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AUSTRALIA'S NORTHERN TERRITORY

Contents

Ambient Noise Tomography constrained gravity inversion for exploration undercover in the East Tennant IOCG province

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Introduction

The East Tennant region (East Tennant) of the Northern Territory (NT) has been of heightened interest to mineral explorers over the past few years as an emerging copper–gold exploration frontier. This is largely due to collaborative pre-competitive geoscience work programs conducted by Geoscience Australia (GA) and the NT Geological Survey (NTGS), which highlighted that Proterozoic basement underlying the Cambrian cover of the Georgina Basin was prospective for iron oxide–copper–gold (IOCG) mineral systems (Schofield *et al* 2020). Results from the Mineral Exploration Collaboration Research Centre (MinEx CRC) National Drilling Initiative (NDI) East Tennant drillhole samples yielded further geochronological evidence to support the prospective nature of East Tennant for IOCG deposits (Kositcin *et al* 2022).

The deposits of the Tennant Creek district occur as polymetallic (gold–copper–bismuth, referred to as Au–Cu–Bi), selective partial replacements of small metasomatic ironstones (magnetite–hematite) that form within the clastic metasedimentary rocks of the Warramunga Formation (Partington and Williams 1999). Ironstones typically occur as flattened elongate bodies that range in size from a few tonnes to over 15 Mt, all of which are thought to be hosted by the Warramunga Formation (Donnellan 2013).

The Tennant Creek Au–Cu–Bi deposits have been classified as IOCG-style deposits (Skirrow 2019). There are several key geological commonalities within the deposits of Tennant Creek, most notably the generally close association with the ironstones within the region, although, significantly, not all ironstones are mineralised. Alteration patterns are typically similar across the deposits and form as pipe-like chlorite-rich alteration zones above and below the deposits, commonly accompanied by carbonate, talc with local muscovite, and variable quartz (Huston *et al* 2020). Recent studies indicate that felsic volcanics of the Ooradidgee Group, which unconformably overlies the Warramunga Formation, may act as a relatively impermeable 'cap' to mineralising fluids in Warramunga-hosted Tennant Creek-style IOCG deposits (Austin *et al* 2024).

Knox Resources Pty Ltd (Knox) was an early entrant to exploring within the East Tennant province with its exploration focused on the IOCG deposit family, and in particular, Tennant Creek-style ironstone associated Au–Cu–Bi mineralisation.

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Background

Knox, an 80%-owned subsidiary of Astute Metals NL, holds ten granted Exploration Licences (ELs) and three EL applications over four distinct locations, covering over 4500 km^2 between the IOCG provinces of Tennant Creek and Mount Isa (**Figure 1**). Most of Knox's tenements are located in the East Tennant region near the Barkly Roadhouse within the Warramunga Province (EL32281–82, EL32296, EL33375-76). EL32285 and EL32286 are located east of this area, in the Ranken project in South Nicholson Basin (**Figure 1**).

Located centrally within the Knox tenement holding, EL33375 has a cluster of prospect areas with IOCG deposit characteristics, including spatially associated magnetic and gravity high anomalies, presence of interpreted Warramunga Formation equivalents, and proximity to regional-scale faults and granitic intrusive rocks. Exploration work conducted by Knox to date on this tenement has been actively supported by the NTGS and the NT Government *Resourcing the Territory* initiative, with successful co-funding applications as part of the Round 15 and Round 16 Geophysics and Drilling Collaborations programs (**Table 1**). Work completed includes 100 m line-spaced airborne magnetic surveying, prospect-scale (200 m x 200 m station spacing) gravity surveying and the drilling of three exploration diamond holes at the Banks, Leichhardt West and Leichhardt East prospects.

The most recent work program comprised an Ambient Noise Tomography (ANT) geophysical survey, with a primary objective to delineate the Georgina Basin cover sequence contacts, as well as faults, other structural features and, potentially, zones of IOCG alteration. It was further proposed, as part of a successful Round 16 co-funding application, that results of the survey might assist with constraining future geophysical inversions.

Ambient Noise Tomography

In a July and August 2023 field program, ANT data acquisition was undertaken utilising Geodes provided by Fleet Space Technologies (Fleet) and placed in field by contract field technicians and Knox personnel. Data were collected across three adjacent survey grids over a period of 19 days for a total area surveyed of ~49 km^2 on EL33375 (**Figure 2**, **Table 2**). Data processing was undertaken by Fleet. High quality surface wave signals between 0.4–3.5 Hz were recovered from ambient noise cross-correlation functions (CCF) between sensor pairs. The ambient noise wave field itself was characterised at the time of data collection as moderately directional, with the azimuth of incoming energy oriented from the north-northeast, correlating to the Barkly homestead and Barkly highway (**Figure 3**).

Leveraging the direct-to-satellite technology of Fleet's Geode sensors, initial analysis and quality control of

