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Seismic velocity (Vp) vs alteration mineralogy in the Olympic Dam IOCG deposit

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SUMMARY

In support of a deep drilling program to define the lower extents of Fe-oxide alteration and potential sulfide mineralisation, BHP undertook a feasibility study to determine the viability of conducting Sparse and Full 3D hardrock seismic surveys of the Olympic Dam deposit. P-wave velocity measurements were systematically collected, via hand held instruments, on diamond drill core spanning the spectrum of alteration and brecciation styles present across the breccia complex and into the granite host rock. The purpose of this data was to provide measured seismic velocities into the feasibility modelling and subsequent processing and interpretation of the seismic surveys.

Prior to data collection several questions were posed to focus the data collection. These questions included 1) what are the velocity (Vp) values of the various alteration and brecciation styles present in the deposit, 2) can Vp be used to directly detect sulfide mineralisation, and 3) are the Vp contrasts across faults great enough to detect the faults? The results of the velocity measurement study, correlated with bulk dry density, magnetic susceptibility, Fe-oxide alteration intensity and sulfide mineralisation clearly demonstrate that 1) disseminated sulfide mineralisation is likely not detectable via Vp measurements, 2) hematite breccias when in fault contact with granite and granite-breccias have enough of a Vp contrast to be detected in seismic surveys, 3) porosity varies significantly within the breccias and does influence Vp, and 4) Vp contrasts in the granites surrounding the deposit are too low to be used for vectoring to Fe-oxide alteration.

Geochemical and mineralogical data combined with geological observations provides a powerful dataset when unravelling the characteristics of complex ore deposits. One of the major insights from this study, is that when petrophysical data (such as Vp, magnetic susceptibility, and bulk dry density) are also used, the multitude of possible geological interpretations can be significantly reduced.

Key words: Vp, acoustic impedance, bulk dry density, magnetic susceptibility, Olympic Dam, IOCG

INTRODUCTION

Potential field methods (i.e. gravity and magnetics) were instrumental in identifying and ranking drilling targets which culminated in the discovery of one of the World's largest metalliferous deposits, Olympic Dam, in 1975 with the completion of the first drill hole RD1 (Rutter and Esdale, 1985; Reeve, 1990; Haynes, 2006). Even though numerous prospects and mineable deposits in the region surrounding Olympic Dam have been discovered, new discoveries are significantly hampered by the ever increasing depth of unmineralized, unrelated cover sequences effectively dampening the geophysical signatures of these deposits.

Olympic Dam (OD) is a breccia hosted iron-oxide Cu-Au-Ag-U deposit (IOCG). Two very important characteristics of IOCG deposits on the eastern margin of the Gawler Craton in South Australia are 1) Fe-oxides (hematite and magnetite) are the most abundant mineral and 2) sulfide mineralisation is disseminated. Direct detection of Fe-oxides, at the deposit scale, due to the relatively high density as compared to the other relatively low density non-hematite minerals is possible. Magnetic signatures can be a bit more complicated because of the variable alteration of magnetite to hematite and the presence of magnetite-bearing mafic intrusions, dykes and lavas. The detection of disseminated sulfides via various electrical methods is negatively impacted by the deep of cover units and saline/hypersaline ground water. Seismic methods applied to hardrock environments is in its infancy, yet are being undertaken more frequently.

This extended abstract is one of three papers which discuss various aspects of conducting 3D Seismic Surveys at Olympic Dam (see also Schijns et al. and Townsend et al. in this volume). P-wave velocity measurements on diamond drill core samples, supported by bulk dry density, magnetic susceptibility and geochemical data will be used to address the following questions: 1) the significant of the relationship between increasing Fe-oxide alteration and bulk dry density, 2) can ore-grade concentrations of disseminated Cu(Fe)-sulfides be directly detected via Vp measurements in the Olympic Dam IOCG deposit, 3) are the reflectivity coefficients high enough to resolve hematite-rich breccias in fault contact with altered, weakly brecciated granites, 4) how does the variable rock porosity created (then destroyed) during brecciation and subsequent alteration impact on Vp measurements, 5) how does Vp change in the damage zones associated with faults, and 6) are there any velocity differences due to increasing muscovite alteration of the host granites, when progressing from the unaltered granites surrounding the deposit towards intense hematite alteration and mineralisation?

