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Chapter 9: Warramunga Province

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Chapter 9: WARRAMUNGA PROVINCE

N Donnellan

INTRODUCTION

The Proterozoic Warramunga Province forms the central part of the Tennant Region, north and northwest of the Davenport Province and south of the Tomkinson Province (**Figure 9.1**). It is bounded by the Short and Whittington ranges in the north, and by the Murchison and Davenport ranges in the south. To the east and west, the province extends subsurface beneath the Phanerozoic Georgina and Wiso basins, respectively. The Warramunga Province differs from the Tennant Creek Block of former usage (eg Le Messurier *et al* 1990) in that it now includes an area of Ooradidgee Group rocks between the Clough Range and the outcropping Unimbra Sandstone at the northern margin of the Davenport Ranges (ie the Pingelly, Edmirringee and Taragan blocks, **Figure 9.1**). The regional extent of the Davenport Province has been correspondingly modified and now comprises the Wauchope Fold Belt. The Davenport Province succession also outcrops in the Osborne and Crawford ranges to the southwest of the Tennant Region. However, these ranges are within the Aileron Province of the Arunta Region, as it is currently defined (**Figure 9.1**).

The geological framework for the Warramunga Province presented here is based on First Edition 1:100 000- and Second Edition 1:250 000-scale mapping undertaken: (1) collaboratively by BMR and NTGS in the southernmost Warramunga Province (and Davenport Province, 1981–1983); and (2) by NTGS in TENNANT CREEK[1] (1989–1993) and HELEN SPRINGS (1995–1997). Major changes to the stratigraphic succession of TENNANT CREEK that resulted from this mapping program (Donnellan *et al* 1991, 1995, 1999, 2001, Donnellan 2005) followed from the recognition of a tectonic, erosional unconformity within the former Warramunga *Group* by Blake (1984) and Blake *et al* (1987). In the First Edition map of TENNANT CREEK (Mendum and Tonkin 1971, Dodson and Gardener 1978), the Warramunga Group included virtually all rocks in that map sheet now variously assigned to the Warramunga Formation, Junalki Formation and Ooradidgee Group. The geological framework presented here is further based on the interpretation (Johnstone and Donnellan 2001, Donnellan and Johnstone 2004) of semi-regional airborne magnetic data collected over TENNANT CREEK by AGSO in 1998 and over BONNEY WELL, FREW RIVER and ELKEDRA in 1999, and on 11 km-spaced BMR regional gravity data. A summary of the Warramunga Province stratigraphic succession is given in **Tables 9.1** and **9.3** and of the intrusive magmatic rocks in **Tables 9.2** and **9.4**.

A simplified geology map of the Tennant Region, including the Warramunga Province, is presented in **Figure 9.2**. A corresponding digital elevation image for the Tennant Region is presented in **Davenport Province: figure 10.2**, and a map of total magnetic intensity (TMI) and the corresponding reduced-to-pole first vertical derivative (RTP 1VD) is in **Tomkinson Province: figure 16.3a, b**.

[1] Names of 1:250 000 and 1:100 000 mapsheets are in large and small capital letters, respectively, eg TENNANT CREEK, SHORT RANGE.

Further details of Warramunga Province geology are shown in **Figure 9.3**.

The oldest rocks of the Warramunga Province predate the ca 1850 Ma[2] Tennant Event, and are divided into the Warramunga Formation, and the correlative Junalki Formation and Woodenjerrie beds. These units are not currently assigned to a group. The name Warramunga has been retained for the formation that hosts iron-oxide-

[2] Ages cited throughout this text are SHRIMP U-Pb zircon ages unless otherwise indicated.

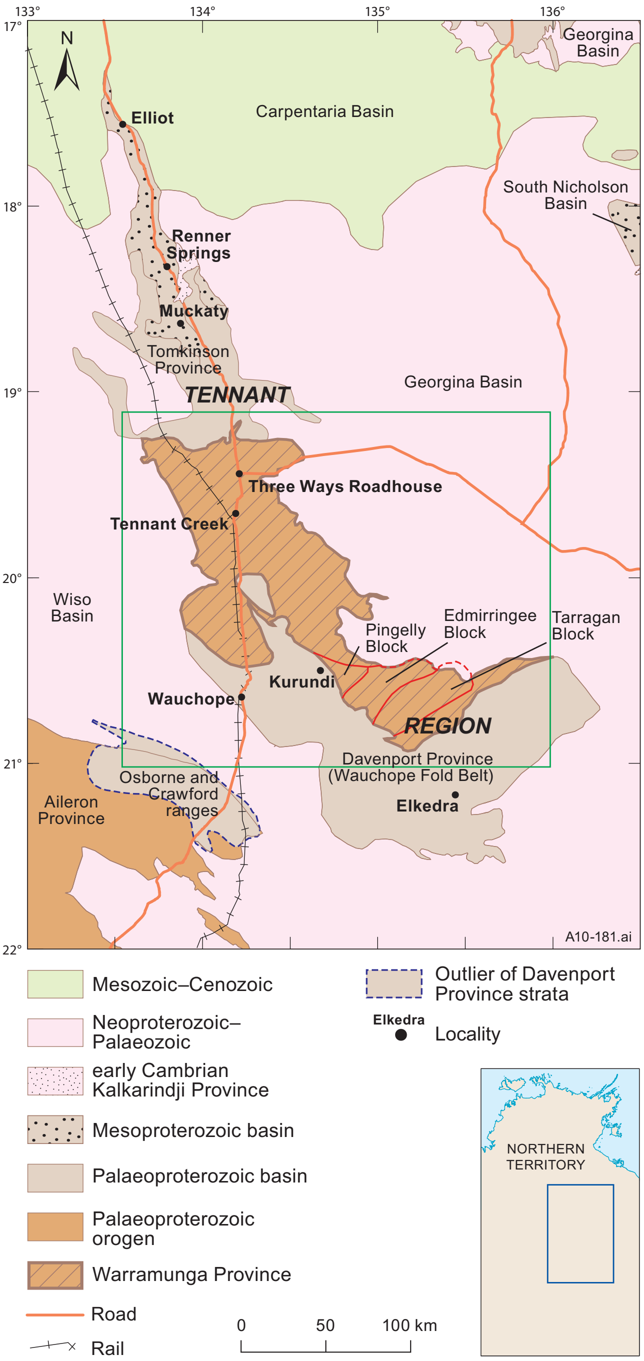


Figure 9.1. Regional geological setting of Warramunga Province, showing locations of Pingelly, Edmirringee and Taragan blocks and Wauchope Fold Belt. NT geological regions slightly modified from NTGS 1:2.5M geological regions GIS dataset. Green box shows location of **Figure 9.3**.

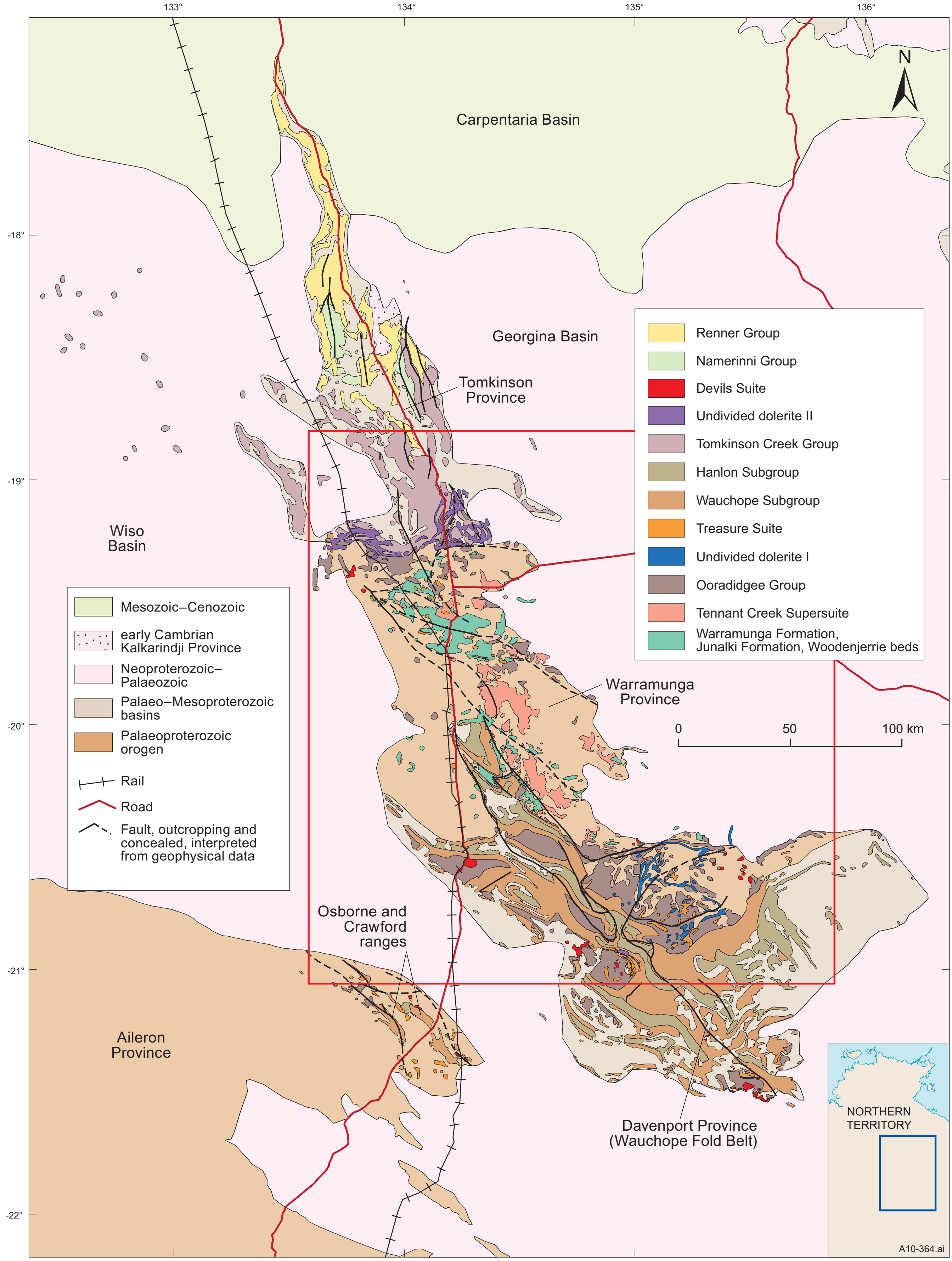


Figure 9.2. Geological map of Tennant Region, derived from GA 1:1M geology and NTGS 1:2.5M geological regions GIS datasets. Isolated inliers of Proterozoic rocks within Wiso Basin to the west of Tomkinson Province are correlated with Tomkinson Creek Group and upper Hatches Creek Group, and are described in **Other Palaeoproterozoic inliers**. Outliers in Osborne and Crawford ranges in east of Aileron Province are described in **Davenport Province**. Dolerite dykes that intrude Hayward Creek Formation in southern Tomkinson Province are very poorly exposed and their extent shown on the map is largely based on interpretation of airborne magnetic data. Although dolerite dykes intruding Ooradidgee Group in the Kurinelli goldfield are better exposed, their extent has been similarly slightly enhanced from geophysical data. Red box shows location of **Figure 9.3**.

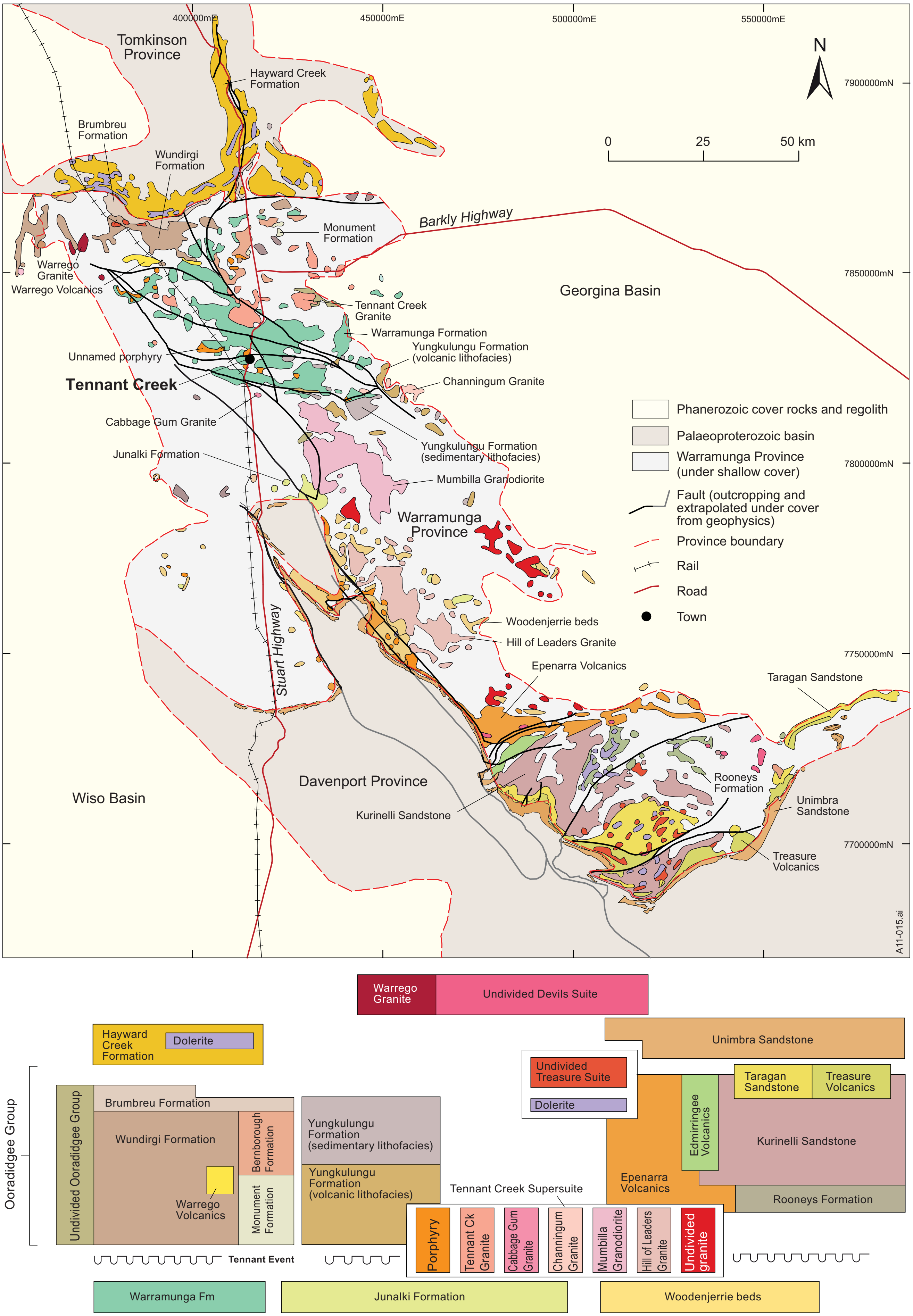


Figure 9.3. Generalised and simplified geological map of Warramunga Province (based on Donnellan *et al* 1998 and Blake *et al* 1988, and modified from Donnellan 2004). map also shows part of both the Hayward Creek Formation and Unimbra Sandstone where they form major upstanding ridges on the boundary between the Warramunga Province and the Tomkinson and Davenport provinces respectively. Faults shown on map are in part derived from interpretation of geophysical data (see Donnellan and Johnstone 2004).

associated copper-gold mineralisation in the Tennant Creek goldfield. These rocks are unconformably overlain by the volcanisedimentary Ooradidgee Group. The Ooradidgee Group was originally defined (Blake *et al* 1985) as a subgroup of the Hatches Creek Group in the Davenport Province. It was upgraded to group status for a number of reasons. In particular, it is a discrete package of rocks characterised by lateral facies variations around a number of volcanic centres. Furthermore, the Ooradidgee Group is overlain in the south by the Wauchope and Hanlon subgroups of the Hatches Creek Group in the Davenport Province, but in the north, it is overlain by the Tomkinson Creek Group in the Tomkinson Province. Although these two groups (ie Hatches Creek and Tomkinson Creek groups) are correlated with one another, there are differences in the details of their individual successions and their chronostratigraphic equivalence has yet to be demonstrated. The Ooradidgee Group also includes correlative rocks of the original Ooradidgee Subgroup that had been assigned to the Flynn Subgroup in TENNANT CREEK by Donnellan *et al* (1995). The name Flynn Subgroup has consequently been abandoned. There is only local minor outcrop of the Hatches Creek Group succession within the Warramunga Province. The Ooradidgee Group was folded together with the Hatches Creek Group during the Davenport Event. This event predates the ca 1710 Ma Devils Suite.

Geochronological data indicate that there were four episodes of felsic volcanism in the Warramunga Province. These span the time interval between Junalki Formation volcanism (ca 1860 Ma) and the end of Ooradidgee Group time (ca 1810 Ma, **Figure 9.4**). They are manifested in: (1) the volcanic rocks in the Woodenjerrie beds and the Junalki Formation (and also by the tuffaceous Warramunga Formation); (2) volcanism in the Yungkulungu, Monument, Bernborough and Wundirgi formations, together with the Warrego Volcanics; (3) the Epenarra Volcanics; and (4) the Treasure Volcanics. Three episodes of predominantly felsic (extrusive and intrusive) magmatism were previously recognised in the Warramunga Province by Wyborn *et al* (1998). The earliest of these is the ca 1850–1840 Ma Tennant Creek Supersuite that includes granite, together with some volcanic rocks of the second and third episodes outlined above. The ca 1820 Ma Treasure Suite mainly comprises volcanic rocks, and includes the Treasure Volcanics together with granophyre and porphyry (as well as intrusive diorite, monzodiorite and dolerite; see below). The ca 1710 Ma Devils Suite includes the Warrego Granite and an unnamed lamprophyre. The latter has been dated at 1711 ± 2 Ma (Maidment *et al* 2006).

Hoatson *et al* (2007) assigned mafic magmatism in the Warramunga Province to three magmatic events. These are the ca 1850 Ma Mumbilla Event, the 1840–1820 Ma Edmirringee Event and the 1820–1800 Ma Mount Hay Event. The first of these comprises locally outcropping dolerite dykes intruding Tennant Creek Supersuite granites. The second is named after the Edmirringee Volcanics, which are localised around four volcanic centres in the Tennant Region (Blake *et al* 1987), including one around Edmirringee Rockhole. The Mount Hay Event includes gabbro and dolerite sills that intrude the Ooradidgee Group in the Kurinelli area of the southern Warramunga Province. Dolerite from the Kurinelli goldfield has an igneous crystallisation age of 1811 ± 5 Ma (Maidment *et al* 2006). It also includes poorly outcropping mafic rocks in the upper Ooradidgee Group in the north of TENNANT CREEK, which are interpreted from airborne magnetic data to be widespread and stratiform, and which are also well represented in the overlying Hayward Creek Formation (below the Whittington Range Member) of the Tomkinson Province. A monzodioritic marginal phase of dolerite intruding the Ooradidgee Group in northwestern TENNANT CREEK has an igneous crystallisation age of 1821 ± 8 Ma (Compston 1994). The regionally widespread Kudinga Basalt in the Davenport Province and the correlative Whittington Range Volcanics in the Tomkinson Province are also currently assigned to this event. A pre-Mumbilla mafic magmatic event was also inferred by Donnellan (1994), on the basis of a probable mafic detrital contribution, to argillaceous banded ironstone ('haematite shale') in the Warramunga Formation.

The ca 1850 Ma Tennant Event included felsic intrusive and extrusive magmatism and east- or east-northeast-trending F_1 folding in the Warramunga and Junalki formations, and in the Woodenjerrie beds. Where exposed, F_1 folding in the Junalki Formation and Woodenjerrie beds now generally trends either east–west or north–south, due to refolding about northeast-oriented axes. The Tennant Event resulted in an erosional angular unconformity between the Warramunga Formation, Junalki Formation and Woodenjerrie beds, on the one hand, and Ooradidgee Group rocks on the other. Minor mafic magmatism at this time, ca 1850 Ma, was assigned to the Mumbilla Event by Hoatson *et al* (2007). The ca 1820–1800 Ma Murchison Event is interpreted to be largely extensional in the Tennant Region. It is associated with mafic magmatism of the Mount Hay Event, which resulted in dolerite, gabbro and minor monzodioritic sills that intrude the Ooradidgee and Tomkinson Creek groups, and is probably also associated with flood basalts of the Kudinga Basalt and Whittington Range Member. The Murchison Event is broadly contemporaneous with the ca 1800 Ma Stafford Event in the Aileron Province of the Arunta Region. The latter is associated with bimodal magmatism and folding in the Lander Rock Formation and Bullion Schist in the Aileron Province. The Davenport Event resulted in the folding of Ooradidgee, Hatches Creek and Tomkinson Creek group rocks and probably also resulted in the overprinting deformations in the Warramunga Formation. It is tentatively correlated with the ca 1730–1690 Ma Strangways Orogeny in the Arunta Region, and may therefore be broadly contemporaneous with Devils Suite intrusive and predominantly felsic magmatism. However, available geochronological constraints do not preclude the Davenport Event being older (ca 1800–1790 Ma).

The Warramunga Formation and the Ooradidgee Group are time correlatives of the Finnis River Group and Edith River and El Sherana groups, respectively, of the **Pine Creek Orogen**. Correlatives of the Ooradidgee Group are also recognised in the **Aileron Province** of the Arunta Region and in the **Tanami Region**, for example the Bullion Schist and Lander Rock Formation, and the Dead Bullock and Killi Killi formations, respectively.

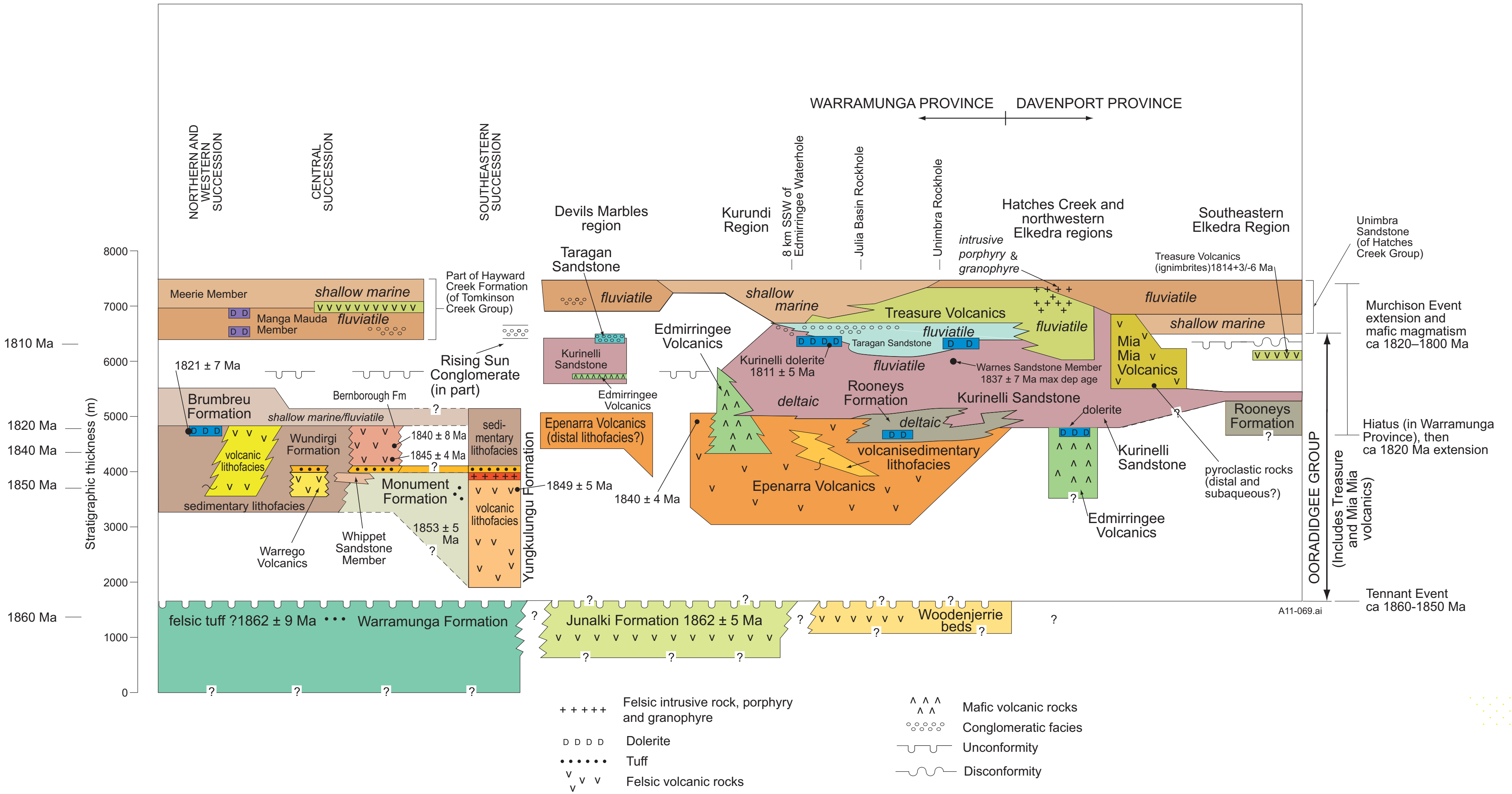


Figure 9.4. Interpretative rock-relationship diagram for Ooradidgee Group, featuring the four successions described in the text. This diagram is consistent with relationships between individual stratigraphic units that were described from original mapping (eg Blake *et al* 1987, Donnellan *et al* 1999). Approximate thicknesses of individual units are shown to scale on vertical axis of diagram. Time is also shown on vertical axis; scale for time is variable and various time horizons (ca 1860 Ma, 1850 Ma, 1840 Ma, 1820 Ma and 1810 Ma) are indicated. This stratigraphic interpretation suggests there were three main felsic volcanic episodes: the oldest, at ca 1850 Ma, is represented by Monument and Yungkulungu formations; the second, at ca 1840 Ma, by Epenarra Volcanics and Bernborough Formation; and the third, at ca 1814 Ma, by Treasure Volcanics. A prior episode of felsic volcanism at ca 1860 Ma is represented by volcanic intervals in Junalki Formation and Woodenjerrie beds, together with tuffaceous Warramunga Formation. A subsequent episode is represented by Newlands, Arabulja and Strzelecki volcanics of Hatches Creek Group. However, igneous crystallisation ages for Arabulja and Strzelecki volcanics (1814 ± 3 Ma and 1805 +6/-3 Ma, respectively) are within error of that of Treasure Volcanics (1813 +3/-6 Ma). This suggest that Unimbra and Gwynnie sandstones of Hatches Creek Group, although possibly diachronous over a period of a few million years, were rapidly deposited. Mafic magmatism is well represented by intrusive sills, particularly in Kurinelli, Last Hope and Short Range areas at northwestern and southeastern extremities of outcropping Warramunga Province. These mafic rocks are interpreted to be associated with extension in the ca 1820–1800 Ma Murchison Event. The mafic Edmirringee Volcanics are, at least in part, contemporaneous with ca 1840 Ma felsic magmatism.

PALAEOPROTEROZOIC

Pre-1850–1845 Ma Tennant Event stratigraphic succession

Warramunga Formation, Junalki Formation and Woodenjerrie beds

Blake *et al* (1987) recognised that the Epenarra Volcanics of the Ooradidgee Group overlie an erosional relief on folded Woodenjerrie beds in the Murchison Ranges. Smith *et al* (1961) had previously recognised this unconformity, but Mendum and Tonkin (1976) had interpreted the unconformity as a detachment surface accommodating different styles of folding in the successions above and below. However, the field relationships reported by Blake *et al* (1987) confirmed that this is a genuine major tectonic/erosional unconformity. An ignimbrite (now mapped as part of the Yungkulungu Formation of the Ooradidgee Group) similarly overlies an erosional surface on folded Warramunga Formation to the southeast of Nobles Nob mine (Blake 1984). This early episode of folding, and contemporaneous magmatism of the Tennant Creek Supersuite, is now called the *Tennant Event* (Donnellan and Johnstone 2004). In the Warramunga Province, pre-Tennant Event successions (**Table 9.1**) are those which are interpreted to have been deformed by this event.

The age of the Tennant Event can be constrained to the time interval ca 1860–1850 Ma by the following:

Unit	Thickness (m)	Lithology	Stratigraphic relationships	Depositional environment	Age	Age constraints
Junalki Fm	ca 1600	Lithic/volcaniclastic sandstone with interbedded siltstone and mudstone; rhyodacitic lava, ignimbrite, crystal-lithic tuff and lapilli tuff; chert; jaspillite; argillaceous banded ironstone; minor dacite and andesite.	Unconformably overlain by Unimbra Sandstone. Interpreted to be laterally equivalent to Warramunga Fm and probably also Woodenjerrie beds.	Shallow marine, grading upwards to sublittoral/ littoral and possibly fluviatile.	**1862 ± 5 Ma** (Smith 2000) for dacitic flow-banded porphyritic lava.	Intruded by 1847 ± 8 Ma Cabbage Gum Granite.
Warramunga Fm	ca 3000	Tuffaceous/volcanilithic sandstone/wacke ('metagreywacke') and siltstone; banded argillaceous ironstone ('haematite shale'); shale; slate; minor schist.	Base not exposed. Unconformably overlain by, and also faulted against, Yungkulungu Fm. Intruded by felsic porphyry, Tennant Creek Granite and unnamed lamprophyre.	Turbiditic. Proximal and distal fan facies that are equated to middle fan to outer fan/basin plain depositional environments. Woodenjerrie beds and Junalki Fm could represent more proximal facies equivalents of Warramunga Fm.	1862 ± 9 Ma for probable tuff from Gecko mine. 1859 ± 13 Ma and 1861 ± 7 Ma (max dep ages) for greywacke from Eldorado and White Devil mines, respectively. Greywacke from White Devil mine and Explorer 28 prospect have yieded *ca 1860 Ma* max dep ages.	Probable distal correlative of **1862 ± 5 Ma** Junalki Fm (Smith 2000). Predates ca 1850–1845 Ma Tennant Event. 1853 ± 8 Ma and *1847 ± 3 Ma* White Devil porphyry postdates foliation in Warramunga Fm that is related to this event, and also postdates Warramumga Fm-hosted ironstone bodies. Intruded and metamorphosed by 1858 ± 12 Ma Tennant Creek Granite (south). Unconformably overlain by **1849 ± 5 Ma** Yungkulungu Fm (Smith 2000).
unnamed sandstone lithofacies		Tuffaceous/volcanilithic sandstone/wacke ('metagreywacke'); siltstone (including banded argillaceous ironstone, ie 'haematite shale'), shale and slate.	Interpreted to conformably overlie unnamed siltstone lithofacies in coarsening-upward succession.	Proximal turbiditic sediment; probable middle fan deposit.		
unnamed siltstone lithofacies		Tuffaceous/volcanilithic sandstone/wacke ('metagreywacke') subequal or subordinate to siltstone (including banded argillaceous ironstone, ie 'haematite shale'), shale and slate.	Base not exposed. Unconformably overlain by, and also faulted against Yungkulungu Fm.	Distal turbiditic sediment; probable outer fan/basin plain deposit.		
Woodenjerrie beds		Greywacke and lithic sandstone, siltstone, shale; subordinate but locally dominant felsic volcanic rocks (ie volcanic lithofacies); chert; jaspillite, argillaceous banded ironstone.	Base not exposed. Unconformably overlain by Epenarra Volcanics and Unimbra Sandstone.	Moderately deep water and, at least in part, turbiditic sedimentary rocks; presumably subaqueous volcanic rocks.	Probable porphyritic dacitic lava in vicinity of BIF Hill has yielded ambiguous age of either **1864 ± 4** or **1854 ± 4 Ma** (Smith 1999, 2000).	Predates ca 1850–1845 Ma Tennant Event; may be either contemporaneous with Warramunga Fm and **1862 ± 5 Ma** Junalki Fm (Smith 2000), or slightly postdates them.

Table 9.1. Summary of Palaeoproterozoic pre-Ooradidgee Group stratigraphic succession of Warramunga Province. Ages reported in ordinary type are from Compston (1995); those in italic type are from Maidment *et al* (2006); those in bold type are from Smith (1999 and/ or 2000, as indicated). Abbreviations: Fm = Formation; max dep age – maximum depositional age.

(a) Foliation in the Warramunga Formation is cross-cut by porphyry at the White Devil mine (Nguyen 1987). Compston (1995) determined the crystallisation age of the porphyry at White Devil as 1853 ± 8 Ma and this is corroborated within error by Maidment *et al* (2006), who reported a crystallisation age for this porphyry of 1847 ± 3 Ma.
(b) The syntectonic Tennant Creek Granite, which intrudes the Warramunga Formation, has been dated at 1850 ± 4 Ma (Maidment *et al* 2006).
(c) A maximum age of sedimentation for the Warramunga Formation has been determined to be ca 1860 Ma (Compston 1995, Maidment *et al* 2006).

The Woodenjerrie beds are overlain with an angular unconformity by the 1840 ± 4 Ma Epenarra Volcanics of the Ooradidgee Group (and also by the basal unit of the Hatches Creek Group, the Unimbra Sandstone) in the Murchison Ranges. Regional tectono-stratigraphic considerations also indicate that the Woodenjerrie beds were deformed during the Tennant Event, rather than an equivalent of the ca 1830 Ma Tanami Event, which affected the Tanami Region (Crispe *et al* 2007). Polydeformation and associated cleavage development in Junalki Formation rocks suggest that this (ca 1862 Ma) unit was also deformed during the Tennant Event.

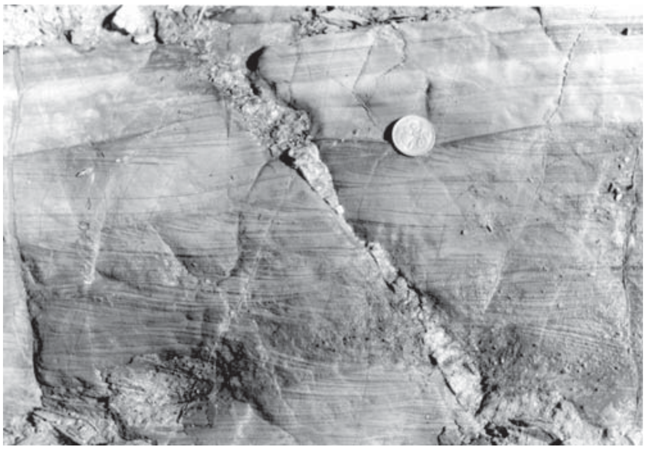


Figure 9.5. Cross-laminated climbing ripples in Bouma C division, Warramunga Formation. Coin is 1.9 cm in diameter. Location 53K 429200mE 7819000mN (after Donnellan *et al* 1995: plate 2).

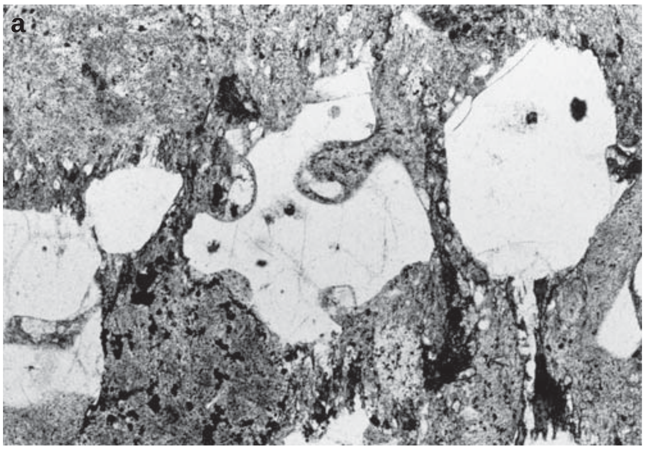
Figure 9.6. Argillaceous banded ironstone, known locally as ‘haematite shale’, photographed in drill core from Mary Lane [photograph KJ Hussey (formerly NTGS)].

Warramunga Formation

The Warramunga Formation is a polydeformed succession of sandstone and wacke, siltstone, terrigenous mudstone and argillaceous banded ironstone. It is probably predominantly tuffaceous, in that it has a substantial component of pyroclastic detritus, but with an admixed component of plutonic igneous and metamorphic detritus. These rocks could be described as turbiditic (ie reworked), very fine- to coarse-grained tuff or tuffaceous sandstone and siltstone (see Mueller and White 2004). Outcrop of the Warramunga Formation is confined to the Tennant Creek goldfield in the central and northern Warramunga Province. However, units hosting Tennant Creek-style mineralisation in the Rover area, 70 km southeast of Tennant Creek, may also belong to the Warramunga Formation or a correlative.

A variety of sedimentary structures is recognisable in the Warramunga Formation (eg normal grading, cross-bedding, climbing ripple lamination, sole marks and Bouma sequences) and this is consistent with turbiditic sedimentation (**Figure 9.5**). The Warramunga Formation has been divided into two mappable lithological units, a sandstone-dominated lithofacies and a siltstone-dominated lithofacies, corresponding with more proximal and more distal facies of a classical, probable coarsening-upward, subaqueous fan. The sandstone lithofacies is generally medium to thickly bedded or massive, whereas the siltstone lithofacies is laminated or thinly to medium bedded. In the field, apparent bedding does not necessarily coincide with individual Bouma sequences, but rather with sandstone or siltstone intervals of that sequence and tends to give a false impression of an alternating succession of sandstone and siltstone beds. Argillaceous banded ironstone is locally called 'haematite shale' and comprises alternating laminae or thin beds of fine-grained, graded siliciclastic and iron-rich detritus (**Figure 9.6**). Haematite shale was interpreted by Donnellan *et al* (1995) as fine-grained turbidite material and may represent overbank deposits in a proximal fan. Thinly interbedded jasperoidal and magnetite/haematite rocks also occur and have been interpreted as silicified haematite shale, although this remains contentious.

Petrographic and geochemical data are consistent with a predominantly dacitic to rhyolitic provenance for the Warramunga Formation (**Figure 9.7a**, **b**), together with a component derived from metamorphic and intrusive igneous sources. It has previously been postulated that the volcanic rocks of the Bernborough Formation were a potential source of detritus for the Warramunga Formation, but current stratigraphic and geochronological considerations preclude this, since the Bernborough Formation is a part of the younger Ooradidgee Group. It is plausible that the Warramunga Formation could in part be sourced from contemporaneous volcanic and volcaniclastic material represented in the Junalki Formation and Woodenjerrie beds. However, Mendum and Tonkin (1976) determined, from current direction indicators, that the Warramunga Formation was derived from the east and there are currently no known outcrops of the Junalki Formation and Woodenjerrie beds in this direction. Comparable ages for detrital zircon populations in greywacke from the White Devil (1861 ± 7 Ma) and Eldorado (1859 ± 13 Ma) mines, and from altered felsic tuff from Gecko mine



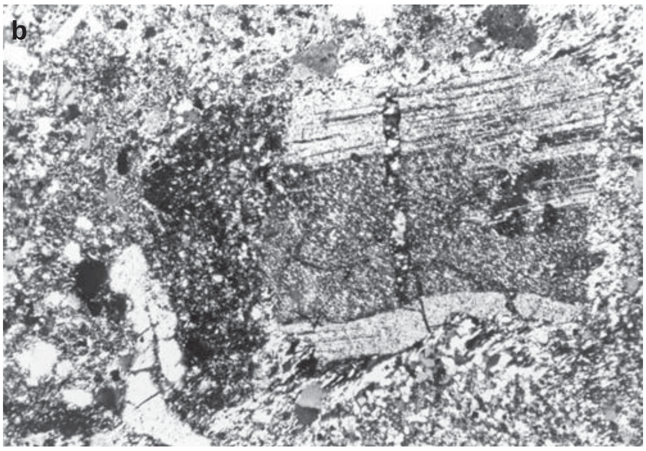


Figure 9.7. Photomicrographs of Warramunga Formation turbiditic sandstone from drillhole DDH14, 'Anomaly 2, Aeromagnetic Ridge' (after Donnellan *et al* 1995: plate 3A, C). Crossed-polarised light; length of each field of view is 2.5 mm. (**a**) Tuffaceous sandstone showing embayed and euhedral volcanic quartz grains, and ghost volcanilithic grains. (**b**) Partially sericitised, equigranular euhedral plagioclase grain and ghost lithic fragments in lithic sandstone.

