3D Geological Modelling of the Tennant Creek Region, Northern Territory, Australia

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1 Introduction

The Tennant Creek mineral field is well known as an iron-oxide copper gold (IOCG) province and is host to high-grade deposits such as Warrego, Peko and Nobles Nob. The region is also host to large igneous intrusions such as Warrego, Peko and Nobles Nob. The IOCG mineralisation but the subsurface extent of the intrusions and their spatial correlation with mineralisation is a subject of debate. 3D geological modelling from our study provides new insight into the role of the intrusions in the genesis of the IOCG mineralisation and improves our understanding of the structural development of the region. This study has completed 3D modelling of the major faults, intrusions and lithological groups in the mineral field using geophysical inversions, interpretations of fault and fold belts and the careful correlation of these interpretations to outcrop mapping. Using detailed geochronology and the 3D distribution of the modelled intrusions we now have the ability to test the spatial and temporal relationships between the intrusions and the IOCG mineralisation. The 3D geological model also maps the development of the major shear zones and faults through five deformation periods as well as the formation of foreland basins and the delineation of sediment sources in the region.

2 Tennant Creek Mineral Field geology

Tennant Creek is part of the Warramunga Province and sits north of the Davenport Province and south of the Tomkinson Province in the Northern Territory of Australia (Fig. 1). The geology of the region is comprised of Paleoproterozoic sediments and intrusive suites that have been folded and faulted during several deformation events. These deformation events and intrusions are associated with the ironstone hosted and structurally controlled Cu-Au-Bi mineralisation in the region.
Fig. 1. Regional geology of the Tennant Creek region. a) 1:1 000 000 scale geological mapping (Lue et al., 2006) showing major sedimentary formations and intrusive suites as well as the major Cu-Au deposits within the study area (blue boundary); b) map showing province areas for Warramunga (Wm), Tomkinson (Tk), Davenport (Dv) and Aileron (Al) as well as the Georgina Basin (Gb), Wiso Basin (Ws), and Carpentaria Basin (Cp); c) map of Australia showing area of map A.
The regional geology can be broadly divided into three sedimentary groups and four intrusive groups. The oldest exposed sediments are from the Warramunga Formation (ca. 1860 Ma) which is an iron-rich sandstone and siltstone that also contains volcaniclastic sediments and argillaceous banded ironstones known locally as a hematite shale. There are no older sediments exposed at Tennant Creek in outcrop or drill core but it has been postulated that there may be a basement of volcanic-dominated successions with a more mafic component lying below the Warramunga Formation (Donnellan, 2013). The Ooradidgee Group (ca. 1853-1825 Ma) sits unconformably atop the Warramunga Formation and is dominated by subaerial volcanic and volcaniclastic sedimentary deposits. The group includes the Wundirgi Formation in the northwest; the Monument and Bernborough formations in the north of the study area; and the Yungkulungu Formation in the southeast. The Hayward Creek formation (ca. 1784 Ma; Compston, 1995) sits unconformably above the Ooradidgee Group and Georgina Basin sediments (ca. 540 Ma; Donnellan, 2013) overly all older units, bounding the margin of the Tennant Creek inlier.

Tennant Creek is also host to three periods of igneous activity. The primary and most voluminous period occurred as part of the Tennant Event (1855 – 1845 Ma) with the emplacement of the Tennant Creek Granite, Channingum Granite, Mumbilla Granodiorite and Cabbage Gum Granite (Donnellan, 2013). The Tennant Event also included felsic porphyritic dikes and sills that include those near the Peko, White Devil and Orlando deposits and minor mafic gabbro, lamprophyre and dolerite dikes. The Warrego Granite (ca. 1835 Ma; this study) in the west of the study area marks the second main period of igneous activity that was followed by the Treasure Suite (ca. 1821 Ma; Compson, 1995). Later events include intrusion of mafic sills and dikes (ca. 1811 Ma; Claoué-Long et al., 2008) into the Ooradidgee sediments; and the Devils Suite intrusions (ca. 1720 Ma; Donnellan, 2013) in the southern region of the study area.

