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EXPLANATORY NOTES

TENNANT CREEK SE 53-14

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MAP

1:250 000 Geological Map of Tennant Creek in pocket
ABSTRACT

Palaeoproterozoic rocks of the Tennant Creek Inlier crop out over an area of ~45 000 km² in central Australia. The Inlier comprises the Ashburton province to the north and Davenport province to the south separated by the Tennant Creek province. The Tennant Creek province occupies a large portion of TENNANT CREEK* together with northern BONNEY WELL. Small portions of the Ashburton and Davenport provinces occupy northern and northwestern, and central-southern TENNANT CREEK respectively.

The Tennant Creek province comprises a turbiditic flysch succession, the Warramunga Formation, which together with granite and granodiorite (‘early’ granite) were respectively deposited and intruded pencontemporaneously with the Barramundi Orogeny (D1). Extrusive, predominantly subaerial volcanic rocks; rhyolitic and rhyodacitic ignimbrite, lava and tuff; and associated volcanioclastic and clastic sedimentary rocks are broadly coincident in both space and time (1845–1830 Ma; Compston 1995) with these felsic intrusives (1860–1830; Compston op cit) and are similarly included in the stratigraphy of the Tennant Creek province. This volcanoclastic sedimentary succession, the Flynn Subgroup, was not deformed during the Barramundi Orogeny and is therefore inferred to be unconformable on the Warramunga Formation. Thus, the age of the Barramundi Orogeny can be constrained locally to between 1860 Ma (the maximum depositional age of the Warramunga Formation) and 1845 Ma.

The Warramunga Formation is host to the so-called ‘Tennant Creek type’, massive ironstone associated, gold-copper-bismuth mineralisation of the Tennant Creek goldfield. This goldfield has produced 150 t of gold, together with 318,000 t of copper, 14,000 t of bismuth, 220 t of selenium and 53 t of silver from 130 mines.

There appears to be a transitional, conformable relationship between Flynn and Tomkinson Creek Subgroups. The latter is confined to the Ashburton province. The Flynn Subgroup is similarly conformably overlain by the Unimbra Sandstone of the Wauchope Subgroup in the south in the Davenport province. Consequently the Flynn Subgroup is a probable correlative of the Ooradidgee Subgroup which is also overlain by the Unimbra Sandstone. The Ooradidgee, Wauchope and Hanlon Subgroups constitute the Hatches Creek Group which is confined to the Davenport province.

The entire Tennant Creek Inlier was probably contemporaneously with the Strangways Orogeny, i.e. pre-1730 Ma (cf. Collins and Shaw 1995) in the Arunta Inlier and prior to the emplacement of post-tectonic or ‘late’ granite (Blake et al 1987).

There are at least two episodes of mafic/intermediate magmatism in the Tennant Creek province. One intrusive episode is essentially contemporaneous with the syn-tectonic (D1) granites and comprises dolerite and gabbro. The second intrusive episode includes dolerite, quartz-diorite and diorite, with a late episode of lamprophyre intrusion. Geochronological data of Compston and McDougall (1994) indicate the second intrusive episode is coeval with the deposition of the Flynn Subgroup, whilst the lamprophyres, minettes and vogesites, intruded at 1685 Ma. Compston (1995) reports a preferred age of 1700–1650 Ma for the two-mica, S-type Warrego Granite and 1712 Ma for the Gosse River East ‘Granite’ (a syenite) which are the only representatives of a ‘late’ (post-tectonic) phase of granitic plutonic rocks in the Tennant Creek province. Post-tectonic granite is more prevalent to the south in the Davenport province.

A late phase of deformation is evident at TENNANT CREEK where a spaced north-south cleavage is developed in the Warramunga Formation. This may relate to easterly compression associated with the Isan Orogeny (1590–1500 Ma) in the Mount Isa terrain (cf. O’Dea et al 1997; Blake and Stewart 1992).

Late Neoproterozoic to early Cambrian sedimentation is represented by the Rising Sun Conglomerate. This is a probable correlative of the Andagerra Formation in the Davenport province and Georgina Basin which in turn probably correlates with part of the Central Mount Stuart Formation on BARROW CREEK. This interval of stratigraphy may represent a regionally extensive, alluvial fan, red bed succession. Basic to intermediate volcanic rocks and clastic sedimentary rocks, the Helen Springs Volcanics, are inferred to be of early Cambrian age.

Middle Cambrian rocks in TENNANT CREEK are now preserved in two distinct sedimentary basins. These are the Georgina and Wiso Basins respectively to the east and west of the Tennant Creek Inlier. Marine transgression in the early Middle Cambrian (Ordian to early Templetonian) led to deposition of the Gum Ridge Formation in the Georgina Basin, and the correlative Montejinni Limestone, Hooker Creek Formation and Lothari Hill Sandstone in the Wiso Basin.

Outcrop at TENNANT CREEK is generally poor and typically lateritised. Much of the KELLY, GOSSE RIVER and BARKLY is covered by Cainozoic sediments.

INTRODUCTION

TENNANT CREEK covers an area of about 17 200 km², between latitudes 19°00'0S and 20°00'0S and longitudes 133°30'E and 135°00'E near the geographic centre of the Palaeoproterozoic Tennant Creek Inlier. It encompasses much of the Tennant Creek province, together with a small portion of the Ashburton province to the north and the Davenport province to the south. Further, it includes the Tennant Creek goldfield which is hosted by the oldest rocks exposed in the Inlier, the Warramunga Formation.

The Warramunga Formation is exposed in a more or less deeply dissected pediplain (remnant Ashburton Surface) with relatively good outcrop in the upstanding ridges (McDouall Ranges) in the immediate vicinity of Tennant Creek township. Again, there is relatively good outcrop of the Palaeoproterozoic rocks in the Ashburton province where they form the Short and Whittington Ranges. Outcrop of the felsic intrusive and volcanoclastic rocks of the Barramundi Igneous Association (BIA; Wyborn 1988) are locally good, but generally discontinuous. The area is ubiquitously, intensely lateritised. Despite this, and the age of the rocks, textural features of the various rock types are, at least locally, well preserved, particularly those of the volcanic rocks. In addition there is relatively poor, and similarly lateritised, exposure of rocks of the Neoproterozoic to Palaeozoic Georgina and Wiso Basins.

* Names of 1:250 000 and 1:100 000 map sheets are given in large and small capitals respectively, eg. TENNANT CREEK and FLYNN.
The goldfield was first mapped by Ivanac and his co-workers during the period 1948 to 1950 (see Ivanac 1954). Further, detailed mapping at Tennant Creek was undertaken by the Bureau of Mineral Resources (BMR) over the period 1958 to 1971 and culminated in the First Edition TENNANT CREEK 1:250 000 map sheet compiled by Mendum and Tonkin (1971) and later published with explanatory notes compiled by Dodson and Gardener (1978). TENNANT CREEK was completely re-mapped by geologists of the Northern Territory Geological Survey (NTGS) during 1989-1993. First edition maps of FLYNN and TENNANT CREEK were released by NTGS in 1995. These maps and accompanying explanatory notes (Donnellan et al. 1995) were based on extensive mapping in the winter months of 1989-1992 inclusive. Mapping over the entire TENNANT CREEK area was completed in 1993.

FLYNN, TENNANT CREEK and SHORT RANGE were mapped on 1:25 000 scale colour aerial photography. Southern FLYNN and TENNANT CREEK were flown as part of a Joint Flying Project in May 1988. NTGS contracted with AirResearch Mapping for ‘FLYNN north’ and ‘TENNANT CREEK south’ aerial photography which were flown in April 1989. SHORT RANGE is the only other 1:100 000 sheet on TENNANT CREEK with substantial outcrop of Proterozoic rocks. NTGS contracted with AirResearch Mapping for 1:25 000 scale colour aerial photography over SHORT RANGE. This was flown in April 1990 and mapping over this area was completed in 1993. BARKLY, GOSSE RIVER and KELLY are largely covered by Cainozoic sediment and these areas were consequently mapped on 1:86 400 scale RC10 black and white aerial photographs flown in 1983.

In order to avoid repetition only a brief summary of the Palaeoproterozoic stratigraphy is given here; the reader is referred to Donnellan et al. (1995) for further details. The Palaeozoic stratigraphy is presented in detail by P D Kruse (based on his field mapping in 1991) in the present notes as it has not previously been covered. In addition P A Ferenci examined all mineral occurrences on TENNANT CREEK in 1993 and the section on Economic Geology in these notes is his work. The section on groundwater is by R Read of the Northern Territory Power and Water Authority (PAWA). The remaining sections are largely the work of Donnellan, Morrison and Hussey. Geophysical interpretation of TENNANT CREEK and the regional synthesis of the geology and geophysics of the Tennant Creek Inlier on the map face were by L J D Farrar in conjunction with NTGS. The section on geophysics in these notes is also by Farrar.

Habitation and access

The township of Tennant Creek is situated 13 km north-northeast of the geographic centre of TENNANT CREEK. It is 505 km north of Alice Springs on the Stuart Highway, the main road link between Adelaide, Alice Springs and Darwin. The town is 25 km south of the intersection of the Stuart and Barkly Highways, the latter being the main road link with Mt Isa. The only other sealed roads in the area are those to the former mines at Warrego, Peko, Juno and Nobles Nob. Many of the main outcrop areas of the Warrumunga Formation and Flynn Subgroup are, however, readily accessible by station roads and tracks.

In the map sheet there are two main pastoral properties, Tennant Creek and Phillip Creek, together with parts of Banka Banka, Brunchilly and Rock Hampton Downs. A substantial portion of TENNANT CREEK is Aboriginal freehold land.

Topography and drainage

There are two main landforms in the Tennant Creek region: Dissected uplands (remnant Ashburton Surface) and surrounding plains (Tennant Creek Surface). The former rise to about 60 m above the latter which, in the vicinity of the town of Tennant Creek itself, is 330 m above sea level.

The Tennant Creek Surface has a thin cover of Cainozoic sediment. Hays (1967) pointed out that this surface predates lateritisation, and correlated the lateritisation of the Tennant Creek and Ashburton Surfaces. This lateritisation predates mid-Miocene. Major outcrops of Palaeoproterozoic volcano-sedimentary rocks on TENNANT CREEK coincide with the residual Ashburton Surface. Drainage is endorheic.

Climate

The area has an arid, tropical climate with long, hot summers and short, mild winters. A summary of salient temperature and rainfall data has been provided by the Bureau of Meteorology in Tennant Creek (see map face).

