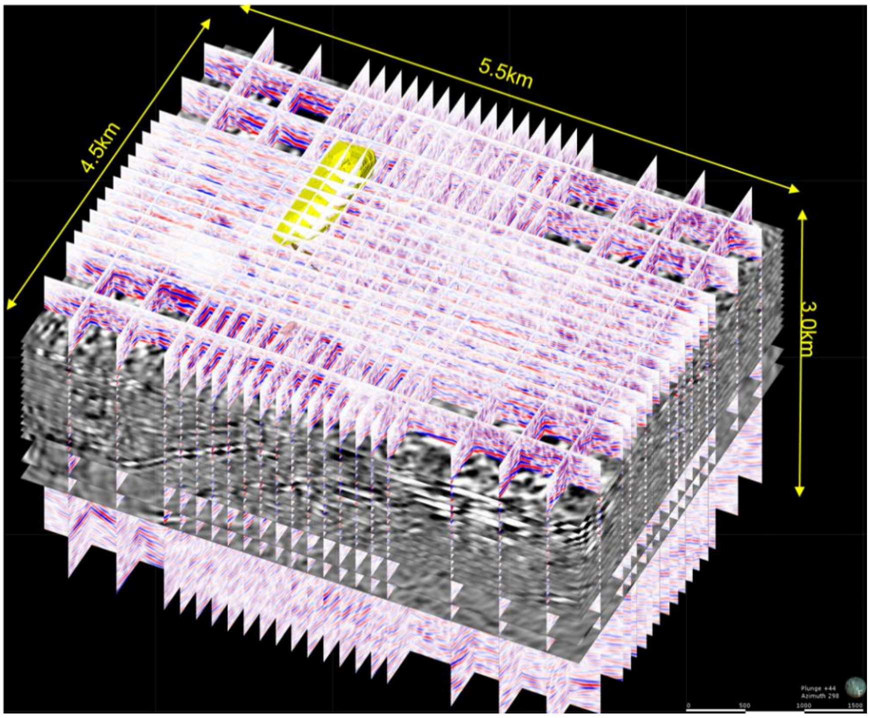

Figure 5 Plot illustrating how the 3D seismic cube was discretised in sections and fliches to allow input into Leapfrog Geo software utilised by Darlot mine and exploration teams

BOREHOLE MEASUREMENTS

Whilst measurements on core provide valuable insights into the rock properties using equipment that is easily hand carried to site, borehole measurements offer a number of advantages with respect to linking seismic data to geology. These relate to the in-situ nature of the measurements, the spacings at which measurements can be efficiently acquired and the signal frequencies used.

Borehole measurements were made at Darlot immediately following acquisition of the 3D data. Due to the short time frame for the survey and previous rehabilitation of many of the areas where drilling had been completed, only a limited number of holes were available for surveying. Of these, three holes were chosen. Two types of data were acquired in each of these holes. These were: Full Waveform Sonic (FWS) and Vertical Seismic Profile (VSP) data.

FWS

FWS is acquired by a downhole geophysical tool which transmits a sonic pulse through the borehole wall to multiple receivers in the same tool. The transit time of the signal provides information on the in-situ velocity properties of the rocks in the immediate vicinity of a drillhole. Measurements are typically made at 5cm intervals. This data allows a very detailed correlation to be made between the seismic velocity variations and geological observation made on the core (including lithology, alteration, structure, assays etc).

The P and S wave velocities measured in one of these holes (GOOD001) by the FWS together with density (SG) measurements made on core, calculated AI and lithology are shown in Figure 6. The FWS measurements were made with an ALT broadband QL40FWS probe. Key correlations that were observed are the lower AI observed in the sediments/felsic rocks (eg approximately 350m, 365m and 570m), the higher AI associated with the dolerite over the interval (approximately 490m-550m) and lower AI around the shears at approximately 115m and 230m.

