The significance of protracted magmatism in the Pine Creek Orogen

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Introduction

The Pine Creek Orogen hosts a wide range of mineral deposits, including gold, uranium, lead–zinc–silver, platinum-group elements, copper (associated with base metals), iron, tin–tantalum–tungsten, phosphate and lithium (Ahmad and Hollis 2013). Recent developments in mineral exploration have led to the discovery and by-product re-evaluation of critical minerals including antimony, graphite, manganese, cobalt, magnesium, gallium, phosphate and rare earth elements (Northern Territory Geological Survey, 2026). Factors including proximity to key infrastructure and known successful history of production (Ahmad and Hollis 2013) make the Pine Creek Orogen a strategic area for development that supports both industry and the imperative of a low carbon emission future (Close 2024). The geological framework of the Pine Creek Orogen has been studied in previous work programs (Ahmad and Hollis 2013) but many of these studies targeted local stratigraphy and lacked regional connection, resulting in ambiguous correlations across the different tectonic domains. Additionally, the absolute timing of deposition of some sedimentary packages, and of emplacement of many igneous units, remains unknown or uncertain. Under the Northern Territory Government's *Resourcing the Territory* program, the Northern Territory Geological Survey (NTGS) is currently undertaking a new program to improve understanding of the geological framework of the Pine Creek Orogen. In this contribution we build on previous work by Burton-Johnson *et al* (2025) and Reno *et al* (2025) by clarifying stratigraphic constraints based on new geochronology and isotopic geochemistry. These constraints will be tested in upcoming field work and compared with previous observations.

Regional geology

The deformed and variably metamorphosed Palaeoproterozoic-aged Pine Creek Orogen (PCO) is in the northern part of the North Australian Craton. It unconformably overlies Neoarchaean-aged basement rocks and is itself covered by younger basins (**Figure 1**). The PCO consists of a thick succession of Palaeoproterozoic metasedimentary and metavolcaniclastic rocks intruded by large granite bodies and minor mafic igneous rocks (Ahmad and Hollis 2013, Hollis *et al* 2014). The PCO is divided into three domains – the Litchfield, Central and Nimbuwah domains – based on differences in protolith sources, metamorphism, magmatism and deformation (Worden *et al* 2006, 2008b, Hollis *et al* 2009). The boundaries between these domains are not fully understood and still debated (Lindsay *et al* 2016, Maidment *et al* 2020, Northern Territory Geological Survey and Geognostics Australia Pty Ltd 2021, Kirscher *et al* 2022, Henson *et al* 2024).

The evolution of the PCO as summarised by Ahmad and Hollis (2013) includes five main stages. Stages 1 and 2 involved the deposition of two sedimentary supergroups – the Woodcutters and Cosmo supergroups – with associated bimodal volcanism and mafic intrusions. Subsequent regional metamorphism and compressional deformation is Stage 3. Stage 4 involved renewed extension, sedimentation and volcanism and widespread felsic magmatism (Cullen Supersuite; **Figure 1**). Finally, Stage 5 involved metamorphic retrogression associated with minor compressional reactivation; Stage 5 marks the end of the PCO succession and the initiation of a new depositional system (eg McArthur Basin) (Ahmad and Hollis 2013).

Sedimentation occurred in three of these stages. The first stage of sedimentation occurred ca 2.02 Ga during a period of continental rifting and produced clastic and evaporitic sedimentary deposits with volcanic-volcaniclastic input (Needham *et al* 1988, Hollis and Glass 2012, Ahmad and Hollis 2013). These sediments are grouped into the Woodcutters Supergroup which is composed of the Manton, Namoona and Mount Partridge groups in the Central Domain, the correlative Kakadu Group in the Nimbuwah Domain and the Fog Bay Metamorphics in the Litchfield Domain (Needham *et al* 1988, Hollis *et al* 2009, Hollis *et al* 2011, Hollis and Glass 2012, Hollis and Wygralak 2012). New geochronological data indicate that this first stage of sedimentation was followed by intrusion of the Burrundie Dolerite (Burton-Johnson *et al* 2025) into the Koolpin Formation in the central part of the Central Domain (see Warren and Kamprad 1990) at ca 2.0 Ga (Reno *et al* 2025). The Koolpin Formation was previously interpreted as part of the second stage of sedimentation of the Cosmo Supergroup ca 1.87 Ga (Ahmad and Hollis 2013) but our new data shows that it is older than previously thought and part of the Woodcutters Supergroup.