Vegetation

The brief summary which follows is based on Stewart et al. (1954) and Perry and Christian (1954).

The Tertiary lateritic plain (Tennant Creek Surface) supports shrublands of Eucalyptus spp (low mallee) and Acacia spp, or woodlands of E brevifolia (snappy gum) and E dichromophloia (variable-barked or mountain bloodwood). The dominant grass species is the sclerophyllous tussock grass Triodia pungens (gummy spinifex); Acacia lysiphloia (turpentine) also occurs.

The Ashburton Surface and surrounding slopes have a light cover of E brevifolia, with smaller areas of A aneura (mulga) woodland or E pruinosa (silver box) shrublands on the gentle slopes, and with some E dichromophloia woodlands on the moderate slopes associated with the Short and Ashburton Ranges. Aristida pruinosa (keroseen grass) is the dominant grass species although Triodia pungens is dominant locally.

Previous geological investigations

The first major study of the geology and ore deposits of the Tennant Creek goldfield was that of Ivanac (1954). This work included geological mapping of the majority of the goldfield, an area of approximately 4000 km², by Ivanac and his co-workers during the period 1948 to 1950.

Ivanac (1954) summarised geological investigations of the area prior to his own. These were few but included a brief visit to the area by Brown (1895) and his subsequent recommendation of the area to prospectors in 1897. Davidson (1905) sampled quartz reefs from the area and his conclusion was that there was little likelihood of finding a major gold deposit. Further geological investigations were undertaken by Woolnough (1936), Rudd in 1937 on behalf of Broken Hill Pty Ltd, and Noakes and Traves (1954). The only prior mapping was that of Owen (1940) over an area of approximately 720 km². There
was a brief report on the Tennant Creek goldfield by Sullivan
(1949).

Further, detailed mapping at Tennant Creek was again undertaken by BMR over the period 1958 to 1971 and culmi-
ated in the First Edition TENNANT CREEK 1:250 000 sheet
compiled by Mendum and Tonkin (1971) and later published
together with explanatory notes by Dodson and Gardener
(1978). Particularly important contributions to the understand-
ing of the regional geology over this period were the Tennant
Creek One-mile sheet and accompanying report (Crohn and
Oldershaw 1965), the Mount Woodcock 1-mile sheet and re-
port (Dunnet and Harding 1967), and the 1:100 000 Preliminary
Edition WARREGO SPECIAL (Mendum and Tonkin 1974) which
included mapping information from Geopeko NL. A more re-
cent contribution to the geology in the extreme south of
TENNANT CREEK is the DEVILS MARBLE REGION (Wyche et al
1987).

Geopeko mapped EL214 on behalf of Peko Mines Ltd. This
mapping was undertaken on 1:12 000 scale black and white
aerial photography and was completed in 1974. A preliminary
1:250 000 scale interpretative solid geology map based on this
work was included in Geopeko’s annual report for EL214 (Love
1974), and also appears in Le Messurier (1976). A refinement of
this map based on BMR mapping, company mapping and geo-
physical interpretation is presented by Le Messurier et al
(1990). Australian Development Limited undertook 1:12 000 scale
geological mapping of their leases in the 1970s. Some of
these areas were recently re-mapped as part of a Newmont-
ADL joint venture.

Loxton, Hunting and Associates undertook a study on
behalf of Marathon Petroleum Australia Ltd, and produced a
photogeological map at 1:83 000 scale over an area of approxi-
mately 3200 km² (Cou pard and Jones 1979).

The importance of magnetic prospecting at Tennant Creek
was recognised early and has remained the major exploration
tool until recent times. Daly (1957) reports that a lack of ge-
ological data, together with the general association of gold with
ironstone bodies, prompted the geophysical surveys by the
Aerial, Geological and Geophysical Survey of Northern Aus-
tralia (AGGSNA) in the Tennant Creek field in 1935, 1936 and
1937. Further impetus for geophysical studies came in 1950
with the discovery of significant copper mineralisation at depth
in the Peko orebody and consequent indications for a signifi-
cant base metal potential in the goldfield.

Results of AGGSNA surveys are reported by Rayner and
Nye (1936), Richardson and Rayner (1937a, and 1937b),
Richardson et al (1936) and Daly (1957). To facilitate interpre-
tation of these data an airborne magnetometer and scintillom-
eter survey was undertaken by BMR in 1956 in order to deline-
ate regional anomalies. The area surveyed included all known
mine workings, and the results were published in a 1:126 720
scale map (BMR 1958). These data and those of a later survey in
1960, which extended coverage over the entire TENNANT CREEK
area, were published as a series of 1:63 360 scale maps
(BMR 1962 a-d) and a 1:250 000 scale map of total magnetic
intensity and radioactivity (BMR 1968).

First edition maps of FLYNN and TENNANT CREEK were
released by NTGS in 1995 with accompanying explanatory notes
(Donnellan et al 1995).

PALAEOPROTEROZOIC STRATIGRAPHY

The following is a summary of the Palaeoproterozoic
stratigraphy of TENNANT CREEK (see also Tables 1 and 2). Further details of these stratigraphic units are presented in

Warramunga Formation

The Warramunga Formation is a succession of tuffaceous
lithic arenite and lithic wacke, and siltstone; terrigenous mudstone
and argillaceous, banded-ironstone (‘haematite shale’).
‘Tuffaceous’ refers to volcaniclastic sandstone of epiclastic
as distinct from pyroclastic origin. These rocks are poly-
deformed and show very low- to low-grade greenschist-facies
metamorphism.

Partial or complete bouna sequences are recognisable, and
two facies have been mapped (sandstone and siltstone
lithofacies) based on the relative proportion of sand to silt
sized material and bed thickness. These two facies broadly
equate with more proximal (predominantly middle) and more
distal (lower) fan facies of a classic flysch succession
respectively.

PALAEOPROTEROZOIC (‘EARLY’) INTRUSIVE ROCKS OF THE
SYN-TECTONIC BARRAMUNDI IGNEOUS ASSOCIATION

Intrusive representatives of the Barramundi igneous
association (BIA) (‘early’ granites; 1.86-1.83 Ga, Compston
1995) are syntectonic biotite-bearing granite and granodiorite,
and minor tonalite. The granitic and granodioritic rocks in
TENNANT CREEK have a macroscopic appearance more
similar to anorogenic (A-type) granites. In particular they are
red to light grey in colour, carry large alkali feldspar phenocrysts
and have seriate to porphyritic and incipient rapakivi (‘white
shirt’; Pave lenko 1974) textures with interstitial not prismatic
mafic minerals (cf. Anderson and Morrison 1992). Salient
characteristics of these early granitic intrusive rocks are given in
Table 3, and further details are presented below.

The modal mineralogy of the ‘early’ intrusives at
TENNANT CREEK ranges from granite (sensu stricto)
to granodiorite (Mumbilla Granodiorite) and minor
tonalite (Figure 1). 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);
strained (frequently also ovoid, blue and opalescent) quartz;
and red-brown biotite. Accessory minerals include magnetite,
sphene, zircon, muscovite, ilmenite, apatite, pyrite, chalcopyrite,
monazite, fluorite, rare amphibole and iddingsite. Secondary
alteration products include: (1) chlorite, epidote, sericite
and muscovite resultimg from the saussurisation of feldspar;
(2) chlorite, haematite, epidote and sponge resulting from the
alteration of biotite; (3) rutile derived from the decomposition
of ilmenite; and (4) minor iddingsite formed from original olivine.
Magnetite is occasionally inter-grown with ilmenite and sponges,
and minor sulphides occur as discrete grains or enclosed in Fe-
Ti oxides. At one locality the granite contained actinolite
replacing primary biotite (GR MU1140). Marginal and more
highly fractured zones of the Tennant Creek Granite are
commonly altered, forming albitised and tourmalinised
leucocratic zones radiating inward from pluton contacts. Faults
or shear zones also show a depletion in mafic constituents. These leucocratic phases of the Granite are characterised by graphic and micrographic inter-growths of quartz and feldspar, albitionisation of alkali feldspar and the occurrence of quartz-tourmaline veins or clots up to 10 cm in diameter (luzullanite). Tourmaline is of the Fe-rich variety (schorl!). These leucocratic bodies result from late-stage boron/sodium metasomatism which altered fractured zones around the pluton margin.

The *Mumbilla Granodiorite* is dominantly a biotite-bearing, light-grey granodiorite (*sensu stricto*), but ranges from tonalite to granite in modal composition (Figure 1). It is characterised by coarse grained seriate porphyritic to equigranular texture with cream-coloured alkali feldspar megacrysts up to 10 cm in diameter, 1 cm plagioclase laths, 0.5-1 cm anhedral, strained quartz and 0.5 cm kinked biotite crystals. Alkali feldspar megacrysts are frequently orientated, forming an indistinct flow foliation. Plagioclase displays normal zoning with labradorite cores (up to An83); but more commonly andesine cores and oligoclase rims. Mafic constituents are dominated by red-brown biotite books, enclosing euhedral (0.5 mm) magnetite octahedra, ilmenite, muscovite and iddingsite (relit olivine Fo10). The north and east margins of the Granodiorite are medium-grained equigranular to seriate porphyritic with ovoid quartz crystals.

The texture of the granites varies according to their degree of foliation and the size and shape of alkali feldspar crystals. The dominant textures range from coarse grained equigranular with subhedral 1-2 cm diameter alkali feldspar and slightly finer grained plagioclase and quartz, to seriate porphyritic which is characterised by rounded, 1-2 cm weakly zoned alkali feldspar, 0.5 cm plagioclase and ovoid quartz. The latter is especially prevalent in the Tennant Creek Granite. Alkali feldspar phenocrysts are often mantled with a thin rim of plagioclase giving an incipient rapakivi texture. Augen of alkali feldspar, commonly with biotite selvedges, form in strongly foliated zones in both the Tennant Creek and Cabbage Gum Granites.

