Update on the geophysical expression of the Abra sedimentary replacement Pb-Ag-Cu-Au deposit, Western Australia

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SUMMARY

The Abra sedimentary replacement Pb-Ag-Cu-Au deposit is located in the Paleoproterozoic Edmund Basin, 900km NNE of Perth. Mineralisation at Abra has no surface expression and the deposit was discovered in 1981 by drill testing coincident magnetic and gravity anomaly highs. The deposit is hosted within siliciclastic and carbonate deposits of the Edmund Group and consists of a stratabound apron of lower grade Pb-Ag-Ba mineralisation in a laminated iron oxide and barite altered siltstone unit that overlies a funnel shaped feeder zone of chloride altered, brecciated and veined carbonate siltstone containing high-grade Pb-Ag in the core, transitioning to Pb-Cu and Cu-Au at depth. As at December 2018, the Abra deposit remains unmined and has an estimated resource of 37.4Mt at 7.5% Pb and 18g/t Ag.

Mutton and McInerney (1987) and McInerney et al. (1994) described the geophysical expression of Abra, and recent geophysical survey results are presented here. Abra is characterised by discrete anomaly responses in magnetic, gravity and TDEM survey data. A +450nT magnetic anomaly is observed in ground and airborne magnetic data, which is caused by magnetite within the lower part of the stratabound zone. Dense galena, barite and iron oxide mineralisation in the stratabound zone, and galena in the feeder zone, is surrounded by low-density sedimentary host rock, resulting in a +1mGal gravity anomaly. TDEM surveys have resolved massive sulphide mineralisation as EM conductors, and petrophysical testing on core samples show this is mostly caused by galena. Inverted AMT-MT data sections resolved the deposit halo as a conductive anomaly. ZTEM data failed to resolve a distinct anomaly response. DDIP surveying failed to resolve a chargeable anomaly coincident to known high-grade mineralisation, despite significant disseminated sulphide mineralisation occurring within the deposit. An IP chargeability anomaly observed on the southern side of the deposit is thought to be associated with an alteration zone and low-grade disseminated sulphide mineralisation in a fault zone.

A 2D seismic reflection survey line resolved the deposit envelope as strong seismic reflectors surrounded by a seismically bland zone, and this is related to the significant density contrast between the high-density stratabound mineralisation in contact with low-density sedimentary host rocks, as the mineralisation and host rock have similar seismic velocities. Passive seismic HVSR surveys resolved the top of Abra as a subtle HVSR response below a flat impedance contrast horizon interpreted as weathered siltstone over diagenetic cemented siltstone.

Key words: Abra, lead, silver, zinc, galena, geophysics

INTRODUCTION

The Abra polymetallic base metal deposit is located in the Jilawarra sub-basin of the Paleoproterozoic Edmund Basin, approximately 900km NNE of Perth, Western Australia (Figure 1). The deposit has no direct surface geochemical expression and no indication of a significant high-grade lead deposit can be inferred from limited outcropping geology. Drill testing of coincident magnetic and gravity high anomaly responses lead to the blind discovery of the deposit in 1981 (Mutton and McInerney, 1987; McInerney et al., 1994).

The Abra deposit has been considered to be a sub-economic, large low-grade Pb and Ag mineralised system, with a surface projection footprint of known mineralisation of around 1.2km x 850m. The Abra project and surrounding exploration tenements were purchased by Galena Mining Ltd in 2017 who aggressively drilled and proved-up a high-grade core.
in 2019-2020. This paper primarily summarises results of the more recent geophysical survey programs, and further characterises the geophysical responses of the Abra deposit.