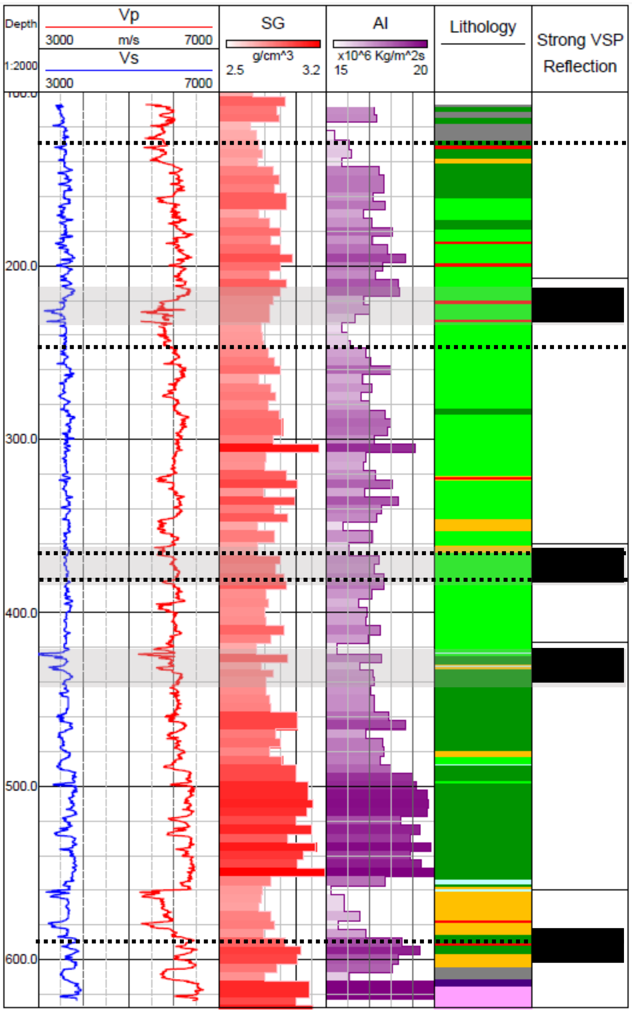

Figure 6: Seismic rock property plot for Darlot borehole GOOD001 showing the correlation between seismic rock properties (Vp, Vs, SG, AI) and lithology (highlighted by dashed lines) together with the correlation of the locations of strong VSP reflectors (highlighted by black bars and grey shading) with lithology and rock properties.

"Zero offset" VSP data is acquired by using a surface seismic source near the collar of a borehole and recording the resultant seismic signal with a borehole geophone progressively moved down that borehole. The borehole geophone measures both the signal travelling directly between the source and receiver and reflections from contacts in the ground where there is a change in AI. The VSP measurements are usually made using the same source as used for a surface survey and this source operates at a frequency that has a longer wavelength than the FWS. Consequently it responds to a larger volume of rock around the drillhole than the FWS measurements. The direct signals provide information on the bulk velocity of the rockmass which is useful for processing of the seismic data. In VSP data seismic reflectors can be traced to their intersection with the drillhole. This allows the macroscopic units (typically from a few metres to tens of metres thick) which are producing reflections to be identified. VSP surveys therefore provide a vital link between the reflectors seen in surface seismic data and the local geology.

The depths where strong seismic reflectors were seen in the VSP data in GOOD001 are shown Figure 6. The precision to which the reflectors can be determined from the VSP alone is of the order of ± 10m Strong reflectors appear to correlate with shear zones around 210m, sediment/felsic units around 360m, the contact between the basalt and dolerite units around 420m and the dolerite/sediment contact around 560m. These observations were used both to allow reflectors like these to be extrapolated away from the borehole and more informed interpretation of other reflectors seen in the data set.

GEOLOGICAL INTERPRETATION

Prior to the seismic survey, a series of cross sections were constructed through the orebody based on relogging of core photos to build up a detailed picture of the deformation associated with mineralisation at Darlot-Centenary. An aim of this exercise was to assess the current 3D fault model and to look for additional structures that may appear in the seismic study. In general, the seismic data verified the current 3D structural model built by the mine and exploration geology teams. However, a number of additional steep northwest-trending Eldorado-style shears were identified and in places appear to control the distribution of mineralised extension veins. This suggests that the early (Eldorado style) shears may play an important role in strain partitioning during the mineralising event.

The cross sections completed from the relogging study were brought into the seismic cube to aid interpretation and enabled the extension of known mineralised structures into areas with little drilling. In addition, structures with similar orientations to the known mineralised structures were observed at depth. Overall, five sets of faults were interpreted, based on both the pre-seismic structural model and the seismic data (see Figure 7). These fault sets include: steep northwest-trending Eldorado-style shears; shallow northeast-dipping Darlot-style thrust faults; moderately northwest-dipping Lords-Oval style faults; sub-vertical east-west trending faults associated with the lamprophyre intrusions; and a series of steep northeast-trending faults. The 3D seismic data was particularly useful for establishing the strike of the faults.

CONCLUSIONS

It is early days in the interpretation cycle of the data cube, which realistically will take months to complete. At this point, the respective Gold Fields teams have completed only limited work due to a decision by the Gold Fields Board during the processing sequence to sell the asset. Initial interpretation sessions by the authors, in conjunction with HiSeis and with the site team have led to much optimism about the value of the data and potential future rewards that are sure to be reaped from it.

Unfortunately, due to the sales process, both in terms of confidentiality periods and the length of the various phases of the sale process (due diligence, tenders and legal), drill testing of newly interpreted structures and /or targets has not yet taken place. Hopefully testing will commence in time to present results at the symposium for which this abstract is intended.

