Delineation of Regolith Zones in Nickel Laterite using Electromagnetic Imaging: Ravensthorpe, Western Australia.

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SUMMARY

Nickel laterite is a product of intensive weathering processes of ultramafic rocks near the surface. The Ravensthorpe Nickel Operation has traditionally used boreholes spaced at 40 meters to delineate the major regolith zones of caprock, limonite, saprolite, and saprock. The high geometric complexity of the weathering profile leads to an inaccurate resource delineation by drilling alone. Loupe is a new ground system for transient or time-domain electromagnetic measurements suitable for resolving shallow electrical conductivity distribution. At Ravensthorpe, the technique was tested in 2019 to improve the spatial resolution of conductivity models and, consequently, to better distinguish different regolith zones. Appraisal of the Loupe system involved experimentation with different transmitter waveforms, assessment of diffusion depths and noise levels, and 1D inversions with and without constraining geological input. Interpretation of the inverted conductivity suggests that the Loupe data are imaging the caprock thickness and reproducing the thinner but continuous conductive zones defined by downhole logging within certain segments of the regolith profile. Below the caprock, the conductivity correlates with higher clay proportion, as defined in visual logging and reflected in higher Al content.

Key words: Loupe EM, Ravensthorpe, Regolith mapping, Nickel laterite.

INTRODUCTION

Electromagnetic (EM) surveys are prevalent in mineral exploration due to their ability to map conductivity contrasts between different geological units, which in turn relate to lithology and alteration mineralogy, or other physical and chemical differences. In nickel laterite deposits, EM has been an important tool for resource delineation and mine planning (Francke and Parkinson, 2000). The high complexity of the weathering profiles precludes traditional reliance on boreholes alone to model resources accurately (Francke and Parkinson, 2000).

Nickel in the Ravensthorpe laterite deposits is contained within both limonite and saprolite zones. The limonite-saprolite interface is geometrically too complex to define using only drill holes which are spaced 40 m apart (Figure 1). Airborne electromagnetic data suggest that the limonite is more electrically conductive than the saprolite. However, the lateral resolution of an airborne survey is not sufficient for resource definition and mine planning. Downhole conductivity logging supports more conductive zones in limonite, but it does not correlate with the entire limonite interval in the geological logging. These discrete zones of high conductivity, which are continuous across multiple drill holes, are probably related to clay materials.

A new ground transient electromagnetic (TEM) system known as Loupe (Street et al., 2018) is a good candidate for mapping regolith layering, including the limonite-saprolite boundary or other discrete regolith zones, at a high spatial resolution relevant for the mining operation. Data were collected along 46 drill lines and modelled using the AirBeo 1D layered earth inversion code (Raiche et al., 2007), experimenting with the Z component, and constrained by downhole conductivity and geological logging. Visual logging is quite robust with respect to the interface between the reddish-brown limonite and pale brown saprolite. An analysis of downhole petrophysics versus geological and geochemical logging informs the constraints to use during inversion work.

