Northern Territory Government

Geology and mineral resources of the Northern Territory

Ahmad M and Munson TJ (compilers)

Northern Territory Geological Survey
Special Publication 5

Chapter 13: Warumpi Province

BIBLIOGRAPHIC REFERENCE: Scrimgeour IR, 2013. Chapter 13: Warumpi Province: in Ahmad M and Munson TJ (compilers). *'Geology and mineral resources of the Northern Territory'. Northern Territory Geological Survey, Special Publicatio*n 5.

Chapter 13: WARUMPI PROVINCE

IR Scrimgeour

INTRODUCTION

The Warumpi Province is an east–west-trending terrane that extends along the southern margin of the Arunta Region, west of Alice Springs (**Figures 13.1**, **13.2**). It was defined by NTGS after regional studies identified that the terrane has distinct protolith ages and isotopic characteristics from the remainder of the Arunta Region (Scrimgeour 2003, Close *et al* 2003, 2004, 2005, Scrimgeour *et al* 2005a). The area of the Warumpi Province significantly overlaps with the former 'Southern Province' of the Arunta Region as defined by Shaw *et al* (1984). The province is characterised by rocks with a protolith age in the range 1700–1600 Ma, including metasedimentary successions dated at 1660–1640 Ma and 1640–1600 Ma, and magmatic suites at 1680–1660, 1640–1630 and 1610–1600 Ma. It has been interpreted as an exotic terrane that accreted to the North Australian Craton at ca 1640 Ma (Scrimgeour *et al* 2005b). The margin between the Warumpi Province and the Aileron Province to the north is defined by a series of faults and thrusts (including the Desert Bore Shear Zone, Redbank Thrust and Charles River Thrust); these have been interpreted as a strongly reworked suture (Central Australian Suture; Close *et al* 2005). The only exception is at the extreme eastern

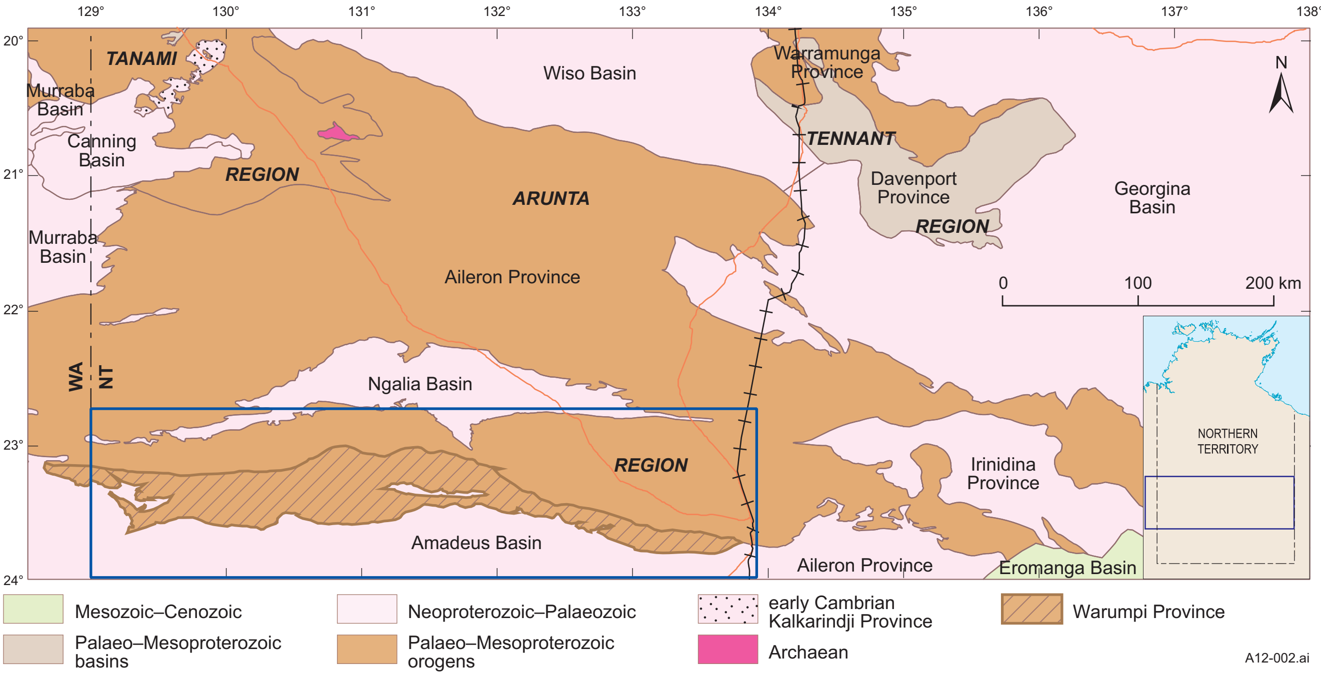


Figure 13.1. Regional geology of Warumpi province. NT geological regions from NTGS 1:2.5M geological regions GIS dataset. WA geological regions simplified and slightly modified from Tyler and Hocking (2001). Box shows location of **Figure 13.2**.

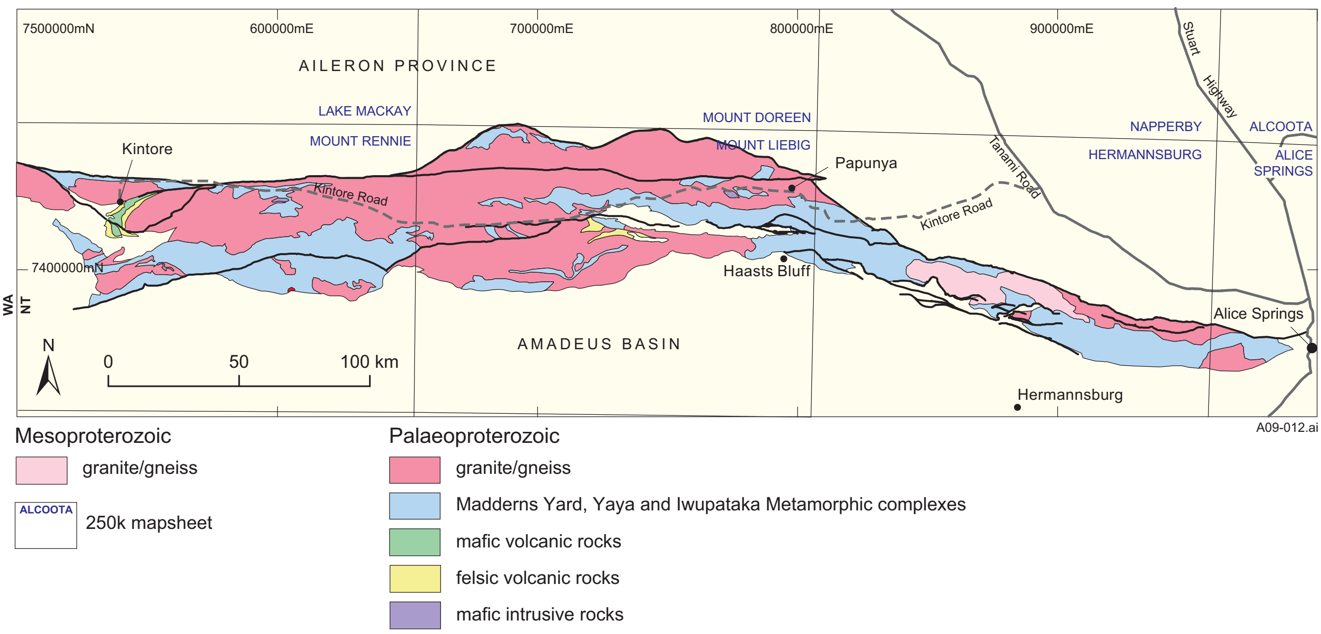


Figure 13.2. Simplified geology of Warumpi Province in NT derived from 1:2500k-scale map of NT (Ahmad and Scrimgeour 2006). Location shown in **Figure 13.1**.

end of the outcropping Warumpi Province near Alice Springs, where the margin is defined by an unconformable relationship between a 1630–1610 Ma cover sequence (Iwupataka Metamorphic Complex) and gneisses that are interpreted to belong to the Aileron Province. The southern margin is obscured by the Neoproterozoic to Palaeozoic Amadeus Basin. The exposed east–west extent of the Warumpi Province is around 650 km, whereas the maximum exposed width of the terrane is 60 km.

The Warumpi Province can be divided into three fault-bounded domains with discrete protolith ages and metamorphic grades (Close *et al* 2003, Scrimgeour *et al* 2005a, **Figure 13.3**). The amphibolite-facies *Haasts Bluff Domain* dominates the eastern and southern Warumpi Province, extending west from near Alice Springs over a strike length of around 400 km, with a maximum exposed width of 25 km. The Haasts Bluff Domain is dominated by 1690–1660 Ma intrusive, volcanic and lesser metasedimentary rocks, with a younger 1630–1600 Ma cover succession.

The *Yaya Domain* is an east-trending, fault-bounded domain that extends for around 300 km from near Mount Heuglin in the east to the Davenport Hills in the west. It is characterised by a 1660–1640 Ma supracrustal succession (Yaya Metamorphic Complex) intruded by voluminous 1640–1630 Ma felsic and lesser mafic suites. Metamorphic grade is typically granulite facies, with deep crustal (8–10 kbar) metamorphism in the east, decreasing to low- to medium-pressure upper amphibolite-facies metamorphism in the far west.

The *Kintore Domain* forms the westernmost part of the Warumpi Province and is separated from the Yaya Domain to the southeast by an obscured east-northeast trending structure. The domain continues west into the Mount Webb and Pollock Hills areas in Western Australia (Wyborn *et al* 1998). The Kintore Domain has been metamorphosed under greenschist-facies conditions and significant areas show no pervasive fabric development. The domain has two main elements: 1690–1685 Ma granites; and a younger supracrustal succession that includes felsic, intermediate and mafic volcanics (Walungurru Volcanics) and a unit of quartzite and phyllite (Sandy Blight Quartzite).

HAASTS BLUFF DOMAIN

The oldest known rocks in the Warumpi Province are voluminous felsic and less abundant mafic igneous rocks that have intrusive ages in the range 1690–1660 Ma, with minor associated metasedimentary rocks. Magmatism of this age corresponds with the Argilke Event of Collins and Shaw (1995), now renamed the Argilke Igneous Event (Scrimgeour 2003). This magmatism has been interpreted to reflect magmatism in a continental arc that was outboard of the North Australian Craton at the time (Close *et al* 2005).

Madderns Yard Metamorphic Complex

The Madderns Yard Metamorphic Complex (Warren and Shaw 1995) comprises upper amphibolite-facies felsic gneiss and lesser metasedimentary rocks that outcrop in the eastern Haasts Bluff Domain. The most widespread unit in the Madderns Yard Metamorphic Complex is the *Glen Helen Metamorphics* (Warren and Shaw 1995, Scrimgeour *et al* 2005a), which comprises migmatitic felsic orthogneiss, with abundant porphyritic biotite granite, and less common metasedimentary rock and amphibolite. The unit is dominated by biotite-bearing migmatitic orthogneiss, with variable hornblende content (**Figure 13.4**). Locally preserved K-feldspar phenocrysts suggest that at least some of the migmatite has a granitic precursor. In places, the migmatitic layering is folded and contorted, but elsewhere, it is strongly transposed into an non-coaxial strain fabric. Mafic amphibolite occurs sporadically as folded and attenuated layers, and also as larger intrusive bodies. Foliated, leucosome-free biotite- and/or hornblende-bearing porphyritic granite is commonly intercalated with migmatite. Metasedimentary rock is a minor component of the unit, comprising biotite- and sillimanite-bearing metapelitic rock with less common psammitic rock, and rare calc-silicate rock. The metasedimentary host rocks to the Stokes Yard base metal prospect were included within the Glen Helen Metamorphics by Warren and Shaw (1995), but these are now considered to belong to a cover succession of the Iwupataka Metamorphic Complex (Scrimgeour *et al* 2005a). The metamorphic grade of the Glen Helen Metamorphics is upper amphibolite facies. P-T estimates of 700–750°C and 8–9 kbar from a garnet-hornblende-clinopyroxene amphibolite from north of the Belt Range (Scrimgeour *et al* 2005b) are likely to be the maximum possible pressures and temperatures within the metamorphics. The precursors to the felsic migmatite in the Glen Helen Metamorphics intruded during the 1690–1660 Ma Argilke Igneous Event (Collins and Shaw 1995). Igneous zircons from the unit 10–15 km west-southwest of Mount Zeil have SHRIMP U-Pb dates of 1663 ± 13 Ma and 1678 ± 6 Ma (Black and Shaw 1995). Igneous zircon cores from a sample of felsic migmatite from north of Belt Range have a SHRIMP U-Pb age of 1688 ± 16 Ma (Scrimgeour *et al* 2005b). Metamorphic rims on these cores show evidence for isotopic disturbance, but the oldest single rim analysis of about 1640 Ma is consistent with metamorphism during the Liebig Orogeny. A sample of weakly migmatitic granite from south of the Belt Range has zircon cores at 1681 ± 3 Ma, with oscillatory zoned prismatic overgrowths at 1661 ± 8 Ma, which are interpreted to reflect 1660 Ma igneous crystallisation with an inherited 1680 Ma zircon population (Cross *et al* 2005). It is possible that some less migmatised granites within the Glen Helen Metamorphics may have younger precursors.