(1862 ± 9 Ma) led Compston (1995) to conclude that the Warramunga Formation was rapidly derived from a penecontemporaneous volcanic source. These age determinations have been complemented and corroborated by detrital zircon geochronology on an additional sample from White Devil mine and a sample from the Explorer 28 prospect (ca 1860 Ma max; Maidment *et al* 2006). However, Compston (1995) recognised a second population of more rounded and heavily abraded zircons, indicating a mixed provenance for the formation. This second population of zircons includes grains with ages between 3 and 2 Ga, and ca 1.93–1.91 Ga, and again, this has been confirmed by the more recent age determinations reported by Maidment *et al* (2006). Compston (1995) stated that source rocks with these ages have not been identified in outcrop. Donnellan (1994) suggested that εNd values for Warramunga Formation rocks are consistent with an admixed component from an older crustal source. REE data for haematite shale indicate that some of these rocks have chondrite-normalised patterns comparable with those of Archaean mudstones (**Figure 9.8a**). Taylor and McLennan (1985) interpreted the REE pattern of Archaean mudstone to reflect a significant contribution from mafic rocks (to the Archaean upper crust). The data for the haematite shales suggest that some mafic material similarly contributed to the provenance of the Warramunga Formation, although this contribution is probably relatively minor and is effectively diluted in the majority of Warramunga Formation sedimentary rocks that consequently show REE patterns indistinguishable from those of PAAS (post-Archaean average Australian Shale; Nance and Taylor 1976, McLennan 1989, **Figure 9.8b**, **c**).

The thickness of the Warramunga Formation is not known. Donnellan *et al* (1995) give an estimate of about 3 km. Finlayson (1981) interpreted from seismic data that the former Warramunga Group was about 2.6 km thick in the east of the Tennant Creek goldfield near Nobles Nob mine, and about 1.2 km in the west near Warrego mine; however, these thicknesses do not take account of folding. Rattenbury (1992a) correlated sections in the southeast of the goldfield, using two intervals of stratiform porphyry and three of haematite shale, and derived a thickness for the Warramunga Formation in excess of 4 km.

The base of the Warramunga Formation is not exposed, nor has it been intersected in drill core. Consequently, it is not known what the formation overlies. Based on the analogy that the Warramunga Province is a Palaeoproterozoic greenstone terrane, the formation might overlie a more volcanic-dominated succession that has a significant mafic volcanic component. This may be of relevance in the context of a possible intrabasinal source for ironstone that is associated with the gold mineralisation, and also for widespread magnesian-rich chlorite alteration in rocks surrounding the ironstone bodies.

The Warramunga Formation hosts over 700 ironstone bodies that range in size from a few tonnes to over 15 million tonnes (Le Messurier *et al* 1990). Less than 20% (approximately 130) of these known ironstone occurrences have recorded gold production and the majority of gold production in the field has come from just thirteen mines (see **Table 9.6**). Discrete magnetic anomalies are a significant feature of the classical Warramunga Formation stratigraphic succession and Le Messurier *et al* (1990) recognised a distinct iron-rich facies in the former Warramunga Group that they called the *Black Eye Member*.

The unconformable relationship between the Warramunga Formation and Ooradidgee Group rocks is locally exposed immediately to the south of the Gosse River road just to the east of the Nobles Nob mine. At this locality, Blake (1984) recognised that quartz-feldspar porphyry has a fragmental and eutaxitic texture, and is an extrusive ignimbrite that grades upwards into tuff. This, in turn, is overlain by conglomerate and cross-bedded sandstone. Blake identified an erosional unconformity between the Warramunga Formation and the overlying ignimbrite which, together with the tuff and conglomerate, he correlated with the Epenarra Volcanics of the Ooradidgee Group. The apparently conformably overlying sandstone was correlated with the Unimbra Sandstone of the Wauchope Subgroup of the Hatches Creek Group. Looking east towards the Gosse River, an angular discordance is evident between Warramunga Formation and Ooradidgee Group rocks. This was originally recognised by Owen (1940), but apparently subsequently disregarded.

Junalki Formation

The Junalki Formation in southern TENNANT CREEK, northeastern BONNEY WELL and northwestern FREW RIVER comprises tuffaceous/volcaniclastic sandstone interbedded with thinly bedded siltstone that commonly shows festoon cross-bedding. It includes thick mass flow deposits. The lower lithofacies of the Junalki Formation consists of rhyodacitic to rhyolitic crystal-lithic tuff, with interbedded tuffaceous volcanic and volcaniclastic rocks, including andesitic to dacitic ignimbrite and lava. This lithofacies has been intersected in drill core and outcrops in BONNEY WELL.

Volcanilithic sandstone and siltstone predominate up-section, although minor andesitic to dacitic lava occurs near the top of the formation. Junalki Formation volcanic rocks are a potential source for, and are considered to be a more proximal equivalent of the Warramunga Formation. These volcanic rocks also impart the distinctive highly magnetic character to the Junalki Formation.

Volcanic rocks of the Junalki Formation are probably mainly subaerial, and associated interbedded sandstone and siltstone are interpreted as marginal marine. The ca 1600 m-thick succession is interpreted to have resulted from progressively shallower-water sedimentation, with environments of deposition varying from shallow marine, to sublittoral/littoral to possibly fluviatile upwards. This contrasts with the deeper-water turbiditic environments represented in both the Woodenjerrie beds and the Warramunga Formation. These two formations are interpreted to be lateral equivalents of the Junalki Formation.

Haematite shale is locally well exposed and shows well developed, parasitic mesoscale F_1 folds (eg at 53K 474613mE 7763167mN, where folds trend and plunge to the northeast). In addition to S_1, there are two weakly developed overprinting crenulation cleavages in the rocks in this area.

A flow-banded, porphyritic dacitic lava from the Junalki Formation in BONNEY WELL has an igneous crystallisation age of 1862 ± 5 Ma (Smith 2000).

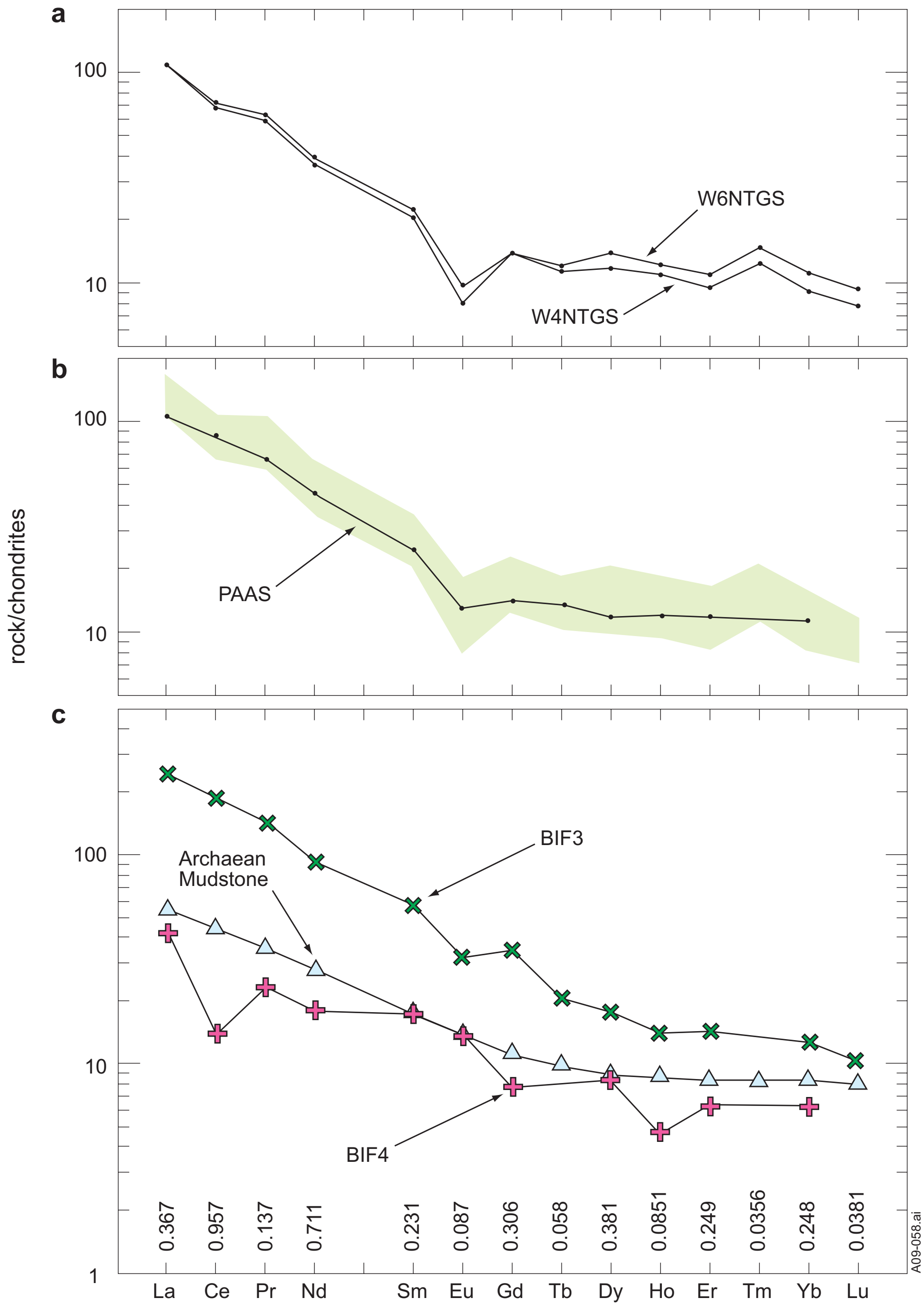


Figure 9.8. Chondrite-normalised REE patterns for Warramunga Formation sedimentary rocks (after Donnellan *et al* 1995: figure 4), including argillaceous banded ironstone ('haematite shale', labelled BIF). (**a**) Two grain-size fractions from single turbidite unit at Burnt Shirt mine. (**b**) Field for 17 Warramunga Formation sedimentary rocks. Note close similarity between Warramunga Formation rocks and post-Archeaen Australian sediment, PAAS (Nance and Taylor 1976, McLennan 1989). (**c**) Two extremes of four samples of Warramunga Formation haematite shale analyses. Note that BIF4 is comparable to 'Archaean Mudstone' of Taylor and McLennan (1985: 181) and BIF3 approximates to PAAS. Chondrite normalising values (in ppm) are from Taylor and McLennan (1985).

The Junalki Formation is intruded by the Cabbage Gum and Hill of Leaders granites, and by the Mumbilla Granodiorite. It is unconformably overlain by the Unimbra Sandstone at the northern end of the Murchison Syncline in TENNANT CREEK.

Woodenjerrie beds

The informal name Woodenjerrie beds is used here for rocks previously mapped as undifferentiated Warramunga Group immediately to the north of the Davenport Province, and excludes rocks now assigned to the Junalki Formation on the basis of their contrasting magnetic character.

The Woodenjerrie beds include interbedded, graded volcaniclastic (tuffaceous greywacke, siltstone and shale) and contemporaneous felsic volcanic rocks. The Woodenjerrie sedimentary rocks are, like the Warramunga Formation, interpreted to be turbiditic, and Blake *et al* (1987) inferred that the contemporaneous intercalated volcanics are probably subaqueous. Chert, jaspilite and thinly bedded banded ironstone (similar to the haematite shale of the Warramunga Formation) are also components of the Woodenjerrie beds. The thickness of the beds is unknown.

A marked angular, erosional unconformity between the Woodenjerrie beds and the overlying Epenarra Volcanics and Unimbra Sandstone is exposed on the flanks of the Murchison Syncline (**Figure 9.9**). In the vicinity of 53K 488984mE 7734740mN, lava at the base of the Epenarra Volcanics dips at about 50° to the south, whereas bedding in the underlying Woodenjerrie beds can be seen to dip at about 70° to the north-northeast.

A volcanic rock of uncertain affinity but interpreted to be a porphyritic dacitic lava has been dated from the Woodenjerrie beds in the vicinity of BIF Hill and has yielded an ambiguous age with either 1864 ± 4 or 1854 ± 4 Ma being equally plausible. The older age (1864 Ma) would suggest that these rocks are age equivalent to the Junalki Formation; the younger age would suggest that they are slightly younger than the Junalki Formation and may also be age equivalent to, or slightly younger than the similarly turbiditic Warramunga Formation.

The Woodenjerrie beds are informally named and have not been included in the Warramunga Formation so far, despite their obvious lithological similarities and probable age equivalence. The distinction is subtle, but is made on the basis of an apparent lack of discrete magnetic anomalies analogous to those associated with the ironstone bodies in the Warramunga Formation. The distinction is thus largely made on the basis of the potential economic implications of extending the Warramunga Formation to the south where analogous rocks are (to date) known to be only very sparingly mineralised (eg Kovacs prospect).

1850–1840 Ma Tennant Event intrusive rocks

Tennant Creek Supersuite

Intrusive magmatism associated with the Tennant Event was assigned to the Tennant Creek Supersuite (**Table 9.2**) by Wyborn *et al* (1998). These intrusive rocks are predominantly granitic (including granite, granodiorite and tonalite), but also include felsic porphyry and dolerite. Also included in the Tennant Creek Supersuite are extrusive felsic volcanic rocks of the Bernborough Formation, Epenarra Volcanics, Junalki Formation and Woodenjerrie beds. Volcanic rocks of the Yungkulungu Formation should also be included in the supersuite. Granitic rocks of the Tennant Creek Supersuite are confined in outcrop to the Warramunga Province and include the syntectonic Tennant Creek Granite (1850 ± 4 Ma; Maidment *et al* 2006) and the immediately post-tectonic

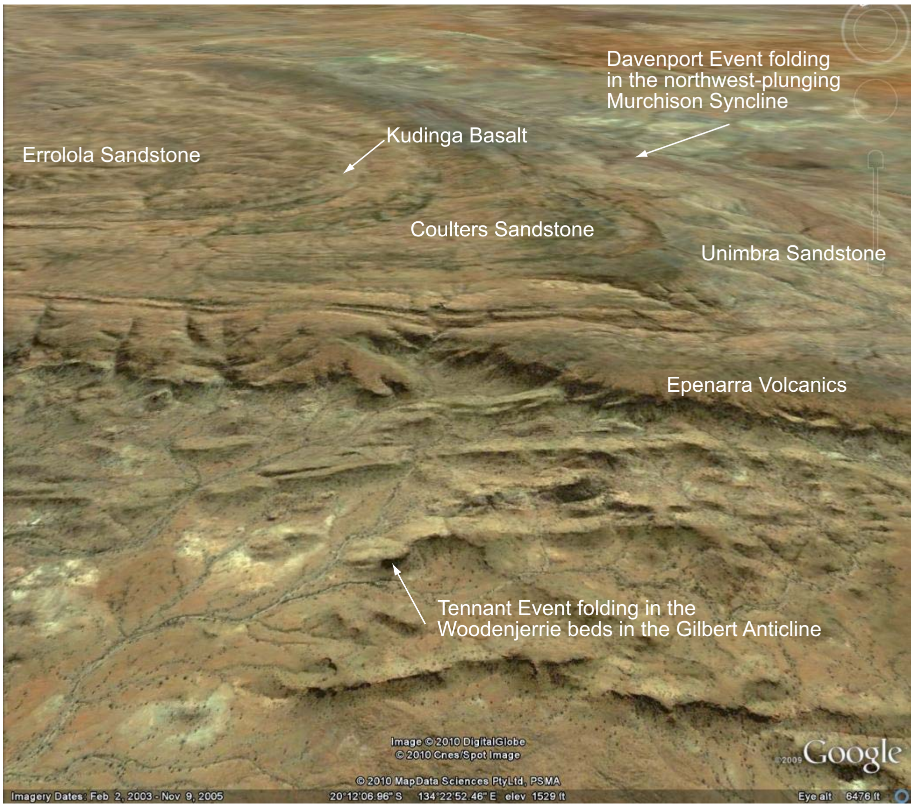
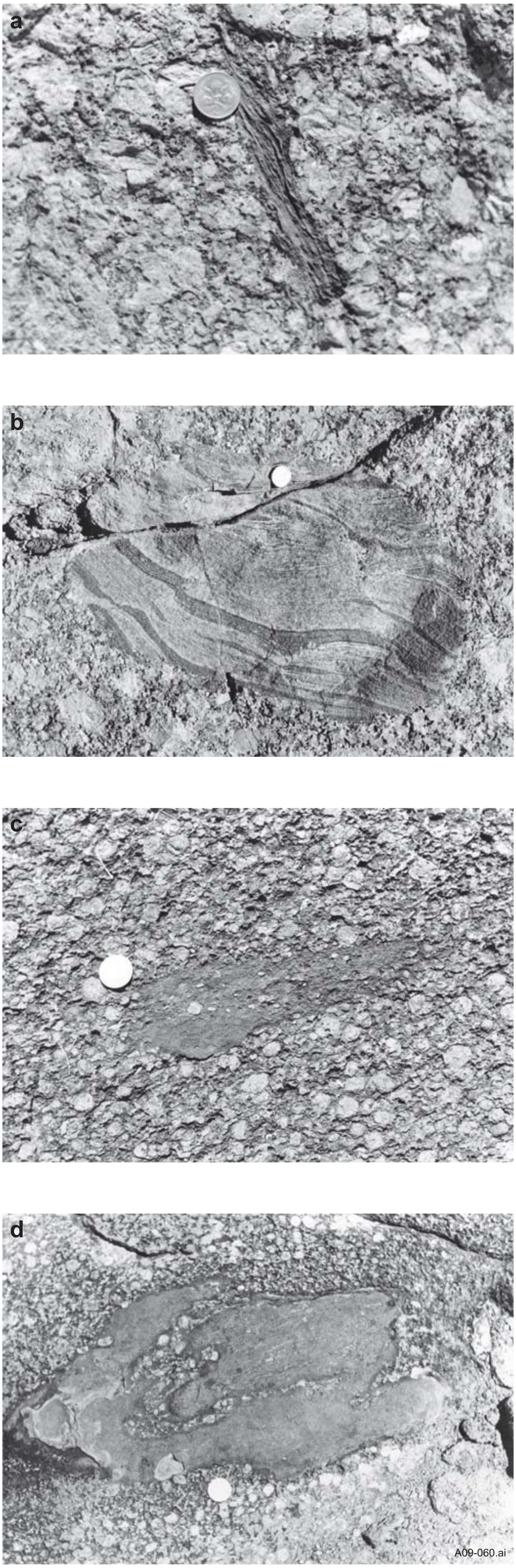


Figure 9.9. Google Earth image looking northwards from approximately 20°12'S 134°22'E at ca 460 m elevation, showing unconformity between Woodenjerrie beds (which are correlated with Warramunga and Junalki formations) and Ooradidgee Group, in nose of Murchison Syncline in Murchison Ranges (DEVILS MARBLES REGION). Woodenjerrie beds are exposed in foreground in Gilbert Anticline. They are overlain, following an angular erosional unconformity, by Epenarra Volcanics of Ooradidgee Group. Unimbra Sandstone of Hatches Creek Group overlies Epenarra Volcanics and to northwest (left of image), it steps across Epenarra Volcanics to directly overlie Woodenjerrie beds.

Unit	Rock types	Relationships	Structures	Igneous crystallisation age
TENNANT CREEK SUPERSUITE				
unnamed dolerite I	Intrudes Hill of Leaders Granite, and also occurs as autoliths/xenoliths in Tennant Creek Granite and Mumbilla Granodiorite (includes minor gabbroic cumulate-rich enclaves).	Contemporaneous with Tennant Creek Supersuite magmatism.		1858 ± 9 Ma, dolerite dyke intruding the 1850 ± 4 Ma *and* 1849 ± 7 Ma Tennant Creek Granite at Red Bluff *(north and west respectively).*
unnamed (older) granite	Foliated grainite with blue opalescent quartz in Short Range; in Kurundi Region, Hatches Creek Region and Devils Marbles Region, unnamed granite is an equigranular to sparcely feldspar-phyric, medium- to coarse-grained biotite luecogranite. Granite variously contains orthoclase, microcline, oligoclase, biotite (often chloritised), secondary muscovite and accessory iron oxides, apatite, zircon, tourmaline and titanite.	In Short Range, forms one isolated outcrop with unknown relationships. This was originally assigned to Warrego Granite by Mendum and Tonkin (1976), but is compositionally different from Devils Suite granites, so is now tentatively assigned to Tennant Creek Supersuite. In Kurundi Region and Hatches Creek Region, unnamed granite assigned to Tennant Creek Supersuite intrudes Junalki Formation and Woodenjerrie beds, and is locally intruded by dolerite and overlain by Epenarra Volcanics.	Unnamed granite in Devils Marbles Region that is probably related to Hill of Leaders Granite has strained quartz.	
unnamed felsic porphyry	Hiatal porphyritic with alkali feldspar and blue ovoid quartz phenocrysts in an aphanitic felsite groundmass.	Mostly intrudes Warramunga Formation, although there may be more than one generation and porphyry may locally intrude Ooradidgee Group. Porphyry intruding Woodenjerrie beds postdates first phase of folding (Tennant Event), and either predates or is comagmatic with ***1840 ± 4 Ma*** Epenarra Volcanics. Locally overlain by Epenarra Volcanics. Commonly forms sills that are concordant with, and/or sheared parallel to regional structure, including folds; locally discordant and forms irregular bodies or a discrete phase of Tennant Creek Supersuite granites. Some concordant porphyries have peperitic margins (eg Smelter porphyry) (McPhie 1993). Cleavage development variably related to Tennant and/or Davenport events.	Larger intrusions are generally massive with foliated margins. Smaller bodies (sills) are weakly to strongly foliated, typically parallel to regional foliation. Locally, cross-cuts early (Tennant Event) foliation (eg at White Devil mine) and includes enclaves of foliated country rock (eg Smelter porphyry). Locally schistose.	1853 ± 8 Ma, *1847 ± 3 Ma* (White Devil porphyry, postdates deformation and ironstone-formation), 1838 ± 9 Ma (Jubilee porphyry), 1829 ± 8 Ma (quartzofeldspathic schist, ie sheared porphyry or granite), *1849 ± 3 Ma* (Quarry porphyry), *1847.5 ± 2.5 Ma* (Smelter Porphyry) and *1846 ± 3 Ma* (Airport Porphyry)
Channingum Granite	Medium- to coarse-grained, equigranular to seriate porphyritic granite (syeno- to monzogranite); minor rapakivi texture; hiatal-textured porphyry forms marginal phase to granite; rare felsic porphyry autoliths and late-stage magmatic aplite dykes.	Intrudes Ooradidgee Group with narrow contact zone of quartz-muscovite schist.	Locally mylonitised adjacent to major fault zones, otherwise weakly foliated or massive.	1840 ± 9 Ma
Cabbage Gum Granite	Medium- to coarse-grained, seriate porphyritic to equigranular granite (restricted compositional range on the boundary of the syeno- / monzogranite fields). Textural variation interpreted to reflect relative intensity of foliation locally (eg gneissic granite, augen gneiss)	No contacts exposed; in drill core, granite intrudes Junalki Formation and is also intruded by dolerite dykes.	Generally moderately to strongly foliated with localised northeast- and northwest-trending mylonite zones.	1848 ± 7 Ma
Mumbilla Granodiorite	Megacrystic seriate porphyritic to coarse-grained equigranular biotite-bearing to biotite granodiorite with large zoned alkali-feldspar phenocrysts, and blue opalescent quartz. Minor granite and tonalite.	Passively intrudes Yungkulungu Formation (volcanic and sedimentary lithofacies); intrudes and also has a faulted contact with Yungkulungu Formation. Intruded by dolerite/gabbro; late-stage aplite and quartz diorite dykes, and an 1841 ± 6 Ma, 20 m-diameter amphibole-rich quartz diorite plug.	Non-foliated in south; east- and northwest-trending foliations increasingly developed to the north and west.	1850 ± 6 Ma
Hill of Leaders Granite	Porphyritic and minor equigranular two-mica and biotite granite; minor aplite and greisen.	Intrudes Junalki Formation and Woodenjerrie beds. Intruded by dolerite and lamprophyre.	Weakly foliated.	*1846 ± 3 Ma*
Tennant Creek Granite	Medium-grained, equigranular to seriate porphyritic biotite to biotite-bearing granite (syeno- to monzogranite); minor rapakivi texture; ovoid autoliths of porphyritic granodiorite, quartz monzonite and quartz diorite.	Intrudes Warramunga Formation and undivided Ooradidgee Group. Spotted hornfels (with quartz and chlorite porphyroblast) at contact with Warramunga Formation; intruded by dolerite dykes, and minor aplite dykes and veins.	East-trending 10–20 m-wide zones of mylonitisation or strong foliation with stretched quartz. Minor north-trending shear zones.	1848 ± 7 Ma (north), 1858 ± 12 Ma (south), *1851 ± 4 Ma* (north), 1853 ± 10 Ma (at Red Bluff), 1849 ± 7 Ma (at Red Bluff west)

Table 9.2. Summary of Palaeoproterozoic Tennant Creek Supersuite intrusive rocks. Ages reported in ordinary type are from Compston (1995); those in italic type are from Maidment *et al* (in press); ages for White Devil and Quarry porphyries were previously reported in Maidment *et al* (2006). Unnamed felsic porphyry includes a number of porphyry intrusions that have informal names, eg White Devil porphyry. Note that three generations (designated I in this table and II and III in **Table 9.4**) of dolerite are recognised in Warramunga Province.



Hill of Leaders Granite (1846 ± 3 Ma; Maidment *et al* 2006). Also included in the supersuite are the Cabbage Gum (1848 ± 7 Ma; Compston 1995) and Channingum granites, and the Mumbilla Granodiorite (1850 ± 6 Ma; Compston 1995). The supersuite is thus syn- to post-tectonic with respect the Tennant Event. The Tennant Creek Granite provides a lower age constraint on folding associated with this event. An upper age constraint on this folding is given by the ca 1860 Ma maximum age of sedimentation of the Warramunga Formation (Maidment *et al* 2006).

In TENNANT CREEK, the geographic isolation of granite outcrops, together with minor petrographic variations, resulted in a large number of 'separate' granites being mapped in the First Edition 1:250 000 mapsheet (Mendum and Tonkin 1971). Recognition of the strikingly similar mineralogy, petrography and geochemistry of granitic rocks of the Tennant Creek Supersuite resulted in unnecessary subdivision being avoided during Second Edition mapping (Donnellan *et al* 1995, 1999). However, notwithstanding evidence for consanguinity, certain distinctions still need to be made. Thus, for example, small stocks or bosses intruding the Yungkulungu Formation in eastern TENNANT CREEK are sufficiently isolated to have been named separately as the Channingum Granite (Donnellan *et al* 1995). Conversely, despite lateral separation by 8 km of Warramunga Formation there is insufficient petrographic and geochemical distinction between the Tennant Creek Granite at Station Hill and the Tennant Creek Granite at Red Bluff for these intrusions to be defined independently.

The granites and grandioritic rocks of the Tennant Creek Supersuite were classified as I-granodiorite type by Wyborn *et al* (1998), who also identified that they are generally unfractionated. However, they have a macroscopic appearance that is in some respects more typical of A-type granites. In particular, they are red to light grey in colour, carry large alkali feldspar phenocrysts, have coarse-grained equigranular to seriate porphyritic as well as rapakivi textures, and mafic minerals are interstitial rather than prismatic (cf Anderson and Morrison 1992). The texture of the granites varies according to their degree of foliation, and the size and shape of alkali feldspar crystals. Xenoliths of country rock are only a minor component, indicating that stoping and assimilation were not significant modes of intrusion (**Figure 9.10a**, **b**).

Figure 9.10. (**a–d**) Xenoliths and enclaves in Tennant Creek Supersuite (after Donnellan *et al* 1995: plates 16, 18, 12, 15, respectively; photographs and descriptions by RS Morrison, formerly NTGS). (**a**) Typical elongate metasedimentary xenolith of probable Warramunga Formation derivation in Tennant Creek Granite at 53K 415500mE 7838000mN. Long axes of these xenoliths are commonly oriented parallel to weak foliation. Coin is 1.9 cm in diameter. (**b**) Rounded metapelitic xenolith of probable Warramunga Formation in Mumbilla Granodiorite at 53K 434000mE 7793000mN. Coin is 2 cm in diameter. (**c**) Attenuated felsic porphyritic enclave in Tennant Creek Granite at 53K 413300mE 7839200mN. Note ovoid quartz phenocrysts in enclave, diffuse enclave margins and rounded alkali feldspar phenocrysts in host granite. Enclave long axis is parallel to weak foliation. Enclave results from mobilisation and segregation of melt from crystal-rich granitic magma during deformation. Coin is 2.8 cm in diameter. (**d**) Irregular, lobate felsic porphyritic enclave in Tennant Creek Granite at 53K 413000mE 7839500mN. Note narrow diffuse margin and shared phenocrysts in both enclave and granite, indicating that both enclave and host granite coexisted as separate melts. Coin is 3.2 cm in diameter.

However, a characteristic feature of both the Tennant Creek Granite and the Mumbilla Granodiorite is an abundant and varied enclave population. These include felsic porphyry enclaves (**Figure 9.10c**, **d**), cognate, cumulate-rich granitic and gabbroic enclaves, late-stage lamprophyric and doleritic enclaves, and rare mafic microgranular enclaves.

The modal mineralogy of the Tennant Creek Supersuite granitoids ranges from granite (*sensu stricto*) to granodiorite (eg, Mumbilla Granodiorite) and minor tonalite (**Figure 9.11**). The *Tennant Creek*, *Channingum* and *Cabbage Gum granites* are two-feldspar, biotite- to biotite-bearing granites. They are composed predominantly of alkali feldspar (microcline and orthoclase); sodic plagioclase (oligoclase); quartz that is generally strained and frequently also ovoid, blue and opalescent; and red-brown biotite. Accessory minerals include magnetite, titanite, zircon, muscovite, ilmenite, apatite, pyrite, chalcopyrite, monazite, fluorite, and rare amphibole and iddingsite. Secondary alteration products include: (1) chlorite, epidote, sericite and muscovite, consequent on saussuritisation of feldspar; (2) chlorite, haematite, epidote and titanite, resulting from alteration of biotite; (3) rutile, derived from the decomposition of ilmenite; and (4) minor iddingsite, formed from olivine. Magnetite is occasionally intergrown with ilmenite and titanite, and minor sulfides occur as discrete grains or enclosed in Fe-Ti oxides. Both marginal, and sheared and fractured zones of the granites are typically leucocratic, albitised and tourmalinised, consequent on late-stage sodium and boron metasomatism. These leucocratic zones are characterised by micrographic intergrowths of quartz and feldspar.

The *Hill of Leaders Granite* outcrops extensively immediately to the east of the Murchison Ranges in the southern Warramunga Province and is a grey, alkali-feldspar megacrystic, medium- to coarse-grained biotite-, and biotite-muscovite granite. It contains blue opalescent quartz in common with the other felsic intrusive rocks of the Tennant Creek Supersuite. This blue quartz is interpreted to be probable granulite-derived restite. The Hill of Leaders Granite is apparently undeformed (at least macroscopically). It contains xenoliths of deformed metasedimentary rocks of the host Woodenjerrie beds and/or Junalki Formation (both of which are correlated with the Warramunga Formation). Thus, the 1846 ± 3 Ma igneous crystallisation age for this granite (Maidment *et al* 2006) provides a (further) lower age constraint on deformation associated with Tennant Event.

The *Mumbilla Granodiorite* is mainly a biotite-bearing, light-grey granodiorite (*sensu stricto*), but ranges from tonalite to granite in modal composition (**Figure 9.11**). It is characterised by a coarse-grained seriate porphyritic to equigranular texture. Alkali feldspar megacrysts range up to a maximum dimension of 10 cm and frequently have a preferred orientation, forming a probable submagmatic foliation. Plagioclase laths are of the order of 1 cm in length and show normal zoning from labradorite, or more typically andesine cores to oligoclase rims. Quartz is generally strained and typically ovoid at the northern and eastern margins of the pluton. Where the Mumbilla Granodiorite is of granitic (*sensu stricto*) composition it is essentially identical with the Tennant Creek Granite and is characterised by a seriate porphyritic texture, blue opalescent ovoid quartz and rounded, thinly mantled alkali feldspar (ie rapakivi *sensu stricto*, or wiborgitic texture). Mafic constituents in the Mumbilla Granodiorite are dominated by red-brown biotite books (enclosing euhedral magnetite octahedra), ilmenite, muscovite and iddingsite (relict olivine).

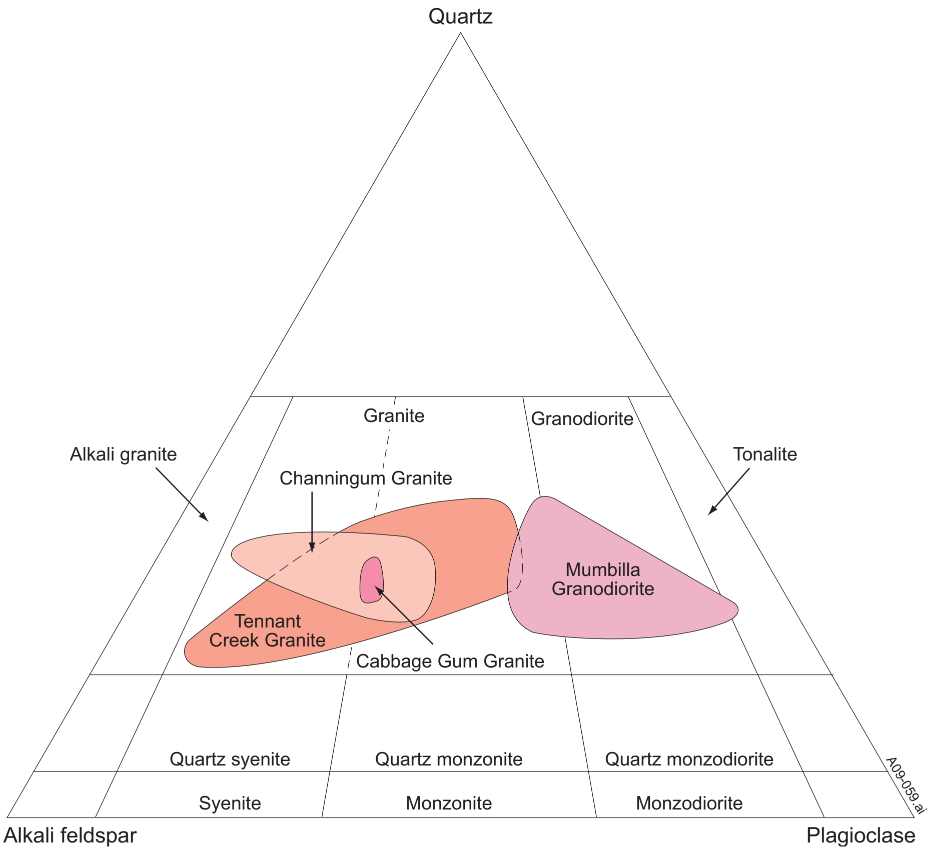


Figure 9.11. Modal classification diagram for selected Tennant Creek Supersuite granites [after Donnellan *et al* (1995) with minor modifications; modal determinations by RS Morrison (formerly NTGS)].

Unnamed *felsic porphyry* is hiatal porphyritic, and of granitic (rhyolitic) composition. In common with the granites the porphyry has weakly developed rapakivi texture, with pale green mantles of plagioclase on concentrically zoned, pink to white alkali-feldspar. It comprises rounded alkali feldspar, green plagioclase and commonly strained, ovoid and blue opalescent quartz in an aphanitic groundmass of quartz, feldspar and chlorite. Plagioclase phenocrysts have more calcic (andesine) cores and more sodic rims. The main mafic constituents are chlorite that, together with magnetite and titanite, probably replaced biotite. Rare primary red-brown biotite and green-amphibole were recognised very locally in porphyry proximal to the Tennant Creek Granite. Accessory minerals include zircon, rutile, apatite, monazite, titanite, magnetite (commonly titaniferous), and rare ilmenite and ilmenite-magnetite exsolutions; minor pyrite and chalcopyrite are also present. There is a marked cleavage or foliation development in more intensely altered porphyry, where quartz also becomes the dominant phenocrystic phase.

At the White Devil mine, felsic porphyry cross-cuts both a foliation in the Warramunga Formation (Nguyen 1987), and ironstone hosting Au-Cu-Bi mineralisation. Maidment *et al* (2006) reported a SHRIMP U-Pb zircon age of 1847 ± 3 Ma (within error of the 1853 ± 8 Ma igneous crystallisation age previously determined by Compston 1995) for this porphyry. This age (1) confirms that porphyry in the Tennant Region is, at least in part, contemporaneous with the Tennant Creek Supersuite; (2) provides a lower age constraint on deformation associated with the Tennant Event; (3) together with the maximum age of sedimentation of the Warramunga Formation, constrains the age of ironstone formation to the time interval ca 1860–1845 Ma; and (4) provides an upper age constraint on the ironstone-associated gold mineralisation.

Several authors have indicated probable folding of porphyry together with the Warramunga Formation on a regional scale (Le Messurier *et al* 1990, Rattenbury 1992a, McPhie 1993). Small intrusive bodies commonly have a flow/submagmatic? fabric that apparently parallels the regional west-oriented (S_1) cleavage in the host Warramunga Formation. Some of the larger bodies show similar flow/submagmatic? fabrics, and also northwest-oriented shears and kink folds. Geophysical interpretations suggest an en echelon arrangement of porphyry in superimposed folds that trend northwest within the Warramunga Formation. Donnellan *et al* (1995) also noted passive irregular intrusive contacts associated with less foliated porphyries, with subsequent localised shearing along such contacts resulting in 'clasts' of porphyry in the metasedimentary rocks and conversely, metasedimentary xenoliths in the porphyry. However, McPhie (1993) demonstrated that a peperitic texture is associated with the margins of a porphyry intruding greywacke in the vicinity of the smelter on the Warrego Road, and also with the Airport porphyry. These complex and potentially contradictory structural/intrusive relationships may be reconciled with two generations of porphyry intrusion. This is apparently corroborated by the 1838 ± 9 Ma igneous crystallisation age of porphyry in the vicinity of Jubilee mine (Compston 1995), although this remains within error of the ages obtained by both Compston (1995) and Maidment *et al* (2006) for the White Devil mine porphyry, and of the 1849 ± 3 Ma age for the Quarry porphyry (Maidment *et al* 2006). However, Maidment *et al* (in press) have reported an igneous cystallisation age of 1846 ± 3 Ma for the Airport porphyry and a new age determination for the Smelter porphyry of 1848 ± 4 Ma. These ages indicate that the porphyries are about the same age, irrespective of whether or not they have a peperitic margin.