OLYMPIC DAM GEOLOGY AND MINERALOGY – SUMMARY

OD Breccia Complex hosts disseminated copper sulfide mineralisation and occurs within the Roxby Downs Granite (RDG). The deposit is concealed beneath ~350m of undeformed/unaltered flat lying, sedimentary rocks which are post-brecciation and post -mineralisation (Reeve et al., 1990; Ehrig et al., 2012). The breccia complex has an areal extent of ~50 km^2, while sulfide mineralisation (~>0.3% Cu) occurs within a volume of approximately 6x3x0.8km (Figure 1 and Figure 2). However, in some areas of the deposit, mineralisation extends to >2km depth. The transition from unaltered RDG (K-feldspar, quartz, plagioclase, <10% biotite, amphibole, magnetite and accessory minerals) to the edge of the breccia complex is gradational and typified by weak albite and potassic and muscovite alteration of the magmatic minerals. Weak brecciation and iron oxide alteration commences at the outer edge of the breccia complex and increases in intensity towards the deposit centre (sulfide barren core with hematite, quartz, barite, with no aluminosilicates). Abrupt changes in brecciation and/or alteration intensity are usually related to the presence of sub-vertical faults. Bedded clastic facies (BCF; McPhie et al. 2016) also occur within the shallower parts of the breccia complex. Distinct contacts within the BCF and with the breccias do occur, but can also be faulted.

Disseminated sulfide (pyrite, chalcopyrite, bornite, chalcocite) mineralisation occurs in breccias composed of variable mixtures of hematite (±magnetite), quartz, sericite, K-feldspar, fluorite, siderite, barite. Vein style mineralisation is rare. The bulk dry density in the RDG ~ 2.65 g/cm^3, but varies within the breccias and BCF from 2.7 - > 4.5, and can be expressed as a function of hematite abundance.

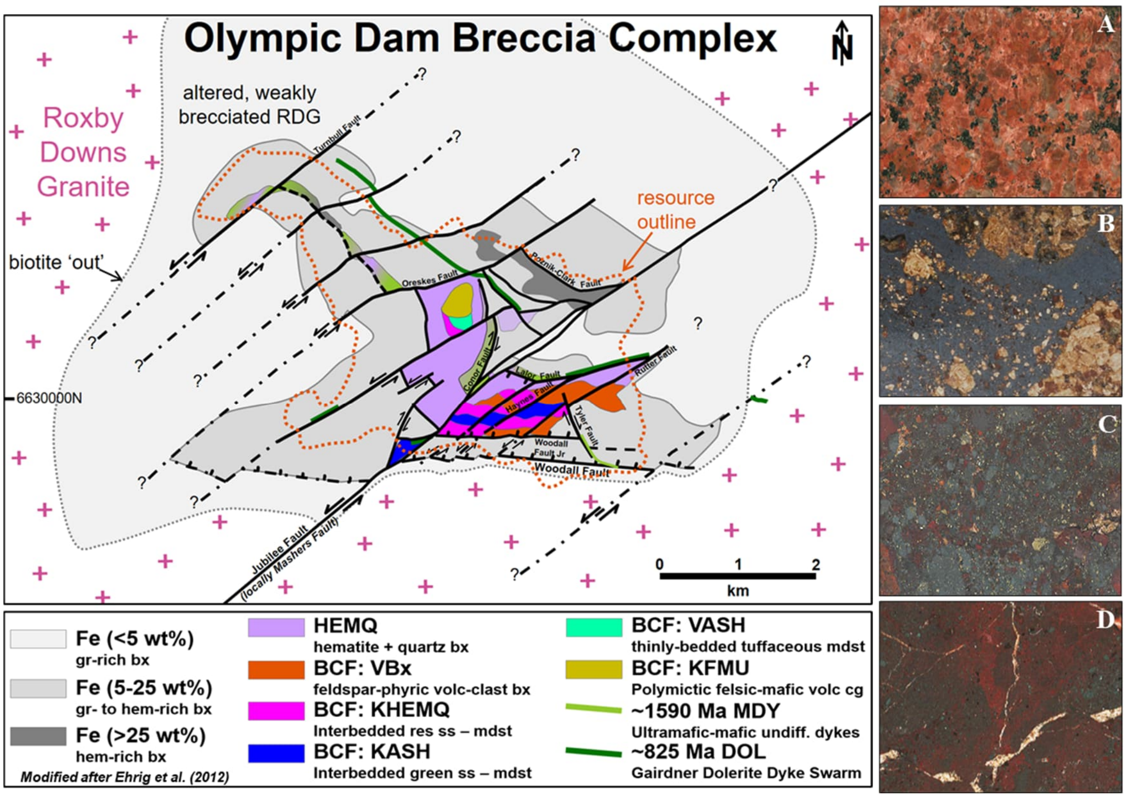


Figure 1. Geological plan (-350mRL) of the Olympic Dam Breccia Complex. Drill core images A-D are examples of progressive Fe-oxide alteration and brecciation the Roxby Downs Granite through granite- to granite-hematite- to hematite-rich breccias ending in barren hematite quartz breccias (HEMQ) located in the shallow, central area of the breccia complex. The deposit also contains various bedded clastic facies (BCF) and is intruded by multiple generations of mafic and ultramafic dykes. The resource outline is indicated by the orange dotted line.