An *unnamed migmatite* (unit Ꝑmo of Warren and Shaw 1995) from north of the Chewings Range in the eastern Madderns Yard Metamorphic Complex is likely to be a correlative of the Glen Helen Metamorphics. It comprises variably biotite-bearing felsic migmatite with minor metasedimentary rocks and amphibolite. An *unnamed granitic gneiss* (unit Ꝑgk of Warren and Shaw 1995) comprises migmatitic leucogranite with small rafts of metasedimentary rocks and lenses of amphibolite. Porphyritic garnet-bearing gneissic granite of the *Boggy Hole Gneiss* has a SHRIMP U-Pb age of 1648 ± 10 Ma, making it the youngest dated meta-igneous rock in the Madderns Yard Metamorphic Complex. Its younger age

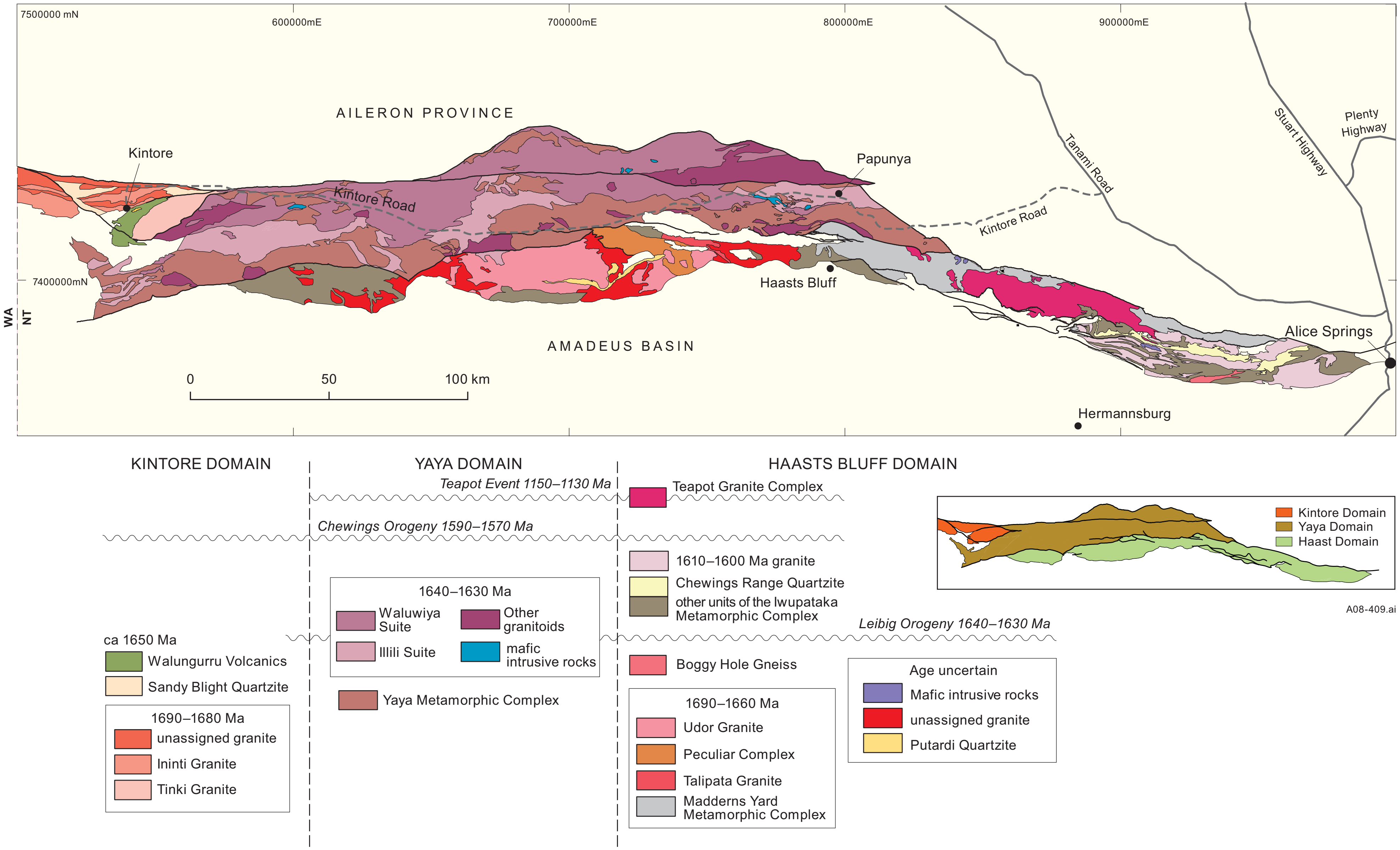


Figure 13.3. Interpreted solid geology of Warumpi Province in the NT.

and the presence of garnet suggest that it may be genetically distinct from other units in the complex.

Peculiar Complex

The Peculiar Complex (Scrimgeour *et al* 2005a) comprises felsic volcanics, associated shallow-level leucogranites and minor intercalated metasedimentary rocks that outcrop west of Mount Palmer and north of Mount Peculiar and Mount Putardi. Scrimgeour *et al* (2005a) divided the unit into three sub-units: rhyolite, banded metasedimentary rocks and leucogranite.

The rhyolite unit in the Peculiar Complex is dominated by flow-banded rhyolite that is variably recrystallised to quartz-muscovite schist. The rhyolite comprises grey, very fine-grained to microcrystalline quartz and K-feldspar with minor muscovite and disseminated Fe-oxides, with swirly flow-banding that is generally only visible on weathered surfaces (**Figure 13.5**). The rhyolite is typically aphyric, with less abundant porphyritic rhyolite. In zones of higher strain, the rhyolite is recrystallised to quartz-muscovite schist and in its northern outcrops, the rock is very quartz-rich, with localised muscovite quartzite suggesting possible clastic input. The felsic volcanic succession appears to be >200 m thick, but it is difficult to resolve any structural imbrication or possible composite emplacement due to the degree of deformation and discontinuity of outcrop. Flow banding occurs at all levels and there are some features that may be flattened pumice lenticles (fiamme). Assuming a thick single 'event' interval is present, the most likely interpretation is that it is a rheoignimbrite or long lava flow (Rawlings in Scrimgeour *et al* 2005a). SHRIMP U-Pb dating of zircon from a sample of rhyolite from near the type locality gives an age of 1680 ± 4 Ma (Cross *et al* 2005), interpreted to reflect the timing of crystallisation of the rhyolite. Large areas of homogeneous, fine- to medium-grained leucogranite occur in the Peculiar Complex and are interpreted to be shallow-level intrusions that are genetically related to the extrusive rhyolites (Scrimgeour *et al* 2005a). Metasedimentary rocks occur within the rhyolite and are best preserved in a succession of laminated sediments, ca 30 m thick, that is bounded on either side by rhyolite. The succession is dominated by fine-grained thinly laminated iron- and manganese-rich sediments that are locally interlayered with thin (<5 cm-thick), structureless, immature quartz-rich sandstone layers containing lithic clasts. The laminated sediments include banded haematite-quartz and manganiferous piemontite-andradite-quartz rock, along with minor fine-grained calc-silicate rock.

Figure 13.4. Glen Helen Metamorphics: felsic migmatite showing leucosome parallel to, and cross-cutting foliation. South of Belt Range, MOUNT LIEBIG[1], precise location unknown.

Figure 13.5. Peculiar Complex: Swirly flow-banding in rhyolite (MOUNT LIEBIG, 52K 723171mE 7411802mN).

1690–1660 Ma intrusive rocks

The *Talipata Granite* (Scrimgeour *et al* 2005a) comprises coarse-grained porphyritic biotite and biotite-hornblende granite that outcrops in the valley between Berry Pass and Mount Palmer. The rock contains phenocrysts of K-feldspar, typically 1–2 cm in diameter, which are flattened and elongated in a well-developed fabric that is locally gneissic. The dominant mafic mineral is biotite, with variable amounts of hornblende, and minor titanite. Zircons from the Talipata Granite have a SHRIMP U-Pb zircon age of 1683 ± 2 Ma (Cross *et al* 2005). The *Udor Granite* (Scrimgeour *et al* 2005a) is a texturally variable but geochemically and geophysically homogenous granite that extends across a large area of the western Haasts Bluff Domain. The extent of the granite has largely been defined on the basis of its distinctively low and flat magnetic signature, and it is interpreted to subcrop extensively beneath surficial sediments. The granite is typically equigranular to weakly porphyritic and is relatively leucocratic, commonly containing <5% mafic minerals. Biotite is the dominant mafic mineral, although the granite is distinctive for the common, but not ubiquitous presence of muscovite. Rock types are most commonly foliated biotite- and biotite-muscovite leucogranite and granite, with less common foliated muscovite granite, muscovite leucogranite and coarsely porphyritic biotite-muscovite granite. The Udor Granite has a SHRIMP U-Pb zircon age of 1663 ± 4 Ma, with evidence of recrystallisation or Pb-loss at about 1590 Ma (Cross *et al* 2005).

A number of texturally diverse, foliated *unnamed granites* occur throughout the western Haasts Bluff Domain, most of which are biotite-bearing and geochemically distinct from the Udor and Talipata granites (Scrimgeour *et al* 2005a). These biotite granites are variably porphyritic, commonly containing K-feldspar phenocrysts up to 1.5 cm in diameter,

[1] Names of 1:250 000 mapsheets are shown in large capital letters, eg MOUNT LIEBIG.

and generally have a well-developed biotite foliation and stretching lineation. Hornblende locally occurs as part of the igneous assemblage, and the granites typically contain abundant titanite and epidote of metamorphic origin. No geochronological data exists for the undivided biotite granites, but they have a broad geochemical similarity with other 1690–1660 Ma felsic rocks in the Haasts Bluff Domain (Scrimgeour *et al* 2005a).

Mafic rocks are relatively rare in the Haasts Bluff Domain, with the exception of narrow mafic layers in the Glen Helen Metamorphics and Peculiar Complex. A number of larger mafic intrusions intrude the Glen Helen Metamorphics, including the Dashwood Gabbro Complex southwest of Mount Ziel, the Cumming Leucogabbro south of the Chewings Range and two unnamed bodies near the Belt Range. All of these units are undated. The *Dashwood Gabbro Complex* (Warren and Shaw 1995) consists of altered gabbro, dolerite and ultramafic rocks surrounded by leucocratic rocks that are interpreted as locally derived melt (Glikson 1984). The mafic rocks are partly hydrated, with assemblages including talc-hornblende-plagioclase and tremolite-hornblende-biotite-plagioclase. The *Cumming Leucogabbro* (Warren and Shaw 1995) is a 6 x 1 km body of weakly deformed tremolite- and actinolite-bearing rocks, which contains rare chromite layers and traces of scheelite. A gabbro that intrudes the Glen Helen Metamorphics north of the Belt Range has locally recrystallised to a metamorphic assemblage containing garnet, clinopyroxene, hornblende, plagioclase, quartz and ilmenite. More commonly, the rock is hornblende amphibolite, with a weak north-dipping fabric and locally developed leucosomes that may represent crystallised partial melts. A second mafic body, variably recrystallised to hornblende amphibolite, occurs in the Glen Helen Metamorphics south of the Belt Range (Scrimgeour *et al* 2005a). North of Mount Kuta Kuta, a body of medium-grained dolerite, 5–20 m wide and 500 m long, intrudes the 1663 Ma Udor Granite and is largely recrystallised to hornblende amphibolite.

Putardi Quartzite

The Putardi Quartzite (Scrimgeour *et al* 2005a) occurs over a discontinuous strike length of ca 100 km as prominent ridges that include Mount Udor, Mount Putardi and Mount Peculiar. The unit is dominated by crystalline quartzite, often containing kyanite and/or muscovite, interlayered with quartz-muscovite and muscovite-biotite phyllite and schist. Most commonly, the Putardi Quartzite occurs within a broad zone of high non-coaxial strain (Udor Deformed Zone, Scrimgeour *et al* 2005a), in which it is structurally repeated and interleaved with granite, with little or no evidence preserved of the original relationship between the two. However, at Mount Putardi, the Putardi Quartzite forms a large basinal structure that is relatively unaffected by non-coaxial strain, and appears to overlie the 1663 Ma Udor Granite. The Putardi Quartzite most commonly has a fabric defined by muscovite and flattened quartz, with a well developed quartz stretching lineation. Where the quartzite is mylonitic, it contains a strong muscovite fabric, with folded and boudinaged quartz veins and locally developed S-C fabrics. In low-strain domains, it is crystalline with well preserved bedding. Kyanite is common within the quartzite and less commonly, it coexists with staurolite. Fine-grained biotite-muscovite-quartz schist and phyllite occur as recessive zones up to 100 m in width and have gradational contacts with the quartzite, with a transitional zone of interlayered quartzite and schist on a centimetre to metre scale. The schist is highly strained and quartzite layers preserve tight to isoclinal mylonitic folds (**Figure 13.6**).

The age of the Putardi Quartzite is poorly constrained. SHRIMP U-Pb dating of detrital zircons from the Putardi Quartzite near Mount Peculiar have yielded a continuum of ages in the range 1915–1745 Ma, with a mode at 1770 Ma, and give a maximum deposition age of 1752 ± 11 Ma (Cross *et al* 2005). However, six grains give younger apparent ages in the range 1705–1560 Ma, and some of these may be younger detrital grains, in which case, two concentrically zoned zircons with ages of 1580 ± 40 Ma (σ) and 1641 ± 18 Ma (σ) may give an alternative maximum deposition age (Cross *et al* 2005). Furthermore, there is uncertainty in the relationship between the 1663 Ma Udor Granite and the quartzite. Wells *et al* (1962) stated that the granite intrudes the quartzite, whereas Scrimgeour *et al* (2005a) proposed that the quartzite overlies the granite.

Iwupataka Metamorphic Complex (1630–1610 Ma)

The Iwupataka Metamorphic Complex (Warren and Shaw 1995) is a metasedimentary succession that occurs throughout the Haasts Bluff Domain, with the most extensive outcrop occurring in the east between Alice Springs and Ormiston Gorge. The Iwupataka Metamorphic Complex is interpreted to unconformably overlie the Madderns Yard Metamorphic Complex and other 1690–1660 Ma granites and volcanic rocks. The age of the Iwupataka Metamorphic Complex is not tightly constrained. Scrimgeour *et al* (2005a) considered it to have been deposited after the Liebig Orogeny, a notion supported by the 1615 Ma age of volcanics of the Rungitjurba Gneiss, although maximum deposition ages of 1670–1650 Ma for a number of constituent units leaves open the possibility that some units in the Iwupataka Metamorphic Complex may be a similar age to the Yaya Metamorphic Complex.

Figure 13.6. Putardi Quartzite: tightly folded interlayered quartzite and phyllite (MOUNT LIEBIG, 52K 702349mE 7399647mN).

In the eastern Haasts Bluff Domain, the Iwupataka Metamorphic Complex comprises five named metasedimentary units. The dominant unit east of Standley Chasm is the *Simpsons Gap Metasediments*, which unconformably overlies the Sadadeen Gneiss near Alice Springs. The basal part of the Simpsons Gap Metasediments comprises conglomerate and grit conglomerate that grades up into a succession that comprises biotite-muscovite-andalusite ± sillimanite schist, quartzite, quartz-muscovite phyllite, meta-arkose and minor amphibolite. The schist locally contains garnet and/or staurolite. The *Rungitjurba Gneiss*, which outcrops in the Simpsons Gap area, comprises a foliated, finely laminated, fine-grained felsic rock with rounded feldspar phenocrysts that are typically 0.5–2 mm in diameter (Wakelin-King 1989). The Rungitjurba Gneiss has been interpreted as a metamorphosed felsic volcanic unit (Shaw and Wells 1983) and has a SHRIMP U-Pb zircon age of 1615 ± 11 Ma (Zhao and Bennett 1995). The relationship between the Rungitjurba Gneiss and the Simpsons Gap Metasediments is not entirely clear, although the contact has been described as concordant with local intercalation of the units (Wakelin-King 1989). Wakelin-King suggested that the Rungitjurba Gneiss may have been deposited conformably on the Simpsons Gap Metamorphics. The Rungitjurba Gneiss is isotopically juvenile and has been linked with granites of the Burt Bluff Gneiss on geochemical and isotopic grounds (Zhao and McCulloch 1995).

