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Airborne EM for mine infrastructure planning

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Abstract. Airborne electromagnetic (AEM) surveys with near-surface vertical resolution provide rapid and comprehensive coverage of a mine site ahead of infrastructure planning. In environments of sufficient electrical conductivity contrast, the data will map variations in the depth to bedrock, providing guidance for expected excavation depths for solid building foundations, or mine pre-strip volumes. Continuous coverage overcomes the severe areal limitation of relying only on drilling and test pits. An AEM survey in northern Finland illustrates the success of this approach for guiding the placement of a mine crusher and related infrastructure. The cost of the EM data collection and interpretation is insignificant in comparison to the US$300 million capital cost of the mine infrastructure. This environment of shallow glacial cover challenges the limits of AEM resolution, yet analysis of subsequently collected three-dimensional (3D) surface seismic data and actual pre-strip excavation depths reinforces the predictive, but qualitative, mapping capability of the AEM. It also highlights the need to tune the modelling via petrophysics for the specific goal of the investigation, and exposes the limitations of visual drill core logging.

Key words: airborne electromagnetics, mine infrastructure, overburden mapping, seismic tomography.

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Introduction

Planning infrastructure for a mining project depends on knowing ground conditions over the site. The main geotechnical approaches used, drilling and test pits, and sometimes single resistivity or seismic refraction lines, suffer from severe areal under-sampling. Point measurements are expected to represent large areas, and engineers extrapolate and interpolate from the geological logging of sparse drillholes to characterise sites for various elements of mine infrastructure. Errors in site characterisation can result in costly extra earthworks or wholesale changes in infrastructure layout.

The placement of crushers is one of the main concerns when developing a mine plan. Constrained by factors such as topography and proximity to ore source, crusher sites must be excavated to solid bedrock for proper foundations, and therefore finding bedrock close to surface translates into lower excavation costs. Given suitable conductivity contrasts between overburden/weathered rock and solid or fresh rock, an airborne electromagnetic (AEM) survey with good vertical resolution in the near surface can be used to map the variations in depth to bedrock. This provides rapid and consistent coverage of an entire mine lease. Properly used, such a dataset informs follow-up geotechnical drilling to confirm geophysical results.

First Quantum Minerals Ltd bought the Kevitsa Ni-Cu-PGE (platinum group elements) deposit in northern Finland in 2008 as part of a strategy to diversify from copper production in the African Copperbelt. This disseminated sulphide body has a measured and indicated resource of 240 Mt that averages 0.3% Ni, 0.41% Cu and 0.47 g/t PGE. This translates to contained metal of 720 000 t of Ni, nearly 1 Mt of Cu and 112 t (3.95 Moz) of PGE (Lappalainen and White, 2010). The deposit is hosted in a mafic-ultramafic intrusion within the Central Lapland Greenstone Belt, surrounded by interlayered volcanic and sedimentary rocks. Subsequent to more resource definition drilling after the purchase, the company came to a decision to develop the mine in late 2009, with construction to begin mid-year 2010. This left little more than six months to finalise the infrastructure plan, including the important task of choosing the site for the crusher, through which the remainder of the plant infrastructure would be constrained.

Glacial till covers the entire Kevitsa mine lease, and is an unsuitable foundation for many buildings. Although the till mostly varies from 0 to 10 m in depth, previous exploration drilling encountered up to 20 m of till, as well as very fractured bedrock to even greater depths. The engineering design team wished to excavate as little as possible, to a maximum of 15 m, for preparing the foundations of any infrastructure. Drillholes were sparse outside of the resource area, so the company turned to AEM to map the depth of till across the entire lease. Coupled with geotechnical drilling, the results were used to modify the initial mine layout and reposition the crusher and associated infrastructure.