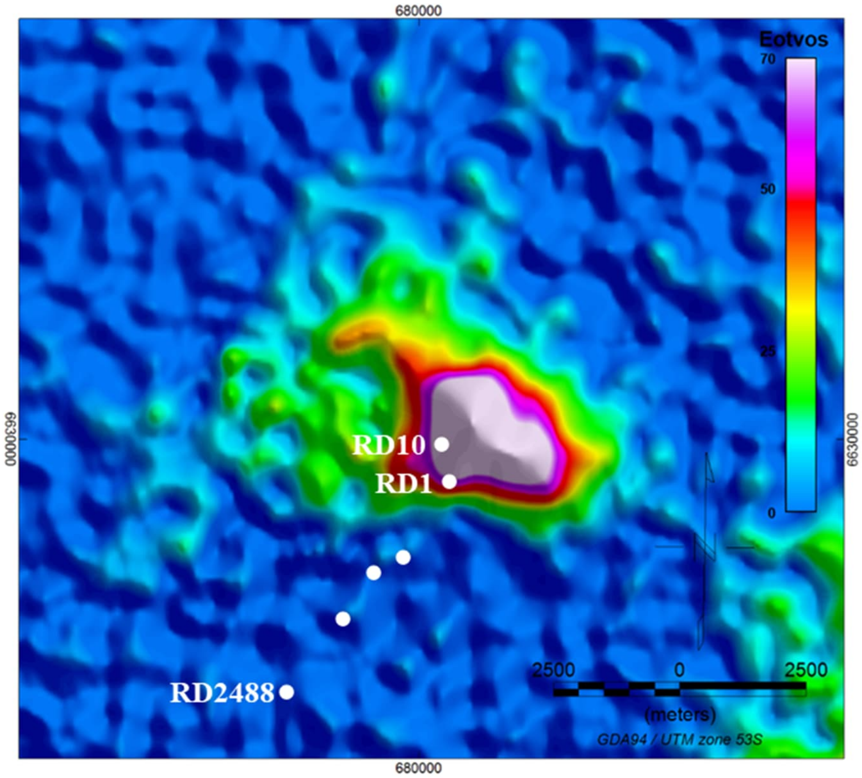


Figure 2: Fourier derived vertical gravity gradient image of the Olympic Dam Breccia Complex and surrounding Roxby Downs Granite. The most striking feature in the gravity gradient image is similarity of the shape (greens to pink the resource outline in Figure 1. Refer to Figure 8 for a discussion about drill hole RD2488 and the 3 other unlabelled white circles.

PETROPHYSICAL and GEOCHEMICAL DATA

The primary purpose of the 3D seismic surveys at Olympic Dam is to access the potential to indirectly detect the presence of Cu(±Fe) mineralisation on the edges of the deposit and at >~1500 metres depth within the deposit. Here we use Vp and magnetic susceptibility data collected as single point measurements per meter on ~42,000m of diamond drill core (HQ3, NQ2, BQTK diameters) via a ACS UK1401 Surfer hand-held ultrasonic tester and a Terraplus KT-10 Magnetic Susceptibility meter, respectively. Bulk dry density measurements (using the Archimedes Principle via collecting the weights in air and water on 5-7kg unwaxed samples) are conducted on every drill core sample (1, 2, 2.5, 4, 5m lengths depending largely on core diameter and whether mineralised or barren of sulfide minerals) to be assayed (~17,050 samples for this study). The 1m Vp and magnetic susceptibility data are composited to match the associated assay interval. Assaying for 33 elements was completed on the drill core samples using 5 different analytical methods suitable for each element and typical concentration range (Ehrig et al., 2012).

RESULTS

The results will be presented via addressing the six questions posed at the end of the Introduction.

Fe-oxide alteration and bulk dry density

At the deposit scale, breccia textures do vary systematically (Reeve et al. 1990). However, at the geological logging and mapping scale, breccia type changes vary considerably and are gradational, not sharp, hence making it very difficult to log and map the deposit based on breccia textures. In contrast, the mineralogy (and geochemistry) does vary systematically across the deposit. The geological descriptive system used at Olympic Dam is based of largely on the systematic replacement of primary magmatic minerals with hydrothermal minerals dominated by hematite (Ehrig et al., 2012). This is reflected in Figure 3 where %Fe is positively correlated with bulk dry density, but negatively correlated with %Si. Granite derived elements which are negatively correlated with Fe include Al, Be, Ca, Hf, K, Li, Mg, Mn, Na, Rb, Si, Th, Ti, Zr. Hydrothermal elements with a positive correlation with Fe include Ag, As, Au, Ba, Bi, Cd, Cl, Co, C, Cr, Cu, F, In, Mo, Nb, Ni, P, Pb, S, Sb, Sc, Se, Sn, Sr, Ta, Te, U, V, W, Y, Zn, and REEs (Ehrig et al., 2012). However, it must be noted that the various negative and positive correlations with Fe are all not as clear as

%Si vs %Fe. An excellent example of this is %Sulfides and %Cu vs %Fe (Figures 3C-3D). The most significant observation in these graphs is the lack of distinct breaks (e.g. gaps) in the data, except for the HEMQ alteration style.