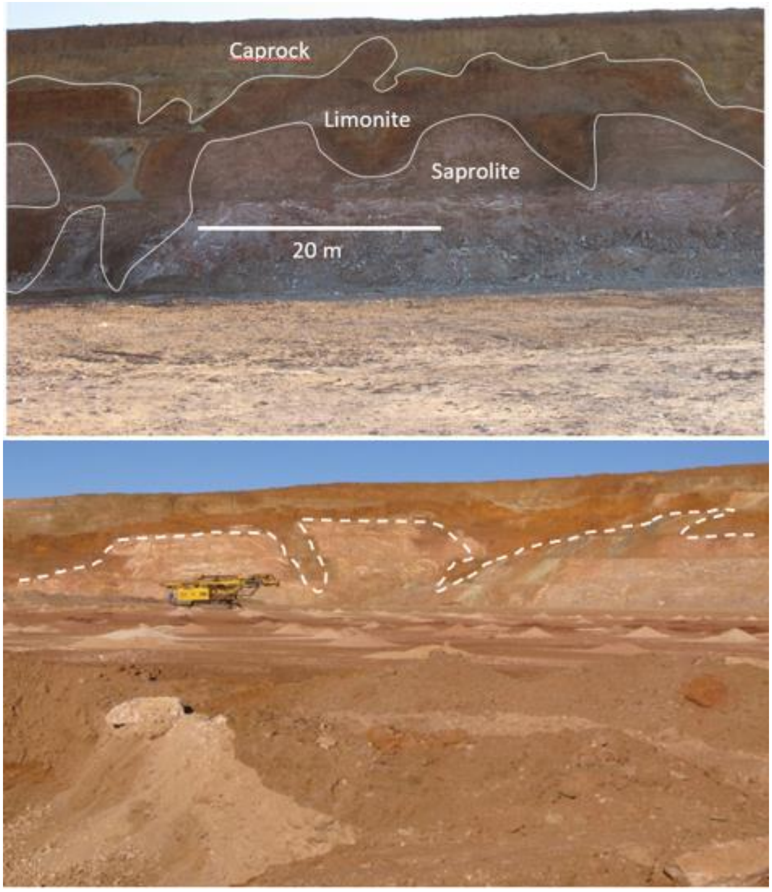

Figure 1. Photograph of pit wall showing the complexity of main material interfaces (top). Note the 20 m scale bar that represents the closest grade control drill spacing. Pre-existing structures control localised, deep weathering, illustrated by the abrupt limonite features traced by the dashed white line (bottom).

Ravensthorpe location and geology

The Ravensthorpe nickel laterite resource comprises five deposits (Halleys, Hale-Bopp, Shoemaker-Levy, Shoemaker-Levy North, and Nindilbillup), which are found on the eastern margin of the Ravensthorpe greenstone belt in Western Australia (BHP, 2003). These deposits were formed by long-term, deep weathering of ultramafic rocks of the Bandalup suite (BHP, 2003), concentrating Ni and Co as a product of weathering processes in the regolith.

Three major regolith layers, or material types, make up the Ravensthorpe deposits: surficial caprock, limonite, and saprolite. The BHP definitive feasibility study (BHP, 2003) describes the caprock as a combination of strongly indurated, ferruginous lateritic residuum and leached, siliceous pedolith. Caprock is considered waste. The limonite layer is goethite-rich and relatively porous, and contains the majority of the Ni resource. Below this is saprolite, with a high clay content, and local zones of magnesite, a carbonate that interferes with the acid leach process. Nickel enrichment occurs in the upper saprolite. Local zones of talc or smectite present processing difficulties but appear to form a very small percentage of the resource. Saprock and fresh ultramafic are classed together in terms of resource modelling, as they do not contain economic Ni or Co, and underlie the resource. The transition to saprock usually occurs from 30 to 60 m below surface. In some areas, the caprock is covered by up to 5 m of unconsolidated sand (Figure 2).

Before proceeding to the plant, nickel ore undergoes a beneficiation process that consists of the physical ore separation of the fine and coarse fractions (BHP, 2003). Silica is largely removed in the coarse fraction, and the fine fraction is an upgraded product that contains most of the nickel. The physical and mineralogical differences between limonite and saprolite dictate that these follow separate beneficiation and processing streams (Krohn, 2004). Limonite is treated by pressure acid leach (PAL), whilst saprolite undergoes atmospheric leach (AL). To improve the nickel recovery using the hydrometallurgical method, it is important to map the interface between limonite and saprolite zones to allow for separate mining of these materials.