There are a number of unnamed granites in the Tennant Region. Unnamed granite outcropping at one locality in SHORT RANGE was mapped as part of the Warrego Granite (of the Devils Suite) by Mendum and Tonkin (1976). However, it has a different composition (orthoclase, plagioclase, blue opalescent quartz and chloritised biotite) from that of the Warrego Granite, and a prominent northeast-oriented foliation. It is considered to be an equivalent of either the Tennant Creek or Cabbage Gum granites. Geophysical data suggest that it is a moderately sized pluton, and it may have been intruded by the Warrego Granite. It appears that another unnamed granite to the northwest of the Last Hope mine has intruded and may have deformed the Brumbreu Formation. If this is the case, then this unnamed granite may be part of the Treasure Suite. Blake *et al* (1987) reported that unnamed granite in the southern Warramunga Province is cut by a dolerite dyke which is overlain by the Epenarra Volcanics and is therefore provisionally interpreted to predate the Ooradidgee Group. Thus, this latter unnamed granite is probably a leucocratic member of the Tennant Creek Supersuite. However, it contains muscovite, although it has not been established whether or not this is primary.

Dolerite intrudes all major Tennant Creek Supersuite granites, including the Hill of Leaders Granite and unnamed granite proximal to it. These intrusive dolerite dykes contrast with lamprophyre, dolerite and gabbro xenoliths (or autoliths) found in both the Tennant Creek Granite and the Mumbilla Granodiorite. A dolerite dyke intruding the Tennant Creek Granite at Red Bluff was dated at 1858 ± 9 Ma, an age that is within error of that of the host granite (1849 ± 7 Ma) at the same locality, and a 'gabbro' (probably a quartz-diorite) intruding the Mumbilla Granodiorite to the southeast of Tennant Creek has an age of 1841 ± 6 Ma (Compston 1994). Compston (1995) pointed out that field relationships indicate that the dolerite intrudes the granite, and a different zircon chemistry militates against zircons in the dolerite being inherited from the granite. A dolerite from drill core about 30 km west-southwest of Tennant Creek was reported to have two discrete baddeleyite age populations of 1842 ± 8 Ma and 1781 ± 18 Ma that Compston (1994) attributed to igneous crystallisation and Pb-loss, the latter probably a consequence of metamorphism. It is uncertain whether the younger age dates this metamorphism, or whether it is a consequence of partial resetting during a younger metamorphic event. Compston and McDougall (1994) reported Ar-Ar and K-Ar ages for muscovites from rocks in this area that indicate a ca 1700 Ma metamorphic episode (see under **Metamorphism**). Compston (1994) reported that the relationship between the dolerite and country rocks is not clear from drill core, but interpreted that apart from uralitisation and deformation at its margins, the dolerite has apparently survived mylonitisation and metamorphism of the country rocks. A later phase of dolerite emplacement (contemporaneous with the Treasure

Suite) is evident (see under **Ca 1820–1810 Ma Treasure Suite intrusive rocks**).

1850–1810 Ma post-Tennant Event stratigraphic succession

Ooradidgee Group

Four spatially discrete successions (**Table 9.3**) have been mapped in the Ooradidgee Group in the Warramunga Province:

(1) A predominantly sedimentary succession with subordinate volcanic rocks in northern and western TENNANT CREEK, comprising the Wundirgi and Brumbreu formations that conformably overlie the Warrego Volcanics.
(2) A mixed volcanic and sedimentary succession in central TENNANT CREEK, comprising the Monument and Bernborough formations.
(3) The Yungkulungu Formation in southeastern TENNANT CREEK, that comprises lower and upper intervals dominated by volcanic and sedimentary rocks, respectively.
(4) A succession exposed in BONNEY WELL and FREW RIVER, which contrasts with the foregoing successions in that it includes mafic as well as felsic volcanic rocks, and also includes ca 1814 Ma volcanic rocks that may be unrepresented in the other successions (**Figure 9.4**, above). This fourth succession comprises the Epenarra, Edmirringee, and Treasure volcanics, the Kurinelli and Taragan sandstones, and the Rooneys Formation.

The first three successions are characterised by an upward change from moderately deep-water to sublittoral/littoral and finally fluviatile sedimentation, and also by predominantly sedimentary rocks lower in the succession with interbedded volcanics becoming more abundant upwards. Volcanic textures are locally well-preserved and the volcanic rocks are mainly interpreted to be subaerial.

In the southern Warramunga Province flanking the Murchison and Davenport ranges, and particularly in the Pingley, Edmirringee and Taragan blocks, the various formations of the Ooradidgee Group have been mapped as a predominantly laterally equivalent succession of felsic and mafic volcanic rocks, and feldspathic and lithiclastic sedimentary rocks deposited in association with growth faults (Blake *et al* 1987, Stewart 1987).

The Ooradidgee Group in the southern Warramunga Province (in BONNEY WELL and FREW RIVER) has been interpreted as a succession of predominantly subaerial volcanic and fluviatile sedimentary rocks, which partly interfinger, and are associated with a number of volcanic centres (Blake *et al* 1987). The Ooradidgee Group in TENNANT CREEK comprises exclusively, rhyolitic to dacitic, felsic volcanic rocks. Similar felsic volcanic rocks are also well-represented in the southern Warramunga Province succession, although they are there associated and interdigitate with basalts in the mafic volcanic-dominated Edmirringee Volcanics. Minor basaltic volcanics are also present in the Treasure Volcanics, the Kurinelli Sandstone and probably also in the Epenarra Volcanics.

The lowermost sedimentary rocks of this southernmost Ooradidgee Group succession (Rooneys Formation and basal Kurinelli Sandstone) are shallow marine to intertidal. However, fluviatile sedimentation predominates throughout the majority of this succession. The most widespread unit of this succession, the Kurinelli Sandstone, comprises tuffaceous, lithic and sublithic (volcanilithic), fluviatile sandstone (with minor mafic and felsic volcanic rocks). The fluviatile depositional environment of these sedimentary rocks is consistent with the subaerial character of the volcanic rocks. The lowermost, deeper-water sedimentary rocks that are comparable with those of the Monument Formation in TENNANT CREEK may simply not outcrop in this more southerly succession, or may be absent. The latter situation would be consistent with the possible absence of the oldest interval of the Ooradidgee Group succession in this area, as mentioned above. Sedimentation during uppermost Ooradidgee Group times is similarly apparently absent in the north. The Brumbreu Formation is inferred to be older than the Treasure and Mia Mia volcanics and probably also the Taragan and uppermost Kurinelli sandstones. Subaqueous sedimentation in progressively shallower water is similarly represented in the lower intervals of the Ooradidgee Group successions to the north in TENNANT CREEK.

A description of the individual lithostratigraphic units of the Ooradidgee Group (see **Table 9.3**) is given below, with the order of description corresponding to the four discrete Ooradidgee Group successions outlined above: (1) northern and western TENNANT CREEK, (2) central TENNANT CREEK, (3) southeastern TENNANT CREEK, and (4) northern BONNEY WELL / FREW RIVER, which is informally called the Kurundi / Hatches succession.

Northern and western TENNANT CREEK succession

This succession comprises the Warrego Volcanics, and the Wundirgi and Brumbreu formations.

The most extensive exposure of the *Warrego Volcanics* is in the Great Western Syncline in SHORT RANGE. The volcanics are also exposed in southwestern FLYNN to the north and northwest of the Gecko mine, and airborne magnetic data indicate that these two main areas of exposure are linked in the subsurface. Airborne magnetic data also indicate that the contact between the Warrego Volcanics and the underlying Warramunga Formation is folded about northwest-trending axes. These folds are second generation with respect to the Warramunga Formation, and the boundary between the Warramunga Formation and the Warrego Volcanics is interpreted to be a tectonic unconformity analogous with that seen in outcrop between the Warramunga and Yungkulungu formations, and between the Woodenjerrie beds and Epenarra Volcanics. The Warrego Volcanics are conformably overlain by the Wundirgi Formation. The boundary is (at least locally) marked by a pale green chert at the top of the Warrego Volcanics, which has a sharp contact with medium to thickly interbedded sandstone and shale of the Wundirgi Formation. This chert is correlated with a similar chert that was defined as the top of the revised, basal Whippet Sandstone Member of the Bernborough Volcanics by Donnellan *et al* (1995). The Warrego Volcanics were previously correlated with the

Unit	Thickness (m)	Lithology	Stratigraphic relationships	Depositional environment	Age	Age constraints
OORADIDGEE GROUP						
Northern and western succession						
Brumbreu Fm	ca 600–1500	Lithic- and volcanilithic-sandstone; magnetite-bearing quartz sandstone; granule and pebble beds; felsic tuff (chert); sandstone is fine- to coarse-grained and thinly to medium bedded.	Apparently conformable and transitional, but also locally an unconformable or faulted contact with overlying Hayward Creek Fm (of Tomkinson Creek Gp). Conformable and transitional with underlying Wundirgi Fm. Intruded by mafic sills.	Marginal marine to fluviatile.		At least in part predates 1821 ± 8 Ma unnamed monzodiorite/ dolerite sills, and ***1814 ± 3 Ma*** Treasure Volcs (dated in Davenport Province
Warrego Volcs	ca 550 in type section	Siltstone, chert, felsic tuff and probable ignimbrite, interbedded with fine- to medium-grained lithic sandstone.	Lateral equivalent of part of Wundirgi, Monument and Yungkulungu formations. Chertified tuff at top of Warrego Volcs is correlated with that at top of Monument Fm and also at base of sedimentary lithofacies of Yungkulungu Fm.	Subaerial pyroclastic rocks and waterlain (shallow-marine?) reworked equivalents.		Correlated with **1849 ± 5 Ma** Yungkulungu Fm volcanic lithofacies.
Wundirgi Fm	ca 3000 by analogy with Monument Fm	Fine- to coarse-grained and thinly to medium bedded sublithic/lithic sandstone; thinly bedded siltstone; minor conglomerate and breccia; felsic volcanic rocks.	Competancy contrast results in *apparent* unconformable relationship between Wundirgi and Brumbreu formations. Laterally equivalent to all or part of Warrego Volcs, and Monument, Bernborough and Yungkulungu formations. Base not exposed. Intruded by basic/intermediate sills.	Predominantly subaqueous (deep-water marine to littoral), with minor subaerial surge and fall deposits.		Predates 1829 ± 8 Ma quartzofeldspathic schist (sheared intrusive porphyry or granite), and 1821 ± 7 Ma unnamed monzodiorite/ dolerite sills. Predates or is contemporaneous with 1827 ± 9 Ma foliated felsic schist (granophyric felsic volcanic rock?).
Central succession						
Bernborough Fm	ca 900 in type section	Dacitic to rhyolitic ignimbrite, tuff, lapilli-tuff and other minor probable volcanic rocks, interbedded with thinly bedded siltstone, shale and chert; thinly to medium bedded lithic- to sublithic sandstone; minor pebble conglomerate.	Correlated with sedimentary lithofacies of Yungkulungu Fm and with upper part of Wundirgi Fm.	Subaerial and subaqueous. Volcanic rocks are predominantly subaerial and include a phreatomagmatic tuff cone or ring succession overlain by ignimbrite.	1840 ± 8 Ma crystal-rich tuff; 1845 ± 4 Ma porpyritic rhyolite.	Probably correlates, in part, with ***1840 ± 4 Ma*** Epenarra Volcs. Apparently intruded by 1848 ± 7 Ma / *1846 ± 3 Ma* Tennant Creek Granite (north).
Whippet Sst Mbr	ca 100 in type area	Fine- to coarse-grained, poorly to well sorted sublithic- and lithic sandstone; minor conglomerate and siltstone.	Conformably overlies Monument Fm. Correlated with part of Yungkulungu and Wundirgi formations.	Sublittoral to littoral and possibly fluviatile. Represents a regressive succession.		
Monument Fm	ca 1000 in type section, may be up to 3000 in east?	Very thinly to thinly bedded, laminated or massive siltstone and chert; shale; fine- to medium-grained lithic sandstone and wacke. Thinly to medium bedded tuff, volcanilithic sandstone and siltstone in the east (ie probably near top of unit).	Conformably underlies *Whippet Sst Mbr* (although succession in east may, in part, correlate with Bernborough Fm?). Correlated with volcanic lithofacies of Yungkulungu Fm, and with part of Wundirgi Fm. Base not exposed.	Moderately deep water, progressively shallowing upwards to conformably overlying sublittoral to littoral, and possibly partially fluviatile *Whippet Sst Mbr*. Succession in east includes both subaqueous and subaerial components.	**1853 ± 5 Ma** dacitic volcanic rock	Correlated with **1849 ± 5 Ma** Yungkulungu Fm volcanic lithofacies.

Table 9.3. Summary of Palaeoproterozoic Ooradidgee Group stratigraphic succession of Warramunga Province. Ages reported in ordinary type are from Compston (1995); those in regular type, but underlined, are from Page (1990); those in *italic* type are from Maidment *et al* (2006); those in **bold** type are from Smith (1999); and those in ***bold italic*** type are from Claoué-Long *et al* (2008). Abbreviations: Fm = Formation; Volcs = Volcanics; Sst = Sandstone; Mbr = Member; Cgt = Conglomerate; Gp = Group; max dep age – maximum depositional age (continued **next page**).

Unit	Thickness (m)	Lithology	Stratigraphic relationships	Depositional environment	Age	Age constraints
Southeastern succession						
Yungku-lungu Fm	ca 5200	Medium- to thickly bedded lithic/volcanilithic sandstone; minor granule and pebble beds. Interbedded tabular siltstone, tuff and felsic ignimbrite. Thick, predominantly foliated porphyritic rhyolitic lava.	Generally faulted contact with Warramunga Fm, but locally unconformably overlies this unit. Unconformably overlain by Rising Sun Cgt. Intruded by Mumbilla Granodiorite and unnamed lamprophyre.	Subaerial and subaqueous volcanic rocks. Shallow-marine, sublittoral, littoral and fluviatile sedimentary rocks.		
unnamed sedimentary lithofacies	ca 3600	Medium- to thickly bedded, cross-bedded and cross-laminated, medium- to coarse-grained lithic/volcanilithic sandstone with magnetite and other heavy-mineral-bearing laminae. Minor granule to pebble beds with rhyolitic clasts towards base of unit; top of unit is better sorted, medium-bedded sublithic- and quartz sandstone. Minor phyllite.	Conformably overlies unnamed volcanic lithofacies. Correlated with Bernborough Fm. Intruded by Channingum Granite.	Shallow marine, grading upwards to sublittoral/ littoral and possible fluviatile; dominated by reworked felsic volcanic detritus.		Conformably overlies and therefore immediately postdates **1849 ± 5 Ma** unnamed volcanic lithofacies; correlated with 1840 ± 8 Ma / 1845 ± 4 Ma Bernborough Fm.
unnamed ignimbritic lithofacies	≤200	Felsic ignimbrite, welded tuff, rhyolitic lava and ashstone. Interbedded reworked volcaniclastic rocks.	Conformable within sedimentary lithofacies.	Subaerial.		
unnamed volcanic lithofacies	ca 1600	Thickly bedded, foliated, porphyritic rhyolite to rhyodacite lava with shattered quartz and/or feldspar phenocrysts in medium-grained matrix. Medium bedded volcanilithic sandstone and ashstone, and ignimbrite towards top of unit.	Conformably overlain by sedimentary lithofacies to northwest. Probably correlates with Monument Fm and lower part of Wundirgi Fm. Intrusive and locally faulted contact with Mumbilla Granodiorite and Cabbage Gum Granite.	Subaqueous volcanic and volcaniclastic rocks, latter become more prevalent up-section and are shallow marine.	**1849 ± 5 Ma** crystal-rich ignimbrite. Intruded by 1840 ± 9 Ma Channingum Granite and 1850 ± 6 Ma Mumbilla Granodiorite.	Correlated in part with **1853 ± 5 Ma** Monument Fm. Unconformably overlies ca 1860 Ma Warramunga Fm.
Kurundi / Hatches succession						
Treasure Volcs	0–3500	Recessive, weakly metamorphosed porphyritic dacitic to rhyolitic lava, and local non-porphyritic felsic lava; minor volcanic breccia; minor quartzic/ feldspathic/ lithic/ volcanilithic sandstone; minor schist. Recessive basaltic lava with minor interlayered quartzose/ volcanilithic/epidotic sandstone locally. Ridge-forming quartz- and feldspathic sandstone locally forms discrete mapable lithofacies.	Conformable on Kurinelli Sst. Conformable on and interfingers withTaragan Sst. Both conformably and unconformably overlain by, and interfingers with Unimbra Sst (Hatches Creek Gp). Intruded by granophyre and mafic sills.	Subaerial volcanic rocks; sandstone records an upward transition from fluviatile to shoreline and shallow subaqueous (marine or lacustrine) sedimentation.	***1814 ± 3 Ma*** ignimbrite from southeastern Davenport Province.	Conformable on ***1837 ± 7 Ma*** (max dep age) sills. Kurinelli Sst. Conformable on and interfingers with Taragan Sst. Intruded by ***1811 ± 5 Ma*** mafic sills.
Taragan Sst	0–900	Ridge-forming polymictic conglomerate (includes quartz-haematite clasts probably derived from Warramunga Fm or lateral equivalents); pebbly sandstone; quartz/ feldspathic/sublithic sandstone. Recessive, variably micaceous siltstone; minor calcareous beds.	Conformable and locally unconformable on, and also interfingers with Kurinelli Sst. Conformably overlain and interfingers with Treasure Volcs. Conformably/ disconformably overlain by Unimbra Sst (Hatches Creek Gp). Intruded by mafic sills and granophyre.	Predominantly fluviatile with three major facies recognised, both vertically and laterally: alluvial fan facies; meandering stream facies; marine facies.		Conformable and locally unconformable on, and also interfingers with ***1837 ± 7 Ma*** (max dep age) Kurinelli Sst. Conformably overlain by and interfingers with ***1814 ± 3 Ma*** Treasure Volcs. Intruded by ***1811 ± 5 Ma*** mafic sills.

Table 9.3. Summary of Palaeoproterozoic Ooradidgee Group stratigraphic succession of Warramunga Province (continued from **previous page** and continued **next page**).

Warramunga Province

Unit	Thickness (m)	Lithology	Stratigraphic relationships	Depositional environment	Age	Age constraints
Edmirringee Volcs	0–2500	Basalt, predominantly massive/ vesicular/ amygdaloidal, non-porphyritic pahoehoe and minor Aa lava; mugearite locally near base of succession in Kurundi Anticline; minor felsic lava and tuff (equivalent to Epenarra Volcs); and sandstone (equivalent to Kurinelli Sst).	Conformable on and interfingers with Epenarra Volcs and Kurinelli Sst; also conformably overlain by Kurinelli Sst. Overlain conformably and/or disconformably by Unimbra Sst.	Erupted from one volcanic centre in Warramunga Province and three in Davenport Province. Predominantly subaerial, but possible pillow lavas locally in KURUNDI REGION. Interdigitates with Kurinelli Sst, which is predominantly fluviatile, but probably marine at its base.		
Kurinelli Sst	0–2630	Ridge-forming feldspathic/ lithic (volcaniclastic/ tuffaceous?) sandstone; quartz sandstone, pebbly sandstone and conglomerate; minor felsic and mafic lava and tuff; siltstone; shale.	Conformable on Epenarra and Edmirringee volcanics, and on Rooneys Fm, and overlain conformably by Taragan Sst and Treasure Volcs. Interfingers with all these formations. Overlain conformably and unconformably by Unimbra Sst. Intruded by mafic sills and granophyre.	Lower Kurinelli Sst (together with underlying Rooneys Fm) is interpreted to be marine portion of delta complex. Remainder of Kurinelli Sst probably represents continued delta progradation, with shallow-water braided river deposits and local salinas in interfluvial areas.		
Warnes Sst Mbr	500	Variably feldspathic (and lithic?) sandstone and quartz sandstone.	Conformable lenses within Kurinelli Sst.		***1837 ± 7 Ma*** max dep age for youngest statistical group of detrital zircons.	
Endurance Sst Mbr	400–500	Thinly interbedded fine-grained, graded, micaceous greywacke and siltstone; feldspathic sandstone.	Conformable lenses within Kurinelli Sst.			
Rooneys Fm	1200+	Thinly bedded to laminated, fine-grained feldspathic/ lithic sandstone and siltstone; generally recessive, with minor ridge-forming subarkose.	Conformable on and interfingers with Epenarra Volcs. Conformably overlain by and interfingers with Kurinelli Sst. Intruded by mafic sills, granophyre and unnamed granite.	Deltaic, including delta-front, wave-affected deposits, and high-energy shoreface, including storm deposits.		Conformable on and interfingers with 1840 ± 4 Ma Epenarra Volcs, and is overlain by and interfingers with ***1837 ± 7*** Ma (max dep) Kurinelli Sst. Intruded by ***1811 ± 5 Ma*** mafic sills.
Epenarra Volcs	0–3200	Generally rececessive, porphyritic felsic lava and eutaxitic-textured ignimbrite; volcanic breccia, agglomerate; felsic tuff and lapilli tuff; phyllitic to schistose felsic volcanic rocks; minor amygdaloidal non-porphyritic mafic lava and tuff. Ridge-forming quartzose and volcaniclastic sandstone and conglomerate locally dominate unit (ie sandstone lithofacies).	Unconformable on Woodenjerrie beds. Overlain by and interfingers with Rooneys Fm, Edmirringee Volcs and Kurinelli Sst. Overlain disconformably/ unconformably(?) by Unimbra Sst (with which it also interfingers in Davenport Province). Apparently overlies intrusive porphyry and unnamed granite; intruded by granophyre.	Subaerial volcanic rocks erupted from two volcanic centres: larger centre to north (Warramunga Province); smaller centre to south in Kurundi Anticline (Davenport Province).	***1840 ± 4 Ma*** fine-grained volcaniclastic (partially welded ignimbrite?), 1837 ± 5 Ma	Probably correlates in part with 1840 ± 8 Ma / 1845 ± 4 Ma Bernborough Fm.
sandstone lithofacies	≤900 max?	Ridge-forming quartzose/ volcaniclastic sandstone; vein-quartz-pebble-bearing sandstone; volcaniclastic conglomerate; minor interlayered volcanic rocks.		Probably fluvial.		

Table 9.3. Summary of Palaeoproterozoic Ooradidgee Group stratigraphic succession of Warramunga Province (continued from **previous page**).

Bernborough Formation (Donnellan *et al* 1995, 2001) of the central TENNANT CREEK succession. However, they are herein considered to largely correlate with the Monument Formation of this succession.

The Warrego Volcanics are best described as tephra. The typically poorly outcropping succession comprises white, pink, mauve and grey siltstone, laminated chert, and fine- to medium-grained lithic sandstone and wacke. Primary structures are poorly preserved, but volcanic textures can be identified locally. Accretionary lapilli-bearing tuffs have been recognised (eg 53K 399200mE 7853200mN); some lapilli have pale rims and are probable rim-type lapilli (cf Schumacher and Schmincke 1991). Randomly dispersed, fractured quartz phenocrysts are also present, as are possible fiamme. These tuffs are thought to represent subaerial surge and fall deposits; some show a degree of welding, and evidence for welding in subaqueous pyroclastic rocks is uncommon and equivocal. Several units have been analysed and are rhyodacite to rhyolite, according to Winchester and Floyd's (1977) classification (which is based on Zr/TiO_2 and Nb/Y ratios). However, Ooradidgee Group volcanic rocks have been variably altered, resulting in probable significant loss of soda and silica enrichment in many samples, and minor enrichment in potash in some samples. Much of the succession is thinly to medium-bedded laminated chert (probable silicified tuff) and fine-grained sedimentary rocks with rare ripples and cross-lamination. Several very thickly bedded, graded, angular mudstone or siltstone clast-breccia deposits in SHORT RANGE (eg at 53K 386300mE 7861200mN) are interpreted as fluidised flows. These may have resulted from surges or ignimbrites entering water.

The *Wundirgi Formation* is a succession of volcanilithic sandstone and siltstone, and subordinate volcanic rocks that include lava and pyroclastic rocks. Volcanic rocks are particularly well-represented to the west of the Last Hope mine. There (at 53K 378000mE 7865900mN), a thick succession of very thinly to thickly bedded, accretionary lapilli-bearing surge and possible fall deposits outcrop near the top of the Wundirgi Formation (ie upper Wundirgi Formation). This interval is correlated with the Bernborough Formation of the central TENNANT CREEK succession. Alternating sandstone and shale of the Wundirgi Formation become medium to thinly bedded and very planar-bedded up section, and beds near the top of the unit show high lateral persistence and have been interpreted as probable storm deposits. The ratio of sandstone to shale increases upwards towards a locally conformable and transitional contact with the Brumbreu Formation, the base of which is marked by a distinctive grey-green, medium to thickly bedded, cross-bedded lithic sandstone.

In SHORT RANGE, a 100 m-thick succession of medium to thickly bedded, cross-bedded, heavy mineral-bearing lithic sandstone, rippled lithic sandstone and minor quartz pebble conglomerate more than half-way up the Wundirgi Formation succession is correlated with the Whippet Sandstone Member of the central TENNANT CREEK succession. This is consistent with the previously held view that the Wundirgi Formation in the northern and western succession is equivalent to a large part of the Ooradidgee Group in the central and southeastern successions in TENNANT CREEK. However, the Wundirgi Formation succession is monotonous and difficult to subdivide. Reference is made here informally to lower and upper Wundirgi Formation: the upper Wundirgi Formation is that interval of the unit stratigraphically above and including the Whippet Sandstone Member-equivalent succession, and the lower Wundirgi Formation is the remainder of the unit. The lower Wundirgi Formation is correlated with the Warrego Volcanics and Monument Formation, whereas the upper Wundirgi Formation is correlated with the Bernborough Formation.

The *Brumbreu Formation* predominantly contains lithic sandstone that has a substantial epiclastic component together with subordinate lava and pyroclastic rocks. Heavy mineral-bearing quartz sandstone, and granule- and pebble-bearing sandstone are additional constituent rock types. It is discontinuously exposed along the southern margin of the Short and Ashburton ranges. Donnellan *et al* (1995) mapped a planar conformable contact between the Brumbreu and Wundirgi formations at 53K 380800mE 78637000mN. There, a distinctive grey-green, medium- to thickly bedded, cross-bedded sandstone and siltstone at the base of the Brumbreu Formation overlies thinly bedded, ripple marked, interbedded sandstone and siltstone of the Wundirgi Formation. The relationship appears to be transitional, with interbedded sandstone and siltstone of the Wundirgi Formation becoming increasingly dominated by sandstone upwards towards the contact with the Brumbreu Formation. A pale green chert at the contact between the Brumbreu and Wundirgi formations in the west (eg 53K 386200mE 78632000mN and 381000mE 7863300mN) is interpreted as silicified tuff.

The Warrego Volcanics are estimated to be about 550 m thick. The thickness of the Wundirgi Formation is difficult to estimate due to discontinuous exposure, folding and faulting. It probably ranges from 600 m at the more easterly limit of its outcrop to about 1500 m in the west. In its type section, the Brumbreu Formation is 900 m thick. Mendum and Tonkin (1976) measured 1450 m of Brumbreu Formation to the north of Last Hope mine; however, this apparent westward thickening may be a consequence of fault repetition. The Brumbreu Formation may be somewhat thinned towards the east, possibly due to erosion prior to Hayward Creek Formation sedimentation. Compston (1995) reported an 1823 Ma population of detrital zircons in the Hayward Creek Formation that would be consistent with the reworking of upper Ooradidgee Group material. Compston also reported a population of 1862 Ma zircons in the Hayward Creek Formation that he attributed to a Warramunga Formation source. These data are consistent with the unconformity at the base of the Tomkinson Creek Group extending across the Ooradidgee Group to the Warramunga Formation.

The sedimentary rocks of the northern and western TENNANT CREEK succession of the Ooradidgee Group appear to be predominantly subaqueous. Those of the Wundirgi Formation probably represent an upward-shallowing environment, from deep-water marine to littoral, and those of the Brumbreu Formation represent marginal marine to fluviatile sedimentation, thus continuing the overall shallowing trend. Where preserved textures allow interpretation of palaeoenvironments, the volcanic rocks are predominantly subaerial. Felsic pyroclastic rocks of the Warrego Volcanics are subaerial and where reworked, they are probably shallow marine, although they are also in part likely to be penecontemporaneous with the earliest Wundirgi Formation sedimentary rocks that probably record deeper-water sedimentation. Volcanic rocks towards the top of the Wundirgi Formation (and correlated with the Bernborough Formation) include subaerial felsic surge and fall deposits that are contemporaneous with shallow-marine to intertidal sedimentary rocks along strike.

Central TENNANT CREEK succession

This succession comprises the Monument and Bernborough formations.

Exposure of the *Monument Formation* is confined to a few areas in FLYNN. These exposures are scattered through an area of well vegetated sandy soil and are low rises or areas adjacent to major quartz veins. There is no exposed, continuous representative section through the unit. The Monument Formation consists of very thinly to thinly bedded, laminated to massive siltstone, shale and chert, and thinly to medium-bedded, laminated to massive, fine- to medium-grained lithic sandstone and wacke. It additionally includes a succession of tuff and tuffaceous sandstone, as well as thinly to medium-bedded, graded, probable ash-fall deposits. These contain well sorted (1–3 mm in diameter) accretionary lapilli, which are similar to the more distal core-type lapilli of Schumacher and Schmincke (1991). Also included in the Monument Formation is a thick succession dominated by volcanic and volcaniclastic rocks, which is exposed near the Blakeway trigonometric station (53K 439400mE 78573000mN). These have been interpreted to be contemporaneous with a similar succession of volcanic rocks intersected in drilling in western BARKLY. A dacitic volcanic rock from this succession has yielded a single-crystal U-Pb zircon igneous crystallisation age of 1853 ± 5 Ma (Smith 1999).

The thickness of the Monument Formation is estimated to be about 1000 m, based on its interpreted extent to the northeast of its type area in the vicinity of Flynn's Monument, which is located near the intersection of the Stuart and old Barkly highways (53K 416700mE 7850700mN). The base of the Monument Formation has not been intersected in drill core and it may be up to about 3000 m thick in the east. This suggests that the central-eastern Monument Formation succession may be equivalent to the entire Ooradidgee Group, and may therefore include correlatives of the Bernborough Formation.

Probable Bouma sequences and laminated to thinly bedded siltstone and shale indicate that the Monument Formation was in part deposited in relatively deep water (below storm wave base). Further deposition took place in shallower-marine to sublittoral environments transitional to the overlying fluviatile Whippet Sandstone Member. The dominantly tuffaceous succession in the east is interpreted as subaerial and associated shallow-water deposits.

The Monument Formation is conformably overlain by the Whippet Sandstone Member of the Bernborough Formation. Le Messurier *et al* (1990) suggested an unconformable relationship between these two units, based on geophysical interpretation. However, conformity is evident in exposures south of Whippet trigonometric station (53K 427100mE 7863600).

An approximately 100 m-thick succession of *Whippet Sandstone Member* is discontinuously exposed in a rounded strike ridge of low relief near 53K 427100mE 78637000mN. The member comprises fine- to coarse-grained, poorly to well sorted sublithic and lithic sandstone with minor conglomerate and siltstone. Sediment maturity, and the rounding and sorting of grains increases upwards. The upper part of the member comprises grain-size-laminated sandstone forming low-angle tabular to broad trough cross-beds in medium to thick sets. These sandstones are moderately to well sorted, and predominantly medium-grained sublithic and lithic sandstones, with some heavy mineral lamination. Where exposed, the uppermost sandstones of this unit carry abundant ripple marks, symmetric ripples, current ripples, and rare truncated and interference ripples. The Whippet Sandstone Member is interpreted to reflect a sublittoral to littoral and possibly partially fluviatile regressive succession. The top of the Whippet Sandstone Member is interpreted to be the base of a thin, slightly recessive, green chert unit that is overlain by sandstone and siltstone. Above this member (in the type area) the *Bernborough Formation* comprises about 800 m of dacitic to rhyolitic pyroclastic rocks, and minor probable lavas forming three discrete units separated by fine-grained sedimentary rocks. Predominant rock types are ignimbrite, tuff, lapilli-tuff and minor probable lava. These are divided in the type section into three volcanic intervals separated by laminated to massive, but mainly thinly bedded siltstone, shale and chert, thinly to medium-bedded sublithic to lithic sandstone and minor pebble conglomerate. Identifying and correlating these three volcanic intervals in outcrop away from the type area is increasingly difficult with distance. These three volcanic intervals are informally referred to here as lower, middle and upper Bernborough Formation.

Macroscopic and microscopic volcanic textures are well preserved in the Bernborough Formation. There is a prominent 2–5 m-thick green chert at the base of the Bernborough Formation volcanic succession, where it immediately overlies the Whippet Sandstone Member. This chert contains rare, large (up to 19 mm in diameter), isolated and intact accretionary lapilli. Such lapilli are common in, but not confined to phreatomagmatic tuffaceous deposits and may be found large distances from their source (Cas and Wright 1987, Schumacher and Schmincke 1991). A subaerial, phreatomagmatic (phreatoplinian?) origin is favoured for this accretionary lapilli-bearing chert.

Elsewhere, the onset of volcanism in the Bernborough Formation is marked by a probable tuff ring or cone sequence and is interpreted to be phreatomagmatic. This lower volcanic unit is predominantly tuff, but also includes moderate to intensely welded, rhyolitic to dacitic ignimbrite, some of which carries rare, rounded mantled lapilli and accretionary lapilli-bearing tuff clasts, indicating that they have incorporated previously consolidated tuff. Facies associations of the lower volcanic interval at, for example 53K 412500mE 7855300mN, appear to represent a tuff ring or cone sequence. The tuffs are relatively crystal-poor, but have a high lithic content by comparison with much of the Bernborough Formation. Also common in this area are probable surge deposits, accretionary lapilli-bearing tuff and non-welded to partially welded pyroclastic rocks (**Figure 9.12a**, **b**). The surge deposits carry mantled lapilli, generally 1–3 cm in diameter, but ranging up to 8 cm (**Figure 9.12a**). Some of these lapilli have multiple rims, indicating that they are transitional to the accretionary lapilli class of Schumacher and Schmincke (1991). The surge deposits also carry rare ballistic blocks.

Above the lower volcanic unit, the Bernborough Formation is dominated by massive to weakly laminated crystal-phyric rocks. Most of these are interpreted to be ignimbrite. However, some have both cross-cutting and interfingering relationships with the sedimentary and unequivocal volcanic rocks, and are considered to be penecontemporaneous intrusive rocks. The ignimbrites are mainly rhyodacite in composition with rhyolite being only a minor component, according to the discrimination diagram of Winchester and Floyd (1977). An apparent flow alignment of abundant crystals in a devitrified glassy matrix indicates that flow-banded subaerial lavas may be at least a component of the succession.

The primary phenocrystic mineralogy of the volcanic rocks is quartz, alkali feldspar and plagioclase in a recrystallised or devitrified glassy groundmass (**Figure 9.13a**) that has obliterated shard textures and is now represented as an interlocking mosaic of quartz, feldspar and fine-grained magnetite euhedra. Relict shard textures are locally preserved (**Figure 9.13b**). Biotite is a minor phase and primary accessory minerals are zircon and magnetite; rare fluorite, hornblende and xenocrystic clinopyroxene are also present. Chlorite, titanite and magnetite occur as alteration products.

The ignimbrites range from weakly to strongly welded (**Figures 9.12a**, **9.13a**); and contain numerous broken and fragmented phenocrysts (**Figure 9.13c**), including strained and conchoidally fractured quartz, that probably resulted from explosive eruptions. The crystal-rich nature of these volcanic rocks indicates that they were relatively cool at the time of eruption (ie below their liquidus temperature). This conclusion is corroborated by their generally low to moderate degree of thermal welding.

Sedimentary rocks within the Bernborough Formation are typically fine-grained lithic sandstone, wacke and siltstone. These rocks are thought to comprise predominantly reworked volcanic material; however, rare metamorphic or igneous grains and tourmaline (absent as an accessory mineral in the penecontemporaneous volcanic rocks) indicate a mixed provenance. The sedimentary rocks generally contain abundant detrital white mica and display a well developed bedding-parallel fissility.

Separate samples of Bernborough Formation volcanic rocks were dated by Compston (1995), using single crystal U-Pb zircons, and have igneous cystallisation ages of 1840 ± 8 Ma and 1845 ± 4 Ma.

Southeastern TENNANT CREEK succession

This succession consists of the *Yungkulungu Formation*, which is divided into a lower felsic volcanic-dominated interval overlain by a predominantly sedimentary interval. The lower interval comprises both volcanic and volcaniclastic rocks and is ca 3000 m thick, whereas the overlying predominantly sedimentary interval is ca 2000 m thick. The two intervals are referred to informally herein as the volcanic lithofacies and the sedimentary lithofacies. In six separate localities, intervals of felsic tuff, ignimbrite and minor lava flows within the sedimentary lithofacies have been recognised and are referred to as the tuffaceous subunit.

In a number of instances, volcanic rocks of the Yungkulungu Formation (particularly those of the tuffaceous subunit) have previously been mapped as intrusive porphyries (Crohn and Oldershaw 1965, Mendum and Tonkin 1971), or granite (Mendum and Tonkin

Figure 9.12. Bernborough Formation volcanic rocks [after Donnellan *et al* (1995: plate 6A, C); photographs and descriptions by KJ Hussey, (formerly NTGS)]. (**a**) Mantled lapilli from lower volcanic unit at 53K 412500mE 7855300mN. (**b**) Welded ignimbrite from middle volcanic unit at 53K 412000mE 7855100mN. Note aligned flattened pumice fragments.

1971). The volcanic origin of these rocks is indicated by their weak to moderate flow foliation, eutaxitic textures, conformable relationships with tuffaceous strata, broken grains, relict shards and volcaniclastic fragments. One example, originally mapped as porphyry, outcrops in the vicinity of the Rising Sun Conglomerate immediately south of the Gosse River Road. This was reinterpreted by Blake (1984), on the basis of its fragmental and eutaxitic textures, to be an extrusive ignimbrite. Blake (1984) determined that this ignimbrite unconformably overlies the Warramunga Formation and he correlated it with the Epenarra Volcanics. It is now included in the Yungkulungu Formation and was correlated by Donnellan *et al* (1995) with the Bernborough Formation.