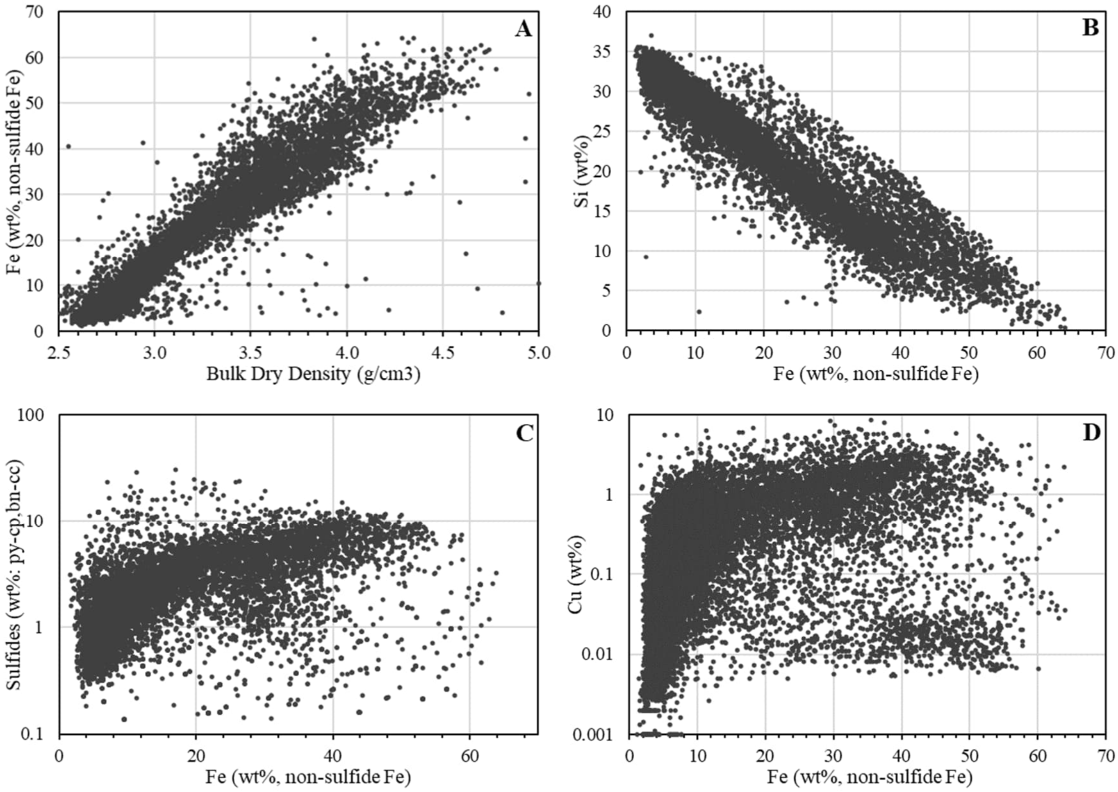
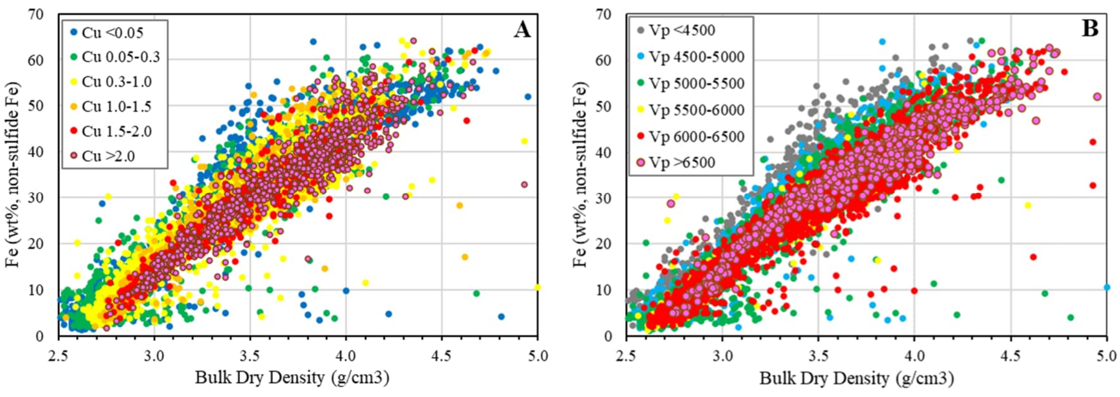


Figure 3: Scatterplots show the relationships between %Fe (non-sulfide Fe) vs bulk dry density (A), %Si vs %Fe (B), %Sulfides (py-cp-bn-cc) vs %Fe (C) and %Cu vs %Fe (D). Note the log scales in C-D. The data point field above the main trend in (B) are largely dominated by HEMQ rocks. The data cluster in the lower right corner of (D) are also the field for HEMQ rocks. Fe (non-sulfide Fe) has the Fe from sulfide minerals removed the from total iron to examine the relationship between sulfides and oxides.