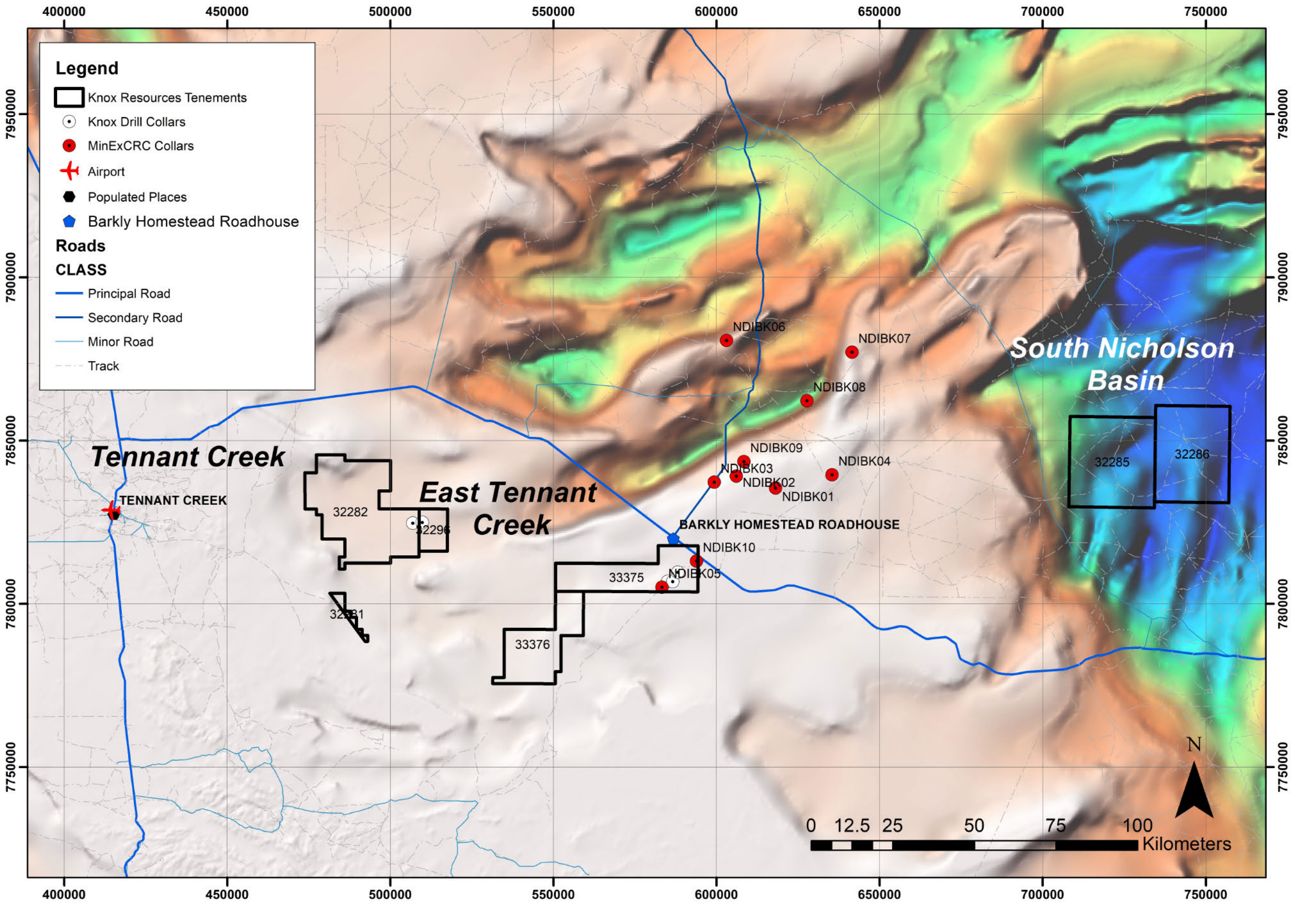

Figure 1. Knox granted tenure in East Tennant Creek and South Nicholson Basin, showing location of Knox and MinExCRC drillholes. overlain on SEEBASE depth to basement model (NTGS and Geognostics 2021).

incoming data occurred in near real-time. Sensor grids were mobilised to the next location when the signal to noise ratio of CCF built to acceptable levels, and surface wave signals in the CCF had stabilised. Final data processing and velocity modelling was applied for the combined survey grids using a 2-step 3D ANT modelling workflow, outlined as follows:

1. cross-correlation and stacking
2. CCF fitting to extract pairwise phase-velocity dispersion measurements
3. data quality control and filtering
4. 2D phase velocity inversion via least-squares method with adaptive damping
5. 3D shear-wave velocity versus depth inversion.

Data quality control at step 3 of the workflow was mainly focused on filtering the pairwise measurements to remove the pairs returning anomalously high, apparent phase-velocity due to their orientation at a high angle to the dominant north-northwest energy source. From a total ensemble of 5939 pairs, 2247 (~38%) remained after quality control review. **Figure 4** shows an overview of the filtered ensemble of pairwise measurements and their resulting relative sensitivity distribution. The relative sensitivity model is derived from a synthetic recovery test where a known 'checkerboard' velocity model is generated, plus forward model for the filtered pairwise

Table 1. Summary of 2020–2024 exploration work programs undertaken on EL33375 (an amalgamation of EL32295, EL32820 and EL32821) by Knox.

Tenement ID	Party/Company	Activities completed
EL32295	Knox	567 gravity stations and 4912 line km airborne magnetic survey. Prospecttivity review and target generation.
EL32295	Knox	Drillholes KNXBA001RDD and KNXLW001RDD at Banks and Leichhardt West were completed in June–July 2022.
EL32295	Knox / NTGS	Round 15 NTGS co-funded drillhole, KNXLE001RDD drilled in November–December 2022. 1 water bore drilled to depth 90 m
EL33375	Knox	1656 station gravity survey completed June-August 2023
EL33375	Knox	83 line km airborne magnetic survey completed in August 2023
EL33375	Knox / NTGS	Round 16 NTGS co-funded ANT survey carried out in August 2023.
EL33375	Knox	Geological Modelling December 2023–February 2024

paths and their sensitivity kernels, and then inverted using the least-squares method, with the apparent sensitivity values being the percentage difference between the input and modelled synthetic velocity model. This method offers a useful way to estimate the relative sensitivity throughout the model space given the distribution of pairwise measurement, although it is only useful as a qualitative assessment.