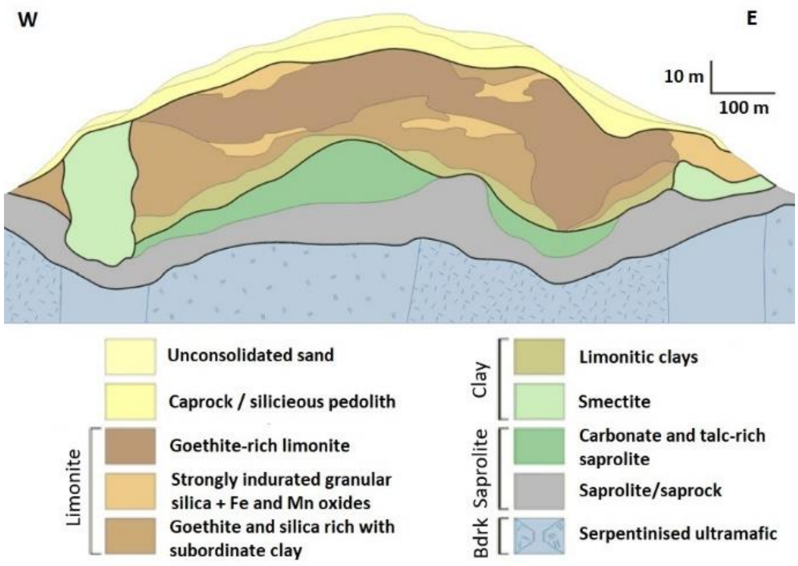

Figure 2. Schematic cross section of regolith layers, adapted from BHP (2003). Limonite, clay, and saprolite contain economic nickel mineralisation. Note 10x vertical exaggeration.

In 2019, a Loupe TEM survey was conducted over the Shoemaker-Levy deposit. This investigation comprises 46 east-west lines ranging in length from 225 m to 1.3 km and spaced by 25-50 m (Figure 3).

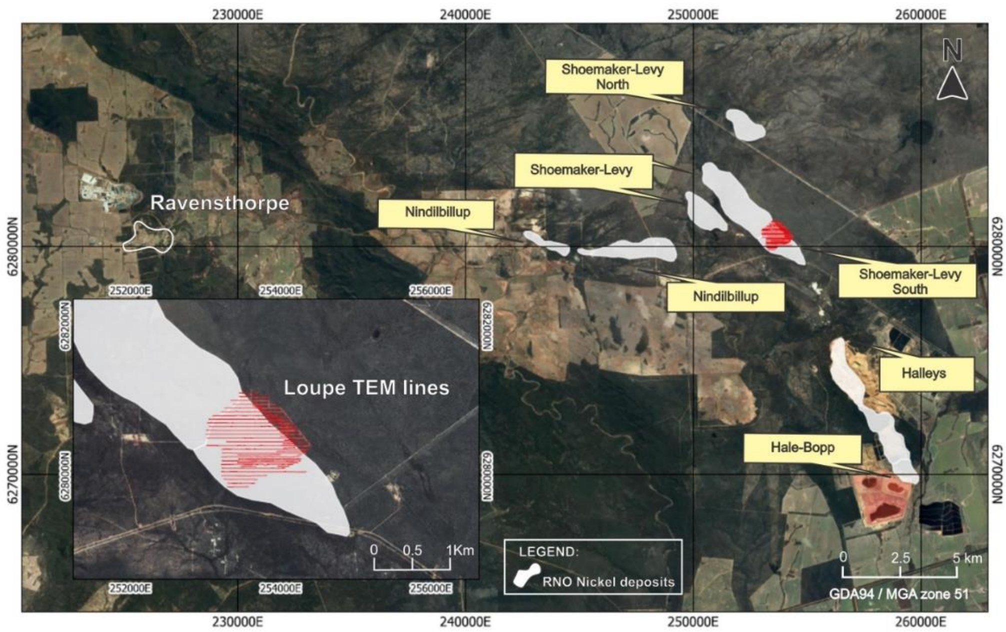

Figure 3. Location of the Loupe TEM lines at the Shoemaker-Levy deposit (Ravensthorpe Nickel Operation).

Loupe TEM

Loupe TEM is a new ground electromagnetic system used to image the shallow subsurface distribution of electrical conductivity (Street et al., 2018). A survey is performed by two people carrying backpacks, one with a transmitter (Tx) coil and one with a three-component receiver (Rx) coil (Van Dam et al., 2020) (Figure 4). The advantage of the Loupe system is its productivity, which is much higher than the moving-loop EM method that uses coils laid on the ground (Van Dam et al., 2020).

