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Applying advanced gravity and magnetic inversion methods to expand the Platreef PGE-Ni-Cu resource in the Bushveld Complex

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SUMMARY

There are many potential field inversion algorithms available, and all are sufficiently capable of generating a model that explains supplied geophysical observations. The challenge is extracting a model that provides real geological insight. Here we present applications of two different styles of advanced inversions to a deep exploration program at the Platreef PGE-Ni-Cu deposit in the Bushveld Igneous Complex of South Africa. The initial approach was to apply generalised focussing constraints to a 3D magnetic vector inversion, an approach chosen to manage the effect of expected strong remanent magnetisation. This resulted in successful prediction and drill definition of inferred resources within a deep, west-dipping extension to the shallow-dipping “Flatreef” deposit. Later, a detailed 3D model of geological constraints based on drilling and mapping was constructed and used to tightly constrain inversions of gravity data derived from a FALCON airborne gravity gradiometer survey. The resulting 3D density model accurately predicted a continuation of the Flatreef host rocks to shallower levels than previously anticipated. This facilitated further drill-definition of additional inferred resources within a southern extension of the Flatreef deposit. Key to the success of the inversions at accurately targeting mineralisation at depths of 700-1300 m depth, was the inclusion and integration of all available information to ensure that predictions were consistent with prior observations.

Key words: magnetic, gravity, inversion, constraints, exploration.

INTRODUCTION

Inversions of geophysical data have become a routine step in mineral exploration and mapping programs as they provide useful estimates of the rock properties beyond the reach of existing geological mapping, drilling and sampling. They facilitate broad inferences regarding the geology that can assist with targeting. However, without direct links to geological observations, inversions of potential field data are fundamentally non-unique and many acceptable models exist. It can therefore be difficult to draw robust conclusions from the models. All commercial gravity and magnetic inversion programs allow inversion constraints to be set based on existing geological observations; the difficulty lies in defining, capturing, and quantifying these observations. Here we provide a case study from Ivanhoe Mines’ Platreef PGE-Ni-Cu deposit, which demonstrates how the use of appropriately integrated geological and geophysical modelling methods can generate real economic success.

Platreef geology

The Platreef ore deposit is a high grade-thickness PGE-Ni-Cu deposit in the Northern Limb of the well-endowed Bushveld Igneous Complex in South Africa. The deposit is hosted in a sequence of Paleoproterozoic mafic-ultramafic rocks 8 km NW of the town of Mokopane. It has an indicated mineral resource of 214 million tonnes at 4.1 g/t Pt-Pd-Au-Rh, 0.34% nickel and 0.17% copper (Parker et al., 2013). The mineralisation lies at a similar stratigraphic position to the Merensky Reef within the Critical Zone, mined at many deposits in the Eastern and Western limbs of the Bushveld Igneous Complex (Grobler and Nielsen, 2012). It is bound above by the Main Zone, a succession of mostly gabbronorites, and below by ultramafic peridotites, harzburgites and dunites of the Lower Zone, or in places by metasedimentary rocks of the Transvaal Supergroup. Although the Critical Zone is a well-described layered mafic-ultramafic sequence in the other limbs (e.g. Cawthorn, 1999, and references therein), the equivalent mafic-ultramafic sequence within the Northern Limb has been difficult to classify and laterally correlate, due to the high degree of assimilation of Transvaal Supergroup rocks by the Bushveld intrusions (Kinnaird et al., 2005; Grobler and Nielsen, 2012). Very generally, this economically important part of the Northern Limb consists of a lower, modestly mineralised zone of pyroxenite, harzburgite, norite, gabbronorite and variably digested and metamorphosed Transvaal Supergroup rocks; an overlying well-mineralised zone comprised mainly of pyroxenite and local harzburgite; and an upper, generally poorly mineralised pyroxenite (Kinnaird, 2005). Collectively these mineralized units have been referred to as the Platreef (Kinnaird et al., 2005).

On Ivanhoe’s property, the Platreef was known from surface mapping and shallow (<600-800m) drilling completed between 2000 and 2010 to dip SW at angles of approximately 40 to 60 degrees from surface. Prior to use of potential field modelling, step-out drilling from mid 2010 had discovered a relatively flat-lying extension to the Platreef, at depths of ~700 to ~900m over an 8.2 km^2 area (the “Flatreef”) southwest of the dipping resource. Continued step-out drilling to greater offsets and depths required additional predictive capacity, and it was decided to use in-house geophysical modelling expertise to produce geologically-constrained inversions.