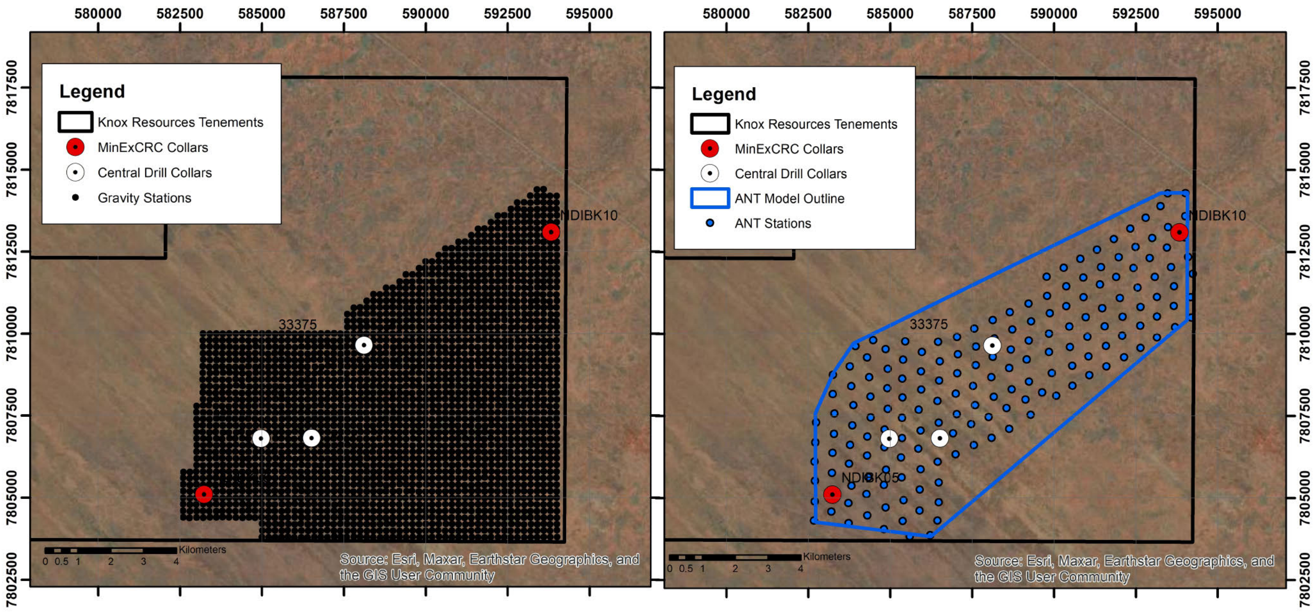

Figure 2. Overview of gravity (left) and ANT (right) survey grids acquired on EL33375.

Table 2. Summary of ANT survey parameters.

Survey name	Number of Geodes; array spacing	Acquisition date	Estimated depth of investigation	Nominal 3D model resolution
South-west	64; 600 x 600 m	31 Jul–5 Aug 23	1550 m	120 m
Central	64; 600 x 600 m	5–13 Aug 23	1750 m	120 m
North-east	64; 600 x 600 m	13–19 Aug 23	1850 m	120 m

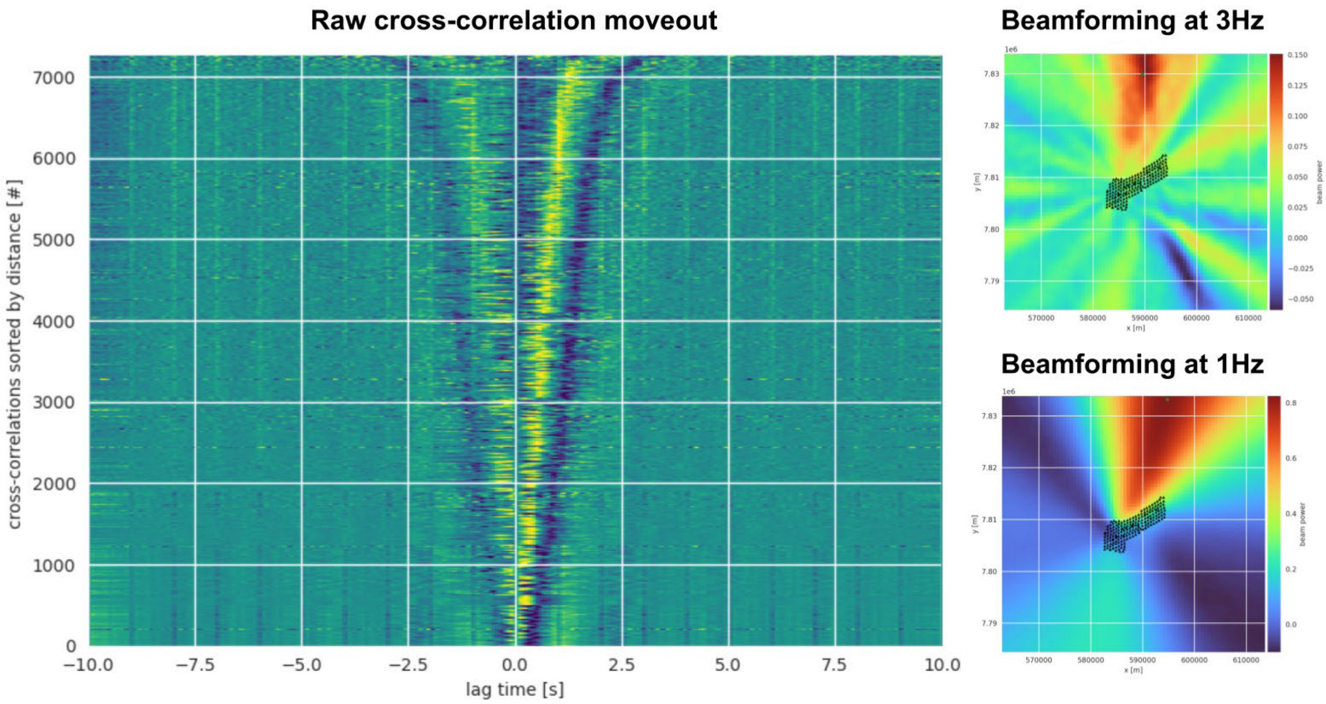

Figure 3. Plots of cross correlation moveout for sensor pairs sorted by distance; and beamforming plots for high and low frequencies indicating the back-azimuth of dominant surface wave energy sources.