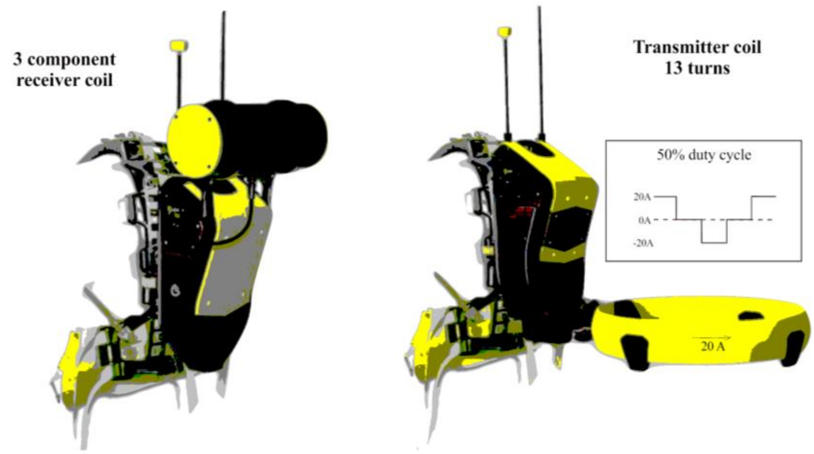

Figure 4. Loupe TEM equipment. Modified from Street et al. (2018).

Conductivity distribution

Clays dominate the distribution of conductivity at Shoemaker-Levy (Figure 5). This is expected, as clays, depending on the quantity, can reduce the bulk resistivity of soils and rocks (Morrison and Becker 2018). The cation exchange capacity (CEC) between the layers of clays contributes to their electrical conductivity (Kaufhold et al. 2014). Electrical current is related to the retained amount of water in the pores of clayey materials (McCarter 1984; Bai, Kong and Guo 2013). This is demonstrated by the relationship between moisture content versus electrical conductivity in the Ravensthorpe data, which is directly proportional (Figure 6). The main regolith layers of caprock, limonite, saprolite and saprock present similar conductivity ranges, which makes it difficult to detect the boundaries between them using EM methods.

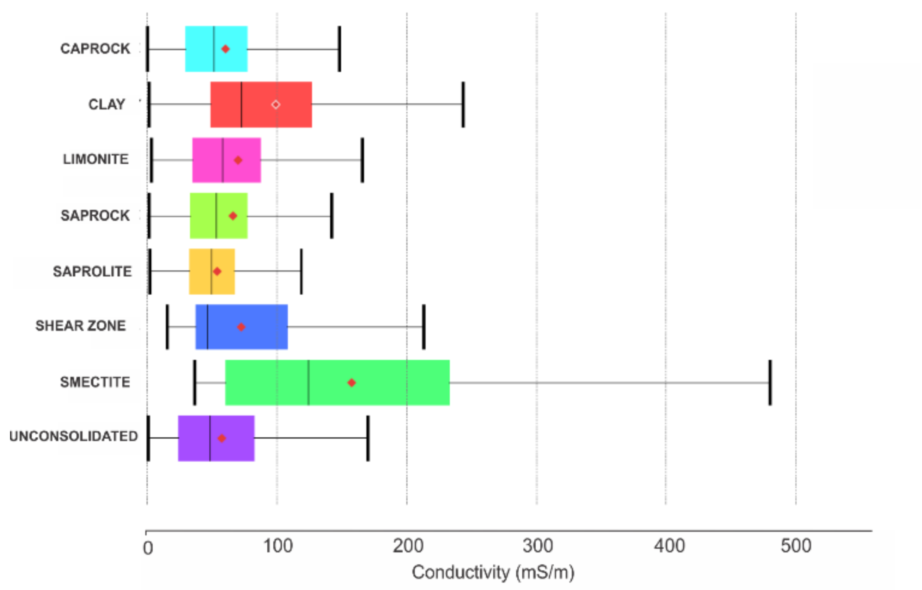

Figure 5. Statistical analysis of Ravensthorpe materials versus electrical conductivity. The red diamond indicates the median value, whilst the thin vertical black line represents the mean value. The solid coloured block contains the range of the conductivity values and the spread indicated between the black bars is 1.5 times the interquartile range. This graph shows smectite as the most conductive material.