The second stage of sedimentation followed a hiatus of at least 130 million years (until ca 1.87 Ga) and resulted in deposition of clastic and volcanic-volcaniclastic sediments of the Cosmo Supergroup. The earliest sediments formed the South Alligator Group which was largely deposited in shallow, euxinic marine environments but which also included periods of felsic volcanism. Sediment deposition later transitioned to a deeper turbiditic environment represented by the Finnis River Group (Ahmad and McCready 2001, Worden *et al* 2008b, Hollis *et al* 2011, Ahmad and Hollis 2013). The tectonic setting of the Cosmo Supergroup is interpreted to represent the sag stages of basin evolution following the initial rifting that resulted in deposition of the Woodcutters Supergroup (Needham *et al* 1988). The Woodcutters Supergroup and the Cosmo Supergroup were both intruded by the ca 1.87 Ga Zamu Dolerite in the South Alligator River Valley (Stuart-Smith *et al* 1987, Ahmad and Hollis 2013, Reno *et al* 2025).

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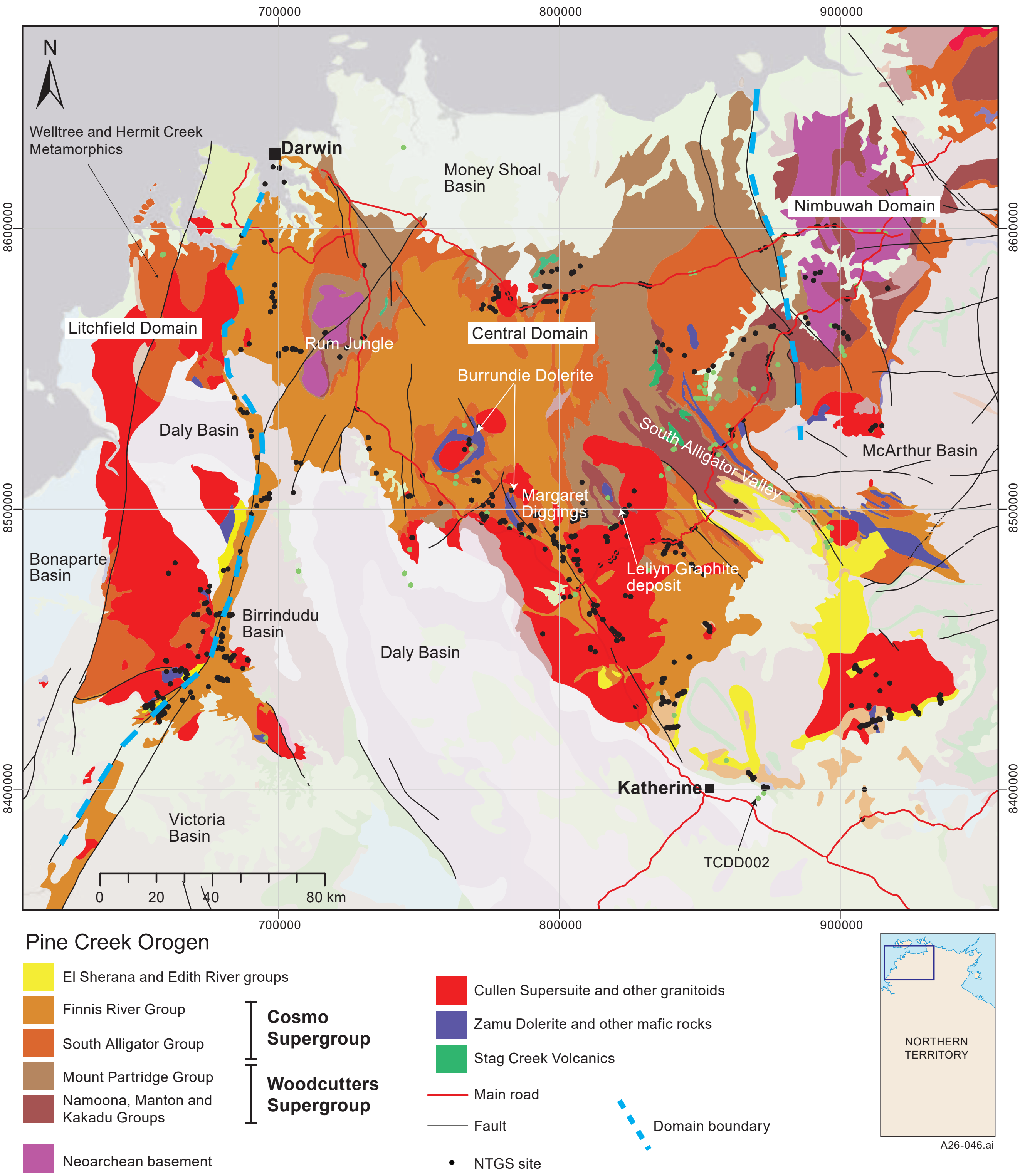


Figure 1. Geological map of the Pine Creek Orogen showing domains, NTGS sites and key locations mentioned in the text. Map after Lally and Doyle (2005).