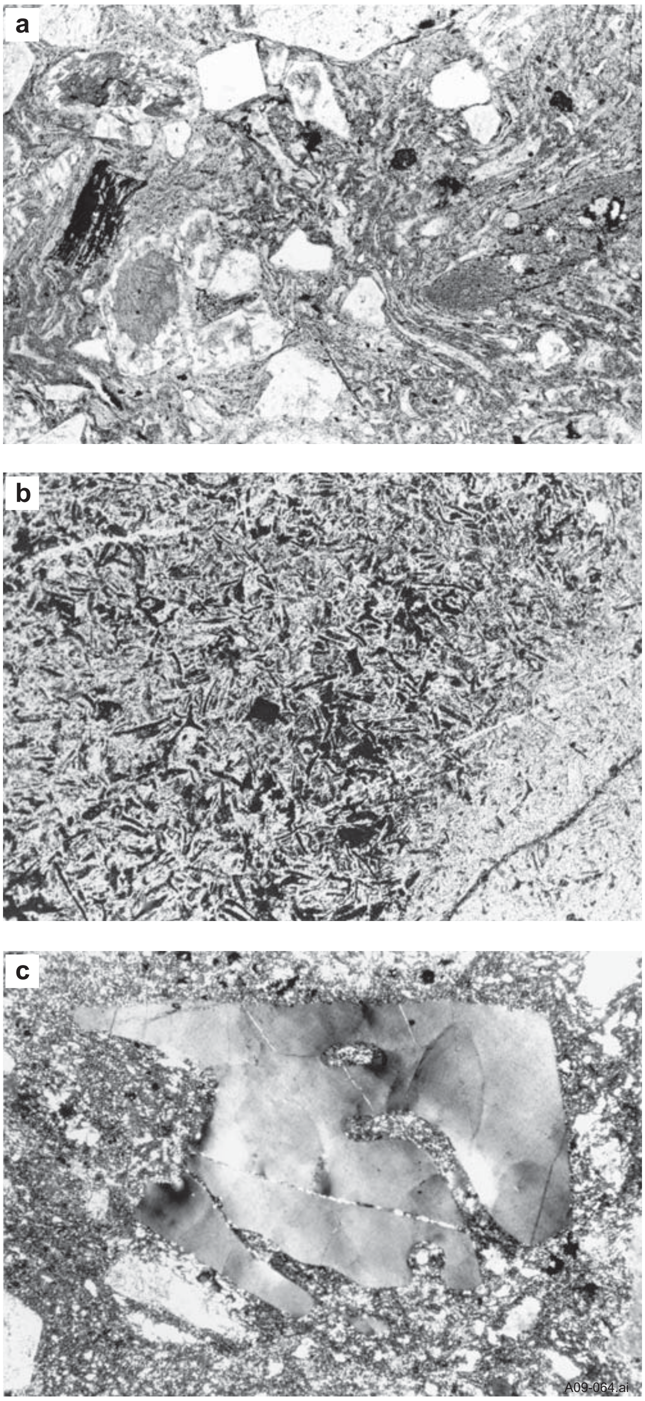


Figure 9.13. Photomicrographs of Bernborough Formation volcanic rocks [after Donnellan *et al* (1995: plate 5A–C); photomicrographs and descriptions by KJ Hussey (formerly NTGS)]. (**a**) Partly recrystallised welded ignimbrite (53K 411000mE 7852100mN, plane-polarised light, length of field of view is 4.3 mm). (**b**) Relict shard textures from accretionary lapilli-bearing tuff (53K 418700mE 7884300mN, plane polarised light, length of field of view is 2.5 mm). (**c**) Resorbed and fractured quartz phenocrysts (53K 411000mE 7852100mN, cross-polarised light, length of field of view is 2.5 mm).

The lower volcanic lithofacies of the Yungkulungu Formation is intruded by the Channingum Granite and the Mumbilla Granodiorite (these intrusive rocks have single-crystal U-Pb zircon igneous crystallisation ages of 1840 ± 9 Ma and 1850 ± 6 Ma, respectively; Compston 1995). The lower volcanic interval of the Yungkulungu Formation has an igneous crystallisation age of 1849 ± 5 Ma (Smith 1999). This age is within error of that for the Bernborough Formation volcanic rocks (1840 ± 8 and 1845 ± 4 Ma; Compston 1995). However, the Yungkulungu Formation volcanic rocks are now considered to predate the Bernborough Formation volcanics on the basis of revised lithostratigraphic correlations. It is probable that the Yungkulungu Formation volcanic lithofacies similarly predates the Epenarra Volcanics, which have an igneous cystallisation age of 1840 ± 4 Ma (Claoué-Long *et al* 2005, 2008).

The volcanic lithofacies of the Yungkulungu Formation comprises medium- to coarse-grained, rhyolitic to rhyodacitic crystal lithic tuff, lava and ignimbrite. Crystals consist of quartz, 1–2 mm across, and feldspar, 2–4 mm across. These are commonly fragmental, although quartz is also commonly bipyramidal and shows resorption along crystal margins. Occasional feldspar phenocrysts are zoned from andesine cores to oligoclase rims. Primary biotite is generally altered to chlorite, epidote and titanite, and feldspar is typically sericitised. Thick lava flows within the Yungkulungu Formation volcanic lithofacies indicate proximity to a volcanic centre.

Undivided, massive quartz sandstone that conformably overlies the Yungkulungu Formation at 53K 439400mE 7821600mN is correlated with the Brumbreu Formation of the northern and western TENNANT CREEK succession. This suggests that the sedimentary lithofacies of the Yungkulungu Formation is contemporaneous with the upper Wundirgi Formation of the western and northern succession, and with the Bernborough Formation of the central succession. However, the uppermost part of the Yungkulungu Formation sedimentary lithofacies may also correlate with the Brumbreu Formation. Light grey, fine- to medium-grained lithic sandstone at the top of the sedimentary lithofacies overlies indurated, medium-bedded, medium-grained quartz sandstone that, in turn, overlies thickly bedded, medium-grained lithic sandstone and interbedded siltstone. The lithic sandstone is well sorted and has a bimodal grain size distribution. Clasts are dominated by immature lithic grains (including fragments of devitrified felsic volcanic glass and strained quartz phenocrysts) and feldspar grains in a matrix of decomposed, sericitised feldspar and a haematitised cement. The base of the sedimentary lithofacies is taken to be a ca 200 m-thick interval of maroon, medium-grained lithic sandstone, although there is a transitional relationship with the underlying volcanic lithofacies that is indicated by a gradual increase in interbedded felsic tuff and sandstone within the upper volcanic lithofacies (eg 53K 432700mE 7817300mN).

The sedimentary lithofacies rocks are of compositionally immature sandstone with a significant or dominant, penecontemporaneous volcanic-derived component. The well sorted character of this sandstone, together with common shallow-angle cross-laminations, and the prevalence of heavy mineral (magnetite-tourmaline-zircon-ilmenite) laminations, oscillation ripples and weathered-out shale clasts, are all suggestive of a high-energy, shallow-marine to locally intertidal environment. An intraformational rhyolite clast-bearing conglomerate locally overlies the tuffaceous subunit and indicates penecontemporaneous reworking of volcanic rocks. Tourmaline in heavy mineral laminations probably reflects an admixed granite-derived component in the sedimentary rocks. The shallow-water depositional environment of the sedimentary lithofacies suggests that the intercalated tuffaceous units (including the volcanics) are possibly also shallow water. The transitional relationship between the sedimentary and volcanic lithofacies may suggest that the upper part of the latter may also be subaqueous; however, the bulk of the volcanic lithofacies may be subaerial.

Southernmost Ooradidgee (Kurundi / Hatches) succession in BONNEY WELL and FREW RIVER

This succession comprises the Ooradidgee Subgroup as it was originally defined by Blake *et al* (1985). It is referred to here informally as the *Kurundi / Hatches succession*. The descriptive details presented below are largely based on Blake *et al* (1986, 1987) and Stewart and Blake (1986). Defined lithostratigraphic units of this succession are the predominantly felsic volcanic/ pyroclastic Epenarra Volcanics, the mafic Edmirringee Volcanics and predominantly felsic Treasure Volcanics; and the sedimentary/volcaniclastic Rooneys Formation, and Kurinelli and Taragan sandstones. The Treasure Volcanics are correlated with the Mia Mia Volcanics of the Davenport Province, which contain minor felsic lava, but are predominantly a succession of pyroclastic and volcaniclastic rocks.

In common with other proximal volcanic successions, the mapped relationships between constituent defined lithostratigraphic units within the Kurundi / Hatches succession are complex. Furthermore, Stewart in Blake *et al* (1987) presented evidence that the deposition of the Taragan Sandstone, and specifically, the termination of this unit along the northwestern margin of the Edmirringee Block, which is coincident with its conglomeratic facies, was influenced by synsedimentary transfer and normal faulting.

The *Epenarra Volcanics* comprise subaerial felsic lava, and pyroclastic rocks that include ignimbrite, tuff, lapilli-tuff, agglomerate and ashstone (typically pale green chert); and intercalated fluviatile volcaniclastic sandstone, conglomerate (with volcanic clasts), quartz sandstone and siltstone (**Figure 9.14a–d**). The Epenarra Volcanics is well exposed in the Pingelly Block, where it locally unconformably overlies the Woodenjerrie beds (eg 53K 488984mE 7734740mN) on the faulted northern boundary of the block. Within the block, the succession predominantly comprises tuff, lava and quartzofeldspathic sandstone of probable penecontemporaneous volcanic provenance. Ignimbrite is a minor component, and rare mafic lavas occur interlayered with sandstone near the top of the sequence. Sandstone becomes more abundant up-succession where it has been mapped as a separate lithofacies. The *Treasure Volcanics* comprise similar rock types and are attributed to comparable subaerial and fluviatile palaeoenvironments, although sandstones in the upper part of the unit in western HATCHES CREEK REGION are probably marginal marine (Sweet in Blake *et al* 1987). Basaltic lavas are present in the Treasure Volcanics in the southwestern HATCHES CREEK REGION (**Figure 9.15**).

Blake *et al* (1987) reported that the mafic rocks of the *Edmirringee Volcanics* are massive or amygdaloidal lavas, and are typically non-porphyritic. Rare feldspar-porphyritic lava occurs locally near the middle of the type section. Pahoehoe lava appears to dominate, but Aa lava has been recognised locally (**Figure 9.16**). This example of Aa lava is apparently towards the base of the succession, but in the type section, Aa lava appears to be confined near the top of the succession. Locally at the base of the Edmirringee Volcanics, amygdaloidal basalt overlies the Epenarra Volcanics and it is inferred that the more massive middle and chilled lower intervals of the lowermost Pahoehoe flow are concealed by scree. The topmost interval of the Epenarra Volcanics at this locality comprises phenocrystic felsic volcanics. Quartz phenocrysts are equant and range up to 2 mm, and K-feldspar phenocrysts are inequidimensional and elongated with a maximum dimension of 2 mm. These phenocrysts are set in a very fine-grained, glassy-appearing matrix. Feldspar phenocrysts are locally aligned and define a eutaxitic texture, and the rocks are interpreted to be lavas. Probable, thin felsic tuff occurs above the base of the Edmirringee Volcanics and there are also minor intervals of quartzofeldspathic, probable volcaniclastic, sandstone. The type succession is in part recessive but at least twenty-four discrete lavas are recognisable (**Figure 9.17**). In detail, the succession, and particularly the stratigraphic level of minor felsic intercalations, contrasts with the succession in the Kurundi Anticline in the Davenport Province. This confirms the interpretation of Blake *et al* (1987) that these were separate volcanic centres. Prehnite and pumpellyite have been identified in the Edmirringee Volcanics from the Pingelly Block.

A 200 m-thick succession of rocks, intersected in drill core on the southern boundary of TENNANT CREEK is of uncertain stratigraphic affinity. The succession comprises rhyodacitic to rhyolitic crystal-lithic and lapilli tuff, and fine-grained tuff, together with andesitic to dacitic ignimbrite and lava overlain by lithic sandstones and siltstone. Volcanisedimentary mass flow units, overlain by autobreccia and massive flow-banded lava within this succession, are interpreted as part of a probable subaqueous cryptodome (Smith 2000). A dacitic lava from this succession has an igneous crystallisation age of 1852 ± 4 Ma (Smith 2000). These rocks were originally considered to be part of the Junalki Formation. This is now refuted, and their inclusion in the Ooradidgee Group is consistent with their crystallisation age. Geophysical interpretation has extended the distribution of the Epenarra Volcanics into this area. However, the Epenarra Volcanics have an igneous crystallisation age of 1840 ± 4 Ma (Claoué-Long *et al* 2005, 2008). It is therefore probable that these rocks are older than the Epenarra Volcanics. They may be correlatives of the Yungkulungu Formation volcanic lithofacies, and they indicate that, rather than being absent from this area, the lowermost Ooradidgee Group rocks simply do not outcrop in the vicinity of the Davenport Ranges (Kurundi-Hatches-Devils Marbles region succession; see **Figure 9.4**).

The remaining formations of the Ooradidgee Group in the Kurundi / Hatches succession are predominantly sedimentary units: the Rooneys Formation, Kurinelli Sandstone and Taragan Sandstone. The *Rooneys Formation* outcrops in the Edmirringee and Taragan blocks, where it comprises mainly fine-grained, and thinly bedded, feldspathic and sublithic to lithic sandstone. The *Kurinelli Sandstone* has a similar distribution in the Kurundi / Hatches succession, but elsewhere in the Davenport Province, it is the most widely distributed unit of the Ooradidgee Group formations. In the Kurundi / Hatches succession,

Figure 9.14. Sandstone interval near top of Epenarra Volcanics. (**a**) Lower bench comprises large-scale (ca 80–100 m-wide) trough cross-bedded interval of upper sandstone unit at 53K 485814mE 7729400mN, immediately overlying tuff and lava. Upper bench is massive to thickly bedded, cobble-bearing, granular, tabular cross-bedded sandstone with imbricate shale (tuff?) clasts and rare interference ripple marks. (**b**) Close-up of sandstone forming lower bench, showing small-scale trough cross-bedding. (**c**) Close-up of massive, cobble-bearing granular sandstone from upper bench in (a). (**d**) Close-up of chertified haematite shale clast in sandstone from upper bench at 53K 485852mE 7729279mN. Note close similarity between sandstone from upper bench (in a, c and d) and basal Unimbra Sandstone. These sandstones significantly predate (by ca 30 million years) the Unimbra Sandstone, but appear to share a similar provenance.

the Kurinelli Sandstone is predominantly lithic sandstone, siltstone and shale, but is locally schistose and there is an unnamed mapped conglomerate member underlying the Taragan Sandstone in the Edmirringee Block. Lenses of felsic lavas and possible ignimbrite, and basaltic lava have been mapped and possibly equate with the Epenarra and Edmirringee volcanics, respectively. Andesitic lava has been identified in the Hatches Creek tungsten field in the extreme southwest of the Kurundi / Hatches succession. The Kurinelli Sandstone includes two named members, the *Endurance Sandstone* and *Warnes Sandstone members*. In addition, schistose metasedimentary rocks and possible tourmalinite, and acid and basic volcanic rocks have been mapped locally in the Kurinelli Sandstone (Stewart and Blake 1986).

Figure 9.15. Poorly exposed mafic lavas in Treasure Volcanics looking west from 53K 511598mE 7696540mN. Three successive south-dipping mafic lavas form dip slopes on distant ridge.

Figure 9.16. Part of 50 cm-thick basaltic lava flow at 53K 484100mE 7725352mN. Lower part of flow shows laminations and locally cross-laminations, and has irregular contact with chilled, vesicular lava with brecciated (Aa) characteristics at top of flow.

The Rooneys and Kurinelli formations were interpreted by Sweet (in Blake *et al* 1987) to comprise a shallow-water deltaic system overlain by fluviatile braided river deposits. The Rooneys Formation conformably overlies the Epenarra Formation, and is conformably overlain by the Kurinelli Sandstone; it has been further interpreted to interdigitate with both these units (Blake *et al* 1986).

The *Taragan Sandstone* conformably overlies the Kurinelli Sandstone. It is characterised by an increased abundance of siltstone and mudstone (intercalated with feldspathic and lithic sandstone), in comparison with the uppermost Kurinelli Sandstone, and comprises a number of fining upward cycles. Sweet (in Blake *et al* 1987) recognised that this lowermost member of the Taragan Sandstone is overlain by fine-grained, rippled sandstone (middle member), which is in turn overlain by an upper member comprising pebble conglomerate and pebbly sandstone. Sweet attributed these members to braided stream, shallow-marine and alluvial fan sedimentation, respectively. The succession is about 600 to 900 m thick.

Two major episodes of felsic volcanism may be represented in the Kurundi / Hatches succession. The earlier of these episodes comprises the Epenarra Volcanics (ca 1840 Ma), and the subsequent episode includes the Treasure (ca 1813 Ma) and correlative Mia Mia volcanics of the Davenport Province. Stewart and Blake (1986) identified two volcanic centres associated with the Epenarra Volcanics, located ca 12 km east and 15 km west-northwest of Kurundi Homestead, and a further two centres that were active during eruption of the Treasure Volcanics, in the Murray Downs Dome and Hatches Creek tungsten field. The distribution of these volcanic rocks suggests that the locus of volcanic activity may have migrated ca 70 km to the southeast between the two periods of felsic volcanic activity (ie, those associated with the Epenarra Volcanics, and Treasure/Mia Mia volcanics).Mafic volcanism is represented in the Kurundi / Hatches succession by the Edmirringee Volcanics in

Figure 9.17. Lower Edmirringee Volcanics looking northwest from 53K 484100mE 7725352mN. View is parallel to and approximately 4 km southwest from Edmirringee Volcanics type section.

the Pingelly Block and by recessive basaltic lava in the Treasure Volcanics in the Taragan Block. These block names refer to structural blocks mapped in the Kurinelli / Hatches area and their extent is shown in Blake *et al* (1987: figure 9), and in **Figure 9.1**. Felsic lava within the Edmirringee Volcanics (KURUNDI REGION), and felsic and mafic lavas within the predominantly clastic Kurinelli Sandstone succession were interpreted by Blake *et al* (1987) to be consistent with partial interdigitation between the Edmirringee Volcanics, Treasure Volcanics and Kurinelli Sandstone. However, mapped relationships suggest it is possible that the Edmirringee Volcanics may largely postdate the Epenarra Volcanics, but predate the Treasure Volcanics. Mafic lavas are intercalated in the lower Treasure Volcanics in the southwestern HATCHES CREEK REGION (Blake *et al* 1986), and probable mafic lavas are similarly intercalated in the Epenarra Volcanics in the KURUNDI REGION (Stewart and Blake 1986) and HATCHES CREEK REGION (Blake *et al* 1986). The Edmirringee Volcanics conformably overlie the Epenarra Volcanics in the KURUNDI REGION (Stewart and Blake 1986), but elsewhere their relationship is not seen.

The Edmirringee Volcanics in the Warramunga Province constitute volcanism from one volcanic centre (Edmirringee Rockhole) of four that were identified by Stewart and Blake (1984). The other three centres associated with this unit (in the Kurundi Anticline, Skinner Anticline and Murray Downs Dome) are in the Davenport Province. The felsic Epenarra and Treasure volcanics are predominantly localised around centres in the Warramunga Province. However, the Epenarra and Treasure volcanics are associated with two centres (proximal to those of the Edmirringee Volcanics) in the Kurundi Anticline and Murray Downs Dome in the Davenport Province.

In the Kurundi / Hatches succession, the Epenarra Volcanics are of the order of 3000 m thick, and the Kurinelli Sandstone is about 2600 m. The Treasure Volcanics are approximately 2000 m thick in the Taragan Block, but wedge out in the Edmirringee Block and are absent from the Pingelly Block. The Rooneys Formation and Taragan Sandstone are both of the order of 800–1000 m thick. Given lateral facies variations and equivalence, it is difficult to estimate the thickness of the Ooradidgee Group in the Kurundi / Hatches succession; however, Blake and Page (1988) indicated that the unit is up to about 3000 m thick.

The Ooradidgee Group in the Kurundi / Hatches succession is extensively intruded by dolerite in the Edmirringee and Taragan blocks. The Edmirringee Volcanics probably predate, or are approximately coeval with dolerite intrusion. Possible dolerite sills within the Edmirringee Volcanics were noted by Blake and Horsfall (1986) in the ELKEDRA REGION. The latter, where not saussuritised, include quartz monzogabbro (Stewart and Blake 1986) and are considered to be contemporaneous with the gabbros intruding the upper Wundirgi Formation and Brumbreu Formation in the northern and western TENNANT CREEK succession of the Warramunga Province. A quartz-monzodioritic marginal phase of these gabbros has an igneous crystallisation age of 1821 ± 8 Ma (Compston 1995).

Hatches Creek Group?

The Hatches Creek Group is generally regarded as being characteristic of the Davenport Province. However, two units from within the Warramunga Province are tentatively assigned to this group. The Rising Sun Conglomerate has a very restricted contemporary geographical distribution and is apparently confined to a small largely fault-bounded block near Tennant Creek. The only other outcropping occurrence of probable Hatches Creek Group rocks in the Warramunga Province are sandstones proximal to the Kelly West astrobleme in southeastern KELLY, which Donnellan *et al* (1998) mapped as Unimbra Sandstone.

Rising Sun Conglomerate

The Rising Sun Conglomerate was defined by Crohn and Oldershaw (1965). Its outcrop is largely confined to the Rising Sun Ridge to the south of Nobles Nob mine (about 15 km east-southeast of Tennant Creek), where it extends for about 4 km east to west. Small outcrops of Rising Sun Conglomerate also occur immediately south of the Nobles Nob mine. Outcrops about 1.5 km northeast of the Rocky Range trigonometric station on the Yungkulungu Ridge are now mapped as Yungkulungu Formation (Donnellan *et al* 1995). The Rising Sun Conglomerate probably includes representatives of several formations mapped elsewhere and the unit is in need of further work and redefinition.

Crohn and Oldershaw (1965) reported that the Rising Sun Conglomerate rests with a marked angular unconformity on an erosional surface of porphyry and Warramunga Formation. They described the formation as comprising a lower unit of grit, conglomerate and quartzite that is overlain by a unit of interbedded siltstone and sandstone. Blake (1984) recognised that the porphyry underlying the Rising Sun Conglomerate immediately to the north of Rising Sun Ridge is an extrusive ignimbrite and that it overlies the Warramunga Formation with an erosional unconformity. Blake correlated this porphyry, together with overlying tuff and conglomerate (at the base of the Rising Sun Conglomerate), with the Epenarra Volcanics, and the overlying quartz sandstone with the Unimbra Sandstone of the Davenport Province. Blake recognised a localised, topmost conglomerate within the original Rising Sun Conglomerate succession, which unconformably overlies an irregular erosional surface on the quartz sandstone, and correlated this uppermost conglomerate with the Ediacaran Andagera Formation of the Georgina Basin. Donnellan *et al* (1995) mapped the porphyry and tuff as part of the Yungkulungu Formation, and the overlying conglomerate, sandstone and quartzite as a correlative of the Andagera Formation, although they retained the name Rising Sun Conglomerate. Tuffaceous siltstone and sandstone at the top of the succession were mapped as early Cambrian Helen Springs Volcanics of the Kalkarindji Province. In contrast, Donnellan and Johnstone (2004) correlated the conglomerate and quartzite in the main outcrop at Rising Sun Ridge with the Blanche Creek and Manga Mauda members of the Hayward Creek Formation of the Tomkinson Creek Province (and by implication the Unimbra Sandstone). This correlation had previously been made by Crohn and Oldershaw (1965).

As currently mapped, the Rising Sun Conglomerate comprises three intervals of conglomerate separated by pebble- and cobble-bearing, very coarse-grained quartz sandstone, with a total thickness of ca 25 m, conformably overlain by up to 60 m of rippled marked, cross-bedded quartz sandstone with a minor component of white feldspar grains. The basal conglomerate overlying the porphyry has a volcaniclastic matrix. There are abundant mudstone clasts or casts on the bedding surfaces of the quartz sandstone, as well as minor fine-grained sandstone and siltstone interbeds. The lower conglomerate and interbedded granular sandstone thins to the west, and there is a concomitant decrease in clast size in the conglomerate and a similar decrease in the relative proportion of conglomerate to interbedded sandstone, which suggests a local derivation from the east. The Rising Sun Conglomerate also thins to the north where it overlies 'porphyry'. Localised conglomerate outcrops that are stratigraphically above the quartzite probably comprise either the Ediacaran Andagera Formation (or possibly the Muckaty Sandstone Member of the Helen Springs Volcanics), and disconformably overlying tuffaceous sandstone and siltstone are assigned to the Helen Springs Volcanics.

Clasts within the Rising Sun Conglomerate comprise coarse- to fine-grained sublithic-quartz sandstone, quartzite and jasper, and Ivanac (1954) and Crohn and Oldershaw (1965) identified recycled boulders within the conglomerate that contain quartzite, jasper and chert pebbles. As noted previously, the matrix includes volcanic-derived material. Clast types within the Rising Sun Conglomerate are not diagnostic with respect to provenance. Similarly, pebbly sandstone and conglomerate in the Ooradidgee, Hatches Creek and Tomkinson Creek groups contain variable amounts of igneous-derived clasts, as well as vein quartz, in addition to 'basement'-derived quartzite clasts. This lack of any specific, diagnostic clast type(s) inhibits the interpretation of provenance and correlations between lithostratigraphic units. Thus, for example, a correlation between the Rising Sun Conglomerate and conglomerate in the Gleeson Formation at the base of the Mesoproterozoic Renner Group (Tomkinson Creek Province) in HELEN SPRINGS satisfies the criterion of comparable constituent clast types. However, a correlation of the unit with the Blanche Creek Member and the Manga Mauda Member in part (Hayward Creek Formation of Tomkinson Creek Province) and the Unimbra Sandstone (Davenport Province) seems to be more plausible.

Correlation between the Rising Sun Conglomerate, the Blanche Creek and part of the Manga Mauda members of the Hayward Creek Formation, and the Unimbra Sandstone implies that there may be regionally widespread unconformity between the Ooradidgee and Hatches Creek groups. However, as noted above, this relationship is often ambiguous locally. Thus, for example, Blake (1984) interpreted a conformable relationship between the volcanic rocks and the conglomerate in the Rising Sun Ridge, whereas Crohn and Oldershaw (1965) and Donnellan *et al* (1995) interpreted that the conglomerate overlay the volcanic rocks with an angular unconformity. It is interesting to note that in proposing their correlation between the Rising Sun Conglomerate and the Blanche Creek Member of the Hayward Creek Formation, Mendum and Tonkin (1976) suggested that there was probably a significant time break between the Ooradidgee and Tomkinson Creek groups. They further noted that any tectonic discordance between these groups is probably obscured by two phases of folding postdating Tomkinson Creek Group deposition.

Ca 1820–1810 Ma Treasure Suite intrusive rocks

The ca 1820–1810 Ma Treasure Suite (**Table 9.4**) was defined by Wyborn *et al* (1998). The suite is mainly represented in outcrop by dacitic, rhyolitic and basaltic volcanic rocks, shallow intrusive granophyres and felsic porphyries, monzodiorite, diorite and gabbro. The volcanic rocks of the suite (ie the Treasure, Newlands, Arabulja and Strzeleckie volcanics) are described in the relevant stratigraphic sections above, or in **Davenport Province**. A monzodioritic marginal phase of a dolerite intruding the Wundirgi Formation in the vicinity of the Last Hope Mine has been dated at 1821 ± 8 Ma (Compston 1994). Baddelyite from dolerite intruding Ooradidgee Group rocks in the Kurinelli area of the Warramunga Province has yielded a crystallisation age of 1811 ± 5 Ma (Maidment *et al* 2006, Claoué-Long *et al* 2008). Poorly exposed (but clearly widespread according to the airborne magnetic data) dolerite sills, which intrude the Hayward Creek Formation, are probably of about the same age. Blake *et al* (1987) recorded that dolerite and gabbro sills that intruded Ooradidgee Group rocks in the Hatches Creek tungsten field were grouped together with granophyre intrusions as the Pedlar Gabbro by Ryan (1961). However, they questioned the validity of this grouping in the absence of any compositionally intermediate rock types. The crystallisation ages of the Kudinga and Whittington Range basalts have not been established; however, these are also considered broadly contemporaneous with the Treasure Suite. The intrusive dolerites and gabbros in the Kurinelli area have been interpreted as probably comagmatic with the Kudinga Basalt (Blake *et al* 1987, Claoué-Long *et al* 2008).

A melanocratic amphibole- and biotite-bearing quartz diorite locally intrudes the Mumbilla Granodiorite. The diorite has an irregular chilled contact with the host granodiorite, and lacks either a foliation or strained quartz. It could represent a cumulate residual phase of the granodiorite or a later intrusion. It is provisionally included in the Treasure Suite. This is consistent with a U-Pb zircon igneous crystallisation age of 1841 ± 6 Ma that was reported for this rock by Compston (1994).

Moderately foliated to mylonitic felsic schists in the Wundirgi Formation to the southwest of Tennant Creek township have been interpreted as sheared granite or porphyry, and granophyric volcanic rocks from this area have been dated at 1829 ± 8 Ma and 1827 ± 9 Ma (Compston 1995). A previously determined Rb-Sr age of 1920 ± 60 Ma for 'amphibolite' from this same area was interpreted as the age of metamorphism and led to the subsequently unsubstantiated conclusion that the rocks in this area represented basement to the Warramunga 'Group' (Black 1977).

There are no known outcropping Treasure Suite granites in TENNANT CREEK. However, Wyborn *et al* (1998) suggested that the Treasure Suite may be implicated with respect to Tennant Creek-style Cu-Au-Bi mineralisation. Wyborn *et al* suggested that a gravity low coincident with the Tennant Creek goldfield may reflect Treasure Suite granitic material in the subsurface, on the basis of the lower density of the Treasure Suite in comparison with to the Tennant Creek Supersuite granites. M Roach (University of Tasmania, pers comm 2006) concluded that this distinction cannot be made on the basis of currently available gravity data.

Ca 1720–1700 Ma Devils Suite

The Devils Suite (**Table 9.4**) was defined by Wyborn *et al* (1998), who described the suite as comprising fractionated, fluorite-bearing I- (granodiorite) type granites, including the Warrego Granite in the Warramunga Province, and the Elkedra and Devils Marbles granites in the Davenport Province. Donnellan and Johnstone (2004) also assigned the Gosse River East Syenite, and the 'unnamed younger granites' of Blake *et al* (1987) to the Devils Suite. In contrast with both the Tennant Creek Supersuite and the Treasure Suite, no extrusive rocks are known to be associated with the Devils Suite. Devils Suite granites appear to show a spectrum of peraluminous compositions, ranging from the monzogranitic Devils Marbles, Elkedra and Warrego granites to the monzonitic Gosse River East Syenite, and also include locally more granodioritic phases in the Elkedra and Warrego granites.

Unit	Rock types	Relationships	Structures	Igneous crystallisation age
DEVILS SUITE				
Warrego Granite	Massive, coarse-grained and equigranular, two-mica, corundum-bearing granite to granodiorite; locally greisenous.	Intrudes Warramunga Fm and Ooradidgee Subgroup; and is intruded by dykes and pods of pegmatite, and by quartz veins. Knotted quartz-muscovite schist forms contact aureole up to 400 m wide; granite has also metamorphosed Warrego Cu-Au-Bi deposit.		ca 1645 Ma?
Gosse River East Syenite	Probably quartz monzonite rather than syenite.	Does not outcrop. Intersected in drill core ca 45 km east of Tennant Creek township.		1712 ± 5 Ma
unnamed lamprophyre	Minette (and minor vogesite).	Intrudes Warramunga, Yungkulungu and Wundirgi formations, and Hill of Leaders Granite.	Massive to foliated.	*1711 ± 2 Ma*
TREASURE SUITE				
Unnamed dolerite / gabbro II (and III?)	Fine-grained dolerite to coarse-grained gabbro; often saussauritised or uralitised; locally approaches quartz monzogabbro in composition (*cf unnamed monzodiorite below*).	Folded sills (and minor dykes) in Ooradidgee Group (Rooneys Fm, Kurinelli and Taragan sandstones, and Edmirringee Volcs); sills are up to about 100 m thick; irregular intrusive bodies. Sills also extensively intrude Hayward Creek Fm (Tomkinson Creek Group) and, to a minor extent, Unimbra Sst (Hatches Creek Group). Ryan (1961) combined gabbro with granophyre in Pedlar gabbro, but Blake *et al* (1987) noted that there are no rocks of intermediate composition between these end-members. However, quartz dolerite locally intruding Unimbra sandstone appears to grade into dacitic granophyre.		***1811 ± 5 Ma*** (and 1821 ± 8 Ma Last Hope dolerite); may be comagmatic with either Kudinga Basalt or mafic volcanics in Treasure Volcs. Errors on reported crystallisation ages overlap. This may mean that there was: (a) only one, rather than two phases of mafic sill (/dyke) emplacement: (b) that there was one phase of sill emplacement extending over ≤10 my; or (c) that there were two phases of sill emplacement of short duration, but seperated by ca 10 my (ie dolerite/gabbro II and III).
unnamed monzodiorite	Monzodiorite forming marginal phase of 1821 Ma Last Hope dolerite.	Sills intruding Ooradidgee Group (Wundirgi and Brumbreu formations).		1821 ± 8 Ma
unnamed diorite	Diorite, quartz-diorite.	Small pluton and dykes; may locally form part of dolerite/gabbro sills.		1841 ± 6 Ma. Intrudes and metamorphoses 1850 Ma Mumbilla Granodiorite.
unnamed granophyre	Dacitic to rhyolitic granophyre and minor microgranite.	Intrudes Ooradidgee Group (Epenarra Volcs, Rooneys Fm, Kurinelli Sst, Taragan Sst, Treasure Volcs and Wundirgi Fm). Forms sills, laccoliths and dykes up to several hundred metres thick. Locally, intrudes unnamed (probable Tennant Creek Supersuite) granite, and is intruded by dolerite.	Foliated.	Postdates lower Wauchope Subgroup and predates 1720 ± 6 Ma Elkedra Granite; 1827 ± 9 Ma foliated felsic schist (granophyric felsic volcanic) in Wundirgi Fm.
unnamed (younger) granite	Fine- to coarse-grained, porphyritic to equigranular, biotite- and biotite-muscovite-bearing granite with accessory allanite, apatite, titanite, zircon and opaque oxides.	Intrudes Rooneys Fm, and Kurinelli and Taragan sandstones. Locally sheared.	Generally massive, locally faulted and brecciated.	Tentatively assigned to Treasure Suite.

Table 9.4. Summary of Palaeoproterozoic Treasure Suite and Devils Suite intrusive rocks of Warramunga Province. Ages reported in ordinary type are from Compston (1995); those in italic type are from Maidment *et al* (2006); and those in bold italic type are from Claoué-Long *et al* (2008a). Note that three generations of dolerite (designated II and III in this table and I in **Table 9.2**) are recognised in Warramunga Province.

The *Gosse River East Syenite* does not outcrop, but was intersected in drill core, approximately 45 km east of Tennant Creek township. It is probably a quartz monzonite, rather than a granite or syenite in modal composition; however, the original name is retained here.

The *Warrego Granite* is a two-mica, corundum-bearing, massive, coarse-grained granite or granodiorite; however, the relative proportions of the different feldspars are difficult to determine due to weathering and sericitisation. Drill core samples have microcline as the sole alkali feldspar and associated plagioclase is slightly zoned, with sericitised andesine or oligoclase cores and unaltered albite rims. Muscovite books are undeformed, iron-rich chlorite replaces primary biotite, and Mendum and Tonkin (1976) reported that minor hornblende also occurs. Accessory minerals in the granite are corundum and apatite, and minor amounts of titanite and zircon also occur. The granite is greisenised proximal to its eastern contact and similarly, the country rock has been intensely metamorphosed over a distance of up to 400 m to a knotted quartz-muscovite schist. Xenoliths comprise metasedimentary rocks and fine-grained quartz-muscovite rock from the metasomatised marginal zones of the granite that has been reincorporated within the main, coarse-grained equigranular granite. The Warrego Granite has contact metamorphosed the Warrego Au-Cu-Bi deposit (Wedekind and Love 1990).

The Gosse River East Syenite has an igneous crystallisation age of 1712 ± 5 Ma (Compston 1995). This granitoid is similar in age to the Devils Marbles Granite (1711 ± 4 Ma, Page 1995) and the informally named Kaidwalla granite in the southeastern Davenport Province (1707 ± 4 Ma, Maidment *et al* 2006). The Elkedra Granite has been dated at 1720 ± 6 Ma, but a single concordant zircon, giving an age of 1633 ± 20 Ma, was obtained in the analysis (Page 1995). The age of the Warrego Granite is uncertain. Black (1977) reported a whole-rock Rb-Sr isochron age of 1703 ± 100 Ma. The large error was attributed to the small range in $^{87}Rb/^{86}Rb$ ratios in the samples. The selective inclusion of a chlorite analysis resulted in an age of 1662 ± 20 Ma. The concordance of three muscovite separates with this whole-rock plus chlorite isochron led Black to conclude that the Warrego Granite is ca 1690 Ma. Single-crystal SHRIMP U-Pb zircon geochronology by Compston (1995) resulted in 1857 ± 12 and 1844 ± 12 Ma ages for inherited xenocrysts, and clusters of dates at ca 1650 and ca 1800 Ma. Rim growth on pre-existing grains was dated at ca 1650 Ma. This younger age was Compston's (1995) preferred crystallisation age for the Warrego Granite, although Compston did point out that the population of low-U zircons with ca 1800 Ma ages could represent the crystallisation age of the granite. Budd *et al* (2002) included the Warrego Granite, along with the Devils Marbles and Elkedra granites, in the (ca 1710 Ma) Devils Suite. There are no known outcropping Treasure Suite granites in TENNANT CREEK, so a ca 1800 Ma igneous crystallisation age for the Warrego Granite would be geologically significant. However, the Warrego Granite is texturally and compositionally distinct from known ca 1800 Ma granites, ie the Ooralingie (1809 ± 5 Ma) and Bean Tree (1803 ± 6 Ma) granites from immediately adjacent to the Tennant Region, in the Aileron Province of the Arunta Region.

Lamprophyre sills, dykes and laccoliths (up to 12 m thick) have intruded the Warramunga, Yungkulungu and Wundirgi formations. Lamprophyre has also intruded the Hill of Leaders Granite. Crohn and Oldershaw (1965) reported the occurrence of rare amphibole-, and pyroxene-bearing lamprophyre (vogesite) intruding the Warramunga Formation. However, Jaques *et al* (1985) classified the majority of the lamprophyres as magnesian minettes, consisting of phlogopite phenocrysts in a biotite-rich groundmass. These rocks have high magnesium, chromium and nickel contents. Duggan and Jaques (1996) recognised two groups of minettes in the Warramunga Province and summarised their contrasting geochemical characteristics as follows: (a) group 1 has Zr/Nb >20, with generally higher Sr, Ba and LREE, and lower U, Th and HREE contents by comparison with (b) group 2, which has Zr/Nb <12.

Owen (1940) recognised what he described as 'pre-gold' hornblendites at the Pinnacles and Mary Lane mines, and a thin horizontal sill of 'post-gold' (ortho)pyroxenite at the Euro, Caroline and Nipples mines. Gently south-dipping pyroxenite was locally seen to intersect a vertical ironstone body at the Caroline deposit, and is itself essentially vertical within the foliation of the country rock at the Euro mine. The hornblendite is metamorphosed to hornblende-serpentine schist and tremolite schist at the Pinnacles mine, and to chlorite schist at the Mary Lane mine. Owen (1940) further reported chrysotile-bearing serpentine at the Euro mine. Owen's (1940) observations raised the possibility that there may be two generations of lamprophyre at Tennant Creek, the earlier generation potentially contemporaneous with the Tennant Creek Supersuite.

Black (1977) dated lamprophyre from TENNANT CREEK at 1664 ± 16 Ma with an initial $^{87}Sr/^{86}Sr$ ratio of 0.701 ± 0.002. This isochron is based on whole-rock and mineral separates from the East New Hope and Ivanhoe mines in the Tennant Creek goldfield and included samples from each of the two geochemically distinct groups of minettes (see above). Compston and McDougall (1994) reported a K-Ar (minimum) age of 1700 Ma for a TENNANT CREEK lamprophyre.

Geochemical data presented by Blake *et al* (1987) for a lamprophyre dyke intruding the Hill of Leaders Granite suggest that this rock should be included in the high Zr/Nb group 1 minettes (and this is apparently corroborated by its other geochemical characteristics, eg high Sr, and low Th and U). Page (1995) determined SHRIMP U-Pb zircon age groupings of 1715 ± 11 Ma and 1690 ± 18 Ma for this lamprophyre. Maidment *et al* (2006) reported a SHRIMP U-Pb zircon age of 1711 ± 2 Ma for a separate sample from the same lamprophyre dyke within the Hill of Leaders Granite. They interpreted this to be the igneous crystallisation age of the lamprophyre.