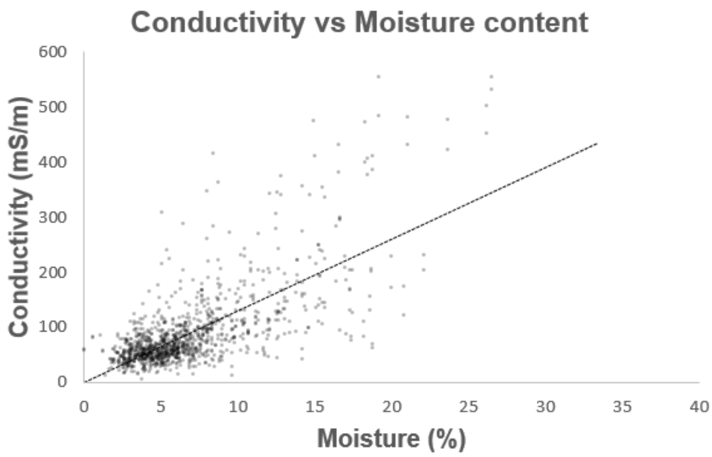

Figure 6. Relationship between electrical conductivity and moisture content at Shoemaker-Levy. While the distribution is scattered, the overall trend is that samples with higher moisture content have higher conductivity values.

A further statistical analysis considers the lithologies within each major material type targeted with the Loupe TEM data. The lithologies within caprock, limonite and saprolite materials are displayed in Figure 7 against their conductivity distributions. TCG, TLC and TSP present the highest conductivity values. TCG is a caprock unit described as fragmental, nodular massive duricrust/mottled zone. TLC belongs to the limonite zone and consists of goethite and silica segregations in sandy clay. TSP is a saprolite-serpentine rich lithology.

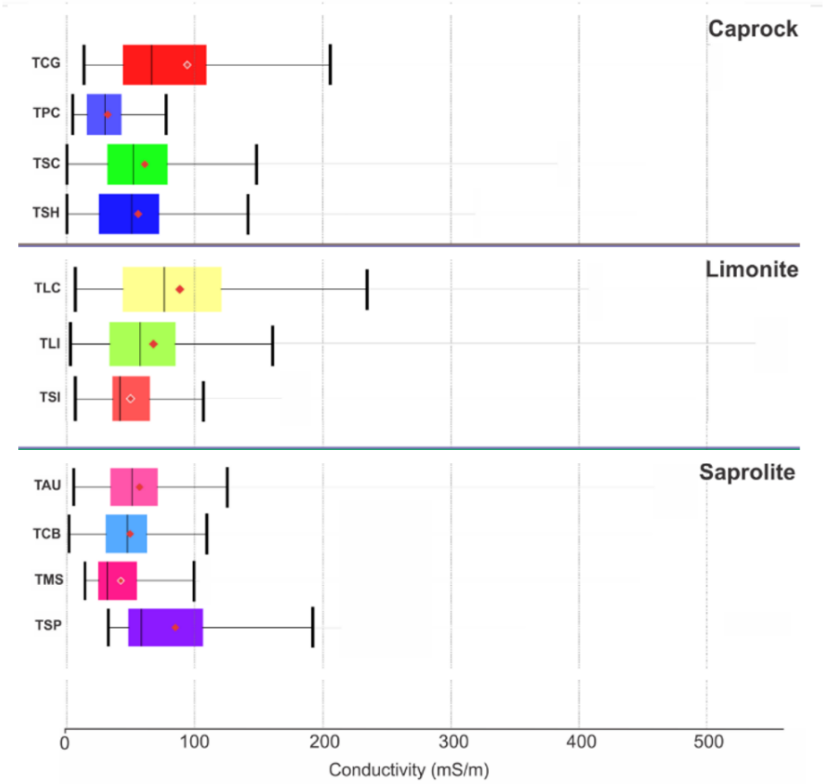

Figure 7. Statistical analysis of the lithologies belonging to caprock, limonite and saprolite materials. TCG: caprock nodular fragmental massive duricrust/molted zone. TPC: caprock pisolitic duricrust. TSC: caprock siliceous duricrust and leached silica and kaolinite clay. TSH: caprock leached, cellular/honeycomb textured silica. TLC: limonite goethite- silica segregations in sandy clay. TLI: limonite goethite- silica rich, w-m indurated laterite. TSI: limonite- silica dominated, goethitic, s. indurated laterite. TAU: saprolite-clay(major) +-Fe+-Si altered. TCB: saprolite- calcium +-Mg carbonate rich. TMS: saprolite -magnesite rich. TSP: saprolite- serpentine rich.