The two supergroups were deformed and metamorphosed to various extent across the PCO domains. In the Litchfield Domain, granulite to amphibolite facies regional metamorphism and felsic and mafic magmatism occurred ca 1.86–1.85 Ga (Pietsch and Edgoose 1988, Wyborn *et al* 2001, Carson *et al* 2008, Worden *et al* 2008b). In the Central Domain, crustal shortening resulted in regional metamorphism to greenschist facies coupled with close inclined folding (Ahmad and Hollis 2013). Recent work by the NTGS indicates that a first deformation event (D1) resulted in the formation of a bedding-parallel to sub-parallel foliation, followed by a second shortening event (D2) that created km-scale faults and shear zones, and open-to-isoclinal, north to northwest trending, inclined, asymmetric folds with associated axial planar foliation (see Weisheit *et al* 2026). In the Nimbuwah Domain, mid- to high-P and mid-T amphibolite facies regional metamorphism was associated with felsic magmatism ca 1.87–1.86 Ga (Needham *et al* 1988, Hollis *et al* 2009).

A third stage of sedimentation in the PCO resulted in the deposition of El Sherana and Edith River groups in the Central Domain (**Figure 1**). Sedimentation was facilitated by crustal extension and rift-related volcanism is primarily preserved in the South Alligator River Valley (Needham and Stuart-Smith 1985, Needham *et al* 1988, Friedmann and Grotzinger 1994, Kruse *et al* 1994, Jagodzinski 1998, 1999). Deposition of these sediments was coeval with voluminous felsic magmatism of the Cullen Supersuite in the Central Domain and magmatism in the Nimbuwah Domain (Pietsch and Edgoose 1988, Worden *et al* 2008a, Ahmad and Hollis 2013). The presence of K-feldspar-cordierite hornfels and the size of the granitoid bodies suggest they intruded at depths of less than 6 km (Stuart-Smith *et al* 1988). Some of the granitoids of the Cullen Supersuite were affected by ductile deformation in mm-scale to 100 m-scale shear zones (eg Needham *et al* 1989). New work by NTGS indicates that these shear zones are commonly conjugate and internally anastomosing and were associated with D2 deformation.

Deposition of the <ca 1.83 Ga Tolmer and Katherine River groups marks the end of the PCO succession and the onset of the McArthur Basin sedimentary cycle (Hollis and Wygralak 2012, Ahmad and Hollis 2013).

Review of stratigraphy

The current understanding of the stratigraphy and tectono-magmatic evolution of the PCO is summarised by Ahmad and Hollis (2013), and the most comprehensive stratigraphic column is presented by Hollis and Glass (2012). Since 2022, the NTGS has acquired new datasets from field work and core, focused on the Woodcutters Supergroup, Cosmo Supergroup, and the mafic and felsic intrusions within the Central Domain. Evaluation of the structural framework of the PCO is ongoing but preliminary interpretations have been reported by Weisheit *et al* (2026). Recent fieldwork in the Central Domain has generated new publicly available datasets, including whole-rock geochemistry (Northern Territory Geological Survey 2024) and petrographic descriptions and interpretations (Ashley *et al* 2025, Ashley and Weisheit in review). Geochronological and isotopic analyses are currently underway, and preliminary results are presented here.

New mapping, petrology, geochemistry and geochronology results challenge some of the previous interpretation of the Central Domain stratigraphy (**Figure 2**). A key issue concerns the contact between the supergroups. The contact between the top of the Wildman Siltstone (Woodcutters Supergroup) and the base of the Koolpin Formation (previously part of the Cosmo Supergroup) was classified as an angular unconformity (Needham *et al* 1988, Ahmad and Hollis 2013, Stuart-Smith *et al* 1987). Stuart-Smith *et al* (1987) described this angular unconformity in the central part of the Central Domain where sandstone ridges of the Wildman Siltstone are truncated at an acute angle by beds of the Koolpin Formation. This unconformity was not observed in our current study but further fieldwork will test this interpretation.

Reno *et al* (2025) reassigned the Koolpin Formation to the top of Woodcutters Supergroup based on intrusive relationships with the Burrundie Dolerite – which has a preliminary age of ca 2.0 Ga (Reno *et al* 2025) – in the central part of the Central Domain. New petrographic evidence suggests uninterrupted sedimentation between the top of the Woodcutters Supergroup and the Koolpin Formation in this area. The upper sections of the Wildman Siltstone share several characteristics with the base of the Koolpin Formation. Both units are composed mostly of iron-rich laminated metasiltstone-metasandstone that is locally carbonaceous and interbedded with discrete, massive, coarser-grained, clast-supported, quartz-rich beds that comprise 10–15% of the formation. These similarities are reinforced by comparable geochemical signatures (Reno *et al* 2025). Evaporitic facies are also common in both units. For instance, quartz pseudomorphs interpreted as replacement after evaporitic minerals in the Wildman Siltstone (Ashley and Weisheit in review) have also been observed in the Koolpin Formation (Crick and Muir 1980, Crick *et al* 1980). Stuart-Smith *et al* (1987) noted that earlier workers, including Nicholson (1980), were unable to consistently differentiate between the Wildman Siltstone and the Koolpin Formation in the Central Domain, highlighting the strong similarities between these two units. Furthermore, the original definition of the Koolpin Formation in Nicholson (1980) included four members, the lowermost of which was later reassigned to the Wildman Siltstone by Stuart-Smith *et al* (1987).