Method and results

The SkyTEM 304 time-domain system (Sørensen and Auken, 2004; Auken et al., 2009), which can record very early off-time channels starting at 6 µs, was chosen to map the thickness of glacial till during the winter of 2010, prior to construction. This system employs a dual moment transmission, alternating between low and high currents in the loop. The turn-off time is very quick after the low moment transmission, and this allows for very early (therefore near-surface) recording times. Even this system is, in fact, incapable of resolving depths of a surface conductive layer much less than 10 m, but it remained one of the best choices for the exercise, and a statistical inversion approach pushes the limits of shallow vertical resolution to better than what is achievable with a single inversion result. The low moment measurements, with a peak moment of ~3140 Am^2, were sufficient for the mapping exercise, although both high and low moments were eventually used in the inversions by the contractor. Lines were flown at 50 m spacing across the entire mine lease, with the EM transmitter loop travelling 30 m above the ground. Previous petrophysical resistivity logging indicates a sharp contrast between the conductive overburden and fresh bedrock. The glacial till overburden is a mixture of clays, sand, transported boulders and peat (Figure 1). The transition between the overburden and bedrock layers is usually rapid, with a very thin weathering layer at the top of bedrock. Both the geological environment and the petrophysical data suggest that AEM would successfully map the depth to the overburden-bedrock interface. Inversion of the EM signal into conductivity versus depth served as the basis for picking this interface that would represent the transition from overburden to intact bedrock.

Petrophysics

In the mine development or operational environment, where risk tolerance is low, it is essential to understand the petrophysics of the rocks to be mapped before deciding on a survey method. Kevitsa is endowed with a large and high-quality database of downhole (in situ) petrophysical measurements collected over many years of exploration. There are few inductive conductivity measurements, but a large number of galvanic resistivity data, including measurements through the transition from overburden to fresh rock. Although galvanic resistivity is less directly related to an AEM survey, the volume and distribution of readings at Kevitsa makes this a more robust dataset from which to study the conductivity of the different geologic layers. Figure 2 illustrates that the conductivity contrast between overburden and fresh rock is large and happens rapidly. The conductivity of weathered and highly fractured bedrock sits in an intermediate population that is nonetheless separate from overburden, and therefore mappable.

EM inversion

The EM data were inverted using a laterally correlated 30-layer model (Christensen et al., 2009). The top layer is 1 m thick to account for the often present thin layer of glacial till, and layer thicknesses increase slowly with depth. Vertical resolution of features within 10 m of the surface taxes the capability of any AEM system, so in order to pick a base of overburden, SkyTEM employed a statistical inversion approach. For each sounding, 1000 models are created by perturbing the best fitting model using the posterior covariance matrix of the inversion models as a prior covariance measure of the perturbation. For each layer, a tally is kept of the number of model realisations that fulfils a chosen resistivity threshold criterion – less than 500 Ωm, for example – that classifies these layers as 'overburden' versus 'bedrock'. This tally is converted into a likelihood of the resistivity being below the threshold, and a global likelihood value – greater than 50%, for example – is used to discern between 'overburden' and 'bedrock', and hence choose the depth of transition.

Fig. 1. Typical profile through the glacial till of northern Finland. This till layer is usually 0–10 m thick around the Kevitsa mine site.

EM-derived overburden depth

The overburden depth was picked using a resistivity cut-off of 500 Ωm. This ensures, according to the petrophysical statistics (Figure 2), that highly weathered and fractured bedrock is included in the overburden category, since such ground would be unsuitable as a foundation for the crusher. At the time of initial planning, there were no drillholes around the crusher location. A few test pits were dug, and these encountered hard rock at depths less than 5 m. Based on logged overburden to ~10 m depth in the prior exploration drillholes nearest the crusher site, and the new test pits that recorded overburden to no more than 5 m, the engineers were ready to interpolate between these to interpret a suitable site for construction. The EM results in Figure 3, on the other hand, show a deepening of the overburden past 30 m, which is far beyond the maximum acceptable excavation depth. These conflicting results cast doubt on the reliability of the existing infrastructure plan. More geotechnical holes were drilled, as shown in Figure 4, to investigate the construction site. These new holes confirmed the EM results. Logging comments are included on the figure and show the extraordinary depth of intense fracturing and weathering around this location. The primary conclusion is that previous logging, and especially test pits, recorded the extent of glacial till up to the first instance of bedrock, regardless of whether this layer was followed by intense fracturing and weathering. The later geotechnical holes recorded alternating fractured bedrock and clay/sand layers, which were never apparent in the test pits that stopped when the excavator shovel first hit bedrock. Most