The *Ryans Gap Metamorphics* (Warren and Shaw 1995) outcrop extensively between Standley Chasm and Ormiston Gorge, and may be a lateral equivalent of the Simpsons Gap Metasediments. Warren and Shaw (1995) divided the Ryans Gap Metamorphics into a lower unit of layered and laminated, quartzofeldspathic biotite-rich schist, and an upper unit of muscovite-bearing quartzofeldspathic gneiss and schist interbedded with thin beds of quartz-rich sediments and, towards the top, layers of quartzite. The upper unit also includes leucocratic rock, minor biotite gneiss and amphibolite, and rare calc-silicate rock. The *Lovely Hill Schist* (Warren and Shaw 1995) outcrops north of the Chewings Range and is a succession of metapelitic rocks, fine-grained quartzofeldspathic rocks (interpreted as felsic volcanic rocks by Warren and Shaw 1995) and minor quartzite, metaconglomerate and calc-silicate rock. The metapelitic rocks are locally garnet- and sillimanite-bearing, and the unit was, at least locally, metamorphosed to upper amphibolite facies, with retrogressive staurolite-bearing assemblages (Warren and Shaw 1995). Marjoribanks and Black (1974) described a siliceous unit known as 'Potrock Gneiss', which may be a meta-felsic volcanic rock; this is now included within the Lovely Hill Schist.

The *Chewings Range Quartzite* (Stewart *et al* 1980) forms the prominent Chewings Range, and comprises crystalline metamorphosed quartz sandstone, which is locally pebbly and interlayered with quartz-muscovite schist (Warren and Shaw 1995). Kyanite occurs locally within the quartzite, and staurolite-bearing interbeds occur near Standley Chasm. SHRIMP U-Pb zircon dating of detrital zircons from the Chewings Range Quartzite at its type locality in eastern HERMANNSBURG yielded a dominant population in the range 1800–1660 Ma, with an interpreted maximum deposition age of 1669 ± 13 Ma (Cross *et al* 2005).

The *Ikuntji Metamorphics* (Scrimgeour *et al* 2005a) outcrop between the Belt Range and the Haasts Bluff Community. It comprises a lower- to mid-amphibolite-facies metasedimentary succession dominated by variably feldspathic to quartzic muscovite-biotite schist, with lesser quartz-muscovite schist, quartzite, amphibolite and calc-silicate rock, grading up into clean quartzite. The dominant rock type is feldspathic biotite-muscovite schist, which is interlayered with quartz-muscovite schist and less common, thinly bedded micaceous quartzite. Rare aluminous schist contains fibrolitic sillimanite, muscovite, biotite and garnet. Towards the upper part of the unit, the succession becomes increasingly quartz rich, and comprises quartz-biotite-muscovite meta-arkose and minor biotite-muscovite schist, interlayered with crystalline quartzite and grading up into a massive, clean, crystalline quartzite unit. The quartzite may be a stratigraphic equivalent of the Chewings Range Quartzite. South of the Western Bluff Range, in the vicinity of the Haasts Bluff copper-gold prospect, a more diverse lithology includes actinolite-rich calc-silicate rock, tremolite marble and abundant haematite-rich, hornblende- and actinolite-bearing amphibolite. The Ulpuruta and Stokes Yard Pb-Zn prospects contain outcrops of mineralised tremolite schist, forsterite marble and less common actinolite-bearing schist. SHRIMP U-Pb dating of detrital zircons from the quartzite unit of the Ikuntji Metamorphics showed a dominant population in the range 1780–1640 Ma, together with a small late Archaean population. The youngest six analysed zircons combine to give an age of 1656 ± 17 Ma (tσ), which is the maximum deposition age for the succession (Cross *et al* 2005). The unit has broad lithological affinities with the upper unit of the Ryans Gap Metamorphics.

A succession of metapelitic schist and metapsammitic rock underlies the Heavitree Quartzite southwest of Mount Liebig. This unit, the *Lizard Schist* (Scrimgeour *et al* 2005a), is dominated by biotite-muscovite-quartz schist interlayered with muscovite-bearing quartz-rich psammitic rock layers (**Figure 13.7**). SHRIMP U-Pb dating of detrital zircons from the Lizard Schist yielded

Figure 13.7. Lizard Schist, showing interlayered metapsammitic rock and biotite schist (MOUNT LIEBIG, 52K 732646mE 7417261mN).

ages that were dominantly in the range 1810–1640 Ma, together with a small number of late Archaean zircons (2540–2435 Ma; Cross *et al* 2005). A maximum deposition age of 1657 ± 28 Ma (tσ) can be calculated from the youngest six analyses. A stratigraphic correlation between the Lizard Schist and Ikuntji Metamorphics is inferred on the basis of their lithological affinities and similar detrital zircon populations.

The *Nguman Metamorphics* (Close *et al* in prep) is a succession of lower amphibolite-facies metasedimentary rocks and minor mafic rocks in the western Haasts Bluff Domain in MOUNT RENNIE (**Figure 13.8**). This unit comprises biotite-muscovite schist, muscovite-quartz schist, and minor mafic amphibolite and quartzite. Small outcrops of tremolite-chlorite schist that occur within the metamorphics are interpreted to have had an ultramafic protolith. The Nguman Metamorphics have a maximum deposition age of 1630 ± 15 Ma (Cross *et al* 2005) and are interpreted to correlate with other schistose metasedimentary rocks of the Iwupataka Metamorphic Complex.

1610–1600 Ma granites

A number of 1610–1600 Ma granites occur in the western Haasts Bluff Domain, where they intrude the Glen Helen Metamorphics and metasedimentary rocks of the Iwupataka Metamorphic Complex. Warren and Shaw (1995) included these granites within the latter unit. The *Ormiston Pound Granite* (Warren and Shaw 1995) comprises foliated granite, leucogranite and pegmatite, that intrudes migmatitic Glen Helen Metamorphics in Ormiston Pound. The granite has a SHRIMP U-Pb zircon age of 1603 ± 10 Ma (Collins *et al* 1995). The *Burt Bluff Gneiss* is a foliated porphyritic biotite granite (**Figure 13.9**) with a SHRIMP U-Pb zircon age of 1603 ± 7 Ma (Zhao and Bennett 1995). The *Brinkley Bluff Gneiss* is a foliated biotite-rich granite that outcrops within and along the north side of the Chewings Range. The *Ellery Granitic Complex* (Warren and Shaw 1995) outcrops as a number of separate intrusions north and south of the Chewings Range and includes biotite-rich foliated porphyritic granite, foliated leucogranite and hornblende granite. Some granites belonging to the complex are interpreted to intrude the Lovely Hill Schist and Boggy Hole Gneiss, but their relationship with the Chewings Range Quartzite is unclear (Warren and Shaw 1995). The 1610–1600 Ma granites (Burt-Rungitjurba Suite of Zhao and McCulloch 1995, including felsic volcanics of the Rungitjurba Gneiss) are isotopically distinct from other granites in the Warumpi Province, and the Arunta Region in general, in that they are significantly more juvenile, with Nd (depleted mantle) model ages of 1.83–1.72 Ga and epsilon Nd values of +0.9 to +2.5 (Zhao and McCulloch 1995).

Figure 13.8. Outcrop of Nguman Metamorphics underlying Heavitree Quartzite, northeast of Nguman outstation (MOUNT RENNIE, 52K 579272mE 7397850mN).

Figure 13.9. Mylonitic porphyritic granite of Burt Bluff Gneiss showing microcline porphyroclasts (from Wakelin-King 1989: plate 6. ALICE SPRINGS, precise location unknown).

YAYA DOMAIN

Yaya Metamorphic Complex (1660–1650 Ma)

The Yaya Metamorphic Complex (Scrimgeour *et al* 2005a) includes all metasedimentary rocks and migmatitic orthogneiss within the Yaya Domain. The complex is dominated by metapelitic rocks, but with significant components of calc-silicate rock, quartzite, mafic granulite and felsic orthogneiss. Four stratigraphic units have been defined within the Yaya Metamorphics Complex, comprising the Speares Metamorphics (Warren and Shaw 1995), Inyalinga Granulite and Alkipi Metamorphics (Scrimgeour *et al* 2005a), and the Liesler Metamorphics (Close *et al* in prep). Outcrops in the west that were previously assigned to the Bunghara Metamorphics in HERMANNSBURG (Warren and Shaw 1995) are also now included within the Yaya Metamorphic Complex. The Yaya Metamorphic Complex was metamorphosed to granulite facies during the 1640–1635 Ma Liebig Orogeny. Due to the degree of deformation, magmatism and metamorphism, no relative stratigraphic relationships have been determined between the constituent units of the Yaya Metamorphic Complex.

Inyalinga Granulite

The *Inyalinga Granulite* (Scrimgeour *et al* 2005a) is a heterogeneous unit comprising largely metasedimentary granulite-facies rocks, including variable amounts of metapelitic rock and psammitic rock, calc-silicate, quartzite, mafic granulite and massive cordierite granulite. It occurs throughout the northern part of the Yaya Domain, where it is extensively intruded by granites belonging to the 1640–1630 Waluwiya and Illili suites. In areas north of the Belt Range, it is subdivided into three mappable units.

A succession of *interlayered mafic granulite and metapelitic rock* (unit Ƥyi$_1$ of Scrimgeour 2005a) occurs north of Mount Larrie, and is extensively intruded by the Warumpi Granite. It is dominated by two-pyroxene mafic granulite interlayered with migmatitic garnet-biotite-sillimanite metapelitic rock containing abundant psammitic layers and rare quartzite. A unit of *quartzite and calc-silicate* (unit Ƥyi$_2$) outcrops north of Mount Larrie and is dominated by clean coarsely crystalline quartzite, which is generally structureless, but is interpreted to have undergone structural repetition (Scrimgeour *et al* 2005a). Recessive zones in the quartzite ridge contain rare outcrops of calc-silicate rock that typically contain diopside, anorthite and quartz, with varying proportions of grossular garnet, scapolite and titanite. SHRIMP U-Pb dating of detrital zircons from the quartzite have yielded zircon populations unlike those in other samples from the Warumpi Province, with a maximum deposition age of 1760 ± 8 Ma (2σ). Metamorphic zircon rims on these detrital cores give an age of 1636 ± 6 Ma for high-grade metamorphism (Cross *et al* 2005).

A succession of massive *cordierite-rich pelitic rock* (unit Ƥyi$_3$), interlayered with calc-silicate and quartzite and intruded by gabbro and charnockite, outcrops on a prominent hill 6 km south of Kakalyi Bore (Hill 830, Scrimgeour *et al* 2005a, b). The massive cordierite pelitic rock is characterised by a lack of preserved bedding or pervasive foliation, and has a pale-brown weathering surface with visible magnetite, garnet and sillimanite (**Figure 13.10**). The unit is very highly magnetic. The mineralogy of the pelitic rock is quartz-poor and contains up to 50% cordierite. Most mineral assemblages contain cordierite, garnet, magnetite, sillimanite and biotite with minor quartz, with the remaining mineralogy comprising either plagioclase, spinel + kornerupine, or orthopyroxene, depending on the bulk composition. A less common cordierite-poor, phlogopite-rich, quartz-absent bulk composition also contains sapphirine, kornerupine and corundum. The unusual silica-poor bulk composition of the massive cordierite pelitic rock may be a result of large-scale hydrothermal alteration of a sedimentary protolith, prior to metamorphism. Interlayered with the cordierite granulite is calc-silicate that typically contains diopside, anorthosite, titanite, grossular garnet and scapolite. Crystalline metasedimentary quartzite also occurs interlayered with calc-silicate and cordierite granulite. SHRIMP U-Pb dating of detrital zircons from a cordierite granulite showed a range of ages from 1880–1640 Ma, with a calculated maximum deposition age of 1661 ± 10 Ma (Kinny 2002, Scrimgeour *et al* 2005b). Metamorphic zircon rims have given an age of 1638 ± 8 Ma for high-grade metamorphism.

Scattered outcrops of metasedimentary rock mapped as *undivided Inyalinga Granulite* outcrop in the area south of the Tjungkuba Hills, and in outcrops 10 km south-southeast of Papunya and 3 km west of Inyalinga outstation. The dominant rock types in these outcrops include banded quartz-diopside-anorthite-titanite calc-silicate rock that locally contains grossular garnet or hornblende, garnet-biotite-sillimanite metapelitic rocks, metapsammitic rocks, mafic amphibolite, quartzite and minor cordierite-rich pelitic granulite. Outcrops 15 km southeast of Papunya that were mapped as Bunghara Metamorphics and Speares Metamorphics by Warren and Shaw (1995) are now considered to be undivided Inyalinga Granulite.

Alkipi Metamorphics

The *Alkipi Metamorphics* (Scrimgeour *et al* 2005a) represents a more homogeneous metasedimentary succession than the Inyalinga Granulite, dominated by a pelitic-psammitic association that grades into more quartz-rich metasedimentary rock. Calc-silicate rock and massive cordierite pelitic rock are generally absent, and mafic rock is less abundant, except as large intrusive bodies. Strained granite and felsic migmatite are common throughout the Alkipi Metamorphics. The unit has been subdivided into a pelitic unit and a quartzose unit (Scrimgeour *et al* 2005a).The *pelitic unit* comprises garnet-biotite-sillimanite metapelitic rock interlayered with psammitic rock, and varying proportions of strained porphyritic biotite granite, felsic migmatite, garnet-biotite gneiss, hornblende-biotite granodiorite, leucogranite and amphibolite. The metapelitic rock has a migmatitic layering that is largely transposed into a strong non-coaxial strain fabric. Mafic amphibolite is most common within the metapelite in the vicinity of the Mount Larrie copper prospect and is interpreted to represent narrow metamorphosed intrusions. The *quartzose unit* has similarities and gradational contacts with the pelitic-psammitic unit, but has a much higher proportion of quartz-rich psammo-pelite and quartzite. These are interlayered with pelitic metasedimentary rocks, and contain variable amounts of biotite granite, hornblende-biotite granodiorite, and biotite-bearing felsic migmatite. Calc-silicate rock is absent.

SHRIMP U-Pb dating of detrital zircons from a garnet-biotite-sillimanite metapelitic rock of the Alkipi Metamorphics from south of Beantree Creek has yielded ages from 2520–2420 Ma and 1770–1670 Ma; these have metamorphic rims that have yielded an age of 1641 ± 14 Ma (Kinny 2002). A sample of garnet-biotite ± sillimanite pelitic rock from drillcore at the Mount Larrie copper prospect has yielded detrital zircons with ages in the range

Figure 13.10. Cordierite granulite, Inyalinga Granulite, Hill 830 (MOUNT LIEBIG, 52K 761285mE 7424660mN).