Altered leucocratic phases of the Channingum Granite resulting from tourmalinition and albitionisation occur in areas immediately adjacent to northwest-trending faults. Towards the margin of the Granite, the texture becomes more hialat porphyritic. This textural variant is dominated by alkali feldspar phenocrysts (2 cm in diameter and thinly mantled by plagioclase; incipient rapakivi texture), oval 0.5 cm quartz and equant, light green plagioclase in a fine grained felsic groundmass. Although poorly exposed, the Cabbage Gum Granite has textural variations and mineralogy identical to the Tennant Creek Granite. In more altered examples of Cabbage Gum Granite (e.g. BMR-NTGS DDH 8 at 90 m and BMR 3 DDH 1 at 194 m), quartz is more strongly deformed and displays a granular texture (recrystallised?) with interlocking mosaic margins. In more deformed examples of Cabbage Gum Granite (e.g. BMR 3 DDH 9 and 11), a strong gneissic texture is accompanied by a decrease in the maximum grain size (1 cm to 0.5 cm).

Where the Mumbilla Granodiorite is of a more granitic (*sensu stricto*) composition, the texture becomes seriate porphyritic - essentially identical to that of the Tennant Creek Granite. Again, it is characterised by blue opalescent ovoid quartz and rounded, thinly mantled alkali feldspar phenocrysts (e.g. GR MU4404). One area, in particular, shows evidence of this porphyritic granite phase both intruding and being intruded by host granodiorite (GR MT3395). Porphyritic quartz diorite to granite was noted intruding the host granodiorite as 1 m wide, east trending dykes. This material also contributes to the igneous enclave population of the Granodiorite. Margins of both the enclaves and dykes are commonly diffuse. These features are consistent with contemporaneous intrusion of granitic magma into a progressively inflating, slowly crystallising granodioritic pluton.

Silicified leucocratic variants of the Mumbilla Granodiorite are characterised by the absence of primary mafic components, and the presence of sericitised feldspar abundant tourmaline, secondary sphene and quartz-feldspar micrographic inter-growths. Minor muscovite and leucosite are present, with anhedral strained quartz and abundant quartz veinitls.

The *felsic porphyry* is biatodal porphyritic, and of granitic (*ryholitic*) composition. Phenocrysts are 1-3 mm rounded alkali feldspar and 0.5-1 cm green plagioclase and quartz in an anphatic groundmass composed of quartz, feldspar and chloride. Quartz phenocrysts are commonly strained, ovoid and blue opalescent. In severely altered felsic porphyries (commonly associated with development of strong cleavage or foliation) quartz becomes the dominant phenocryst phase. Plagioclase forms smaller (>0.5 cm) equant laths which have been ubiquitously sericitised. Remnant unaltered phenocrysts have calcic (andesine) cores (up to An50) and progressively more sodic rims. The main mafic constituents include 0.1 mm chloride, magnetite and sphene (replacing biotite). Rare primary biotite and minor sulphides (pyrite and chloropyrite) were noted.

Clots of chloride and magnetite (0.5-1.5 mm in diameter) may replace original biotite. One porphyry (GR MU0936) was noted to contain primary red-brown biotite and minor green amphibole, but all others examined have had their primary mafic constituents ubiquitously altered. The relative lack of alteration
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| Root Creek Formation (Etb)
~200 m | Quartz arenite and sublithic arenite, siltstone; medium- to coarse-grained, parallel- and cross-bedded, rippled; thin- to medium-bedded | Transitional contact with underlying carbonate unit of Attack Creek Formation. Top not seen. | Shallow marine to intertidal |
| Attack Creek Formation (Eta) | Dolostone, siltstone, cherty siltstone, quartz arenite | Conformable on Short Range Sandstone | Shallow marine/tidal flat, at least in part protected from terrigenous input |
| Carbonate interval (Eta) Combined Eta and Eta, ~375 m | Dolostone and limestone; cryptomicrobial boundstone, stromatolitic bioherms; ooid and pisoid carbonate; laminated and cross-laminated quartz dolostone | Conformably underlies sandstone interval and in part conformably overlies siltstone interval with which it also shows a lateral facies variation | |
| Siltstone interval (Eta) | Siltstone and cherty siltstone; cross-laminated quartz arenite; laminated mudstone | | |
| Short Range Sandstone (Eta) | Quartz arenite, sublithic and lithic arenite, feldspathic sublitharenite; siltstone | Conformably underlies Attack Creek Formation and conformably overlies Morphee Creek Formation | Littoral to sublittoral marine |
| Upper sandstone interval (Eta, ~400 m | Quartz arenite, sublitharenite and feldspathic sublitharenite; locally trough cross-bedded near base, predominantly planar bedded with parallel-laminated to thin-bedded units arranged in medium to massive sets. Ripples, rhysonetron and desiccation cracks at various levels | Channeled contact with lower sandstone interval locally, although predominantly faulted. A probable siltstone interval has been largely faulted out | Intertidal/beach |
| Lower sandstone interval (Eta, ~625 m | Quartz arenite, sublitharenite, feldspathic sublitharenite and siltstone; medium-to coarse-grained, tabular; well developed bidirectional tabular cross-bedding; extensively rippled | | Predominantly shallow marine, sublittoral, with intertidal sedimentation in at least two intervals |
| Morphee Creek Formation (Etm)
~2500 m | Conglomerate, sublithic and lithic arenite, feldspathic litharenite, siltstone, cryptomicrobial boundstone and quartz carbonate | Conformable with Hayward Creek Formation below and Short Range Sandstone above. Relationships between individual lithofacies are obscured by paucity of outcrop | Predominantly sublittoral, in part intertidal? |
| Lithofacies a | Sublithic and lithic arenite, thin-bedded | Transitional to lower sandstone interval of Short Range Sandstone | Fluvial? |
| Lithofacies b | Siltstone, cryptomicrobial boundstone and quartz carbonate (predominantly dolostone?) | | Intertidal/shallow marine |
| Lithofacies c | Sublithic and lithic arenite characterised by abundant weathered out shale clasts; planar, tabular, predominantly medium-, but minor thick- to massive-beds | | Fluvial? |
| Lithofacies d | Conglomerate and coarse feldspathic litharenite | | Fluvial? |
| Hayward Creek Formation (Etth)
~3000 m | Lithic and sublithic arenite; feldspathic sublitharenite; pebbly sandstone; siltstone; volcanic rocks | Conformable with Morphee Creek Formation above, and transitional contact with Brumbee Formation below. Local channelling at both top and bottom contacts. Conformable, locally channelled, transitional contacts between constituent lithofacies | Fluvial, intertidal/shallow marine |
<table>
<thead>
<tr>
<th>UNIT, WITH MAP SYMBOL AND THICKNESS</th>
<th>LITHOLOGY</th>
<th>STRATIGRAPHIC RELATIONSHIPS</th>
<th>DEPOSITIONAL ENVIRONMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Hayward Creek Formation (Pth)</strong> (continued)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Whittington Range Member (Eth&lt;sub&gt;w&lt;/sub&gt;) ~500 m</td>
<td>Andesitic veiular volcanic rock, interbedded black and pink siltstone and fine sandstone; quartz arenite; green mudstone</td>
<td></td>
<td>Shallow marine?</td>
</tr>
<tr>
<td>Upper sandstone lithofacies (Eth&lt;sub&gt;s&lt;/sub&gt;) ~1000 m</td>
<td>Lithic and sublithic arenite and feldspathic sublitharenite; pebbly arenite. Medium- to coarse-grained; thin- to medium-bedded; planar and very shallow-angle cross-beds; beds show lateral persistence; rippled</td>
<td></td>
<td>Mainly fluviatile</td>
</tr>
<tr>
<td>Unnamed siltstone lithofacies (Eth&lt;sub&gt;s&lt;/sub&gt;) ~100 m</td>
<td>Siltstone and fine-grained sandstone; thin-bedded, planar-bedded. Probable conformable volcanic rocks along strike</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Middle sandstone lithofacies (Eth&lt;sub&gt;s&lt;/sub&gt;) ~1000 m</td>
<td>Siltstone and fine-grained sandstone; thin-bedded, planar-bedded. Probable conformable volcanic rocks along strike</td>
<td></td>
<td>Predominantly intertidal to shallow marine</td>
</tr>
<tr>
<td>Unnamed siltstone lithofacies (Eth&lt;sub&gt;s&lt;/sub&gt;) ~100 m</td>
<td>Sublitharenite and pebbly sublitharenite; well sorted and rounded; fine- to medium-grained; medium- to thick-bedded or massive, becoming thinner-bedded towards top of succession</td>
<td></td>
<td>Predominantly fluviatile</td>
</tr>
<tr>
<td>Unnamed volcanic lithofacies (Eth&lt;sub&gt;v&lt;/sub&gt;) ~100 m</td>
<td>Siltstone and fine-grained sandstone; thin-bedded, planar-bedded</td>
<td></td>
<td>Subaerial?</td>
</tr>
<tr>
<td>Lower sandstone lithofacies (Eth&lt;sub&gt;s&lt;/sub&gt;) ~900 m</td>
<td>Lithic and sublithic arenite and pebbly arenite. Predominantly medium-grained; medium- to thick-bedded; planar and shallow-angle cross-bedded</td>
<td></td>
<td>Predominantly fluviatile</td>
</tr>
</tbody>
</table>