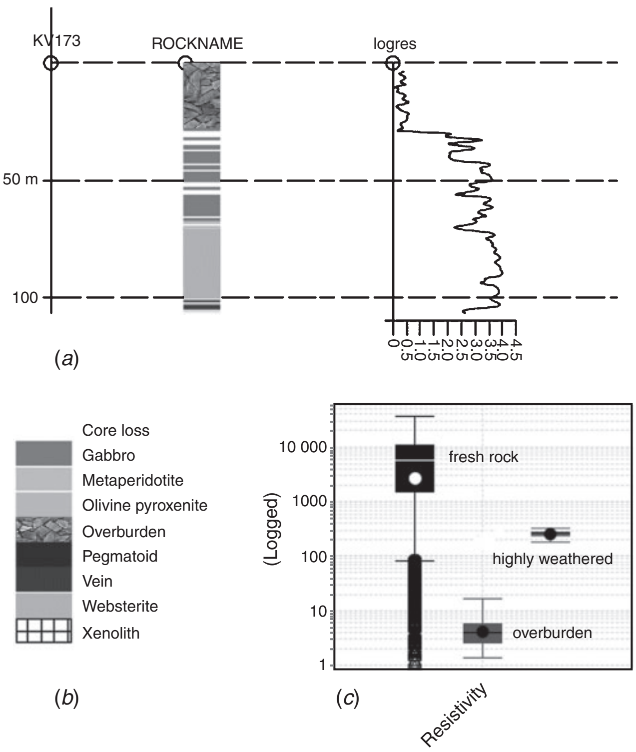

Fig. 2. (*a*) Downhole galvanic resistivity profile showing a typical jump at the interface between overburden and bedrock. (*b*) Lithology legend for (*a*). (*c*) Galvanic resistivity statistics from ~80 downhole logs across the resource area illustrate the distinct classification between overburden, fresh rock, and highly weathered bedrock.

