Petrophysical properties of the Cobar Province: key deposits to better understand magnetisation

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SUMMARY

Despite our reliance on geophysical surveying in mineral exploration, we have a relatively poor understanding of the link between petrophysical properties (at the scale of <1 metre) and geophysical response (at the scale >100 metres). Drilling campaigns is critical because it bridges the two end-member scales and constitutes rocks that can be sampled and from which observations can be made. There are a range of techniques for measuring rock properties in drill holes and on drill core that vary in cost, time, data quality and resolution. A key question for explorers is: What are the optimum data to collect (and at what resolution) to adequately constrain and make geological sense of our geophysical models? A complicating factor is that petrophysical properties are not routinely collected and reconnaissance techniques (e.g., handheld MagSus) provide only part of the picture.

This study sets out to define a methodology for petrophysical sampling of mineralised rocks using three mineralised drill holes from separate deposits in the Cobar Province. The inspected core are from the structurally controlled New Cobar deposit and two skarn-type deposits, Nymagee and Hera. New Cobar sits nearby to the magnetic high of the Great Cobar deposit. It contains both magnetite and pyrrhotite; however, not all the pyrrhotite is magnetic, which results in a relatively small geophysical signal. The Nymagee anomaly is a strong dipole and holds a remanence component. The deposit preserves both magnetite and pyrrhotite. At Hera, magnetite is completely absent and the deposits is often described as non-magnetic. As shown in this study, all three deposits do have some magnetic susceptibility associated with, or in the vicinity of, mineralisation. Natural gamma radiation response varies and conductivity responses are locally observed (scale <0.5 metre) across mineralisation for the three deposits.

Results of this study are used to develop a methodology that uses core logging tools to support building integrated high-density datasets in drill core analysis. Logging can be assisted by Hylogger data and shows potential as a reference when extrapolating vector data, from laboratory petrophysics, back to the core scale and beyond.

Key words: Cobar, Province, Nymagee, Hera, petrophysics, susceptibility

INTRODUCTION

There is an opportunity in mineral exploration for petrophysical data to be collected, analysed, and interpreted at different scales (e.g., petrophysical round, drill string) to develop methods of upscaling. The best way to improve on such methodologies is to test them in real world scenarios (case studies). A case study area should be relatively well understood with independent data on petrology, geochemistry and/or isotopic dating. It should also provide a challenge such as magnetic minerals with some complexity i.e., a mix of (monoclinic) pyrrhotite or magnetite associated with skarn.

The Cobar Province in NSW hosts numerous Au, Au-Cu and Pb-Zn-Ag deposits that have been categorized as epithermal, structurally controlled, skarn-type and VAMS systems. In general mineralisation sits within structurally controlled lodes, limited to a few hundred metres in width, but with up to more than a kilometre depth extent. With a long history of mining in the Cobar Province, there has been extensive exploration programs and much research done along the fault margins associated with the CSA, Cobar, Peak and other early discoveries (Figure 1).

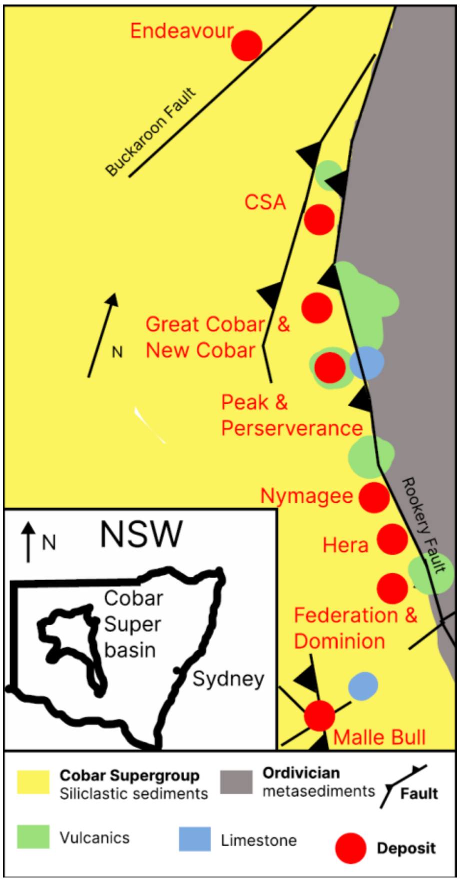


Figure 1. Sketch of Cobar Province deposits, their relative location and major fault and intrusives. Redrawn after David V., 2018.