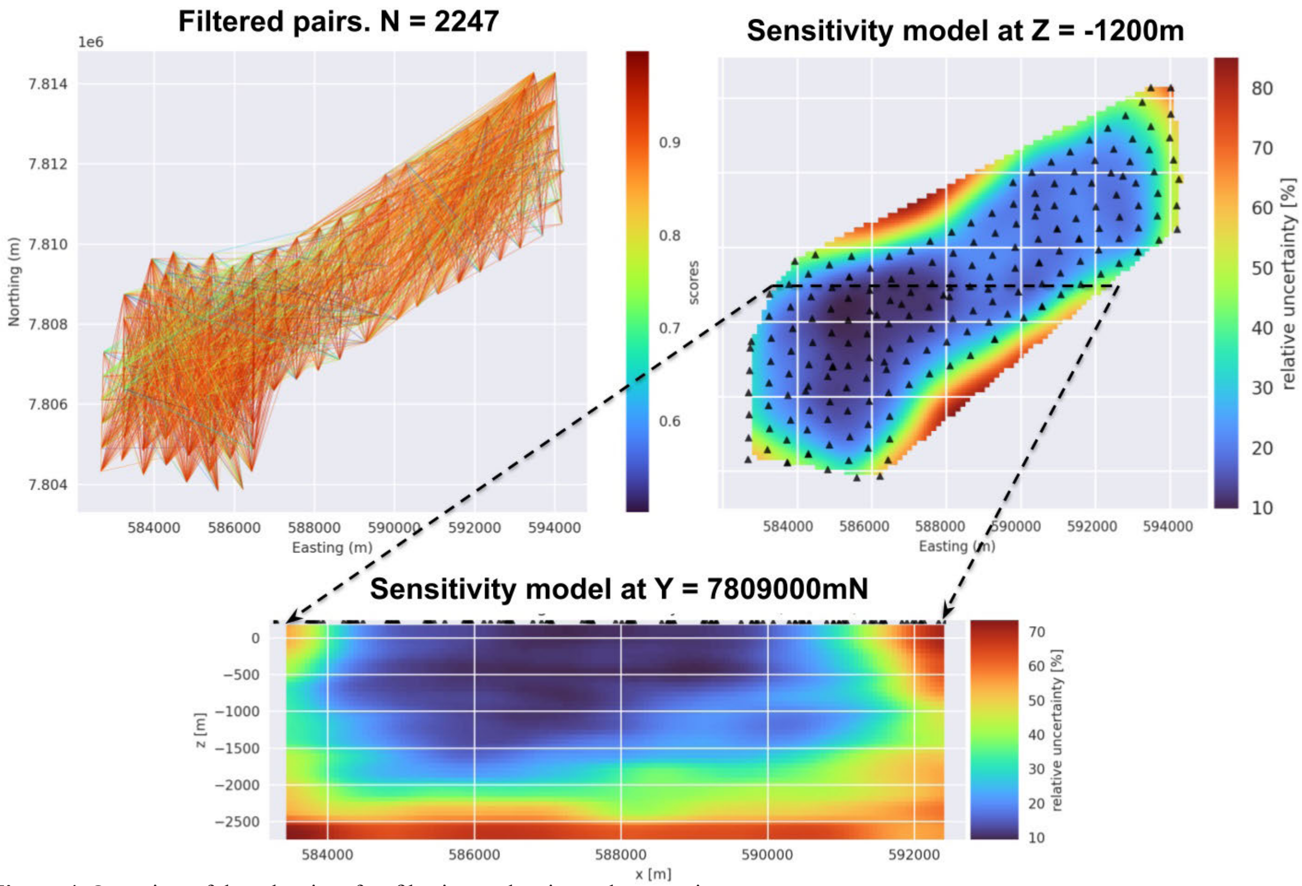

Figure 4. Overview of data density after filtering and estimated uncertainty.

Results from final stage 3D shear-wave velocity versus depth inversion were incorporated into a Voxel block model. The block model consisted of three spatially coherent populations of seismic velocity data, comprising a shallow low-velocity (2300–2500ms^{-1}) zone, a mid-velocity (2500–3300ms^{-1}) and a high-velocity (3500–3800ms^{-1}) zone (**Figure 5**). A fourth subordinate zone was also identified (2700–3200ms^{-1}) internal to the mid-velocity zone. The shallow zone is thought to be suitable as a proxy for the Georgina Basin sedimentary sequences and was used in a constrained inversion of gravity survey data discussed in the following section.

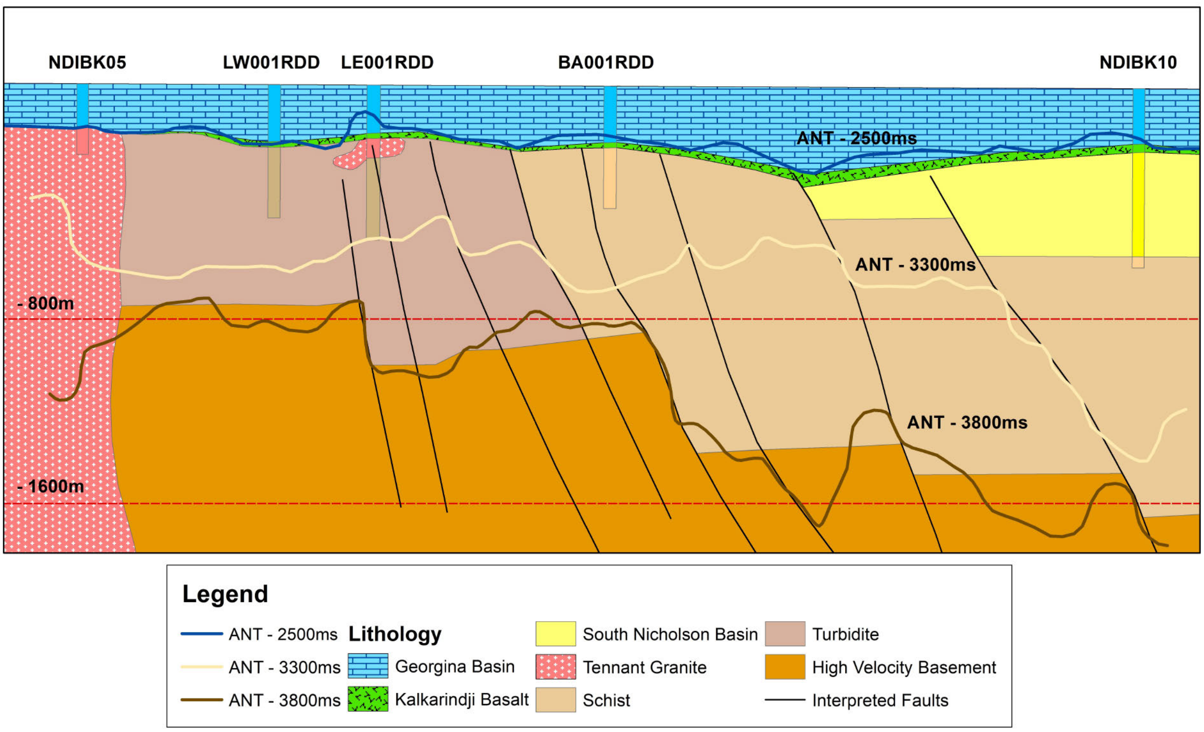

Figure 5. Conceptual SW–NE cross section showing coherent velocity structures, drillholes and geologic interpretation.