**FLYNN SUBGROUP**

**Northern and northwestern (SHORT RANGE) succession**

<table>
<thead>
<tr>
<th>UNIT, WITH MAP SYMBOL AND THICKNESS</th>
<th>LITHOLOGY</th>
<th>STRATIGRAPHIC RELATIONSHIPS</th>
<th>DEPOSITIONAL ENVIRONMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brumbre Formation (Ebr) ~600-1500 m</td>
<td>Lithic arenite and volcanic litharenite; magnetite-bearing quartz arenite; granule and pebble beds; felsic tuff (chert); fine- to coarse-grained; thin- to medium-bedded</td>
<td>Conformable and transitional with underlying Wundirgi Formation and overlying Hayward Creek Formation. Locally faulted contact with Hayward Creek Formation</td>
<td>Marginal marine to fluviatile</td>
</tr>
<tr>
<td>Warrego Volcanics (Eno) ~550 m in type area</td>
<td>White, pink, mauge, grey and green siltstone, chert and felsic tuff and possible ignimbrite interbedded with fine- to medium-grained lithic arenite</td>
<td>Correlates in large part with Bemborough Formation and with upper parts of Wundirgi and Yungkulungu Formations</td>
<td>Subaerial felsic pyroclastics and waterlain (shallow marine?) reworked equivalents</td>
</tr>
<tr>
<td>Wundirgi Formation (Ewn) ~3000 m by analogy with Monument Formation</td>
<td>Thin- to medium-bedded, fine- to coarse-grained sublithic and lithic arenite; thin-bedded siltstone; minor conglomerate and breccia; felsic volcanic rocks</td>
<td>Conformable transitional contact with Brumbre Formation. Competency contrast results in an apparent unconformable relationship between these units locally. In part a lateral facies equivalent of Warrego Volcanics, Whippet Sandstone Member and Monument Formation of FLYNN. Probably equivalent in large part to Yungkulungu and Junalki Formations on TENDNANT CREEK</td>
<td>Predominantly subaqueous (deep water marine to littoral) with a minor subaerial component comprising felsic surge and fall deposits</td>
</tr>
<tr>
<td>UNIT, WITH MAP SYMBOL AND THICKNESS</td>
<td>LITHOLOGY</td>
<td>STRATIGRAPHIC RELATIONSHIPS</td>
<td>DEPOSITIONAL ENVIRONMENT</td>
</tr>
<tr>
<td>-----------------------------------</td>
<td>---------------------------------------------------------------------------</td>
<td>-------------------------------------------------------------------------------------------</td>
<td>-------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Central succession</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bernborough Formation (Enb)</td>
<td>Dacitic to rhyolitic ignimbrite, tuff, lapilli tuff and minor probable volcanic rocks interbedded with predominantly thin-bedded siltstone, shale and chalk; thin- to medium-bedded lithic to sublithic arenite, minor pebble conglomerate</td>
<td>Correlates with Warrego Volcanics and parts of Wundirgi and Yungkulungu Formations. May correlate (as a lateral facies equivalent) with part of Monument Formation</td>
<td>Subaerial and subaqueous. The thick succession of volcanic rocks is predominantly subaerial and includes a pheatonomagmatic tuff cone or ring sequence in the basal part overlain by ignimbrite</td>
</tr>
<tr>
<td>~900 m in type area</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Whippet Sandstone Member (Enb)</td>
<td>Fine- to coarse-grained, poorly to well sorted sublithic and lithic arenite with minor conglomerate and siltstone</td>
<td>Correlates with part of Yungkulungu and Wundirgi Formations</td>
<td>Sublittoral to littoral and possibly fluvial. Represents a regressive succession</td>
</tr>
<tr>
<td>~100 m in type area</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Monument Formation (Ezm)</td>
<td>Very thin- to thin-bedded, laminated or homogeneous siltstone, shale, chalk and fine- to medium-grained lithic arenite and wacke. Thin- to medium-bedded tuff and volcaniclastic sandstone and siltstone in east (which probably represent uppermost part)</td>
<td>Conformably underlies Whippet Sandstone Member. Correlated with lower part of the Wundirgi and Yungkulungu Formations. Eastern part may correlate as a lateral facies equivalent of Bernborough Formation</td>
<td>Moderately deep water, progressively shallowing upwards to the sublittoral/littoral Whippet Sandstone Member. Eastern part includes both subaerial and subaqueous components</td>
</tr>
<tr>
<td>~1000 m in type area; may be up to ~3000 m in east</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Southern and southeastern succession</td>
<td></td>
<td></td>
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<tr>
<td>Yungkulungu Formation (Eay)</td>
<td>Medium- to thick-bedded lithic arenite and volcanic litharenite with magnetite/heavy mineral lamina. Minor granule and pebble beds. Cross-bedded with minor ripples. Interbedded tabular siltstone, felsic ignimbrite and tuff. Thick, predominantly foliated porphyroitic rhyolite lava flows</td>
<td>Base of sequence not exposed. Commonly faulted contact with Warramunga Formation. Intruded by lamprophyre dykes</td>
<td>Shallow marine, grading upwards to sublittoral/littoral and possibly fluvial. Dominated by reworked felsic volcanic detritus</td>
</tr>
<tr>
<td>~5200 m</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Sedimentary lithofacies (Eay)</td>
<td>Medium- to thick-bedded, cross-bedded and cross-laminated, medium- to coarse-grained lithic arenite, volcanic litharenite and wacke with magnetite/heavy mineral lamina. Minor granule and pebble beds with rhyolitic clasts to base of unit. Top of sequence characterised by medium-bedded, better sorted, sublithic arenite and quartz arenite. Minor phyllite</td>
<td>Conformably overlies felsic volcanic rocks and volcanic litharenite of volcanic lithofacies (Pny). Correlates with Wundirgi Formation and base of the Brumbyra Formation. Intruded by Channingum Granite</td>
<td></td>
</tr>
<tr>
<td>~3600 m</td>
<td></td>
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<tr>
<td>Iginimbritic lithofacies (Eay)</td>
<td>Orange-coloured felsic ignimbrite, welded tuff, rhyolitic lava and cream-coloured ash. Interbedded reworked volcaniclastic rocks</td>
<td>Conformable within the sedimentary lithofacies (Pny)</td>
<td>Subaerial</td>
</tr>
<tr>
<td>no greater than 200 m</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Volcanic Lithofacies (Eay)</td>
<td>Thick, foliated porphyritic, rhyolitic to rhydodicritic flows with shattered quartz and/or feldspar phenocrysts in a medium-grained matrix. Medium-bedded volcanic litharenite, ignimbrite and ash toward top of sequence</td>
<td>Conformably overlain by sedimentary lithofacies (Pny) to northwest. Probably correlates with Bernborough Formation. Intruded by lamprophyre dykes. Intrusive and locally faulted contact with Mumbilla Grandodiorite to south and Cabbage Gum Granite to southwest</td>
<td>Subaqueous volcanic rocks. Volcaniclastic rocks deposited in a shallow marine environment becoming more prevalent towards top of sequence</td>
</tr>
<tr>
<td>~1600 m</td>
<td></td>
<td></td>
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<tr>
<td>Junalki Formation (Enj)</td>
<td>Medium-bedded volcanic litharenite with interbedded orange-coloured felsic ignimbrite. Volcanic agglomerate(?), graded mass-flow litharenite and intrusive lamprophyre dykes in drillcore. Medium-bedded litharenite towards top of sequence with interbedded andesitic and lava flows</td>
<td>Base of sequence not exposed, intruded by Mumbilla Grandodiorite to north. Conformable contact with Unimbra Sandstone of Wauchope Subgroup to south; faulted to the southeast</td>
<td>Shallow marine, grading upwards to sublittoral/littoral and possibly fluvial. Overlain by fluvialite Unimbra Sandstone</td>
</tr>
<tr>
<td>UNIT, WITH MAP SYMBOL AND THICKNESS</td>
<td>LITHOLOGY</td>
<td>STRATIGRAPHIC RELATIONSHIPS</td>
<td>DEPOSITIONAL ENVIRONMENT</td>
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<tr>
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</tr>
<tr>
<td><strong>HATCHES CREEK GROUP</strong></td>
<td></td>
<td></td>
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</tr>
<tr>
<td><strong>HANLON SUBGROUP</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Errolola Sandstone (Ehe, Ehe,)</td>
<td>Quartz arenite, and feldspathic arenite; pebble conglomerate</td>
<td>Conformable on the Kudinta Basalt; down-faulted against the Unimbra Sandstone</td>
<td>Probably peritidal</td>
</tr>
<tr>
<td><strong>WAUCHOPE SUBGROUP</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kudinta Basalt (Eeh) 150 m</td>
<td>Amygdoloidal basalt with minor interlayered sandstone</td>
<td>Conformable on the Courters Sandstone</td>
<td>Broad fluvial plane or shallow marine shelf</td>
</tr>
<tr>
<td>Courters Sandstone (Ehe) 350 m</td>
<td>Lithic, feldspathic and quartz arenite</td>
<td></td>
<td>Probably shallow marine/shelf</td>
</tr>
<tr>
<td>Yeeradgi Sandstone (Ehd) ~300 m</td>
<td>Lithic, feldspathic and micaceous arenite; greywacke; siltstone</td>
<td>Conformably overlies the Unimbra Sandstone</td>
<td>Probably fluvialite</td>
</tr>
<tr>
<td><strong>UNGROUPIED</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Warramunga Formation (Ew)</strong> ~3000 m</td>
<td>Lithic arenite, volcanic litharenite and wacke, siltstone, shale and phyllite; banded ironstone ('haematite shale'); chert and jasper. Very low- to low-grade metamorphism</td>
<td>Base not exposed. Locally faulted against overlying Flynn Subgroup, but regionally interpreted to be lithostratigraphically and tectonically transitional, with one additional deformation mappable relative to Flynn Subgroup</td>
<td>Flysch</td>
</tr>
<tr>
<td>Sandstone lithofacies (Ew,)</td>
<td>Coarse-grained, medium- to thick-bedded or massive lithic arenite, volcanic litharenite and wacke; subordinate fine-grained lithic arenite and wacke, siltstone, terrigenous shale and phyllite; banded ironstone ('haematite shale'); arranged in partial (or complete?) Bouma sequences. Minor, thick-bedded to massive fluidised flow deposits</td>
<td>Interpreted to be a lateral facies equivalent and to predominantly overlie siltstone lithofacies of Warramunga Formation. Interpreted transitional relationship with lower sedimentary lithofacies of Flynn Subgroup which probably includes mass-flow and other shelf to shallow water deposits</td>
<td>Proximal flysch</td>
</tr>
<tr>
<td>Siltstone lithofacies (Ew,)</td>
<td>Fine- to medium-grained lithic arenite and volcanic litharenite, siltstone, terrigenous shale and phyllite; red-, green- and purple-weathering shale; pebbly sand; banded ironstone ('haematite shale'). Subordinate to subequal sandstone and siltstone/shale arranged in partial Bouma sequences. Very low- to low-grade metamorphism</td>
<td>Interpreted to be a lateral facies equivalent and to predominantly underlie sandstone lithofacies. Interpreted transitional relationship with sedimentary lithofacies of Flynn Subgroup</td>
<td>Distal Flysch</td>
</tr>
</tbody>
</table>

in this one porphyry may be due to its proximity to the Tennant Creek Granite. The latent heat from emplacement of this pluton may have prevented access to any circulating connate fluids responsible for alteration. Chlorite was also noted filling small veins and cleavage traces.

Accessory minerals include zircon, rutile, apatite, monazite, sphene and magnetite. Sphene is anomalously high in Al₂O₃ (up to 10 wt%), consequent on its derivation from the breakdown of primary biotite (Tulloch 1979). Fine, euhedral magnetite is commonly titaniferous with up to 7 wt% TiO₂. Rare ilmenite and magnetite-ilmenite exsolutions are present in some grains.