Geophysics continues to play an important role in the discovery of deposits in the Cobar Province. However, more recent discoveries such as Hera and Federation (Aurelia Metals Limited, discovered by Lead Soil Geochemistry, Gravity surveys, Induced Polarisation and Fixed Loop Electromagnetics), indicate a decreasing likelihood that future successes will be based on drilling the 'bullseye' of a magnetic highs.

Geophysical models of pyrrhotite dominated deposits, where constraining parameters are collected solely by using handheld magnetometer, are unlikely to be in perfect correlation with the geophysical signal. Part of the anomaly will likely be caused by remanence from magnetic (monoclinic) pyrrhotite. By adding petrophysical parameters from laboratory measurements, and with interpretation that makes geological sense, the geophysical model can be constrained and improved on. However, the last published laboratory petrophysical work on the province was done more than 20 years ago. Clark and Tonkin (1994) did highlight that the Endeavour and Magnetic Ridge (close to CSA mine) hold significant remanent magnetisation, with strengths up to eight times that of their induced magnetisation. As outlined by Fitzherbert and Downes (2021), these northern deposits were affected by an additional fluid event during the late Tabberaberan inversion. It is still unknown what the petrophysical characteristics are for other pyrrhotite dominated deposits that were not metasomatized during this last fluid event.

This study sets out to define a methodology for petrophysical sampling of mineralised rocks using three mineralised drill holes from separate deposits in the Cobar Province. The inspected core are from the structurally controlled New Cobar deposit and two skarn-type deposits, Nymagee and Hera. New Cobar sits nearby to the magnetic high of the Great Cobar deposit. It contains both magnetite and pyrrhotite; however, not all the pyrrhotite is magnetic, which results in a relatively small geophysical signal. The Nymagee anomaly is a strong dipole and holds a remanence component. Together these deposits provide complexity in geophysical signal and their different mix of magnetite and pyrrhotite (magnetic and non-magnetic) are distinctly different (Table 1.).

Table 1. Review of (magnetic) minerals in the Cobar Province. Compiled after Downes et. al. (2016) and Edgecombe and Soininen (2019).

Deposit	Magnetite	Pyrrhotite	Hematite
Endeavour		Primary	
CSA	Secondary	Primary	Minor
Great Cobar	Secondary	Primary	Minor
New Cobar	Secondary	Primary	
The Peak		Primary	
Perseverance	Minor	Primary	
Nymagee	Secondary	Primary	
Hera		Primary	
Mallee Bull		Primary	
Federation		Primary	

DATA INTEGRATION AND SCALING

Integration of various datasets, including petrophysics, will maximise its use at a variety of scales. However, the datasets themselves are collected at different scale and will represent different sample components of a rock. For example, handheld magnetometer data is often the first data at hand that can be used to evaluate the magnetic properties of drill core and is collected on a spot-by-spot basis. However, the density of the dataset will be dependent on the amount of time available to collect the dataset and needs is a trade off with understanding the scale of magnetic vectors to mineralisation. Spectral data collection programs (e.g., HyLogger^{TM}) is high density (continuous) data. Maximising the value of petrophysical (and other) datasets on drill core requires integration of results to a format usable in geological interpretation of features including faults, shear zone, lithological boundaries and alteration zones. However, data integration is hampered by:

- Selection of a sampling interval that is appropriate to the task. For example, if the question relates to veins and bands of mineralisation, then the petrophysical data and other techniques needs be at a scale able to distinguish between veins and matrix.
- Consideration of the analytical technique sample size and volume, which may result in variations in what part of the sample the data represents (volumetric versus surface analysis) and the size of the analysed area (Table 2).
- Retrofitting sampled core by comparing photos with Hylogger photos (or other) can take a lot of time and provide some challenges when the rock is part look homogenous.
- Different dimensions of core, half/quarter cut, trouble in the 2D half-space (Schmidt and Lackie 2014),