Geophysical modelling workflow

Campbell and Direen (2023) described the merging of the GA regional gravity with the 2021 ground gravity acquired by Atlas (Allpike 2021) and a tranche of stations also acquired by Atlas in June 2023 (Allpike 2023). These stations are shown in **Figure 2**, relative to the ANT survey footprint and the existing drillholes.

After checking processing reports, columns labelled OrthoHTM were used as the elevation for the digital elevation model (DEM) heights. The geoidal Bouguer anomaly, calculated at 2.67 $g.cm^{-3}$ in milliGals, was gridded at 65 m, corresponding to the grid cell size of the ANT surfaces.

A specialised workflow was developed for the next stage of the analysis. Firstly, the ANT base Georgina points (defined as solutions with Vs velocities between 2300ms^{-1} and 2500ms^{l}) were converted to a 65 m grid cell size surface; this grid cellsize was based on the Fleet 65 m gridding parameters for their inverted products (Fleet 2023). This surface was then bulk shifted downwards 98 m to match the average drill intercepts of the base Georgina Basin unconformity in the five diamond holes in the study area. For the purposes of optimising voxel-based operations, the depth surface was converted to a regular rectilinear grid using maximum entropy padding, which preserves the spectral content of the grid, as well as 'wrapping' values between the grid edges to prevent noise propagation during Fourier transform operations. The DEM surface from the gravity observation points OrthoHTM field was also gridded at the same cell size (65 m) and padded in the same way. Finally, the geoidal Bouguer anomaly (2.67 g/cm^3) grid was also padded to the regular dimensions of the other grids.

These starting grids were then imported into ModelVision v17 (Tensor Research Pty Ltd 2021) and a 3D voxet was created between the DEM surface and the base Georgina surface. This 3D voxet was further extended 2000 m (~10 x its depth extent) out beyond the existing grids to prevent edge effects in calculations (**Figure 6**).

A single average density of 2.78 g/cm^3 was assigned to this geobody, based on extraction of bulk wet densities for the Thorntonia Limestone (Georgina Basin) from the database of Hallett (2023). Densities were from drill cores in Elkedra7, CKAF0001, NTGS01/1, and Owen2. The key assumption of this work is that the average of these density values is representative of the carbonate sequence within the study area. The 3D Bouguer gravity response of this geobody was then calculated. The result is shown in **Figure 7**.

The gravity effect of the Georgina Basin layer was then subtracted from the geoidal Bouguer anomaly (2.67 g/cm^3) grid to give a basement residual geoidal Bouguer gravity anomaly. A comparison between the original and basement-only response grids is shown in **Figure 8**; there are some definite, albeit subtle, changes in the anomaly shapes due to the influence of the base Georgina Basin geometry unconformity on the top basement gravity response. In theory, the basement-only response should have removed the gravity effect of any subcropping basement hills, leaving only responses due to variation within the basement.

The basement residual Bouguer gravity anomaly was contoured to identify closed features. A 0.5 mGal anomaly of interest lies 270 m away on a bearing of 301° from drillhole KNXLE001RDD (LE001) collar position at the Leichhardt East prospect. The gravity anomaly of interest has dimensions of 1600 x 900 m, elongated in the north-northeast direction. Given the encouraging results of U, Bi, Ag and Cu anomalous ironstone and sulfide alteration at LE001 (Astro Resources NL 2023, Crawford 2023), this anomaly was chosen for further testing by constrained inversion. A Windisp UBC 3D gravity inversion (Paine 2002) was created to evaluate the source of the residual gravity anomaly west of LE001. This solution was based on a 65 m x 65 m x 30 m cell size voxel model with 2290 m X, 2925 m Y and 3390 m Z dimensions.

The section of the model from the DEM surface to the base Georgina horizon surface was used to force the model solution deeper than this constraint, and the cells below the base Georgina unconformity were inverted for a density

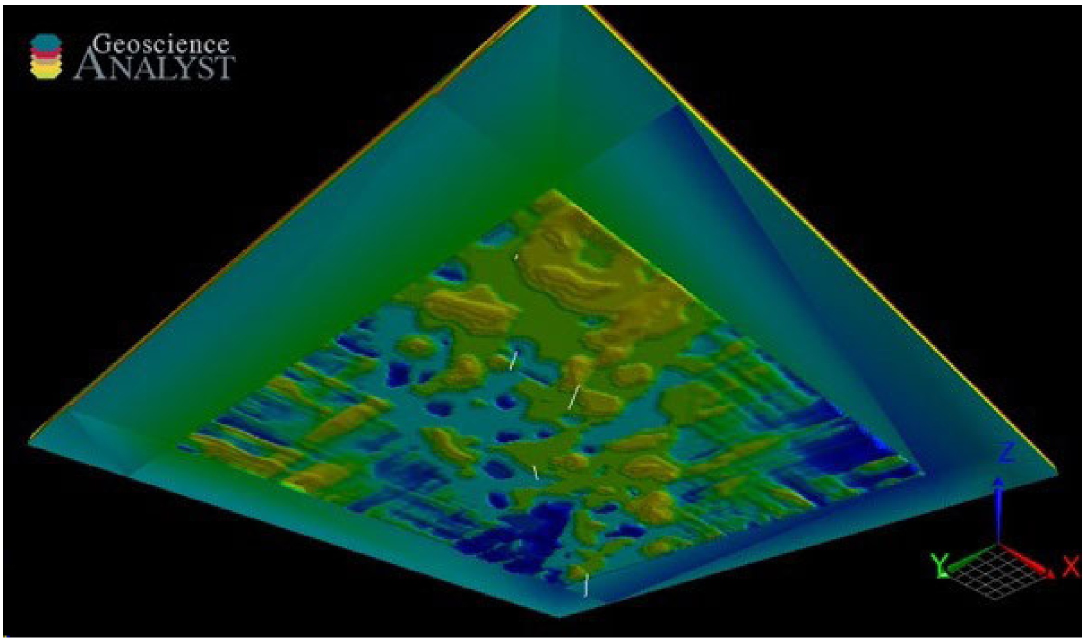

Figure 6. Georgina Basin geobody, oblique view from below towards the northeast. Drill traces shown.