A characteristic feature of both the Tennant Creek Granite and the Mumbilla Granodiorite is a varied and abundant enclaves population. These include felsic porphyry enclaves, cognate, cumulate-rich granitic and gabbric enclaves, late-stage lamprophyric and doleritic enclaves, and rare mafic microgranular enclaves. Xenoliths of country rock are a minor component indicating that stoping and assimilation were not significant modes of intrusion. Rafts or pendants of relict Flynn Subgroup rocks (100-200 m in diameter) in the Mumbilla Granodiorite and the Cabbage Gum Granite do however indicate passive emplacement at shallow depths through stoping. In contrast, the Tennant Creek Granite has a 100 m wide contact metamorphic aureole composed of spotty (quartz and chlorite porphyroblasts) hornfels in distal turbidites of the Warramunga Formation.

**CHURCHILLS HEAD GROUP**

Rocks of the Churchills Head Group are distinguished from Warramunga Formation on lithological grounds, and the absence of the earliest (west-northwest) phase of folding (Barramundi Orogeny). The Churchills Head Group includes
<table>
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<tr>
<th>Table 2</th>
<th>Comparative summary of the Palaeoproterozoic stratigraphy of TENNANT CREEK, according to various workers.</th>
</tr>
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<tr>
<td><strong>Le Messuret al. (1990)</strong></td>
<td><strong>Large (1975)</strong></td>
</tr>
<tr>
<td>Tomkinson Creek beds</td>
<td>Tomkinson Creek beds</td>
</tr>
<tr>
<td><strong>Warrawunga Group</strong></td>
<td><strong>Warrawunga Group</strong></td>
</tr>
<tr>
<td><strong>Carman Formation</strong></td>
<td><strong>Ew:</strong> Sandstone, minor siltstone, chert. Conformably overlies Ew3</td>
</tr>
<tr>
<td><strong>Incl. ‘Warrawunga Member’</strong></td>
<td><strong>Ew:</strong> Warrego Volcanics</td>
</tr>
<tr>
<td><strong>Ew:</strong> Geoko Volcanics</td>
<td><strong>Ew:</strong> Warrego Volcanics</td>
</tr>
<tr>
<td><strong>Ew:</strong> Whippet Sandstone</td>
<td><strong>Ew:</strong> Whippet Sandstone Member</td>
</tr>
<tr>
<td><strong>Whippet Sandstone</strong></td>
<td><strong>Ew:</strong> Greywacke, shale, minor felsic volcanic rocks. Conformably overlies Ew3</td>
</tr>
<tr>
<td><strong>Bn:</strong> Bernborough Formation</td>
<td><strong>Ew:</strong> Bernborough Formation</td>
</tr>
<tr>
<td><strong>Ew:</strong> Whippet Sandstone Member</td>
<td><strong>Ew:</strong> Bernborough Formation</td>
</tr>
<tr>
<td><strong>Whippet St. Fm</strong></td>
<td><strong>Ew:</strong> Bernborough Formation</td>
</tr>
<tr>
<td><strong>Whippet Sandstone</strong></td>
<td><strong>Ew:</strong> Bernborough Formation</td>
</tr>
<tr>
<td><strong>Ew:</strong> Whippet Sandstone Member</td>
<td><strong>Ew:</strong> Warramunga Formation</td>
</tr>
<tr>
<td><strong>Bn:</strong> Whippet Sandstone</td>
<td><strong>Ew:</strong> Warramunga Formation</td>
</tr>
</tbody>
</table>

‘Basement’ includes Monument Fm. (Ew.) of Le Messuret (1976)
<table>
<thead>
<tr>
<th>Intrusive Unit</th>
<th>Textures</th>
<th>Minerals</th>
<th>Alteration</th>
<th>Contacts</th>
<th>Enclaves</th>
<th>Structures</th>
<th>Age</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tennant Creek Granite – Pgt Biotite granite</td>
<td>Medium to coarse grained seriate porphyritic with minor development of rapakivi texture. Development of hiatal porphyry around margin of some plutons.</td>
<td>Anhedral and ovoid quartz, microcline, oligoclase to andesine. Biotite, magnetite, chlorite, muscovite, epidote, sphene and zircon.</td>
<td>Plagioclase is commonly strongly sericitised, biotite often chloritised with secondary sphene and epidote. Extensive groundwater-induced kaolisation.</td>
<td>Generally finer grained towards contacts with Flynn Subgroup felsic volcanic and volcaniclastic rocks, minor quartz schist.</td>
<td>Locally abundant rounded and porphyritic quartz diorite to granite autoliths or enclaves, silicified metasedimentary xenoliths, rare dolerite xenoliths.</td>
<td>10-200m wide E-W zones of mylonitisation or strong foliation with stretched quartz. Minor N-S shear zones.</td>
<td>1850±7 Ma</td>
</tr>
<tr>
<td>Cabbage Gum Granite – Pgg Granite to granodiorite</td>
<td>Medium to coarse grained, equigranular to equigranular. Strongly foliated to gneissic in drill core.</td>
<td>Ovoid quartz, microcline, oligoclase to andesine, biotite, magnetite and ilmenite. Minor sphene, zircon, haematite. Rare ilmenite.</td>
<td>Localised albitionisation along fault zones. Tourmaline forming rounded clots and filling fractures along with quartz. Minor saussuritisation; epidote-chlorite-sphene replacing biotite.</td>
<td>Generally finer grained towards contacts with Flynn Subgroup felsic volcanic and volcaniclastic rocks, minor quartz schist.</td>
<td>Large rafts of Flynn Subgroup material has been encountered in drill core. Minor silicified metasedimentary xenoliths.</td>
<td>Moderately to strongly foliated in drill core; locally mylonitised in NE-SW and NW-SE shear or fault zones.</td>
<td>1853±10 Ma</td>
</tr>
<tr>
<td>Channining Granite – Pgc Granite</td>
<td>Medium to coarse grained, equigranular to equigranular. Strongly foliated to gneissic in drill core.</td>
<td>Ovoid quartz, microcline, oligoclase to andesine, biotite, magnetite and ilmenite. Minor sphene, zircon, haematite. Rare ilmenite.</td>
<td>Localised albitionisation along fault zones. Tourmaline forming rounded clots and filling fractures along with quartz. Minor saussuritisation; epidote-chlorite-sphene replacing biotite.</td>
<td>Generally finer grained towards contacts with Flynn Subgroup felsic volcanic and volcaniclastic rocks, minor quartz schist.</td>
<td>Large rafts of Flynn Subgroup material has been encountered in drill core. Minor silicified metasedimentary xenoliths.</td>
<td>Moderately to strongly foliated in drill core; locally mylonitised in NE-SW and NW-SE shear or fault zones.</td>
<td>1853±10 Ma</td>
</tr>
<tr>
<td>Felis Porphyry – Pp</td>
<td>Hiatal porphyritic with alkali feldspar and blue ovoid quartz phenocrysts in an aphanitic felsite groundmass. More altered equivalents have relic alkali feldspar phenocrysts.</td>
<td>Quartz and/or zoned feldspar (oligoclase to andesine and microcline) phenocrysts in a felsite groundmass with relic biotite (chlorite, epidote and sphene), muscovite, magnetite, haematite and zircon.</td>
<td>Ubiquitous alteration of biotite to Al-rich sphene, chlorite, haematite and magnetite. Decrepitisation of feldspar, especially in foliated or sheared equivalents.</td>
<td>Commonly concordant and/or sheared parallel to regional structure; locally discordant. Mostly intrudes Warramunga Formation.</td>
<td>Small, locally abundant silicified Warramunga Fm., metasedimentary xenoliths.</td>
<td>Generally massive to weakly foliated with mylonitisation of plutons adjacent to major fault zones.</td>
<td>1838±9 Ma</td>
</tr>
<tr>
<td>Mumbilla Granodiorite – Pgm Biotite granodiorite to granite</td>
<td>Megacrystic seriate porphyritic to coarse grained equigranular, with large zoned alkali feldspar phenocrysts. N and E margin is medium grained equigranular to seriate porphyritic with ovoid quartz.</td>
<td>Zoned feldspar phenocrysts; plagioclase with labradorite cores. Ti-rich biotite, anhedral quartz, magnetite, ilmenite, sphene, pyrite, chalcopyrite, and zircon. Rare ilmenite.</td>
<td>Minor chloritisation of biotite. Saussuritisation of calcic plagioclase. Localised leucocratic albitionisation, tourmalinisation and silicification.</td>
<td>Intrudes Flynn Subgroup. 500m finer grained towards N contact. S contact has a 0.5m porphyritic margin dipping north.</td>
<td>Rounded quartz diorite to granodiorite porphyritic enclaves; metasedimentary and rare dolerite and lamprophyre xenoliths; minor gabbroic or cumulate-rich enclaves.</td>
<td>Larger bodies are massive with foliated margins; smaller bodies are weakly to strongly foliated. Foliation is commonly parallel to the regional fabric.</td>
<td>1845±6 Ma</td>
</tr>
</tbody>
</table>

1 These ages are from Compton (1991 and 1995) and are single-crystal, ion microprobe U-Pb, zircon determinations.
2 Tennant Creek Granite at Red Bluff
3 Possible discrete norther pluton of the Tennant Creek Granite according to Compton (1995)
the volcano-sedimentary Flynn Subgroup and, a conformably overlying succession of sandstone together with subordinate carbonate and volcanic rocks, the Tomkinson Creek Subgroup. Only the lower part of the Tomkinson Creek Subgroup outcrops on TENNANT CREEK.

The Flynn Subgroup comprises seven mapped Formations and one Member. Three spatially discrete successions have been mapped in the Flynn Subgroup. These are: (1) a predominantly sedimentary succession with subordinate volcanic rocks comprising the Wundirgi and Brumbreu Formations, and the Warrego Volcanics which crop out in the north and northwest of the Tennant Creek province; (2) a mixed volcanic and sedimentary, central, succession comprises the Monument and Bernborough Formations; and (3) in the southeast of the Tennant Creek province the Yungkulungu Formation crops out. This comprises lower and upper intervals dominated by volcanic and sedimentary rocks respectively.