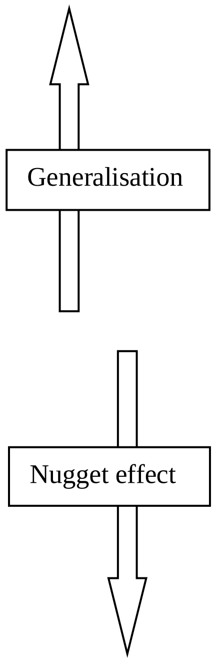
If the data are collected systematically, they can be averaged, filtered, or clustered in ways so that they make more sense at the scale of interest. How much will depend on the complexity of the system and the question that needs to be answered. At some scale we need to accept that laboratory measurements are necessary to provide more detail and might be much more insightful and even cost efficient. However, the number of samples that can be taken to the laboratory is limited by access, core dimensions and whether the rock can withstand being resampled without breaking.

There is value in doing logging systematically and repeatable at each step. The methodology should make sure that each dive-in that is done on spots are spatially relatable to a larger scale (same spot on the drill core). You could argue that if this is done while having enough statistical assurance generalisation it would be a done deal. However, you can also argue that high-resolution data should be positioned so that it is characteristic (representative) to its domain and therefor can be generalised (upscaled) on a larger sample group (lithology and/or zonation).

The preferred way is likely: 1. The statistics component relates to rolling-average-filters and clustering algorithms. 2. Making sure the data is characteristic of the domain relates to geologist analysing the data from a domain knowledge lens and making a judgement on what is relevant to answer the question at hand.

Table 2. List of common instruments and techniques used in core logging and their respective sensor/sample size and type of raw (data) outputs.

Instrument / Technique	Size / Spot window / sensor sensitivity	Output
Acid Digestion	1 metre	Traditional assays (elements such as Cu, Fe, Pb, Zn, and As).
Cut core	6 to 20 cm	Photos and set of subsamples for detailed lab studies
Hylogger (automated technique)	every 1 cm (continuous)	Interpreted mineralogy (from spectra)
Radiometer	5 by 5 cm	Natural Gamma Radiation records (dose rate and calculated U, Th and K)
Handheld magnetometer	Similar to the Radiometer but core size is adjusted for by settings: full/half core, AQ to PQ sizes and 2.4 cm to 12 cm.	MagSus and Conductivity (induced)
Subsamples for lab (Paleomagnetic round)	2 cm in diameter and 10 cubic centimetre cylinder.	Vector data for remanence and anisotropic magnetic susceptibility
pXRF (handheld tool)	3 mm beam (and spot window)	Multi-element geochemistry



METHOD

Core logging and sampling for lab petrophysics were conducted at the WB Clark Geoscience Centre in Londonderry, NSW. All core was logged by the Geological Survey of NSW by Hylogger^{TM} techniques and mineralised sections had been cut for assays. The core available was mostly half or quarter core of NQ diameter. MagSus and conductivity were collected on with a KT10 magnetometer at 0.5 and 1 metre intervals across mineralisation in three drill cores (one from each deposit). A couple of high MagSus values for the Nymagee core had to be recorded using a MagRock magnetometer. Those spots also lack conductivity records as a result. Natural gamma radiation data was collected at the same spots using a RS-125 (Radiation Solutions Multipurpose Gamma-Ray Spectrometer). Measurements are taken directly on the core (preferably on a flat surface) and measurement time in this study is set to 120 seconds sampling time.

Density measurements were done in the lab using a Mettler Toledo MS204TS analytical balance and the Archimedes principle. Magnetic bulk susceptibility was measured using an Agico MFK1-A Kappabridge magnetometer. The magnetic susceptibility was corrected for volume variations (from the 10 cm3 sample cylinder standard), using the density measurements' volume determinations.

The first set of results logging and was compared with the Hylogger spectral data. The Hylogger data is publicly available (through NSW Survey Portal – Minview), and the physical core can be viewed on request. NSW Geological reports and assays were also used for referencing as well as confidential company assays. Both survey reports and company data can be inquired for through the DIGS (Digital Imaging Geological System) NSW geoscience records repository. The intervals logged are: New Cobar core DD09NC099 - 387 m to 540 m; Nymagee core NMD068 - 187 m to 277 m; and Hera HRD003 - 342 m to 414 m. More for each drill hole than twenty samples for from each drill hole were collected and redrilled for laboratory measurements.