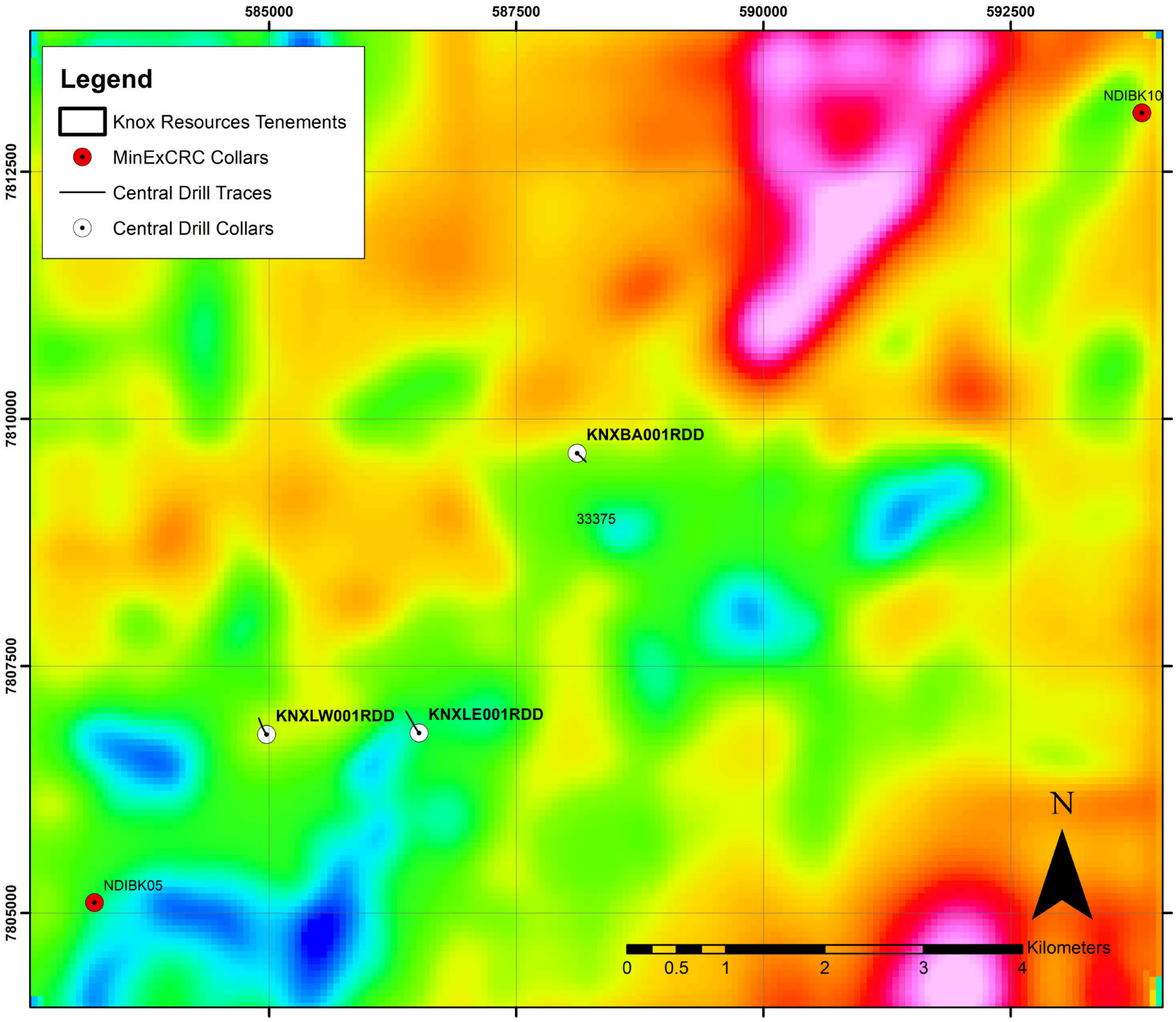

Figure 7. Bouguer gravity response of the Georgina Basin geobody with drillholes and traces.