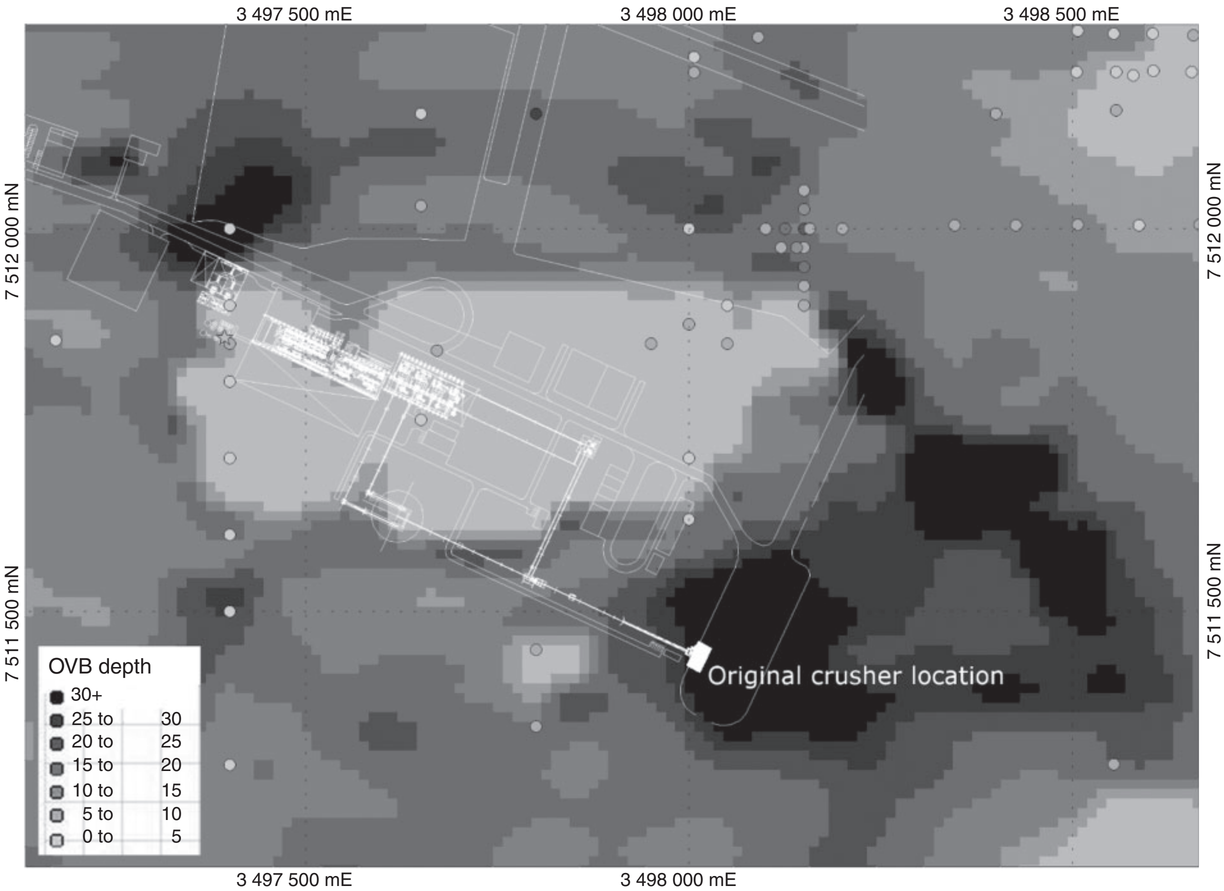

Fig. 3. Overburden (OVB) depth around the plant site derived from AEM data. Drillhole collars are coloured according to logged depth of overburden using the same scale as the EM-derived depth, where black is more than 30 m.

strikingly, at the original crusher site, these periodic clay/sand layers and fractured bedrock persist to 50 m depth, which would have been disastrous for the construction phase.

On the strength of the EM results, supported by new geotechnical holes, the plant infrastructure was shifted ~150 m to the north-west (Figure 4). This brought the crusher onto shallow bedrock according to both EM and drilling results, which now satisfied the engineering team. The EM mapping exercise cost US$75000 for data collection, processing and inversion for bedrock depth, and saved the company from placing US$300 million worth of crusher and plant infrastructure on unsuitable ground.

Figure 5 compares the EM-derived overburden depth to that derived from visual drill core logging. The correlation is quite poor, with the EM-derived depth usually much greater than the logged depth. As explained above, the visual core logging, like the test pits, recorded overburden depth at the first instance of bedrock, whereas the EM inversion was 'tuned' through the 500 Ωm threshold to include areas of highly weathered and fractured bedrock.

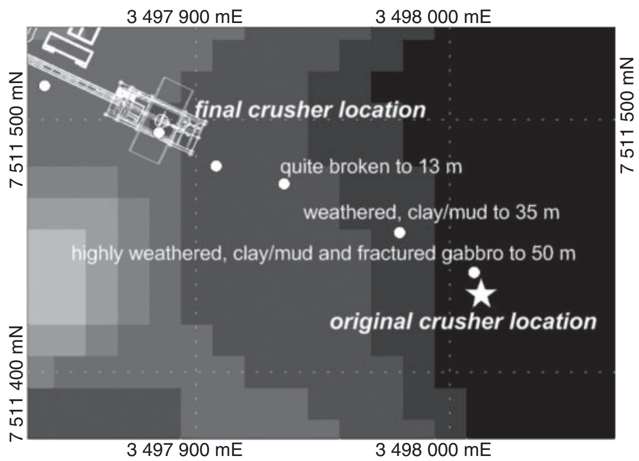

Fig. 4. EM-derived overburden depth around the crusher with follow-up geotechnical holes and geological logging results that confirm the EM results. The final crusher location is 150 m north-west of the originally planned location.

Seismic tomography

In the same year that the EM was flown, First Quantum acquired a three-dimensional (3D) seismic survey over the Kevitsa resource area, which represents a subset of the EM coverage. Malehmir et al. (2012) provide full details of the seismic survey. These data were not processed and available in time for the infrastructure planning, but now provide an independent comparison with the use of conductivity mapping for the depth of overburden. Seismic velocity variations discriminate between overburden, fractured and weathered bedrock, and intact bedrock (Figure 6). Tomographic processing of the seismic data produced a 3D velocity model for the first 150 m below the surface. The petrophysical statistics suggest that overburden should be extracted using a cut-off of 5500 m/s as the maximum velocity, although this will include most fractured gabbro and serpentinised dunite. Instead, a surface was extracted for a threshold velocity of 3000 m/s, which is a good match with the rock quality designation (RQD) model surface created by the