1750–1650 Ma and metamorphic zircon rims that give an age of 1639 ± 20 Ma (Kinny 2002).

Speares Metamorphics

The Speares Metamorphics (Warren and Shaw 1995, Biermeier *et al* 2003a) occur south of the Mount Heuglin massif and in outcrops extending to the western margin of HERMANNSBURG; they are now considered likely to include a number of units mapped in the Yaya Domain in MOUNT LIEBIG to the west (Scrimgeour et al 2005a). The Speares Metamorphics include augen gneiss (probably Warumpi Granite), felsic gneiss, mafic granulite and amphibolite, metapelitic rock, quartzic metasedimentary rocks, quartzite and calc-silicate rocks. Given the similarities of these lithologies with the Inyalinga Granulite, Alkipi Metamorphics and other units to the east, the Speares Metamorphics is likely to be a combination of these units.

Liesler Metamorphics

The Liesler Metamorphics (Close *et al* in prep) includes metapelitic migmatites that form low rounded outcrops and boulders east of the Davenport Hills, in the far western Yaya Domain. The rocks contain patchy and randomly oriented leucosome and cordierite-rich melanosome that are interlayered on a small scale (**Figure 13.11**). The melanosome of the rock is dominated by cordierite and opaque oxides, with less abundant sillimanite, andalusite, biotite and quartz. The leucosome is dominated by K-feldspar and quartz, with minor cordierite. Biotite-sillimanite-quartz intergrowths occur between K-feldspar and cordierite, and muscovite-quartz symplectites locally separate sillimanite and K-feldspar. The leucosome within the metapelitic rocks has locally mobilised to form bodies of melt containing aluminous xenoliths, and grades into S-type biotite ± cordierite granite with small, subhedral, rectangular K-feldspar phenocrysts. Isolated outcrops of fine-grained metamorphosed quartz diorite occur in the vicinity of the metapelitic rock, although no contacts are exposed.

Undivided Yaya Metamorphic Complex

A heterogeneous unit of *felsic migmatites* and strained granites with minor mafic rock and quartzic and pelitic metasedimentary rocks occurs in an east-trending belt north of the Belt Range (Scrimgeour *et al* 2005a) and in scattered outcrops across the Yaya Domain. It is distinguished from the rest of the Yaya Metamorphic Complex by the predominance of felsic migmatite with a granitic or felsic volcanic precursor, and a relative lack of metasedimentary rock. The most common rock types in the unit are migmatites with a variable composition, ranging from migmatitic biotite-poor leucogneiss to hornblende-rich migmatite that has hornblende-bearing leucosomes and a biotite- and hornblende-rich mesosome. Strained mafic granulite occurs locally and is extensively retrogressed to amphibolite. The precursors of the felsic migmatites are interpreted to be compositionally variable granites that intruded sediments of the Alkipi Metamorphics and Inyalinga Granulite prior to the Liebig Orogeny, although they may also include metamorphosed felsic volcanic rocks.

Scattered outcrops of pelitic metasedimentary rocks and localised calc-silicate rock (unit Ꝑy$_2$) outcrop across the Yaya Domain between Mount Liebig in the east and the Davenport Hills in the west (Scrimgeour *et al* 2005a, Close *et al* in prep). The unit includes biotite-sillimanite-garnet metapelitic rock interlayered with psammitic rock, calc-silicate rock, mafic amphibolite and granulite, quartzite and strained biotite granite. A zone of retrogressed metapelitic rock and felsic migmatite (Ꝑy$_3$, Close *et al* in prep) 15 km north and northeast of Mount Rennie includes biotite-muscovite and biotite-muscovite-garnet schist, and is interpreted to reflect a zone of high fluid flow and retrogression of higher-grade metasedimentary and meta-igneous precursors.

1640–1630 Ma intrusive rocks

Waluwiya Suite

The Waluwiya Suite (Scrimgeour *et al* 2005a) is an extensive suite of variably deformed charnockite and granodiorite, with lesser granite, that extends in an east-trending belt through the Yaya Domain. The Waluwiya Suite is geochemically homogeneous, despite textural and mineralogical variations between the constituent units. There is a high range in silica values (62–71 wt% SiO_2). Relative to SiO_2 content, K_2O, Th and Rb have positive correlations and CaO, FeO, MgO, TiO_2 and P_2O_5 have negative correlations, reflecting variations due to magmatic differentiation. Relative to upper continental crust, the Waluwiya Suite is depleted in Nb and Ba, and enriched in Ti.

The *Larrie Granodiorite* is a large east-trending body, forming prominent hills, including Mount Larrie, as well as smaller bodies of granodiorite and charnockite that are intercalated with the Inyalinga Granulite and Warumpi Granite. It is a medium-grained, weakly porphyritic to equigranular granodiorite with abundant mafic xenoliths. Plagioclase typically forms phenocrysts 3–5 mm in diameter, and aggregates of mafic minerals form clots a few millimetres in diameter. The granodiorite has largely recrystallised to a metamorphic assemblage of hornblende, biotite, garnet, plagioclase, K-feldspar and quartz, although igneous clinopyroxene is rarely preserved. Veins and dykes

Figure 13.11. Liesler Metamorphics, showing patchy and randomly oriented leucosome and cordierite-rich melanosome (MOUNT RENNIE, 52K 534552mE 7397111mN).

of the Larrie Granodiorite locally intrude mafic granulite and gabbro of the Papunya Igneous Complex.

The *Kakalyi Gneiss* (Scrimgeour *et al* 2005a) is a distinctive hornblende-biotite migmatitic orthogneiss, which is geochemically indistinguishable from the remainder of the Waluwiya Suite, but is characterised by being strongly migmatitic, with a generally high proportion of leucosome. The mesosome has a granitic composition and typically contains biotite and hornblende, with accessory titanite and ilmenite, and rare garnet. In places, the migmatite grades into a weakly porphyritic biotite-hornblende granite with relatively limited migmatisation. Zircon from a stromatic migmatite from the Kakalyi Gneiss west of Yaya Creek (**Figure 13.12**) has igneous cores yielding a SHRIMP U-Pb age of 1644 ± 5 Ma, with metamorphic rims that give an age of 1571 ± 5 Ma. In comparison, a migmatite from east of Yaya Creek, which has a high proportion of randomly oriented hornblende-bearing leucosome (**Figure 13.13**), has metamorphic rims that give an age of 1149 ± 3 Ma (Scrimgeour *et al* 2005b).

The *Talyi-Talyi Charnockite* (Scrimgeour *et al* 2005a) outcrops in the Talyi-Talyi Hills north of Mount Liebig, and is medium grained and weakly porphyritic, with blue-grey phenocrysts of plagioclase feldspar up to 8 mm in diameter. Igneous ortho- and clinopyroxene are only rarely preserved, and are largely replaced by a metamorphic assemblage including hornblende, biotite, garnet and secondary clinopyroxene, associated with a variably developed foliation. Plagioclase and K-feldspar occur in approximately equal proportions. The Talyi-Talyi Charnockite has a SHRIMP U-Pb age of 1631 ± 4 Ma (Cross *et al* 2005). Foliated and variably migmatitic biotite-hornblende granodiorite of the *Tjungkuba Granodiorite* occurs through much of the Tjungkuba Hills and also outcrops to the west of the hills. It is geochemically very similar to the Talyi-Talyi Charnockite. The granodiorite is medium grained and equigranular to weakly porphyritic, with plagioclase phenocrysts. It commonly contains discontinuous hornblende-bearing leucosomes, interpreted to reflect incipient partial melting.

The *Russell Charnockite* (Close *et al* in prep) forms prominent hills at Mount Russell and in the Ehrenberg Range, and scattered small outcrops between the Ehrenberg Range and the Davenport Hills. This distinctive rock type contains orthopyroxene, clinopyroxene, plagioclase, quartz, hornblende, magnetite, minor biotite and K-feldspar, with abundant mafic xenoliths (**Figure 13.14**). It is most commonly undeformed, with abundant rounded plagioclase phenocrysts, 3–5 mm in diameter, and pyroxene phenocrysts, 1–2 mm in diameter, in a fine-grained granoblastic groundmass. The groundmass contains hornblende, particularly at the edges of pyroxene phenocrysts, and may reflect static metamorphic recrystallisation. Plagioclase phenocrysts are zoned and have embayed margins. In the Ehrenberg Range the charnockite is cut by amphibolite- and

Figure 13.12. Stromatic felsic migmatite of Kakalyi Gneiss (MOUNT LIEBIG, 52K 756267mE 7426472mN).

Figure 13.13. Felsic migmatite of the Kakalyi Gneiss, with a high proportion of randomly oriented leucosome and lesser hornblende- and biotite-rich melanosome (MOUNT LIEBIG, 52K 761325mE 7428008mN).

Figure 13.14. Russell Charnockite, exhibiting mafic xenoliths, abundant small rounded plagioclase and pyroxene phenocrysts in a fine-grained granoblastic groundmass (MOUNT RENNIE, 52K 640709mE 7420388mN).

greenschist-facies shear zones, assigned to the Chewings and Alice Springs orogenies, respectively.

Illili Suite

Foliated to gneissic, porphyritic biotite granite belonging to the Illili Suite (Scrimgeour *et al* 2005a) outcrops as prominent hills southeast of Papunya, and as scattered exposures throughout the Yaya Domain. The unit includes the formally named granites described below, as well as additional isolated outcrops of biotite granite. The Illili Suite comprises high-K calc-alkaline granites, with 70–76 wt% SiO_2 that show minor depletion in Y, Ba and Sr. The *Warumpi Granite* forms prominent hills north of Mount Larrie, as well as a large hill (Warumpi) 3 km east of Papunya Community. It is dominated by foliated to gneissic, porphyritic biotite granite, with rounded phenocrysts of K-feldspar, typically 1–2 cm in diameter, that are commonly flattened and elongated in the fabric and locally preserve rapakivi textures. In places, the granite contains a granulite-facies fabric and has undergone local partial melting. The Warumpi Granite intrudes the Inyalinga Granulite, and has intrusive contacts (with no clear timing relationships) with the Larrie Granodiorite. Two samples of Warumpi Granite yielded SHRIMP U-Pb zircon ages of 1642 ± 3 Ma and 1639 ± 3 Ma (Cross *et al* 2005). The *Ehrenberg Granite* (Close *et al* in prep) is a variably porphyritic, felsic biotite granite that mainly outcrops south and west of Ehrenberg Range. The *Gunbarrel Granite* (Close *et al* in prep) is a coarsely porphyritic biotite granite that occurs in scatted outcrops between the Ehrenberg Range and the Davenport Hills. The Gunbarrel Granite is characterised by coarse, rounded K-feldspar phenocrysts with locally well developed rapakivi textures (**Figure 13.15**).

Papunya Igneous Complex

The Papunya Igneous Complex (Scrimgeour *et al* 2005a) comprises multiple bodies of variably recrystallised gabbro, gabbronorite and rare plagioclase pyroxenite, with lesser quartz gabbro, tonalite and leucogranite, which intrude the Yaya Metamorphic Complex. The size of these bodies is variable, with the largest being up to 4 km in length and elongated parallel to the dominant fabric. The complex predominantly comprises tholeiitic gabbro, and geochemistry shows a general lack of linear trends of element abundances relative to SiO_2 content, possibly implying varying magmatic sources and/or crustal contamination. Field descriptions and maps of a number of the bodies can be found in Hoatson and Stewart (2001).

Figure 13.15. Gunbarrel Granite, showing distinctive rounded rapakivi K-feldspar phenocrysts (MOUNT RENNIE, 52K 591498mE 7411672mN).

Other intrusive rocks

The *Ulambaura Granodiorite* (Scrimgeour *et al* 2005a) comprises a large number of discrete bodies of weakly porphyritic hornblende-biotite granodiorite and tonalite that intrude metasedimentary rocks and orthogneiss of the Yaya Metamorphic Complex. The granodiorite is foliated and contains coarse igneous hornblende overprinted by secondary hornblende and biotite with minor titanite and epidote that are metamorphic in origin. K-feldspar is rare to absent. The Ulambaura Granodiorite is geochemically distinct from other felsic rocks in the Yaya Domain and comprises relatively low-K calc-alkaline granodiorites and tonalites, with relatively low silica and potassium contents. The Ulambaura Granodiorite shows marked negative Nb, Zr and Cu anomalies, positive Sr and Ba anomalies, and has an arc-like geochemical signature (Scrimgeour *et al* 2005a)

Foliated, weakly porphyritic biotite and biotite-hornblende granite of the *Belt Granite* (Scrimgeour *et al* 2005a) occurs in a region of subdued topography north of the Belt Range. The most common rock type in this unit is porphyritic granite and granodiorite containing abundant biotite, K-feldspar, plagioclase and quartz, and less abundant hornblende, ilmenite and titanite. It intrudes the Yaya Metamorphic Complex and is intruded by numerous dykes of the Stuart Pass Dolerite. The *Lyell Brown Granite* (Close *et al* in prep) outcrops west of the Ehrenberg Range, and is a coarse-grained porphyritic biotite granite that is characterised by grey K-feldspar phenocrysts up to 5 cm in length in a coarse-grained matrix. The granite is commonly undeformed, but has a locally developed biotite foliation. K-feldspar phenocrysts vary from being tabular and simply-twinned to more rounded and ellipsoidal.

A 2 x 1 km body of gabbro, which is texturally and geochemically distinct from other gabbros in the Yaya Domain, outcrops 4 km northeast of Mount Larrie. It has an equigranular texture and comprises >50% white plagioclase, and cumulus orthopyroxene and clinopyroxene with coronas of hornblende. The gabbro has undergone localised strain resulting in recrystallisation to hornblende-bearing mafic granulite. It is interpreted to have intruded the Warumpi Granite and has subsequently undergone granulite-facies metamorphism.

An *unnamed granite in the Tjungkuba Hills* is geochemically and geophysically distinct from other granites in the Yaya Domain and is strongly enriched in K, Th and U. The granite has two distinct phases: a medium-grained, foliated, peraluminous leucocratic garnet-bearing granite and a more biotite-rich, porphyritic granite. The leucocratic granite contains biotite and fine-grained sillimanite, with lesser garnet and tourmaline. The mineralogy of the granite suggests that it is peraluminous and was probably derived from the partial melting of pelitic sedimentary rocks.

