# Building the 3D geological model of the Central Domain of the Pine Creek Orogen: A reinterpretation and integration of the existing database

*Gemma Mitjanas[1,2] and Steven Micklethwaite[1]*

The Palaeoproterozoic Pine Creek Orogen (PCO) has a long history as a gold and uranium province, but it is also rich in polymetallic natural resources. This includes some of the Northern Territory's critical and emerging minerals such as zinc, cobalt, nickel, antimony, graphite, platinum group elements, tantalum, and tin (NTGS 2023). The wide spectrum of metals, the variety of rock types of different ages, the varied chemistry of magmatic rocks, the presence of Archaean basement, and the complex structural and metamorphic patterns, together suggest that the PCO is likely to present a variety of opportunities for exploration, aligning with the mineral systems concept (Wyborn *et al* 1994; McCuaig *et al* 2010).

With the aim of encouraging investment in this region and supporting exploration and government decision-making, the Sustainable Minerals Institute (The University of Queensland) has collaborated with the Northern Territory Geological Survey (NTGS) to produce a 3D geological reinterpretation of the main mineralised area in the Central Domain of the PCO (AoI, **Figure 1**). By integrating open-source geophysical and geological data, this project has gained critical insights into the area's structural and stratigraphic complexity, highlighting the importance of accurate, high-quality open datasets for a preliminary evaluation of the area's sustainable potential. This project lays the foundations for future mineral systems analysis of the AoI, identifies knowledge gaps, and recommends new surveys needed to improve understanding of the structural framework of the region.

[1] Sustainable Minerals Institute, The University of Queensland, 40 Isles Rd, Indooroopilly QLD 4068, Australia

[2] Email: g.mitjanascolls@uq.edu.au

## An iterative methodology

This project has employed an iterative methodology encompassing five main phases:

1. reviewing available data and its quality
2. updating the geological map by comparing it with outcrop and geophysical data
3. creating geological cross-sections, and gravity and magnetic forward models
4. conducting preliminary 3D gravity data inversion
5. building a 3D geological model.

This iterative process required that maps, sections, and the final model were continuously improved until a result was generated that was geometrically and physically consistent with the available data.