METAMORPHISM

The Warramunga Formation is regionally metamorphosed to sub- to lowermost-greenschist grade. Localised contact metamorphic effects are also recognised.

Widespread slaty cleavage in the Warramunga Formation is defined by the alignment of fine-grained iron oxide minerals, sericite, mica and chlorite, and by differentiation between these domains and siliciclastic microlithons. Locally, in high-strain zones, phyllosilicate minerals are more coarse grained and crenulations more pronounced. Plagioclase is partially sericitised but is not generally recrystallised as albite in the Warramunga Formation. Quartz shows undulose extinction. Locally, in shear zones the Warramunga Formation is schistose.

Whittle (1966) reported amphibolite facies mineral assemblages (eg garnet-mica, grunerite-garnet, and hornblende-tremolite-garnet gneiss) from drill core 30km west-southwest of Tennant Creek township. Black (1977) interpreted that a nine point Rb-Sr whole-rock isochron indicated a 1920 ± 60 Ma model 3 age for the amphibolite facies metamorphism of these rocks and suggested that they may predate, and therefore represent basement to the Warramunga Formation. However, Compston (1995) determined an 1827 ± 9 Ma age for foliated felsic schist, that he interpreted: (1) to be a granophyric felsic volcanic or intrusive rock, and (2) to provide a minimum age for the associated sedimentary rocks. It is unlikely that these rocks predate Warramunga Formation, and are most likely part of the Ooradidgee Group succession. Compston and McDougall (1994) interpreted Ar-Ar and K-Ar ages for muscovite from these rocks to indicate metamorphism at *ca* 1700 Ma.

A 30 m-wide spotted hornfels with poikiloblastic biotite is developed in the Warramunga Formation at the contact with the Tennant Creek Granite. Crohn and Oldershaw (1965) described the recrystallisation of fine-grained Warramunga Formation sedimentary rocks as an interlocking mosaic of quartz, whereas sericite is irregularly scattered throughout these contact rocks. Wedekind and Love (1990) reported that the Warrego Granite has contact metamorphosed the hydrothermally altered Warramunga Formation sedimentary rocks hosting the Warrego orebody. These authors reported metaquartzite and chlorite spotted-slate, and noted that in the footwall stringer zone (at greater depth in the mine), chloritised sedimentary rocks contain euhedral andalusite or porphyroblastic cordierite.

Diorite and monzodiorite (of the Treasure Suite) intruding Ooradidgee Group rocks near Last Hope in the northwest of the Tennant Creek goldfield show replacement of clinopyroxene, hornblende and biotite by ferroactinolite and chlorite-bearing assemblages, and also show sericitisation and epidotisation of plagioclase. These may represent alteration rather than metamorphic assemblages as they are not associated with development of a foliation, nor are they retrogressive with respect prior deformation-associated metamorphic assemblages. Haematite and chlorite-carbonate veining is also developed in these rocks.

Blake in Blake *et al* (1987) described a range of characteristics that are indicative of predominantly greenschist-facies metamorphism in Ooradidgee Group rocks. These included: (1) cleavage development, with associated white mica and biotite or chlorite, particularly in tuffaceous rocks; (2) albitisation of plagioclase, deformed quartz, and chloritisation or biotitisation of both groundmass and ferromagnesian minerals in felsic lavas and ignimbrites; and (3) local prehnite-pumpellyite-, but predominantly greenschist-facies mineral assemblages (albite, actinolite, epidote, chlorite, biotite) in basic lavas and intrusive rocks, although primary igneous textures are, at least in part, preserved.

STRUCTURE

East–west-trending folding (F_1) in the Warramunga Formation (and its correlatives) has a well developed, axial planar slaty cleavage (S_1; Ivanac 1954, Dunnet and Harding 1967, Mendum and Tonkin 1976, Rattenbury 1992a, 1994, Donnellan *et al* 1995). The subscripts used for deformation events and cleavages in this section are based on Donnellan *et al* (1995). The relationship of these to the various original schemes of a number of different workers in the Tennant Creek goldfield is summarised in **Table 9.5**. On a regional scale, F_1 folds are cylindrical, open to close and have horizontal fold axes (Rattenbury 1992a, 1994). The cleavage is variously defined by iron oxides, fine-grained mica and chlorite. This phase of folding, associated low-grade metamorphism and penecontemporaneous (predominantly felsic) magmatism is now assigned to Tennant Event. A prior phase of folding in the Warramunga Formation was postulated by Dunnet and Harding (1967), following their structural studies in the Mount Woodcock one-mile sheet. However, this was refuted by Mendum and Tonkin (1976), after structural studies in the Marion Ross 1:50 000 map area.

Ivanac (1954) noted that the strike of bedding was westerly in the south, and tended more northwesterly in the north of the Tennant Creek goldfield. Ivanac also recognised a second, superimposed phase of folding about northeast-trending axes. Dunnet and Harding (1967) recognised that the second phase of deformation comprised conjugate shears with an associated fracture or crenulation cleavage (ie northwest-trending S_2, **Figure 9.18a**), or a crenulation cleavage (ie northeast-trending S_3). The style of associated folds is variable, depending on the relative degree of shearing, but an open, chevron style of folding is common. Small-scale chevron folds, associated with D_2, are well preserved (eg, in the Mary Lane shear zone, **Figure 9.18b**). Dunnet and Harding (1967) recognised conflicting timing relationships between these conjugate structures. One or other of these structures is dominant in any given area. In the Quartz Hill subarea, an S_3 cleavage was recognised and interpreted to be either synchronous with, or to postdate S_2. Besides the quartz-filled, northwest-trending Quartz Hill–Rocky Range and complementary northeast-oriented shears in the Tennant Creek one-mile area, Crohn and Oldershaw (1965) recognised a number of additional, consistently oriented shear zones, faults, ironstones and quartz veins (see **Figure 9.19**). They concluded that the mineralised shears (ie, those hosting ironstone ± gold-copper-bismuth) predominantly trend westerly, but also trend west-northwesterly or east-northeasterly. However, the most prominent (and apparently generally non-mineralised) shears trend northwesterly or northeasterly and are typically quartz-filled; additional minor sets of shears trend north-northwesterly and north-northeasterly.

Ivanac (1954)		**D1**, W-trending folds F_1		**D_2**, superimposed NE-trending folds F_2	
Dunnet and Harding (1967)	**D_1**, a phase of folding (F_1) inferred from relationship of D_2 structures: (a) rapid plunge reversals of mesoscale D_2 folds, and the S_0/S_2 intersection lineation; (b) symmetrical distribution of poles to bedding about NW-trending fold axes.	**D_2**, main phase of W-trending folding (F_2), slaty cleavage (S_2) development, and (more or less) contemporaneous metamorphism.		**D_3**, two conjugate structural elements: (1) NE-trending faults and crenulation cleavage, S_4; (2) NW-striking faults, fracture/crenulation cleavage, S_3. Associated (F_3, F_4) fold style is variable depending on degree of shearing, but open, chevron folds are common.	
Crohn and Oldershaw (1965)		**D_1**, E–W folding.	**Late D_1 or D_{1a}***, W-, ENE-, and WNW-striking shears associated with ironstone bodies (and occassionally Au-Cu mineralisation). (Timing[†] inferred from association with mineralisation, eg Nguyen *et al* 1989).	NW- and complementary NE-trending quartz-filled shears and faults.	Minor NNW- and NNE-trending shear zones or faults. (Timing[†] not known, inferred to be late from regional map).
Mendum and Tonkin (1976)	**No D_1**, refuted Dunnet and Harding's F_1, and attributed it to Dunnet and Harding's conjugate D_3 being superimposed on their D_2.	**D_2**, F_2 Open to close, gently NNW-plunging folds.		**D_3 and D_4**, synchronous asymmetric sinistral, dextral, and symmetric chevron folds; and sinistral and dextral kink bands F_3 and F_4. Viewed down-plunge F_3 generally dextral, F_4 sinistral. Penetrative axial planar cleavage (S_3), and closely spaced fracture cleavage (S_4). Generally NW-trending faults include dextral and (more rarely) sinistral strike-slip faults.	
Rattenbury (1992a)		**D_1**, upright, open to close, horizontal W-trending folds(F_1) and thrust faults. Folding is disharmonic, and probably therefore thin-skinned.		**D_2**, strike-slip faults, kink folds.	**D_3**, strike-slip faults.
Donnellan *et al (*1995)		**D_1**, west-trending F_1 folds.	Shearing of late syn-tectonic granite and porphyry.	**$D_2/D_{2'}$**, conjugate NW (S_2) and NE ($S_{2'}$) weak crenulation cleavages and associated folds [mesoscale chevron folds; meso- and macro-scale kink (and rare open?) folds; rare meso-scale asymmetric conjugate kink folds]. Faults.	N-trending cleavage recognisable locally throughout Warramunga Formation. NNE-trending faults?
Donnellan *et al* (2001)		**D_1**, west-trending F_1 folds and faults.	**$D_2/D_{2'}$** shears, faults and folds trending west-northwest and/or east-northeast.	**$D_3/D_{3'}$** northwest- and northeast-oriented shears, faults and folds.	
Current interpretation		**D_1**, upright, open to close, horizontal W-trending folds (F_1) and thrust faults.	**D_{1a}**, ENE- and WNW-striking shears associated with brecciation of ironstone bodies (and occasionally with Au-Cu mineralisation). Local folds.	**$D_2/D_{2'}$**, NW and NE-striking strike-slip faults and shear zones, chevron and kink folds.	
Deformation event		*Tennant Event*, ≥ca 1850 Ma. Ironstone formation? Wedekind *et al* (1988) noted that (except where subsequently reoriented) individual ironstone bodies are generally in the plane of the E–W cleavage, with their long axes vertical (or less commonly horizontal).	*Murchison Event* ca 1815–1805 Ma, postdates (ca 1850–1845 Ma?) D_{1a} and predates Davenport Event. Probably mainly associated with extension, and emplacement of mafic sills in Ooradidgee and lower Tomkinson Creek groups?	*Davenport Event*, post-1790 Ma and possibly ca 1710 Ma? Rattenbury (1990) noted that the strong cleavage (S_1) in the Mary Lane Shear (MLS) has been folded. These F_2 folds have either sinistral or dextral vergence. (This F_2 folding is interpreted to be contemporaneous with concentric and disharmonic folding (and thrusting) (F_1) in Ooradidgee, Hatches Creek and Tomkinson Creek groups).	

Table 9.5. Comparative summary and interpreted correlation of regional structural events recognised by various workers in Tennant Creek goldfield. *Deformation resulting from late-stage of progressive D_1 or superimposed D_{1a} (ca 1850–1845 Ma)? Eg: (1) Rattenbury (1992b) noted that the ENE-striking MLS was developed slightly oblique to the regional E–W fold (F_1) axes, resulting from a slightly oblique (dextral) component to the predominantly reverse movement on the shear zone; (2) shear zone postdates, but subparallel to F_1 at White Devil and hosting Au-Cu mineralisation (Nguyen et al 1989); and (3) Skirrow and Walshe (2002) recognised that generally ESE-plunging parasitic folds (that host Eldorado deposit) may result from superposition of a second fold set or from shearing of F_1, resulting in reversals of minor fold plunge and non-cylindrical forms. E–W-oriented local groups of ironstones have an apparent en echelon arrangement in a number of WNW-trending 'Lines of lode' (eg Juno, Peko, Lone Star and Gecko lines). Brecciation and shearing of ironstones. Au-Cu mineralisation. †Note that Crohn and Oldershaw (1965) did not indicate relative timing relationships, those that are inferred herein are shown in brackets.

Three cleavages (S_1, S_2 and $S_{2'}$) have been recognised in the Warramunga Formation (**Figure 9.20**) and were mapped throughout the Tennant Creek goldfield by Donnellan *et al* (1995: figures 28, 29). These authors considered that the second deformation may have been progressive. Probable incremental cleavages are recognisable locally, but were not generally measured, given that the three cleavages routinely measured appeared to encompass the major elements of the structural history of the Warramunga Formation. A similar situation was recognised in the Quartz Hill area by Mendum and Tonkin (1976), and they also recognised two northwest-oriented cleavages in the Olive Wood area. Mendum and Tonkin reported that S_1 was locally obliterated by S_2; this was not apparent to Donnellan *et al* (1995), although they did recognise that S_2 is locally a well developed slaty cleavage. The superimposed structures (D_2) were considered conjugate and close to synchronous by Mendum and Tonkin (1976) and Donnellan *et al* (1995). Locally, there is evidence for conflicting timing relationships between northeast- and northwest-oriented crenulation cleavages (Dunnet and Harding 1967, Mendum and Tonkin 1976, Donnellan *et al* 1995), although generally, the northwesterly-striking cleavage predates that striking northeasterly, and the northwesterly trend is generally dominant.

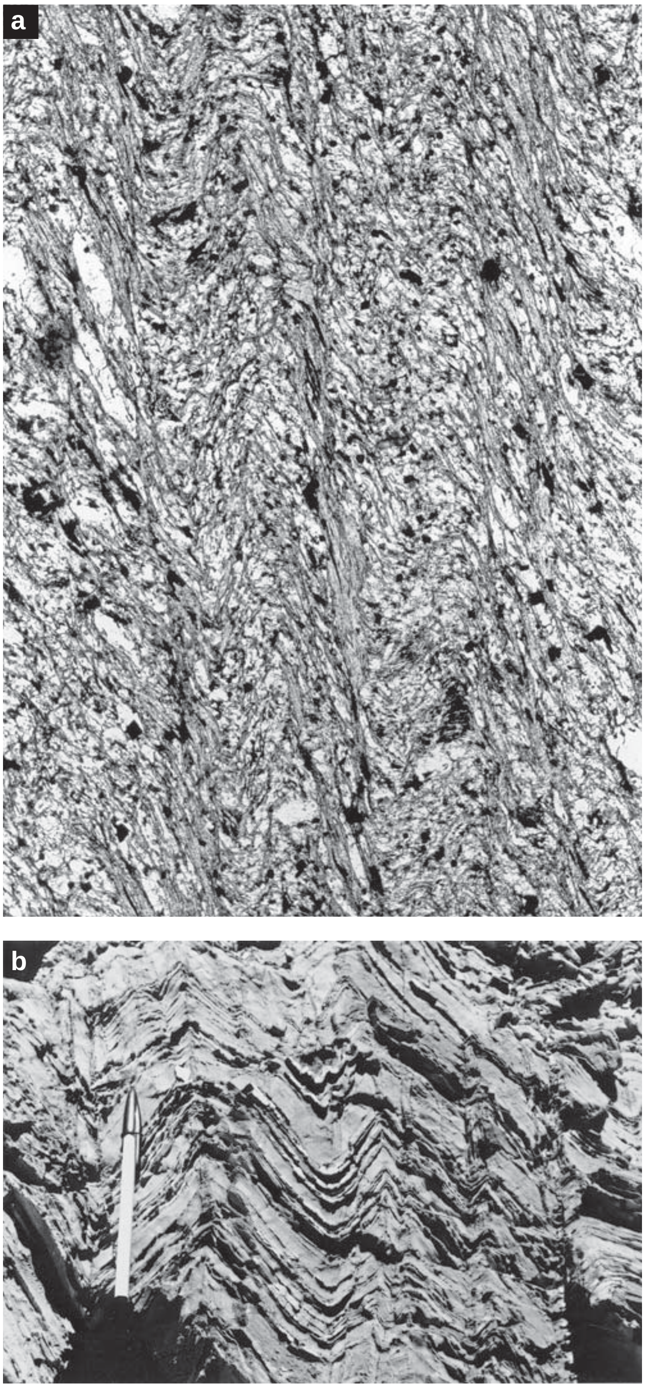


Figure 9.18. (**a**) Warramunga Formation phyllite at 53K 463000mE 7818200mN, showing S_1 slaty cleavage crenulated by spaced, differentiated S_2 cleavage. Length of field of view is 4.2 mm. (**b**) Chevron folding in Mary Lane Shear Zone.

F_2 folds are recognisable in major northwest- and northeast-striking kink bands. Reorientation of S_0 and S_1, particularly adjacent to the Quartz Hill–Rocky Ridge trend (eg Iris, and Olive Wood–Orlando mine areas), is consistent with superimposed northwest-plunging folds. This superimposed folding probably corresponds with that previously recognised by Dunnet and Harding (1967) in the northern part of the Tennant Creek goldfield. A similar effect was apparently recognised at Warrego by Goulevitch (1975). However, the deformation at Warrego was probably contemporaneous with the emplacement of the Warrego Granite, and may therefore postdate the regional D_2. In the extreme southeast of the Warramunga Formation area of outcrop, the effects of superimposed northeast-plunging folds are apparent, consistent with the northeast-oriented cross-folding originally recognised by Ivanac (1954).

Rattenbury (1992a, 1994) developed a thin-skinned fold/thrust model for the east–west-oriented folding in the Warramunga Formation, and for the later superimposition of asymmetric kink-folding and associated strike-slip faulting. Rattenbury (1992a) calculated bedding-cleavage intersection lineations to investigate fold plunge variability on a smaller scale, and concluded that in the southern part of the goldfield, superimposed folding is unlikely to have rotated F_1 fold axes without deforming the S_1 cleavage, which has remained planar. Conversely, he suggested that the conical distribution of bedding reported by Dunnet and Harding (1967) in the northern part of the goldfield may reflect superimposed strike-slip deformation with steeply northwesterly dipping fold axes. Northwest-oriented folding is well developed in the Orlando and Queen of Sheba mine areas, where Dunnet and Harding (1967) recognised a change from northwest to southeast fold plunges, which they attributed to possible superimposition of northwest-on-west-oriented phases of folding.

A regional tectonic unconformity (related to the ca 1860–1850 Ma Tennant Event) is recognised between the Warramunga Formation (and the correlative Woodenjerrie beds and Junalki Formation) and the Ooradidgee Group (Smith *et al* 1961, Blake 1984, Blake *et al* 1987). Two phases of concentric folding (now called the Davenport Event) have been recognised in the Ooradidgee and Hatches Creek groups (Blake *et al* 1987). Northwest-oriented folds are superimposed by northeast-trending folds in the Ooradidgee and Hatches Creek groups resulting in type one interference folds, but Blake *et al* (1987) did not provide any details of the temporal separation of these two phases of folding, which were subsequently interpreted to be contemporaneous with $D_2/D_{2'}$ in the Warramunga Formation (Donnellan 2005).

Faulting

Faults in TENNANT CREEK are only very discontinuously exposed, but show much greater continuity in geophysical data. Faults parallel the principal cleavage orientations, ie east-, northwest- and northeast-oriented faults are widespread. Rattenbury (1992a) recognised a reverse sense of movement on many of the bedding-subparallel easterly-trending faults in the Warramunga Formation and inferred from this and from the disharmonic character of the folding, that deformation was relatively thin-skinned and that shortening was achieved at depth by thrusting. Rattenbury projected blind thrusts into the axial zones of the anticlinal folds and suggested they are an important structural control on the distribution of mineralisation. Strike-slip faulting is also associated with D_2, with major faults trending northwest (eg the Quartz Hill–Rocky Ridge, Bernborough, and Navigator faults). Multiple phases of movement are inferred for many of these faults with a net component of movement in a subhorizontal and dextral sense (Mendum and Tonkin 1976). There are conflicting timing relationships between the northeast-trending Northern Star shear zone and the northwest-trending Quartz Hill and Bernborough faults, which is taken to indicate synchronicity (Mendum and Tonkin 1976).

Mendum and Tonkin (1976) described north-trending faults which are predominantly confined to northern TENNANT CREEK, although a north-trending fault at Peko mine is a notable exception. Movement on these faults was predominantly dextral strike-slip, with up to 5 km horizontal movement, and some of these faults had little or no vertical component of movement. However, there are some faults which show the opposite, ie sinistral, sense of movement. Mendum and Tonkin (1976) suggested that, with the exception of these north-striking faults, the structure of TENNANT CREEK could be reconciled with a principal stress direction oriented north-northeast. They attribute the north-oriented faults to reactivation of pre-Warramunga Formation basement structures. However, Mitchell and Reading's (1978) model for oblique orogeny can accommodate north-oriented normal faults in a stress field with the principal stress oriented north-northeast.

Northeast-trending faults can be seen to curve into northwest-trending faults; eg the Stuart Highway Fault curves into the Quartz Hill–Rocky Range Fault. The sense of movement on both of these faults is dextral. However, the sense of movement indicated by the collective geometry of a group of these curved faults is sinistral, whereas the major fault systems are further organised into a system of regional, en echelon faults with a dextral sense of shear.

Timing of deformation

Easterly-trending folds in the Warramunga and Junalki formations, and in the Woodenjerrie beds are attributed to the *Tennant Event*. Locally, this generation of folding apparently trends approximately northeasterly in the Junalki Formation (eg 53K 474550mE 7763171mN) with overprinting (weakly crenulating) cleavages striking north-northeast and west-southwest. The Tennant Event involved deformation, low-grade metamorphism and syn-tectonic, predominantly felsic magmatism. The age of the event is quite closely constrained to the time interval ca 1860–1850 Ma by the maximum age of sedimentation of the Warramunga Formation (ca 1860 Ma),

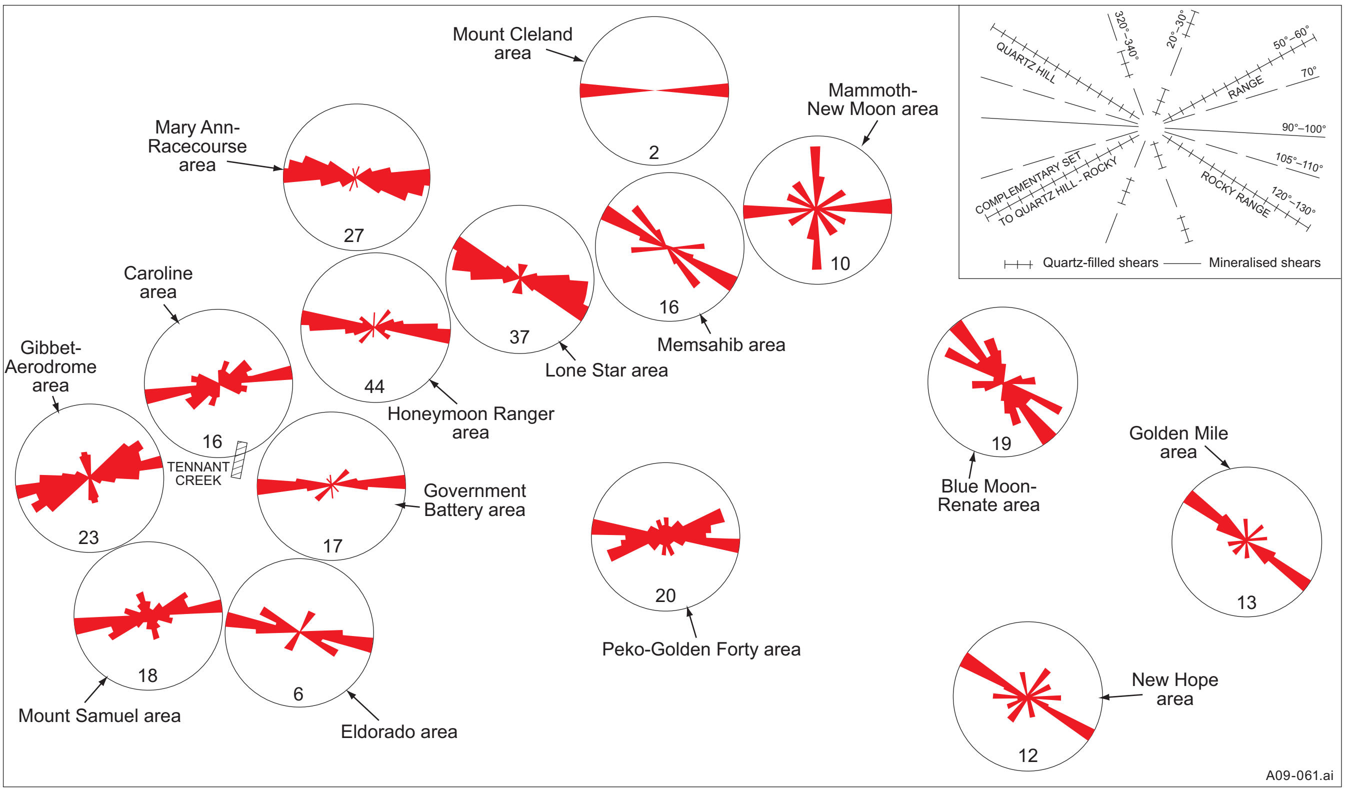


Figure 9.19. Shear zone orientations from selected areas of Tennant Creek One-mile sheet [after Crohn and Oldershaw (1965: figure 4)]. Numbers of individual observations in each area are recorded. Names of subareas are after Crohn and Oldershaw (1965: figure 10). Inset is summary of orientations of main sets of shear zones after Crohn and Oldershaw (1965: figure 3); unbroken lines indicate mineralised shear orientations, and lines with cross-markings indicate quartz-filled shear orientations.

and by the igneous crystallisation ages of syn-tectonic Tennant Creek Supersuite intrusive rocks. In particular, the ca 1847 Ma White Devil porphyry cross-cuts the (Tennant Event) foliation in the Warramunga Formation.

The age of the second and third (conjugate and penecontemporaneous?) deformations ($D_2/D_{2'}$)in the Warramunga Formation is not well constrained. Donnellan (2005) interpreted that $D_2/D_{2'}$ in the Warramunga Formation corresponds with concentric northwest- and northeast-oriented folding in the Ooradidgee Group. This folding is also developed in the Hatches Creek and Tomkinson Creek groups in the Davenport and Tomkinson provinces respectively, although the folds trend more northwesterly and northerly in the latter province. This phase of deformation has been called *Davenport Event*. Folding associated with the event was interpreted by Blake *et al* (1987) to predate the ca 1720 Ma Elkedra Granite. However, the ca 1707 Ma Kaidwalla granite may be syn-tectonic with respect to the Davenport Event. Currently, the uppermost (ie youngest) age limit on Hatches Creek Group sedimentation is poorly constrained and the possibility that the age of the Davenport Event is ca 1790–1770 Ma cannot be precluded.

Dunnet and Harding (1967) interpreted that the second phase of deformation in the Warramunga Formation started at the close of D_1. However, if D_2 in the Warramunga Formation is related to the Davenport Event, this cannot be the case.

The ca 1815–1805 Ma *Murchison Event* is interpreted to be a largely extensional event in the Tennant Region. It is associated with mafic magmatism that resulted in 1821 and 1811 Ma dolerite, gabbro and minor monzodioritic sills that intrude the Ooradidgee and Tomkinson Creek groups, and probably with flood basalts of the Kudinga Basalt and Whittington Range Member. This mafic magmatism was called the Mount Hay Event by Hoatson *et al* (2007), and contemporaneous felsic magmatism was assigned to the Treasure Suite by Wyborn *et al* (1998). The Murchison Event is broadly contemporaneous with the ca 1800 Ma Stafford Event in the Aileron Province of the Arunta Region. The Stafford Event is associated with bimodal magmatism and with folding in the Lander Rock Formation and Bullion Schist in the Aileron Province.

The Murchison Event is tentatively interpreted to have extended over about ten million years. However, the errors on crystallisation age determinations for the 1821 ± 8 Ma and 1811 ± 5 Ma dolerites and gabbros overlap and may relate to a single short-lived episode of extension and mafic magmatism, rather than to two discrete episodes with a time break between them. This extensional event in the Tennant Region is interpreted to have resulted in a change in style of sedimentation (from lateral facies changes to layer-cake) and style of volcanism (from localised around volcanic centres to flood basalts) between the Ooradi dgee Group on the one hand, and the Hatches Creek and Tomkinson Creek groups on the other. Locally, the relationship between Ooradidgee Group rocks and those of the Hatches Creek and Tomkinson Creek groups is variable and may be: conformable and apparently transitional; disconformable; unconformable; or an angular unconformity with localised (synsedimentary) folding of the Ooradidgee Group rocks. There is a foliation that is probably associated with localised deformation contemporaneous with Murchison Event.

Figure 9.20. Outcrop of Warramunga Formation in road cut (near 53K 417300mE 7825600mN) on approach to Bill Allen lookout. Bedding dips steeply to south-southwest (ie to left of photograph) and S_1 cleavage dips steeply to north-northeast (ie to right of photograph).

MINERAL RESOURCES

This section describes (1) Tennant Creek-style gold-copper-bismuth mineralisation in the Tennant Creek and Rover goldfields; (2) vein-quartz-associated gold mineralisation in the Tennant Creek and Kurundi goldfields; (3) copper (and gold) mineralisation in the Edmirringee Volcanics; (4) granite-related mineralisation in the Hatches Creek mineral field and Mosquito Creek tungsten field; and (5) the Mundagee uranium prospect. Vein quartz-associated gold mineralisation at the Last Hope, Bull Pup and Dolomite mines in TENNANT CREEK is atypical with respect to (and probably later than) the Tennant Creek-style gold-copper-bismuth mineralisation that dominates the Tennant Creek goldfield. These three small mines probably constitute a link with typically vein-quartz-associated gold mineralisation in the southern Warramunga Province. Placer gold has been recovered proximal to quartz-vein-hosted gold mineralisation in both the Tennant Creek and Kurinelli goldfields, and minor placer gold has also been recovered proximal to the Mascott, Lady Pearl / Mary Ann, Mary Lane, Havelock and Little Ben small, ironstone-associated gold mines in the Tennant Creek goldfield. In addition to tungsten mineralisation in the Mosquito Creek field in the Warramunga Province, tungsten mineralisation also occurs in the Hatches Creek and Wauchope mineral fields, which are described in **Davenport Province**.

A brief history of mining, exploration and production in the Tennant Creek field

The first record of gold in the Tennant Creek region is an 1874 report of its occurrence in the Last Hope area in SHORT RANGE (*Northern Territory Times and Gazette* of October 1881). Subsequent to this, Brown (1895) reported panning gold from Bishops Creek in 1894, although Davidson (1905) sampled quartz reefs in TENNANT CREEK with little success and downgraded the area's gold potential. However, the association of gold with vein quartz at Last Hope, and the nearby occurrence of eluvial and alluvial gold (in the Moonlight Rockhole area) is atypical of the Tennant Creek goldfield. When prospectors turned their attention to the quartz-magnetite (/haematite) (ironstone) bodies, high-grade gold and copper mineralisation was discovered in samples taken 9 km south-southwest of the Old Telegraph Station in 1925. Payable gold was subsequently discovered beneath the abandoned workings at this prospect (Great Northern) in 1932.

Numerous Tennant Creek-style ironstone-associated mineral deposits were found in 1933 and 1934. These deposits included those at Nobles Nob and Eldorado, although payable gold was not discovered at Nobles Nob until 1939. Ivanac (1954) reported that immediately prior to the Second World War, one hundred and thirteen mines were in operation in the Tennant Creek goldfield. However, all mines except Eldorado closed during the war (Le Messurier *et al* 1990, **Figure 9.21**). By 1947, twenty-five mines were again operating, but the number had dropped to eight by 1952. Despite the large number of prospects that are mineralised (about 130 have recorded production, **Figure 9.22**), they represent less than 20% of the more than 700 known ironstone occurrences within the Warramunga Formation. Furthermore, about 87% of the ca 156 t of gold produced to the year 1999 (Donnellan *et al* 1999, Ahmad *et al* 1999) was contained in just twelve mines, with subsequent combined production of 1101 kg of gold from Chariot in 2003–2005 and from Malbec West in 2005 (see **Table 9.6**).

Production figures until 2010 indicate that only about 30 mineralised ironstone bodies (**Figure 9.23**) had more than 25 kg of contained gold. Three mines, Warrego (41.3 t Au recovered, including 3.3 t from re-processing of tailings), Nobles Nob (34.6 t Au recovered) and Juno (26.1 t Au recovered), accounted for approximately 65% of total gold production. The Warrego mine near the western end of the goldfield (in SHORT RANGE) has also produced 91 500 t Cu. The high-grade White Devil deposit produced 19.8 t of gold from 1.3 million tonnes of ore before it closed in September 1999. Immediately west of White Devil, the Black Angel mine produced 176 kg Au from 25 900 t of ore in two periods of production, from 1936–1964 and 1985–1986 (Ferenczi 1996). The association of gold (and copper) mineralisation with massive ironstone (magnetite-haematite) bodies provided a well-defined exploration target, and the first ground-based magnetic surveys were undertaken in the mid 1930s (Aerial, Geological and Geophysical Survey of Northern Australia, AGGSNA 1935–1937). Results of the AGGSNA surveys were reported by Rayner and Nye (1936), Richardson *et al* (1936), Richardson and Rayner (1937a, b) and Daly (1957). Daly reported that an airborne magnetometer and scintillometer survey was undertaken by the Bureau of Mineral Resources (BMR) in 1956 in order to facilitate the interpretation of the ground-based surveys by putting the anomalies in a regional context. The area covered included all the known mine workings, and the results were first published (BMR 1958) as a 1:126 720-scale map. These data and those of a later survey in 1960, which extended coverage throughout TENNANT CREEK, resulted in a series of 1:63 360-scale maps (BMR 1962a–d).These surveys identified a number of new ironstone-related magnetic anomalies and, in turn, stimulated company-funded surveys.

A 1984 aeromagnetic survey by Austirex (at 200 m line spacing, and 80 m terrain clearance) covered 3400 km^2, and a survey undertaken on behalf of Peko Mines Ltd in the late 1980s covered 1500 km^2 in the southeast of the Tennant Creek goldfield. This generation of aeromagnetic surveys identified even largely oxidised shallow ironstones. In 1998, the Australian Geological Survey Organisation (AGSO, now Geoscience Australia) contracted Kevron to fly a low-level 200 m line-spaced aeromagnetic and radiometric survey over the entire TENNANT CREEK map area. NTGS extended this survey over CHALUBA, BONNEY and OORADIDGEE in BONNEY WELL, EPENARA in FREW RIVER and HANSON in LANDER RIVER in 1999.

Farrar (1979) described Richardson and Kirkpatrick's mathematical model to analyse ellipsoidal magnetic anomalies associated with pipe-like, flattened ironstones in TENNANT CREEK. Farrar also discussed how the model was successfully applied in targeting the Warrego orebody and in identifying a residual anomaly associated with a satellite body immediately to the north. Down-hole magnetics were first applied to exploration at Tennant Creek in 1984, according to Williams (1987), who provided a history of exploration in the Tennant Creek goldfield. Hoschke (1991) described how a down-hole magnetometer was vital to the discovery of the two lodes at West Peko.

In 1996, NTGS contracted World Geoscience to undertake a low-level, closely spaced radiometric survey over a small area in the Tennant Creek goldfield. The philosophy behind this exercise was to test the method as an exploration tool for economic mineralisation using U as a pathfinder. An association between gold and uranium

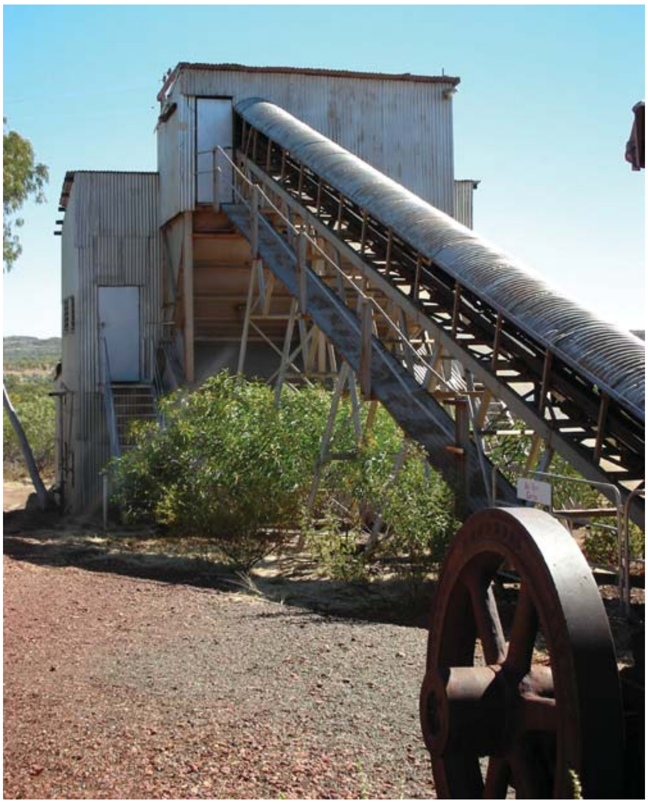


Figure 9.21. Ten-stamp-head Number 3 Government Battery at Battery Hill, about 1.5 km to west of Tennant Creek town centre. Ore was first crushed at this battery in June 1941 (Balfour 1989). It operated until 1987 and was restored in 1993, when the Tennant Creek Regional Tourist Association took over management of the site (http://thebestevents.com.au/gold-stamp-battery.htm, accessed August 2011).

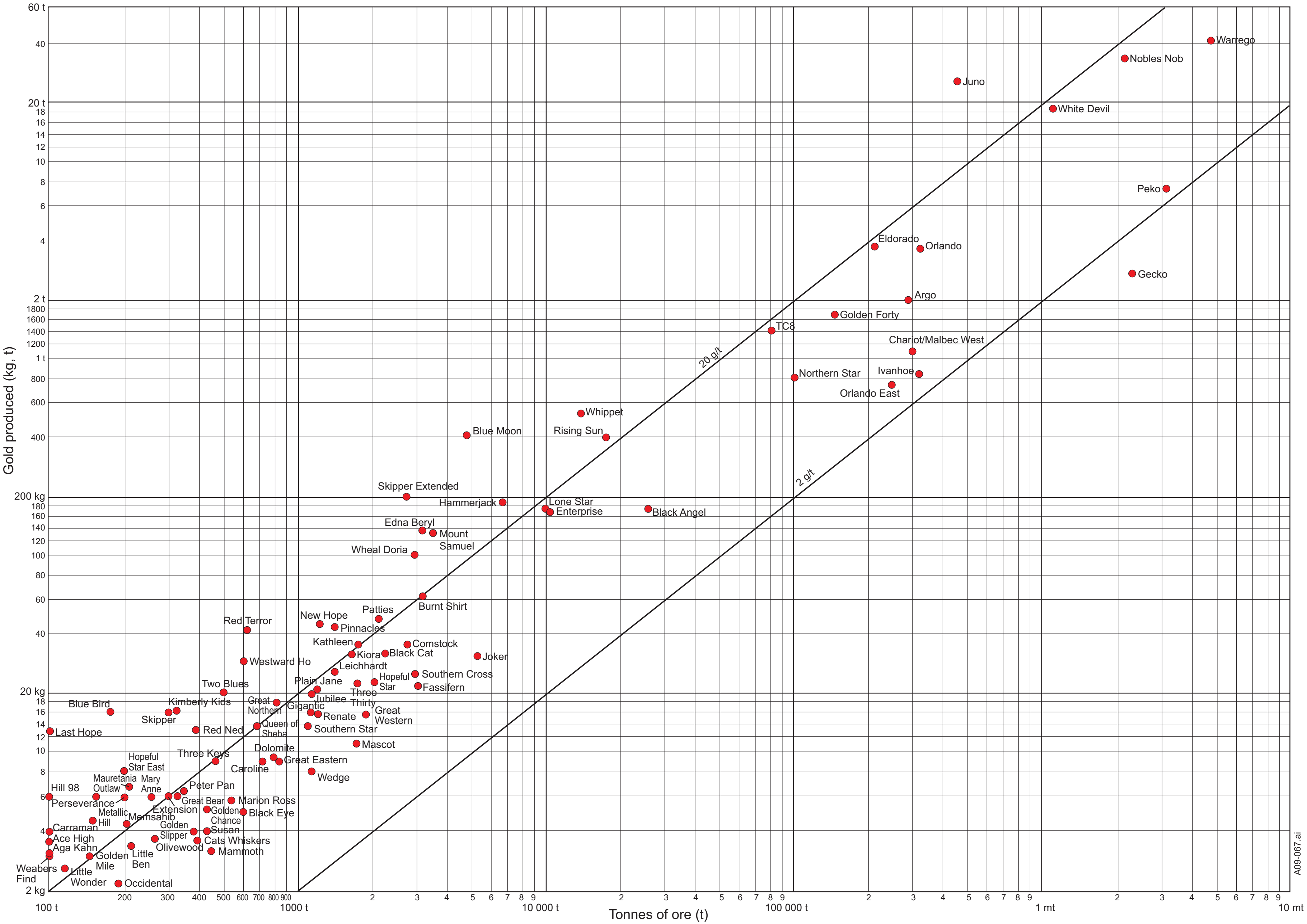


Figure 9.22. Tennant Creek goldfield production graph (tonnage/grade diagram), compiled by PA Ferenczi (formerly NTGS), but with figures for combined production from Chariot and Malbec West added (modified from Donnellan *et al* 1999).

was known in at least some of the Tennant Creek gold deposits, suggesting that this was a potential testing ground for the method. There proved to be a very high correlation between the magnetic signal and a high-U signal in eight existing ironstone prospects in the test area, and the radiometric survey identified a similar number of prospective targets.

