Olympic Dam seismic revisited: reprocessing of deep crustal seismic data using partially preserved amplitude processing

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SUMMARY

Two deep crustal seismic profiles, centred on the Olympic Dam Cu-Au-U deposit, were reprocessed by HiSeis Pty Ltd. using a proprietary method. This processing method aimed to enhance subtle variations in signal strength and highlight upper crustal discontinuities. The resulting images enable interpretation of steep structures and regions of enhanced/reduced reflectivity possibly associated with large-scale alteration zones. This work highlights additional information within these deep crustal seismic lines that illuminate different aspects of the geology.

Key words: Seismic, Olympic Dam, IOCG, Alteration, Conductivity

INTRODUCTION

Deep seismic reflection data is collected around the world in order to image the structure of the crust. Two dimensional seismic data can be processed in a variety of ways, each technique permitting investigation of different aspects of the data and thus of the geology the line is transecting. A focus of deep crustal seismic surveys has been to investigate the nature of the lower crust, the geometry across the Moho, or the geometry of paleosuture zones between crustal blocks (Hammer et al., 2010; Kennett et al., 2013). The processing methods that are applied in order to image the Moho at depths of 30 to 50km, can be adjusted to enhance the reflectivity features in the upper crust. For example, the application of a low pass filter emphasizes continuity between individual seismic traces, which enhances consistency between individual traces to produce a 'smooth' image.

An alternative method to extract more detail on the upper crust is to apply a processing method known as Partially Preserved Amplitude (PPA) processing, a proprietary method of HiSeis Pty Ltd. (Jakica and Pridmore, 2014). This processing technique emphasizes variations in signal strength by preserving the temporal relative amplitude ratio, which has the effect of sharpening the output image. This resulting image is more sensitive to fabric within a rock, particularly in the upper crust but also in the presence of discontinuities.

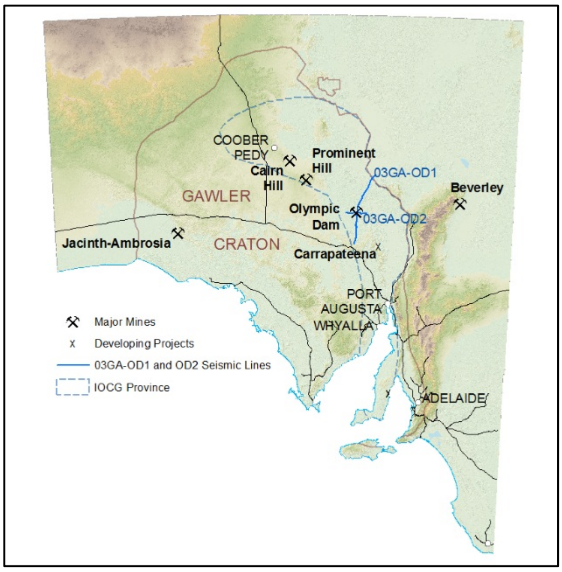

Figure 1; Location map of seismic lines 03GA-OD1 and 03GA-OD2

In this paper we provide new observations on the upper and middle crust around the Olympic Dam Cu-Au-U deposit, South Australia, from seismic data re-processed using the PPA technique. Olympic Dam is the type example of hematite breccia iron oxide-Cu-Au (IOCG) style deposits (Williams, Barton, Fontboté et al., 2005; Skirrow, 2009) and lies buried ~400m beneath sedimentary cover of the Stuart Shelf. A major challenge to exploration in much of the Olympic Cu-Au Province is thick sedimentary cover that results in a reliance on geophysical data and limited drillholes to obtain an understanding of the geology. In

2003, two orthogonal deep crustal seismic lines were acquired by Geoscience Australia, centered on the Olympic Dam deposit (03GA-OD1 and 03GA-OD2; Figure. 1; Goleby et al. 2003). Seismic images with original Geoscience Australia processing were downloaded from the Geoscience Australia website (http://www.ga.gov.au/metadata-gateway/metadata/record/gcat_74869). We discuss some of the geological features that appear to be enhanced using PPA processing and suggest that seismic data may be directly imaging the hematite alteration associated with the Olympic Dam deposit.