An additional revision to the Woodcutters Supergroup is the identification in 2025 that the Leliyn graphite deposit (**Figure 1**) is hosted in a narrow (200–300 m wide) section of the Wildman Siltstone, stratigraphically above the Mundogie Sandstone to the south (to which it is currently assigned), and intruded by the Minglo Granite to the north.

Possible Woodcutters Supergroup in southern Central Domain

In the southern Central Domain near Katherine (**Figure 1**), the stratigraphy is currently mapped as being dominated by upper Cosmo Supergroup (Finnis River Group) and younger units, including El Sherana and Edith River groups (eg Needham *et al* 1989). As in the rest of the Central Domain, these units were locally affected by contact metamorphism associated with intrusion of the Cullen Supersuite (Walpole *et al* 1968, Ahmad and Hollis 2013). Approximately 10 km northeast of Katherine, the Tollis Formation and its Dorothy Volcanic Member (both part of the Finnis River Group) are intruded by the Maud Dolerite (Walpole *et al* 1968, Needham *et al* 1989). New *in situ* titanite U–Pb geochronology from the Maud Dolerite suggests a preliminary crystallisation age ca 1.93 Ga and isotopic resetting ca 1.83 Ga. These ages are comparable to those found by Reno *et al* (2025) in the Burrundie Dolerite hosted in Koolpin Formation at Margaret Diggings (**Figure 1**). This implies that the host metasedimentary succession of the Maud Dolerite is older than ca 1.93 Ga and so potentially correlates with the Woodcutters Supergroup.

Three lines of evidence support this reinterpretation. First, the Dorothy Volcanic Member, that hosts the Maud Dolerite, comprises thickly bedded, polymictic basalt breccia