Vp vs ore-grade concentrations of disseminated Cu(±Fe)-sulfides, bulk dry density, %Fe

A question that requires addressing is Vp correlated with increasing sulfide mineral concentration. Figures 4A-B are Figure 3A with the data points coloured for %Cu and Vp, respectively. Copper concentrations >1% are present in samples spanning the range of 5-50 %Fe (Figure 4A). Likewise, samples with Vp >5500 m/s also occur across the entire %Fe concentration range. However, the question must be asked, is Vp responding to %Fe and/or %Cu? The important fact to note is the Cu concentration range is approximately an order of magnitude less that the Fe concentration range. Acoustic impedance vs Vp demonstrates that samples with Cu >1% span the acoustic impedance and Vp range.



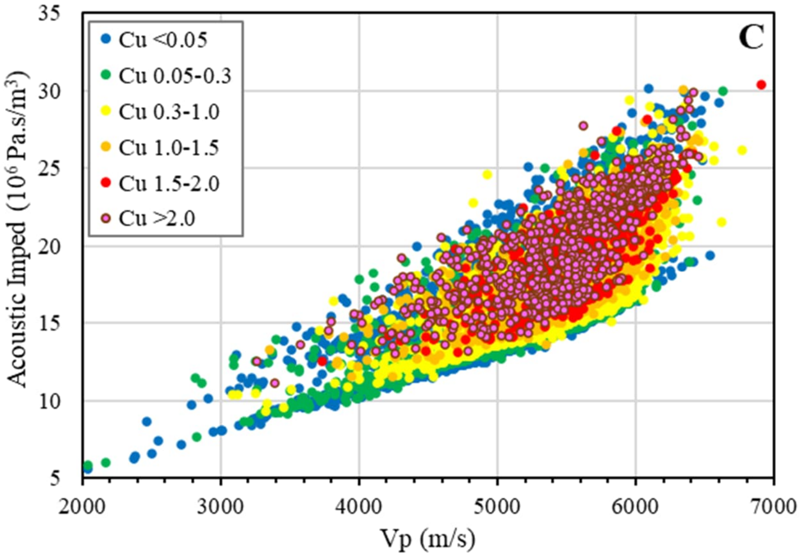


Figure 4. Scatterplots showing the (A) %Fe vs bulk dry density, points coloured by %Cu, (B) %Fe vs bulk dry density, points coloured by Vp and (C) Acoustic impedance vs Vp, points coloured by %Cu.

Vp and acoustic impedance contrasts in 'deep' style mineralisation

Distinct lithologic boundaries within the Olympic Dam deposit occur in bedded clastic facies and more commonly across faults. They do not occur in the granite- to hematite-rich breccia spectrum which typifies the mineralised breccias in most of the deposit. Relatively deep mineralisation (<1500m below surface) at OD was first discovered in 2006 with the drilling of RD1988 (near vertical dip) in the south-eastern part of the deposit. RD1988 ended at a depth of 1898m in ~1.5 % Cu and 1 ppm Au. This was quickly followed up by navi-drilling of RD2785 and RD2786A (collared west and east of RD1998, respectively) to determine the approximate ore zone width. One of the characteristics discovered during the drilling of RD2785 and RD2786A was the ore zone was fault bounded against altered granites and granite-rich breccias to the north and south. Recent drilling has commenced to further define the zone of 'deep' mineralisation. Hence the question, is there a Vp contrast across the faulted bounded hematite-rich breccias?

Iron concentration, Vp, bulk dry density and acoustic impedance are plotted as a function of depth in Figure 5. The deep zone of mineralisation is defined by the sudden increase and subsequent decrease in Fe % from ~1400-1660m depth. Altered granites and granite-rich breccias are faulted against both sides of the mineralised interval. There are also corresponding step changes in the velocity, bulk dry density and acoustic impedance profiles.