In the south the Junalki Formation is a probable correlative of the upper, sedimentary, part of the Yungkulungu Formation. These two units are spatially separated by the Mumbilla Granodiorite. In outcrop the base of the Junalki Formation is intruded by the Granodiorite. The northern, western and southern successions are separated by major "early" granite intrusions; the Tennant Creek Granite (at Station Hill, White Hill, Red Bluff and north of Barkly Highway). The immediate locus of granite emplacement is fringed primarily to the north and northwest by the central succession. The interpreted relationships between these lithostratigraphic units are present in the legend on the mapface.

The Wundirgi and Brumbreu Formations of the northern and western successions predominantly comprise sedimentary rocks that have a substantial epiclastic component. The Brumbreu Formation includes subordinate lava and pyroclastic rocks. The Warrego Volcanics includes both subaerial and subaqueous tuffaceous rocks, including accretionary and rimtype lapilli-bearing tuff, some of which show a degree of welding. The Warrego Volcanics probably correlate with the subaerial tuffaceous rocks of the Wundirgi Formation. This assertion is further corroborated by a conformable relationship between the Warrego Volcanics and sedimentary rocks of the Wundirgi Formation (e.g. GR LU0053). Here, a pale green chert at the top of the Warrego Volcanics has a sharp contact with interbedded sandstone and shale of the Wundirgi Formation.

The succession is monotonous. The basal, medium to thickly interbedded sandstone and shale sequence becomes thin- to medium- and very planar- bedded upwards; and the ratio of sandstone to shale increases transitional to the Brumbreu Formation. The base of the latter is marked (at least locally) by a distinctive grey-green lithic arenite (e.g. GR LU8164). The relationship between the Brumbreu Formation and the overlying Hayward Creek Formation of the Tomkinson Creek Subgroup is similarly transitional, although locally erosional or faulted. The first cobble conglomerate as distinct from gravel- and pebble-bearing sandstone is taken as the base of the Hayward Creek Formation (e.g. GR LU8765). The northern and western successions thus show a progressive change from subaerial volcanic dominated, through offshore marine to littoral, to intertidal and finally fluvialite sedimentation upwards. There is a similarly a decline in the epiclastic volcanic derived component although volcanic clasts persist and are locally dominant in the otherwise predominantly quartz arenite and sublitharenite of the Hayward Creek Formation.

The Monument Formation of the central succession comprises siltstone, shale, chert, lithic arenite and wacke. Some of these rocks show probable Bouma sequences and are overlain by tuff, tuffaceous sandstone and siltstone; and accretionary lapilli-bearing probable fall deposits. The Monument Formation is conformably overlain by the Whippet Sandstone Member of the Bernborough Formation. The Bernborough Formation consists of dacitic to rhyolitic pyroclastic rocks (ignimbrite, tuff and lapilli tuff) and minor probable lava with three intervals of predominantly fine grained sedimentary rocks (siltstone, shale and chert). This overlies shallow marine and locally probable fluvialite lithic and sublithic sandstone and minor siltstone of the Whippet Sandstone Member.

A thick succession of volcanic and volcanioclastic rocks near the Blakeway trigonometric station (GR MU3957) has been included in the Monument Formation (Donnellan et al 1995). However, this upper, volcanic interval of the Monument Formation is considered a distal equivalent of the Bernborough Formation (and a similar sequence of volcanic rocks known from drilling in western Barkly).

In the southeast of TENNANT CREEK the lower sequence of the Yungkulungu Formation (i.e. volcanic lithofacies) is composed of rhyolitic to rhyodacitic crystal lithic tuff, lava and ignimbrite. It is overlain by tuffaceous lithic arenite and siltstone (sedimentary lithofacies) which includes discrete conformable intervals up to 130 m thick of felsic volcanic rocks (tuffaceous lithofacies) including felsic tuff, ignimbrite and minor lava flows with accretionary lapilli. There is a transitional relationship between the volcanic and sedimentary lithofacies. Quartz arenite towards the top of the sedimentary lithofacies is probably broadly contemporaneous with similar rocks in the Brumbreu Formation.

In outcrop the Junalki Formation is largely confined to the south of TENNANT CREEK and is dominated by interbedded felsic crystal-lithic tuff, and tuffaceous sandstone of felsic volcanic derivation. Towards the top it comprises fine grained lithic arenite and siltstone with minor interbedded, 1-2 m thick, andesitic to dacitic lava.

Drilling in the southwest of TENNANT CREEK intersected rhyodacitic to rhyolitic crystal-lithic tuff, and andesitic to dacitic ignimbrite and lava. These rocks are interpreted as a lower, volcanic dominated interval of the Junalki Formation.

The lower and middle parts of the Flynn Subgroup mainly comprise volcanic rocks. These are predominantly subaerial pyroclastic rocks with phreatomagmatic activity evident in most sequences. Lavas are only a minor component of the Subgroup. The top of the sequence is dominated by shallow water epiclastic sedimentary rocks. The sedimentary rocks do, however, show an upward progression from deeper water to shallow marine and continental; fluvialite or lacustrine. This volcano-sedimentary succession records the onset and waning of a period of felsic; calc-alkaline volcanic activity and sedimentation. Volcanic rocks are more prevalent in the southern and central successions and form only a much more subordinate part of the northern and western succession.

The Tomkinson Creek Subgroup is a succession of sandstone and subordinate siltstone, carbonate and volcanic rocks. It comprises the Hayward Creek, Morphett Creek and
Attack Creek Formations, Short Range Sandstone and lowermost Bootu Formation on TENNANT CREEK. The Bootu Formation was previously mapped on FLYNN and TENNANT CREEK (Donnellan et al. 1995) as an uppermost sandstone interval of the Attack Creek Formation. This succession continues upwards on HELEN SPRINGS with the remainder of the Bootu Formation and the Carmilly Formation, together with the (?) unconformably overlying Namerinni Group (Hussey et al. in prep).

ON FLYNN and TENNANT CREEK Donnellan et al. (1995) describe two members in the Short Range Sandstone and three in the Hayward Creek Formation. These have had to remain informal in the absence of any suitable names for geographical features in their outcrop areas. Recognising this, lithofacies is substituted for member on TENNANT CREEK and they can be traced to the north on HELEN SPRINGS. The basin interval of the lowermost sandstone lithofacies of the Short Range Sandstone is to be defined as the Deagan Member on HELEN SPRINGS (see Hussey et al. in prep).

HATCHES CREEK GROUP

The Hatches Creek Group is a 10 km thick sequence of clastic sedimentary, and both felsic and mafic volcanic rocks. It is folded into open domes and basins. While outcropping extensively in the Davenport province on FREW RIVER, BONNEY WELL, BARROW CREEK and ELKEDRA, its exposure is restricted to some 10 km on southernmost TENNANT CREEK, in the Murchison Range (e.g. GR MT2389) at the northern extremity of the Davenport province. Here, the sequence is sandstone, conglomerate, siltstone, mudstone, shale, carbonate and possible evaporite, with interbedded lava and pyroclastic rocks, and is described fully in Blake et al (1987) and Wyche and Simons (1987).

Many rocks included in the Warramunga Group of former usage (Dunnet and Harding 1967; Mendum et al. 1978) are now excluded from the revised Warramunga Formation on both lithological and structural grounds (see Donnellan et al. 1995; Table 2). Thus, the Warramunga Formation appears to be of limited areal extent at least in outcrop. Some rocks of the former Warramunga Group mapped in the Davenport province on BONNEY WELL and FREW RIVER are here excluded from the Warramunga Formation and are considered correlatives of the Flynn Subgroup.

Unimbra Sandstone

The base of the Hatches Creek Group is represented on TENNANT CREEK by the ridge forming Unimbra Sandstone, a light grey, medium bedded, rippled, planar cross-bedded quartz arenite and pebble conglomerate which conformably overlies the Junalki Formation of the Flynn Subgroup (GR MT2390). Noted within this sequence were 1-2 m thick interbedded andesitic lava flows with subvertical east-west cleavage, indicative of deformation comparable with that of the underlying Junalki Formation. Blake et al. (1987) regarded this unit as having been deposited in either a fluvial or beach environment.

Yeeradgi Sandstone

Conformably overlying the Unimbra Sandstone is the 300 m thick Yeeradgi Sandstone. It forms a recessive volcanic-lithic sandstone unit.

Coulters Sandstone, Kudinga Basalt and Errolola Sandstone

The Coulters Sandstone is a 350 m thick succession of lithic-bearing quartz arenite. It overlies and is separated from the ridge-forming Errolola Sandstone (Ehe) by approximately 150 m of recessive Kudinga Basalt (Ehb). The Errolola Sandstone is the uppermost unit of the Hatches Creek Group cropping out on TENNANT CREEK. A pebble conglomerate unit (Ehe,) is locally mappable within it. The Errolola Sandstone is commonly down-faulted against the Unimbra Sandstone.

Palaeaniprotérozoic (Late) Intrusive Rocks

The Warrego Granite is a massive coarse grained equigranular muscovite granite or granodiorite. It is readily distinguished from other intrusive rocks in TENNANT CREEK by its two mica, corundum-bearing composition; the relative abundance of pegmatitic segregations; and the development of a quartz-biotite contact metamorphic aureole and greisenisation. It crops out as small hills and low rises and along watercourses, and is typically deeply weathered with many small hills capped by silcrete. Discontinuous outcrop indicates that the Granite extends approximately 7 km east-west and up to 15 km north-northwest of Warrego.

The Warrego Granite is a peraluminous, S-type granite. Mineralogically it comprises 1-3 cm diameter feldspar, muscovite and quartz. Muscovite books 0.5-1 cm in diameter are undeformed. Feldspar is extensively sericitised in outcrop, and the relative proportions of feldspar cannot be determined. Drill core samples (BMR-NTGS DDH7) reveal microcline to be the sole alkali feldspar, whilst plagioclase is slightly zoned with andesine or oligoclase cores and albite rims. Iron-rich chlorite replaces primary biotite. Mendum and Tonkin (1976) reported minor hornblende in the type area which is centred around a low hill on the eastern margin of the Granite at GR LU7155. Accessory minerals include corundum and apatite with minor sphene and zircon.

A 20 m wide body of melanocratic amphibole- and biotite-bearing unnamed quartz diorite (Egz) intrudes the centre of the Mumbilla Granodiorite (GR MU3113). It is composed of medium-grained equigranular plagioclase (andesine), quartz, red-brown biotite, actinolitic hornblende, alkali feldspar and minor sphene. An irregular, chilled contact between this quartz diorite and the host Granodiorite, together with a lack of foliation or strained quartz in the quartz diorite, all indicate passive emplacement postdating Granodiorite crystallisation, deformation and cooling. This quartz diorite may represent a cumulate-rich residuum of the host magma, or may be associated with a separate magmatic event. Furthermore, quartz diorite dykes intruding the Granodiorite in an east orientation may be related to the same post-emplacement phase of magmatism.