For the purposes of this paper, the Platreef deposit is divided into four geographic zones. Zone 1 consists of the shallow, west-dipping deposit defined by mapping and pre-2007 shallow drilling. Zone 2 contains the gently-dipping "Flatreef" underground resource identified from step-out and subsequent infill drill programs in 2007-2011. Zone 3 encompasses the deeper, west-dipping deposit extensions originally identified using 3D magnetic inversion modelling, and confirmed with deep drilling in 2010-2012. Finally, Zone 4 represents a southern extension to the "Flatreef" delineated by gravity inversions and subsequent drilling after 2012.

Platreef physical properties

The upper Critical Zone (or Platreef) forms the host to mineralisation and lies at a distinct physical property change between lower density gabbronorites of the Main Zone, and higher density rocks of the Critical Zone and the Lower Zone (Figure 1). The Main Zone gabbronorites have a mean density of 2.91 ± 0.07 g/cm^3. In the Critical Zone and Lower Zone, densities are typically 10% higher: pyroxenites have a density of 3.20 ± 0.09 g/cm^3, and norites have a density of 3.14 ± 0.12 g/cm^3. This sets up an ideal physical contrast whereby gravity and reflection seismic data provide the best methods for geophysical mapping of the stratigraphic position of mineralisation. Campbell (2011) describes the importance of reflection seismic data in the Bushveld Igneous Complex, so its application is not considered here.

Magnetic properties within the Main Zone – Critical Zone – Lower Zone sequence are more variable. Most lithologies have modest magnetic susceptibilities, but moderately to strongly magnetic ultramafic and serpentinised rocks are present in the Critical and Lower Zones. Main Zone gabbronorites have susceptibilities of $2.2 \pm 2.5 \times 10^{-3}$ SI, whereas the Critical Zone and Lower Zone pyroxenites have susceptibilities of $10.7 \pm 7.7 \times 10^{-3}$ SI and norites have susceptibilities of $4.3 \pm 7.0 \times 10^{-3}$ SI. In contrast the less common serpentinite, harzburgite, and other olivine-bearing ultramafic rocks have mean susceptibilities ranging from 45 to 90×10^{-3} SI.

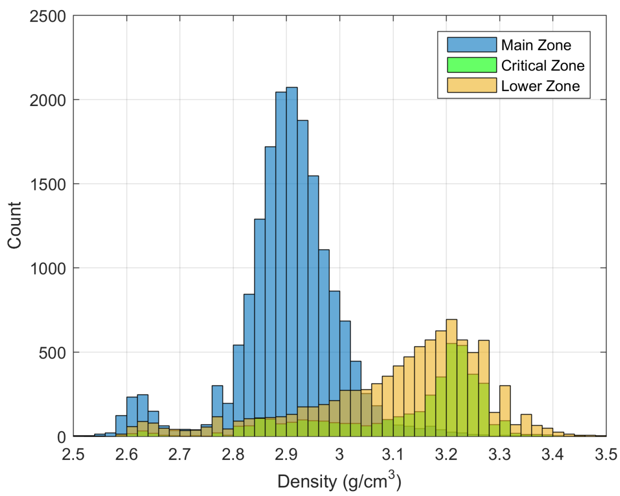

Figure 1. Density of drill core samples classified by stratigraphy.

Measurements of remanent magnetisation are unavailable for the Platreef project, however Letts et al. (2009) showed that there is very strong remanent magnetisation throughout the Bushveld Igneous Complex stratigraphy, with Koenigsberger ratios (representing the ratio of remanent magnetisation intensity to induced magnetisation intensity) averaging 41 and a general pattern of stronger remanent magnetisation in the Main Zone than in the Critical Zone. They did not sample the Lower Zone. A subset of 14 Main Zone samples analysed by Letts et al. (2009) were taken 14-28 km north of the Platreef project and show mean Koenigsberger ratios of 32 with a reverse polarity remanent magnetisation direction.

The magnetic susceptibilities of the ultramafic rocks in the Platreef stratigraphy are one to two orders of magnitude higher than for other common rocks. Even assuming only mild remanent magnetisation for the ultramafic rocks, it seems likely that their total magnetic amplitude (induced susceptibility plus remanent magnetisation intensity) should be higher than for much of the rest of the Platreef stratigraphy. This should be sufficient to generate notable magnetic anomalies for the ultramafic rocks. Even a factor of 30-40 increase in the total magnetic amplitude of the rocks in the Main Zone due to extreme remanent magnetisation may not be enough to exceed the anomalies associated with the ultramafic rocks in the Critical Zone, making it likely that the ultramafic rocks can be used as a proxy for mapping the Critical Zone stratigraphy as long as modelling accommodates remanent magnetisation effects.