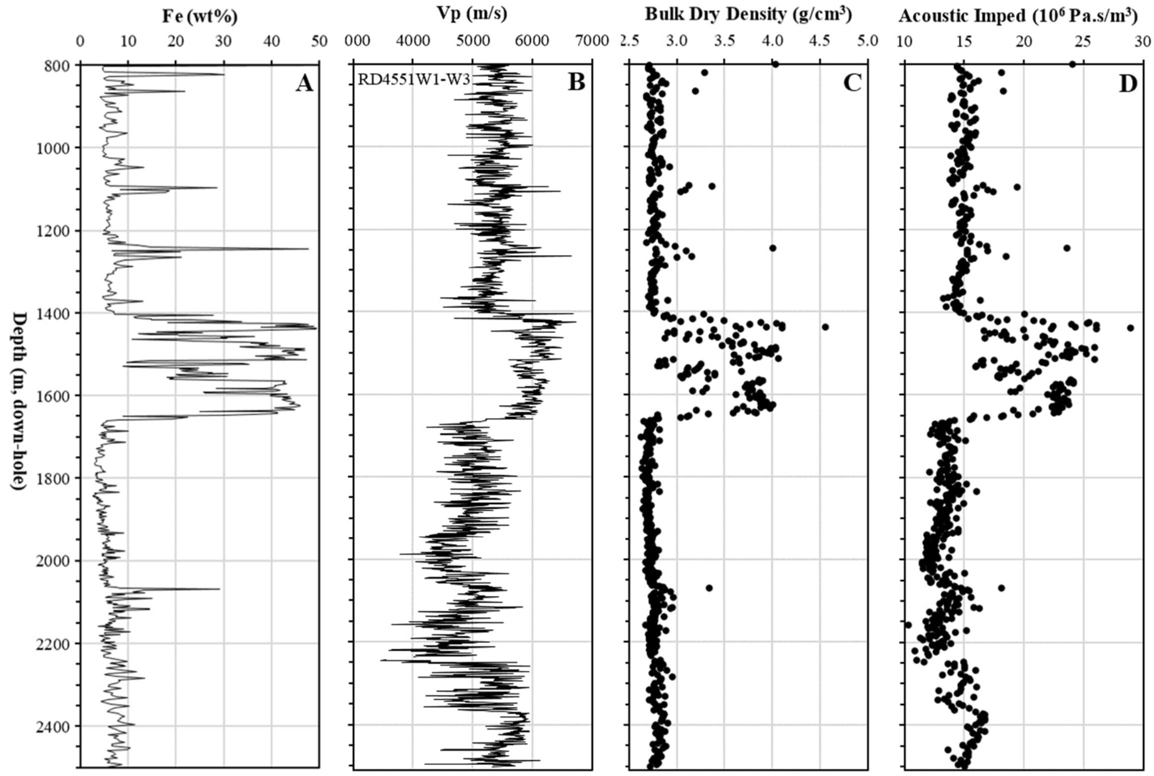


Figure 5. %Fe, Vp, bulk dry density and acoustic impedance depth profiles across fault bounded hematite-rich breccias for drill hole RD4551W1-W3.

Macro-porosity: high hematite yet variable Vp

Cycles of porosity creation and destruction are ubiquitous with the formation of hydrothermal ore deposits, e.g. fluids require pathways to migrate through the rocks. Fluid pathways can vary from the macro to nano scale. Is there evidence of variable porosity in the Olympic Dam Vp data?

Figure 6 is a down-hole profile showing the variation of Fe%, Vp and bulk dry density with depth. Two intervals at approximately 75 and 150m depth have an Fe concentration of ~50%. The corresponding bulk dry density is ~3.5 and 4.4 g/cm3, respectively. The Vp values are also significantly different. For the same Fe concentration, it is expected that the bulk dry density and Vp results should also be similar. One interpretation of this data is that at ~75m, the low density is due to a higher porosity when compared to the high Fe, Vp and density at ~150m depth. These intervals are in barren hematite-quartz breccias, so the overall mineralogy between the two intervals is very similar. This deviation of Fe concentration against a given density value continues down to approximately 300m depth.

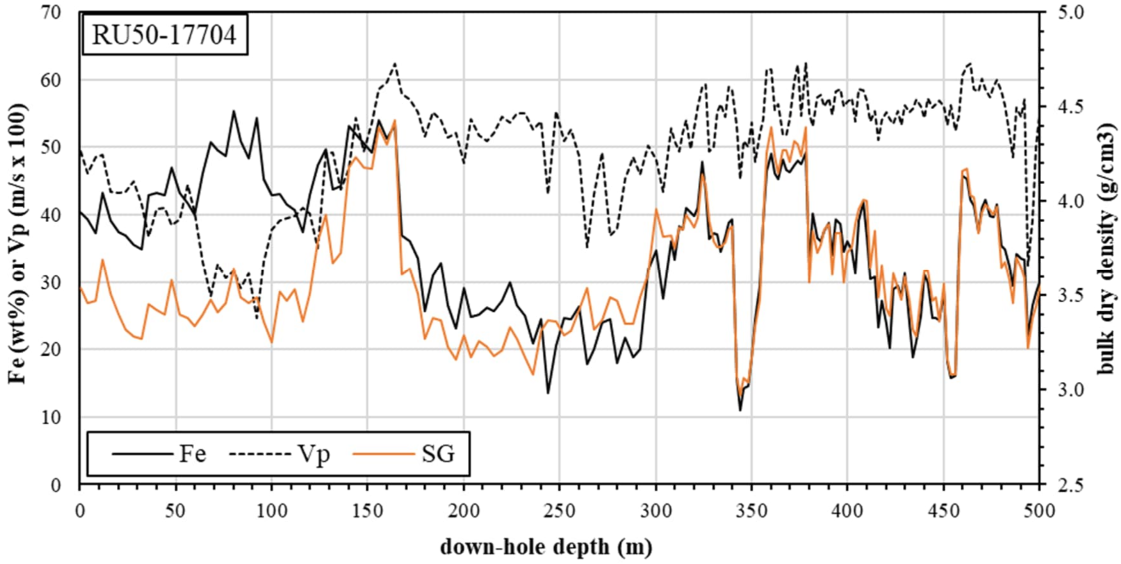


Figure 6. %Fe, Vp and bulk dry density down-hole profiles for drill hole RU50-17704.