Diorite dykes (Egz) intrude the Warramunga Formation in the vicinity of Gecko mine. Similar material intrudes as
10-20 m wide ferruginised dykes in the Brumbreu and Wundirgi Formations (e.g. GR LU9663).

Dolerite dykes (Ddl) similarly intrude all the major igneous intrusive bodies described above. These apparently contrast with lamprophyre, dolerite and gabbro xenoliths (or autoliths) noted above in both the Tennant Creek Granite and Mumbilla Grandiorite. These autoliths differ from porphyritic xenoliths in having sharp margins with a slight contact-metamorphic aureole, indicative of crystallisation prior to incorporation into the granitic magma. Thus, there is both an early episode of mafic intrusion predating granite emplacement, and a post-crystallisation episode of intrusion of dolerite, quartz diorite and diorite.

Lamprophyre sills, dykes and laccoliths (Elp) (up to 12 m thick) intrude the Warramunga Formation, Yungkulungu Formation felsic volcanic rocks and Wundirgi Formation sedimentary rocks. Crohn and Oldershaw (1965) reported the occurrence of rare amphibole- and pyroxene-bearing lamprophyre intruding the Warramunga Formation. Jaques et al. (1985) classified the majority of these lamprophyres as magnesian minettes, consisting of phlogopite phenocrysts in a biotite-rich groundmass, with high magnesium, chromium and nickel contents.

Black (1977) dated a lamprophyre at 166±4 Ma with an initial $^{87}Sr/^{86}Sr$ ratio of 0.701±0.002. Jaques et al. (1985) interpreted the geochemical characteristics and very low initial $^{87}Sr/^{86}Sr$ ratio as resulting from primary mantle magmatic activity unrelated to the generation of the earlier granites. Compston and McDougall (1994) reported a 1695 Ma single crystal U-Pb date for a lamprophyre, and suggested that a K-Ar date of 1690 Ma on a biotite from the same lamprophyre is a post-crystallisation cooling age. It is possible that there is an earlier episode of lamprophyric magmatism manifest as ‘clots’ or ‘segregations’ in the Tennant Creek Granite. These may be contemporaneous with the BIA.

NEOPROTEROZOIC-CAMBRIAN STRATIGRAPHY

Rising Sun Conglomerate (Pur)

Owen (1940) noted the occurrence of a conglomerate-sandstone sequence 2 km east-southeast of the Rising Sun mine. This was later informally referred to as the ‘Rising Sun Conglomerate’ by Crohn and Oldershaw (1965), who noted it unconformably overlying the ‘Warramunga sediments’ and ‘porphyry’.

Outcrop of the Rising Sun Conglomerate is largely confined to a 500 m wide, 8 km long east-trending ridge of coarse sandstone and cobble conglomerate extending from GR MU2320 to GR MU3118. In the east where the sequence is thickest, this ridge follows the east-trending faulted contact between the Warramunga Formation to the south and Yungkulungu Formation to the north, forming a distinctive angular unconformity overlying the Palaeoproterozoic stratigraphy. The sequence thins towards the northern contact with the Yungkulungu Formation, whereas further west only the uppermost conglomerate unit and conformably overlying medium-grained quartz arenite are exposed. Minor exposures of quartz arenite, possibly part of the Rising Sun Conglomerate, and designated Pur, on the map, were noted in southern TENNANT CREEK (GR MU1191), but may alternatively be equivalent to similar rocks in the Wauchope or Hanlon Subgroups.

Three conglomerate horizons at the local base of the Rising Sun Conglomerate sequence are composed of very well rounded and sorted cobbles up to 0.5 m, but commonly 0.1-0.2 m in diameter of highly indurated, silicified, coarse- to fine-grained lithic-bearing quartz arenite, quartzite and jasper. The conglomerate ranges from clast supported to matrix supported, with the matrix composed of coarse grained quartz. Individual conglomerate horizons are separated by pebble- and cobble-bearing, very coarse grained quartz arenite. Clasts probably originate from the Tomkinson Creek Subgroup or the Wauchope and/or Hanlon Subgroups of the Hatch Creek Group (Blake 1984).

Up to 60 m of rippled, cross-bedded, medium grained, and medium bedded quartz arenite overlies the interbedded conglomerate and sandstone succession (Blake 1984). This arenite contains minor white feldspar grains and abundant mud casts. It is disconformably overlain by fine tuffaceous sandstone and siltstone of possible Helen Springs Volcanics affinity (GR MU3018).

The sequence is interpreted as fluvial, and resulting from repeated tectonic rejuvenation. The fault which currently bounds the southern margin of the outcrop may have defined the original valley in which the sediments accumulated, and may similarly have been active at the time of deposition. A weak imbricate structure indicates palaeoflow from the high-energy cobble-dominated rocks in the east to lower-energy sand-dominated rocks in the west.

The Rising Sun Conglomerate is correlated with the latest Neoproterozoic to earliest Cambrian Andagera Formation of the southwestern Georgina Basin (Stidolph et al. 1988). It represents the proximally eroded remnants of Hatch Creek Group or Tomkinson Creek Subgroup rocks. Its presence implies that these Palaeoproterozoic successions once (at least partially) covered the currently exposed Warramunga Formation and Flynn Subgroup, possibly connecting the Tomkinson Creek Group strata to those of the Hatch Creek Group.

The Rising Sun Conglomerate (Ivanac 1954) was dated as Late Proterozoic (‘Adelaidean’) by Dodson and Gardener (1978), and as Early Cambrian by Shergold et al. (1985). Blake (1984) argued that the unit is a composite of Early Proterozoic elements of the Flynn and Tomkinson Subgroups on the one hand, and the basal Gum Ridge Formation on the other.

PALAEozoic Stratigraphy

CAMBRIAN

Early Cambrian deposition in TENNANT CREEK is represented by the Helen Springs Volcanics, which straddle the Proterozoic rocks of the presently exposed Tennant Creek Inlier.

Middle Cambrian rocks are now preserved in two distinct sedimentary basins: the Georgina Basin to the east of the Tennant Creek Inlier, and the Wiso Basin to the west. However, while each Basin bears its own unique lithostratigraphic nomenclature, it is apparent that in the Middle Cambrian, these and other central and northern Australian cratonic basins were interconnected.
Thus initial marine transgression in the early Middle Cambrian (Ordian to early Templetonian) led to deposition of the Gum Ridge Formation in the Georgina Basin, and the correlative Montejinni Limestone, Hooker Creek Formation and Lothari Hill Sandstone in the Wiso Basin. These and coeval lithostratigraphic units are collectively designated sequence 1 by Southgate and Shergold (1991). In the Georgina Basin, the Gum Ridge Formation of the Barkly Sub-basin was separated from the Arthur Creek Formation and its equivalents in the Undilla Sub-basin by the Alexandria-Wonarah Basement High (Southgate and Shergold 1991).

A second marine transgressive event, commencing in the late Templetonian, deposited sequence 2 sediments unconformably on sequence 1 units. Early sequence 2 units in TENNANT CREEK are the Anthony Lagoon beds (Georgina Basin) and Point Wakefield beds (Wiso Basin). While sequence 2 deposition continued elsewhere in the Georgina Basin throughout the Middle Cambrian, it was terminated much earlier (by Floran time) in the northern and western parts of the Basin (including TENNANT CREEK), and probably also in the Wiso Basin.

With the exception of the Lothari Hill Sandstone, all these Cambrian units are described below. As well, the Montejinni Limestone is here formally defined, and PJ Kennewell’s unpublished formal definitions of the remaining Cambrian Wiso Basin units are reproduced (see Appendix 1). Formal definition of the Georgina Basin units is not possible using available outcrop. The existence of the Lothari Hill sandstone in the TENNANT CREEK subsurface is not confirmed, although available outcrop may be represented by the variegated yellow-brown-red-grey quartziferous dolostone of interval L (Figure 2) in drillholes Explorer 108 (GREEN SWAMP WELL) and Navigator 14 (LANDER RIVER).

Helen Springs Volcanics (Clth)

The flat-lying Helen Springs Volcanics are largely composed of amygdaloidal or vesicular tholeiitic basalt. They crop out extensively on HELEN SPRINGS (Bulitude 1972), where they incorporate a basal sandstone unit. On TENNANT CREEK, the Helen Springs Volcanics crop out at the base of ridges of Gum Ridge Formation in the vicinity of Gum Ridge (e.g. GR MU4035), where they unconformably overlie folded Warramunga Formation. Agglomerate and tuff, described by Ivanac (1954), crop out in the vicinity of Blue Moon (GR MU4133). On FLYNN, up to 6 m of ferruginised basalt of the Helen Springs Volcanics has been recognised, commonly unconformably overlying folded Flynn Subgroup (e.g. GR MU2946). Here, basalt of the Helen Springs Volcanics rests on a thin pebble conglomerate and fine- to medium-grained arenite.

Elsewhere on TENNANT CREEK, ferruginised basalt 1 m thick unconformably overlies Warramunga Formation in the vicinity of Mary Ann Dam (GR MU1632). Previously mapped as quartz porphyry (Mendum and Tonkin 1976), flat-lying felsic volcanics up to 4 m thick unconformably overlie the Mumbilla Granodiorite at GR MT3793 and on GOSSE RIVER at GR MU5692. These probably represent the felsic variant of the bimodal Helen Springs Volcanics.

Restricted occurrences of ferruginised tuffaceous volcanic rocks unconformably overlie the Rising Sun Conglomerate (e.g. GR MU2919). These are finely bedded (andesitic) volcaniclastic rocks with interbedded fine-grained litharenite. These tuffs are separated from the underlying quartz arenite of the upper Rising Sun Conglomerate by a fault or disconformity.

Gum Ridge Formation (Cmg)

Ivâk (in Ivanac 1954) proposed the formation name for isolated fossiliferous Middle Cambrian outcrops on the eastern flank of the Tennant Creek Inlier. The formation has been mapped extensively on HELEN SPRINGS, TENNANT CREEK, BONNEY WELL and FREW RIVER (Randell and Brown 1969; Dodson and Gardner 1978; Wyche and Simons 1987; Walley 1987). Silification and lateritisation of these rocks is pervasive, so that outcrops are typically low, rubble-covered rises. The unit remains undefined, as no suitable stratotype has been identified in outcrop. Greatest known thickness is represented by the 145 m of clay, dolostone and cherty dolostone intersected in water bore Epinarr 5A on FREW RIVER (Walley 1987).