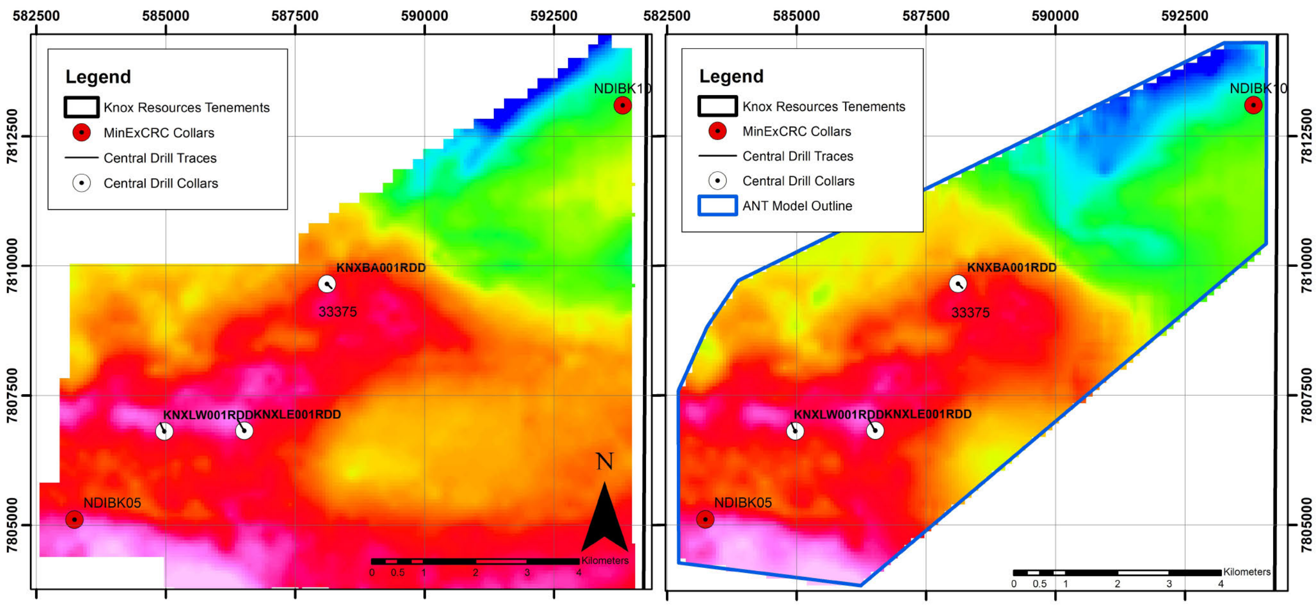

Figure 8. Merged geoidal Bouguer anomaly gravity map (left) and basement residual geoidal Bouguer gravity (reduction density 2.67 g/cm^3; right) with drillholes and traces.

property without other constraints. Several parameters were trialled before finalising a model, shown in **Figure 9**.

Modelling results

Although the absolute densities cannot be assigned using this method due to removal of a 'regional' background, the density contrasts to the 2.67 g/cm³ reduction density of the data is suggestive of a body with a density of >3.15 g/cm³ as the source of the gravity anomaly. This density is significantly greater than the average density of all core measured in LE001 (average 2.77 g/cm³); however, it is similar to 17 intervals in LE001 with measured densities >3 g/cm³, all of which were associated with hematite–jasper alteration, and in some cases, sulfides. The average density of these intersections is 3.40 g/cm³ (**Figure 10**).

An alternative parametric solution was trialled using ModelVision, with serial models of 2.5D polygonal prisms to fit the gravity feature. Parametric model bodies that fit the anomaly have densities of 3.5, 3.5 and 3.7 g/cm³; this high density is greater than would be expected from mafic rocks such as metagabbros or metaperidotites/pyroxenites (max

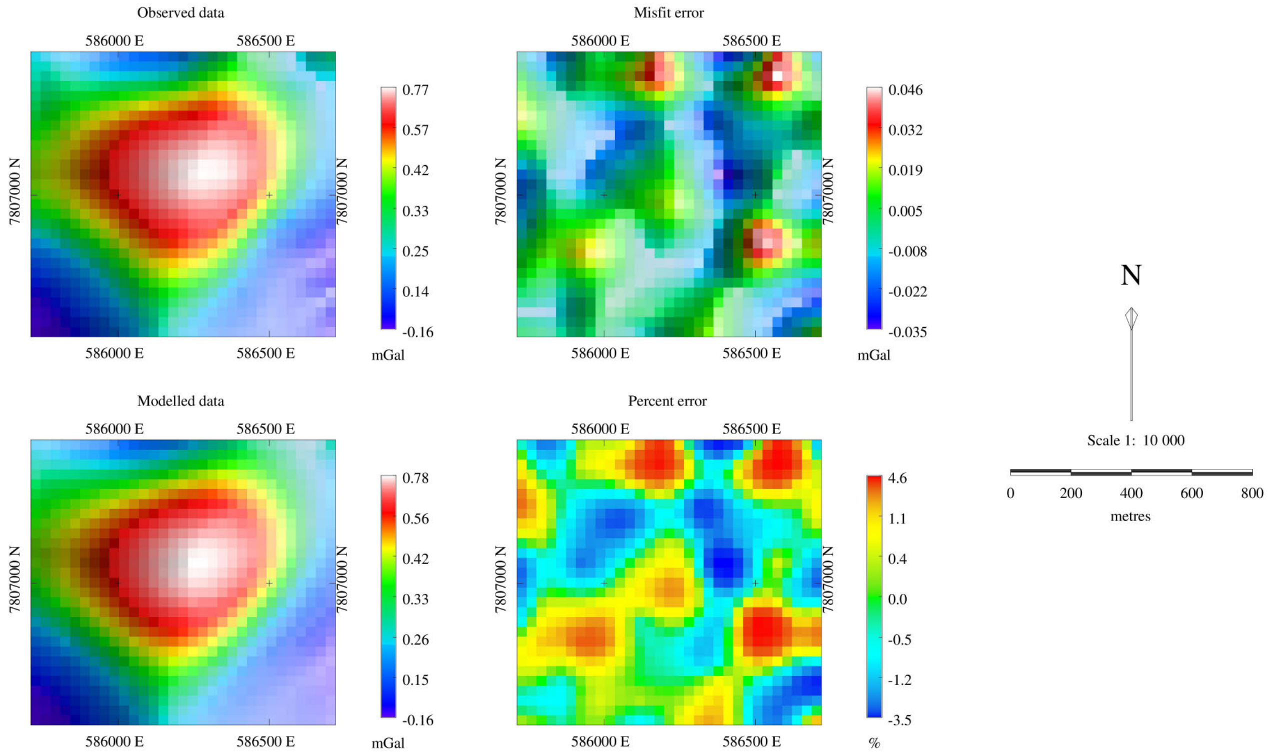

Figure 9. Plan view of density isoshells of +0.5 to +0.1 g/cm³ from the Windisp UBC inversion model, centred on the main density feature. Top left: Observed basement residual gravity anomaly. Bottom left: Calculated Bouguer gravity anomaly of the final inverted model. Top right: Misfit in mGal between the observed and calculated responses. Bottom right: Percent error difference between the calculated and observed responses.