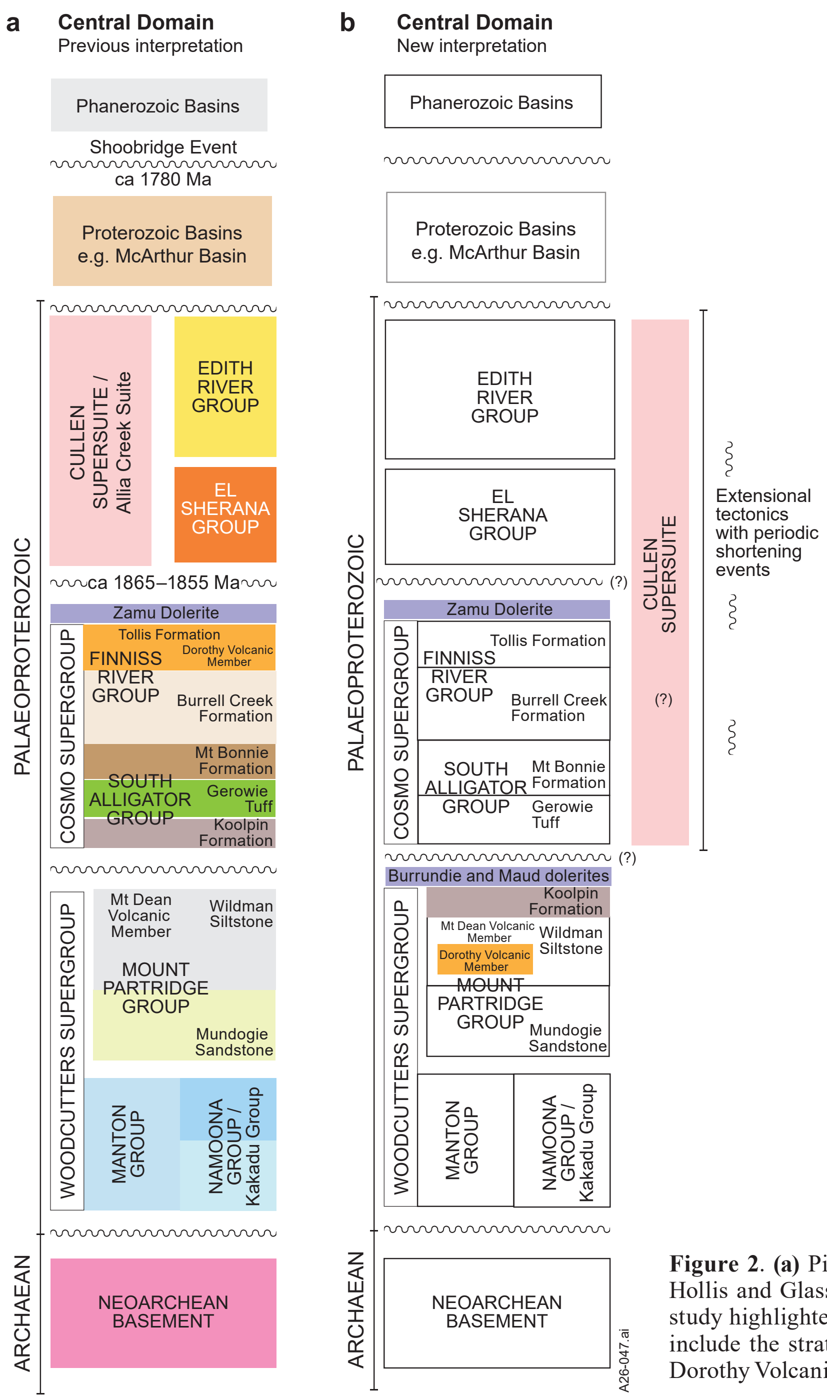


Figure 2. **(a)** Pine Creek Orogen stratigraphic column based on Hollis and Glass (2012). **(b)** Preliminary modifications after this study highlighted in coloured boxes. The main proposed changes include the stratigraphic position of the Burrundie Dolerite and Dorothy Volcanic Member, and the extent of the Cullen Supersuite.

interbedded with volcanogenic sandstone and mudstone (McPhie 2023). Deposition occurred below wave base and was controlled by basin extensional faults (McPhie 2023). The composition of the Dorothy Volcanic Member suggests derivation from a small-volume alkaline basalt, erupted during early stages of continental extension (Crawford 2024). Electron microprobe analyses of fresh chromite show elevated TiO_2 and reduced Al_2O_3, which, following Kamenetsky *et al* (2001) and Barnes and Roeder (2001), were interpreted by Crawford (2024) as indicative of early rift magmatism, consistent with the limited eruptive volume from low degree of partial melting (Ahmad and Hollis 2013). Such tectonic conditions align more closely with Woodcutters Supergroup evolution than the sag-phase basin development that characterises the Cosmo Supergroup.

Second, a diamond drillhole (TCDD002) 10 km east of Katherine intersected laminated, Fe-rich, carbonaceous and chert-rich metasiltstone beneath Cambrian-aged Daly Basin sedimentary rocks (**Figure 1**). These metasiltstones closely resemble Koolpin Formation rocks in the Central Domain (Newmarket Gold and PNX Metals 2017). As previously discussed, there is a possibility that the Koolpin Formation represents the upper Woodcutters Supergroup.

Third, there are lithologically comparable mafic units that occur elsewhere within the Woodcutters Supergroup. In the Rum Jungle area of the Central Domain (**Figure 1**), the Wildman Siltstone includes the Mount Dean Volcanic Member (Ahmad and Hollis 2013). The Mount Dean Volcanics consists of altered mafic volcanic rocks that are in places vesicular or brecciated (Lally and Doyle 2005, Hollis and Glaser 2011, Ahmad and Hollis 2013). In the South Alligator River Valley (**Figure 1**) the ca 2.05 Ga Stag Creek Volcanics (Worden *et al* 2008a) amygdaloidal porphyritic basalts are hosted in the lower Woodcutters Supergroup (Stuart-Smith *et al* 1993, Ferenczi and Sweet 2005, Lally and Doyle 2005). These units may represent widespread mafic volcanism associated with the Woodcutters Supergroup.

Collectively, these observations suggest the possible presence of Woodcutters Supergroup around Katherine, an area that was previously interpreted as upper Cosmo Supergroup. This possible reinterpretation will be tested with further field work and structural and geochronological analyses. If correct, this interpretation would significantly impact mineral prospectivity of the region given that the Woodcutters Supergroup is the main host for polymetallic systems including U, REE, Pb-Zn-Cu, Fe, Cu-Co, Mg and graphite (Crick and Muir 1980, Bone 1983, 1985, Ahmad *et al* 1993, Goulevitch and Butler 1998, Bowden 2000, McCready *et al* 2004, Ahmad and Hollis 2013, McCready *et al* 2022, Baumgartner and Pejcic 2025).

Insights from isotopic geochemistry

New whole-rock isotopic data

New whole-rock isotopic data from the Bludells, Burrundie and Zamu dolerites, Cullen Supersuite granitoids, and metasedimentary rocks of the Cosmo and Woodcutters supergroups help to interpret the tectonic evolution of the PCO (**Figure 3**). The oldest mafic rocks (ca 2.0 Ga Burrundie Dolerite; preliminary results) and metasediments of the Woodcutters Supergroup have positive to slightly negative εNd values (**Figure 3a**), consistent with depleted mantle sources that are typical of early-stage continental rifting. Younger ca 1.90–1.80 Ga igneous and sedimentary units yield more negative εNd values indicating continental crust contamination, recycling or mixing. The ca 1.70 Ga Oenpelli Dolerite in the Nimbuwah Domain has positive εNd values, suggesting renewed extension and mantle input.