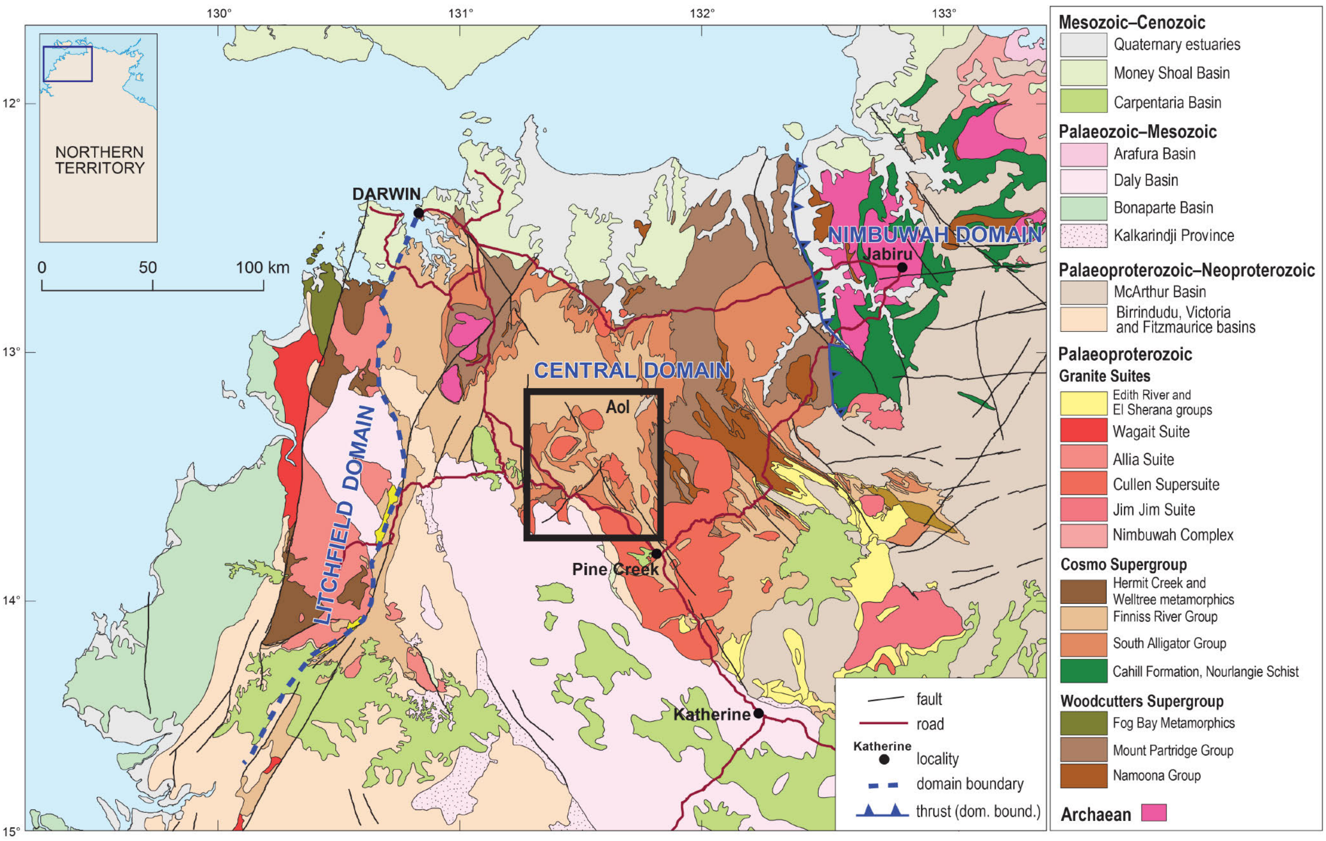


**Figure 1**. Generalised geology of the PCO with the location of the area of interest (AoI). The AoI includes key features as the Pine Creek Shear Zone, satellite Cullen Supersuite intrusions (eg Burnside and Margaret), and the northern part of the Daly Basin. Figure modified from Ahmad and Hollis (2013).

All the regional GIS geological and geophysical data used for this project are available to download from the NTGS' Geoscience Exploration and Mining Information System (GEMIS) portal[3] and through the NTGS' Geophysical Image Web Server (GIWS[4]) ensuring the reproducibility of the final results.

## Geological map update

After a quality review of the geological and geophysical maps used in this project, the initial phase involved updating the *1:500 000 Pine Creek Orogen interpreted geology* map (Lally and Doyle 2005) by integrating the *1:250 000 Pine Creek geological map* (Hollis and Glass 2011) and identifying potential discrepancies. In conjunction, the geophysical grids from the NT-wide series (airborne magnetics, airborne radiometrics, gravity surveys, and derived ones) were used to confirm these changes and target additional inconsistencies. The use of geophysical data was particularly relevant for units with distinct physical responses, eg some faults often show a related magnetic anomaly. Examples include the *Cullen Supersuite* unit, which is distinguished by low-gravity and characteristic radiometric signals, and the *Zamu Dolerite* unit, often characterised by higher magnetic anomalies. **Figure 2** presents an example of the Bons Rush area, where discrepancies between the outcrop map and the interpreted geology were addressed; this outcome is also supported by geophysical grids.

[3] https://geoscience.nt.gov.au/gemis/ntgsjspui/community-list
[4] https://geoscience.nt.gov.au/giws/