Seismic data acquisition and processing

The seismic reflection data was collected in 2003 along two broadly orthogonal lines totalling ~250km (Jones et al, 2005). The longer of the two lines known as 03GA-OD1 was 193 km long and oriented approximately north–south, broadly orthogonal to the regional strike. The shorter line, 03GA-OD2 was 57 km long and oriented approximately east–west, thus providing a three-dimensional image of the Olympic Dam region (Figure. 1). The lines were recorded to 18 s two way time, equivalent to ~55 km depth at a sample rate of 2 ms using three in-line 60,000 lb vibrators (IVI HEMI60) as the energy source. Vibration points were 80 m apart and three upsweeps of 12 s-duration, with a frequency sweep of 7 to 56 Hz, 12 to 80 Hz and 8 to 72 Hz at each vibration point. Receiver groups were spaced at 40 m intervals with 12 geophones being spaced at 3.33 m apart. The data were correlated in SEG-Y format (Jones et al, 2005).

The original processing of surveys 03GA-OD1 and 03GA-OD2 was conducted by Geoscience Australia using the Disco software package. The processing workflow was designed to image the entire crust while avoiding down grading the data in the near surface (Jones et al, 2005). The processing work flow summarised in Table 1 consists of crooked line processing, refraction statics corrections, velocity analysis, spectral equalisation, sort to common mid-point gathers, dip moveout corrections, stack, post-stack migration, bandpass filtering and post-stack signal enchantment (digistack).

HiSeis Pty Ltd reprocessed approximately 160 km of surveys 03GA-OD1 and 03GA-OD2 with the aim to enhance structural and stratigraphic features in the top 5 km as well as attempting to image alteration related to IOCG mineralisation (Jakica and Pridmore, 2014) whilst preserving the amplitude integrity. The processing work flow used by HiSeis is summarised in Table 1. Attention was paid to attenuating strong noise trains (such as vehicles travelling along the seismic line whilst data was being acquired) during the pre-processing phase to better image shallow features (Jakica and Pridmore, 2014). The main difference to the Geoscience Australia processing work flow (Jones et al, 2005) is that HiSeis used partially preserved amplitude processing and in deeper areas a low-pass filter, and did not use 3 trace running mix nor digistack.

Initially, Constant Velocity Stacks (CVS) were used to obtain a velocity function for input into the residual static calculation and dip-moveout (DMO). The final Interactive Velocity Analysis (IVA) was carried out on DMO-corrected gathers in order to reduce velocities of dipping reflectors and obtain the velocity model that was used for migration. Quality control stacks were created and used as the basis on which to judge improvement of the data after subsequent processing steps. The application of DMO correction, or partial pre-stack migration, removes any dipping component to seismic events in common depth point (CDP) gathers, and solves conflicting dips at consecutive CDP positions. The edges of faults are more clearly defined and the resolution of events is increased. The application of DMO also facilitates the use of a post-stack migration algorithm as the final processing step of the data. A post-stack phase-shift migration was applied to migrate the seismic events to their true geological position. This typically results in dipping events steepening and moving up-dip. The algorithm migrates data, regardless of where the energy was reflected from in 3D space and therefore geological features out of the 2D plane will appear within the 2D plane.

Observations and discussion on the reprocessed data

While broadly similar features can be observed with both processing techniques (Figure 2), the PPA technique enables several distinct features to be detected. Three features of particular interest in the PPA processed data near the Olympic Dam deposit are described herein.