A body of *unnamed charnockite* occurs in the vicinity of Hill 830, where it intrudes the Inyalinga Granulite (Scrimgeour *et al* 2005a). It also occurs as veins that intrude calc-silicate of the Inyalinga Granulite. This is a two-pyroxene granitoid that varies from being medium-grained and equigranular to porphyritic with rounded plagioclase phenocrysts. The rock has undergone limited metamorphic recrystallisation at granulite-facies conditions and contains abundant xenoliths of mafic granulite. As the charnockite intrudes rocks with a granulite-facies fabric, but is itself deformed at granulite-facies conditions, it is interpreted to have intruded during high-grade metamorphism. Igneous zircon from this charnockite has a SHRIMP U-Pb age of 1637 ± 2 Ma, with metamorphic rims that have an indistinguishable age (Cross *et al* 2005). This is equivalent to the timing of high-grade metamorphism in the adjacent Inyalinga Granulite (1638 ± 8 Ma; Scrimgeour *et al* 2005b).

A number of isolated granite outcrops in the Yaya Domain have not been assigned to any named unit and are dominated by foliated, porphyritic biotite granite and lesser hornblende-bearing granodiorite (Scrimgeour *et al* 2005a).

Ilpilli Dolerite

The Ilpilli Dolerite is a swarm of north-trending dolerite dykes that intrude the Russell Charnockite in the Ehrenberg Range, Mount Russell and surrounding areas. The dykes are up to 10 m in width and are offset by amphibolite-facies shear zones, interpreted to have formed during the 1590–1570 Ma Chewings Orogeny. In general, the dykes are only preserved within the Russell Charnockite, as the charnockite formed a coherent body that was not significantly deformed during the Chewings Orogeny. SHRIMP U-Pb dating of zircon from the Ilpilli Dolerite has yielded an age of ca 1633 Ma, implying a period of extension synchronous with the Andrew Young Igneous Complex in the Aileron Province immediately to the north (Close *et al* 2005).

KINTORE DOMAIN

1690 Ma granites

The oldest known rocks in the Kintore Domain are biotite granites that intruded at ca 1690 Ma. The *Tinki Granite* (Close *et al* in prep) comprises undeformed biotite granite and quartz monzonite that forms scattered bouldery outcrops and pavements east of the Kintore Range. It is typically coarse-grained and ranges from being equigranular to porphyritic, with tabular K-feldspar phenocrysts up to 4 cm in length. The granite contains common mafic xenoliths and is intruded by fine-grained to microcrystalline felsic dykes. The Tinki Granite has a SHRIMP U-Pb zircon age of 1691 ± 4 Ma (Cross *et al* 2005). The *Ininti Granite* (Close *et al* in prep) forms a number of low isolated outcrops and pavements northwest of the Winnecke Hills near the Western Australian border. It is a biotite porphyritic granite, with K-feldspar phenocrysts up to 2 cm in diameter and 10% biotite that defines a well developed foliation. In places, the feldspar is tabular and simply twinned. The Ininti Granite has a SHRIMP U-Pb zircon age of 1688 ± 3 Ma (Worden *et al* 2006). A sample of syenogranite 10 km across the border in Western Australia, also interpreted to be Ininti Granite, has a SHRIMP U-Pb zircon age of 1691 ± 5 Ma (Kirkland et al 2009a).

Sandy Blight Quartzite

The Sandy Blight Quartzite (Close *et al* in prep) forms a series of isolated hills and ridges that extend west from near Sandy Blight Junction over a distance of 45 km, in the Kintore Domain. It comprises crystalline metasedimentary quartzite containing a variably defined muscovite foliation, with less abundant quartz-muscovite phyllite that contains a bedding-parallel cleavage and 5–20 cm-thick quartzite interbeds (**Figure 13.16**). Metamorphic grade appears to be greenschist facies. The timing of deposition of the Sandy Blight Quartzite remains uncertain, although SHRIMP U-Pb dating of detrital zircons from crystalline quartzite south of Ininti outstation have yielded a maximum deposition age of 1680 ± 3 Ma (Worden *et al* 2006).

Walungurru Volcanics

The Walungurru Volcanics (Close *et al* in prep) outcrop in the Kintore Range and comprise a succession of dominantly mafic to felsic volcanic rocks, with minor intervals of tuffaceous claystone, sandstone and mudstone. Based on dips and outcrop widths, the succession is estimated to be >2000 m thick. Although the base is not exposed, it is interpreted to overlie the Tinki Granite, and is unconformably overlain by the Neoproterozoic Heavitree Quartzite. The lithology of

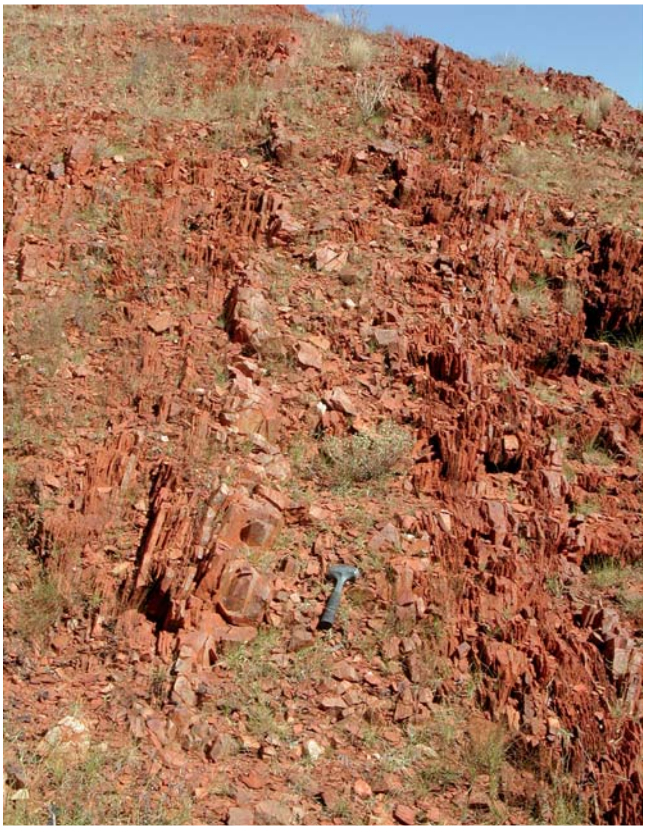


Figure 13.16. Sandy Blight Quartzite: interlayered quartzite and quartz-muscovite phyllite (MOUNT RENNIE, 52K 516680mE 7434318mN).

volcanic rocks varies over a spectrum from basalt to high-K dacite, with a range in SiO_2 from 46–68% and MgO from 1.1–7.9%. True andesitic rocks (57–63% SiO_2) are present in the succession, mainly near the base. The more mafic end members of the Walungurru Volcanics occur as flow units 10–30 m thick, whereas the felsic rocks occur as sheets that are typically 70–150 m thick. The margins of mafic flow units are defined by marginal facies, characterised by either vesicular textures or hyaloclastic breccias (Rawlings 2002). Evidence of interaction with water is rare, and Rawlings (2002) interpreted deposition in a terrestrial environment. The more mafic volcanics include variably amygdaloidal, grey to black, silicified microcrystalline basalt, microdolerite, basaltic andesite, andesite, microdiorite and minor dolerite with local plagioclase phenocrysts and epidote-chlorite-sericite-quartz alteration (**Figure 13.17**). More felsic rocks include black to grey, hard, glassy, cryptocrystalline porphyritic andesite and dacite with phenocrysts of K-feldspar, plagioclase and lesser quartz. Within felsic rocks, planar flow banding is common (**Figure 13.18**), and is locally dismembered into stratified and discordant clast-supported domains of autobreccia.

The overall calc-alkaline characteristics of mafic rocks of the Walungurru Volcanics indicate contamination of mafic magma by a 'sedimentary component' during melting

Figure 13.17. Walungurru Volcanics: basalt with quartz- and epidote-filled amygdales (MOUNT RENNIE, 52K 541621mE 7423357mN).

Figure 13.18. Walungurru Volcanics: flow-banded dacite (MOUNT RENNIE, 52K 543497mE 7423253mN).

or ascent to the surface. These characteristics are unlikely to have been derived from the asthenosphere or by partial melting of chemically 'normal' lithospheric mantle. Three possibilities exist: (i) assimilation of subducted sediment in the accretionary wedge of a subduction zone (ie 'arc magmatism' or 'orogenic andesites'); (ii) contamination of mantle-derived magmas by wall rocks during AFC processes in large lower-crustal magma chamber; or (iii) mixing of asthenospheric magma with a partial melt from 'subduction modified' lithosphere. These three scenarios are difficult to distinguish. Rawlings (2002) considered a subduction-related source to be likely for the magmas, with evidence including the wide range of SiO_2, the prevalence of andesites (and absence of bimodal composition), and the extent of the Nb, Ta, P and Ti depletion over the full range of compositions. An alternative possibility is that it is a fractionated flood basalt. Rawlings (2002) considered that the Walungurru Volcanics appear to be genetically related to the Ilpilli Dolerite. No direct dating exists of the Walungurru Volcanics in the Northern Territory. However, a massive rhyodacite interpreted to belong to the Walungurru Volcanics in the Dovers Hills in the adjacent regions of Western Australia has a SHRIMP U-Pb zircon age of 1650 ± 4 Ma (Kirkland *et al* 2009b).

LIEBIG OROGENY (1640–1630 Ma)

The Liebig Orogeny (Scrimgeour *et al* 2005b) is a major tectonothermal event that affected the Warumpi Province at 1640–1630 Ma. This event has been interpreted as reflecting oblique accretion of the Warumpi Province onto the North Australian Craton (Scrimgeour *et al* 2005b, Close *et al* 2005). Evidence for this interpretation includes the rapid deep burial and exhumation of the Yaya Domain, a linear belt of calc-alkaline felsic magmatism, and a hairpin bend in the apparent polar wander path for northern Australia at the time. The localisation of 1690–1635 Ma magmatism within the Warumpi Province rather than the Aileron Province to the north is consistent with south-dipping subduction preceding accretion (Scrimgeour *et al* 2005a), a notion supported by magnetotelluric imaging of the central Australian lithosphere (Selway *et al* 2007). In the period 1640–1630 Ma, localised deep burial and exhumation occurred in some parts of the Warumpi Province, while other parts of the province underwent extension or remained at relatively shallow crustal levels. This partitioning of the Warumpi Province into discrete zones of broadly synchronous extension and compression is attributed to the oblique nature of the accretion (Close *et al* 2005).

Deformation and metamorphism

Yaya Domain

Structures that developed during the Liebig Orogeny in the Yaya Domain are generally poorly preserved, due to the near-pervasive nature of overprinting fabrics associated with the Chewings Orogeny. Throughout the Yaya Domain, the regional Liebig Orogeny fabric occurs most commonly as a migmatitic layering that is reworked and often completely transposed into a non-coaxial regional strain fabric. Rare information on the orientation of Liebig Orogeny fabrics can be derived from within zones of low strain. A megaboudin of granulite to the east of Mount Liebig preserves a variably developed granulite-facies strain fabric that dips moderately west, with rare, poorly-developed, south-southwest-plunging mineral lineations. Granulite-facies fabrics in the Warumpi Granite and Inyalinga Granulite to the west of Papunya are folded by open east-plunging folds and have a well-developed stretching lineation that plunges towards ca 110°. No kinematic information exists for the Liebig Orogeny.

The highest grades of metamorphism associated with the Liebig Orogeny are preserved around Hill 830, east of Mount Liebig, where cordierite granulites of the Inyalinga Granulite occur adjacent to large gabbro and charnockite bodies (Scrimgeour *et al* 2005a, b). These rocks include orthopyroxene-sillimanite-garnet granulites and silica-undersaturated sapphirine-, corundum- and kornerupine-bearing lithologies. Within silica-understaurated lithologies, the peak metamorphic assemblage includes orthopyroxene, sillimanite, garnet, corundum, kornerupine and biotite. Abundant cordierite- and sapphirine-bearing symplectite textures occur (**Figure 13.19**) that are consistent with a high-T decompressional evolution from peak conditions of 9–10 kbar and ≥800°C (Scrimgeour *et al* 2005b). Lower P-T conditions of 8–9 kbar and 750–800°C have been estimated in the Alkipi Metamorphics and cordierite coronas in these pelitic rocks are interpreted to reflect near-isothermal decompression following peak metamorphism, predating reworking during the Chewings Orogeny (Scrimgeour *et al* 2005b). Metamorphic grade and burial depth decreases to the west, with low-pressure, upper amphibolite-facies metamorphism of the Liesler Metamorphics near the Davenport Hills.

The timing of the Liebig Orogeny in the Yaya Domain has been established by the dating of metamorphic zircon rims from two samples of Inyalinga Granulite that yielded ages of 1638 ± 8 Ma (Scrimgeour *et al* 2005b) and 1636 ± 6 Ma (Cross *et al* 2005). Furthermore, the 1637 ± 2 Ma unnamed charnockite and 1631 ± 4 Ma Talyi-Talyi Charnockite both have evidence for metamorphic zircon growth with an age indistinguishable from the magmatic crystallisation age (Cross *et al* 2005). Further evidence is provided by chemical Th-U-Pb dating of monazite from a sample of the Speares Metamorphics, which yielded a population with an age of 1644 ± 13 Ma (Biermeier *et al* 2003a).

Haasts Bluff Domain

In the Haasts Bluff Domain, the Glen Helen Metamorphics underwent migmatisation at upper amphibolite facies and is the only unit in this domain interpreted to have undergone significant metamorphism during the Liebig Orogeny. The migmatitic S_1 fabric in the Glen Helen Metamorphics is considered likely to be related to the Liebig Orogeny, although SHRIMP analysis of metamorphic zircon rims from a sample of Glen Helen Metamorphics showed that they had undergone significant Pb-loss, and gave a spread of ages in the range 1640–1530 Ma (Scrimgeour *et al* 2005b).

Evidence for metamorphic conditions in the Glen Helen Metamorphics during the Liebig Orogeny is preserved within a metagabbro north of Mount Edward, which preserves an early metamorphic assemblage of garnet, clinopyroxene, hornblende, plagioclase, and minor quartz and ilmenite. P-T estimates on this assemblage gives pressures of 8–9 kbar for temperatures of 700–750°C (Scrimgeour *et al* 2005b).

Around Mount Palmer, there is a dramatic change in the metamorphic grade of the Liebig Orogeny in the Haasts Bluff Domain. To the west, there is no clear evidence of any metamorphic effect of the Liebig Orogeny, with peak metamorphism at lower amphibolite facies being attributed to the Chewings Orogeny (Scrimgeour *et al* 2005a).