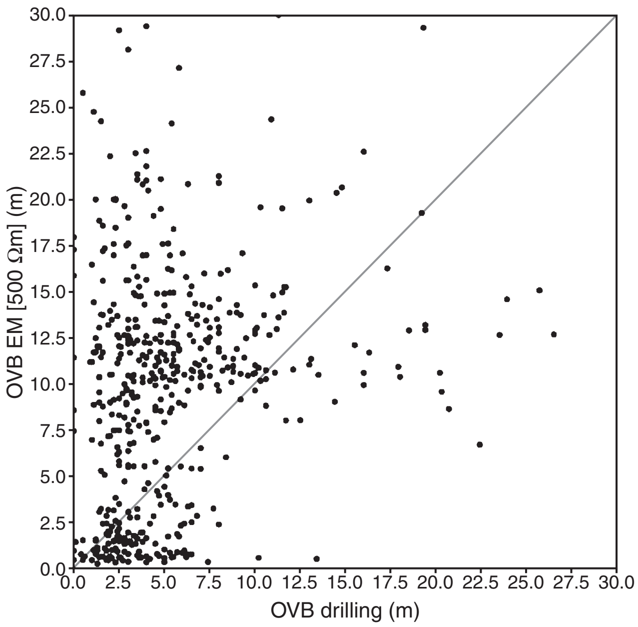

Fig. 5. EM-derived overburden depth using a 500 Ωm threshold versus logged overburden (OVB) depth from diamond drilling. The straight line shows a 1 : 1 correlation.

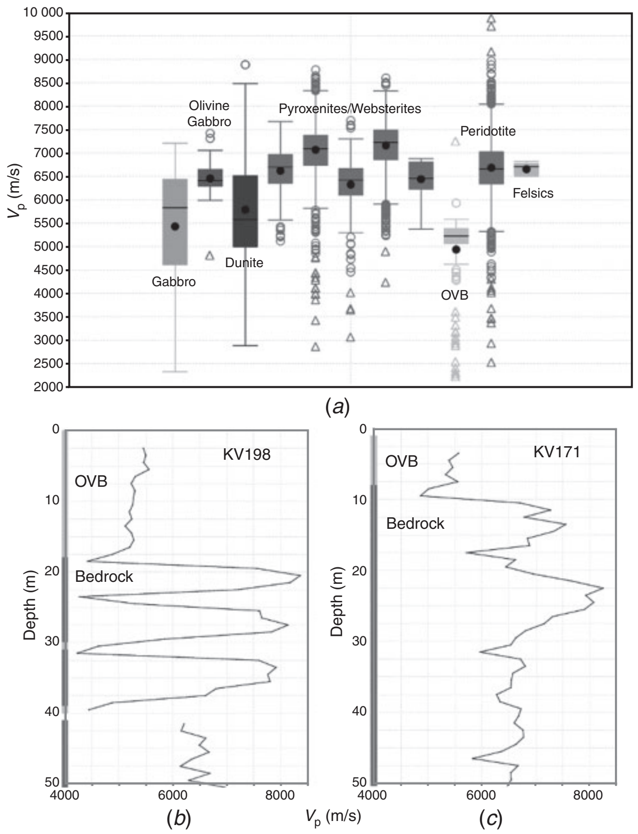

Fig. 6. (*a*) Statistics from downhole logging for seismic compressional velocity V_p per lithology. Overburden (OVB) velocities are markedly lower than all other lithology categories save the altered and fractured samples of gabbro and dunite. Much of the dunite component near the surface has been heavily serpentinised, and the heavily fractured and deeply weathered area at the original crusher site is gabbro. (*b*, *c*) Downhole V_p logs for two holes showing contrast between overburden and bedrock, with bedrock showing high variability. Deep weathering and fracture zones show extreme negative excursions of the velocity profile in (*b*).

Kevitsa geotechnical team to represent depth of weathering. RQD is a measure of how fractured and broken the drill core is, and represents rock competency. The reality is that the original seismic source and receiver station spacing (45 m × 80 m and 15 m × 70 m, respectively) is not adequate to resolve the thin overburden depth, which is mostly less than 10 m. The tomography cube is a good proxy for RQD, where low RQD encompasses much more than just glacial till. In this sense, it compares well with the 500 Ωm resistivity threshold from the AEM, and entirely backs up the inadequacy of the original crusher site (Figure 7).