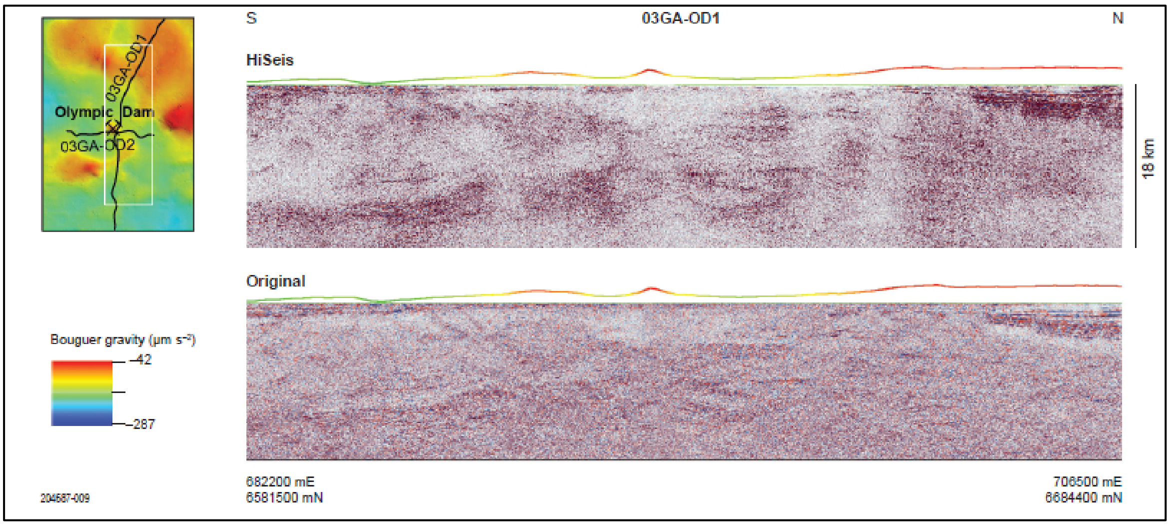

Figure 2; North-south line 03GA-OD1: HiSeis partially preserved amplitude processing (top) and Geoscience Australia original processing (bottom).

Detection of Fe-oxide alteration associated with Olympic Dam deposit within the Burgoyne Batholith

The Burgoyne Batholith, a large Hiltaba Suite granite in which the Olympic Dam deposit is hosted, has previously been identified by potential field data and drillhole intersections. It is broadly imaged as a non-reflective zone within both 03GA-OD01 and 03GA-OD02 allowing interpretation of its extent both laterally and vertically. Of particular interest, is a zone with numerous stronger reflectors within this generally non-reflective body (Figure 3). On the north-south line (03GA-OD1), the reflective zone narrows at depth and is made up of sub-horizontal reflectors typically several hundred meters long at depths ranging from ~400m to ~4000m (between 683000mE 6628500mN and 684300 mE 6631450 mN) with a width of approximately 3000 m (Figure 3a, c and d) and corresponds to the known location of the Olympic Dam orebody. These reflectors are bound by narrow, semi-continuous, sub-vertical and non-reflective features. This more reflective zone correlates with a high gravity (and elevated magnetic) response (Figure 3f). Taken together, the seismic and potential field data suggest that these seismic features are likely imaging the Fe-oxide alteration of the Hiltaba Suite granite, associated with the Olympic Dam deposit. This observation is consistent with rock property studies and synthetic seismic modelling of the Olympic Dam Breccia Complex (Jakica and Pridmore, 2014), which demonstrated that the contact between Fe-oxide alteration and silica-rich lithologies should be reflective, and hence can be imaged with reflection seismic techniques.