TCG, TLC and TSP are more conductive than the other units because of the quantity and the type of clays included in them (downhole logging description). Table 1 contains the cation exchange capacity values for various clay minerals, showing the large difference between kaolinite and clays such as smectite and bentonite (Christidis, 2013). In clay minerals, the interface conduction of electrical current is directly proportional to its CEC (Weisenberger et al., 2020).

Clay mineral	*Cation exchange capacity (CEC)*
Kaolinite	1-15
Illite, Chlorite	10-40
Montmorillonite (incl. Bentonite)	70-120
Smectite	70-150
Vermiculite	130-210

Table 1. CEC of clay minerals. Modified from Christidis (2013) and Baker et al. (2017).

Figure 8 shows an example of downhole inductive conductivity logging versus visual geological logging. It is apparent that saprolite and limonite zones do not correspond in their entirety to measurable changes in conductivity. High conductivity values present consistent zones that cut across different lithologies. These zones are real and not captured by the geological logging, and their importance remains to be ascertained.

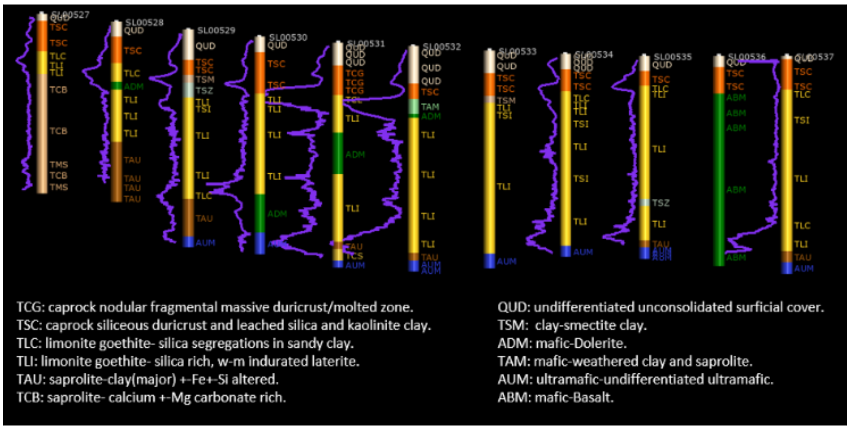

Figure 8. Inductive conductivity versus geological logging.

DISCUSSION

Relationship between geology/geochemistry and the Loupe conductivity model

Similarly to the statistical studies on the petrophysics, the Loupe inverted conductivity values have been sampled against the geology and show that the main regolith materials (limonite and saprolite) have similar conductivity ranges, which makes it difficult for the Loupe system to separate them. Clays, once again, appear as the most conductive material. Caprock and unconsolidated layers are the most resistive lithologies (Figure 9), which is reflected in the well-defined, resistive surface layer in most inversion results. The caprock resistivity is explained by the high content of Kaolinite (low CEC).

The difference in the smectite conductivity range between petrophysical (Figure 5) and Loupe statistics is related to depth accuracy and spatial resolution. The downhole logging is exactly located against lithology whereas the Loupe model includes the uncertainty of an inversion. The smectite zones are localised, which poses a difficulty for accurate inversion imaging.

The inversion results detect the conductivity contrast between caprock and limonite zones. Multiple Loupe models were able to accurately map the thickness of the caprock as defined by resource modelling based on drillhole geology and assays. Figure 10 displays a comparison between the petrophysically constrained model and the base of the caprock surface modelled from drillholes.