Pit pre-strip excavation

The actual surveyed bedrock surface, after excavation of all overburden in the pit area, constitutes an ultimate reference dataset against which AEM, seismic and drillhole interpretations can be measured. Comparisons with this pre-strip depth must be made against interpretations that consider overburden depth alone with no fractured/weathered bedrock. This is in contrast to the exercise of predicting total excavation depth required for the crusher site, where it was necessary to remove not only overburden, but fractured and highly weathered bedrock as well. As discussed above, both the seismic tomography and AEM datasets are pushed beyond their limits to image glacial till depths alone. Figure 8 confirms that visual logging of overburden depths, at least over the pit area, tended to define only the glacial till – these visually logged depths are therefore close to the excavated depths. The same logging was thus unsuitable for identifying the crusher site, and would have needed to record the base of weathered and fractured bedrock.

With varying goals in mind, different EM-derived models of the overburden depth used different threshold resistivities in the statistical inversion scheme. Figure 9 illustrates three EM models against the actual excavated depth of glacial till during the pit pre-strip. Consistent with the galvanic resistivity statistics of Figure 2, the models using thresholds of 200 and 300 Ωm leave out the weathered rock and are in better agreement with the excavated depths in terms of overall magnitude, but not on a point-by-point basis. The 500 Ωm model significantly overstates the depth of glacial till.

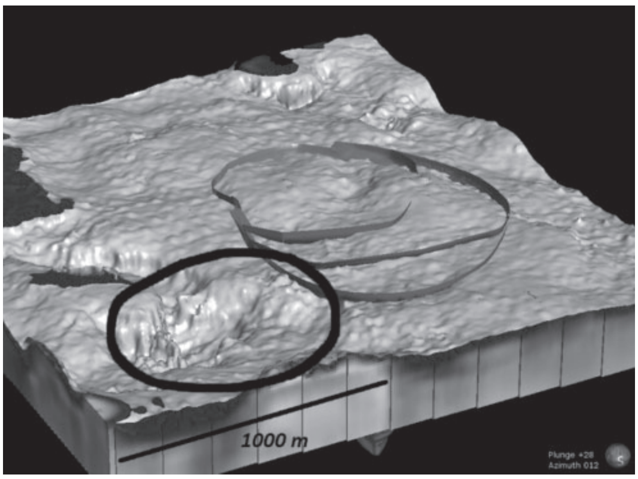

Fig. 7. Top of intact bedrock represented by a surface at $V_p = 3000$ m/s, viewed to the north-east. The known weathering trough appears along a large structure running NE–SW through the pit shells. The area circled in black is the same deep weathering area indicated by the AEM, which led to the repositioning of the crusher.

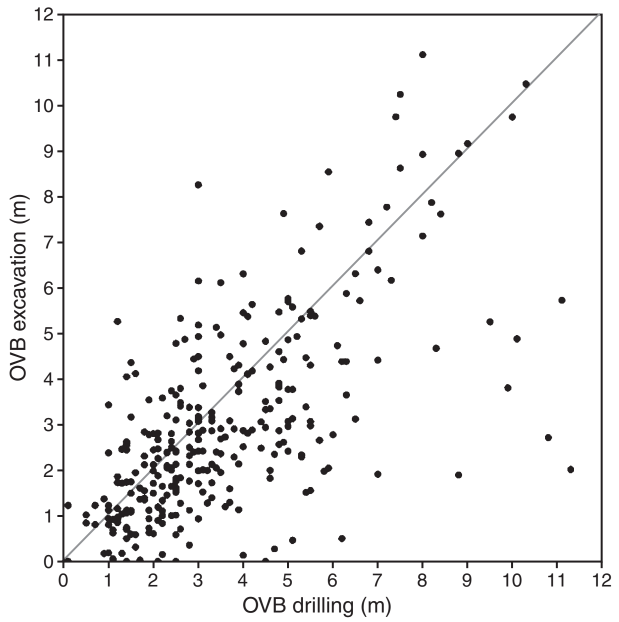

Fig. 8. Overburden (OVB) depth based on pit pre-strip excavation versus logged overburden depth from diamond drilling. The straight line shows a 1 : 1 correlation.