The region also underwent a long period of multi-phase deformation with up to five stages recognised as part of this study. Initial D₀ extension developed large approximately east-west trending normal faults and basins for sediment accumulation, this was followed by basin inversion and north-verging fold-thrust belts during D₁. Intrusive magmatism known as the Tennant Event occurred during D₂ and D₃, with the later involving syntectonic brittle-ductile deformation of the intrusions in major shear zones. Late brittle strike-slip faulting occurred during D₄ before minor folding and faulting that followed during D₅.
Tennant Creek is well known for its Cu-Au-Bi mineralisation that occurred in at least three phases. An initial deposition of magnetite-hematite-quartz bodies (ironstones) formed hydrothermally into folds, cleavage planes and fault planes during D\textsubscript{1} deformation (Skirrow and Walshe, 2002). The ironstones were then hosts to the main episode of Cu-Au-Bi mineralisation that occurred ca. 1845 Ma (Fraser et al., 2008) during D\textsubscript{3} and a later phase of Cu-rich mineralisation that occurred during D\textsubscript{4}. The Tennant Event correlates temporally with the ironstone hosted Cu-Au-Bi mineralisation throughout the region and the 3D geological modelling from this project has been able to refine interpretation of the extent of the granite and porphyry intrusions in the upper crust.

3 3D modelling of the Tennant Creek mineral field

A 3D model of the Tennant Creek mineral field was created after inversion modelling of geophysical data provided new insight into deep structures and intrusions in the region. The model was constructed with the aim of improving visualisation of the crustal structure and determining the depth extent and geometry of the igneous intrusions. Modelling was undertaken over an 80 x 60 km study area from a flat surface at 300 m to a depth of 15 km using Leapfrog Geo implicit 3D modelling software. The area was first divided into large fault-bound blocks by modelling the major faults and shear zones; smaller structures and lithological boundaries were then defined within each block using stratigraphic topology for layered units and cross-cutting relationships for intrusional units. Faults within the blocks were separated into planar and listric groups depending on their generation and relationship to interpreted deep décollements.

Boundaries within the model were constructed using data imported into the 3D model space (Fig. 2). Data was used from a detailed interpretation of surface structures as well as structural measurements of contacts and faults. Surface mapping from the Northern Territory Geological Survey (NTGS), historic exploration company mapping, and field mapping from this project were used as surface controls of the lithology in the study area. Sections from thirty-five cross-gradient joint inversion models that used magnetic and gravity geophysical data supplied by Emmerson Resources Ltd (Hill and Gallardo, 2012) were also used to interpret structures and lithologies at depth after correlation with surface data.

To construct surfaces within the model, boundary lines were digitised from maps and sections using Leapfrog Geo then assigned to a stratigraphic boundary or fault in the model along with any structural measurements or interpolant trend data. Relative stratigraphic
relationships were setup using the modelling software to ensure that units onlap, erode or crosscut each other correctly. A fault network was also created so that small structures are restricted to fault bound domains or above décollements. The model was updated after the addition or review of each dataset and then carefully checked against the surface outcrop data to ensure the model correctly represented known surface data. The final model was processed using 250 m triangulations for the surfaces that therefore represents the scale of the interpretation for this model.

Fig. 2. Data used to create the 3D geological model that included cross-gradient joint inversion modelling, magnetic and gravity geophysical data, structural interpretations and surface mapping.
4 3D geological model of Tennant Creek

The 3D model produced from this project maps the geological architecture of the Tennant Creek region; in particular the model maps the distribution of crustal structures and the extent of large magmatic intrusions in relation to regional sedimentary formations (Fig. 3). The extent and depth of the Warramunga Formation, the Ooradidgee Group and the younger Hayward Creek Formation sediments have been mapped from interpretations in this model. Intrusions from the Tennant Event represent an enormous intrusion of magma into the central region with an interpreted total crustal volume of >12,425 km$^3$. As well as the large Tennant Event intrusions, porphyry dikes and sills from the same event that were too small to be mapped in this model and the younger Warrego and Devils Suite granites add further to this volume of intrusive material in the study area.

The model maps the steep south dipping $D_0$ faults (brown planes in Fig. 3) that form controls on emplacement of intrusives during the Tennant Event and were reactivated in later deformation events. $D_1$ faults (blue planes) are restricted to domains created by the early $D_0$ basin architecture and within the Warramunga Formation; they have anastomosing intersection relationships and are linked to an interpreted décollement at depth. $D_3$ faults (red planes) are found throughout the model area and are zones of brittle-ductile deformation and shearing of intrusions shortly after the Tennant Event. $D_4$ faults (green planes) are mainly a conjugate northeast and northwest trending strike-slip structures that cross-cut older structures and sediments. Some of the earlier structures, if well orientated for slip during this deformation period, were also reactivated.