RESULTS

New Cobar

The New Cobar core (Figure 3a) is dominantly of low magnetic susceptibility with a major peak at ~408 metres just before the mineralisation. There is also one single point measurement of very high conductivity. This is located at 438 metres just after main mineralised part of this core. As can be seen in the Hylogger data (both SWIR and TIR) the interval between 430 to 455 metres is rock rich in sulphides and minerals that aspectral (minerals that cannot be classified by the Hylogger). Note further that there is also another smaller zone recognised in the SWIR data (with chlorite and aspectral) in the metres above the high magnetic susceptibility readings. The radiometric data has a weak trend with lower dose rate across towards the mineralisation and to then back up again after. The lab samples from New Cobar show a linear relationship from low-density-low-magnetic-susceptibility to moderate-density-moderate-magnetic-susceptibility (Figure 2). The values are in line with what is expected of part non-magnetic part monoclinic pyrrhotite.

Nymagee

The Nymagee core (Figure 4a) show low magnetic susceptibility, but with an increase across a mineralised zone within the 190 to 220 metres interval. The KT10 had some issues measuring magnetic susceptibility on core with copper ore and a MagRock magnetometer had to be used for a couple of the moderate magnetic susceptibility readings. These moderate values, between 215 to 222 metres, correlates well with a majority of aspectral in the Hylogger data (both SWIR and TIR). Another strong feature both these logs can be found at 208 to 212 metres with spectral data interpreted as hornblende and chlorite. This also coincides two moderate conductivity readings. The dose rate from the natural gamma radiation is consistent across the full length of the measurements. A slightly larger core diameter needs to be considered before comparing dose rate of Nymagee with other deposits in this study. The NMD068 is half-core 6 cm diameter compared to NQ 4.7 cm) core for the other deposits. The lab samples from Nymagee show (Figure 2) low magnetic susceptibility but a range of densities (2.6 to 3.6 g/cc).

Hera

The Hera core (Figure 5a) shows minimal to no magnetic susceptibility except for a small but genuine peak at around 401 metres. This coincides with Hylogger SWIR data showing an increase in interpreted hydrous sulfates, chlorite, and feldspars. The peak in magnetic susceptibility is approximately 10 meters deeper than a zone of moderate conductivity and an abrupt decrease in the dose rate from the natural gamma radiation. The transition is in the Hylogger SWIR large weight on quartz and in TIR on chlorite and aspectral. The lab samples from Hera show (Figure 3) as a tight cluster with close to no magnetic susceptibility and narrow band of densities. Both properties are close to that expected of surrounding host rock.