CHEWINGS OROGENY (1590–1560 Ma)

The term Chewings Orogeny was originally restricted to deformation in the eastern Warumpi Province (Teyssier *et al* 1988) that was considered to have occurred in the interval 1610–1600 Ma (Collins *et al* 1995, Collins and Shaw 1995). However, subsequent studies in the Aileron Province established that the Chewings Orogeny was a major high-grade metamorphic event throughout large areas of the central and southern Arunta Region (Rubatto *et al* 2001, Hand and Buick 2001) during the period 1590–1560 Ma (see **Aileron Province**). In the Warumpi Province, metamorphic grade relating to the Chewings Orogeny varies from upper amphibolite facies to greenschist facies and is largely associated with south-southwest-directed non-coaxial strain.

Yaya Domain

The Yaya Domain is dominated by moderately north-dipping non-coaxial strain fabrics that are attributed to the Chewings Orogeny. These fabrics occur with variable intensity and are locally mylonitic, with stretching lineations that plunge towards 000–030° and rare kinematic indicators giving a north-over-south sense of movement. The non-coaxial strain fabrics in the Yaya Domain are upper amphibolite facies, with an assemblage in metapelitic rocks that contains garnet, biotite, sillimanite, K-feldspar, plagioclase, quartz and ilmenite. P-T estimates on these rocks consistently give temperatures of 670–730°C

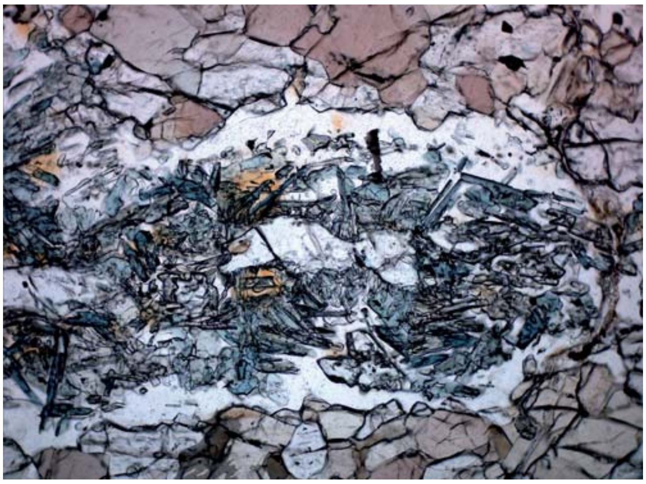


Figure 13.19. Photomicrograph of sapphirine granulite of the Inyalinga Granulite, showing sapphirine (blue) and cordierite (colourless with yellow radiation haloes) separating sillimanite (centre from a mosaic of garnet and orthopyroxene (MOUNT LIEBIG, 52K 761285mE 7424660mN).

and pressures of 5.3–6.2 kbar (Scrimgeour *et al* 2005b). Two samples of the 1640 Ma Warumpi Granite near Papunya have high-U zircon rims that have SHRIMP U-Pb ages of 1590 ± 4 Ma and 1585 ± 8 Ma (Cross *et al* 2005). Metamorphic zircon rims in a felsic migmatite from the Kakalyi Gneiss near Mount Liebig have a SHRIMP U-Pb age of 1571 ± 5 Ma (Scrimgeour *et al* 2005b). The intensity of strain and metamorphic grade associated with the Chewings Orogeny in the Yaya Domain appears to decrease to the west.

Haasts Bluff Domain

In the Haasts Bluff Domain, the structural and metamorphic evolution of the Chewings Orogeny is well preserved in rocks of the Iwupataka Metamorphic Complex (Scrimgeour *et al* 2005a).

The Ikuntji Metamorphics, near Haasts Bluff, contain a foliation defined by biotite and muscovite that is axial planar to tight to isoclinal folds, with a locally developed north- to northeast-plunging mineral lineation (Scrimgeour *et al* 2005a). This fabric is folded by north–south-trending open to tight upright folds. Metapelitic rocks in the Ikuntji Metamorphics have an assemblage of garnet, biotite, muscovite, fibrous sillimanite, plagioclase and quartz. Pressure-temperature estimates on this assemblage yielded P-T conditions of 590–630°C at pressures of 4.5–6.0 kbar (Scrimgeour *et al* 2005a).

West of Mount Palmer in the Haasts Bluff Domain, there are lower- to mid-amphibolite-facies foliations and little evidence for mylonitic deformation associated with the Chewings Orogeny. However, an intense zone of non-coaxial strain (Udor Deformed Zone), up to 3 km wide, occurs along ridges of Putardi Quartzite from Mount Udor West to Mount Peculiar. Although the mylonitic fabrics have been folded by subsequent deformation, S-C fabrics at a number of localities consistently give a north-over-south (south-directed) sense of movement (Scrimgeour *et al* 2005a). Mylonitic fabrics contain kyanite and muscovite, and less commonly staurolite, with intense mineral lineations defined by kyanite and elongated quartz. Less commonly, south-vergent asymmetric folds and kink bands occur. The Udor Deformed Zone is interpreted to have formed as a shallowly dipping, south-directed high-strain zone that has been subsequently folded into both north- and south-dipping orientations. The P-T conditions of deformation in the Udor Deformed Zone are likely to be 500–600°C at pressures of >4 kbar, consistent with the stability of the assemblage kyanite-staurolite-muscovite-quartz (Scrimgeour *et al* 2005a). SHRIMP U-Pb zircon dating of the nearby Udor Granite has provided evidence of zircon recrystallisation or Pb-loss at 1594 ± 12 Ma (Cross *et al* 2005). Further west, two concordant zircon rim analyses in the lower amphibolite-facies Nguman Metamorphics, north of Mount Rennie, have a SHRIMP U-Pb age of ca 1600 Ma (Cross *et al* 2005).

The apparently strong evidence for south-directed deformation in the central and western Haasts Bluff Domain contrasts with the findings of Teyssier *et al* (1988), who documented evidence for north-directed thrusting and isoclinal folding in the Chewings Range region to the east. Teyssier *et al* proposed that the fabrics in the Chewings Range were initially flat-lying before subsequently being rotated into a north-dipping orientation. The north-directed transport was determined on the basis of analysis of microfabrics including quartz *c*-axis measurements. Teyssier *et al* (1988) estimated very high degrees of strain with 100–150% stretching. The significance of this apparent north-directed thrusting remains unclear, given the evidence for south- to southwest-directed deformation elsewhere in the Warumpi Province and in the Anmatjira Range. Metamorphic grade in the Chewings Range region was similar to that in the Ikuntji Metamorphics, with mid-amphibolite facies deformation, and both garnet-sillimanite and kyanite-staurolite assemblages recorded (Offe and Shaw 1983, Warren and Shaw 1995). Although Collins *et al* (1995) considered the Chewings Orogeny to be syn-tectonic with the 1603 Ma Ormiston Granite, metamorphic rims on zircons from a xenolith within the Ormiston Granite have yielded a SHRIMP U-Pb zircon age of 1575 ± 20 Ma (Collins *et al* 1995).

Redbank Thrust

The Redbank Thrust is a north-dipping crustal-scale structure that forms the northern margin of the eastern Warumpi Province and continues east into the Aileron Province. Shaw and Black (1991) recognised that shearing on the Redbank Thrust can be separated into a Proterozoic upper amphibolite-facies episode and a later greenschist-facies episode associated with the Alice Springs Orogeny (Teyssier *et al* 1988, Shaw and Black 1991, Shaw *et al* 1992, Biermeier *et al* 2003b). Shaw and Black (1991) considered the timing of the earlier, upper amphibolite-facies phase of movement to have occurred at 1500–1400 Ma, on the basis of Rb-Sr isochrons from mylonites. However, the oldest of their Rb-Sr ages were 1560 ± 150 Ma and 1530 ± 70 Ma, and given the strong similarities between the metamorphic grade and structural nature of the Redbank Thrust and the Chewings Orogeny fabrics in the Yaya Domain (Scrimgeour *et al* 2005a), it seems likely that the upper amphibolite-facies thrusting along the Redbank Thrust, with associated reworking of the northern margin of the eastern Warumpi Province, occurred during the Chewings Orogeny.

Kintore Domain

In the Kintore Domain, metamorphic grade during the Chewings Orogeny was greenschist facies. The Walungurru Volcanics and Tinki Granite are typically undeformed, whereas in the Sandy Blight Quartzite, north and northwest of the Kintore Range, quartz-muscovite phyllite has a bedding sub-parallel greenschist-facies foliation that is folded around east-trending upright fold axes.

TEAPOT EVENT (1150–1130 Ma)

Deformation and metamorphism

The Teapot Event is a predominantly thermal and magmatic event at 1150–1130 Ma that affected the southern half of the Arunta Region. It may be related to the Musgrave Orogeny and associated magmatism in the Musgrave Province. In the Warumpi Province, the Teapot Event resulted in the intrusion of the Teapot Granite Complex (1136 ± 6 Ma, Black and Shaw 1995), as well as localised migmatisation and widespread resetting of isotopic systems. The metamorphic grade during the Teapot Event locally reached upper amphibolite facies in the Yaya Domain, with partial melting of granitic lithologies suggesting temperatures in excess of ca 650ºC. In the Kakalyi Gneiss, east of Mount Liebig, this migmatisation is intense with up to 40% leucosome. Temperatures throughout much of the Warumpi Province during the Teapot Event are likely to have been in excess of 500ºC, given the regional resetting of $^{40}Ar/^{39}Ar$ and Rb-Sr isotopic systems in hornblende and muscovite in the Warumpi Province at this time (Shaw *et al* 1992, Biermeier *et al* 2003b, McLaren *et al* 2009). The relatively limited extent of migmatisation associated with the Teapot Event suggests that a localised heat source, such as an 1150 Ma intrusion, may underlie the Kakalyi Gneiss.

The timing of the Teapot Event is well constrained by metamorphic zircon rims in a migmatite in the Kakalyi Gneiss that have an age of 1149 ± 3 Ma. This is consistent with electron microprobe monazite and xenotime ages of 1139 ± 25 Ma and 1173 ± 42 Ma, respectively, for metamorphism in the Speares Metamorphics (Biermeier *et al* 2003b). In addition, a number of samples from MOUNT LIEBIG showed evidence for isotopic disturbance of zircons in the late Mesoproterozoic, and this is also interpreted to reflect the effects of the Teapot Event.

Magmatism

The *Teapot Granite Complex* comprises an extensive area of homogeneous leucocratic granite, locally containing K-feldspar phenocrysts, and associated intensely migmatitic felsic gneiss. The granite intrudes the Glen Helen Metamorphics, whereas the associated felsic gneiss may be intensely migmatised country rock. Warren and Shaw (1995) interpreted the granite to be an anatectic melt derived from the migmatisation. A sample of porphyritic granite of the Teapot Granite Complex has yielded a SHRIMP U-Pb zircon age of 1136 ± 6 Ma (Black and Shaw 1995). The Teapot Granite Complex is likely to have been formed through melting associated with the same thermal event that resulted in intense migmatisation of the Kakalyi Gneiss in the Yaya Domain, dated at 1149 ± 3 Ma (Scrimgeour *et al* 2005b). The Teapot Granite Complex is strongly enriched in radioactive elements and forms a distinct positive radiometric anomaly.

STUART PASS DOLERITE

The Stuart Pass Dolerite (Warren and Shaw 1995; formerly the Stuart Dyke Swarm of Zhao and McCulloch 1993a, b) forms an extensive swarm of dykes in the eastern Warumpi Province. Individual dykes range in width from 1–50 m, and dykes are most commonly oriented north–south, although other orientations, including conjugate sets, occur. The dykes contain cumulus olivine and are dominantly olivine-normative, high-Mg tholeiites, with a geochemical signature similar to island-arc basalts from subduction regimes (Zhao and McCulloch 1993a). The Stuart Pass Dolerite has an Sm-Nd mineral isochron age of 1076 ± 33 Ma (Zhao and McCulloch 1993b), and is correlated with the Alcurra Dolerite in the Musgrave Province (Zhao and McCulloch 1993a, b, Edgoose *et al* 2004). The dolerite has been interpreted as reflecting crustal extension, with melting of a subduction-modified sub-continental lithospheric mantle (Zhao and McCulloch 1993a).

UNNAMED ULTRAMAFIC INTRUSIONS

Rare isolated outcrops of undeformed ultramafic intrusive rocks occur in the western Yaya Domain between the Ehrenberg Range and the Davenport Hills and these also extend into the Haasts Bluff Domain to the south (Close *et al* 2004, in prep). These mafic rocks include plagioclase-phlogopite-wehrlite and lherzolite containing olivine, clinopyroxene, orthopyroxene, and phlogopite. These ultramafic rocks coincide with distinctive, small, rounded to elongate, remnantly magnetic features, clearly visible on regional-scale aeromagnetic images. These are interpreted to be mantle-derived bodies that intruded relatively late in the geological history.

ALICE SPRINGS OROGENY (450–300 Ma)

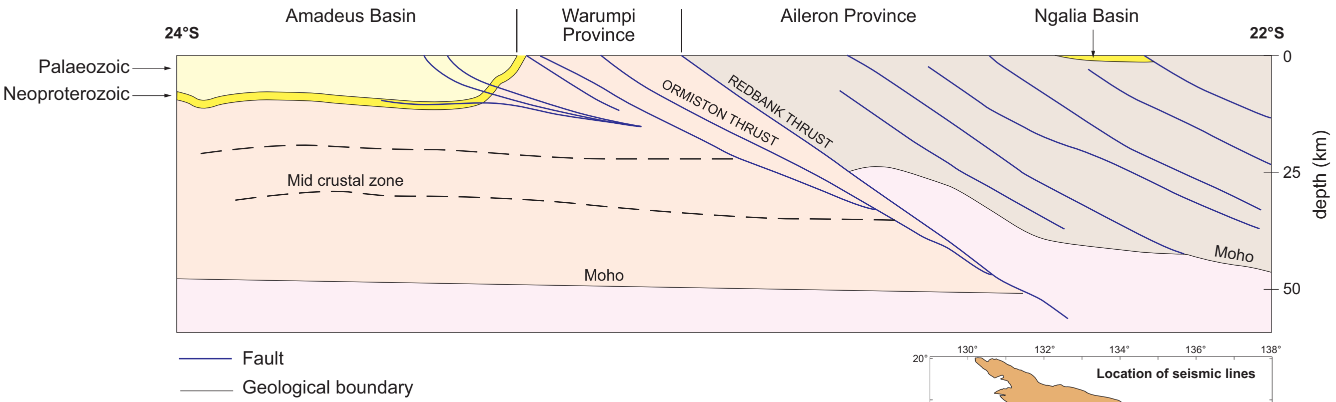
The Alice Springs Orogeny was a major and long-lived compressional event that affected large regions of central Australia from 450 to 300 Ma (Shaw *et al* 1992, Dunlap and Teyssier 1995, Haines *et al* 2001). Low-grade north-dipping shear zones related to the Alice Springs Orogeny crosscut and dissect the Warumpi Province, and interleave the Warumpi Province with basal units of the Amadeus Basin. The orogeny also involved substantial reworking of the suture between the Warumpi and Aileron provinces, with reactivation of the Redbank Thrust leading to significant offset of the Moho (Korsch *et al* 1998; **Figure 13.20**). Most Alice Springs Orogeny structures within the Warumpi Province dip moderately to steeply to the north and have stretching lineations that plunge towards 010–040°. Structural interleaving of Amadeus Basin units with Warumpi Province basement is restricted to the Heavitree Quartzite and Bitter Springs Formation, suggesting that a major decollement occurs within the Bitter Springs Formation with thin-skinned deformation at higher levels of the Amadeus Basin succession (Flottmann and Hand 1999). The intensity of deformation and apparent degree of shortening decreases to the west.