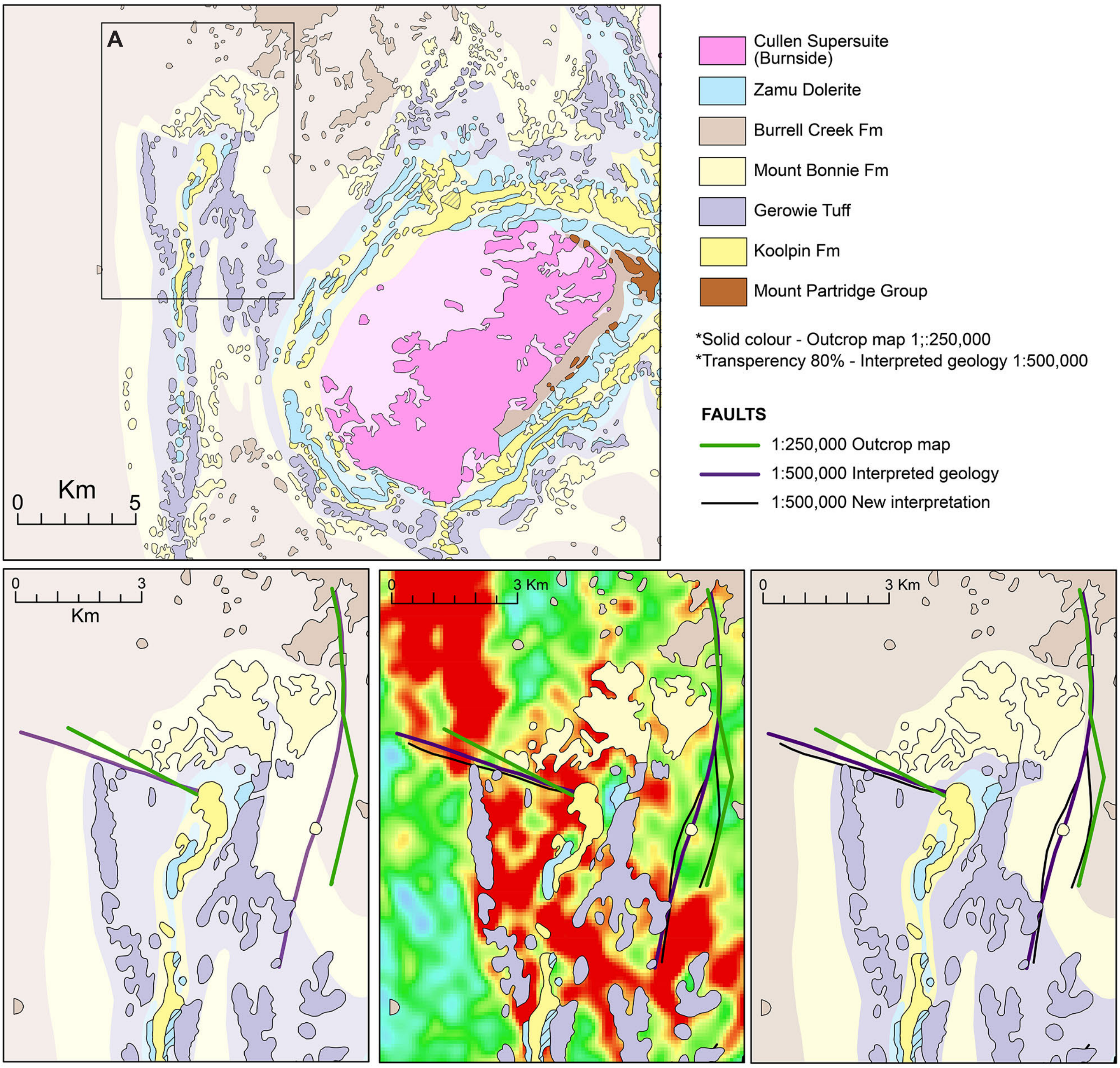


**Figure 2**. Upper map: inset A shows location of lower maps. Lower maps: examples of inconsistencies between the 1:500 000 interpreted geology (transparent, left image) and the 1:250 000 outcrop map (solid colour, centre image). The figures are located around Bons Rush where outcrops of Mount Bonnie Formation are present in areas mapped as Gerowie Tuff. The image on the right shows the changes applied to the interpreted geology and the suggested new fault trace. The new fault trace has been drawn after a qualitative analysis of the airborne radiometric (uranium – U) and magnetic grids.

In addition, the analysis of geophysical data at map scale was also useful to recognize some unit's layering and internal deformation. For example, we have recognized magnetic layering in units like *Burrell Creek Formation,* which could be used to review the stratigraphy subdivision. This magnetic layering has evidenced polyphase deformation affecting the units outcropping within the AoI, leading to variations in the thickness of different formations across the area, and therefore, complicating the cross-sections and 3D model building.

**The 2D approach – cross-sections and analysis of geophysical profiles**

A comprehensive understanding of the tectonic history of the PCO is essential for justifying subsurface geometries in cross-sections given the lack of deep boreholes or deep geophysical data, such as magnetotellurics or seismic refraction profiles. However, the tectonic framework of the PCO remains subject of debate (eg Johnston 1984 and Stuart-Smith *et al* 1980), and there are no recent works on the deformation phases or fault sets affecting the AoI. After the map analysis, it was anticipated that there could be lateral changes in the thickness of the sedimentary units due to the complex deformation history. Nonetheless, we assumed constant thickness in the cross-sections building process as a method to retain self-consistency within the interpretation, and to establish a preliminary constraint for the cross-sections. The 3D geological model building relies on these cross-sections, and therefore, the final model also reflects these assumptions.