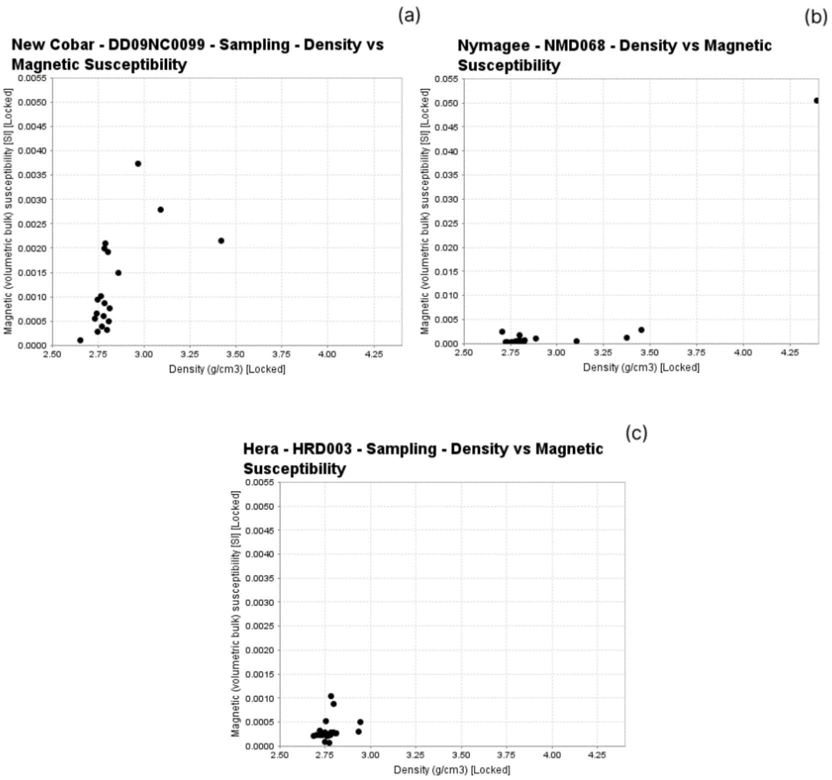


Figure 2. Density vs Magnetic susceptibility from laboratory measurements for (a) New Cobar; (b) Nymagee; and (c) Hera. Sampling was limited to approximately 20 samples per deposit.