In 2001, Scintrex, on behalf of AGSO and NTGS acquired systematic gravity coverage over TENNANT CREEK. These data were mainly collected on a 4 km grid (with some areas collected on a 2 km grid), and were integrated with detailed open file company data, where it was available. The dataset has recently been modelled (see Roach 2006) in an effort to evaluate the interpreted solid geology map for TENNANT CREEK produced by Johnstone and Donnellan (2001), and further to investigate the possibility of constraining the distribution of rock types in the third dimension.

Gravity methods provide a potential exploration tool for oxidised, weakly or non-magnetic ironstone bodies. The potential of this method to find deposits associated with predominantly haematitic ironstones was realised with the discovery of Chariot by Normandy Mining Ltd in 1998, and Emmerson Resources Ltd has undertaken detailed gravity studies on their tenements (Emmerson Resources, ASX announcement 7 March 2008, Investor presentation 16 March 2009). A number of other geophysical techniques (IP, EM and AMT) have also been applied during exploration at Tennant Creek.

Giants Reek Mining Ltd found a small deposit about 27 km east of Tennant Creek in 1998. This deposit, Billy Boy, has an indicated resource of 8122 t of ore at 19.6 g/t Au, 5.1% Cu and 0.8% Bi (Giants Reef Mining 2000). The ore is hosted by steeply dipping shoots of haematite-chlorite-clay breccia, and the high-grade zone occupies only a small portion of a 300 m-long zone of mineralisation that remains open at both ends (Ahmad *et al* 2009).

There has been a recent resurgence of exploration activity in both the Tennant Creek and Rover fields, and in a largely unexplored area to the west of Warrego,

Mine	Ore (Mt)	Grade	Calculated recovered Au grades (g/t)	Metal produced	Approx % of total (ca 157 t) gold production to 2005
Warrego	4.75	8.0 g/t Au	8.7	41 280 kg Au	26.3
		2.0% Cu		91 500 t Cu	
				5 500 kg Ag	
		0.3% Bi		12 000 t Bi	
Nobles Nob	2.14	17.0 g/t Au	16.1	34 580 kg Au	22.0
				ca 1730 kg Ag	
Juno	0.45	57.0 g/t Au	58.0	26 130 kg Au	16.6
		0.4% Cu		1 429 t Cu	
		7.0 g/t Ag		2 752 kg Ag	
		0.6% Bi		2 293 t Bi	
White Devil	1.30	15.2 g/t Au	15.2	19 800 kg Au	12.6
Peko	3.16	3.5 g/t Au		7 481 kg Au	
		4.0% Cu		118 884 t Cu	
		14.0 g/t Ag		44 163 kg Ag	
		0.2% Bi		7 350 t Bi	
Orlando	0.32	11.0 g/t Au	11.7	3 772 kg Au	2.4
		1.8% Cu		4 852 t Cu	
		3.5 g/t Ag		1223 kg Ag	
		0.1% Bi		4.7 t Bi	
Gecko	3.0	1.2 g/t Au	0.9	3 450 kg Au	2.2
		4.0% Cu		122 700 t Cu	
Eldorado	0.21	20.0 g/t Au	18.0	3 800 kg Au	2.4
Argo	0.29	8.6 g/t Au	7.1	2 050 kg Au	1.3
Chariot and Malbec West combined	0.13	8.9 g/t Au		1 101 kg Au	0.7
Golden Forty	0.15	12.0 g/t Au	11.5	1762 kg Au	1.1
TC8	0.08	18.0 g/t Au	17.8	1420 kg Au	0.9
Ivanhoe	0.32	3.0 g/t Au	2.6	847 kg Au	0.5
		3.0% Cu		8 950 t Cu	
		12.0 g/t Ag		3 872 kg Ag	
Northern Star	0.115	6.7 g/t Au	8.1	810 kg Au	0.5

Table 9.6. Gold production figures from major deposits in Tennant Region after Donnellan *et al* (1999) and Ahmad *et al* (2009) with minor modications. Production figures for Northern Star are from Ferenczi (1996). Note that gold production from Warrego includes ca 3.3 t Au produced from the re-processing of tailings. The calculated recovered grade is derived from dividing the total gold produced by the amount of ore processed.

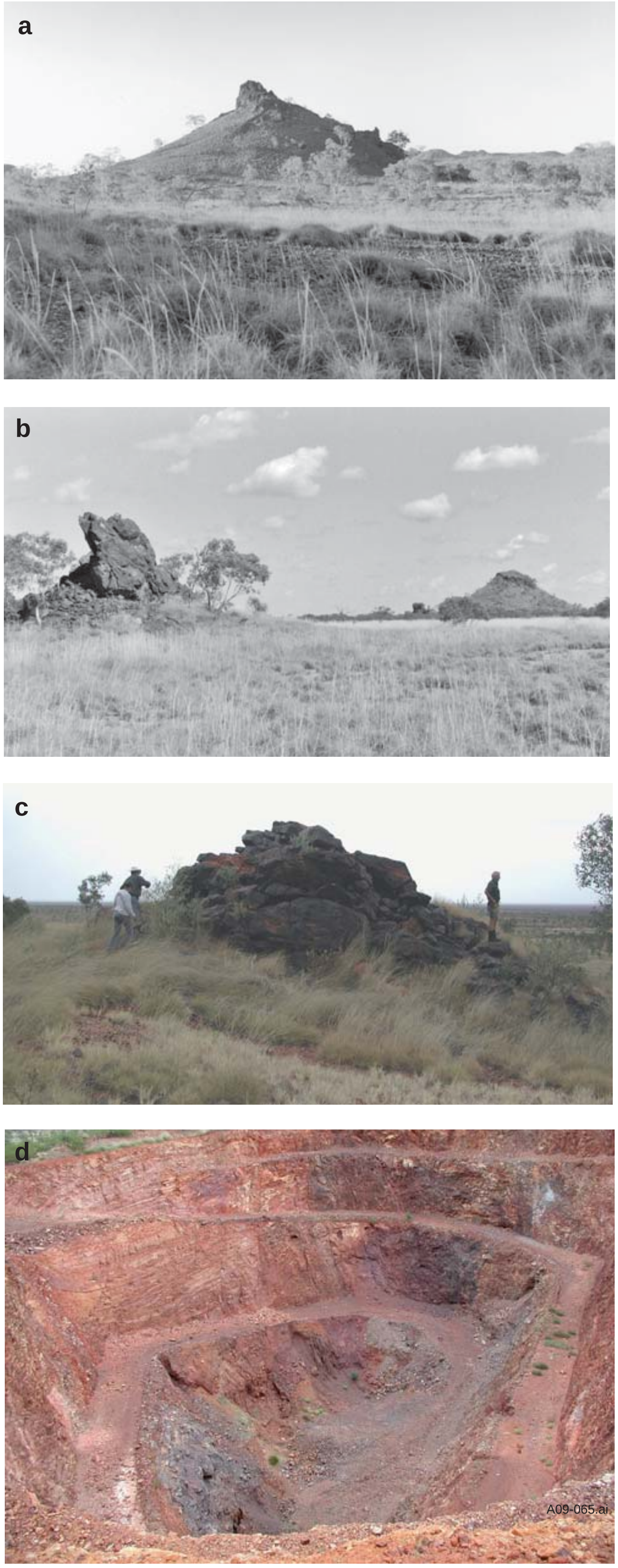


Figure 9.23. Surface expression of massive ironstone bodies. (**a**) View to east-southeast from near Shamrock Mine to ridge of ironstone at 53K 414300mE 7830000mN (with porphyry at far left-hand side of ridge). (**b**) View to west-northwest of unnamed ironstone at 53K 407600mE 7836350mN in foreground. A second ironstone body is along strike at 53K 407100mE 7836550mN, immediately to left of prominent hill in distance. (**c**) Surface expression of ironstone in vicinity of Eldorado mine and (**d**) ironstone orebody (darker phototone) within open cut at Eldorado mine (c and d after Ahmad *et al* 2009: figure 60).

where Sipa Resources has identified a number of magnetic anomalies and has intersected typical Tennant Creek-style ironstone-associated mineralisation (Sipa Resources, ASX Announcement 8 December 2009). A number of companies have recently reported significant mineralised intersections in the region. Emmerson Resources (ASX Announcement 21 December 2009) reported a 2 m intersection of 50.6 g/t Au, associated with talc-magnetite alteration, at Pinnacles North. This company described Pinnacles North as being a large, overlapping magnetic and gravity anomaly with an associated multi-element geochemical 'leakage anomaly'. Emmerson Resources has also reported significant gold intercepts at Golden Kangaroo East (ASX announcements 14 July 2008 and 29 July 2008), the Analytic One project (ASX announcements 15 December 2008 and 4 June 2009), the Golden Forty project (ASX announcement 1 September 2008, and at Rising Star (ASX announcement 21 December 2009). Truscott Mining Corporation Ltd (ASX announcement 20 May 2010) has identified alteration and polymetallic mineralisation adjacent to porphyry contacts over the 1.4 km strike length of a shear zone that includes a number of ironstones and former small, high-grade gold mines (eg Peter Pan, Wheal Doria) at their Westminster Project. This company reported that several high-grade ore shoots with at least 120 m down-plunge continuity had been intersected in the Westminster Project area (Media release 2 February 2010, ASX announcement 20 May 2010).

Major economic Tennant Creek-style deposits associated with ironstone bodies

The following sections provide a general description of the Tennant Creek ironstones and their associated gold, copper and bismuth mineralisation. In particular, a brief summary of (a) possible structural and stratigraphic controls on mineralisation, (b) hydrothermal alteration assemblages, and (c) ore mineralogy and texture is given. This is followed by specific descriptions of the fourteen major deposits (**Figure 9.24**) that have been mined in the Tennant Creek goldfield to date. This summary and the descriptions of the main deposits are in part based on Ahmad *et al* (1999, 2009), Ferenczi in Donnellan *et al* (1999) and Donnellan *et al* (2001). Descriptions and production figures for many of the smaller deposits are given in Ivanac (1954) and brief descriptions are also provided in the Appendices to Ahmad *et al* (1999, 2009).

The ironstone bodies are irregular ellipsoidal lenses or flattened pipe-like bodies. They range in size from a few tens of tons to more than 15 million tons (Le Messurier *et al* 1990). Hypogene ironstones consist of magnetite (50–80%), quartz (0–60%) and chlorite (5–40%), with minor pyrite, talc, dolomite, muscovite and sericite (Wedekind *et al* 1989). In the oxidised zone, which typically extends to 100 m below the present land surface, the ironstones predominantly comprise haematite together with remnant magnetite. Large (1975) recognised that magnetite pseudomorphed primary haematite in some deposits and Hargreaves (1974) concluded that an intimate association of magnetite and haematite at Golden Forty indicated that, at the time of ironstone formation, oxygen fugacity was close to that of the magnetite–haematite buffer. Subsequently, Skirrow

(1993, 2000) and Skirrow and Walshe (2002) identified that the Tennant Creek-style deposits range from reduced pyrrhotite-bearing to oxidised primary-haematite-bearing types, which may carry copper-gold-bismuth or gold-bismuth (-copper) mineralisation, respectively.

The ironstones typically consist of massive, fine-grained (0.02–0.5 mm) sutured aggregates of magnetite, which is brecciated and infilled with chlorite and quartz (± dolomite, talc, muscovite, chalcopyrite, pyrite, bismuthinite and gold). Magnetite commonly shows colloform textures and spherulitic aggregates with chlorite. Magnetite also occurs in veins and as disseminated octahedra associated with highly chloritised Warramunga Formation rocks in breccias and in stringer zones, respectively adjacent to and below the ironstone bodies.

Structural and stratigraphic controls

Several structural controls on ironstone distribution are evident on both regional and local scales. The regional slaty cleavage (S_1) in the Warramunga Formation, and shears subparallel to this cleavage, which approximately coincides with the axial orientation of moderate to tight F_1 folds, are responsible for the broadly east–west alignment of ironstone bodies. These are the 'lines of lode' that have been recognised (particularly in the southern portion of the goldfield) by several workers. Major shear zones are generally barren, although the Mary Lane Shear Zone, which hosts a number of small mineralised ironstones (eg Mascot, Hidden Mystery, Mary Ann) is an exception. Economically mineralised ironstones are generally in smaller east-trending brittle-ductile shear zones (eg White Devil, Argo), and many gold-bearing ironstones are in areas of pitch reversal associated with parasitic F_1 anticlines (Ivanac 1954, Whittle 1966). In addition to the approximately east-trending (ie ca 90–100°) shear zones, Crohn and Oldershaw (1965) recognised that south-southeast and east-northeast (ie trending ca 105–110° and ca 70°, respectively) shear zones also carry (mineralised) ironstones. Some ironstone bodies have been reoriented by later tectonism associated with folding, faulting or granite emplacement (eg Warrego ironstone; see Goulevitch 1975 and Wedekind *et al* 1988). Post-ore thrust faults with displacements of up to 170 m have been recognised in several deposits (eg Eldorado, Northern Star, Golden Forty, Lone Star). Other minor faults displace

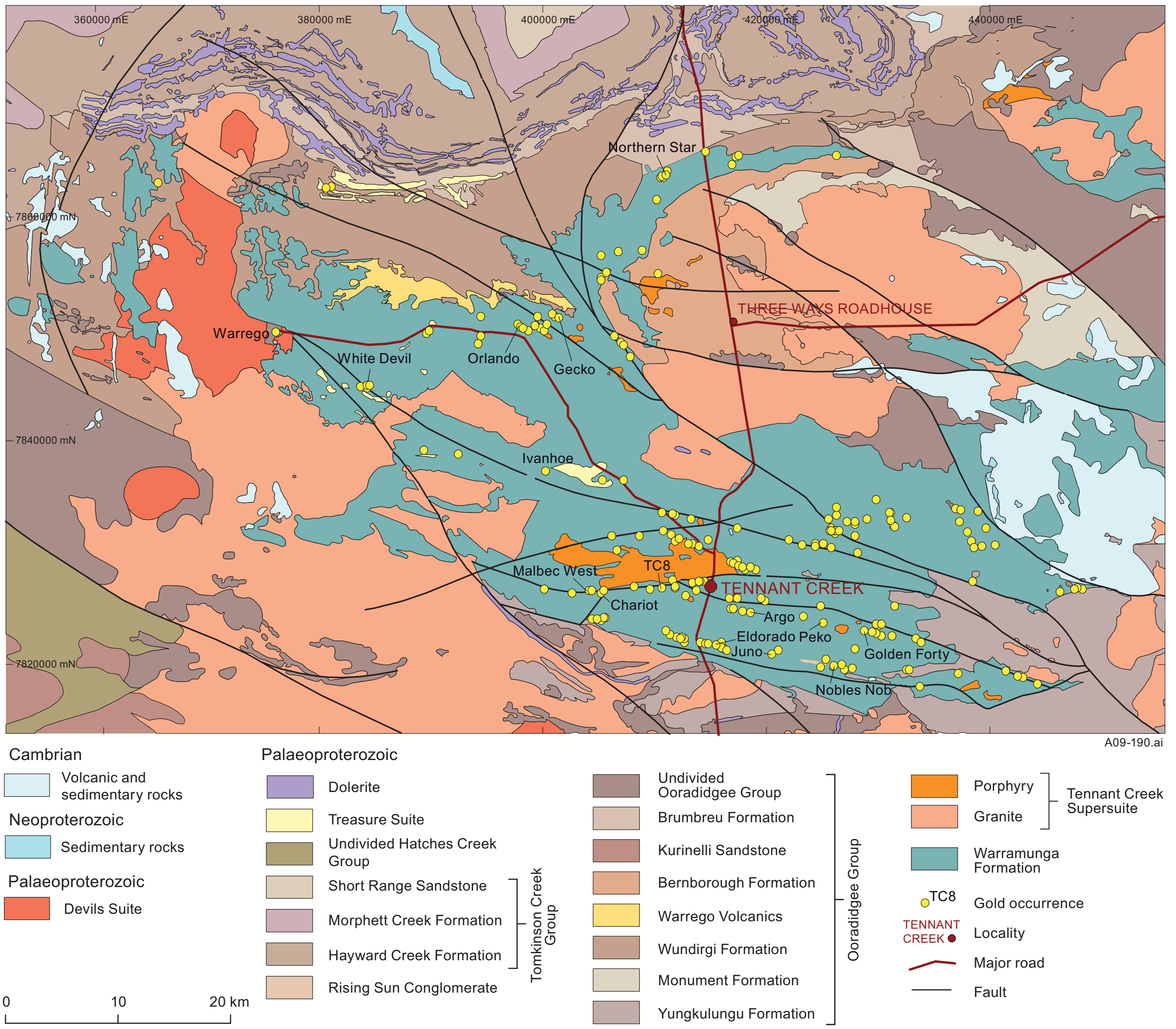


Figure 9.24. Interpretative map of Palaeoproterozoic geology of TENNANT CREEK, showing gold occurrences and with major mines labelled (slightly modified from Ahmad *et al* 2009, and based on Donnellan *et al* 1998 and Johnstone and Donnellan 2001).

and brecciate the ironstone pods, which has allowed the entry of later Au-Cu-Bi-bearing hydrothermal fluids and oxidising meteoric waters. Skirrow (2000) noted that shear-hosted gold-copper mineralisation, apparently unrelated to ironstones, represents a discrete class of deposit at Tennant Creek.

Apparent stratigraphic controls on ironstone distribution, particularly their apparent association with 'haematite shale' and quartz-feldspar porphyry, are also recognised. At the surface, there is, for example, a close association between mineralised ironstones and 'haematite shale' in the line of lode form Mount Samuel (**Figure 9.25**) to the Rising Sun mine in the south of the goldfield, and similarly, from Mensahib via Little Wonder, Black Cat and Gigantic to Golden Mile. In the subsurface, the ironstones at Nobles Nob, Juno and TC8 are centred on, and partially replace 'haematite shale.' However, there is no consensus on how many intervals of 'haematite shale' are present within the Warramunga Formation succession, nor if they are associated with a specific interval of the succession. Similarly, the importance of the primary chemical composition of the host sediments as reductants triggering the precipitation of iron oxides is also uncertain (for example, carbonaceous shale that might have acted as a reductant has been identified locally by Reveleigh 1977).

Hydrothermal alteration assemblages

Hydrothermal alteration is recognised (particularly subsurface) in association with many of the ore deposits. This alteration comprises: (a) chlorite-; (b) dolomite-talc-; (c) sericite-muscovite-; and at Warrego, (d) chlorite-tourmaline-bearing assemblages. Large (1975) concluded that stringer zones and leached sedimentary rocks located below the ironstone bodies represent former hydrothermal channelways.

Chloritisation has accompanied both ironstone formation and Au (Cu-Bi) mineralisation (Wedekind *et al* 1989, Huston *et al* 1993). It is intense in ironstones and in the metasedimentary Warramunga Formation country rocks both adjacent to, and below the ironstones (particularly in 'stringer zones'). This earlier formed chlorite (typically repidolite) is fine-grained and foliated.

Figure 9.25. Looking southwest from Bill Allen lookout to prominent ironstone ridge at Mount Samuel, about 6 km south-southwest of Tennant Creek town centre.

Later-formed chlorite tends to be more coarse grained, non-foliated and is confined to the gold mineralised zones and to altered sedimentary rocks adjacent to the gold mineralised envelope.

Dolomite-talc alteration is present as discrete envelopes up to 15 m wide, above and in part adjacent to the massive ironstone pods (eg Juno, Argo, TC8, Golden Forty, Northern Star, Gecko Anomaly 3), or as irregular zones adjacent to the main ore zone (eg Orlando, Ivanhoe, White Devil, Peko).

Fine-grained foliated aggregates of talc with fine-grained disseminated magnetite commonly form talc-magnetite zones above and adjacent to the massive magnetite-chlorite zone (eg Juno, TC8, Argo), or magnetite-quartz zone (eg Golden Forty, Nobles Nob). Anthophyllite is present, together with talc, in the footwall alteration zone at the Pinnacles mine, and in the main lode (at depths below 275 m) at Peko (Whittle 1966). Talc (±anthophyllite) appears to be the alteration product of earlier-formed hydrothermal chlorite, which has experienced subsequent intense magnesian alteration and partial desilicification.

Dolomite-rich lithologies completely surround the talc-magnetite zone to form an outer alteration zone that commonly contains a variety of minerals including talc, chlorite, quartz, magnetite, pyrite, chalcopyrite and tremolite. Dolomite may be found in pink, white and colourless varieties; it is typically coarse grained and forms late crosscutting veins, massive aggregates and breccias replacing wall rocks. Dolomitic zones are best developed adjacent to haematite shale units (eg Argo, Juno and Gecko Anomaly 3) and appear to have been formed by the carbonation and desilicification of talc-rich lithologies.

Sericite-muscovite alteration is present in the Au-bearing zones of many surface and subsurface deposits. Disseminations, irregular patches and veinlets of fine- to coarse-grained sericite are common in oxidised orebodies (eg, Nobles Nob, Rising Sun, Patties, Joker, Kiora), whereas disseminated, non-foliated coarse-grained muscovite flakes within the massive magnetite-chlorite zone predominate at depth (eg, Warrego, TC8, Golden Forty, Orlando).

Ore mineralogy and texture

Gold (-copper-bismuth) mineralised zones vary from 10% (eg Golden Forty) to >70% (eg Noble Nob) by volume of the ironstone bodies, and ore zonation is well developed in some cases and absent in others. Ore mineralisation is also developed in altered metasedimentary rocks above, adjacent to and below the ironstones. The following descriptive details are largely from Ferenczi in Donnellan *et al* (1999).

Primary gold is commonly concentrated towards the base, or in the footwall of the ironstone bodies in a magnetite-chlorite ± muscovite/sericite gangue mineral assemblage. The gold typically ranges from a few microns to 1 mm in grain size. Gold grades are variable, but average about 20 g/t for most of the major deposits (**Figure 9.22**), and gold fineness is generally high (900–1000), except where gold occurs in copper orebodies (Wedekind 1990).

Supergene enrichment of gold is significant in most of the surface deposits, producing high-grade zones (eg up to 1500 g/t Au at Nobles Nob) above the water table. These supergene zones contain small nuggets and coarse flakes of gold disseminated in altered (clay/sericite) and brecciated ferruginous mudstone, or in quartz-haematite assemblages. At the surface, the supergene zone is often overlain by a leached (2–3 m deep) barren zone.

Bismuth mineralisation in the primary ore zone predominantly consists of bismuthinite, together with minor bismuth-sulfides (wittchenite, emplectite, aikinite) and occasionally seleniferous bismuth-sulfosalts (junoite, wittite, guanajuatite). Bismuth may be closely associated with primary gold, and commonly occurs partially within or above the gold zone in a magnetite-chlorite± muscovite/ sericite± talc gangue. Bismutite [$(BiO)_2CO_3$] and bismite (Bi_2O_3) are commonly encountered in the oxide zone of bismuth-bearing deposits.

Bismuthinite may form anhedral aggregates or discontinuous veinlets intergrown with sulfide, silicate and/ or carbonate minerals that infill fractures in magnetite. The intimate association and preservation of intricate intergrowth textures between gold, bismuth minerals and chalcopyrite suggests contemporaneous precipitation and minimal post-crystallisation deformation (Large 1974). Bismuth grades range from 0.1% (Orlando) to 1% (Jubilee) and averaged 0.3% at Warrego (the largest bismuth-bearing deposit).

The dominant primary copper-bearing mineral is fine- to medium-grained chalcopyrite. Primary copper mineralisation occurs in zones, which either overlap with those of gold (eg Warrego and Orlando), or which form relatively discrete zones within talc-magnetite-dolomite gangue (eg Juno, Golden Forty, TC8). At Gecko chalcopyrite is relatively evenly distributed throughout massive magnetite and is associated with very low-grade gold mineralisation.

Chalcopyrite has commonly replaced and infilled fractures in massive magnetite and early-formed pyrite. In other cases, chalcopyrite is intergrown with magnetite and quartz, suggesting coprecipitation of these three minerals (Large 1974). Veinlets of chalcopyrite may be present within the alteration pipe below ironstone pods. Minor bornite also occurs and a bornite-rich copper lode within a talc-dolomite zone has been delineated at TC8 (Giants Reef Mining 1993).

Chalcocite and minor covellite are commonly found in the supergene ore of copper-bearing ironstone bodies (eg Gecko, Peko, Orlando, TC8), and have replaced primary chalcopyrite. Malachite, and rarely native copper and chrysocolla, are present in surface exposures. Grades are generally in the range of 2–4% copper.

Sulfide minerals that may occur in minor or trace amounts in association with economic mineralisation are: galena and sphalerite (Orlando, Juno, Peko, Gecko, Ivanhoe); cobaltite (Peko, Gecko, Orlando); molybdenite (Gecko, Peko, White Devil, Golden Kangaroo); tetrahedrite (Peko, Gecko); and enargite (Nobles Nob, TC8).

Pyrite is usually the most common sulfide mineral within mineralised ironstones, often forming disseminated subhedra or veinlets replacing massive magnetite. Pyrite-rich (up to 90%) zones may form adjacent to (eg Argo) or within (eg Peko and Gecko) the ironstone lodes and can occasionally contain economic concentrations of copper and gold. Pyrrhotite and arsenopyrite are significant sulfide phases in the Peko and West Peko orebodies, but are minor or absent in most of the other deposits. Uraninite has been identified in several deposits, including Juno, Northern Star, Warrego and Gecko. At Juno, sub-microscopic grains of uraninite occur in the magnetite-chlorite pod on the outer edge of the gold zone (Large 1974), whereas at Northern Star disseminated fine-grained (0.02 mm) secondary uraninite is located within chloritised thrust fault zones (Edwards 1987).

A generalised mineral paragenesis for Tennant Creek-style ironstone associated iron-oxide, copper-gold deposits is shown in **Figure 9.26**. Cross-sections showing gangue mineral and ore zonation for ten major iron-oxide, copper-gold deposits from the Tennant Creek goldfield are presented in **Figure 9.27**, and these deposits are described below. Genesis of Tennant Creek-style gold-copper-bismuth mineralisation is discussed in 'Deposit classification and genetic models' below.

Major ironstone-hosted gold-copper-bismuth deposits

Present tense is generally used in the following descriptions of the major, mined ore deposits in the Tennant Creek goldfield. However, in some cases, mining may have resulted in some of the features described no longer being

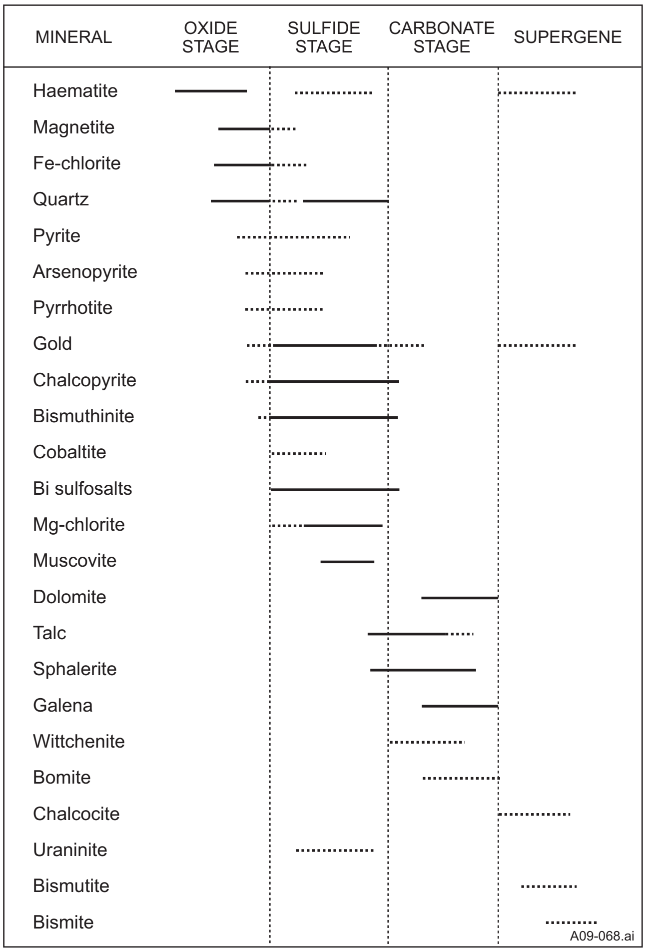


Figure 9.26. Generalised mineral paragenesis for ironstone-related Au (-Cu-Bi) deposits [after Donnellan *et al* 1999, figure 8, compiled by PA Ferenczi (formerly NTGS)].

readily evident. Descriptive details of a number of deposits, Nobles Nob, Warrego, White Devil, TC8 and Juno, are largely based on Ahmad *et al* (1999, 2009).

Nobles Nob

Nobles Nob mine is located 13 km southeast of Tennant Creek and was discovered in 1933. Production commenced in 1939, when payable gold was struck at a depth of 16.5 m. During 1939–43, about 3582 t of ore was mined for the production of 80.5 kg Au. Australian Development Ltd (ADL) acquired the leases over Nobles Nob in 1948 and mined the deposit using underground (1949–67) and open cut (1968–85) methods to produce 34.5 t Au from 2.14 Mt of ore (see **Table 9.6**). Figures quoted by Excalibur Mining Corporation Ltd (Excalibur Mining) indicated that 828 000 oz of gold were produced from the underground operations, at an average grade of 48.8 g/t

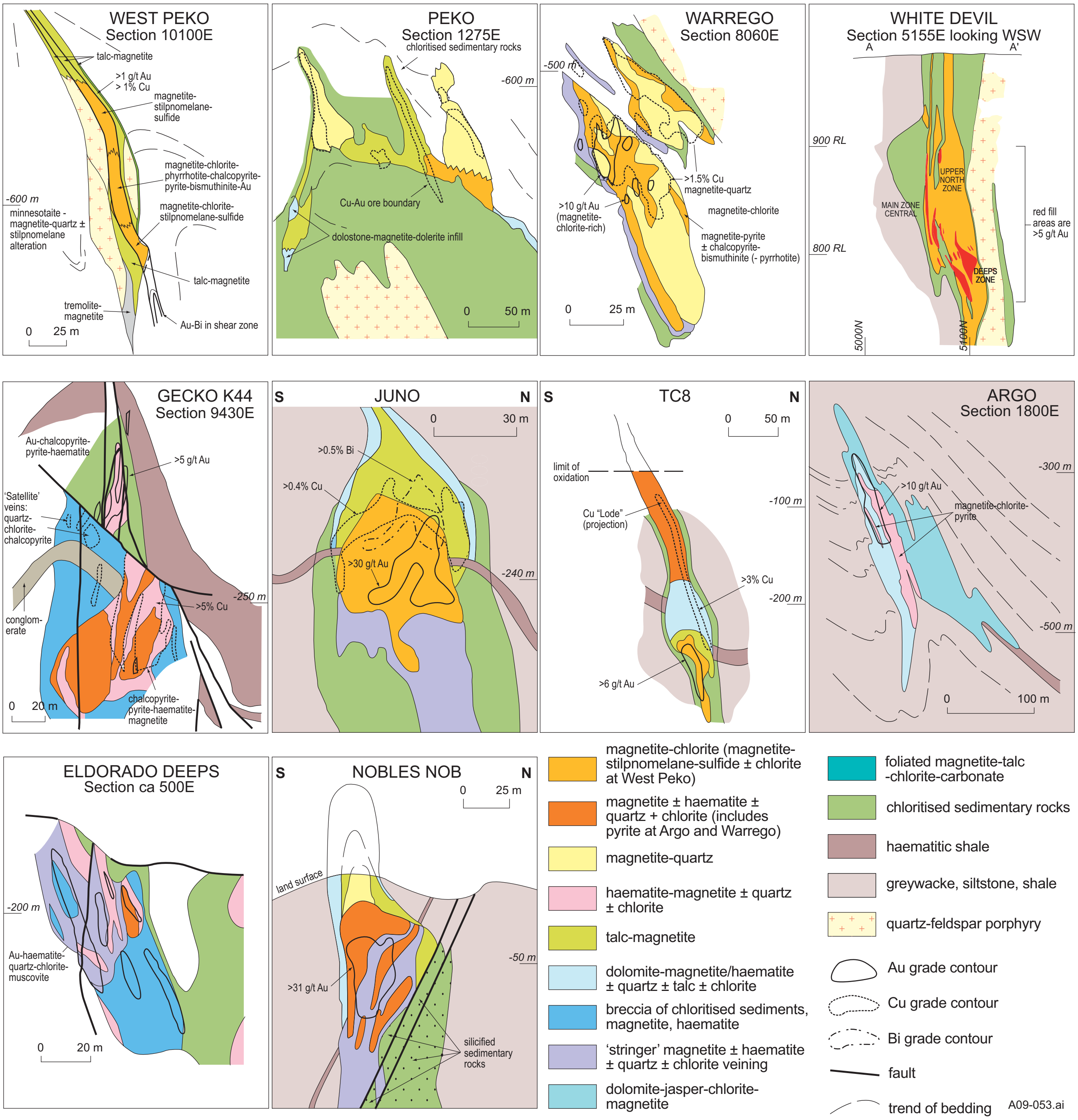


Figure 9.27. Cross-sections showing ore and guangue mineral zonation for ten major Tennant Creek-type mineral deposits from Warramunga goldfield. Sections for West Peko, Peko, Warrego, Gecko K44 and Eldorado Deeps are from Skirrow 2000: figure 2; Juno, TC8 and Nobles Nob are from Ahmad *et al* 1999: figure 40 with TC8 gold zone added from Hill (1990); White Devil is from Edwards *et al* 1990: figure 4; Argo is from Horvath 1988: figure 31 (but see Meade 1986 for more details), gold zone contour and RLs provided by S Russell, Emmerson Resources Ltd, pers comm 2011. Primary data sources are reported in these references. Sections are arranged in order of relative distribution between reduced (pyrrhotite-bearing Cu-Au-Bi; eg West Peko) and oxidised [haematitic Au-Bi(-Cu); eg Eldorado Deeps] deposit endmembers, following Skirrow and Walshe (2002: table 1), and as described by Skirrow (2000). Skirrow and Walshe (2002) concluded that haematite-rich high-grade copper and gold-rich ore zones at Gecko K44 are atypical of Tennant Creek deposits. They suggested that an earlier, reduced, sulfide-bearing mineralising system may have been overprinted by an oxidising brine and consequently haematitised. Positioning of this section within diagram is therefore somewhat arbitrary.

(ASX announcement 22 March 2010: AGES March 2010 presentation).

The host rock succession consists of tightly folded greywacke and shale of the Warramunga Formation. Bedding trends easterly and dips steeply (60–80°) south, occupying the southern limb of a major F_1 anticline. A well developed cleavage (S_1) trends east–west and dips steeply (70–80°) north. The main ironstone body (No.1 lens) is predominantly hosted within drag-folded and brecciated shale, including a destructively silicified, haematitic shale unit. The North Wall fault zone truncated the main ironstone lens, which was also offset to the east by numerous north-trending vertical faults (Reveleigh 1977). The quartz-haematite lode trends east–west and plunges at 20° to the east. The lode was lenticular in both plan and cross-section (**Figure 9.27**), with maximum dimensions of 190 m strike length, 40 m width and 80 m depth. The lode appears to have been localised at the intersection of bedding and cleavage (Yates and Robinson 1990). Gold mineralisation was concentrated in the central zone of the pod (30–82 m depth) within brecciated quartz-haematite (magnetite-content of the ironstone increased below 55 m), and in stringer veins in altered sericite-chlorite-haematite shale below the ironstone. Supergene enrichment produced grades in excess of 1550 g/t Au between the 30 and 60 m levels. The supergene gold was quite pure (fineness of 960) and generally very fine grained (< 0.2 mm), except in some rich ores, where it formed elongate masses several centimetres in length. Bismutite and bismite were closely associated with gold in the upper levels of the primary deposit, which locally, originally contained up to 10% bismuth. Bismuthinite with minor pyrite, chalcopyrite and enargite were present below the zone of oxidation.

In a recent reinterpretation of previously acquired geophysical data, Excalibur Mining has identified a number of EM, gravity and magnetic targets at the company's Nobles Nob leases (**www.excaliburmining.com.au**). Excalibur Mining reported (ASX announcement 6 August 2010) a JORC-compliant Inferred Resource of 12 700 oz Au at Nobles Nob, 4800 oz Au at Nobles Nob West and 4300 oz Au at Rising Sun (about 2 km east of Nobles Nob).

Warrego

The Warrego mine is situated about 45 km northwest of Tennant Creek and has been the most productive mine in the Tennant Creek goldfield to date, producing 41.3 t Au (including 3.3 t from re-processing of tailings), 91 500 t Cu and ca 12 000 t Bi and ca 5.5 t Ag from 4.75 Mt of ore (see **Table 9.6**). This subsurface deposit was first identified as a 2200 nT magnetic anomaly during an airborne magnetic survey flown by BMR in 1956. The first lode intersection was made in 1962 and full-scale production commenced in 1973 (Wedekind and Love 1990). Underground operations ceased in late 1989, and retreatment of the tailings (4.98 Mt at 1 g/t Au) was undertaken between 1994 and 1998, producing 3280 kg Au (**Table 9.6**).

The hangingwall succession consists of a 30–50 m-thick quartz-porphyry sill that has intruded chloritic slates (**Figure 9.27**). The footwall succession east of the Footwall Fault consists of interbedded chlorite-muscovite schist, metaquartzite and spotted chloritic slate. Contact-metamorphosed and potassically altered greywacke and shale are present west of the Footwall Fault. The Warrego Granite is exposed about 800 m west of the deposit (Wedekind and Love 1990). The sedimentary rocks and the local cleavage generally trend northwest and appear to have been rotated about 90° by intrusion of the Warrego Granite (Wedekind 1990). This granite has an imprecise U-Pb igneous crystallisation age of ca 1645 Ma (Compston 1995) and a K-Ar age for muscovite from the granite is 1684 ± 17 Ma (Compston 1994).