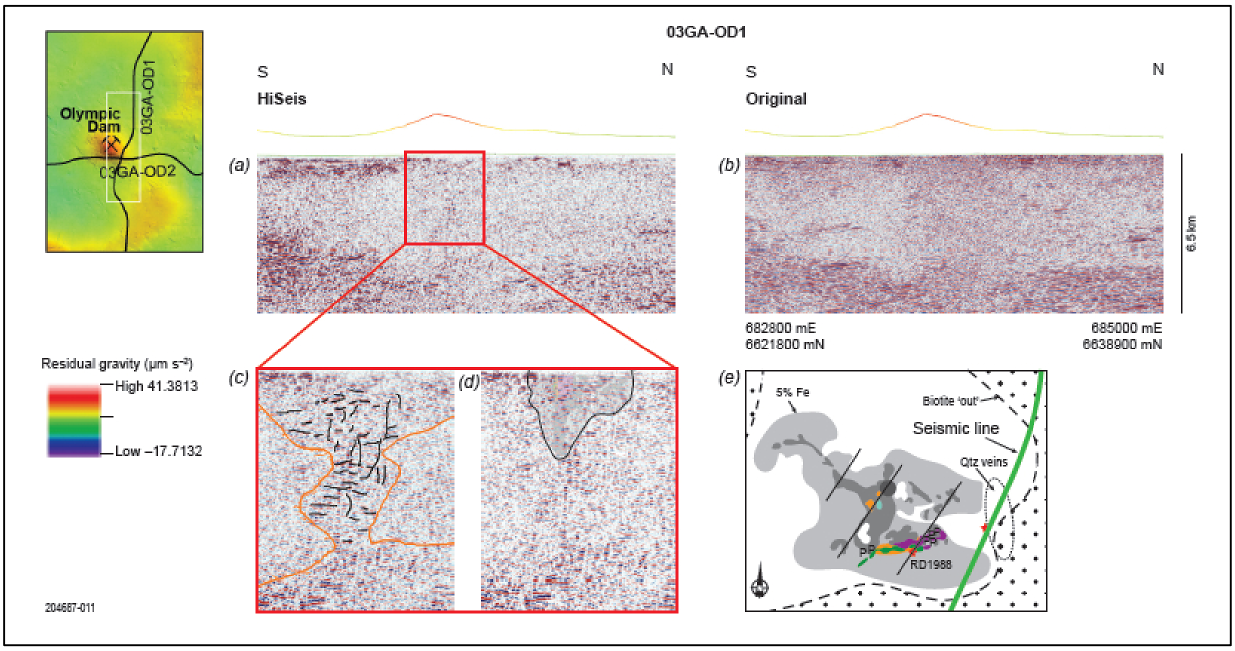

Figure 3; North–south line 03GA-OD1. (a) HiSeis partially preserved amplitude processing displaying the zone of high reflectivity (red box) within the non-reflective zone of Hiltaba Suite granite. (b) Geoscience Australia original processing. (c) Enlarged section of HiSeis processed line showing increased reflectivity and possible vertical fractures (examples highlighted in black). Unmodified low reflectivity zones shown in orange. (d) Enlarged section of HiSeis processed line superimposed over Ehrig et al (2012) breccia complex cross-section. This shows a correlation between the known distribution of >5% total Fe in Hiltaba Suite granite and the zone of high reflectivity made up of subhorizontal reflectors typically several hundred metres long (~300 m wide at ~400–4000 m depth). (e) Ehrig, McPhie and Kamenetsky (2012) plan view of the Olympic Dam breccia complex. The cross-section displayed in (d) is positioned ~3 km east, and is subparallel to the seismic line.

An approximate section through Olympic Dam can be projected onto line 03GA-OD1 (N-S line; Figure 4d and e). This shows an approximate correlation between the known distribution of >5% total Fe in Hiltaba granite from Ehrig et al, (2012) and the more reflective zone. This suggests that the seismic data can directly map the extent of Fe alteration and may be a potential exploration tool for this style of deposit in deeply covered terrains.

Similar seismic features appears on the E-W line (03GA-OD2) at depths from ~900 m to ~2500 m (Figure 4b), which is slightly deeper than on the N-S line. This apparent difference in depth may be a result of out-of-plane effects, imaging reflectors not directly beneath the line. In such a situation, the reflectors coming from the dense body take longer to return to the receivers, and hence appear deeper in a 2-D section. The displacement of the seismic feature is consistent with the reflectors being derived from the dense Fe-alteration related to the Olympic Dam system.

Using the conventional Automatic Gain Control (AGC) processing, these amplitude differences between seismic events are normalised and hence the change in reflectivity is more difficult to detect. PPA processing preserves the amplitude differences of the reflections to the extent the data quality permits, and better represents the amplitude variation related to contacts of different lithologies and textures. Using PPA processing, a zone with distinct reflectors is imaged underneath the Olympic Dam deposit and is interpreted to reflect different lithologies of the deposit, with narrow, sub-vertical non-reflective features potentially mapping the location of faults through the system (Figure 3c). A series of short but distinct reflectors extends from the base of the projected section of known Fe-alteration at Olympic Dam (Figure 3d) and may represent the extension of Fe-alteration within narrow structures at depth.