Structural interleaving between the Warumpi Province and basal Amadeus Basin, associated with south-directed thrusting, is exposed in the Ormiston, Mount Sonder, Stokes, Edwards and Amunurunga Thrust Complexes. The degree of shortening and intensity of structures decreases from east to west. Flottmann and Hand (1999) estimated the degree of shortening within the Ormiston Thrust Complex to be 12 km. At Mount Sonder, the thrust complex is fronted by a basement-cored, downward-facing, nappe-style synformal anticline. This structure, known as the Razorback Nappe, is characterised by downward-facing Heavitree Quartzite overlain by Glen Helen Metamorphics and Teapot Granite Complex. A more steeply-dipping imbricate fault system juxtaposes basement against Heavitree Quartzite through the Stokes Thrust Complex (Warren and Shaw 1995, Scrimgeour *et al* 2005a). The Edward Thrust Complex comprises an imbricate stack of moderately north-dipping, south-directed thrusts that juxtapose Warumpi Province over Heavitree Quartzite and result in significant structural thickening of Heavitree Quartzite in the Belt Range. The thrusts typically dip at 25–40° to the north, with a north to north-northeast (010–030°) plunging muscovite lineation. The northernmost splay of the thrust zone separates the Yaya and Haasts Bluff domains north of Belt Range. Along strike to the east, greenschist-facies shear zones in the basement dip more steeply (ca 70–80°) to the north. The Amunurunga Thrust Complex comprises a series of moderately to steeply north-dipping south-directed thrusts in the vicinity of the Amunurunga Range and Mount Liebig, which juxtapose basement against Heavitree Quartzite. In zones between the thrusts, shallowly to moderately-dipping Heavitree Quartzite unconformably overlies Warumpi Province basement, although there is locally intense structural repetition and folding within the quartzite. The Amunurunga Thrust Complex is interpreted to have formed during progressive south-directed deformation, beginning with early thin-skinned deformation forming bedding sub-parallel thrusts and folds, followed by thicker-skinned deformation and the development of basement-cored asymmetric folds and steeply-dipping thrusts (Scrimgeour *et al* 2005a). The metamorphic grade of the Alice Springs Orogeny in the Belt Range and Amunurunga Range is middle to lower greenschist facies with localised fine-grained muscovite growth and ribbon deformation of quartz (Regime 2 of Dunlap *et al* 1997). The metamorphic grade further north is poorly constrained, as $^{40}Ar/^{39}Ar$ data suggest that many lower amphibolite- to greenschist-facies mylonites in the basement are Proterozoic in age (McLaren *et al* 2009).

Constraints on the timing of deformation in the Warumpi Province during the Alice Springs Orogeny are provided by $^{40}Ar/^{39}Ar$ dating by McLaren *et al* (2009). Two samples provided evidence for the timing of new Palaeozoic mineral growth. Muscovite from within strained Heavitree Quartzite interleaved with Warumpi Province basement from the Amunurunga Thrust Zone, has yielded a plateau-like segment of 376 ± 1 Ma and a total-gas age of 390 ± 1 Ma. A garnet-muscovite-chlorite schist from a mylonite zone north of Mount Larrie has a plateau-like segment with an $^{40}Ar/^{39}Ar$ age of 401 ± 1 Ma, which closely matches the total-gas age of 403 ± 2 Ma (McLaren *et al* 2009). There is no evidence in the Mount Liebig region for active deformation and/or new mineral growth in the Carboniferous, which was a time of significant deformation and metamorphism in parts of the Aileron Province. McLaren *et al* (2009) proposed that Palaeozoic deformation in the Mount Liebig area began during the earliest compressional stages of the orogeny, in the period 440–380 Ma, with ongoing cooling extending until the late Carboniferous. The data suggest that deformation in the Alice Springs Orogeny in the Mount Liebig area ceased in the Devonian, consistent with a shift from a major east–west-trending thick-skinned orogen in the Devonian to a higher geothermal gradient event in a more restricted area of the Aileron Province during the Carboniferous (350–300 Ma; Hand *et al* 1999, Dunlap and Teyssier 1995). The data of McLaren *et al* (2009) is broadly consistent with $^{40}Ar/^{39}Ar$ data from mylonites in the vicinity of the Redbank Shear Zone (Biermeier *et al* 2003a), where hornblende typically preserves cooling ages from the Teapot Event (ca 1150 Ma) and biotite recrystallised in mylonite zones records ages in the range 450–400 Ma.

MINERAL RESOURCES

The Warumpi Province has been little explored, although a number of small lead-zinc and copper prospects have been identified. It has significant untested potential for base metals, including metamorphosed VMS, Broken Hill and skarn mineralisation styles, as well as potential for iron-oxide copper-gold. The mafic rocks of the Yaya Domain have untested potential for mafic-hosted mineralisation, and the Haasts Bluff Domain is considered prospective for gold (Close *et al* 2004). The eastern half of the Warumpi Province was the subject of a regional stream sediment geochemical survey by NTGS in 2000 (Dunster and Mügge 2001). Lead isotope studies have shown that the source of lead for the base metal mineralisation in the Warumpi province is more juvenile than for the Aileron Province (Huston *et al* 2003).



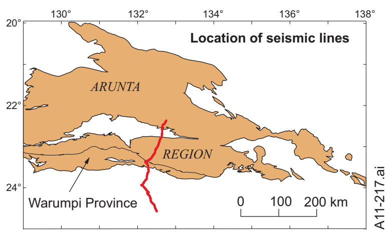


Figure 13.20. Portion of seismic profiles BMR85.1A, B and C, showing a crustal profle across the Warumpi Province (Haasts Bluff domain), showing offset of the Moho by the Redbank Thrust. Adapted from Korsch *et al* (1998).

Base metals

A number of small, but locally high-grade base metal prospects occur in the Warumpi Province. The *Stokes Yard* Zn-Pb-Cu-Ag prospect occurs approximately 170 km west of Alice Springs and 6 km north-northwest of Stokes Bore, within upper amphibolite-facies metasedimentary rocks that were mapped as Glen Helen Metamorphics by Warren and Shaw (1995), but are now considered to form part of the Ikuntji Metamorphics (Scrimgeour *et al* 2005a). Mineralisation is hosted in a mylonite zone containing calc-silicate, forsterite marble, amphibolite and leucogranite/pegmatite. Stokes Yard was inspected and rock-chip sampled by Asarco (Australia) Pty Ltd in 1970. The averaged assay results were 2.1% Zn, 1.4% Pb, 0.23% Cu and 30.6 g/t Ag (Fruzzetti 1972). Reconnaissance rock-chip sampling at the prospect by Northern Mining Limited in 2007 returned results of up to 27.55% Zn, 3.02% Pb, 0.65% Cu and 75 g/t Ag from individual samples (Northern Mining Ltd, ASX Announcement, 31 October 2007) and grab samples collected on a surface traverse by Frater (in prep) assayed up to 12.2% Pb, 8.8% Zn, 1.5% Cu and 50 g/t Ag. The prospect consists of calc-silicate breccia with sub-gossanous outcrop extending over an area of around 60 x 10 m (**Figure 13.21**). Sulfides that have survived weathering include galena, pyrite, sphalerite and a trace of covellite. Tremolite, carbonate, epidote, epizoisite and rhodonite are common gangue minerals, occurring in veins and breccia fill. The area is structurally complex and diamond drilling by NTGS in 1972 failed to intersect the mineralised calc-silicate at depth. Subsequent mapping by Frater (in prep) suggests that the immediate mineralisation may be confined in a keel-like synform. Although the Fe-deficient nature of the Stokes Yard mineralisation raises the possibility that it represents a deformed and metamorphosed Mississippi Valley-type (MVT) deposit, Frater (in prep) considered that the deposit is more likely to be a carbonate-replacement or skarn deposit, on the basis of fluid inclusion and stable isotope evidence.

The *Ulpuruta* Pb-Zn prospect (Barraclough 1975, 1976, Scrimgeour *et al* 2005a, Frater in prep) occurs in amphibolite grade calc-silicate rocks of the Ikuntji Metamorphics. Exposures are restricted to two small isolated occurrences surrounded by extensive sand cover, with the largest being 40 x 10 m in area. The subsurface extent of mineralisation is not known. The calc-silicate is associated with folded and sheared dolomitic marble and quartz-feldspar-biotite (-muscovite) schist. Besides shallow auger drilling, there has been no exploration at the prospect. The main outcrop (**Figure 13.22**), immediately adjacent to the Papunya–Haasts Bluff road, comprises marble and tremolite schist, and contains malachite, with lesser galena, chalcopyrite, azurite and chrysocolla. Additional mineralised outcrop, 400 m to the northwest, comprises forsterite marble and actinolite schist with minor rhodonite. One sample from the northern end of this outcrop contained 11.5% Zn (Barraclough 1975). A short rock-chip sampling traverse over oxidised and weathered rock in the main outcrop by Frater (2005) returned assays up to 19.7% Zn, 4.04% Pb and 3.03% Cu. The calc-silicate is Fe-stained and weathered, and consists of tremolite (after clinopyroxene), with subordinate talc, serpentinite, chlorite, biotite, carbonate, secondary Mg-clay minerals and quartz. Late iron-rich mineral veins and veinlets are thought to represent oxidised sulfides and Fe-bearing silicates (Frater in prep). The mineralised calc-silicate is characterized by relatively low Fe and elevated Mg contents. Zn and Pb are dominant over Cu in mineralisation and Ag is present only as an accessory metal. Fresh galena and pyrite occurs in quartz-protected veinlets, and malachite, azurite and chrysocolla are present on joints and foliation. Frater (in prep) proposed that Ulpuruta could be considered as a carbonate-replacement base metal deposit, with possible skarn associations.

The *Mount Larrie* copper prospect occurs in metapelitic rock of the Alkipi Metamorphics, southwest of Papunya community (Clarke 1975, Scrimgeour *et al* 2005a). The mineralisation is restricted to malachite-stained, garnet-feldspar-quartz rock of a hydrothermal or magmatic origin, with very biotite- and garnet-rich, quartz-poor alteration selvages (**Figure 13.23**). It comprises numerous small bodies, only a few square metres in size, that may have formed in small dilatational zones during deformation, and which occur in a zone about 1.7 km in length. Mineralisation is patchy and grades range up to 5.9% Cu (Clarke 1975). Mineralisation observed at the surface includes malachite, azurite and minor chalcopyrite, locally associated with

Figure 13.21. Stokes Yard prospect, showing sub-gossanous outcrop (HERMANNSBURG, 53K 203637mE, 7406262mN).

Figure 13.22. Outcrop of mineralised tremolite schist at the Ulpuruta Pb-Zn prospect (MOUNT LIEBIG, 52K 804656mE 7405643mN).

magnetite and pyrite. Nine diamond drillholes at wide intervals along strike failed to encounter significant mineralisation (Clarke 1975).

Copper-gold

A second style of mineralisation within metasedimentary rocks of the Iwupataka Metamorphic Complex is the *Haasts Bluff* Cu (+/-Au) prospect (Barraclough 1975, Scrimgeour *et al* 2005a). In 1956, BMR reported malachite and cuprite associated with Fe-oxides and epidote in a coarse- to medium-grained amphibolite, over a strike length of approximately 100 m at the site (Barraclough 1975). Large representative samples from two locations were reported to average 11.76% and 9.85% Cu, but it was concluded at the time that the volume of mineralised outcrop was uneconomic to mine. At the surface, the prospect is represented by malachite, azurite and chalcopyrite mineralisation associated with quartz, carbonate, magnetite and other Fe-rich minerals within tightly folded, sheared and altered calc-silicate and amphibolite. Grab samples from the prospect grade up to 27.7% Cu, with significant Au (up to 0.8 g/t) and Zn (up to 1.9%; Frater in prep). Mineralisation occurs in a distinctive package (typically <12 m wide) of amphibolites, calc-silicate and marble within a quartz-feldspar-mica schist of the Ikuntji Metamorphics. Mineralisation is associated with retrogression accompanying later shear deformation. Mineralisation is confined to a narrow horizon (up to 2 m wide) with malachite-azurite occurring in oxidised amphibolite, and chalcopyrite and pyrite in marble and calc-silicate. As in the other prospects, primary mineralisation occurs in a calc-silicate; however, Haasts Bluff differs from Stokes Yard and Ulpuruta in being a Cu-Au prospect rather than Pb-Zn-Ag. In addition, mineralisation is associated with magnetite (+ haematite), with Fe being enriched and Mg depleted in contrast to the Ulpuruta and Stokes Yard prospects. Frater (in prep) considered that the mineralisation at Haasts Bluff can be broadly classified as iron-oxide copper-gold (IOCG) style.

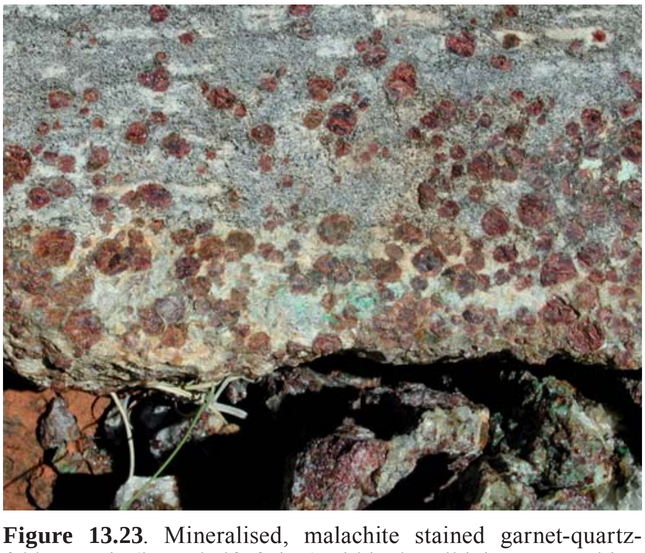


Figure 13.23. Mineralised, malachite stained garnet-quartz-feldspar vein (lower half of view) within the Alkipi Metamorphics, Mount Larrie copper prospect. Coarse garnets occur both within the vein and in the country rock, but decrease in intensity away from the vein. (MOUNT LIEBIG, 52K 787707mE 7422326mN).