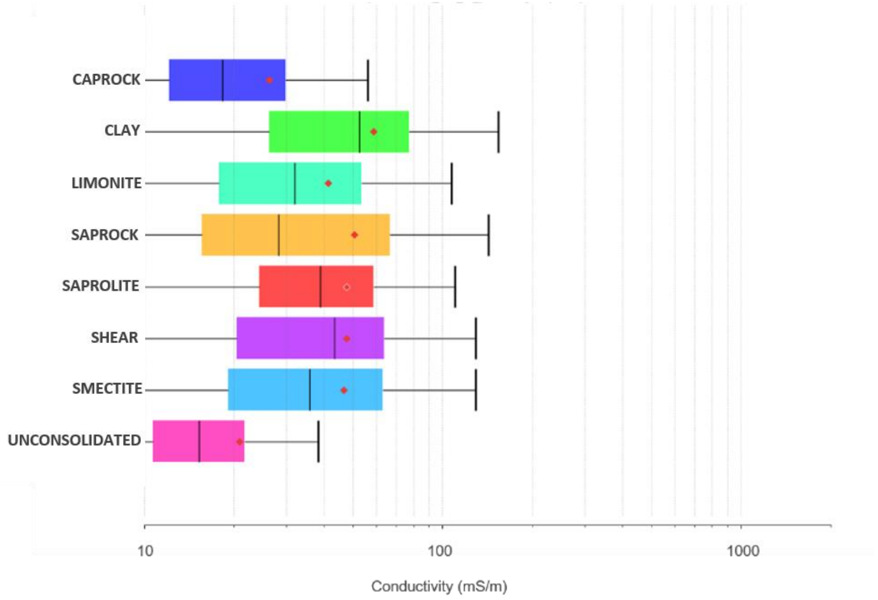

Figure 9. Statistical analysis of Ravensthorpe materials versus electrical conductivity of the Loupe model. The red diamond indicates the median value, whilst the thin vertical black line represents the mean value. The solid-coloured block contains the range of the conductivity values and the spread indicated between the black bars is 1.5 times the interquartile range. This graph shows clays as the most conductive material.

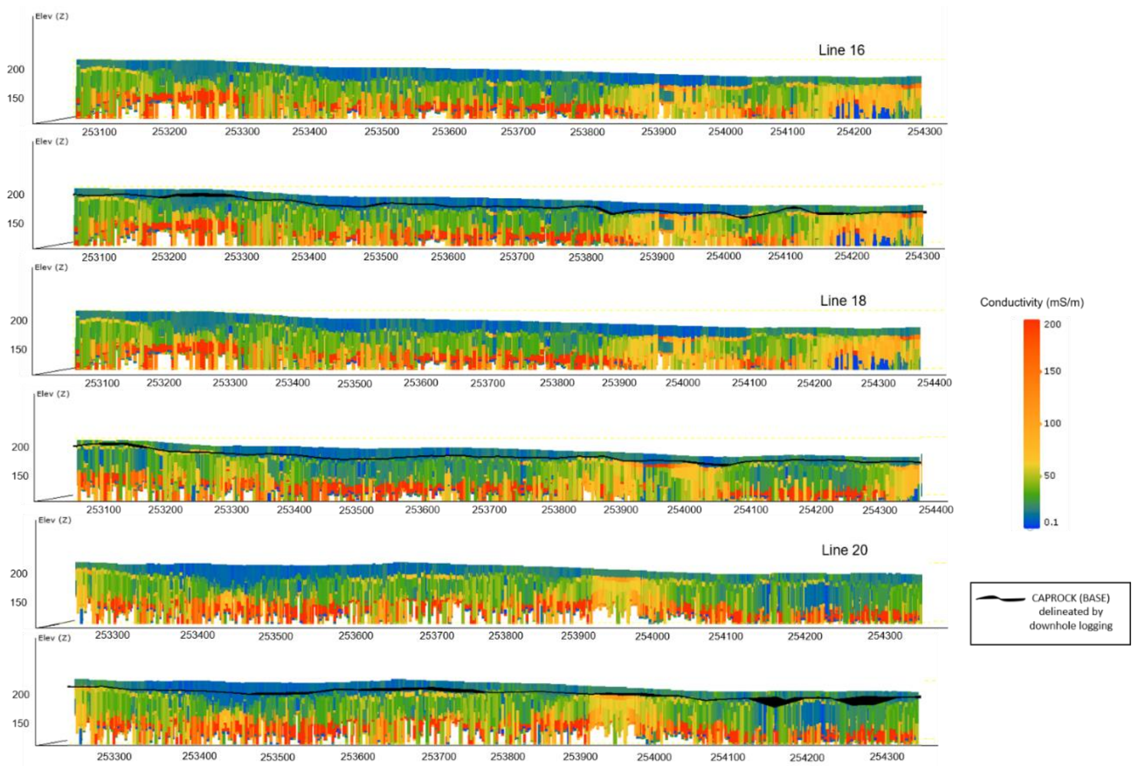

Figure 10. Base of caprock versus conductivity. The black surface represents the interpreted caprock base from resource modelling of drill hole information.