Potential field data

This study used aeromagnetic data and airborne gravity gradiometer data acquired on separate geophysical surveys. The aeromagnetic data was collected in 2004 on east-west oriented lines spaced 100 m apart, at an altitude of 30 m (Figure 2). The data shows several zones of tightly juxtaposed intense positive and negative TMI anomalies (adjacent pink and blue anomalies in Figure 2). This is often a signature of remanent magnetisation, and together with the literature values of remanent magnetisation reported for the Bushveld Igneous Complex, provides a warning that remanent magnetisation may be a critical factor in any magnetic modelling.

The gravity survey was completed using the FALCON gravity gradiometer in May 2012, flying on 200-m-spaced NW-trending lines at ~140 m flight height (Figure 3; Fugro Airborne Surveys, 2012). The derived residual gravity response shows a relatively simple geometry, with two broad magnetic highs crossing the project area.

METHOD

In this study we applied two different potential field inversion algorithms. For magnetic inversions we used the Geosoft VOXI magnetic vector inversion (MVI) package, which inverts total magnetic intensity data to recover a 3D vector distribution of magnetic sources, subject to compact, focussing constraints. Using this algorithm avoids the geometric artefacts that are introduced when neglecting the effect of remanent magnetisation, a standard assumption in many potential-field model codes. It also suits a geological scenario where magnetism is associated with a spatially restricted package of rocks, as with the ultramafic rocks.

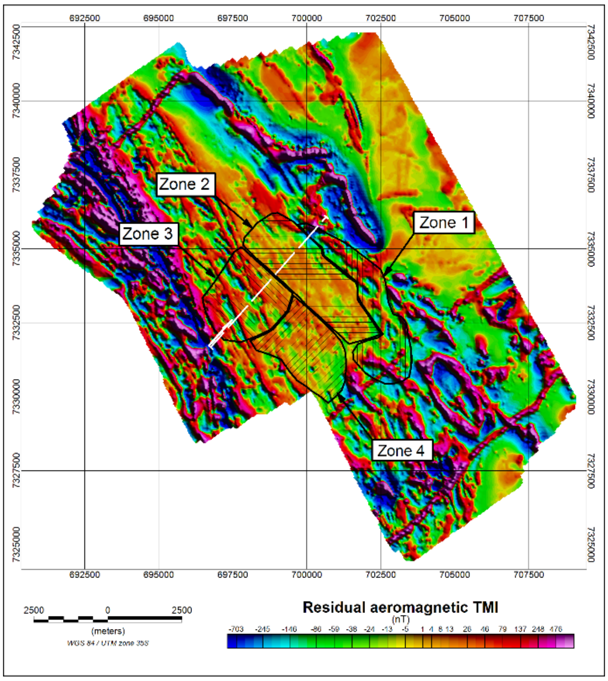

Figure 2. Residual aeromagnetic TMI after removal of a 2 km residual trend. The key zones described in the text are outlined in black, and the section shown in later images is shown in white.

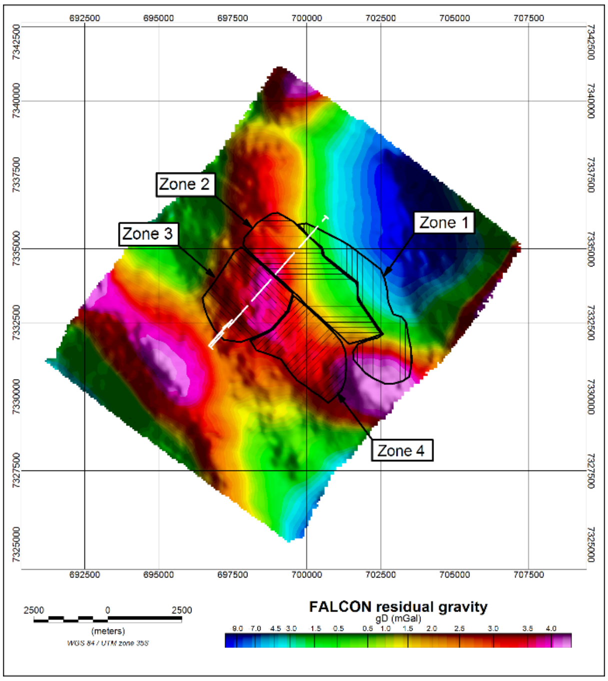

Figure 3. Residual gravity response computed from FALCON gravity gradiometer data, after removal of a 3 km regional trend.