Prior to mining, the Warrego deposit consisted of two major and several smaller lenses of ironstone (magnetite-chlorite-quartz), which trended northwest, dipped 70° to the northeast and plunged 47° to the southeast. The strike of these lenses is parallel to bedding, but they have steeper dips than the bedding, more or less coinciding with that of the cleavage. The main pipe (No.1 orebody) extends from 140–790 m below the surface and is up to 75 m wide. Gold mineralisation was concentrated in high-grade (average 20 g/t Au) en echelon pods, composed of magnetite, chlorite and muscovite, in the footwall of the ironstone lens. There is a distinct vertical and lateral zonation of ore and gangue minerals away from the gold-rich pod into bismuth-rich and then copper-rich zones (**Figure 9.27**). Gold grains (commonly 0.5–1 mm) and bismuth minerals (bismuthinite-guanajuatite) occurred intergrown with randomly oriented laths of chlorite and muscovite, whereas chalcopyrite typically infilled fractures within massive magnetite. Gold was also present in the copper ore zones as minute (1–3 μm) inclusions within fractured chalcopyrite and pyrite grains.

In addition to chlorite-muscovite-magnetite and chloritoid-chlorite-muscovite-magnetite wall-rock alteration assemblages at Warrego, Large (1974) also identified tourmaline-chlorite and andalusite-chlorite-magnetite-tourmaline alteration assemblages on the hangingwall side of the deposit. Chloritoid and andalusite in these assemblages are now largely replaced by chlorite and muscovite, respectively. Wedekind and Love (1990) have reported quartz-muscovite-K-feldspar-tourmaline-bearing greisen veins associated with the Warrego Granite at the Warrego deposit, on either side of the footwall fault and in surface outcrop.

White Devil

The White Devil deposit is located 35 km northwest of Tennant Creek. The deposit was first worked along with the neighbouring Black Angel deposit throughout the period 1937–1941 for the production of 4.2kg Au from 379 t of ore. In 1986, Australian Development Ltd (later Poseidon Gold Ltd) acquired the leases from Peko-Wallsend Ltd and commenced open pit and later underground mining to produce 19.8 t Au from 1.3 Mt of ore from 1987–1999 (**Table 9.6**). A small amount of gold remains at both White Devil and Black Angel. The following brief description is largely summarised from Edwards *et al* (1990), Nguyen *et al* (1989) and Huston and Cozens (1994).

The host succession comprises tightly folded greywacke and shale, and is intruded by post-D_1 quartz-feldspar porphyry dykes, which also crosscut the ironstone lode and which have undergone chloritic and sericitic alteration associated with the introduction of the Au ± Cu ± Bi-bearing fluids. During deformation (D_1), the host succession was metamorphosed to lower greenschist facies and folded into an upright, 50° west-southwesterly to westerly-plunging anticline with a pervasive axial planar cleavage. The lodes were emplaced along a chloritised east-northeast-trending shear zone that developed subparallel to the axis of the F_1 anticline early during a second deformation (D_2). Nguyen *et al* (1989) described that this second (progressive) deformation at White Devil comprised: (1) the intrusion of the porphyries; (2) early shearing associated with ironstone emplacement; and (3) progressive shearing asssociated with the Au ± Cu ± Bi mineralisation. Nguyen *et al* correlated this second deformation at White Devil with the second phase of deformation recognised by Mendum and Tonkin (1976), which produced the conjugate northwest- and northeast-trending cleavages that had been mapped in the Warramunga Formation by Dunnet and Harding (1967). However, the association of the shear zones with Au ± Cu ± Bi mineralisation suggests that the second deformation of Nguyen *et al* probably correlates with D_{1a} in the Tennant Creek goldfield (see **Table 9.5**).

Two styles of Au ± Cu ± Bi orebodies are present: (1) thin, shear-related mineralisation (Main Zone and Pinter B orebodies) with ore grades of 17 g/t Au, 0.5–0.8% Cu and 0.15% Bi; and (2) pod-like ironstone-hosted mineralisation (Deeps Zone and Pinter C orebodies, **Figure 9.27**) with ore grades of 22 g/t Au, 0.1% Cu and 0.25% Bi.

The 'Main Zone' was characterised by 0.5–7 m-wide ore zones, consisting of gold, chalcopyrite, pyrite, bismuthinite and marcasite, hosted by highly chloritised sedimentary rocks. Magnetite stringers occur in the hangingwall and adjacent brecciated ironstones. The 'Deeps Zone' comprises: gold, bismuthinite and bismuth sulfosalts with minor chalcopyrite and pyrite within chlorite-magnetite-altered sedimentary breccia; elliptical, fractured chlorite-magnetite ironstone pods; and stringer zones (up to 50 m wide) beneath and adjacent to these ironstones. In the deeper levels of the orebody, a mineralogical and chemical zonation is evident; this was gold-rich in the footwall and proceeded via a bismuth-rich section to copper-rich in the hangingwall.

Pervasive chloritisation with minor amounts of talc alteration extends 15–20 m into the adjacent sedimentary rocks. Dolomite alteration has been intersected in the lower portions of the Pinter and Deeps Zone orebodies. Gold in both ore types is generally fine grained. The fineness for White Devil bullion for 1991–1992 was 933.

TC8

The TC8 deposit is situated 4.5 km west of Tennant Creek. The original target was identified in 1970 by Western Nuclear during a low-level aeromagnetic survey and drilled in 1972 as a joint venture between Western Nuclear, Aquitaine Australia Minerals and Geopeko. The deposit was mined in 1986–1988 by Norseman Gold Mines and produced 1420 kg Au from 80 000 t of ore (**Table 9.6**). A separate copper lode (**Figure 9.27**) containing an inferred resource of 104 000 t at 5% Cu, 0.3 g/t Au and 34 g/t Ag (Ahmad *et al* 2009) exists above and northward of the exhausted gold pod. Mine tailings have a reported grade of 0.7 g/t Au, 0.3% Bi and 0.5% Cu (Giants Reef Mining 1993).

The host succession consists of folded chloritic slate, siltstone and greywacke, and a 5–10 m-thick haematitic shale unit. Cleavage (S_1), strikes east–west and dips 70° to the north. The ironstone pipe is about 160 m long, 10–25 m wide and extends to a depth of 375 m (Hill 1990). This pipe occupies a shear zone, which parallels the regional cleavage and which intersects the haematitic shale unit about 200 m below the surface (**Figure 9.27**). The gold mineralisation is located within a sericite-chlorite-magnetite stringer zone, within and below a discrete chlorite-magnetite ironstone pod. Gold grains (up to 0.25 mm) occur, intergrown with bismuthinite and chalcopyrite. Copper mineralisation consists of bornite and chalcopyrite, with minor wittichenite and covellite, and traces of gold within a dolomite-magnetite-quartz-talc gangue that forms the hangingwall envelope of the gold pod.

Juno

The Juno deposit is located about 8 km southeast of Tennant Creek and has produced 26.13 t Au, 1429 t Cu, 2293 t Bi and 2.752 t Ag from 455 000 t of ore (**Table 9.6**). This subsurface deposit was first identified as a discrete magnetic anomaly in an airborne survey flown by BMR in 1937 (Daly 1957). However, the first lode intersection was not made until 1965 and full-scale production commenced in 1967 (Large 1975). Mining operations ceased in 1977. Average gold grade was about 56 g/t, and Excalibur Mining reported (ASX announcement 3 December 2009) that an historical intersection of 32 m at 670 g/t Au, including 1.5 m at 12 883 g/t Au, was recorded during the original drilling program at the deposit.

Two east–west-trending orebodies were mined at Juno. The eastern No 1 orebody has a strike length of 150 m, is up to 15 m wide and dips 85° to the north. Most of the ore was extracted from the relatively compact western No 2 orebody, which is 75 m long and up to 30 m wide. The orebodies occupy the hinge area of an east–west-oriented anticline and formed where shears intersected a 5–7 m-thick, haematite shale bed, about 230 m below the present-day land surface. Bedding dips near-vertically, while a distinct axial plane cleavage (S_1) dips 80° north, parallel to the elongation of the orebodies.

Juno No 2 orebody has a distinct mineral zonation within and around the ironstone body. The core of the ironstone body consists of 80% magnetite and 20% chlorite, and is enclosed above by a talc-magnetite zone containing minor pyrite. An outer dolomite envelope contains haematite, quartz and magnetite, and separates the talc-magnetite zone from chloritised metasedimentary rocks above the ironstone body. Drilling has shown that a magnetite-chlorite stringer pipe extends about 350 m below the ironstone body.

Assay data indicates that Au, Bi, and Cu occur in distinct overlapping zones (**Figure 9.27**). Gold is generally present as minute grains (10–30 μm) dispersed within the magnetite-chlorite (ironstone) body. Larger gains (up to 1 mm) are present in subhorizontal chlorite-filled cracks, or in shrinkage cracks in magnetite. Bismuth sulfosalts (junoite, wittite, emplectite and bismuthinite-aikinite series) were concentrated in an umbrella-shaped zone partially overlapping, but also above the gold zone. The bismuth zone is partly within the magnetite-chlorite pod, but also extended into the talc-magnetite zone at its apex. Chalcopyrite is concentrated along the outer contact between the magnetite-chlorite and talc-magnetite zones. Pyrite is also concentrated in the copper zone, but persists further into the talc-magnetite zone. Traces of cassiterite and wolframite have been recorded in the stringer zone (Large 1974).

Excalibur Mining identified a number of EM, gravity and magnetic targets in a reinterpretation of historical geophysical data at their Juno leases (**www.excaliburmining.com.au**). They reported (ASX announcement 6 August 2010) a JORC-compliant Inferred Resource of 185 300 oz Au at Juno. The M10 orebody is situated about 200 m below Juno and Excalibur Mining has reported (ASX announcement 6 August 2010) a JORC-compliant Inferred Resource of 65 200 oz gold for this deposit.

Gecko (including K44)

Gecko is situated about 27 km northwest of Tennant Creek and was a copper-bismuth mine with only minor associated gold. About 122 700 t of copper and 3450 kg of gold were produced from 3 Mt of ore with average grades of 4% Cu and 1.2 g/t Au. These figures include production from the K44 satellite orebody. Le Messurier *et al* (1990) reported that production from Gecko started in 1973, but the mine was put on care-and-maintenance in 1981 (Main *et al* 1990). The mine was subsequently worked intermittently until 1998.

The Gecko deposit (**Figure 9.27**) was described by Large (1974) and Huston *et al* (1993), and the satellite K44 orebody by Main *et al* (1990). The following is summarised from these sources. Initially, a broad, poorly defined aeromagnetic anomaly (Explorer 1) was resolved into four discrete first-order anomalies (ironstones) by detailed ground magnetic surveying. A drilling program that commenced in 1967 identified significant mineralisation associated with three of these anomalies. The ironstone bodies are within subsidiary folds on the northern limb of a west-trending anticline. They are hosted by a stratiform breccio-conglomeratic horizon immediately underlying a haematite shale unit within the Warramunga Formation. Subsequent magnetic modeling of the ironstone bodies resulted in the recognition of the K44 ironstone. This ironstone occurs within a domical structure on the northern limb of the regional anticline.

Large (1974) described Anomalies 1 and 2 as being lensoidal to elliptical and elongated parallel to the (westerly) strike of the bedding, whereas Anomaly 3 is a pipe-like body plunging at about 75º to the east. At both Anomalies 1 and 2, the lode was haematite-quartz. The predominantly chalcopyritic mineralisation was concentrated in two magnetite-rich pods within the quartz-haematite lode at Anomaly 1, and in a similar magnetite body at the core of the Anomaly 2 lode, where chalcopyrite ranged from 5–50% with an average of about 15%. Ore-grade bismuthinite was present in a zone of magnetite-haematite-quartz at Anomaly 2. The magnetite lode at Anomaly 3 is of interest in that in addition to chalcopyrite, it carried an average of 5–10% bornite in the central and upper parts of the lode.

Large (1974) described the outer portion of the lode at Anomaly 2 as comprising an ill-defined massive haematite/haematite-quartz zone, and a haematite-magnetite-quartz-chlorite zone, in which chalcopyrite is patchily distributed and only locally of ore grade. The haematite-magnetite zone hosted the F10 bismuth body (which produced 40 000 t of ore at 1% Bi). The upper portion of the Anomaly 2 ironstone is surrounded by a zone of chlorite and, more proximally, by chlorite-haematite alteration within the host breccio-conglomeratic Warramunga Formation. The Anomaly 3 magnetite-talc-dolomite-calcite-haematite lode is surrounded by a carbonate-rich replacive envelope within the breccio-conglomerate, and the wall-rock shales are chloritised.

The *K44* ironstone, in common with the other lodes at Gecko, is hosted by breccio-conglomeratic facies of the Warramunga Formation, immediately underlying a haematite shale unit. Main *et al* (1990) reported that the ironstone was elongated parallel to the east-striking, north-dipping S_1 slaty cleavage in the host rocks, and that this cleavage remains uniformly oriented throughout the clasts in the breccio-conglomerate. These authors interpreted the latter observation to indicate that the breccio-conglomerate is a mass-flow deposit within the turbiditic Warramunga Formation. Main *et al* (1990) described the ironstone as comprising about 75% magnetite + haematite, generally in subequal proportions. However, haematite dominates in the margins of the ironstone body and is the only iron oxide present in the gold-bearing (generally ≤3 g/t) sulfide-rich uppermost extension ('tongue') of the orebody. Quartz, chlorite and dolomite were associated with the ironstone, together with minor talc, sericite, calcite, magnesite and barite. Quartz was more abundant in the haematite-dominated parts of the ironstone. Chlorite dominates the alteration zone, which surrounds and extends upward from the 'tongue', and also defines former fluid pathways near the base and southern margin of the ironstone. Chalcopyrite constituted about 75% of the total sulfide mineralisation, which is generally >10% and locally varied up to about 80% of the ironstone body by volume. Although pyrite constituted most of the remainder of the sulfides present, additional sulfide minerals were bornite (see above), cobaltite, pyrrhotite, chalcocite, tetrahedrite, molybdenite, sphalerite, galena and bismuth sulfosalts. Native copper and uraninite also occurred.

Huston *et al* (1993) recognised three paragenetic stages associated with the mineralisation at Gecko K44 (and also at White Devil). These stages are: (1) an early syndeformational ironstone formation stage from low-temperature (250ºC) connate brines; (2) introduction of syn- to post-deformational, higher-temperature (350ºC), sulfide-bearing Au-Cu-Bi fluids with variable magmatic and connate components; and (3) a late, minor carbonate stage. Skirrow and Walshe (2002) concluded that the haematite-rich high-grade copper and gold-rich ore zones at K44 are atypical of the Tennant Creek deposits. They suggested that an earlier reduced sulfide-bearing mineralising system may have been overprinted by an oxidising brine and consequently haematitised.

Eldorado

Eldorado is situated about 5 km south of Tennant Creek. It was discovered in 1932 and mining started in 1934. Ivanac (1954) reported that Eldorado was the only mine operating in Tennant Creek at the onset of World War II and it was consequently permitted to stay operational during the war. However, Le Messurier *et al* (1990, figure 4) indicated that a number of other mines (Whippet, Nobles Nob, Peko, Northern Star, Rising Sun, Hammerjack, Enterprise (in the Eldorado Group of mines) and Blue Moon were also in production during the war. Eldorado was apparently the only mine to have been operational throughout the war. In 1989–1991, tailings at Eldorado were re-treated, and open cut mining was undertaken in 1992. The Eldorado deposit has been described by Ivanac (1954), Horvarth (1988) and Skirrow and Walshe (2002), and salient details from these sources are summarised herein. Eldorado (Shallows) has produced 3800 kg of gold from ore with an average grade of 20.0 g/t (**Table 9.6**).

Ivanac (1954) reported that the Eldorado Shallows orebody was truncated by the Turner thrust, which offset this orebody approximately 170 m to the west-southwest relative to the Deeps orebody. Skirrow and Walshe (2002) recorded that drilling by Geopeko indicated a resource of about 29 200 t of ore at 20.8 g/t (with a 3 g/t cut-off), about one-sixth the amount of gold that was contained in the Shallows. Skirrow and Walshe regarded the Deeps orebody (**Figure 9.27**) as representative of the oxidised (haematite-rich, gold-rich and copper-poor) end-member of a spectrum of deposit types they recognised at Tennant Creek; this spectrum extends to a reduced (copper- and sulfide-rich) end-member represented by the West Peko Cu-Au-Bi deposit. The Deeps deposit is considered the primary equivalent of the weathered and oxidised Shallows orebody (Skirrow and Walshe 2002).

Skirrow and Walshe (2002) interpreted that the Deeps ironstone formed under conditions of low sulfur activity. Fluid fO_2, was close to that of the boundary between the haematite and magnetite stability fields, and the early-formed ironstone was haematitic, but was partially replaced by magnetite at a later stage in D_1. Skirrow and Walshe concluded that the subsequent gold-copper-bismuth ore-bearing fluid was reducing. However, interaction with mixed-chloride basinal brines resulted in: (1) the precipitation of the sulfide-stage mineralisation, and (2) subsequent oxidation and haematitisation of the ironstone. Warramunga Formation metasedimentary rocks (quartz-sericite-magnetite-haematite-chlorite), adjacent to ironstones and in 'stringer' zones, were altered to an assemblage containing more iron-rich chlorite, together with muscovite, magnetite and haematite that were contemporaneous with the later-stages of D_1. The Shallows ironstone is probably analogous to this, except the ironstone contains less magnetite, probably as a consequence of late-stage (weathering) processes.

The Shallows ironstone is partially brecciated at the margins and the lower part of the Deeps ironstone is similarly brecciated. Brecciation of the ironstones is associated with silicification and quartz-haematite (-martite-magnetite) alteration and veining, forming stringer zones. These stringer veins are crosscut by later chlorite-quartz veins. High-grade gold and associated bismuth mineralisation are located within the zones of brecciation and the stringer zones, and also occur at the Deeps in late-stage chlorite-associated micro-shear zones that postdate the chlorite-quartz veins. Brecciation and associated alteration and mineralisation were attributed to a second deformation by Skirrow and Walshe (2002).

In the regional context, the Eldorado deposit was recognised by Ivanac (1954) to be associated with east-southeast parasitic folding on the southern limb of an F_1 anticline. Skirrow and Walshe (2002) attributed parasitic fold plunge reversals, and their non-cylindrical character, to probable fold superposition.

Peko and West Peko

The Peko mine is situated 12.5 km east of Tennant Creek. The deposit outcropped as a massive quartz-haematite body, described by Ivanac (1954) as two contiguous lenses that became more quartzic to the west. Mining was initially undertaken between 1935 and 1942; operations then ceased during the remainder of the War. During this first stage of mining, 5589 t of copper ore were mined from the small, oxidised, supergene-enriched lode (Ivanac 1954). Gold recovery was very poor with only about 23 kg produced, and about 20 g/t of Au (Higgins, pers comm in Ivanac 1954) was lost to the tailings. Peko Mines NL was formed in 1949 and about 2 kg of gold was recovered from 505 t of ore in the 1950/51 fiscal year. Recoveries were apparently much better in the 1951/52 fiscal year, with >1.6 kg Au recovered from ca 83 t of ore. Ivanac (1954) reported that the tailings were cyanide processed by Central Gold Milling Company, but the gold recovery figures have been lost. About 7481 kg Au and 118 884 t Cu were produced from 3.16 Mt of ore from Peko between 1954 and 1976 (**Table 9.6**).

The Peko orebody (**Figure 9.27**) was described by Whittle (1966) and the following details are summarised from this reference. The main and satellite lodes are on the southern limb of a syncline. The main lode is a steeply plunging pipe-like body whose dimensions increase downwards giving it an essentially pear shape, and together with the host syncline, the ironstone body pitches 70° to the west. The hypogene zone comprised pyrite and chalcopyrite together with minor pyrrhotite, bismuthinite and cobaltite. The upper extremity of the sulfide-bearing core of the orebody extended above the water table to form an oxidised zone where cuprite and native copper were present in a quartz-haematite ironstone. A zone of secondary enrichment included gold leached from the overlying oxidised zone and, near the water table, there was a change downwards from copper oxide minerals to copper carbonate and sulfide minerals. The upper part of the orebody is enveloped by barren quartz-magnetite that was altered to quartz-haematite, the uppermost part of which contains fine-grained gold, sericite, manganese and iron oxide minerals, and bismite and bismutite. This uppermost (quartz-haematite) zone of the lode is in contact with country rocks showing chloritic alteration. In contrast, Whittle (1966) reported that the quartz-magnetite body is in contact with essentially unaltered sedimentary rocks, although at depth, the host rocks are chloritised. In the upper part of the alteration halo, silicified and jasperoidal rocks separate the lode from the chloritically altered host rocks. At greater depth, chloritic alteration gives way to a zone of talc-anthophyllite alteration the inner part of which is extensively brecciated. Carbonate veins are present within the chloritic zone. At still greater depth, late pneumatolytic alteration resulted in tourmaline and pyrite in part replacing previously chlorite-, and talc-anthophyllite-altered rocks.

The *West Peko* orebody (**Figure 9.27**) is situated about 2 km west of the Peko. According to Skirrow and Walshe (2002), West Peko contains several hundred thousand tons of Au-Cu-Bi ore, and includes drilling intersections with up to 10% Cu and 10 g/t Au. The West Peko orebody was described by Skirrow and Walshe (2002) as a reduced end-member copper-gold deposit, and the following details are summarised from their paper. In common with the Peko orebody, West Peko is hosted by Warramunga Formation sedimentary rocks, including minor haematite shale, which have relatively high magnetic susceptibility. Deformed and chloritised porphyry occurs about 50 m below the two east-trending, steeply north-dipping to essentially vertical West Peko ironstone bodies. These bodies are each of the order of 30x150x300 m. The deformed porphyry contrasts with a stratiform quartz-feldspar porphyry lower in the succession, and the former is interpreted to predate D_1 and the mineralisation.

Skirrow and Walshe (2002) reported that the magnetite bodies comprise up to 30% by volume of quartz, and that minor haematite is present in jasperoidal bands as an early-formed phase, although it is now largely replaced by magnetite. The central parts of the ironstones contain zones of chalcopyrite, gold and bismuthinite; these are associated with magnetite, pyrrhotite and chlorite, and with zones of magnetite + stilpnomelane-pyrrhotite, magnetite-talc-stilpnomelane or magnetite-quartz-minnesotaite, and a narrow zone of magnetite-stilpnomelane-chlorite-pyrite proximal to the contact between ironstone and chloritised country rocks. Tremolite/actinolite, siderite and rhodochrosite are associated with magnetite and quartz in the lower parts of the ironstones. Skirrow and Walshe (2002) described four discrete stages of chlorite formation in West Peko.

Golden Forty

Golden Forty is about 6 km northeast of the Nobles Nob mine, and is situated on the intervening limb between the Nobles Nob anticline and the Peko syncline. Wyborn (1971) described the Golden Forty deposit and the following is summarised from his thesis. The deposit comprises a pipe-like, east-trending ironstone body about 200 m long and plunging 45° to the west. The pipe has a circular section at the top, but an ellipsoidal section at the base. It is one of a number of en echelon ironstone bodies trending east-southeast at an angle to the east-trending regional cleavage. The trend of these ironstones crosses the Peko syncline obliquely and the bodies are therefore interpreted to postdate the syncline. Pontifex (1964) reported that from Golden Forty to Great Eastern, ironstone bodies are localised along vertical east-trending fold axial planes and pitch 30° to the west. The Golden Forty ironstone body varies from massive magnetite with minor quartz to the converse and extended to the surface, where the top of the body had been eroded away. A chlorite-magnetite zone constituted the main mineralised zone, although some mineralisation extended into the overlying quartz-magnetite ironstone body. Mineralisation comprised bismuthinite, chalcopyrite and pyrite, together with native gold, the latter extending into the underlying stringer zone. The chlorite in this zone is intensively foliated, and there are irregular lenses of talc-chlorite-magnetite rock in the southern part of the zone. The stringer zone comprises (muscovite-bearing) chlorite-magnetite veins within the cleavage planes of the host rock. Wyborn (1971) suggested a possible two-stage mineralising system, with iron and copper predating gold, bismuth and selenium. Pontifex (1964) described that the ironstone bodies from Golden Forty to Great Eastern are blue-black, as a result of martitisation, and that minor quartz is associated with the magnetite, although a later generation of sheared quartz fills fractures within the ironstones. He also reported the occurrence of pyrrhotite, specularite, bornite, chalcocite and marcasite among the primary and secondary ore minerals and graphite among the gangue minerals.

According to Reveleigh (1977), there were four mineralised bodies at Golden Forty, plunging at 45° to the west and having clearly defined alteration zones, comparable with those described from Juno. Reveleigh described chloritised sedimentary rocks, including a zone of black chloritised rocks that represented the initial stage of alteration, which gives way to a more completely altered, green chloritic stringer zone. Hargreaves (1974) reported that chlorite in the metasedimentary rocks hosting the Tennant Creek orebodies is generally Mg-rich. He also reported that, although Mg-rich chlorite was found in the Golden Forty orebody, Fe-rich chlorite is common in the upper portion of the chlorite-magnetite zone and in the quartz-haematite zone. A dolomite zone comprises ≤60% dolomite, together with chlorite, talc, magnetite, haematite, quartz and jasper. According to the cross-section in Reveleigh (1977: figure 18) the dolomite zone forms a vertically oriented lens within the talc-magnetite zone. The zone of talc-magnetite alteration extends vertically below and down-pitch from the dolomite zone, below which is a quartz-magnetite zone and then the mineralised zone, which contains chlorite-magnetite-haematite. Interestingly, Reveleigh (1977) noted that minettes in the vicinity of Golden Forty include those that both predate (ie, are altered by the mineralising fluids) and postdate the mineralisation. Reveleigh reported that haematite-shale at Golden Forty is purple-grey and contains 0.2% carbon.

Golden Forty produced about 1762 kg of gold from 0.15 Mt of ore, with an average grade of 12 g/t Au (**Table 9.6**). Emmerson Resources Ltd (ASX announcement 1 September 2008) reported significant gold intercepts from recent drilling at their Golden Forty project; these were 5 m at 7.03 g/t including 3 m at 10.1 g/t, and 4 m at 5.96 g/t, including 1 m at 15.4 g/t.

Northern Star

Northern Star is located about 25 km almost due north of Tennant Creek. This orebody was described by Edwards (1987), from which source the following information is summarised. Figures compiled by Ferenczi (1996) indicate that about 810 kg Au was produced from Northern Star from 115 000 t of ore (see **Table 9.6**).

Edwards (1987) described a number of ellipsoidal ironstone bodies arranged en echelon on the southern limb of an east-trending F_1 anticline. These ironstone bodies are flattened in the direction of F_1 fold axial planes. There is a well-developed S_1 slaty cleavage that is axial planar to second-order open to isoclinal and generally upright to slightly overturned folds developed on this limb of the regional anticline. A second deformational event has resulted in a number of east-striking and moderately to steeply north-dipping reverse faults (or thrusts), including the uranium-mineralised Higgins thrust, and there is a weakly-developed S_2 crenulation cleavage. The country rocks are a silty facies, with a generally low magnetic response, of the turbiditic Warramunga Formation and include haematite shale.

According to Edwards (1987), the ironstone bodies are predominantly haematitic (50–90%), with massive anhedral or colloform haematite pseudomorphing magnetite, of which generally <1% remains. There is a second generation of late-stage specular or micaceous haematite. The centre of the ironstone body that was mined in the open cut comprised haematite (50–90%), quartz (5–30%) and chlorite (5–20%); however, the depth of oxidation is ≥100 m and, above this depth, chlorite has been largely altered to clay. Chlorite forming the matrix around haematite/magnetite within the ironstone and also associated with vertical shears at the margins of the ironstone is iron-rich. The ironstone body was brecciated, and its northwesterly dip (in contrast to the northerly dip of the other proximal ironstone bodies) was also attributed to the effects of D_2 by Edwards (1987). Brecciation resulted in magnesian-chlorite and quartz invading the ironstone, both as matrix and also forming veinlets infilling cracks. This mineral assemblage carried the chalcopyrite, pyrite and gold mineralisation.

At the top, and locally on the flanks of the haematite-quartz-chlorite (ironstone) zone is a talc-chlorite-haematite zone. Above the level of oxidation, this zone was converted to haematite, goethite, clay (after talc and chlorite) and quartz, and carried minor sulfides and gold. Immediately above the talc-chlorite-haematite zone was a dolomite-haematite zone with dolomite veins to 10 cm wide cutting massive haematite. Near the surface dolomite and vugs in the haematite were replaced / filled with secondary haematite, goethite, specularite and limonitic clay, or silicification resulted in jasper-haematite rock. In both these assemblages, chalcocite and gold were concentrated by supergene processes.

A stringer zone comprises haematite and 10–60% Fe-rich chlorite with veinlets of Mg-rich chlorite, quartz, copper sulfides and gold. Edwards (1987) described that the stringer haematite zone approximately parallels the strike of the (haematitic) ironstone bodies. Chloritised sedimentary rock forms an outer halo with up to 80% Fe-rich chlorite, 5–10% haematite (after magnetite) and 10–15% quartz. Very low-grade chalcopyrite and gold grades are associated with dolomite veins subparallel to the S_1 cleavage within this halo. These veins have quartz selvedges. Leached, chlorite- and haematite-free sedimentary rocks occur directly below the ironstone bodies, and the rocks are highly silicified.

The Northern Star haematite body is anomalous with respect to uranium (ca 20 ppm), and ore-grade uranium (up to 0.6% uraninite) is associated with chloritic schists, which also carry haematite, apatite and pyrite along the Higgins thrust zone (and a lower tenor of uranium also occurs in a similar context along the Nilsens and McFarland faults).

Argo

The Argo deposit was described by Meade (1986) as an east-trending, flattened pipe-like body, paralleling the axial plane of an anticline, dipping north at about 65° and pitching steeply to the southeast. Foliation within the orebody parallels the axial plane cleavage of the anticline, suggesting that ironstone formation was pre- or syn-D_1. The ironstone is a massive magnetite body comprising 50–90% magnetite, 10–40% pyrite and 1–20% chlorite, together with minor haematite. It also contains up to 25% jasper. In the upper parts of the magnetite body, pyrite fills fracture veins and cavities. At deeper levels, pyrite rims magnetite and may, in turn, be rimmed by banded dolomite. Replacement pyrite veins and grey-white dolomite veins also occur. A magnetite-carbonate zone contains pink dolomite, postdating this veining and crosscutting clasts, and is associated with chlorite and minor pyrite.

A massive pyrite body, with up to 90% pyrite and 10% magnetite, and with fine dolomite veins, is situated on the hangingwall side of the ironstone. Both the ironstone and the pyrite body are surrounded by a carbonate zone comprising dolomite, jasper, chlorite, magnetite and ore minerals. According to Meade (1986), this carbonate zone includes a number of subzones: (1) a foliated magnetite-talc-chlorite-carbonate subzone; (2) magnetite-carbonate and veined magnetite-carbonate; (3) veined magnetite-jasper-carbonate; (4) banded-carbonate, pyrite-carbonate, jasper-carbonate and haematite-carbonate subzones; and (5) lath-carbonate-bearing subzones. The carbonate zone is, in turn, surrounded by chloritised sediments.

Mineralisation (Au, Cu and Bi) is largely restricted to the massive magnetite body and the hangingwall pyrite zone. There is no distinct zonation. Gold and bismuth are associated, but apparently occur in randomly distributed pods, including some high-grade pods in the footwall dolomite zone. Chalcopyrite is the only copper mineral present and replaced magnetite and pyrite in the magnetite zone. Traces of scheelite were reported from the deeper-levels of the Argo deposit by Meade (1986).

Ahmad *et al* (2009, table 5) reported that 2050 kg of gold were produced from Argo from 0.29 Mt of ore with an average grade of 8.6 g/t Au. About 2000 t of copper were also produced from this deposit (see **Table 9.6**).

Orlando

Orlando is situated approximately 30 km northwest of Tennant Creek, and the associated magnetic anomaly was discovered during the 1935–1937 AGGSNA surveys. The deposit has produced 4852 t of Cu, 3772 kg of Au, 4.7 t of Bi and 1223 kg of Ag from 0.32 Mt of ore, with an average grade of 1.8% Cu and 11.0 g/t Au (Ahmad *et al* 2009, table 5, see **Table 9.6**).

The deposit was described by Whittle (1966) and is a flattened, lenticular body that plunges 25° to the northwest, with a steep southerly dip parallel to the Orlando shear, and parallel to bedding and cleavage in the country rocks. A wide zone of brecciation on the hangingwall side dips at a shallower angle to, and postdated the shear zone. A Pb-Zn-bearing ore shoot is associated with dolomitic and talcose rocks within the hangingwall breccia. Below the level of oxidation (and brecciation), the main orebody comprised sheet-like veins parallel to the cleavage in chloritic schists. Veins varied from simple pyrite or magnetite to magnetite, pyrite, chalcopyrite and bismuthinite, together with minor haematite and gold. Dolomite, quartz and coarse chlorite constituted the gangue and coarse magnetite and chlorite (contrasting with the fine chlorite and detrital magnetite in the host rocks) were replacive, whereas pyrite is associated with more talcose intervals of the shear zone. Chalcopyrite, bismuthinite and gold postdated magnetite, pyrite, chlorite and talc. Chalcopyrite and bismuthinite replaced chlorite and the chalcopyrite carried gold.

Ivanhoe

According to Whittle (1966), Ivanhoe is a flattened, lenticular, vertically dipping and steeply east-plunging structurally controlled orebody, located along a continuation of the Mary Lane Shear Zone. Situated approximately 17 km northwest of Tennant Creek, Ivanhoe produced 8950 t of Cu, 847 kg Au and 3872 kg Ag from 0.32 Mt of ore grading 3% Cu, 3 g/t Au and 12 g/t Ag (see **Table 9.6**).

Whittle (1966) noted that the wall rocks to the hypogene ore zone are unaltered chloritic slate and tuffaceous sandstone with a vertical cleavage and a steeply-plunging lineation, defined by quartz and chlorite growth. Three assemblages of ore and gangue were recognised in the primary ore zone:

1. Rhythmically banded (parallel to bedding and cleavage in host rocks) magnetite (haematite) and pyrite, with incipient chalcopyrite mineralisation in interstitial chlorite around magnetite, but resulting in little or no replacement of magnetite or pyrite.
2. Advanced massive sulfide mineralisation with chlorite replaced by chalcopyrite. The host rock slate is almost completely replaced; actinolite, tremolite and talc-filled fractures in the slates are remnant.
3. Complex sulfide ores comprising: (a) chalcopyrite, pyrite, magnetite and quartz, together with galena and sphalerite, with the galena enclosing relict magnetite or pyrite; (b) veinlets of chalcopyrite, gold-bearing specularite and subordinate pyrrhotite, pyrite, bismuthinite, galena, wittichenite, and quartz as fracture filling and replacement veins in a pyrite- or magnetite-dominated lode.

Chariot

The following description is summarised from Giants Reef Mining (2005). Chariot was discovered by Normandy Mining Ltd in 1998 and the nearby Malbec West by Giants Reef Mining Ltd in 2004 (see **www.emmersonresources.com.au/History-Emmerson-Resources.htm**). The ironstone at Chariot comprises two east-striking (80°), steeply north-dipping zones. The ironstones are tabular in plan and flattened and pipe-like in section, and lie on the same sinistral strike-slip line as the TC8, Argo and Peko mines. The more northerly zone, which hosted the recovered gold (plus minor copper-bismuth) mineralisation, was associated with a low-amplitude magnetic anomaly located to the east of a 500 nT magnetic anomaly (Explorer 11, Malbec West). The low magnitude of the anomaly reflected the proportion of primary haematite in the magnetite-haematite-chlorite ironstone body. There is a chloritic alteration envelope on both the footwall and hangingwall side, and a locally well developed external dolomite ± quartz ± talc zone. The sulfide mineralisation comprised chalcopyrite, minor pyrite and trace bismuthinite, and chalcopyrite and may form a weak zone external to the main ore zone. The gold is hosted by veins of haematite ± quartz and disseminated haematite.

A pervasive S_1 foliation parallels D_1 shear zone(s) and is axial planar to F_1 folds. There is a weak, localised shallowly-dipping S_2 foliation. This predates sinistral(?) reactivation of the shear(s), which resulted in open space and ironstone formation. Ironstone formation in turn predates north-over-south shearing associated with the gold mineralising event, which was also associated with haematite and chlorite alteration.

The combined gold production from Chariot and Malbec West was 1101 kg from 127 000 t of ore, with production coming from Chariot in 2003–2005 and Malbec West in 2005 (Ammad *et al* 2009, table 5, see **Table 9.6**).

Rover field

The Rover field is situated to the southwest of Tennant Creek and is partially within TENNANT CREEK, GREEN SWAMP WELL, LANDER RIVER and BONNEY WELL. It underlies 70–200 m of Cambrian sedimentary rocks of the Wiso Basin. Exploration in the field started in the 1970s and early 1980s, but ceased in 1982, when the area became Aboriginal Freehold Land. During this phase of exploration, Geopeko Ltd conducted a low-level aeromagnetic survey over a significant area of the field, and targeted and drilled a number of magnetic anomalies comparable with those in the Tennant Creek goldfield. The company intersected significant high-grade gold-copper-bismuth mineralisation at the Rover 1 prospect (Westgold Resources Ltd ASX announcement 19 December 2007).

A new phase of exploration was started in the Rover field in 2005 (Ahmad *et al* 2009). Drilling by Westgold Resources Ltd and Adelaide Resources Ltd has confirmed that copper and gold mineralisation is associated with magnetite-haematite and haematite-jasper-dolomite ironstone bodies, and is hosted in intensely chloritically altered sedimentary rocks. Adelaide Resources has announced significant intersections of copper at Rover 1, with associated gold (ASX announcement 23 March 2010, AGES 2010 presentation, ASX broker presentation 20 May 2010). Adelaide Resources has also noted that the copper-mineralised zone at Rover 4 is partially hosted by a magnetite-dominated ironstone that, together with the presence of gold, bismuth and cobalt, indicates that the mineralisation is of the Tennant Creek-style (ASX announcement 23 December 2009). The Rover 1 anomaly straddles the boundary between tenements held by Adelaide Resources and Westgold Resources. Westgold Resources is also exploring Rover 1, as well as other former Geopeko prospects at Explorer 142 and Explorer 108, and is identifying additional new targets in the field.

The Rover 1 mineralisation occurs within a 700 m-long coincident intense magnetic and gravity anomaly. It is hosted in a chlorite-rich brecciated 'stringer zone', with copper mineralisation also extending into magnetite-rich ironstone. Bismuth and cobalt are associated metals. Westgold Resources (ASX Release 9 June 2009) likened the mineralisation (and also that at Explorer 142) to typical Tennant Creek-style, iron-oxide copper-gold mineralisation. This company started drilling at Rover 1 in 2008 (Westgold Resources ASX announcement 26 March 2008) and has subsequently identified three significant gold-copper mineralised zones (Western Zone, Jupiter Zone and Southern Zone) over a strike length of about 500 m, including some bonanza grade intervals (Westgold Resources ASX announcements 4 June 2008, 29 August 2008, 10 September 2009). The company has announced a Maiden JORC-compliant Resource of >1 Moz (gold equivalent) for Rover 1 (Westgold Resouces ASX announcement 23 February 2010).