PETROPHYSICAL STUDIES

Petrophysical testing of 11 core samples was carried out in 2009, expanding on 6 core samples analysed in 1995. The petrophysical test results highlight high magnetic susceptibility values of between 141x10^{-8}SI to 1,120x10^{-8}SI from core samples of the magnetite-rich black zone of the stratabound mineralisation, with other parts of the deposit displaying relatively low magnetic susceptibility values. Density measurements show that samples from the barite zone, and the deeper hydrothermal vein zone, display the highest density values of around 4.3-4.53/m^3. These samples host barite, galena and pyrite mineralisation, suggesting that the higher density of the core samples is likely attributed to the presence of these heavy minerals. Samples from the red, black and dolomite banded zones display a density range of 3.6-3.8t/m^3, and those from the sedimentary breccia zone range between 2.8-3.1t/m^3. Galvanic resistivity measurements show a reasonable correlation to the EM conductivity results, with conductive EM samples displaying low resistivity. Samples with the lowest galvanic resistivity values (0.03-140hm.m m), were from the black banded zone, barite zone and hydrothermal vein zone. The higher conductivity samples (10-40S/m) correlate to high concentrations of pyrite and galena. Since both minerals are present in all but one of the samples, it is difficult to determine exactly which mineral is responsible for the conductive properties of the sample, but galena is generally much more conductive than pyrite, and one sample with only galena, and no pyrite, has a comparable apparent conductivity (10S/m). It is most likely that galena mineralisation is responsible for the majority of the bulk conductivity at Abra (see also Wood et al., 2012). Core samples with both galena and pyrite, and minor chalcopyrite mineralisation, show significantly elevated chargeability results and low galvanic resistivity values, with the highest chargeability measurements coming from dolomite, barite and vein samples (up to 212msec).

GEOLOGICAL SETTING AND MINERALISATION

The tectonic evolution of the Capricorn Orogen and Edmund Basin and geological setting of the Abra deposit has been detailed in an extensive amount of literature, with important publications including Vogt and Stumpfl (1987), Mutton and McInerney (1987), Boddington (1990), McInerney et al. (1994), Pirajno et al. (2009 and 2016), and Lampinen et al. (2017 and 2019), amongst others. The authors of this paper refer readers to these papers for detailed description of the project geology and evolution of the Capricorn Orogen.

The Abra sedimentary replacement Pb-Ag-Cu-Au deposit is hosted within siliciclastic and carbonate deposits of the Irregully and Kiangi Creek formations of the middle Proterozoic Edmund Group. Base metal mineralisation at Abra does not outcrop, with the uppermost part of the ore body being over 250m deep and extending to depths of over 600m (Figure 2). The upper part of the deposit consists of a stratabound or ‘apron’ zone of Pb-Ag-Ba mineralisation associated with a laminated iron oxide and barite altered siltstone at the top of the Irregully Formation. This stratabound apron is divided into two domains; an upper oxidised ‘red zone’ identified by conglomerate and laminated to banded hematite-barite-jaspilite, which overlies a magnetite-rich ‘black zone’ dominated by magnetite, barite, quartz and dolomite. The stratabound mineralisation overlies a funnel shaped ‘stockwork’ or ‘feeder’ zone of chlorite altered, brecciated and extensively veined carbonaceous siltstone of the Irregully Formation, containing high-grade Pb-Ag veining in the core of the feeder zone and transitioning to more Pb-Cu and Cu-Au veined mineralisation at depth. The deposit is unmined, and remains open at depth and to the sides.

Figure 1. Regional geological setting of the Edmund Basin, with the location of the Abra deposit shown as a black star. Figure reproduced from Pirajno et al. (2016).
Handheld P-wave velocity (Vp) analysis was carried out on core samples from a representative diamond drillhole extending through the deposit. The Vp measurements acquired on the Kiangi Creek Formation core ranged between 2,000-4,000m/s in siltstone units and 5,000-6,000m/s in sandstone units, with the low values representing weathered rocks. Within the stratabound mineralisation, Vp values were 3,500-4,500m/s, whereas the high-grade core zone had Vp velocities generally between 4,000-5,000m/s. A very high-grade interval within the core zone (62% Pb) returned a Vp value of 3,820m/s. The Vp values downhole did not show a large degree of variation, and so bulk density measurements were also taken on the same core intervals as the Vp measurements. This clearly showed that sharp increases of density occur in the mineralised intervals, and therefore an acoustic impedance contrast would occur between mineralisation and host rocks mainly due to changes in density within the fresh rock zone.