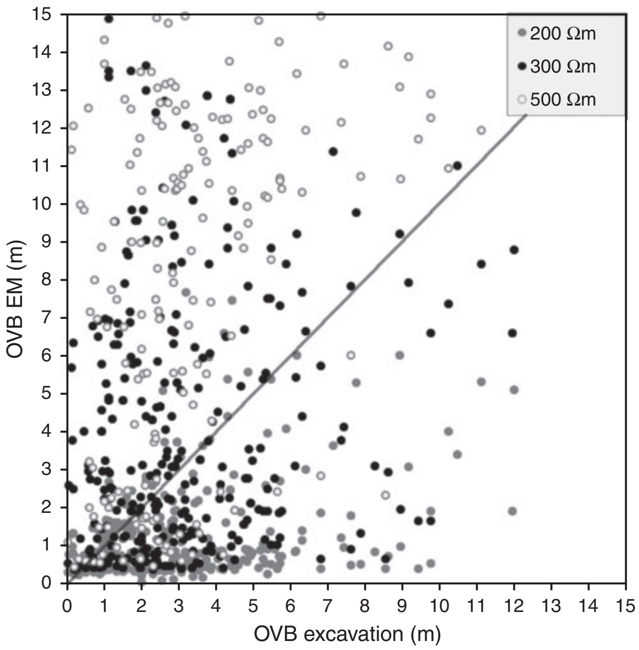

Fig. 9. Overburden (OVB) depth from three EM models at different resistivity thresholds versus actual pit pre-strip excavation depth, sampled at drillholes. While there is a large spread for all models, the 300 Ωm model (solid black dots) has the best average match with pre-strip depth. The straight line shows a 1 : 1 correlation.

Discussion

One of the main issues with geophysical mapping, particularly demonstrated by this study, is that precise correspondence between mapping and drillhole data is unreasonable on a hole-by-hole basis. Test pits and post-excavation bedrock topography can be included as point data. Figures 5 and 9 attest to the general lack of point-by-point correlation. The scatter is extreme, and in the EM model chosen to help site the crusher, most depths are much greater than the logged depths. There are three general causes for the scatter. The first is that the footprint of a single AEM reading is over 300 m^2 at the surface (from the SkyTEM loop of 18 m in width). The footprint of the core from a PQ-sized geotechnical drillhole is 57 cm^2 (0.0057 m^2), which is 19 millionths of the EM footprint area. The EM reading represents a very large volume average and provides a qualitative way to interpolate between drillholes, and can verify how well a single hole may represent the rock volume around it.

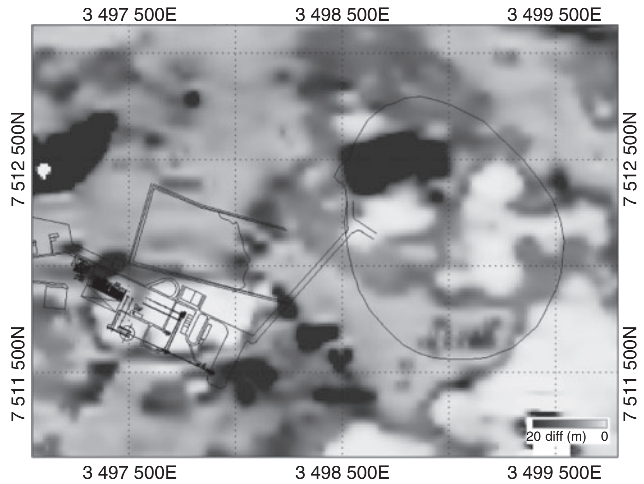

Fig. 10. Difference between overburden depths from EM models with 500 Ωm and 200 Ωm thresholds, with ultimate pit outline and mine infrastructure overlaid. White areas of zero difference indicate where overburden depth from these two different models converges to a shallow value and this represents robust near-surface bedrock. Black areas indicate either (1) deep bedrock weathering, or (2) near-surface bedrock conductors. The maximum difference has been capped at 20 m for display, although the value is often much larger.