New zircon geochronology and isotopic data

Previous studies concluded that the main phase of emplacement of the Cullen Supersuite in the Central Domain was ca 1.83–1.82 Ga (Wyborn *et al* 1997, Worden *et al* 2008a, Ahmad and Hollis 2013). These rocks were thought to be largely post deformational and broadly synchronous with ca 1.83 Ga extensional volcanism and deposition of El Sherana and Edith River groups (Ahmad and Hollis 2013).

New preliminary zircon U–Pb LA–ICP–MS data extends the period of felsic magmatism of the Cullen Supersuite to between ca 1.87 and ca 1.79 Ga, with a possible outlier at ca 1.90 Ga (Shoobridge Granite). Age interpretations are complicated by the high U content of the granites and of individual zircon grains that results in metamict zircon and lead loss. Most granites (by area) were emplaced ca 1.87 Ga, and younger, smaller granites were progressively emplaced towards ca 1.79 Ga. Zircon Hf composition of these granites shows a progressive decrease in εHf, indicating increasing assimilation of continental crust (**Figure 3b**). Two-stage depleted mantle Sm–Nd model ages (T_{DM2}) of the Cullen Supersuite granitoids are in the range 3.0–2.6 Ga, indicating an Archean age for this felsic continental crust component. Additionally, an increase in zircon Ce/Ce* anomaly and decrease in zircon Eu/Eu* anomaly with time suggest an increase in the oxidation state of granitic magmas with time (**Figure 3c**). Overall, these data suggest long-lived felsic magmatism with a progressive increase in crustal assimilation during the formation of the Cullen Supersuite.

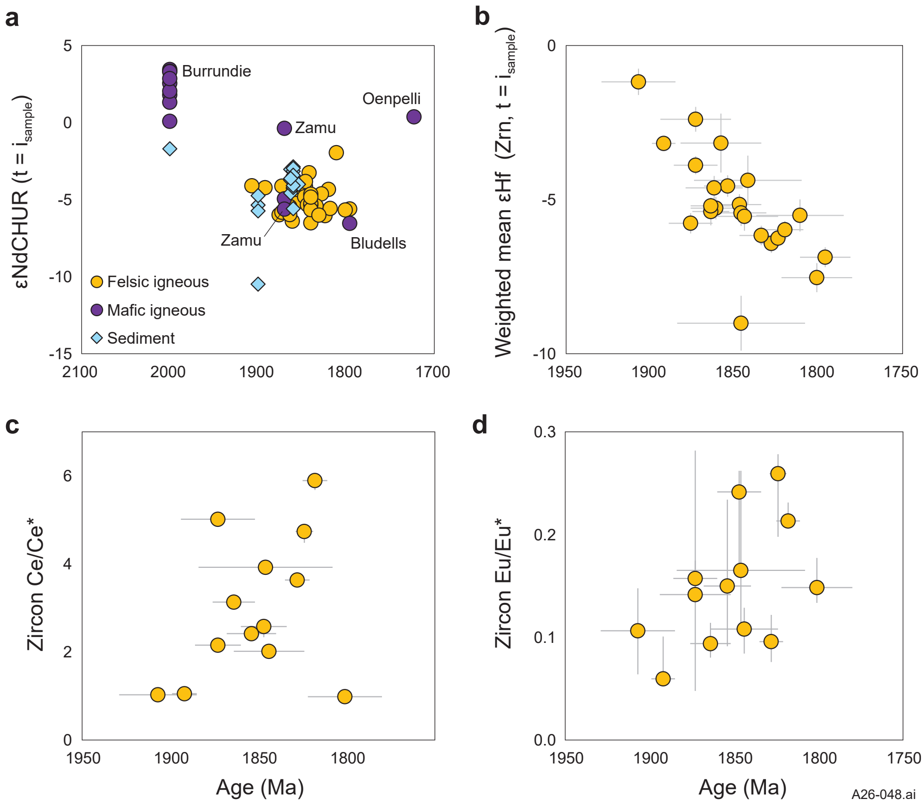
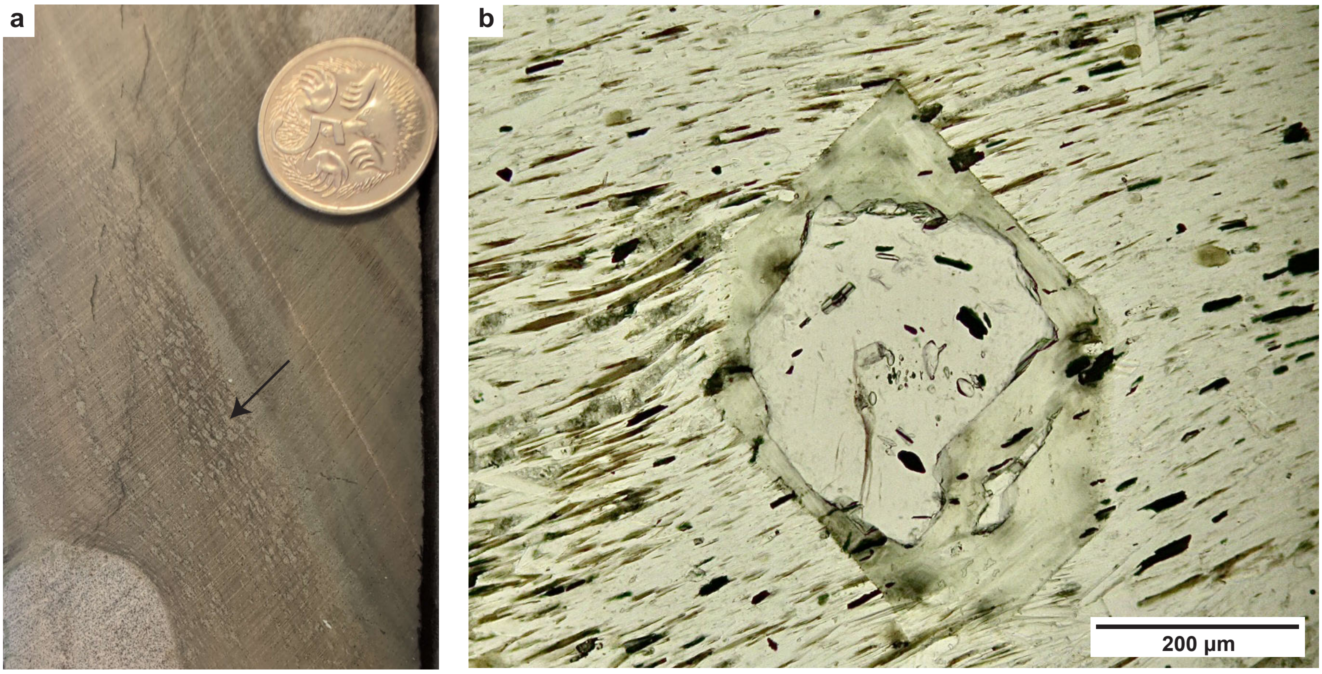