Damage zones around faults

Micro- to macro-scale fracturing of rocks are likely to occur in fault zones, particular ones which have not been healed post the last fault movement. This damage zone may extend beyond the identified fault. The down-hole variation in Vp (Figure 7) clearly shows low Vp zones in granite-breccias. In this case, faults were logged at ~750m and 1650m. The low Vp data which extends beyond the logged faults have cleared identified damage zones significantly more existence than the fault alone.

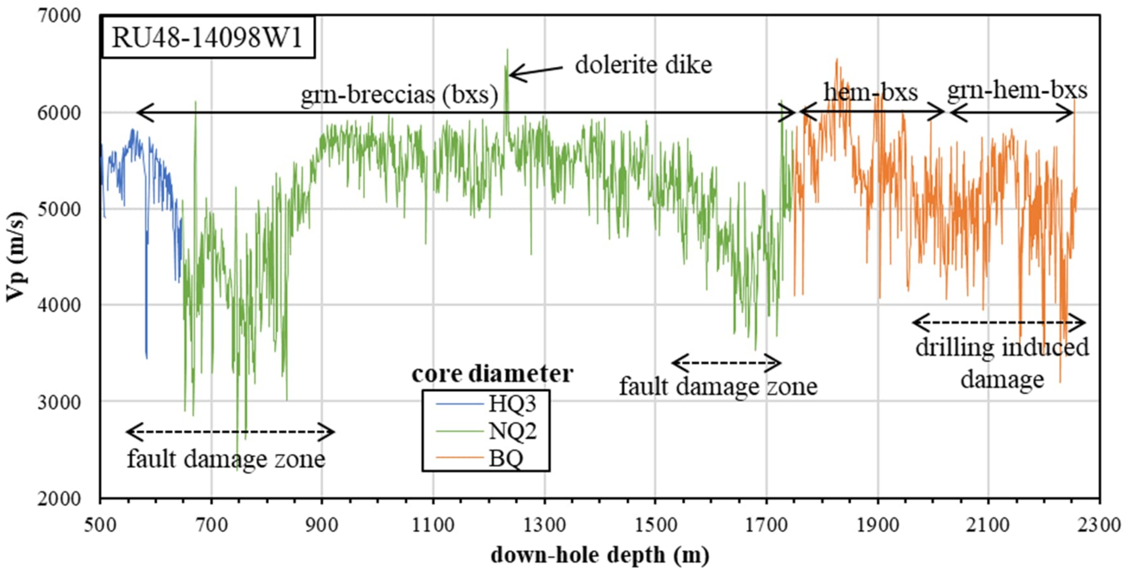


Figure 7. Vp vs depth for a drill hole with multiple core diameters (coloured for HQ3, NQ2, BQ). Granite-breccias are present from ~550-1750m and ~2000-2250m depth, with hematite breccias from 1750-2000m. Note the narrow dolerite dike at ~1250m. Fault damage zones are labelled, along with drilling induced damage to the core resulting in lower than expected Vp values.

Vp as a function of white mica alteration in unbrecciated granites

Fresh to weakly altered, yet unbrecciated, Roxby Downs Granite surrounds the breccia complex for distances up to ~5 km from the outer boundary of the breccia complex. Refer to the biotite 'out' contour in Figure 1 which denotes the outer edges of the breccia complex. The alteration style in the surrounding granites is dominated by weak sodic and potassic alteration of the magmatic plagioclase and K-feldspar followed by muscovite alteration of the albite and secondary K-feldspar (Kontonikas-Charos et al., 2017) prior to the onset of brecciation and hematite-alteration.

Magmatic biotite is replaced by chlorite and magmatic magnetite is replaced by hematite. Is there a unique Vp signature to this style of alteration?

Down-hole Vp and magnetic susceptibility profiles are shown in Figure 8 for four drill holes located along a drill hole traverse from the freshest example of Roxby Downs Granite (RD2488) through to an altered yet unbrecciated RDG (RD451). The Vp profiles for RD2488 and RD2495 look very similar, RD2499 displays an increasing number of low values, while the Vp for RD451 shows overall lower values. However, nothing significantly different. The magnetic susceptibility profiles record a progressive decrease (i.e. destruction of magnetite) as the edge of the breccia complex is approach. The bottom of RD451 does show a slight increase in magnetitic susceptibility. This may be a remanent of the magmatic magnetite or the early indication of the introduction of hydrothermal magnetite. Microscopic evaluation is required to distinguish magmatic from hydrothermal magnetite.