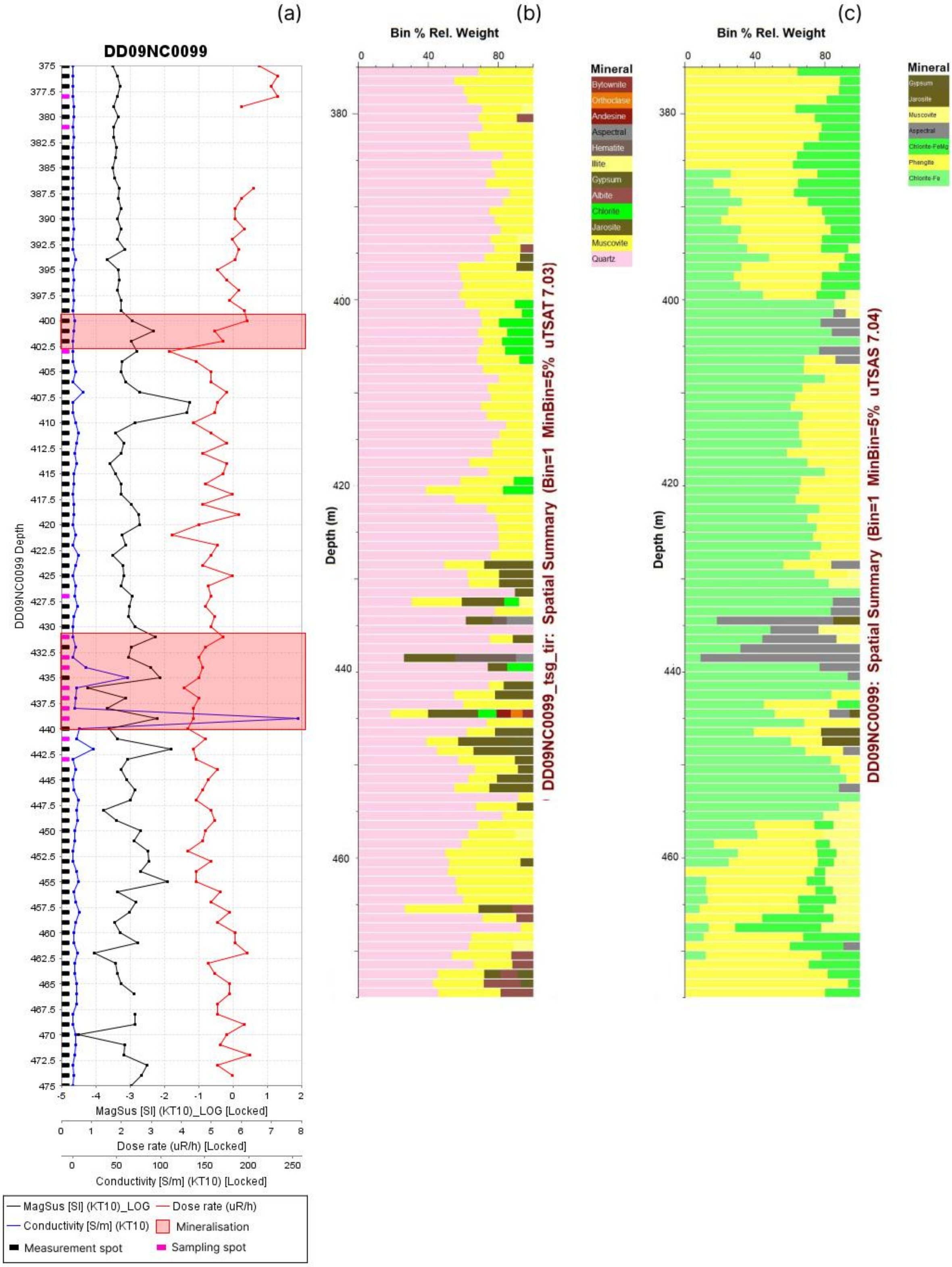


Figure 3. Downhole logs for the New Cobar deposit drill hole DD09NC0099. (a) MagSus, Conductivity and Dose rate (Natural gamma radiation); Interpreted mineralogy (as weighted % bars) from (b) Hylogger SWIR (Short-wave infrared) spectral data; and (c) Hylogger TIR (thermal infrared) spectral data.