For the gravity inversions we used the UBC-GIF GRAV3D inversion package. This provides a 3D density model that explains the supplied gravity data (ground or airborne), subject to measures of smoothness and similarity to a reference model. It provides a very flexible and customisable approach to building geological constraints based on the available data, without requiring definition of a full 3D model that applies everywhere.

A series of cross section images through the models are shown in Figures 4-9. The same section location is used for each image, and is plotted in white in Figures 2 and 3. In each figure, the available drill hole traces at the time are plotted with black lines, and schematic PGE-equivalent assay grades are plotted in black bars along the drill trace. These help identify the true location of mineralisation near the Main Zone – Critical Zone contact.

Magnetic vector inversion

The aeromagnetic data were filtered to remove a 2 km regional trend to eliminate anomalies from sources deeper than the 2 km tall inversion mesh. The smallest cells in the mesh measured 50 m x 50 m x 25 m, but the height of the cells increased slightly with depth to reflect the reduce data resolution. The data were inverted subject to a uniform uncertainty of 24 nT (5% of the data range). Due to the lack of specific remanent magnetisation intensity and directional measurements within the project area, it was not possible to build specific, observation-based, geological constraints. Instead, a model-based constraint was applied to generate small, focussed magnetic anomalies, using an iterative reweighting scheme (Geosoft, 2013). Recovery of smaller more intense anomalies is geologically appropriate given the extreme magnetic susceptibility associated with the volumetrically-limited ultramafic rocks.

Geologically-constrained gravity inversion

Given the strong density contrast observed from drill core measurements, available mapping, and the thorough coverage of drilling in Zones 1 and 2, with additional drill hole support starting to appear in Zone 3, Platreef provided an ideal scenario for applying geologically-constrained gravity inversions. Generating geological constraints requires translation of the available geological and physical property data into a set of prior 3D density models that are used to guide the inversion towards a solution that is consistent with both the geological information and the observed geophysical data. The approach used here follows that outlined by Williams et al. (2009).

A reference model of best estimate densities was generated from the drilling data (Figure 4), using density measurements where available, and lithological logs as a proxy for estimating densities. As the inversions are based on density contrast rather than density a series of trials were run to identify a suitable background density of 2.94 g/cm^3. Conversions between density and density contrast were then made relative to that value. A model of reliability weights was generated with weights assigned to each cell based on the quality of the geological sampling in that cell (Figure 5). Higher weights were assigned to cells with robust and evenly distributed sampling, and low weights were assigned to those cells that have been either poorly sampled or not sampled at all by mapping or drilling. Finally, a set of bounding densities was generated, indicating the absolute minimum and maximum density that can be present in each cell, again based on the quality of sampling. The bounds were defined using 95% confidence intervals of the density measurements, so that where confidence in the reference model was higher, from better sampling, the bounds are more restrictive.

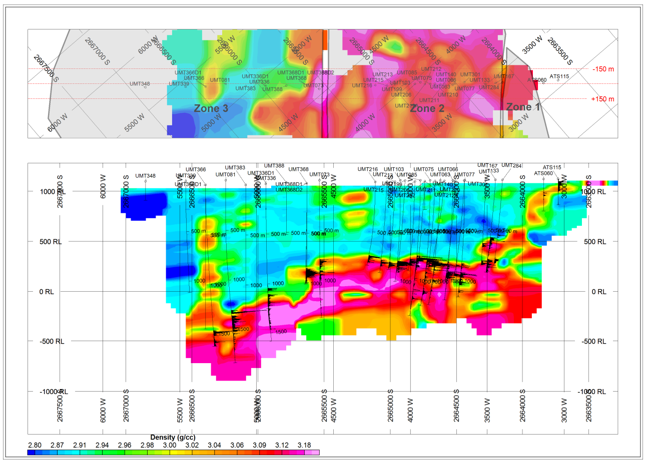

Figure 4. SW-NE section through the reference density model based on drilling and mapping. Only those cells with non-default values are shown, with drilling circa 2012. Top panel shows plan view of a slice through the 0 m RL.