Clays are the main contributing material for the conductivity distribution at Ravensthorpe (section 1.3). Within the limited set of element assays, aluminium is the most related to clays, and there is a correlation between Al % and the Loupe conductivity. This relationship is evident when considering a 2D surface within the limonite zone (Figure 11).

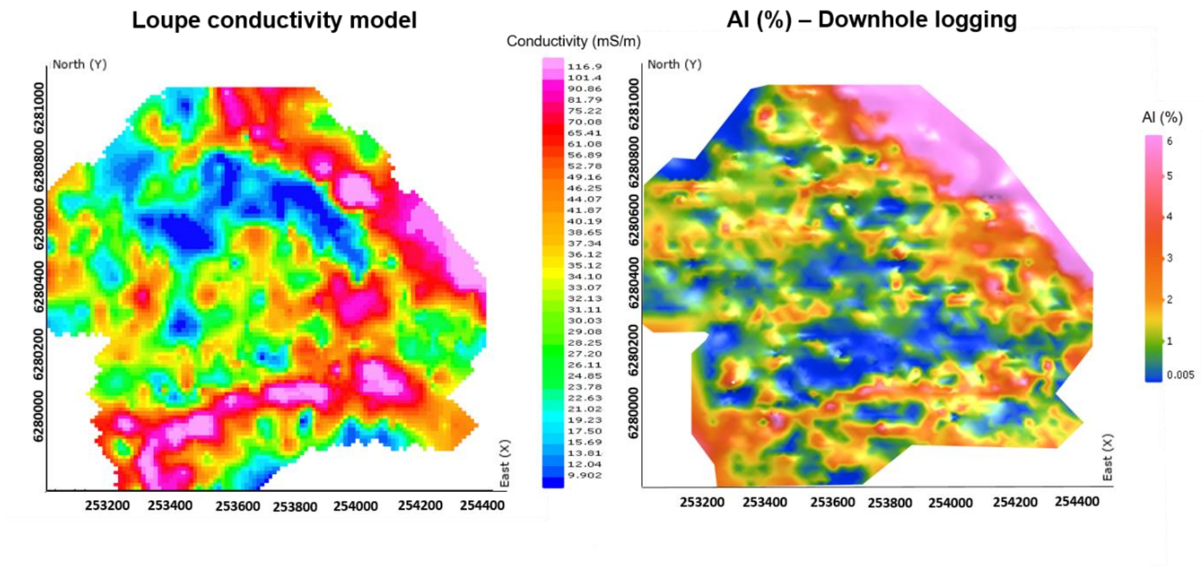

Figure 11. (Left) Inverted conductivity and (right) Al content sampled onto a surface below the top of limonite. Conductivity correlates with the aluminium content, which, below caprock, is mostly related to clays.

CONCLUSIONS

The Loupe TEM appears to be a robust method and has successfully mapped the base of the caprock. Multiple inverse models were trialled, and most could resolve this unit. The limonite and saprolite zones could not be separated, indicating the importance of further investigations with other geophysical methods such as electrical resistivity imaging. The system was also found to have sufficient spatial resolution for imaging thin conductive zones defined by the downhole logging.

Below the caprock within the limonite zone, there is a correlation between conductivity and clays/high Al content. This is backed up by statistical analysis from both petrophysical studies and the Loupe system defining clays as the most conductive materials and, in conjunction with moisture content, a significant influencing factor for the Ravensthorpe conductivity distribution.

The research has shown that the Loupe system has a better lateral resolution than airborne surveys. It validates this technique as an alternative method for mapping the caprock zone thickness in Nickel laterite deposits.

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