In addition to the cross-sections, the 2D approach included their validation through gravity and magnetic forward models. Despite the lack of complete petrophysical data to support model validation, we found value in the straightforward analysis of the profiles, which allowed the identification of the causes behind gravity and magnetic anomalies. The results confirmed the relationship between the negative gravity anomalies and the *Cullen Supersuite* granitoids, which slightly varies depending on the volume and shape of the intrusion as there are not significant differences in density (Klomínský *et al* 1996). The magnetic susceptibility data showed evidence of being influenced by multiple variables, such as the different formations classification (as *Zamu Dolerite*), but also by the degree of metamorphism. One of the clearest magnetic anomalies detected in the area is the linear magnetic dyke that limits the Pine Creek Shear Zone towards the west. This dyke also shows a positive gravity anomaly, although this could be related to the squeezing and compaction process of that region in particular. As such, it is recommended that future surveys of the AoI include the systematic collection of samples for petrophysics to improve the quality of information that can be extracted from its geophysical data.

**3D geological model – the Cullen Supersuite unit as the key volume**

The final 3D geological model was built using Leapfrog Geo©, a 3D visualization/modelling software. The modelling process involved importing data, digitizing geological units and faults (both in map and cross section), and generating geo-surfaces and finite fault volumes (faults that do not terminate at a model boundary, or against another fault, but rather in the middle of a domain). The *Cullen Supersuite* was the first unit to be modelled due to its significance and because of the data inputs that could be used as a constraint.

The outcomes of the 2D analysis identified an additional constraint for the *Cullen Supersuite* surface building, ie the gravity-derived data. The gravity data used in the 3D approach included the residual anomaly grid, processed to depict the mass effects corresponding to depths between -125 m and -5000 m below the topographic surface, and the gravity inversion voxel. The residual anomaly grid was presented as point data, attributing the point's height (z) to a factor of the anomaly value, thus producing a better representation of the shape of the anomaly. The 3D gravity inversion was modelled with Oasis Montaj© software; and we used the representation of the lowest density cells for qualitative constraining of the final volume (**Figure 3A**).

Faults were modelled as volumes, or fault zones, following the best practices for modelling finite faults in Leapfrog. Fault traces were digitized in the map and cross-sections, and the structural data was used to constrain the subsurface geometries. The fault zone volume was created using the *Distance Function* tool, a numerical modelling process utilizing the fault mesh and a defined buffer (50 m in average for this project). These fault zones were incorporated into the geological model as *Intrusions* in the *Surface Chronology* (**Figure 3B**). Finally, the remaining formations were modelled also using map traces, cross-sections, and the structural data.

The final 3D geological model, covering ~3600 km$^2$ to a depth of 2 km (**Figure 3C**), provides a robust preliminary basis for future improvements from new information, such as deep boreholes, geophysical data contributions, or by increasing resolution in areas of interest using industry data. However, when using the model, it should be taken into consideration that it is based on numerous assumptions.

**Preliminary outcomes from the 3D geological model**

The geological model has provided a new and more thorough way of analysing the distribution of the commodities in the Central Domain of the PCO. The two main analyses made during the project were the structural influence on commodity distribution and the Cullen Supersuite multidisciplinary study.

Previous references have shown that distinct tectonic settings in different parts of the PCO have had an important bearing on the distribution and style of mineralisation in the PCO (Hollis and Wygralak 2012). Some of these are noted in the new geological model. Major faults seem to demarcate mineral provinces, highlighting the need for a better understanding of structural characteristics in the AoI and their influence on hydrothermal fluid circulation.

The Cullen Supersuite is one of the key geological units of this project because the different batholiths influence deformation in the host stratigraphy, and therefore the geometries defined in the final model; and because of its connection to mineral commodities. Previous references