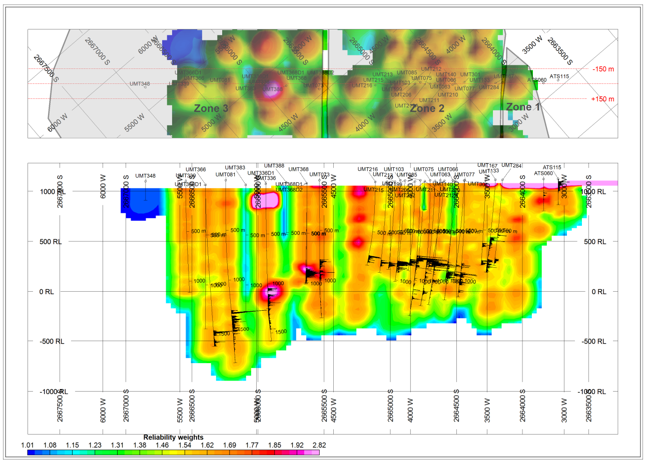

Figure 5. SW-NE section through the reliability weighting model for the reference densities in Figure 4. Only those cells with non-default values are shown, with drilling circa 2012. Values of 1 indicate default reliability (no knowledge), and larger values indicate more reliability due to sampling of the cell or its nearest neighbours. Top panel shows plan view of a slice through the 0 m RL.

Cells containing geological observations were assigned densities directly from those observations. Cells within a 300 m radius of an observation were assigned densities using a distance-weighted averaging scheme, however as they were not sampled directly, a low reliability weight, and wide property bounds are assigned.

Since there is a clear correlation of stratigraphic position, lithology and density, it was also appropriate to define a stratigraphic-scale weighting scheme that ensures some lateral continuity between widely-spaced cells. This was achieved by assigning global smoothness lengths scales that indicate the typical scale of property variations. For this model, length scales of 1500 m E-W, 1500 m N-S and 500 m vertical were used.

The FALCON vertical gravity component was derived from the gravity gradiometer data, and a 3 km regional trend was removed using filtering, to remove sources deeper than the base of the model mesh. The data were assigned a flat uncertainty of ±0.06 mGal. This value is not representative of the general high quality of the FALCON gravity data, but was required to allow for the poor drape associated with tie lines that had to fly to higher altitudes over mountain ranges in the SW and NE. The smallest cells in the mesh measured 50 m x 50 m x 25 m, but the height of the cells increased slightly with depth to reflect the reduce data resolution.

RESULTS

Magnetic vector inversion

The key advance in the magnetic modelling was the use of a magnetic vector inversion, which provided a dramatic improvement in the accuracy of the model, as it correctly accounted for the high remanent magnetisation observed in the TMI data, characterised by extreme positive to negative data variations in close proximity on the TMI map (Figure 2).

Two inversions were run using the same data and parameters: a default magnetic susceptibility inversion using Geosoft VOXI (Figure 6), and a magnetic vector inversion (MVI, Figure 7). The geometry shown in the MVI model is consistent with that available from drilling and mapping, and therefore provides a more reliable prediction of the geometry at deeper levels away from prior drilling. In contrast, the north-easterly dips and stratigraphic associations depicted in the magnetic susceptibility inversion do not match the available geological knowledge, and therefore cannot be used with confidence.

Drill hole UMT081 and later holes were targeted based on the confidence provided by the MVI model that the magnetic "shelf", which correlated well with drill intersections of the flat-lying "Flatreef" throughout Zone 2, provided a prediction of the lateral extensions of ultramafic and serpentinised rocks in the upper Critical Zone (Figure 7). The results from UMT081 validated that model, providing a new intersection 1 km SW and 500 m deeper than previous intercepts, at a depth of 1300 m. Subsequent drilling throughout the 6.1 km^2 of Zone 3 intersected additional lateral extensions of PGE mineralisation, which were defined to inferred resource status.

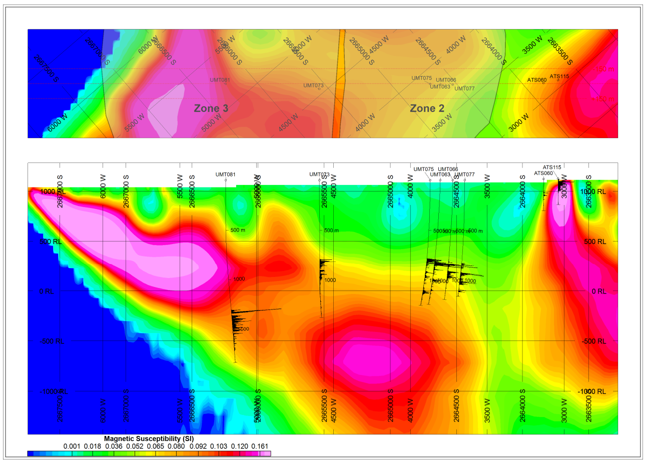

Figure 6. SW-NE section through the magnetic susceptibility inversion result, showing available drill holes on section circa 2011. The dipping low and high magnetic features at the SW end of the section are inferred to be artefacts associated with a strong remanently magnetised body near surface to the SW. Top panel shows plan view of a slice through the 0 m RL.