**GEOPHYSICAL EXPRESSIONS**

**Magnetic Anomaly Response**

McInerney et al. (1994) highlight a +450nT magnetic anomaly in regional airborne magnetic data, and this magnetic anomaly is associated with the magnetite-rich black zone of the stratabound mineralisation. Figure 3 shows an image of the magnetic pole total magnetic intensity data (TMI-RTP) from a more recent high resolution merged aeromagnetic and ground magnetic data grid covering the Abra project area, with an outline of the apron mineralisation directly correlating to a discrete magnetic high anomaly, surrounded by magnetically quiet sedimentary deposits of the Kiangi Creek Formation, with some magnetic chatter caused by maghemite in the regolith. The discrete magnetic anomaly response was modelled using a 3D ellipsoidal polygonal body, and subsequent drill testing of the magnetic polygonal model lead to the discovery of the deposit in 1981. A constrained potential field inversion study by Eden (2011) showed that the known magnetic apron mineralisation can fully explain the observed magnetic anomaly pattern, except in the NW corner where there was no historical drilling; recent drilling in this area intersected more mineralisation to close off the main magnetic anomaly.

**Gravity Anomaly Response**

Abra is associated with a gravity anomaly high of up to +1mgal (Figure 4), and this anomaly response was modelled using 3D polygonal bodies which was targeted by the drill program that lead to discovery of the deposit. Petrophysical studies indicate that the source of the gravity anomaly high is mainly iron oxide, galena and barite mineralisation in the stratabound zone, and galena-chalcopyrite mineralisation in the feeder zone. Since the study by McInerney et al. (1994), more detailed ground gravity data were acquired using a smaller station spacing. A constrained inversion study by Eden (2011) showed that the known mineralisation at that time was only able to account for roughly 50% of the observed gravity anomaly response, suggesting that the gravity expression is a combination of the known mineralisation and an underlying excess mass, possibly elevated basement rock, dolomite or additional mineralisation at depth. This study has not yet been refined, but given the recent significant increase in the current resource by extending the Abra deposit at depth, some of this excess mass can be explained by deeper extensions to the mineralisation.

**Electromagnetic Anomaly Response**

McInerney et al. (1994) highlighted anomalous EM responses of the Abra deposit in the early 1980s from SIROTEM moving loop EM (MLEM), fixed loop EM (FLEM) and downhole EM (DHEM). The results of these EM surveys, and another MLEM survey program carried out in 2006 using a coil sensor, identified broad anomalous EM responses associated with a weakly conductive source.

MLEM surveying using a LANDTEM B-field SQUID sensor was carried out in 2012, and this resolved a mid-time EM decay channel anomaly centred over the known base metal mineralisation. The Z component EM response profiles from MLEM survey programs carried out in 1982, 2006 and 2012 are shown in Figure 5 for comparison. EM conductor plate modelling using the 2012 MLEM survey data resulted in a thin conductor plate having a conductance of 20S at a similar depth, strike extent and dip to the known stratabound mineralisation horizon, and the results of petrophysical testing on core indicate that the source of the EM conductor responses is mainly galena (±pyrite) mineralisation.

DHEM surveys were carried out in 2012 on multiple drillholes that intersected high-grade Pb mineralisation, with the DHEM...
survey data resolving both in-hole and off-hole anomalous EM conductor responses. DHEM surveying carried out recently on an 800m long drillhole located just to the south of the Abra deposit, and only intersecting minor mineralisation, resolved a broad off-hole anomalous EM response, which was modelled using several modelled EM conductor plates orientated and positioned within the December 2018 high-grade Pb resource wireframes. Downhole magnetic data were also extracted from the digi-Atlantis B-Field EM sensor, and modelling of the off-hole magnetic response matched the black zone of the stratiform mineralisation. The DHEM conductor plates modelled within the apron mineralisation used a conductivity of 35S, and conductor plates within the feeder zone used a conductivity of 25S.

In 1996, a GeoTEM-Deep airborne EM survey resolved the Abra massive sulphide mineralisation as a weak anomalous EM conductor response with an amplitude slightly above the noise envelope in both the Z and X receiver component data. Since this survey, several different airborne EM systems have been flown over Abra, and include: VTEM-Plus (2012), XTEM (2012), VTEM-Max (2014), and Xcite (2017); the ZTEM system was also flown over Abra for CSIRO in 2017. Both VTEM systems and the Xcite system resolved discrete and high amplitude mid-to-late-time EM decay channel anomaly responses over Abra in both the Z and X component receiver data. The XTEM survey was carried out for regolith mapping purposes and did not resolve an anomalous EM response associated with the Abra deposit (Wood et al., 2012). A plan image of the VTEM-Plus Z component dB/dt time decay channel 35 data is shown in Figure 6, and illustrates the strong EM anomalism associated Abra, despite its depth of >250m; mainly due to only weakly conductive regolith cover.