The second cause of discrepancy stems from a ubiquitous caveat on visual geological logging: it is inconsistent because it relies on visual observation and interpretation, and the greater the number of geologists involved, the more inconsistent the record becomes. In the context of Kevitsa, holes were logged by many geologists from different companies for almost a decade. Each would have had their own determination of the transition from overburden to bedrock. The comparison of logging to excavation in Figure 8 attests to the fact that the logging can be off by more than a factor of two with true depths of glacial till.

Geophysical measurements, properly calibrated on common instrument models, are consistent across space and time. The detrimental aspect of this consistency is the inability to make informed and adjustable decisions about, for example, slightly resistive overburden versus equally resistive fractured bedrock. This is the third reason for the lack of correlation in Figure 3. While the transition from glacial till and peat to bedrock should usually be easy to spot while logging geology, the EM is responding to conductivity and not lithology. In the present case of mapping depth to competent (unfractured) bedrock, the EM is providing a more useful picture by including highly fractured bedrock with intercalated sands and clays as part of the overburden.

Figure 10 illustrates the results of an exercise to add robustness to the determination of shallow bedrock using the difference between EM models with maximum thresholds of 500 and 200 Ωm. The larger threshold includes weathered and fractured bedrock in the resistivity envelope, whereas the smaller threshold includes only glacial till (c.f. Figure 2). A difference tending to zero occurs where the depths converge near surface, whereas a large difference occurs for two reasons: weathered and fractured bedrock extends low resistivity to depth, or a legitimate near-surface bedrock conductor pulls the resistivity envelope downwards, so that in most cases the threshold is not found at all. The difference between these two cases must be established via comparison with late-time EM channels or inverted resistivity depth slices to find the bedrock conductors. The black area in the north of the pit in Figure 10 is a near-surface bedrock conductor where the Kevitsa deposit subcrops, whereas the grey to black areas just east of the mine infrastructure represent the deep weathering that was avoided for the crusher site. The seismic velocity surface in Figure 7 provides an independent check on both the lack of deep weathering in the north of the pit and the existence of deep weathering east of the plant infrastructure. Figure 10 also reinforces the deeper weathering along the major structure running NE–SW through the pit.

The comparison and analysis of overburden depths extracted from EM modelling, drillhole logging, seismic tomography and actual excavation to bedrock leads to the conclusion that the geophysical models should not be treated as quantitative maps. Properly used as a guide to expectations, geophysical surveys generally inform follow-up work attuned to the needs of the investigation. An equally strong conclusion is that relying on visual logging alone is a dangerous approach to site characterisation. In the particular case of Kevitsa, mapping depth to bedrock had two distinct goals, neither of which was fully served by the geological logging and test pitting, nor by a single interpretation of the AEM or the seismic tomography. For siting the crusher, excavation needed to bypass all highly fractured bedrock. In this case, logging needed to identify the deepest instance of competent bedrock and not the first occurrence. The EM interpretation, taking into account the galvanic resistivity envelope of both overburden and weathered/fractured bedrock, did a better job of (qualitatively) mapping areas unsuitable for the crusher site. For estimating volumes of pre-strip material over the pit area, only the glacial till depth is required, since fractured and weathered bedrock will be mined and sent to the crusher. Logging needs to identify only the first instance of bedrock, so in this case the 200 or 300 Ωm model is the better choice, as it accounts for the resistivity statistics of the overburden alone (Figure 9).

Conclusions

Determination of overburden depth is essential prior to siting mine infrastructure, especially for equipment like crushers that require a solid bedrock footing. Characterising the depth to bedrock from sparse geotechnical drilling is fraught with danger, and the consequences of faulty characterisation can be anything from annoying to disastrous, with the price tag attached. Given a reliable conductivity contrast, airborne EM mapping of the subsurface can offer a cheap way to reduce uncertainty beyond what geological mapping (logging) can do. This approach paid dividends for First Quantum Minerals when mapping the depth of glacial till ahead of finalising site infrastructure in northern Finland. On the strength of the EM model of overburden depth, backed up by subsequent geotechnical drillholes, the infrastructure plan was modified to shift the crusher from very poor ground to relatively shallow and competent bedrock. The success of the project was based on the availability of petrophysical statistics to tune the EM modelling, and ultimately, on the use of the modelling to guide further drilling to the satisfaction of the engineering team.

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