Figure 3. Results from whole-rock isotopic analyses and zircon isotopic compositions. **(a)** Sample age versus εNd from whole-rock geochemistry. Positive εNd indicates mantle sources and negative εNd indicates assimilation of continental crust. **(b)** Zircon age versus εHf of Cullen Supersuite granitoids. εHf values can track changes in magma source characteristics, in this case a transition from juvenile mantle input ca 2.0 Ga to reworked and evolved crustal material ca 1.80 Ga. **(c)** Zircon age versus Ce/Ce* anomaly of Cullen Supersuite granitoids. **(d)** Zircon age versus Eu/Eu* anomaly of Cullen Supersuite granitoids.

The new constraints on timing of granite emplacement overlap with inferred depositional ages of the Cosmo Supergroup, implying a long-lived magmatism and extensional tectonic setting. This interpretation is supported by the presence of a mineral fabric within the granite. Mineral lineations are defined mostly by feldspar megacrysts, elongated mafic enclaves, and opening directions of late aplite dykes and veins; all suggest dominantly northeast–southwest oriented extensional strain, orthogonal to the later D2 shortening fabrics in the host metasedimentary rocks (Burton-Johnson *et al* 2025).

This extended period of magmatism requires changes to the previously interpreted relationships between stratigraphic units and deformational events. Structurally, this relationship is indicated by the fabric in the metasedimentary rocks that were affected by contact metamorphism. In the Central Domain, there is evidence of pre-, syn- and post-compressional porphyroblasts, locally preserved in the same sample (**Figure 4**). D1- or D2-foliated cordierite and/or andalusite porphyroblasts formed prior to or during the associated intrusion (**Figure 4a**). Some garnets preserve internally rotated foliation defined by aligned inclusions (syn-kinematic indicators; **Figure 4b**). Post-kinematic and randomly oriented andalusite porphyroblasts commonly overprint the compressional D1 and D2 fabric in the contact aureoles (**Figure 4c, d**). Additionally, extensional structures filled with quartzofeldspathic material have been observed parallel to bedding in metasedimentary rocks proximal to a granitic intrusion. Together with the syn-magmatic fabrics, this indicates a mixed compressional-extensional setting during the intrusion of the Cullen Supersuite. Compositional evidence also indirectly supports a mixed tectonic regime.