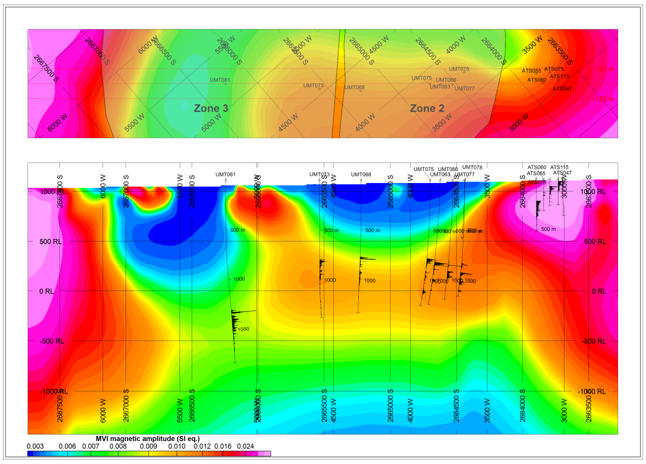

Figure 7. Magnetic amplitude section from the magnetic vector inversion model, on the same section. The clear magnetic "shelf" correlating with shallower drilling to the NE was interpreted to continue to greater depths to the SW, which was a key driver for drilling UMT081. Top panel shows plan view of a slice through the 0 m RL.

Geologically-constrained gravity inversion

When geological constraints are included in a UBC-GIF GRAV3D inversion, the inversion seeks a solution that best matches the following criteria, in order of decreasing priority: 1) the recovered model lies between the specified property bounds; 2) the predicted response of the recovered model is "close" to the observed geophysical data, subject to specified noise levels; 3) the model is "close" to the input prior reference model; and 4) the model is "close" to the defined smoothness requirements. The exact definition of "close" depends on several of the input parameters. The algorithm can be tuned to work as hard to match the prior geological inputs as the geophysical data, providing a true holistic model that satisfies all supplied geological and geophysical controls. Just as there is a tolerance on fitting the geophysical data (based on the estimated noise content), there is also a tolerance on how close the recovered model must be to the reference model. As a result, the recovered model can handle the seemingly noisy and inconsistent property variations seen in the reference density model (Figure 4), and still produce a model that is smooth and consistent with the geophysical data.

The value of the geological constraints is apparent when comparing a default, geologically-unconstrained inversion (Figure 8) with the geologically-constrained result (Figure 9). Both explain the supplied geophysical data equally well, but the geologically-constrained result is also consistent with the prior density estimates available from drilling and mapping (Figure 4).

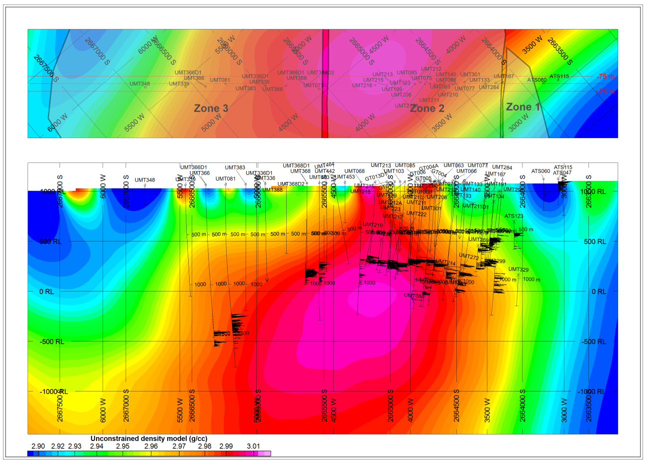

Figure 8. SW-NE section through the default, geologically-unconstrained gravity inversion result, showing available drill holes on section circa 2012. There is a clear response to the Critical Zone density contrast, but poor definition of its depth. Top panel shows plan view of a slice through the 0 m RL.