A boundary between the Warramunga Formation and a basement sedimentary formation (pre-Warramunga sediments) has been interpreted from the cross-gradient joint inversion models (see Fig. 3 inset section). A basement formation below the Warramunga Formation has long been inferred at Tennant Creek, although it has never been seen at the surface or in drill core (Skirrow and Walshe, 2002; Donnellan, 2013). This basement formation is interpreted from a density change observed in the inversion modelling and the contact occurs between 3 and 10 km below the surface and may also be a décollement for $D_1$ faulting. Similar fault models with décollements at this depth are inferred from seismic studies south of Tennant Creek (see Korsch et al., 2011). This model also infers a lower contact that we interpret as a transition towards the lower crust or other brittle-ductile transition at 10-12 km.
A foreland basin model can be used to describe the uplift and erosion of Warramunga Formation sediments and Tennant Event igneous intrusions into basins to the north that collect and form units in the Ooradidgee Group. For example this model shows where the Warramunga Formation and Tennant Creek Granite were eroded during D$_1$ uplift on the south-dipping Gecko Shear Zone northwards into a broad east-west elongated fault controlled basin (see Fig. 3 inset section). The Monument Formation (after 1853 Ma) was formed within this basin before deposition of the subaerial volcanic sediments of the Bernborough Formation (ca. 1843 Ma); these sediments were then gently folded into an open and gently west plunging anticline during D$_4$. Intruded granites from the Tennant Event and sediments from the Warramunga Formation are also exposed within the hinge zone of the anticline after uplift and erosion.
Fig. 3. 3D geological model of Tennant Creek over an 80 x 60 km surface area down to a depth of 15 km. Model shows main lithological units within the region (including intrusions from the Tennant Event) and structures related to the five deformation sequences in the region. IOCG mineral occurrences are shown as yellow spots. Inset figure of section at E 418,700 showing shear zones and basin sediment development. Inset location map showing study area and Warramunga Province (W), Tomkinson Province (T) and Davenport Province (D).
5 Spatial correlation between Tennant Event intrusions and mineralisation

IOCG deposits have been defined as being temporally, but not necessarily spatially, associated with magmatism (e.g. Groves et al., 2010) and the 3D geological modelling from this study allows us to test the spatial association between intrusions in the Tennant Creek region and ironstone hosted mineralisation statistically. There is a clear temporal association between the Cu-Au-Bi mineralisation at Tennant Creek from 1847 to 1851 Ma (Fraser et al. 2008) and the Tennant Event magmatism from ca. 1855 to 1840 Ma (Donnellan, 2013). Mineralising fluids are interpreted to be a mix of oxidised magmatic hydrothermal fluids and basinal brines (Huston et al., 1993; Stolz and Morrison, 1994) and the chemistry of the mineralisation that includes bismuth and molybdenum in some deposits indicates that intrusions may be involved with the mineralisation. The 3D model shows a much larger volume of subsurface intrusive rocks than previously thought, which opens up the possibility that there may also be a spatial association. To test this hypothesis a model of the distance from Tennant Event intrusions was created and tested against ironstone hosted Cu-Au mineral occurrences for a statistical correlation using a weights of evidence Bayesian statistical technique.

A 3D distance model was created in Leapfrog Geo using the geometries of the intrusions related to the Tennant Event. Volumes of the Tennant Creek Granite, Channingum Granite, Mumbilla Granodiorite, Cabbage Gum Granite, and the Peko and Airport porphyries from the 3D geological model were combined with any small surface outcrop occurrences of these intrusions that were too small to map in the main 3D geological model. The surface outcrop polygons were extended 100 m below the surface and combined with the volumes from the 3D geological model and a distance interpolant was created from the combined dataset (Fig. 4a). The distance values at the surface (RL 300 m) were exported to ArcGIS for spatial testing with ironstone hosted mineral occurrences (Fig. 4b). By using a 3D distance interpolant in Leapfrog instead of a 2D distance grid in a GIS we gain knowledge about the true spatial distance to intrusions that might be closely buried below surface sediments or that become distal quickly due to steep edges. The spatial correlation testing was carried out in 2D using 3D data extracted at the level of our training data that are from relatively near-surface mineral occurrences.
The weights of evidence modelling technique (Bonham-Carter, 1994) is a Bayesian statistical approach and was used to test the spatial correlation between igneous intrusions and ironstone Cu-Au mineralisation. This method used the 2D surface map that represents the distance to an intrusion from the surface and a training data set of 223 ironstone hosted Cu-Au deposits within the study area from the NTGS mineral occurrence database. Several sets of training points were tested in the analysis, these included two sets from a 50% random selections of the 223 main data set and a 75 point selection of the most economic locations; all training point sets gave similar spatial results in this study so results from the main 223 main data set are presented here. The modelling was carried out in ArcGIS using the Spatial Data Modeller extension (Sawatzky et al., 2009) which tests the relationship of the area covered by the distance to an igneous intrusion and the number of training points that fall within that area being tested.