In terms of measuring this success against some of the initial objectives, the following points can be stated at this time:

- Rapid deployment of a 3D seismic survey is possible if an all hands on deck approach is taken and more importantly owned by the intended site.
- The seismic data has added significant confidence in validating and refining existing structural models.
- New structural elements are evident in the data cube, some of which are thought to be potential major controls of the Darlot – Centenary mineral system.
- Several targets have been "defined" that are within 6-12 months development distance of the present underground infrastructure; a key objective of the survey!

It is hoped, come presentation time, that additional hard evidence and more definitive outcomes will be available for disclosure.

ACKNOWLEDGMENTS

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REFERENCES

Swager C. P. 1997. Tectono-stratigraphy of late Archaean greenstone terranes in the southern Eastern Goldfields, Western Australia. *Precambrian Research* **83**, 11–42.

Urosevic, M., Bhat, G. and Grochau, M.H., 2012. Targeting nickel sulfide deposits from 3D seismicreflection data at Kambalda, Australia. Geophysics, 77(5), pp.WC123-WC132.

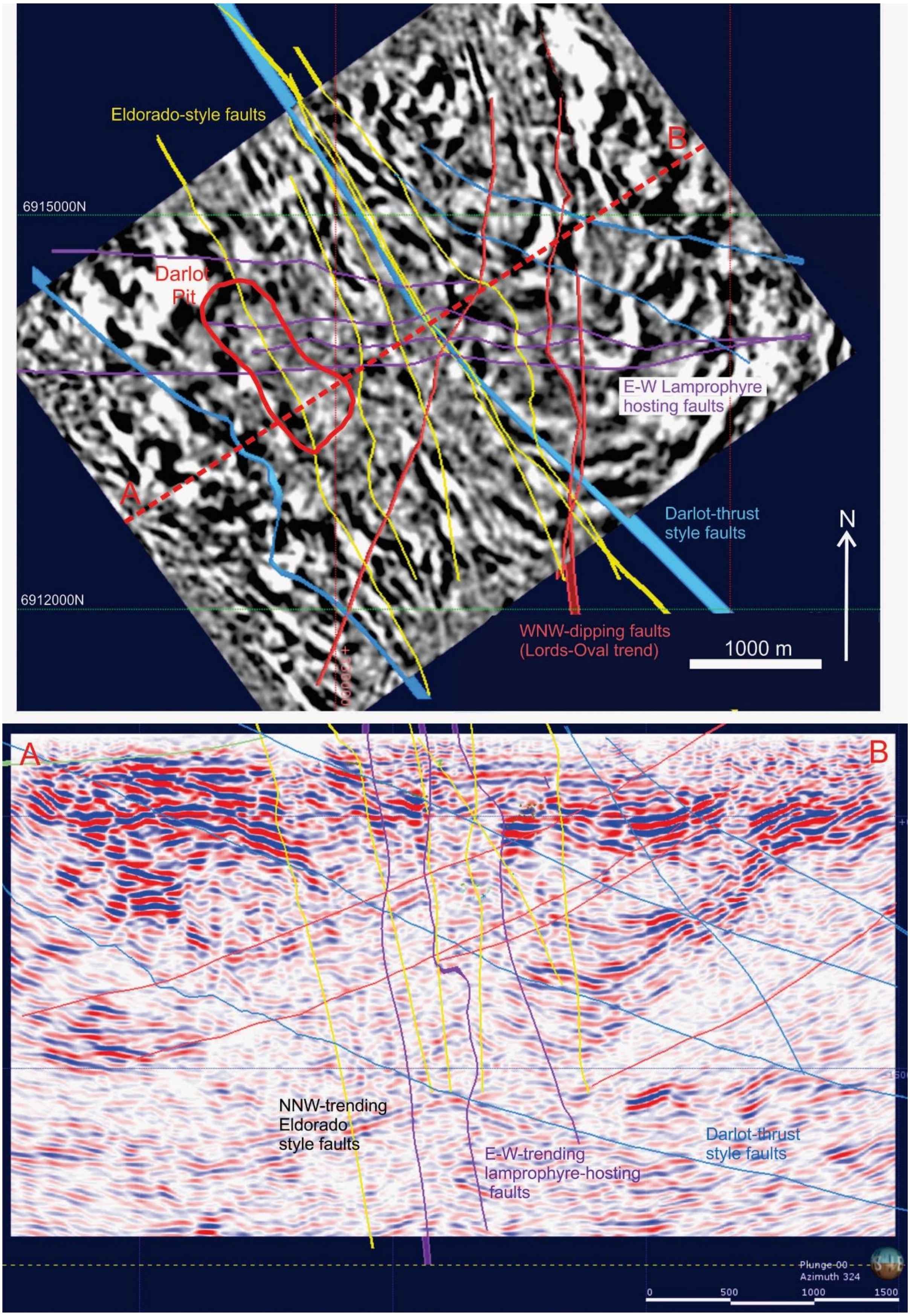

Figure 7 Structural framework overlain on a depth slice (top) and a vertical section (bottom) through the 3D seismic cube