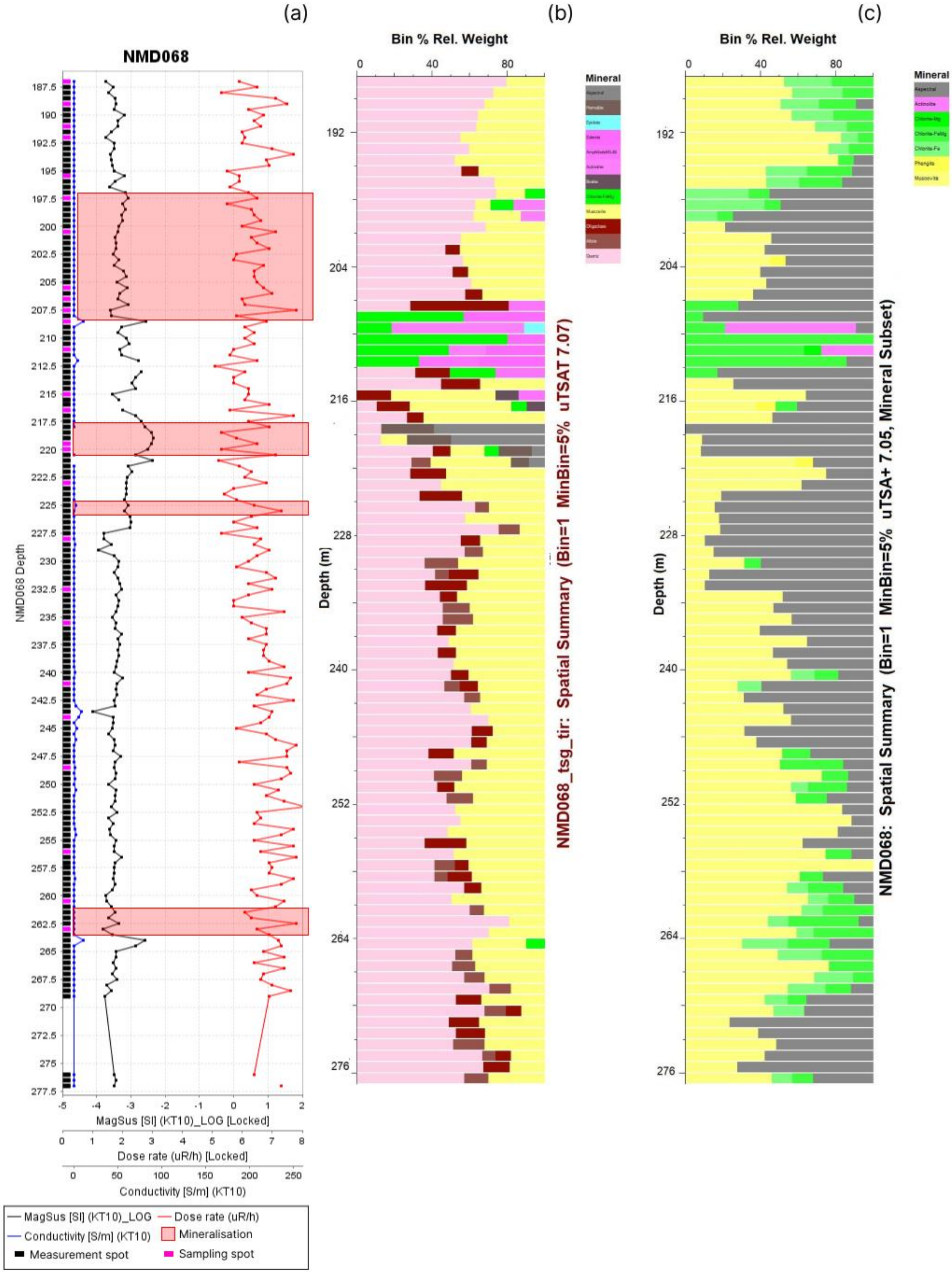


Figure 4. (a) Nymagee: Downhole logs for MagSus, Conductivity and Dose rate (Natural gamma radiation). (b) Downhole Hylogger SWIR (Short-wave infrared) spectral as interpreted mineralogy as weighted % bars. (c) Downhole Hylogger TIR (thermal infrared) spectral as interpreted mineralogy as weighted % bars.