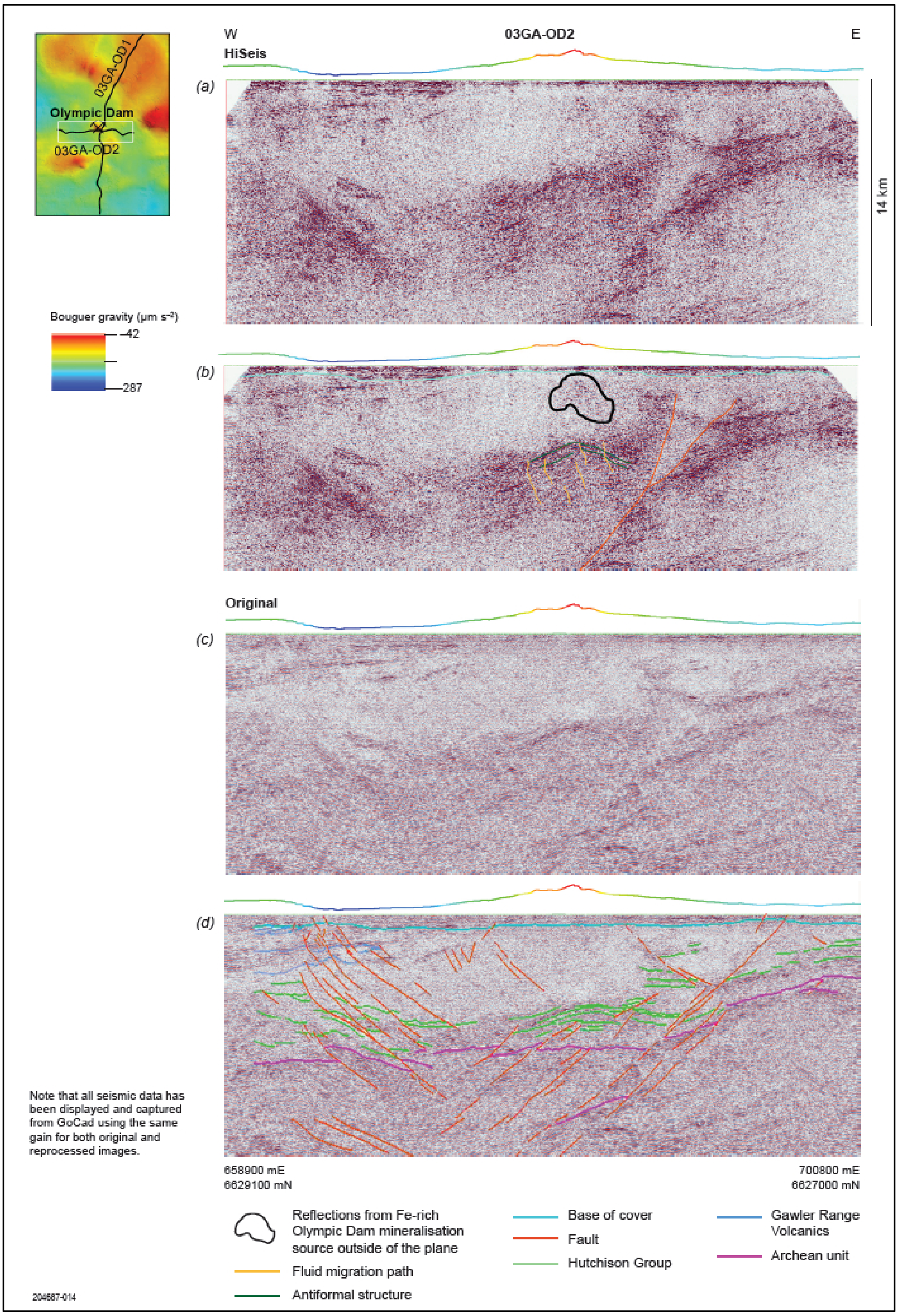

Figure 4; Central section of east–west line 03GA-OD2 displaying differing geometries of folding and faulting. HiSeis partially preserved amplitude processing: (a) un-interpreted seismic data; (b) partially interpreted seismic section (note that only interpretations in the middle part of the section are shown in this figure). Geoscience Australia original processing: (c) un-interpreted seismic data; (d) original Geoscience Australia interpretations (Drummond et al. 2006).