The dB/dt Z component EM response profiles of flight lines over the Abra deposit from various airborne EM systems are shown in Figure 7. Conductor plate modelling and 1D conductivity inversions show that the anomalous airborne EM responses are associated with conductive mineralisation in the stratiform zone of the Abra deposit. A late-time channel anomalous EM conductor response observed at 7,274,500mN in Figure 7 in both VTEM datasets remains untested by drilling. An interpretation of the ZTEM anomaly responses remains inconclusive as to whether the conductive mineralisation was resolved above similar surrounding weak anomalies, which may just represent background noise.

Petrophysical studies indicate that high-grade parts of the Abra deposit should result in a moderate to strong chargeability anomaly from IP surveying. Dipole-dipole IP (DDIP) surveying carried out in 2006 resolved a high amplitude chargeability anomaly offset just to the south of the Abra deposit. Geophysical case study 2.0.
high-grade mineralisation at Abra (Figure 8). The DDIP inversion process was carried out independently by four geophysical consulting and contracting companies, and the chargeable anomaly offset was repeated in all inversion results. Although assay data provided no clear evidence for high-grade mineralisation coincident with an IP chargeability anomaly, the observed chargeability anomaly sitting to the south could represent a zone of intense alteration or dissemination of highly chargeable minerals and fluid distribution on the periphery of the deposit, and is consistent with physical property measurements on similar types of altered rocks.

Combined magnetotelluric (MT) and audio-magnetotelluric (AMT) data were collected over the Abra deposit in 2014 to map electrical structures and stratigraphic units to a depth of 5km. AMT data were recorded for approximately 1-2 hours and MT data recorded for 10-16 hours along a 10km long N-S orientated survey line. Joint 2D inversions on the MT and AMT data have resolved the Abra deposit as a broad conductive response within a resistive background, as well as resolving conductive graphitic shale units of the Kiangi Creek Formation to the north and south of the deposit, forming broad fold and thrust structures from rift basin inversion (Figure 9).

A 2D multichannel seismic reflection survey using an accelerated weight drop source and 426 channel spread was carried out at Abra in 2011 as part of a Curtin University 3rd year geophysics field program. Data were recorded along a 2.5km N-S orientated traverse centred directly over the Abra deposit, and were acquired using a 5m shot spacing and 5m geophone spacing (Meyers, 2012). The 2D seismic reflection data have since been reprocessed by HiSeis, and a migrated and depth converted section is shown in Figure 10. The Abra stratabound mineralisation is resolved as strong seismic reflectors, which is most likely caused by the significant density contrast between galena and barite mineralisation and the surrounding low-density sedimentary host rock, as the Vp of the mineralisation is similar, if not lower, than the surrounding and overlying sedimentary host rocks. The Abra mineralisation is also observed to be bounded to the north and south by faults in the seismic reflection profile, along with other fault structures sitting below Abra which likely represent important fluid pathways for the sedimentary replacement mineralisation.