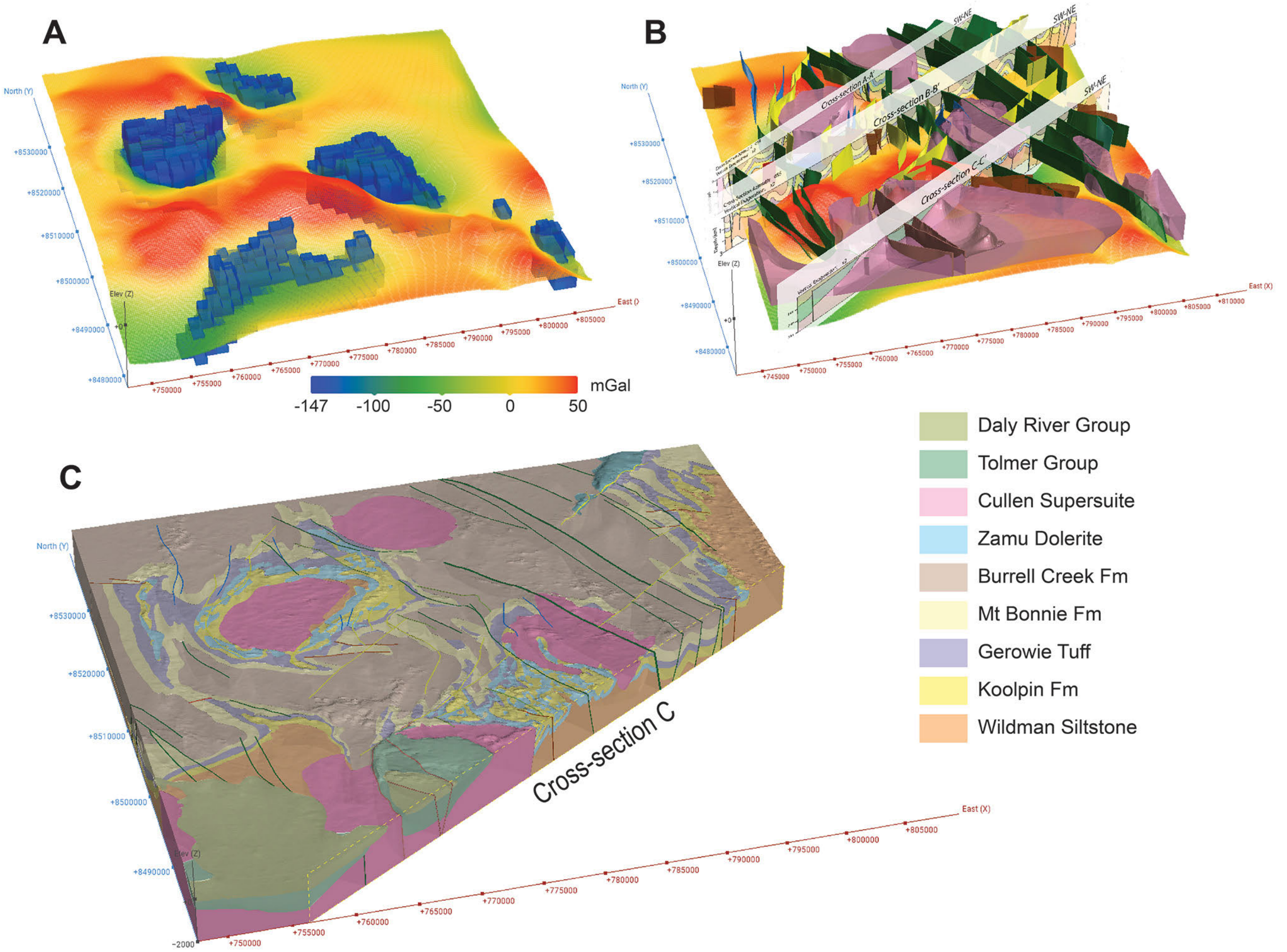


**Figure 3**. (**a**) Residual anomaly map corresponding to the depths between -125 m and -5000 m plot in 3D. The voxel obtained after the inversion is filtered to the lowest density values (blue cells) for modelling the Cullen Supersuite unit. (**b**) Cullen Supersuite unit (pink), main faults and cross-sections. (**c**) Final 3D geological model cut at 'Cross-section C' trace in (**b**).

note that PCO gold deposits occur almost exclusively within 3–5 km of the Cullen Batholith (eg Matthai *et al* 1995); however, we extended this analysis to all the commodities.