Steep faults within the upper crust

The processing sequence used by HiSeis enables imaging of steeper structures than that used by Jones et al (2005). One of the dominant features of the E-W profile in both the PPA and original GA processed lines is a highly reflective zone beneath the interpreted Hiltaba Suite granite (Figure 4). Using both methods, this zone appears to be disrupted by major west dipping faults. However, using the PPA reprocessed image, the lateral continuity of reflectors appears to stop against a zone of low reflectivity that forms an apparent wedge shape, the edges of which are orientated at ~70° and ~45° (Figure 4). The original interpretation emphasised the lower bound of this zone and hence the area was considered to represent a low angle, west-dipping fault (Figure 4). In the reprocessed data, the eastern boundary of this low amplitude zone is much steeper, and could be interpreted as a wedge of rock between two faults.

Whilst one example is highlighted in this paper, a thorough interpretation of these re-processed lines is warranted as it may have significant implications for the structural architecture and style in the region. A possible inference that could be drawn from the identification of more steep structures in this region is that deformation in the Olympic Dam region may not have developed as a purely fold-thrust regime as proposed by Drummond et al. (2006).

Regional sub-vertical zones of low seismic reflectivity

One of the features evident in the seismic data is a mid-upper crustal zone of high reflectivity at 10km depth which is particularly prominent in the N-S line. In the original processed image, the top of this mid-crustal layer is well defined and appears to shallow to the north-east. Drummond et al. (2006) described this zone as being dominated by laterally continuous sub-horizontal reflectors, between which lateral reflections of limited extent vary from sub-horizontal to north-dipping. These reflectors were interpreted from the original imagery as being faults associated with apparent roll over structures (Drummond et al. 2006)

In the reprocessed image this reflective zone, while still evident, does not show the same evidence for dipping reflectors. Rather, disruption to the lateral continuity is evident as a series of broadly sub-vertical zones of lower reflectivity with widths up to ~5 to 10km (Figure 5). These apparent sub-vertical zones appear throughout the N-S line and are shown on Figure 5. Four of these zones correspond to the approximate position of known IOCG deposits or prospects (A- Wirrda Well; B-Olympic Dam; C-Vulcan; D-Titan). Such zones of reduced reflectivity are potentially caused by pervasive textural destruction of large regions of the crust. Textural destruction on this scale may be caused by geological processes such as fluid migration either in the form of partial melt migration, or via pervasive hydrothermal alteration. Melt movement through sub-vertical vein networks (e.g. Brown, 1994; Diener et al, 2014) could readily explain the lack of laterally continuous reflectors observed in these regions of the crust. Large scale granitic plutonism is observed above, or proximal to, these broad zones of reduced reflectivity, e.g. Burgoyne Batholith, which is consistent with this notion. Hydrothermal alteration, as suggested above, may link these features to the broad zones of enhanced electrical conductance observed in regional magnetotelluric data in the vicinity of Olympic Dam (Heinson et al, 2006; Thiel and Heinson, 2015).