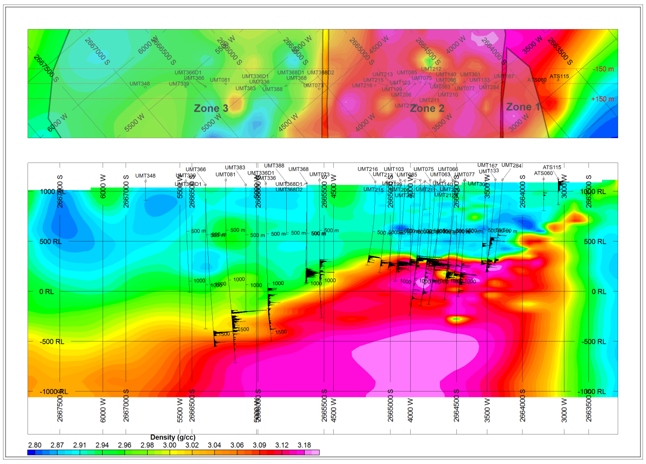

Figure 9. SW-NE section through the geologically-constrained gravity inversion result, showing available drill holes on section circa 2012. The depth of the Critical Zone is well resolved, and the density contrast surface provides a very tight prediction of the higher density upper Critical Zone strata host to PGE mineralisation. Top panel shows plan view of a slice through the 0 m RL.

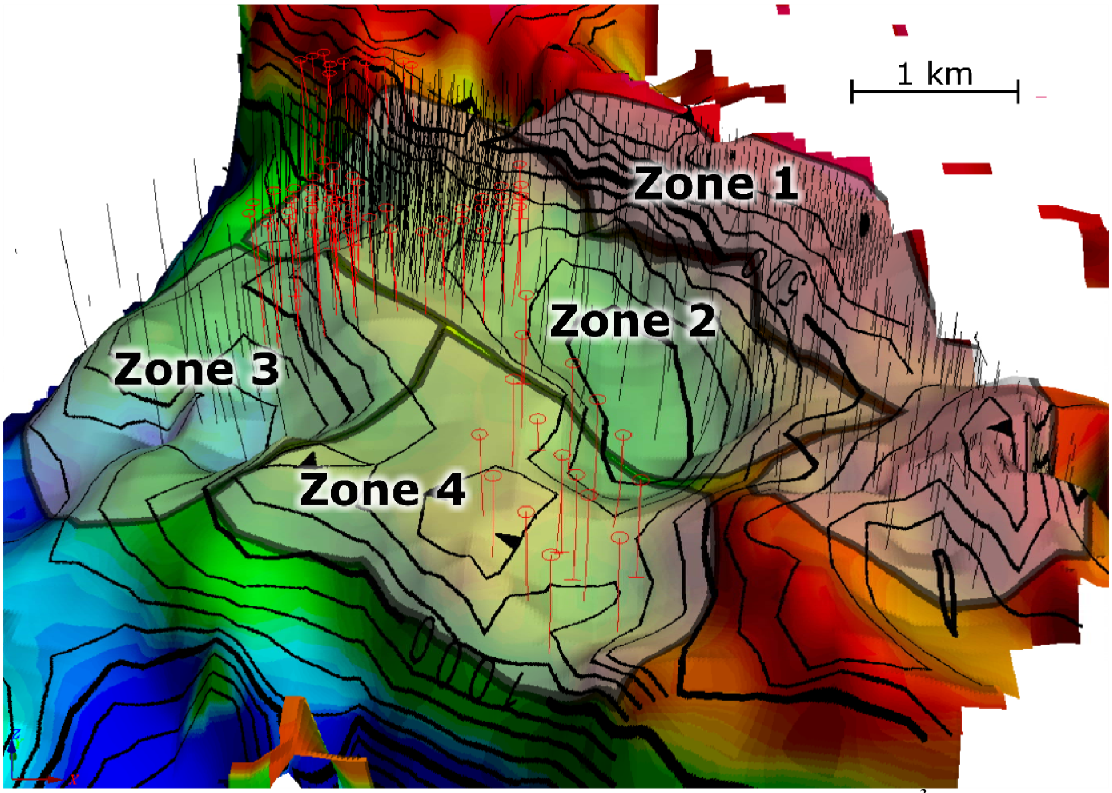

Figure 10. 3D perspective view, looking down to the north, showing the extracted 2.97 g/cm^3 isosurface, coloured and contoured by depth below surface. Black drill hole traces are pre-gravity inversion, circa 2012; and red drill holes are more recent.