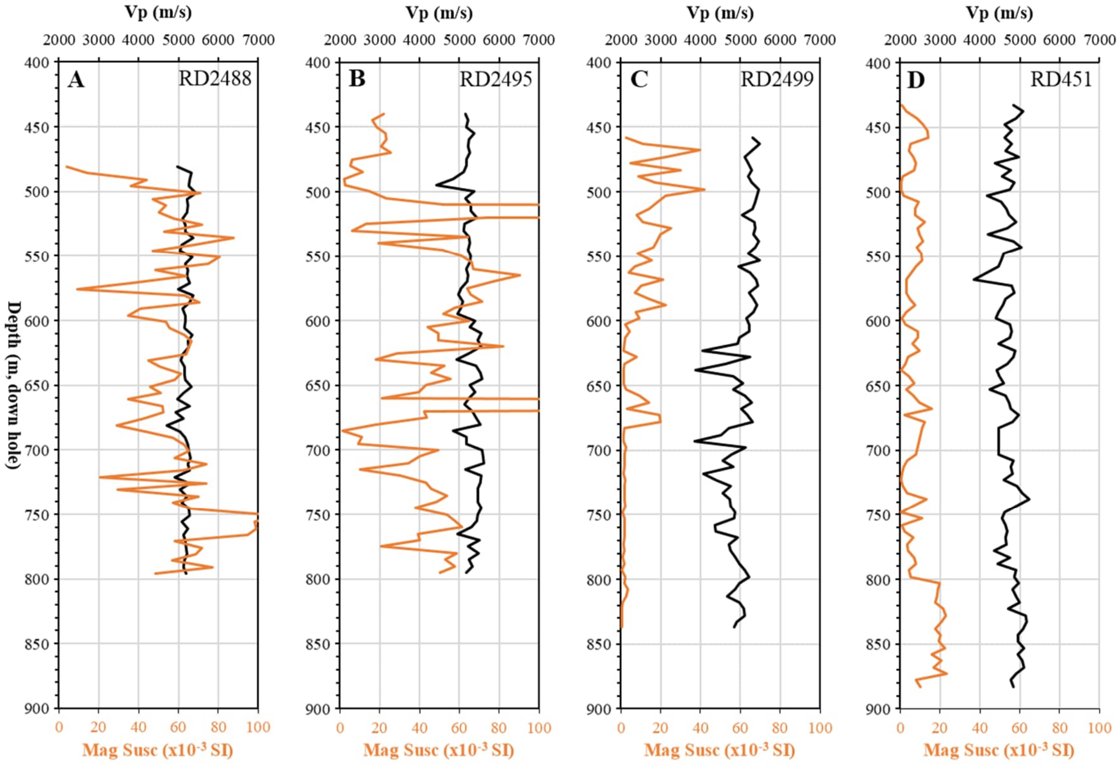


Figure 8. Vp and magnetic susceptibility down-hole profiles along a drill hole traverse in unbrecciated granites off the SW edge of the breccia complex. Refer to Figure 2 for the location of these holes relative to the deposit.

CONCLUSIONS

The data presented here demonstrates, at Olympic Dam: 1) the overwhelming positive correlation of hematite (Fe) with bulk dry density, 2) direct correlation of Vp with copper mineralisation in Fe-oxide dominant systems is unlikely to be clear, 3) hematite-rich breccias in fault contact with granite and granite-rich breccias will likely produce good p-wave reflectors, 4) variable porosity in the rocks does cause variable Vp results, 5) damage zones surrounding faults are detectable by Vp measurements, and 6) muscovite alteration in granites, prior to brecciation and Fe-oxide alteration, is unlikely to produce a systematic change in Vp which makes it unusable as a vector to mineralisation.

The Vp data were collected by the first author, who is not a geophysicist. From a geological/mineralogical background perspective, the Vp values, or any petrophysical properties, must be related to features that can be seen in the samples or in the associated assay data. The act of being physically involved in the data collection exercise forces one to really look at the rocks while collecting the data and developing a rock awareness of what the petrophysical data is revealing in the rocks. Preparing the list of focus questions prior to the commencement of the Vp data collection exercise was critical in selecting the drill holes to be measured and determining what should be considered as far as data quality. The focus questions were developed via discussions with geophysical experts/colleagues, by reading large sections of Eaton et al. (2003) and by reviewing the petrophysical publications based on data collected from the Stuart Shelf / Gawler Craton IOCG related rocks (Funk, 2013; Harris et al., 2013; Hossain et al., 2015; Onojasun, 2018; Vella, 1997; Vella and Cawood, 2012; Wise et al., 2016).

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Effectively executing studies and massive data collection activities within the mining industry are always a team effort with contributions from everyone in the team. This seemingly simple Vp measurement activity on +42,000 metres of diamond core involved the Olympic Dam Geoscience Team including the geologists and support technicians/specialists designing the drill holes, managing the approvals required to drill the holes, managing the drilling crews, logging the core, processing the core, preparing the core for assaying, and interpreting/modelling the results. The commercial analytical laboratories that assay the drill core samples are also acknowledged. But most importantly, the geophysical expertise provided by the co-authors is also recognised, we couldn't have done this without you.

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