Passive seismic horizontal to vertical spectral ration (HVSR) surveying was carried out over Abra as a trial of the survey technique (see Owers et al., 2016), and to acquire detailed information about the thickness of the regolith cover to assist with static corrections of the 2D seismic reflection data and future 3D seismic reflection surveying. The HVSR survey was carried out along the same traverse as the 2D seismic reflection survey and along an E-W orientated survey line. Data acquisition using 8x Tromino® seismometer units took place over a 1-day period, and utilised 50m station spacing and 20-minute recording time. The HVSR data are considered to be of good quality, although the method failed to resolve high amplitude HVSR peaks associated with strong acoustic impedance contrasts with the top of the Abra deposit, due to a strong impedance contrast layer sitting above Abra in overlying siltstone units. The HVSR data were normalised based on the maximum and minimum HVSR amplitude response observed at each station, and then gridded to generate a normalised HVSR cross section (Figure 11). The HVSR frequency responses were converted to depth using a constant average Vs of 3,000m/s which is consistent with converted Vp values obtained using a handheld meter on core samples. The normalised HVSR data resolves a strong acoustic impedance contrast within sedimentary deposits of the Kiangi Creek Formation at a modelled depth of approximately 150m. This interface is associated with a rapid increase in Vp recorded by a handheld meter on core and this acoustic impedance contrast interface was also resolved by refraction tomography studies as part of the 2D seismic reflection data reprocessing recently carried out by HiSeis. This increased velocity along this sub-horizontal layer is likely reflecting a diagenetic cementation zone between oxidised
sediments above and less weathered to well-cemented sediments below. The northern fault which bounds the Abra mineralisation is resolved as a break in the continuity of this main HVSR interface (compare Figures 2 and 11). Parts of the stratabound mineralisation are resolved as subtle HVSR responses below the main shallow interface, and these zones are likely due to dense galena and barite mineralisation, or lower density alteration haloes surrounding the mineralisation. The Abra core zone is too far below the main horizontal HVSR response to be detected, but some deep HVSR responses to the north of Abra occur in the same location as deep VTEM EM anomalies (compare Figure 6 and 11), which has been plate modelled to occur in the same location and forms an exploration target. Some shallow and low amplitude HVSR horizons also occur in the weathered zone above Abra and may represent stratigraphic layers and/or regolith features, such as calcrete or silcrete cementation horizons (Figure 11).

CONCLUSIONS

The geophysical expression of the Abra Pb-Ag-Cu-Au sedimentary replacement deposit can be characterised by discrete magnetic, gravity and EM anomaly responses. The magnetic anomaly response is related to magnetite mineralisation within the black zone of the stratabound mineralisation. Galena, iron oxide and barite mineralisation in the apron, and galena mineralisation within the feeder zone, are the main sources of the gravity anomaly high. Downhole, surface and airborne EM surveying has resolved discrete EM conductor anomaly responses associated with the known massive sulphide mineralisation, and this conductive response is mainly related to galena (+pyrite). Abra was also resolved as a broad and moderate conductor response in inverted AMT-MT data, but was not well defined in ZTEM data.

Petrophysical testing on selected drill core suggests that Abra should be associated with a chargeable IP anomaly, however DDIP surveying carried out across the deposit has failed to identify a coincident chargeable anomaly with the main mineralised zone.

Reprocessing of 2D seismic data has resolved the stratabound mineralisation as strong seismic reflectors surrounding a seismically bland zone, and this is related to the dense properties of the galena, iron oxide and barite mineralisation within the stratabound zone, as the mineralisation has a similar seismic velocity to the overlying and surrounding sedimentary host rocks. Passive seismic HVSR surveying has identified a strong, flat acoustic impedance contrast layer where there is an observed increased in measured seismic velocity from core samples. This flat horizon is a combination of folded stratigraphy and likely a diagenetic cementation front between oxidised silstone above and unweathered and re-cemented silstone below. Some shallow (regolith and sediments) and deeper (mineralisation?) HVSR responses were also observed.

REFERENCES


Table 1. Averaged petrophysical results from Abra core samples analysed in 2009 by System Exploration.

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<th>Sample</th>
<th>Depth (m)</th>
<th>Lithology</th>
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<th>Mag Sus (SIx10^{-3})</th>
<th>Density (g/cc)</th>
<th>EM Conductance (S/m)</th>
<th>Galvanic Resistivity (ohm.m)</th>
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Figure 5. Z component EM time decay profiles from MLEM survey programs carried out at Abra in 1982 (SIROTEM, left), 2006 (coil sensor, centre), and 2012 (LANDTEM SQUID, right).

Figure 11. 3D view looking towards the west showing the passive seismic HVSR amplitude normalised cross section converted to depth using a constant average shear wave velocity of 3,000m/s, overlain by the Abra resource wireframes and drillhole Vp information, with thickness of downhole discs based on handheld Vp measurements on diamond core samples crossing though Abra and surrounding host rocks.