The strong density contrast can be mapped across the inversion area by extracting an isosurface of 2.97 g/cm^3. The surface was smoothed slightly by down-sampling the node density to capture the broad trend of the upper contact of the Critical Zone, and is shown in Figure 10, with the circa 2012 drilling used to constrain the gravity inversion (black), and drilling completed after the inversion modelling (red). The deeper zones predicted by the magnetic inversion modelling and validated by UMT081 are contained in Zone 3, but the extracted isosurface predicts much shallower flat extensions of the Critical Zone contact southwards from shallow intersections in Zone 2. This southwards extension enclosed by Zone 4 covers an area of 5.8 km^2 that prior to the 2012 inversions had not been drilled. Follow-up drilling (shown in red) confirmed continuation of mineralisation through most of this zone at depths of 600-900 m below surface, adding substantially to the available inferred resource.

Figure 11 shows a direct comparison of stratigraphy, mineralisation, and magnetic and density properties along hole UMT081 from the sections above. The inversion properties along the hole are extremely smooth, but do capture the bulk trends shown by the drill core property measurements: stronger magnetic responses associated with accumulations of relatively thin sections of ultramafic rocks in the Critical Zone, and higher densities throughout the Critical Zone. Although the bulk averaging associated with surface-based magnetic and gravity measurements and the uncertainties associated with 3D inversion prevent high precision mapping at depth, use of appropriate inversion schemes, constraints, and physical property data have provided valuable predictions.

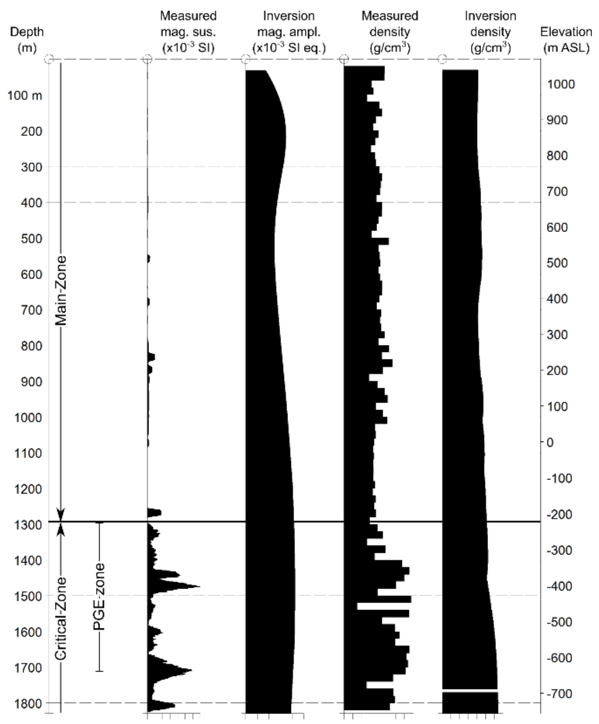

Figure 11. Stratigraphy, mineralisation, drill core physical property measurements, and recovered MVI model and geologically-constrained density model logs for hole UMT081. Drill core measurements were averaged over 20 m intervals.

CONCLUSIONS

Two examples of advanced inversion approaches have been presented here that have both had real economic impact by facilitating successful exploration of deep targets around the Platreef PGE-Ni-Cu deposit. The initial magnetic inversions used available literature documentation of high remanent magnetisation to select an appropriate inversion algorithm that adequately managed the strong remanent magnetisation. The strong correlation with available drilling information provided support for an aggressive step-out drill program that mapped out further, deep, extensions of the ore zone to depths of more than 1300 m. The strongest magnetic inversion response in Figure 11 lies within the zone of PGE mineralisation.

More detailed geologically-constrained gravity inversion modelling followed, and further refined models of the target horizon. It was critical to combine both the extensive drilling database with the geophysical data to obtain an accurate result. A default gravity inversion over the area provided a reasonable explanation for the observed gravity data, however it correlated poorly with available density measurements and drill hole logs, which clearly showed a sharp density contrast of 0.3 g/cm^3 at the contact between the Main Zone and Critical Zone. Inclusion of the known drilling information into the inversion resulted in a more accurate prediction, and led to successful drill testing and resource definition within a large southern extension of the deposit. The density model predicted the position of the contact to within 150 m at 1400 m below surface, and to within 50 m at depths of 700 m.

The critical lesson from these models is that geophysical inversions can provide robust targeting at depth and under cover, so long as all of the available information is used to select the most appropriate tools and critical constraints for the modelling.

ACKNOWLEDGMENTS

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