The weights of evidence correlation test was carried out using the cumulative ascending method on 20,029 unique classes of distance from an intrusion. The resulting statistical test produces a W+ result based on training points falling within the map area of the distance tested and a W- result based on training points falling outside the distance tested. A W+ value greater than zero indicates a positive correlation with the mapped area, whereas a W- less than zero indicates a negative association with the non-mapped area. The model also produces a contrast value which is the difference between W+ and W-; this value becomes higher with an increase in the correlation between the distance from intrusions and the training data. Contrast values > 0 indicate a positive correlation between the training data and the map being tested; however, the studentised contrast (studC) which is the ratio between the contrast and its standard deviation, ideally needs to be larger than 1.5 for the
contrast to be considered real (Bonham-Carter, 1994). Therefore positive values of contrast and studC are required to infer a strong spatial correlation between the distance being tested and the training data.

Results from this spatial analysis show a weak correlation between the mineralisation and the intrusions and the results for W+, W-, contrast, and studC relative to the distance from an intrusion are shown in Fig. 5. 154 of the training points were found in the map area within 2 km of an intrusion with the rest accumulating over the remaining area out to 4.5 km. There is a poor correlation between any map area within 2 km of an intrusion and the training points as seen by the low W+ and studC values and the negative contrast in Fig. 5. The total area covered by the distance buffer is too large compared with the number of training points within it for a good statistical correlation. After 2 km in distance from an intrusion the contrast levels increase along with the studC indicating that the correlation is improving. At a distance of 4 km from an intrusion high contrasts of 2 to 3 are reached; however, these contrast levels are associated with reducing studC values indicating that the contrast is not real due to the reduction in training points and large map area.

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**Fig. 5.** Spatial correlation graph between distance to intrusions temporally related to mineralisation and ironstone hosted Cu-Au mineral occurrences. W+ and W- (red and blue lines); contrast (C) and studentised contrast (studC) (orange and green lines); cumulative count of training points within distance from granite shown as labelled crosses along studC line.
The results from this analysis indicate that there is not a good spatial correlation between areas near Tennant Event intrusions and ironstone hosted mineralisation in the Tennant Creek region; however, there may be a better association between mineralisation and distal parts of the intrusion. Other spatial studies of intrusion related mineralisation have the best correlation with intrusions occur at 600 m with W+ values > 2, contrasts > 3 and studC values > 2 (e.g. Kreuzer et al., 2015) which is closer and with higher values than seen here. In our study at distances between 2 and 4 km the correlation improves. This distal increase in the correlation indicates that mineralisation may be related to smaller porphyry dikes and sills that were too small to be mapped in our 3D model but are known to occur away from the intrusions.

6 Conclusions

The 3D geological model of the Tennant Creek mineral field was constructed to map the geological architecture of the major structures, sedimentary formations and intrusions. Fault network modelling maps domains of anastomosing faults within larger fault blocks controlled by early regional architecture. The model shows that large shear zones in the area have controlled the emplacement of intrusions as well as the development of foreland basins, these have been filled by sediments from the uplifted and eroded blocks. Modelling suggests that a dense basement may exist below the Warramunga Formation. This basement may be an intrabasinal source of alteration minerals, metals and iron-rich fluids related to the precipitation of ironstone bodies and the subsequent Cu-Au-Bi mineralisation. The model of Skirrow and Walshe (2002), where mineralising fluids are sourced from outside the relatively oxidised Warrumunga Formation to produce the reduced end member mineralisation is supported from this mapping of new deep and dense sediments below the Warramunga Formation and the D1 faults that extend down into these sediments.

Our model maps a large volume of intrusive rocks that were emplaced into the region during the Tennant Event and although they are temporally associated with mineralisation, statistical analysis indicates that regions near the intrusions do not correlate well with the ironstone hosted Cu-Au-Bi mineralisation. The large intrusions could therefore be driving some other mechanism that is causing mineralisation, such as a possible heat source to enhance circulation of basinal brines (e.g. Wyborn, 2001) or smaller distal intrusions, such as porphyry dikes and sills, may be providing mineralising magmatic fluids. Our study therefore supports the models of Wedekind et al. (1989), Zaw et al. (1994) and Skirrow and
Walshe (2002) where ironstone and Cu-Au-Bi mineralisation is formed from brine circulation within the crust as well as a contribution from magmatic fluids (albeit from distal parts and not the main intrusional bodies) that are mixed with them as proposed by Huston et al. (1993) and Stolz & Morrison (1994).

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8 References