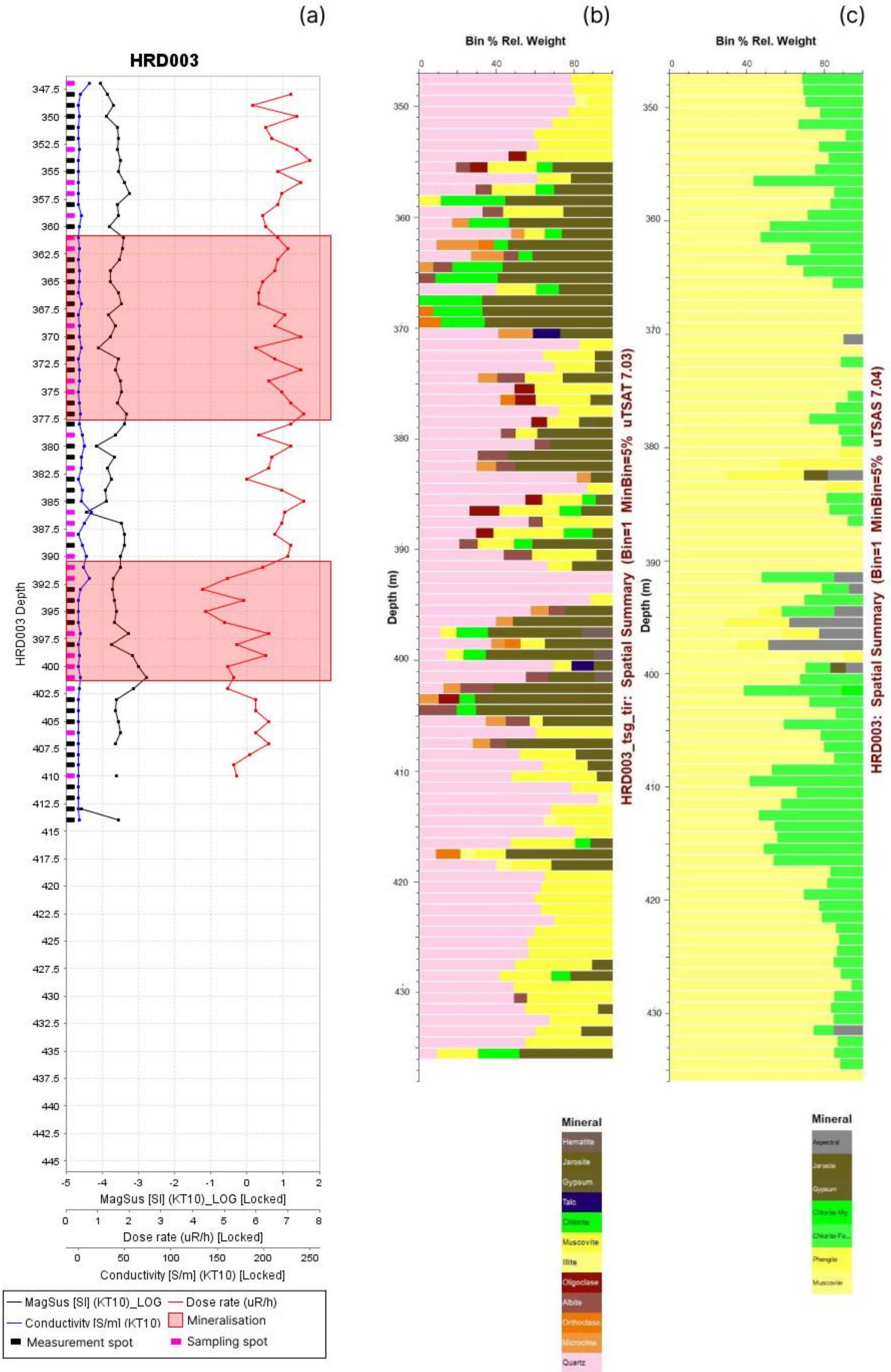


Figure 5. (a) Hera: Downhole logs for MagSus, Conductivity and Dose rate (Natural gamma radiation). (b) Downhole Hylogger SWIR (Short-wave infrared) spectral as interpreted mineralogy as weighted % bars. (c) Downhole Hylogger TIR (thermal infrared) spectral as interpreted mineralogy as weighted % bars.

DISCUSSION

Petrophysical sampling generally tends to focus on the mineralised zone and alteration haloes. Our preliminary data shows magnetic susceptibilities equivalent to what often would be considered as 'non-magnetic' or that of host-rocks. For the core investigated, moderate magnetic susceptibilities are found within narrow intervals of around one (New Cobar) and twenty (Nymagee) metres. The core from Hera does have an increase in the magnetic susceptibility at around 400 metres. This sits at the lower end of the mineralisation and drop in white mica Al-OH absorption (less phengite) (Figure 5c).

Logging magnetic properties at a 1 metre interval provides poor resolution for the New Cobar core. The first set of lab measurements confirm the results from the logging, but one or two points could still be the result of a 'nugget' effect. Measurements of conductivity always come with some uncertainty and the results suggest that the interval between measurements should be smaller. Performing more measurements is a 'quick' way to find out whether peaks in conductivity is an effect to a few nuggets/veins or a property representative to the lithology.

A second round of magnetometer measurements was done on the Nymagee and Hera core at a higher density of 0.5 metres intervals. The results for the MagSus were clearly improved, however the higher density readings were not sufficient for the conductivity. For Nymagee a second round of measurements were also done with the radiometric tool. Although this makes the data at first look noisy there is no doubt the trend of dose rate across the Nymagee mineralisation is more consistent than that of New Cobar and Hera.

Downes et al. (2016c) did a petrographic determination for HRD003 from thin section and compared these with the interpreted minerology from the Hylogger. Two lithologies match the before and after the 407 metre depth: Chlorite–epidote–carbonate-veined metasiltstone (thin section at 398.5 metre) and coarse-grained biotite flooded metawacke (thin section from 309.6 metres). This may seem like a backwards way of logging core, but this is of course only the start. Lithologies can be determined in many ways and many times the scale is very subjective.

In the results in this study hydrous sulfate and aspectral were used to give an indication of the depth extent of mineralisation in these cores. Hylogger data can be scaled and subsampled. More importantly the depth in metres and centimetres is exact. This means that any sampling of core and the data that comes with laboratory measurements becomes backcompatible with the Hylogger data. While the Hylogger cannot identify all types of minerals, it has the potential to be integrated with other techniques such as pXRF to provide lithology logs that are objective and can be scaled.

CONCLUSION

This abstract covers the first steps to develop an integrated petrophysical approach for Cobar-style deposits, that draws on minerology and petrology, and where sampling interval is set to address the influences of alteration events. A petrophysical deep-dive comparison study of the magnetic minerology of the classic Cobar deposits is necessary to fully understand optimal sampling intervals and techniques to produce fully integrated datasets in the Cobar Province.

The preliminary results from central and south Cobar show density and magnetic susceptibility contrasts are as narrow in extent as the mineralisation. As this research continues is will become clearer whether petrophysical contrasts at the Cobar deposits are associated with veins and bands exclusively or if there are gradual transitions. Drill core logging using a handheld magnetometer alone, with 1 or 0.5 metres, does not provide data at a resolution high enough to discriminate key magnetic features. Reducing the sample interval and tying it together with indexing and Hylogger™ data (spectral and optical) will remove this bias.

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