Nickel-copper sulfide

Mafic intrusions of the Papunya Igneous Complex have been assessed for their mineral prospectivity as part of a broader study of mafic rocks in the Arunta Region by Hoatson *et al* (2005). These mafic bodies are S-saturated and are considered to have moderate potential for Ni-Cu-Co sulfides and lesser potential for PGE mineralisation. Hoatson *et al* (2005) considered the pyroxenite body within the Papunya Igneous Complex to have potential for Ni-Cu-Co sulfide mineralisation in feeder conduits and embayments or structural depressions in the basal contacts of the body. Traces of pentlandite have been recorded within this zone.

Uranium and rare earth elements

The Teapot Granite Complex in the Haasts Bluff Domain is locally enriched in uranium and rare earth elements, and has potential for Rossing-style granite-hosted uranium mineralisation. Exploration by Crossland Uranium Mines Ltd at the Cockroach Dam prospect, 7 km northeast of Mount Razorback, yielded numerous anomalous uranium rock chip results, with a maximum result of 0.54% U_3O_8, and an arithmetic average of 439 ppm U_3O_8 from 186 rock chips. A preliminary drill program at the prospect yielded a best intercept of 2m at 876 ppm U_3O_8 (Crossland Uranium Mines Ltd, ASX announcements, 28 January 2010 and 1 December 2010). The Teapot Granite Complex is also postulated as the source for rare earth elements hosted in monazite and xenotime in Cenozoic sediments on alluvial and eluvial plains to the north (*Charley Creek* prospect; see **Cenozoic geology and regolith**).

REFERENCES

Ahmad M and Scrimgeour IR, 2006. *Geological map of the Northern Territory. 1:2 500 000 scale*. Northern Territory Geological Survey, Darwin.

Barraclough D, 1975. Report on the Haasts Bluff copper prospects. *Northern Territory Geological Survey, Technical Report* 1975-017.

Barraclough D, 1976. Costeaning at the Haasts Bluff copper prospects. *Northern Territory Geological Survey, Technical Report* 1976-011.

Biermeier C, Wiesinger M, Stuewe K, Foster DA, Gibson HJ and Raza A, 2003a. Aspects of the structural and late thermal evolution of the Redbank thrust system, central Australia: constraints from the Speares Metamorphics. *Australian Journal of Earth Sciences* 50(6), 983–999.

Biermeier C, Stüwe K, Foster DA and Finger F, 2003b. Thermal evolution of the Redbank thrust system, central Australia; geochronological and phase-equilibrium constraints. *Tectonics* 22(1), 1002, doi:10.1029/2001TC901033.

Black LP and Shaw RD, 1995. An assessment, based on U-Pb zircon data, of Rb-Sr dating in the Arunta Inlier, central Australia. *Precambrian Research* 71, 3–15.

Clarke D, 1975. The Mount Larrie copper prospect, Mount Liebig 1:250 000 sheet area SF 52-16, Northern Territory. *Northern Territory Geological Survey, Technical Report* 1975-002.

Close DF, Scrimgeour IR, Edgoose CJ, Claoué-Long J, Kinny P and Meixner AJ, 2003. Redefining the Warumpi Province: in *'Australian Geoscience Exploration Seminar (AGES) 2003. Record of abstracts'. Northern Territory Geological Survey, Record* 2003-001.

Close DF, Scrimgeour IR, Edgoose CJ, Frater M and Cross A, 2004. New insights into geology and prospectivity of the southwestern Arunta Region: in *'Annual Geoscience Exploration Seminar (AGES) 2004. Record of abstracts.' Northern Territory Geological Survey, Record* 2004-001.

Close DF, Scrimgeour IR, Edgoose CJ, Wingate MTD and Selway K, 2005. Late Palaeoproterozoic oblique accretion of a 1690–1660 Ma magmatic arc onto the North Australian Craton. *Geological Society of Australia, Abstracts* 81, 36.

Close DF, Scrimgeour IR and Edgoose CJ, in prep. *Mount Rennie, Northern Territory (Second Edition). 1:250 000 geological map series explanatory notes, SF 52-15.* Northern Territory Geological Survey, Darwin.

Collins WJ and Shaw RD, 1995. Geochronological constraints on orogenic events in the Arunta Inlier: a review. *Precambrian Research* 71, 69–89.

Collins WJ, Williams IS, Shaw SE and McLaughlin NA, 1995. The age of the Ormiston Pound granite: implications for Mesoproterozoic evolution of the Arunta Inlier, central Australia. *Precambrian Research* 71, 91–105.

Cross A, Claoué-Long JC, Scrimgeour IR, Close DF and Edgoose CJ, 2005. Summary of results. Joint NTGS-GA geochronology project: August 2003–December 2004. *Northern Territory Geological Survey, Record* 2004-003.

Dunlap WJ and Teyssier C, 1995. Palaeozoic deformation and isotopic disturbance in the southeastern Arunta Block, central Australia. *Precambrian Research* 71, 229–250.

Dunlap WJ, Hirth G and Teyssier C, 1997. Thermomechanical evolution of a ductile duplex. *Tectonics* 16, 983–1000.

Dunster J and Mügge A, 2001. Stream sediment survey of the Western MacDonnell Ranges: *Northern Territory Geological Survey, Digital Information Package* DIP-002.

Edgoose CJ, Scrimgeour IR and Close DF, 2004. Geology of the Musgrave Block, Northern Territory. *Northern Territory Geological Survey, Report* 15.

Flottmann T and Hand M, 1999. Folded basement-cores tectonic wedges along the northern edge of the Amadeus Basin, central Australia: evaluation of orogenic shortening. *Journal of Structural Geology* 21, 399–412.

Frater KM, 2005. Mineralisation of the 1690-1610 Ma Warumpi province. in *'Annual Geoscience Exploration Seminar (AGES) 2005. Record of abstracts.' Northern Territory Geological Survey, Record* 2005-001

Frater KM, in prep. Base metal prospects and stream sediment geochemistry of the Warumpi Province, Arunta Region, Northern Territory. *Northern Territory Geological Survey, Record*.

Fruzzetti O, 1972. The Stokes Yard base metal prospect, Hermannsburg 1:250 000 sheet area SF 53-13, Northern Territory. *Northern Territory Geological Survey, Technical Report* 1972-025.

Glikson AY, 1984: Granulite-gneiss terrains of the southwestern Arunta Block, central Australia: Glen Helen, Narwietooma and Anburia 1:100 000 sheet areas. *Bureau of Mineral Resources, Australia, Record* 1984/022.

Haines PW, Hand M and Sandiford M, 2001. Palaeozoic syn-orogenic sedimentation in central and northern Australia: a review of distribution and timing with implications for intracontinental orogens. *Australian Journal of Earth Sciences* 48, 91–928.

Hand M, Mawby J, Kinny P and Foden J, 1999. U-Pb ages from the Harts Range, central Australia: evidence for early-Ordovician extension and constraints on Carboniferous metamorphism. *Journal of the Geological Society, London* 156, 715–730.

Hand M and Buick IS, 2001. Tectonic history of the Reynolds-Anmatjira Ranges: a case study of reactivation in central Australia: in Miller JA, Holdsworth R, Buick IS and Hand M (editors) *'Continental reactivation and reworking.' Geological Society, London, Special Publication* 184, 237–260.

Hoatson DM and Stewart AJ, 2001. Field investigations of Proterozoic mafic-ultramafic intrusions in the Arunta Province, central Australia. *Geoscience Australia, Record* 2001/39.

Hoatson DM, Sun Shensu and Claoué-Long JC, 2005. Proterozoic mafic–ultramafic intrusions in the Arunta Region, central Australia. Part 1: Geological setting and mineral potential. *Precambrian Research* 142, 93–133.

Huston DL, Hussey KJ, Claoué-Long J and Wygralak AS, 2003. Lead isotope constraints on the ages and metal sources of lode gold and base metal deposits from the Tanami, Warumpi and southeast Arunta provinces: in *'Annual Geoscience Exploration Seminar (AGES) 2003. Record of abstracts.' Northern Territory Geological Survey, Record* 2003-001.

Kinny PD, 2002. SHRIMP U-Pb geochronology of Arunta Province samples from the Mount Liebig and Lake Mackay 1:250 000 mapsheets. *Northern Territory Geological Survey, Technical Note* 2002-015.

Kirkland CL, Wingate MTD, Spaggiari CV and Tyler IM 2009b. 184359: metarhyodacite, Dovers Hills. *Geochronology Record 815, Geological Survey of Western Australia*, 4p.

Kirkland CL, Wingate MTD, Spaggiari CV and Tyler IM 2009a. 184364: metasyenogranite, Buck Hills. *Geochronology Record 845: Geological Survey of Western Australia*, 4p.

Korsch RJ, Goleby BR, Leven JH and Drummond BJ, 1998. Crustal architecture of central Australia based on deep seismic reflection profiling. *Tectonophysics*, 288, 57-69.

Marjoribanks RW and Black LP, 1974. Geology and geochronology of the Arunta Complex north of Ormiston Gorge, central Australia. *Journal of the Geological Society of Australia* 21(3), 291–299.

McLaren S, Sandiford M, Dunlap J, Scrimgeour IR, Close DF and Edgoose CJ, 2009. Distribution of Palaeozoic reworking in the western Arunta Region and northwestern Amadeus Basin from ^{40}Ar/^{39}Ar thermochronology: implications for the evolution of intracratonic basins. *Basin Research*, 21, 315–334.

Offe LA and Shaw RD, 1983. *Alice Springs region, Northern Territory. 1:100 000 geological map commentary.* Bureau of Mineral Resources, Australia.

Rawlings DJ, 2002. Volcanology and geochemistry of Walungurru Volcanics and Peculiar Complex, Warumpi Province, southwestern Arunta Region. *Northern Territory Geological Survey, Technical Note* 2002-21.

Rubatto D, Williams IS and Buick IS, 2001. Zircon and monazite response to prograde metamorphism in the Reynolds Range, central Australia. *Contributions to Mineralogy and Petrology* 140, 458–468.

Scrimgeour IR, 2003. Developing a revised framework for the Arunta Region: in *'Annual Geoscience Exploration Seminar (AGES) 2003. Record of abstracts.' Northern Territory Geological Survey, Record* 2003-001

Scrimgeour IR, Close DF and Edgoose CJ, 2005a. *Mount Liebig, Northern Territory. 1:250 000 geological map series explanatory notes, SF 52-16.* Northern Territory Geological Survey, Darwin.

Scrimgeour IR, Kinny PD, Close DF and Edgoose CJ, 2005b. High-T granulites and polymetamorphism in the southern Arunta Region, central Australia: evidence for a 1.64 Ga accretional event. *Precambrian Research* 142, 1–27.

Selway K, Heinson G, Hand M and Scrimgeour IR, 2007. Magnetotelluric imaging of the central Australian lithosphere: in *'Annual Geoscience Exploration Seminar (AGES) 2007. Record of abstracts.' Northern Territory Geological Survey, Record* 2007-001.

Shaw RD and Wells AT, 1983. *Alice Springs, Northern Territory (Second Edition). 1:250 000 geological series explanatory notes, SF 53-14.* Bureau of Mineral Resources, Australia.

Shaw RD, Stewart AJ and Black LP, 1984. The Arunta Inlier: a complex ensialic mobile belt in central Australia. Part 2: tectonic evolution. *Australian Journal of Earth Sciences* 31, 457–484.

Shaw RD and Black LP, 1991. The history and tectonic implications of the Redbank Thrust Zone, central Australia, based on structural, metamorphic and Rb-Sr isotopic evidence. *Australian Journal of Earth Sciences* 38, 307–332.

Shaw RD, Zeitler PK, McDougall I and Tingate PR, 1992. The Palaeozoic history of an unusual intracratonic thrust belt in central Australia based on ^{40}Ar-^{39}Ar, K-Ar and fission track dating. *Journal of the Geological Society of London* 149, 937–954.

Stewart AJ, Shaw RD, Offe LA, Langworthy AP, Allen RG and Clarke DB, 1980. Stratigraphic definitions of named units in the Arunta Block, Northern Territory. *Bureau of Mineral Resources, Report* 216/70.

Teyssier C, Amri C, and Hobbs BE, 1988. South Arunta Block: the internal zones of a Proterozoic overthrust in central Australia. *Precambrian Research* 40/41, 157–173.

Tyler IM and Hocking RM, 2001. A revision of the tectonic units of Western Australia. *Geological Survey of Western Australia, 2000–01 Annual Review,* 33–34.

Wakelin-King GA, 1989. Geology of Simpsons Gap National Park. *Northern Territory Geological Survey, Report* 6.

Warren RG and Shaw RD, 1995. *Hermannsburg, Northern Territory (Second Edition). 1:250 000 geological map series explanatory notes, SF 53-13.* Northern Territory Geological Survey, Darwin.

Wells AT, Foman DJ and Ranford LC, 1962. Geological reconnaissance of the north-west Amadeus Basin. *Bureau of Mineral Resources, Australia, Record* 1962/63.

Worden KE, Claoué-Long JC, Scrimgeour IR and Doyle N, 2006. Summary of results. Joint NTGS-GA geochronology project: Pine Creek Orogen, Tanami Region, Arunta Region and Amadeus Basin, July–December 2004. *Northern Territory Geological Survey, Record* 2006-005.

Wyborn L, Hazell M, Page R, Idnurm M and Sun Shensu, 1998. A newly discovered major Proterozoic granite-alteration system in the Mount Webb region, central Australia, and implications for Cu-Au mineralisation. *AGSO Research Newsletter* 28, 1–6.

Zhao Jianxin and McCulloch MT 1993a. Melting of subduction-modified continental lithospheric mantle: evidence from Late Proterozoic mafic dyke swarms in central Australia. *Geology* 21, 463–466.

Zhao Jianxin and McCulloch MT 1993b. Sm-Nd mineral isochron ages of Late Proterozoic dyke swarms in Australia: evidence for two distinctive events of mafic magmatism and crustal extension. *Chemical Geology* 109, 341–354.

Zhao Jianxin and Bennett VC, 1995. SHRIMP U-Pb zircon geochronology of granites in the Arunta Inlier, central Australia: implications for Proterozoic crustal evolution. *Precambrian Research* 71, 17–43.

Zhao Jianxin and McCulloch MT, 1995. Geochemical and Nd isotopic systematics of granites from the Arunta Inlier, central Australia: implications for Proterozoic crustal evolution. *Precambrian Research* 71, 265–299.