From a review of the results and practical outcomes of this project, we have related the different geophysical signatures of the batholiths with other potentially associated parameters, such as heat production, geographic locations, age of formation, and relationship to satellite or massive intrusions in the geological model (**Figure 4**). Some of the main observations include:

- Intrusions with complex inner structures and high radiometric signatures, especially those from the Early Igneous Suite (EIS) and Transitional Igneous Suite (TIS), are more likely to host a broad spectrum of mineralisation.
- There is a correlation between high-radiometric signal, high-heat production, and gold fertility. In contrast, lowest radiometrics values correspond to the southern massive batholith Fenton West–Fenton East–McMinns Bluff, lowest heat production, and polymetallic environments.
- The spatial correlation analysis has shown that certain granites are consistently associated with particular mineral commodities. The southern massive intrusions of McMinns, Fenton and Allamber Springs exhibit a diverse array of associated minerals, indicating polymetallic mineralisation environments that could be of significant interest for multi-commodity exploration.
- The geological model has confirmed the possibility of deep connectivity between McKinlay and Mount Porter granitoids. This would align with the fact that they show similar commodity percentages.

These observations highlight the potential of the products and the methods used in this project for forming the foundations of future mineral systems analysis for this and other regions.

## Conclusions

The results of this project have allowed us to deliver products and methods that are key in understanding the geological framework of the Central Domain of the PCO, thus encouraging exploration, and enhancing sustainable procedures. The whole development process of this geological model has underscored the critical role of high-quality geological and geophysical open-source data. These sources of information can make a big difference in providing the knowledge base for the mineral resources' evaluation. While the current model provides a solid preliminary basis

| Names | Symbol | Location | Radiometrics | | | Magnetics | Gravity | Geochronology | Zonation | Heat Production | Classification (*Wyborn & Stuart-Smith, 1993*) | | Major Commodity (gold-dependant) | Intrusion shape |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | From N to S | K | Th | U | *Inner structure* | *Bouguer anomaly* | | *Klomínský et al. (1996)* | *Wyborn et al. (1997)* | *Plutons type* | *Granite type* | *4 km radius* | *Satellite/Massive* |
| MARGARET | Pgg | 1 | Low | Mid | Mid | YES | Mid | EIS | NO | > 7 | Granite | Mixed | G3 | S |
| BURNSIDE | Pgb | 2 | High | High | High | NO | High | YIS | YES | > 7 | Leucogranite | - | G1 | S |
| PRICES SPRINGS | Pgp | 3 | High | High | High | NO | High | EIS | NO | 5-7 | Granite | Mixed | G1 | S |
| McKINLAY | Pgk | 4 | High | High | High | NO | Low | EIS | NO | < 3 | Granite | Mixed | G1 | S |
| FENTON W | Pgf | 5 | Mid | Mid | Low | NO | Low | YIS + Xenolith | NO | 3-5 | Leucogranite | - | G3 | M |
| FENTON E | Pgf | 6 | Mid | Low | Low | NO | Low | EIS | YES | 5-7 | Granite | Biotite | G3 | M |
| McMINNS BLUFF | Pgm | 7 | Mid | Low | Low | NO | Low | EIS | YES | 3-5 | Granite | Biotite | G2 | M |
| MOUNT PORTER | Pgh | 8 | High | High | High | NO | Low | TIS | NO | > 7 | Granite | Mixed | G1 | S-M |
| ALLAMBER SPRINGS OUTTER | Pga | 9 | High | High | High | YES | Low | TIS | YES | > 7 | Leucogranite | - | G2 | M |
| ALLAMBER SPRINGS INNER | Pga | 10 | High | High | High | NO | Low | EIS | YES | 5-7 | Granite | Biotite | G2 | M |