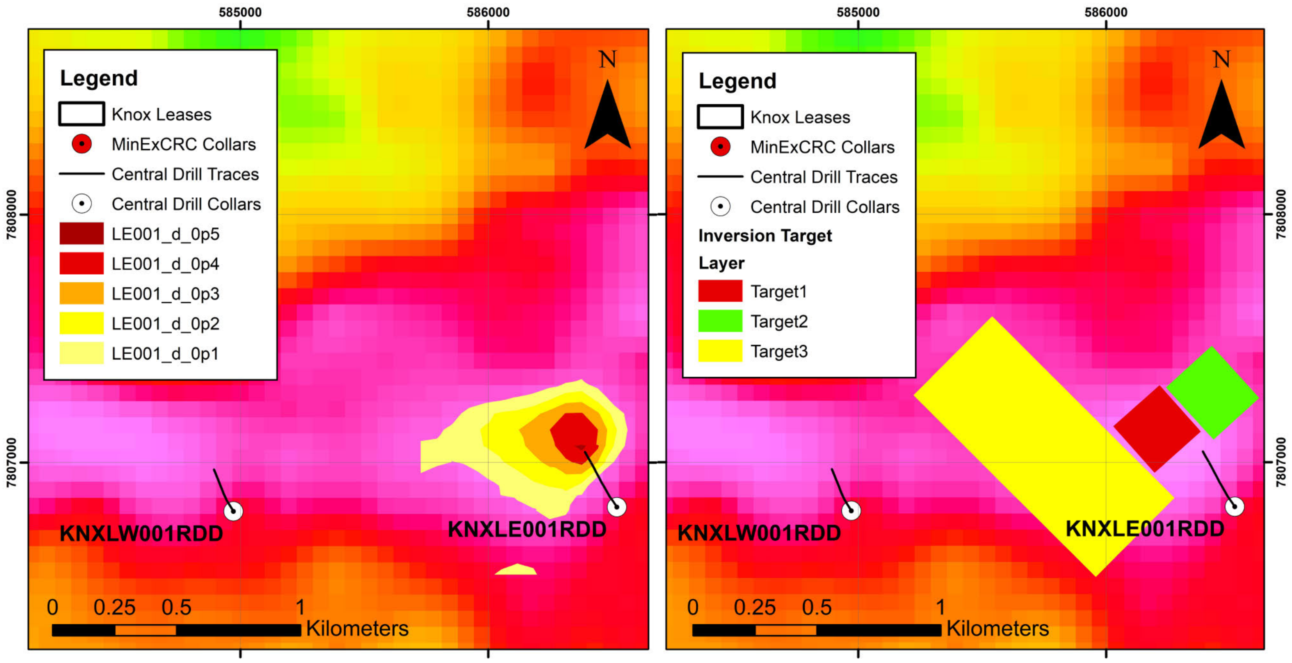

Figure 10. Plan view of UBC inverted gravity source (left) and parametric solution (right) near LE001 over residual Bouguer anomaly image.

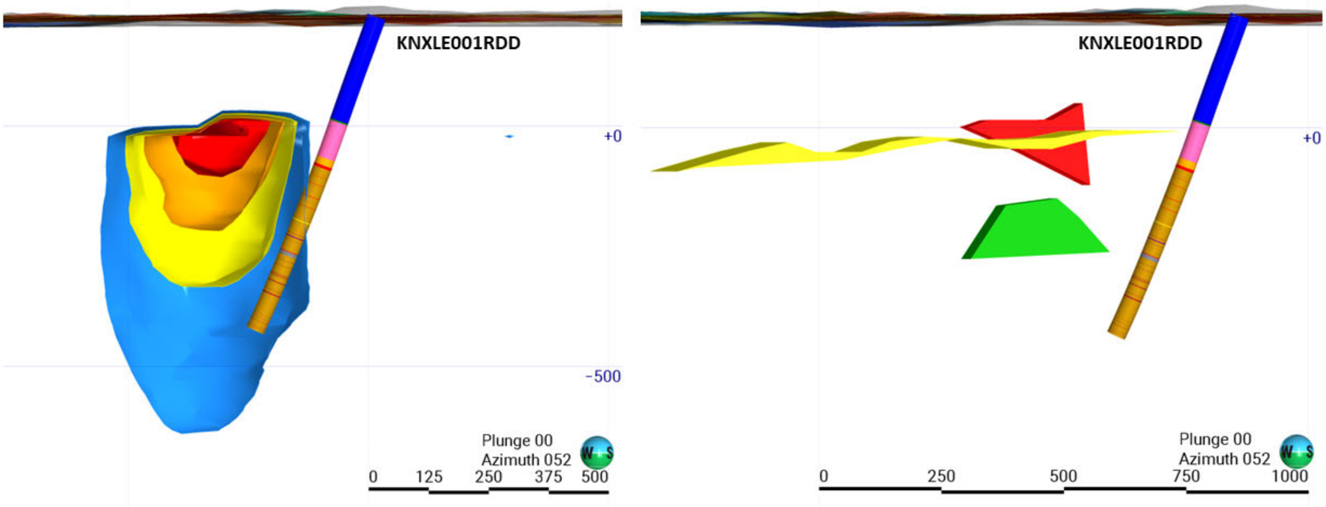

Figure 11. Along strike view of the UBC inverted source (left) and parametric solution (right) near LE001 below the base Georgina unconformity surface; LE001 (trace shown) did not intersect either implied source.

3.3 g/cm^3: Hanneson 2003) and in the range of chlorite-hematite + sulfide brecciated granite samples reported from such IOCG deposits as Carrapateena (Vella and Emerson 2009). These results suggest that the gravity anomaly west of LE001 is worthy of further drill testing as an IOCG target, given that LE001 has not intersected the likely source of the anomaly as shown in **Figure 11**.

Conclusions

Knox is continuing to explore their East Tennant tenure. The completion of an ANT survey on EL33375, supported by the Geophysics and Drilling Collaborations program, allowed for the generation of a surface representing the Georgina Basin unconformity as a function of the seismic velocity contrast between the Georgina Basin limestone with the underlying Proterozoic basement and Kalkarindji flood basalt. This surface has been used to leverage the gravity survey data set by calculation of the gravitational effect of the Georgina Basin to generate a residual basement Bouguer gravity anomaly at the Leichhardt East prospect. Inversion of the residual basement Bouguer gravity anomaly was conducted by two methods, both of which produced a dense (3.5 to 3.7g/cm^3) geobody positioned beneath the interpreted Georgina Basin unconformity surface. The bespoke workflow employed at Leichhardt East demonstrates a novel approach to exploring for dense mineral deposits, such as IOCGs, under cover.

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