Age of mineralisation

The age of mineralisation in the Tennant Creek goldfield can either be considered relative to the phases of deformation in Warramunga Formation, or from the perspective of isotopic dating. As noted above, the regional, broadly east–west-striking, slaty cleavage (S_1) in the Warramunga Formation, and shears parallel to this cleavage approximately coincide with the axial orientations of moderate to tight (F_1) folds, and are important controls on the distribution of many ironstone bodies. The ironstones have undergone brittle-ductile deformation and are associated with foliated chloritic alteration, characteristics that are consistent with their emplacement during the first (ca 1850 Ma) phase of deformation (D_1) in the Warramunga Formation. Chlorite and muscovite, closely associated with the Au (Cu-Bi) mineralisation, are typically non-foliated, suggesting that this mineralisation was late in, or postdated D_1. Structural evidence, presented by Nguyen (1987) from the White Devil mine, indicates that the Au-Cu-Bi mineralisation accompanied D_2. Skirrow and Walshe (2002) reached the same conclusion and they also agreed that D_2 was a separate deformational event from D_1 and may have significantly postdated it. On the basis of regional geological considerations, the Au-Cu-Bi mineralising event may therefore have been in the time interval 1830–1790 Ma.

Rb-Sr isotopic ages for muscovite from the Juno, Warrego, Golden Forty and Nobles Nob mines indicated a mineralisation age of about 1810 Ma (Black 1977). More recent $^{40}Ar/^{39}Ar$ isotopic analyses of hydrothermal muscovite from Peko, Argo, Nobles Nob and Juno indicated a minimum age for mineralisation between 1825–1830 Ma (Compston and McDougall 1994). Conventionally determined Pb-isotopes in lead-rich gold lodes from Tennant Creek (specifically the Gecko, Argo, Juno and Peko deposits) allowed Warren *et al* (1995) to determine model ages for these deposits. These authors identified that seven discrete end-member lead sources (A–G) can be mixed to form a wide range of known volcanigenic massive sulfide deposits. Mixing isochrons between source end-member 'C' and either 'F' or 'E' [both enriched sources with high μ (ie, $^{238}U/^{204}Pb$)] values gave age ranges of 1856–1835 Ma and 1834–1819 Ma, respectively (with individual age determinations having an error of ± 15 Ma) for the Tennant Creek deposits. Warren *et al* (1995) considered that source E represents subcontinental lithospheric mantle.

Fraser *et al* (2006) concluded that a combination of a revised age for the GA-1550 argon age standard (Spell and McDougall 2003) and cross-referencing the U-Pb and $^{40}Ar/^{39}Ar$ timescales (Kwon *et al* 2002) allowed a revision of Compston and McDougall's (1994) $^{40}Ar/^{39}Ar$ muscovite ages to ca 1850 Ma.

McInnes *et al* (2008) reported a Re-Os whole-rock isochron (derived from seven samples of high-grade copper sulfide ore) of 1665 ± 66 Ma with an initial $^{187}Os/^{188}Os$ of -0.05 ± 0.32 from the Gecko K44 ore deposit. These authors therefore concluded that Tennant Creek Cu-Au-Bi mineralisation postdated the Tennant Event (and Tennant Creek Supersuite magmatism) by more than 100 my. This conclusion is markedly different from those based on the other isotopic systems and outlined above.

Ironstone-associated copper-gold (IOCG) mineralisation in the Rover field is apparently of the typical Tennant Creek style (Westgold Resources Ltd ASX Release 9 June 2009, Adelaide Resources Ltd ASX Announcement 24 August 2009). However, the host rocks are apparently younger than those of the Warramunga Formation, but see Maidment *et al* (in press) for further discussion of this. A volcaniclastic rock from the field has a SHRIMP U-Pb maximum depositional age of 1842 ± 5 Ma (Maidment *et al* in press), which could be close to the true depositional age of the rock. Previously, Smith (2001) determined a SHRIMP U-Pb maximum depositional age of 1798 ± 5 Ma for a volcaniclastic rock from the Explorer 142 DDH 4 (Rover field/Babylon area). Explorer 142 is considered to be a similar, Tennant Creek-style, IOCG deposit type to Rover 1 (Westgold Resources Ltd, ASX announcement 23 March 2010). Smith described that the rock represented a 4 m-thick mass flow that underlies a haematite-jasper-quartz rock (argillaceous banded ironstone/'haematite shale'?). Zircons used in the determination of this age were interpreted by Smith to be of juvenile magmatic origin; they have pyramidal terminations, are euhedral and prismatic, and have euhedral oscillatory growth zones. Admixed, variably abraded, broken and anhedral zircons that are also present in the rock were interpreted as locally derived and incorporated in the rock during deposition or redeposition.

Deposit classification and genetic models

The classification and genesis of the Tennant Creek-type gold-copper-bismuth ore bodies remains a subject of debate. Skirrow (2000) considered that the Tennant Creek deposits are characterised by their association with epigenetic magnetite ± haematite (ironstone) bodies (and by their occurrence in the 1860 Ma Warramunga Formation). The association with ironstone bodies was considered by some previous workers (eg Ferenczi 1994), to be a feature that made these deposits unique. However, ironstone-associated gold mineralisation was included in the iron-oxide copper-gold (IOCG) deposit type of Hitzman *et al* (1992), and the Tennant Creek ironstone-associated gold-copper orebodies were included in a rather broad class of 'Proterozoic Cu-Au deposits' by Davidson and Large (1998), a class that also includes Olympic Dam (South Australia) and Ernest Henry (Queensland). Olympic Dam is three orders of magnitude larger in tonnage, and has approximately thirty times more contained gold than Nobles Nob, whereas conversely, the gold grade at Nobles Nob was approximately thirty times that of Olympic Dam. Skirrow (2000) considered that the Tennant Creek deposits are distinctive in that they are among the highest-grade deposits of the global IOCG association.

Critical aspects of the debate on the genesis of Tennant Creek Au-(Cu-Bi) mineralisation have focused on: (1) the timing of ironstone and gold mineralisation (single and two-stage models); (2) whether the ironstones represent replacement or open-space fill; and (3) the nature of chemical triggers for the precipitation of ironstone and economic gold-copper mineralisation.

The earliest theories concerning the genesis of the ironstone-related Au (Cu-Bi) mineralisation at Tennant Creek suggested that both the iron oxides and the metals (ie Au, Cu and Bi) were magmatic in origin and probably derived from granitic and felsic porphyry intrusive rocks (Woolnough 1936, Owen 1940, Ivanac 1954, Crohn and Oldershaw 1965). In contrast, Pontifex (1964), Whittle (1966) and Dunnet and Harding (1967) suggested that mafic intrusive rocks (diorite, gabbro and dolerite) were the source of the mineralising fluids, whereas Reveleigh (1977) favoured metal-rich hydrothermal fluids derived from a series of blind intrusions that were also associated with lamprophyre dykes. Skirrow (1993) reported that results from preliminary Sm-Nd isotopic studies at West Peko indicate an input to the Cu-Au-Bi mineralised zone from a relatively primitive source. Large (1991) attributed the Proterozoic Cu-Au-iron oxide deposits to the products of oxidised, saline, high-temperature magmatically derived fluids that can transport gold, copper and rare metals as chloride complexes in a variety of magmatic and exhalative environments. Wyborn *et al* (1998) suggested felsic rocks of the 1820–1810 Ma Treasure Suite as a possible source of gold, copper and bismuth together with a wide range of other minor rare metals, including Se, Co, W, Sn and Mo. Contact metamorphism of the Warrego Au-Cu-Bi deposit by the Warrego Granite (Wedekind and Love 1990) means that, as noted by Wyborn *et al* (1998), this granite could not be responsible for the mineralisation, contrary to the suggestion of Stolz and Morrison (1994).

In contrast with the magmatic models, Elliston (1966) proposed that the ore-forming metalliferous brines were derived from dewatering and remobilisation during diagenesis of the Warramunga Formation. Large (1974, 1975) subsequently argued that the mineralising fluids were derived from connate water released from argillaceous sediments in the vicinity of granitic and porphyritic intrusive rocks.

The first two-stage model was probably proposed by Norris (1980), who suggested that the mineralised ironstones may represent remobilised, sediment-hosted massive oxide deposits that were originally formed at, or close to the sea floor from metal-rich solutions. Main *et al* (1990) and Goulevitch (in Giants Reef Mining 1993) shared this view of ironstone formation. Wedekind *et al* (1989), Nguyen *et al* (1989), Wall and Valenta (1990) and Skirrow and Walshe (1993) also suggested that two stages were involved in mineralisation. These are: (a) ironstone formation from connate brines, followed by (b) the introduction of hydrothermal sulfur and Au (Cu-Bi)-bearing fluids. In the two-stage model, several theories on the nature and source of mineralising fluids, and the precipitation of ironstone and Au (Cu-Bi) from these fluids have been proposed.

In their studies of the Gecko and White Devil deposits, Huston *et al* (1993) recognised three paragenetic stages: (1) syndeformational ironstone formation from low-temperature (250ºC) connate brines; (2) introduction of syn- to post-deformational higher-temperature (350ºC) sulfide-bearing Au-Cu-Bi-mineralising fluids, with variable proportions of magmatic and connate components; and (3) a late, minor carbonate stage. A carbonate stage had previously been recognised at Peko by Wright (1965) and at Argo by Meade (1986).

Fluid inclusion and stable isotope studies have been undertaken by several workers on a number of the more important Tennant Creek orebodies in an attempt to characterise the mineralising fluids and identify their sources (**Table 9.7**, **Figures 9.28**, **9.29**). Skirrow (1993) has reviewed this work. In particular, fluid inclusion studies have been undertaken on Eldorado (Horvath 1988, Khin Zaw *et al* 1994, Skirrow 1993), White Devil (Nguyen *et al* 1989, Huston *et al* 1993), Gecko (Huston *et al* 1993, Khin Zaw *et al* 1994), West Peko (Skirrow 1993), Juno and TC8 (Khin Zaw *et al* 1994). Fluid inclusion studies indicate that the oxide-stage fluids were moderately saline, ie ca 20 wt% NaCl equivalent. Temperature estimates for these same fluids are variable, and both lower temperature (ca 250°C, eg Huston *et al* 1993) and higher temperature (ca 350–400°C, eg Nguyen *et al* 1989, Skirrow and Walshe

Author [deposit]	Oxide stage	Sulfide stage
Horvath (1988) [Eldorado]	ca 220°C ca 18 wt% NaCl eq	ca 300°C ca 40 wt% NaCl eq
Nguyen *et al* (1989) [White Devil]	ca 350° 22 wt% NaCl eq	ca 300°C 5 wt% NaCl eq
Huston *et al* (1993) [White Devil, Gecko]	ca 250°C 15–20 wt% NaCl eq	ca 350°C ca 20 wt% NaCl eq
Skirrow and Walshe (1994) [West Peko]	350–400°C 12–20 wt% NaCl eq	300–350°C 3–10 wt% NaCl eq
Khin Zaw *et al* (1994) [Juno, TC8, Eldorado, Gecko, White Devil]	200–250°C ca 22 wt% NaCl eq	ca 350°C ca 35 wt% NaCl eq

Table 9.7. Summary of results of fluid inclusion studies on ironstone-related Au (Cu-Bi) deposits of Tennant Creek goldfield [after Donnellan *et al* (1999, table 6), compiled by PA Ferenczi (formerly NTGS)].

1994) determinations for these oxide-stage (ironstone-forming) fluids have been reported. Skirrow (1993) stated that quartz-magnetite oxygen-isotope geothermometry indicates it is necessary to apply a substantial pressure correction (2.5–3.5 kb) in fluid inclusion studies of oxide-stage fluids at West Peko and Eldorado. In contrast, Huston *et al* (1993) estimated that a very much lower-pressure correction (of 850 bars) was necessary for the oxide-stage fluids they studied. Huston *et al* estimated their pressure correction from quartz-magnetite oxygen-isotope geothermometry studies of barren ironstones, ie lacking gold-copper-bismuth mineralisation. Skirrow (1993) considered that it is therefore possible that the disparate temperature estimates for the oxide-stage fluids may potentially be reconciled.

Skirrow (1993) pointed out that the absence of quartz and the small-size of inclusions associated with the sulfide-stage has exacerbated the problem of characterising the (Au-Cu-Bi) mineralising fluids. All workers have suggested that sulfide-stage heterogeneously trapped fluids had a temperature of about 300–350°C (with N_2 and $CH_4 \pm CO_2$ being present in vapour-rich inclusions). However, Nguyen *et al* (1989) and Skirrow and Walshe (1994, 2002) indicated that the sulfide-stage fluids were of low to moderate salinity (ca 3–10 wt% NaCl equivalent), whereas all other workers have reported that they had high salinities (up to ~40 wt% NaCl equivalent). Skirrow (1993) did not dispute the validity of high-temperature, high-salinity fluids, but he did not consider these (probable oxidised basinal brines) to be fluids that were responsible for the Au-Cu-Bi mineralisation (although they may have introduced minor uranium-mineralisation). Skirrow and Walshe (2002) suggested that there was mixing between a calcic-brine and the sulfide-stage mineralising fluids which, together with phase separation in the latter, resulted in high-salinity (20–35 wt%) $CaCl_2$-NaCl-bearing inclusions and vapour-phase N_2-CH_4-rich inclusions at, for example, West Peko. A range of δS^{34} values in sulfides (from White Devil and Gecko K44) were attributed to fractionation during the reduction of SO_4 by Huston *et al* (1993). Large (1991) suggested variable mixing between connate SO_4 and magmatic H_2S-bearing fluids would explain the variable oxidation state of the mineralising fluids. Skirrow (1993) similarly concluded that the ironstone-forming oxidised basinal brines, and the reduced Au-Cu-bearing fluids were discrete. Furthermore, he suggested that the interaction of reduced gold-transporting fluid with ironstone, or with post-ironstone oxidising basinal fluids was an effective trigger for precipitating the Au-Cu-Bi mineralisation, and could result in a spectrum of gold-rich oxidised, and copper sulfide-rich (pyrrhotite-bearing) reduced deposits. Skirrow considered that ^{13}C depletion of carbonate associated with the mineralisation, together with N_2 and CH_4 in fluid inclusions, was evidence for an organic fluid component. Genetic models have therefore evolved from single-stage magmatic (eg Crohn and

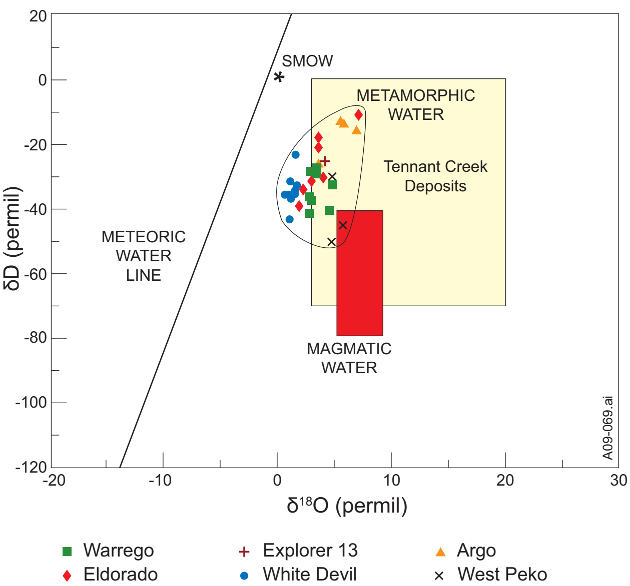


Figure 9.28. δD SMOW–δ18O SMOW diagram for chlorite separates from Tennant Creek Au (Cu-Bi) deposits [after Donnellan *et al* (1999: figure 9, compiled by PA Ferenczi (formerly NTGS) and modified after Huston (1991), with additional data for West Peko from Skirrow (1993)].

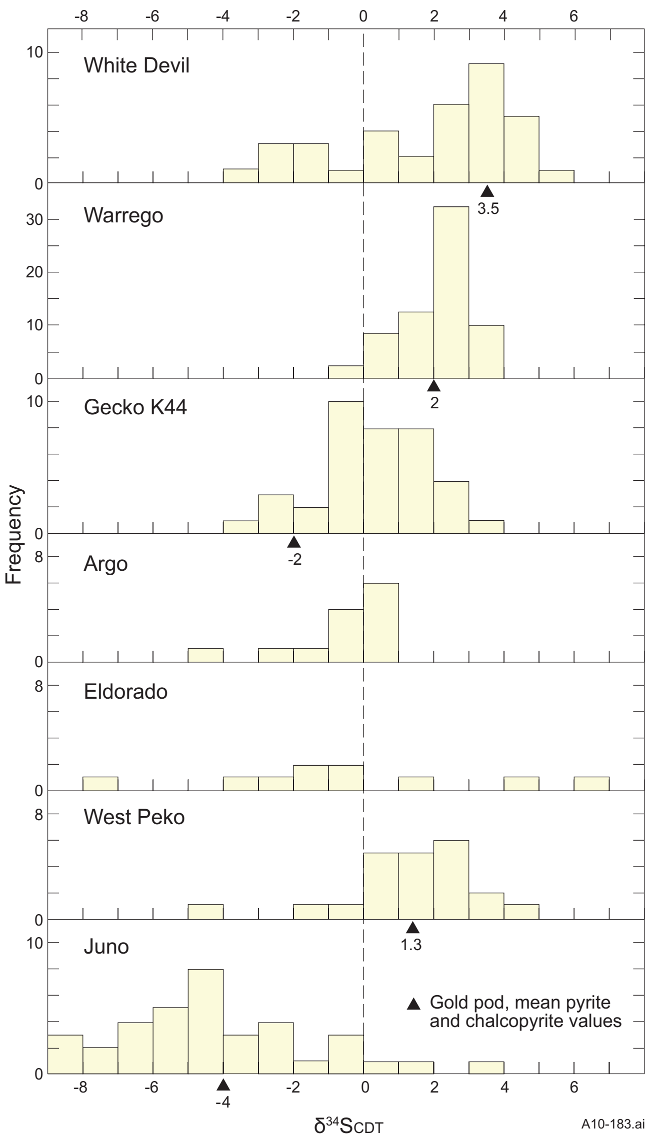


Figure 9.29. Histograms showing variation in $\delta^{34}S$ CDT for some ironstone-related Tennant Creek Au (Cu-Bi) deposits [after Donnellan *et al* (1999), compiled by PA Ferenczi (formerly NTGS) and modified after Large (1991), who cited primary data sources for White Devil, Warrego, Gecko K44, Argo and Juno to be Large (1975)].

Oldershaw 1965) or hydrothermal (eg Large 1975) ones, to essentially two-stage models with ironstone formation (oxide stage) predating the (sulfide stage) Au-Cu-Bi mineralisation (eg Nguyen 1987, Edwards 1987, Wedekind *et al* 1989). However, Large (1991) still favoured a single-stage model for the development of both oxide and sulfide mineralisation. Huston *et al* (1993) emphasised that the recognition of three stages in the development of the mineralisation and associated alteration/gangue assemblages does not necessarily imply any time break between stages. Skirrow and Walshe (2002) interpreted that the ironstones formed during D_1 from fluids with low sulfur activity and fO_2 close to that of the haematite/magnetite buffer. Skirrow and Walshe attributed the variable 'primary' oxidation state of the ironstones associated with gold-copper-bismuth mineralisation to the interaction of discrete, reduced sulfide mineralising fluid and oxidised, basinal mixed-chloride brine, and their interaction with the earlier-formed ironstone.

The timing of ironstone formation, contemporaneous with that of deformation and low-grade metamorphism of the Warramunga Formation during the ca 1860–1850 Ma Tennant Event, is well-substantiated. However, many important aspects of ore genesis at Tennant Creek remain unresolved. These include: (1) the time interval between ironstone formation and gold-copper-bismuth mineralisation; (2) the source of the gold-copper-bismuth; (3) the sources for, nature of, and relative contributions from initially discrete fluids; and (4) the mechanical and chemical triggers for mineralisation.

Gold-bearing vein quartz deposits in the Tennant Creek field

There are only three known Au-bearing vein quartz deposits in TENNANT CREEK. The *Last Hope* mine has produced 12.9 kg Au derived from bedding-parallel quartz veins, located at the contact between metasedimentary rocks of the Wundirgi Formation and a dolerite sill (Ivanac 1954). The *Bull Pup* mine has produced 1.7 kg Au from quartz veins in faulted sandstone of the Wundirgi Formation (Tapp 1966). At the *Dolomite* mine (also known as *Pinnacles Extended*), about 7.5 kg Au has been extracted from quartz and dolomite veins in a fractured felsic porphyry intrusive.

Placer gold deposits

Small-scale eluvial and alluvial mining has been undertaken adjacent to gold-bearing vein quartz deposits in the *Last Hope*, *Bull Pup* and *Dolomite* mine areas. In the Last Hope mine area (also known as the *Moonlight Rockhole* area), gold was first discovered in 1874 and has been found both as fine grains and as nuggets weighing up to 32 oz (ca 1 kg) in the eluvials and alluvials near the hard-rock workings (Ivanac 1954). The alluvial field was re-discovered in 1936 and about 16.7 kg Au was extracted by prospectors in the following two years (Balfour 1989). Gold slugs and nuggets have also be extracted from eluvials adjacent to the Dolomite mine.

The amount of placer gold derived from ironstone-related Au (Cu-Bi) deposits is very minor. Mines with some recorded placer gold production include: *Mascot* (8.2 kg), *Lady Pearl*/*Mary Ann* (684 g), *Little Ben* (93 g), *Mary Lane* (75 g) and *Havelock* (47 g), according to Balfour (1989) and Northern Territory Mines and Energy mineral production records.

Kurundi goldfield

The Kurundi goldfield includes mines and occurrences in the vicinity of the Kurundi anticline (near Kurundi homestead), around the abandoned Kurinelli Outstation, and in the vicinity of the Hatches Creek tungsten field. In a history of this goldfield, Roarty (1977) described that gold was discovered in the Kurundi area in 1898 by Professor A Davidson who led an expedition on behalf of the Central Australian Exploration Syndicate, and in the Kurinelli area in 1925 by G Masters who recovered about half a kilogram of alluvial gold from the area. Roarty also records that in the same year (1925) W Garnet discovered gold at the Power of Wealth mine and the Prima Donna prospect in the Kurundi area. In 1934 small batteries were erected at the Kurinelli and Dempseys Choice mines (**Figure 9.30**). Production continued intermittently and from 1926 to 1975 and total recorded production during that time from the Kurinelli area was about 12.4 kg from reefs with an additional 1.2 kg of alluvial /eluvial gold, and a further 1 kg from reefs in the Kurundi area (Roarty 1977, Blake *et al* 1986). Ahmad *et al* (1999) reported that official mineral production records indicate that about 25 kg of gold was produced from the Kurundi goldfield between 1926 and 1995. However, they state that discussions with the local miners and prospectors suggested that total production from the field may be closer to 75 kg. Whilst most of the gold has been derived from small scale eluvial and hard rock mining of auriferous quartz veins in the Kurinelli area, Ahmad *et al* noted that significant amounts of gold was also recovered as nuggets using metal detectors over about a twenty year period.

Ahmad *et al* (1999) record that the gold-bearing quartz veins are widely scattered, with most of them occupying bedding-parallel faults or shears within sedimentary rock/dolerite contact zones or within sedimentary and volcanic rocks of the Ooradidgee Group. The tabular veins are typically narrow (0.5 to 1.5 m wide) and 10 to 100 m long; and stockworks are common. Roarty (1977) concluded that whilst the field contains numerous (possibly several hundred) reefs the gold is irregularly and unpredictably

Figure 9.30. Old Kurinelli battery near Dempseys Choice mine (53K 504500mE 7720800mN).

distributed and the veins are of low overall grade. Further, Roarty (1977), and Ahmad *et al* (1999) reported that drilling and sampling of the previously worked Power of Wealth, Cairns and Great Davenport mines indicated that they had little economic potential. Ahmad *et al* noted that exploration of the prospects in the Kurundi area has been mainly by costeaning and chip sampling (Cullen 1987, Shields and Boyer 1987, Sanderson 1987), and has indicated that these deposits are unsuitable for 'large-scale' mining.

Ahmad *et al* (1999) noted that within the auriferous veins gossanous boxworks after pyrite, and brecciation are often present in high grade (>10g/t) zones which are themselves very irregular. These authors also stated that the origin of the auriferous veins is uncertain but suggested that they were most likely derived from fractionated granitic intrusive rocks at depth. However, Blake *et al* (1986) noted the close association between the auriferous veins and dolerite and gabbro in both the Kurinelli and Hatches Creek areas and suggested that the gold may have had a mafic igneous source. Dolerite intruding Ooradidgee Group rocks in the Kurinelli area has yielded a baddelyite crystallisation age of 1811 ± 5 Ma (Maidment *et al* 2006, Claoué-Long *et al* 2008). Gold mineralisation hosted in quartz veins that cross-cut dolerite in the Kurinelli area is therefore 1811 Ma or younger in age. In the Kurinelli area, Ewens (1975) reported that the fine to coarse grained native gold is erratically distributed and sometimes associated with chalcopyrite and pyrite. Blake *et al* (1986) considered that the gold-bearing quartz veins may have been related to the main episode of folding and metamorphism that affected the Ooradidgee and Hatches Creek groups (ie Davenport Event). The age of this event is not firmly established but was interpreted by Blake *et al* (1987) to predate the ca 1720 Ma Elkedra Granite of the Devils Suite. Fraser (2004) reported ca 1700 Ma $^{40}Ar/^{39}Ar$ ages for muscovite associated with mineralisation at the Black Hills prospect in the Kurinelli goldfield; and at the Green Diamond, Copper Show and Bonanza prospects in the Hatches Creek tungsten field.

Auriferous quartz veins at the contact between dolerite sills and Wundirgi Formation at Last Hope northwest of Tennant Creek are described above under 'Gold-bearing vein quartz deposits in the Tennant Creek field'. This mineralisation and associated alluvial and eluvial gold may provide a link with gold mineralisation in the Kurundi field.

The following descriptive details of the gold-bearing quartz veins in the Kurundi field are from Ahmad *et al* (1999). In the Kurundi area, gold is present in bedding-parallel quartz veins, which are 1–3 m wide and up to 200 m long. These veins are hosted in a variety of lithologies including quartz sandstone and shale of the Kurinelli Sandstone (Great Davenport, Power of Wealth, Aztec and Priesters); acid volcanics of the Epenarra Volcanics (Millars) and the Junalki Formation (Opengidgi); basalt of the Edmirringee Volcanics (Kurundi); sandstones of the Taragan Sandstone (Cairns); granophyre and quartz-feldspar porphyry (Davidsons). In the Kurinelli area, Ahmad *et al* recorded that gold is generally located in northeasterly trending quartz-filled shear zones within dolerite or gabbro, lithic sandstone (Rooneys Formation) or at the dolerite /sedimentary rock contact. These quartz veins are subparallel to bedding, are 0.2 to 2 m wide and can be traced up to 200 m along strike. At the Crystal mine, in the Hatches Creek area, en-echelon gold-bearing quartz veins trend northeast and dip 50° to the southeast and can be traced discontinuously for about 400 m parallel to the bedding in altered volcanilithic sandstone (of the Taragan Sandstone) which is enclosed within dolerite/gabbro. There are no official records of production from this deposit, however, local prospectors have obtained about a thousand ounces of gold using metal detectors (pers comm to P Ferenczi, by R Hall 1996, as reported in Ahmad *et al* 1999). At the Crystal mine gold-rich sections of the narrow iron oxide-bearing quartz veins contain up to 34g/t Au (Ryan 1961).

Arafura Resources Ltd (**http://www.arafuraresources.com.au**) have recently undertaken exploration in the Kurinelli area of the Kurundi goldfield. Soil sampling programs undertaken by Arafura Resources Ltd from 2005–2007 have identified a widespread gold anomalism that awaits drill testing.

Uranium

The Munadgee uranium prospect (53K 456250mE 7754900mN) in OORADIDGEE was discovered by Bill Cairns, a local prospector, in 1955. The host rock is cleaved quartz-feldspar porphyry and this is altered, sheared and brecciated in the lode zone. The porphyry was interpreted to be a felsic volcanic rock by Lord (1955) and Newton (1979), but was reinterpreted as an intrusive porphyry by Stewart and Blake (1986). Proximal to the porphyry is a quartzite; this is better exposed in the north of the prospect, where it is up to 3 m thick. Newton interpreted this to be a sedimentary quartzite. However, he described that it forms discontinuous lenses of variable width and length, and shows silicification, jaspilitisation and locally haematitisation that, together with minor associated copper and gold, suggest that it may be at least partially of hydrothermal origin. Newton reported that three phases of folding have affected the quartzite. The country rock is cross-cut by quartz veinlets and the lode by quartz veins.

Stewart and Blake (1986) recorded that the mineralisation comprises secondary uranium minerals, autunite, torbenite and possible carnotite. Newton (1979) interpreted that intersecting north-northeast and east-northeast joints, that dip east and south respectively, probably reflect similarly oriented faults at depth and that these are the major control on the mineralisation. Ahmad and Ferenczi (1996) recorded that the ore zone trends 340° and plunges at 65° to 165°, and that it is up to 14 m long and 8 m wide at the 35 m level. Sampling by Gold and Mineral Exploration NL in a cross-cut at the base (40 m) of Shaft No2 returned 0.82% U_3O_8 over 1.2 m (Australian Financial Review, 10 February 1970, Stewart and Blake 1986).

Granite-associated tungsten vein systems

Mineralisation in the Hatches Creek and Mosquito Creek tungsten fields occurs as wolframite-bearing and scheelite-bearing, quartz vein systems, respectively. In the Hatches

Creek field, the mineralisation is hosted by sheeted veins within Palaeoproterozoic metasedimentary and igneous rocks, and in the Mosquito Creek field, it is hosted by shear zones in greisenised granite. Sullivan (1951, 1953a, b), Ryan (1961), Stewart and Blake 1986, Blake *et al* (1987) and Ferenczi and Ahmad (1996) provided descriptive details of these fields and their individual prospects, and Balfour (1978) and Ferenczi and Ahmad summarised available production figures. The summaries presented here are based on these sources.

A wide range of metals is associated with the Hatches Creek W-mineralisation (Cu, Bi, Mo, Co, and minor U and Sn) and Wyborn *et al* (1998) noted that a wide variety of metals (Bi, Mo, Se, Pb, Co, and minor W and Sn) is also associated with ironstone-associated copper-gold mineralisation in the Warramunga Province. They suggested that ca 1820–1810 Ma Treasure Suite magmatism may provide a genetic link between these two deposit types. Budd *et al* (2002) contrasted the polymetallic (W-Cu-Bi-Mo-Au-Sn) style of tungsten mineralisation that is associated with Treasure Suite granites in the Warramunga Province with W-Sn mineralisation that is related to Devils Suite granites in the Mosquito Creek tungsten field and at the Juggler mine, both of which are described in **Davenport Province**. Tungsten mineralisation in the Wauchope field is hosted by the ca 1846 ± 3 Ma (Maidment *et al* 2006) Hill of Leaders Granite of the Tennant Creek Supersuite, but, as discussed below, it is possible that the mineralisation relates to the later emplacement of a ca 1710 Ma Devils Suite granite. Granite is not exposed in the Hatches Creek tungsten field, but Blake *et al* (1987) interpreted that it was related to granite emplacement, possibly during a region-wide hydrothermal event at 1645 ± 44 Ma (Blake and Page 1988). The Elkedra Granite that hosts the Juggler mine has an interpreted igneous crystallisation age of ca 1720 Ma (Blake and Page 1988). It is therefore possible that both styles of tungsten mineralisation relate to ca 1720–1710 Ma Devils Suite magmatism.

Hatches Creek tungsten field

Ferenczi and Ahmad (1996) reported that mining activity between 1913 and 1977 at the Hatches Creek tungsten field produced about 3065 t of tungsten concentrate (ca 65% WO_3), 5.7 t of bismuth concentrate and 70 t of copper concentrate from shallow lodes (ca 30 m depth) averaging 1–3% WO_3. The main metallic minerals are wolframite and scheelite, but tungstite and probable cupro-tungstite also occur. Molybdenite is a less important ore mineral and native bismuth, bismuthinite, bismutite, bismite, chalcopyrite (and a wide variety of copper minerals in the oxidised zone), molybdenite, wulfenite, galena and pyrite all occur. Ryan (1961) remarked on the paucity of cassiterite. Ryan also reported that minor gold at the *Crystal Gold* gold mine is hosted in quartz veins associated with blocks of Kurinelli Sandstone within the Pedlar Gabbro.

The mineralised quartz veins are ca 40 cm wide, and are subvertical, parallel or en echelon. Ore shoots vary from about 7–120 m in length. In the north of the field, they trend northeast, subparallel to bedding, and in the south of the field, they trend north or east and are discordant to bedding. High-grade ore shoots occur in dilatational jogs and erratic wolframite-rich patches occur at vein–vein intersections, fault–vein intersections, vein bifurcations, at contacts of dislodged wallrock blocks and in low-angle off-shoots from the main veins (Ryan 1961). North-trending lodes are generally better mineralised than those trending east (Ryan 1961).

In the south of the field, the veins are hosted mainly by the Treasure Volcanics, but also by the Taragan Sandstone, and include the *Hit or Miss* and *Treasure Gully* groups of deposits. In the north of the field, the *Wolfram Hill* group of deposits are hosted by the Kurinelli Sandstone (and particularly by the Warnes Creek Member), and in the *Pioneer* group, the veins are hosted within the Pedlar gabbro or are within blocks of Kurinelli Sandstone within the gabbro.

Ryan (1961) identified three types of deposit on the basis of their mineralisation: (1) a wolfram-scheelite (+Bi-Cu-Mo) type that is confined to lodes within the Pedlar gabbro; (2) a wolfram-copper type with minor Bi and Mo, but lacking scheelite, which is typically associated with the Treasure Volcanics; and (3) wolfram lodes, which are the least well defined group, and which occur both in the Treasure Volcanics and the Kurinelli Sandstone. Ferenczi and Ahmad (1996) noted that narrow, 1 cm-wide, coarse-grained muscovite and biotite commonly form discontinuous selvedges on one or both walls of the veins. They also suggested that other gangue minerals reported by Ryan (1961), including K-feldspar, sericite, chlorite, epidote, tourmaline and fluorite, indicated minor greisenisation and potassium silicate alteration associated with vein emplacement. Probable topaz was also reported as a gangue mineral by Hoatson and Cruikshank (1985). Ryan (1961) had previously concluded that the only evidence for hydrothermal alteration was sericitisation and kaolinisation at the *Green Diamond* mine. The mineralisation is thought to have been derived from a highly fractionated two-mica granite, which is anomalous in W (12 ppm) and Sn (20 ppm), and which is only very locally exposed some kilometres to the south of the field, where it intrudes the Mia Mia Volcanics in the Mia Mia Dome (Ryan 1961, Blake *et al* 1987). This granite is interpreted to belong to the ca 1820–1810 Ma Treasure Suite.

Ferenczi and Ahmad (1996) reported that assessments of the field have been conducted by Howard (1978) and Clarke and Howard (1978), who estimated that about 877 t of WO_3 concentrate remained in quartz veins grading 1.5–3% WO_3 at a number of mines. Thor Mining (ASX Announcement 29 July 2008) reported that 174 samples of quartz veins from old workings and stockpiles at the Hatches Creek field averaged 2.19% W, 1.92% Cu, 0.22% Bi and 5.36 ppm Ag.

Mosquito Creek tungsten field

The Mosquito Creek tungsten field extends over an area of about 2 km^2, and is situated about 22 km north of Kurundi homestead. The mineralisation comprises scheelite and wolfram and was discovered in the early 1940s. The veins vary from 10–30 cm wide, range from 30–200 m in length and some have thin (60 mm-wide) selvedges of quartz, tourmaline, muscovite greisen. The lodes occupy shear zones, trend north to northwest, dip east to northeast and contain irregular patches of coarse-grained scheelite, together with minor wolframite. These ore minerals are also often present in minor amounts in the greisenous margins to the veins.

Mining activity in the field was sporadic and short lived. Balfour (1978) recorded that about 38 t of tungsten concentrate was produced in the field from 1200 t of ore, grading 2% WO_3, between 1943 and 1957. The bulk of the ore production came from the *Hill of Leaders* mine (*MacDonalds/Falcon Lease*), and was recovered from a northwest-trending, northeast-dipping lode with an average width of 20 cm over a 200 m strike length. Falcon Gold Mines (1952) estimated that about 1800 t of ore, with an average grade of 1.5–2% WO_3, remains at depth in the main mineralised vein at Hill of Leaders mine and 320 t of ore in a parallel vein to the south. However, these are very approximate figures. Mitchell and Roarty (1975) estimated that there is possibly also 10 000 t of alluvial and dump material with an average grade of 0.75% WO_3. The mineralised veins are hosted in The Hill of Leaders Granite, which is a porphyritic-plagioclase, two-mica granite/granodiorite. Geophysical data indicate that there is a subcircular gravity low, more or less coincident with, but extending beyond the mineral field. Non-magnetic gravity lows of this type are typically associated with ca 1710 Ma Devils Suite granites in the Tennant Region. A lamprophyre dyke outcropping within the Mosquito Creek field has an SHRIMP U-Pb single crystal zircon age of 1711 ± 2 Ma (Maidment *et al* 2006). It is possible that the mineralisation is associated with a poorly or non-exposed granite of about this age that locally intruded the more areally extensive, and older (1846 ± 3 Ma SHRIMP U-Pb single-crystal zircon igneous crystallisation age; Maidment *et al* 2006) Hill of Leaders Granite in this area. However, there are not only greisenous selvedges to the tungsten-mineralised veins, but greisen is also quite widely developed in the Hill of Leaders Granite. This suggests that greisenisation resulted from late-stage fluids associated with the crystallisation of the Hill of Leaders Granite, rather than being superimposed at the time of emplacement of a much younger granite; ie, it suggests that the mineralisation most probably relates to the Hill of Leaders Granite.

Woodenjerrie mine

Blake *et al* (1986) reported that there was minor wolframite production from the Woodenjerrie mine (53K 456470mE 7749125mN) in 1952–1953. The lode comprises quartz veins, with haematite and pyrite as additional gangue minerals, hosted in greywacke and siltstone of the Woodenjerrie beds.

Base metals

Explorer 108

Westgold Resources Ltd has reported polymetallic base and precious metals (Zn-Pb-Ag ± Cu and Au) mineralised intersections at Explorer 108 in the Rover Field, and a 'Maiden' Resource Statement in an ASX announcement on 19 March 2008. The company has recorded that this mineralisation occupies wide mineralised zones, containing high-grade lenses (with 7–15% combined Zn and Pb) within an even wider zone of hydrothermal alteration, in a succession of felsic volcanic and sedimentary rocks that are folded into an approximately north-northeast-trending anticline. According to Westgold Resources, the high-grade mineralisation is located at the basal contact between brecciated carbonate ('dolomite') and the underlying volcanic rocks, and is also below this contact within the sheared volcanics.

Whistleduck area

Several minor copper (±gold) occurrences have been reported in the Edmirringee Volcanics, about 20 km southeast of Kurundi homestead. The mineralisation in the northern part of the area ('*Unnamed*' at 53K 485300mE 7624500mN) consists of chalcopyrite and secondary copper minerals (chalcocite, bornite, chrysocolla and covellite) occurring in discrete concentrically zoned nodules up to 3 mm in diameter, and located in amygdales in meta-andesite and basalt (Pontifex 1965).

The southern part of the area contains several mineralised quartz veins which were investigated by Geopeko Ltd. This company reported the following assay data (Wright 1965): (1) at the *Whistleduck* prospect, a vertical, northwest-trending (330°) quartz-filled shear zone, up to 2 m wide and 100 m in length, returned a chip sample assay of 5% Cu and 13 g/t Au; and (2) a wedge shaped quartz vein located about 1300 m to the north assayed up to 0.45% Cu and 3.3 g/t Au.

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