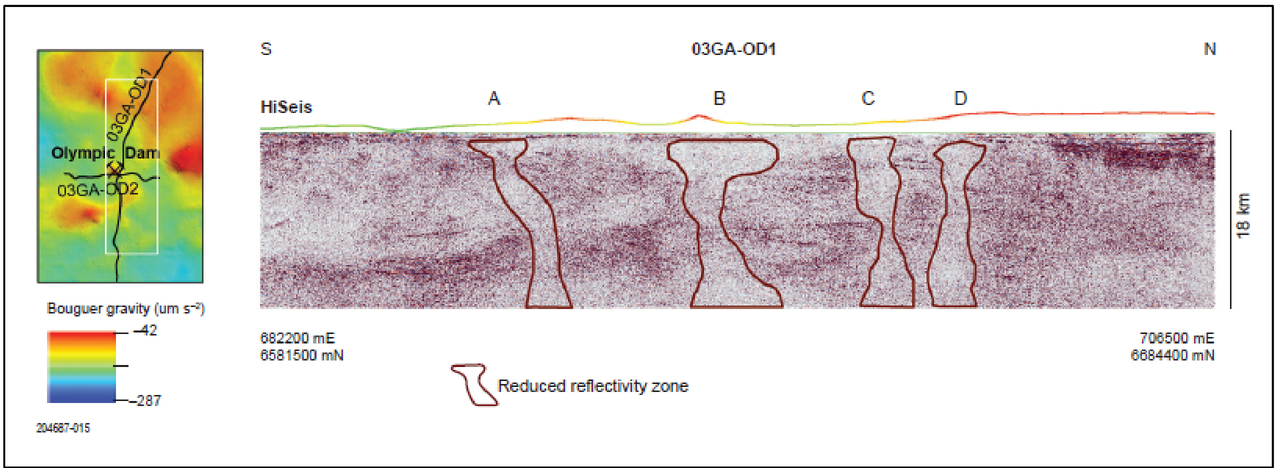

Figure 5; HiSeis partially preserved amplitude processing imaging subvertical zones of reduced reflectivity on north-south line 03GA-OD1. A – Wirrda Well; B – Olympic Dam; C – Titan (15 km NNW of section); D – Vulcan.

CONCLUSIONS

To obtain a crustal-scale image of reflection seismic data, certain processing techniques are favoured. This necessarily limits the degree to which certain upper crustal features can be imaged/and or enhanced. However, there is a range of processing techniques available and each can emphasize different aspects of the data. The Partially Preserved Amplitude processing (PPA) technique is interpreted to have detected features that relate to Fe-alteration around the Olympic Dam orebody and has revealed steeper structures than were imaged with previous processing techniques. Several kilometre-scale, sub-vertical 'bland' zones that extend from at least the mid-upper crust to the near-surface in the vicinity of several known IOCG deposits have been identified and these correlate to conductive features in magnetotelluric modelling. Such features may relate to partial melt migration or pervasive hydrothermal alteration.

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Geoscience Australia	HiSeis P/L
Line geometry and crooked line definition (fixed common depth-point interval)	SEG-Y input
Field SEG-Y to Disco format: resample to 4 m/s and 8 s	Geometry assignment and quality control – bin size 20 m
Quality control display. Selected trace edits and 50 Hz notch	First break picking and refraction static computation: final datum at 120 m; replacement velocity 4500 m/s
Spectral equalisation (with 1000 m/s gate automatic gain control)	Quality control of the refraction static solution (on shot records, every 20th shot)
Common mid-point sort (bin wide open)	Surface consistent amplitude recovery
Gain recovery (spherical divergence)	Spherical divergence correction: time-power 1.2
Application of refraction statics, datum 0 m (AHD)	Application surface consistent spiking deconvolution – operator length 80 m
Application of automatic residual statics (autostatics calculated on 0.25–4.0 s gate)	Surface wave noise attenuation (apparent velocity of 2200 m/s)
Band filtered	Air-blast attenuation
Time (s) — Bandpass (Hz)/slope (db/octave) 0.0–1.5 — 20/36 – 80/36 2.0–8.0 — 10/36 – 80/36	Bandpass filter (Ormsby, 5–12–80–100 Hz)
Velocity analysis using VELEX. First pass after refraction statics. Second pass after autostatics. Third pass after dip moveout (DMO)	Automatic gain control based trace normalisation 3000 m/s
Normal moveout correction on common offset gathers	Noise attenuation
Stretch mute used as front end mute	Constant velocity stack analysis
DMO correction on common offset gathers	Time gate picked for residual static calculation
Common mid-point stack	Computation of surface consistent residual reflection statics (delay time based) normal moveout and application of residual statics
Trace amplitude balance	Application of top/bottom mute
F-X migration using 90% of modified velocities	Application of T-X DMO
3 trace running mix (weights 1:1:0)	Interactive velocity analysis on DMO-corrected data
Signal enhancements (digistack 0.8)	Final stack (DMO)
Trace amplitude scaling	Post-stack phase-shift time migration
	Post-stack F-X deconvolution, TV bandpass filter and trace mix (3/2)
	Generation of seismic attributes – perigram x cosine phase
	Time/depth conversion using average velocities
	SEG-Y files to specification

Table 1; Processing work flows used by Geoscience Australia and HiSeis