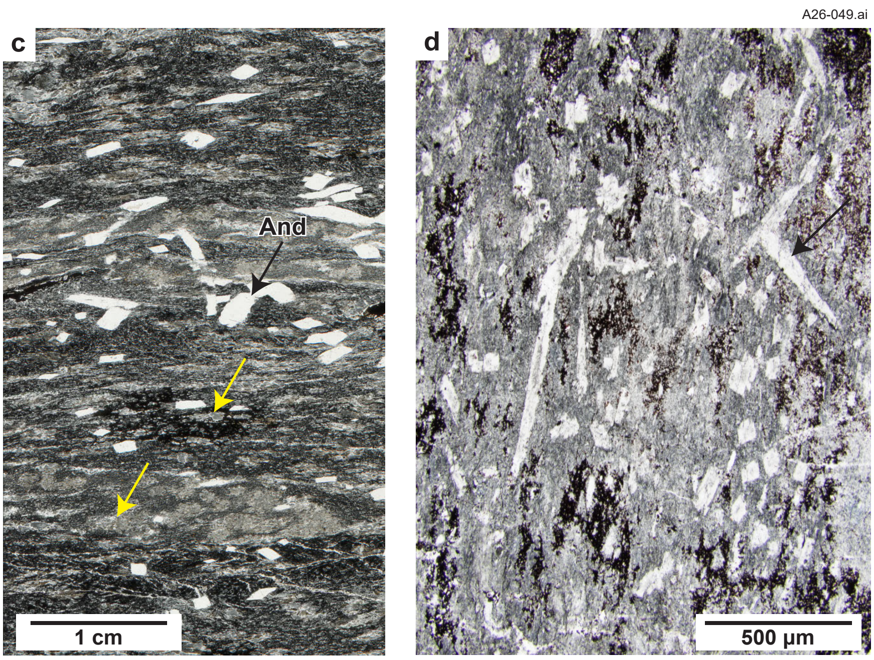


Figure 4. Evidence of pre-, syn- and post-deformational contact metamorphism associated with the Cullen Supersuite. **(a)** Drill core with D1-deformed porphyroblasts (pre- to syn-kinematic, indicated by arrow) in metasiltstone of the Koolpin Formation. **(b)** Transmitted, plane polarised light photomicrograph showing syn-kinematic garnet porphyroblast in the Koolpin Formation overgrown by a post-kinematic rim. Based on the shape of the post-kinematic rim, it could be a pseudomorph after andalusite. **(c)** Transmitted, plane polarised light photomicrograph of graphitic metasiltstone of the Koolpin Formation with evidence of retrogressed and foliated porphyroblast ghosts (pre- to syn-kinematic, indicated by yellow arrows), and post-kinematic, randomly oriented euhedral andalusite porphyroblasts (indicated by black arrow) (Ashley and Weisheit in review). **(d)** Transmitted, plane polarised light photomicrograph of graphitic metasiltstone of the Koolpin Formation with pre- and post-kinematic andalusite porphyroblasts (indicated by black arrow) similar to that shown in **(c)** (Ashley and Weisheit in review).

Trace element-based tectonic discrimination (eg Ta, Yb) shows the Cullen Supersuite has mixed volcanic arc affinity and within-plate chemistry associated with post-collisional granitoids (Burton-Johnson *et al* 2025). This chemical character suggests a mixture of shortening and extension during the intrusion of the granites.

Summary

The petrographic, compositional and stratigraphic similarities between the Wildman Siltstone and the Koolpin Formation, in addition to the likely absence of an unconformity between the units (pending further investigations), support reassignment of the Koolpin Formation to the upper Woodcutters Supergroup. Likewise, a stratigraphic update is possibly required in the southern Central Domain, where the ca 1.93 Ma (preliminary age) Maud Dolerite intruded juvenile mafic rocks of the Dorothy Volcanic Member; these observations indicate that the Dorothy Volcanic Member and its hosts are not part of the Cosmo Supergroup but are instead part of the Woodcutters Supergroup. This reinterpretation substantially enhances the prospectivity of the region as the Woodcutters Supergroup is known to be more fertile for strategic and critical metals than the Cosmo Supergroup.

New igneous geochemistry and geochronology indicates that felsic magmatism of the Cullen Supersuite began earlier and persisted longer than previously recognised (ca 1.90–1.80 Ga; preliminary data). This protracted magmatic history overlapped deposition of the Cosmo Supergroup and the intrusion of mafic igneous rocks; it implies sustained syn-magmatic extension punctuated by intermittent compressional events. This interpretation is similar to processes described by Collins (2002a, 2002b). Sm–Nd systematics indicate mantle-derived input during the deposition of the Woodcutters Supergroup followed by increasing crustal contribution during deposition of the Cosmo Supergroup and younger sediments. This trend is consistent with zircon isotopic composition data that show progressive continental crust assimilation coupled with increasing magmatic oxidation states through time in granitoids of the Central Domain.

Future work

The newly collected data have raised specific questions regarding the rock relationships across the Central Domain as well as relationships between the rocks and structural events. These questions will be addressed this year by further targeted field work and geochronological studies that aim to constrain the stratigraphic and structural relationships across all three domains of the PCO and to interpret the tectonic setting of this part of the North Australian Craton during the Palaeoproterozoic.

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