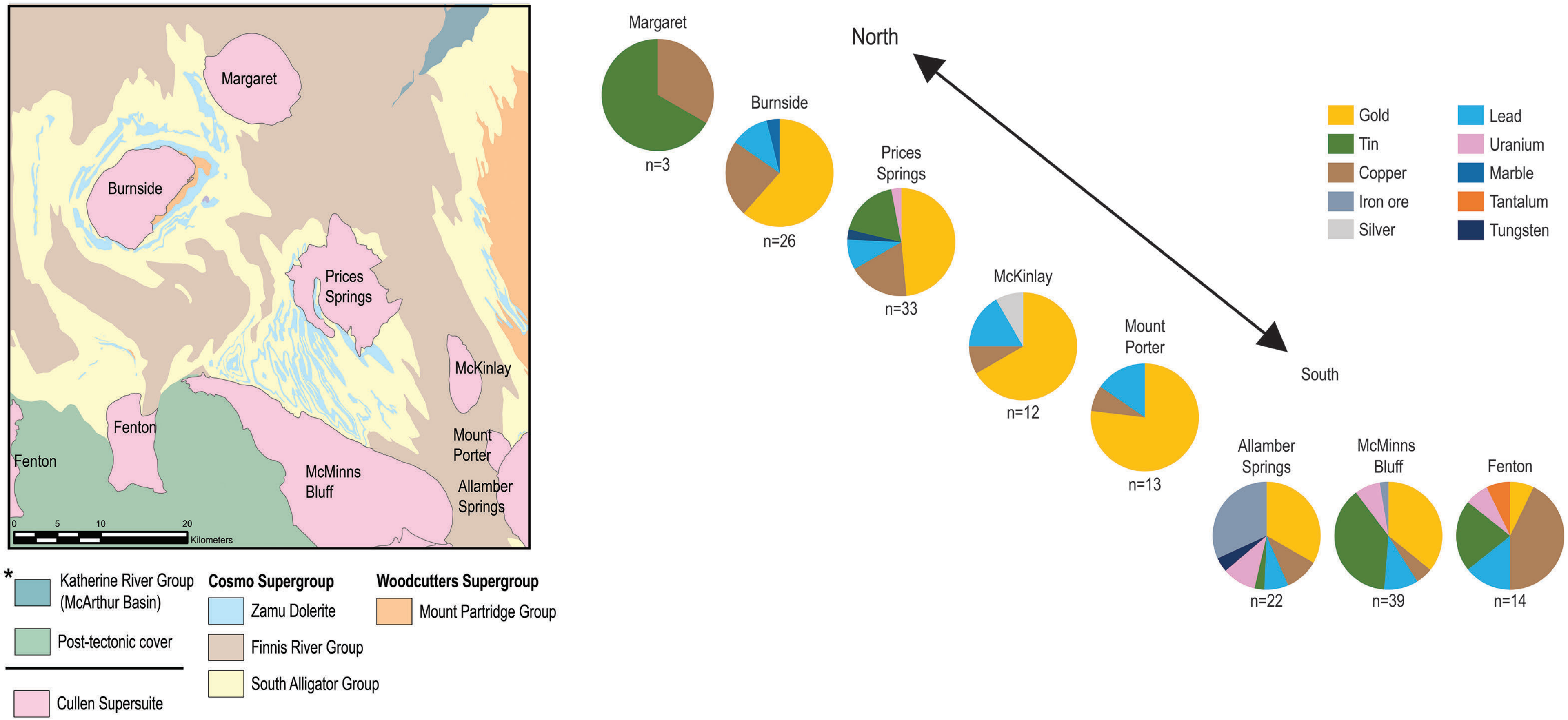


**Figure 4**. Summary of the Cullen Supersuite intrusions of the AoI and review of related physical properties, genesis, shape (satellite/massive) and mineral commodities. Geochronology: The first phase is subdivided in the EIS (ca 1830 Ma) and the TIS (ca 1825 Ma). The second phase include the Young Igneous Suite (YIS; ca 1800 Ma; Klomínský *et al* 1996). Gold-dependant: We have classified the nearby commodities for each batholith considering the percentage of gold (from disk graphs). The disk graphs present the commodities in a 4 km radius.

for exploration, it is built upon certain assumptions and needs additional validations. Specifically, discrepancies in the data quality used might significantly impact the model reliability as revealed through the project reports; these discrepancies include irregular site distribution in gravity surveys, potential shifts between regional geological and geophysical maps, the lack of updated petrophysical data, and the limited structural context knowledge.

To progress exploration in the area, there is a clear opportunity to extend the insights gained from this project through a focused mineral systems analysis. Such an analysis would leverage the existing geological model to unravel the complex interplay of geological processes that makes the Northern Territory well-placed to become an important player in the global supply chains for critical minerals. However, part of the mineral systems concept relies on the understanding of the structural framework and the fault systems, and thus the related fluid flow pathways to potential commodities depositions. Our work has noted this knowledge gap during the process of the geological model building. An improvement in the structural knowledge of the area, together with updated geophysical surveys, would provide key foundations to support the mineral systems, driving improved exploration targeting and thereby reducing environmental impacts and enhancing the sustainability of mining activities in the region.

**Acknowledgements**

We acknowledge the traditional owners of country across Australia on whose land on which this study was undertaken. We thank Wess Edgar (Agnico Eagle Mines Limited) for the supply of structural field data that contributed to the generation of the prototype model. We thank the NTGS team, especially Jo Whelan, Pablo Farias, Tania Dhu, Barry Reno, Peter Eagleton and Dorothy Close for the comprehensive review and feedback along the project.

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