The contact with the underlying Helen Springs Volcanics is poorly exposed at Gum Ridge (GR MU4133), from where a total 14 m of strata has been reported (Ivanac 1954; Crohn and Oldershaw 1965:17).

This contact is better exposed 11 km to the southeast (GR MU4728), where it is observed to be irregular (with 1-2 m stratigraphic relief) and hence disconformable on the Helen Springs Volcanics. At this locality, contact highs show transition from weathered, dark purple volcanic rocks upward into basal thin-beded maroon mudstone of the Gum Ridge Formation. Conversely, contact troughs are floored by dark maroon-purple, rippled or cross-laminated, fine- to medium-grained quartz-rich sandstone of the basal Gum Ridge Formation. These pass upward within 1 m into dark maroon to brown, micaceous mudstone more typical of the formation. In these basal few metres, the mudstone incorporates small lenses of red-brown quartz-rich medium-grained sandstone.

Despite the pervasive alteration, two principal lithotypes can be recognised as characteristic of the bulk of the Gum Ridge Formation.

A common lithotype is represented by red-brown to yellow-grey tabular chertified rocks, derived from the silicification of original centimetre-scale bedded impure lime mudstone or marl. Occasional trilobites (Redlichia) and lingulate brachiopods are typically aligned parallel to bedding.

Scattered nodules derived from this bedded lithotype are found on outcrops throughout eastern TENNANT CREEK. Smooth, spheroidal to enterothelithic forms probably represent initial carbonate nodules. Rough-surfaced cauliflower nodules 1-5 cm in diameter indicate original evaporites; such nodules are distributed as far south as FREW RIVER (Shergold et al. 1985). A recurring peritidal influence is indicated.

A second, less common lithotype includes lenticular areas of fossiliferous grey, in places red- or yellow-tinted quartzite and chert. Fossils, including trilobites, hyoliths, molluscs and brachiopods, are chaotically oriented, some displaying probable okloid coatings, indicating an original massive limestone texture. Rare examples of bedded silicified hyolith coquinas, about 5 cm thick and several metres in extent, also belong to this limestone lithotype. These latter are presumed to be the basis of Iviâk’s ‘Biocunilites Layer’ in Table 4 of Ivanac (1954). Rarer still are pale cream-yellow, sinuously laminated chert, which may be cryptomicrobial
Figure 2 Cambrian intersections of cored drillholes in southwestern TENNANT CREEK and adjoining sheet areas, Wiso Basin. Hole elevation corrected by normalising to a datum of 100 m based on contouring of the Rover grid (Harbon 1982). Depths not corrected for hole inclination.
laminites if not derived from the Neogene-Quaternary silicites crowning many outcrop rises.

The Gum Ridge Formation was deposited in shallow shelf epicontinental seas subject to episodic peritidal influence. Fossils listed by Opik (in Ivanc 1954; 1958, 1970, 1975), together with additional forms, are documented by Kruse (1998). They include the trilobites Redlichia amadeana Opik, Xystridura verticosa Opik, hyoliths including Gudugwu hardmani (Etheridge), bradoriids, brachiopods, molluscs and putative sponge spicules indicating an Ordian-early Templetonian (early Middle Cambrian) age.

Contacts with overlying units have not been identified in TENNANT CREEK, but the Gum Ridge Formation is thought to be overlain by the Anthony Lagoon beds (Randal 1973:20).

**Anthony Lagoon beds (Cmy)**

Tracts of silicified rubble in northeastern TENNANT CREEK are referred to the Anthony Lagoon beds (Plumb and Rhodes 1963, 1964). These beds are considered to underlie large parts of the Barkly Tableland, including WALLHALLOW, BRUNETTE DOWNS, BEETALOO, HELEN SPRINGS and TENNANT CREEK (Plumb and Rhodes 1964; Randal 1966; Brown and Randal 1969 and Randal and Brown 1969; Dodson and Gardener 1978). While exposures in TENNANT CREEK are silicified, outcrops elsewhere additionally include dolostone, limestone (including ooid grainstone), quartz sandstone (some calcareous) and siltstone (Smith 1972). At least 395 m of carbonate and minor sandstone and shale in Brunette Downs 1 drillhole (BRUNETTE DOWNS) has been attributed to the Anthony Lagoon beds (Mines Administration 1965; Randal 1966).

Fossils are rare and fragmental, including undetermined trilobites, echinoderms, lingulate brachiopods and stromatolites. On regional stratigraphic grounds, the Anthony Lagoon beds are correlated by Shergold et al (1985) with the Wonarah beds and Burton beds of late Templetonian-Florian (early Middle Cambrian) age. They are presumed to overlie the Gum Ridge Formation with minor disconformity.

In TENNANT CREEK, outcrop of Anthony Lagoon beds consists of residual rubble on or beside low rises which bear scattered ferruginous black pebbles. The rubble includes red-brown, yellow-brown and grey, silicified and chertified pebbles and cobbles representing original limestone, quartz sandstone and probable calcimudstone. The latter are most commonly identified, and include finely cross-laminated chert. Less common tabular, fine- to medium-grained quartz sandstone pebbles may have initially borne a carbonate cement, now leached.

A minority of pebbles, though silicified, preserve original carbonate textures. Typical among these are peloid/ intraclast grainstone of rounded, coarse silt- to fine sand-size grains, often with a flat-pebble calcimudstone intraclast component in which flat pebbles up to 25 mm long are oriented quasiparallel to bedding. Variants of the above include examples with irregularly shaped, medium to coarse sand-size coated grains (oooid- or ooid-bearing peloid/intraclast grainstone), and others with a dominant calcimudstone flat-pebble component of sand to granule size (flat-pebble intraclast grainstone).

Rare cauliflower siliceous nodules up to 8 cm in length imply original evaporites.

The above TENNANT CREEK rock types suggest a shallow marine depositional environment of moderate to high energy, ranging into the peritidal zone - consistent with the postulated transgressive nature of the basal Anthony Lagoon beds.

**Montejinni Limestone (Cmn)**

Traves (1955) introduced the Montejinni Limestone for grey limestone exposed around 'Montejinni' homestead in the northern Wiso Basin (VICTORIA RIVER DOWNS), where it rests unconformably on Antrim Plateau Volcanics (Early Cambrian). Traves original dual subdivision of the Montejinni Limestone was modified by Randal and Brown (1967; Randal 1973) to a threefold cherty limestone-calcareous mudstone-limestone subdivision (from base to top). The trilobite Redlichia was noted from the lower and upper limestones, and hyoliths ('Biconulites') from the upper limestone only. The 'giravellids' reported by Traves (1955:34) are almost certainly onkoids. Milligan et al (1966) additionally noted lingulate (including acrothelid) brachiopods, hyoliths, echinoderm plates, sponge spicules and chancelloriids. The total fauna of the formation, including Redlichia cf. foraminifera Sun & Chang and other trilobites, bradoriids, brachiopods, hyoliths, molluscs and putative sponge spicules, is described by Kruse (1998); it indicates an Ordian-early Templetonian (early Middle Cambrian) age. Echinoderm plates, sponge spicules, chancelloriids and problematic tubes are also present.

The Montejinni Limestone is apparently continuous across the entire Wiso Basin. It thickens and becomes more dolomitic southward, attaining a known maximum of 151 m in BMR drillhole Green Swamp Well 6, where the same threefold subdivision has been recognised (Kennewell and Huleatt 1980:10). There, it is conformably overlain by Hooker Creek Formation.

A series of Geopeko cored mineral exploration drillholes in the southwestern corner of TENNANT CREEK and adjoining areas (Figure 2) can be correlated with Green Swamp Well 6 as depicted by Kennewell and Huleatt (1980:56-57; Duck 1976, 1977; Harbon 1982, 1984; Kitt 1974; Maehl 1973). Among these drillholes, at least 90 m of Montejinni Limestone is preserved in a near-complete section in Rover 12 (GREEN SWAMP WELL). Successive lithotypes in logs of these drillholes have here been informally designated as intervals A to L (Figure 2), of which A to F are assigned to the Montejinni Limestone. In terms of Randal and Brown's (1967) threelfold subdivision, intervals A and B constitute the lower limestone unit, intervals C the middle mudstone unit, and intervals D to F the upper limestone unit.

The basal breccia interval A appears to be areally restricted, as it has not been reported from the central or western Wiso Basin. Its development here may be due to the proximity of the Kelly High on adjacent BONNEY WELL (Wyche and Simons 1987), from which Proterozoic detritus may have been shed. It is a maximum 26 m thick in drillhole Rover 1. It is a breccia unit with granule- to pebble-size clasts variously comprising dark grey or green shards, flakes and tablets of foliated mudrock, angular to subrounded maroon, green, brown or red volcanics (including porphyritic types), grey or white marble and siliceous rocks (Figure 3A). In thin
section, volcanics display original plagioclase laths, now altered to quartz-sericite, in a finely mottled groundmass. Siliceous rocks are megaquartz mosaics with interstitial sericite and/or muscovite. Perthitic alkali feldspar phenocrysts may also be present, as are sand-size quartz, muscovite and tabular alkali feldspar. Granitic, volcanic and metamorphic sources are implicated. Matrix is typically a light grey to pink-brown dolomitic mosaic, in places with darker grey-green silt laminations and styololites wrapping around clasts. Bedding-subparallel gypsum veins are locally present.

The breccias tend to grade upward into maroon siliciclastic or grey dolomitc mudstone, with localised darker grey-green silt laminations and related styololites, in upper interval A. These mudstones commonly show evidence of brecciation by evaporite dissolution. An example from Rover 1 (Figure 3B) consists of well sorted, angular to subangular, coarse silt- to medium sand-size quartz and minor glauconite and lithic fragments (chert, fine megaquartz, quartz-sericite), with interstitial iron oxides and/or clay minerals imparting the characteristic maroon colour. Areas of mosaics and rhomb dolomite are also interstitial.

The light to mid-grey or yellow-grey dolostones (intervals B, D, F) include cryptomicrobial dolomudstone, intraclast dolarenite (Figure 3C), onkoid floatstone comprising onkoids 1-3 cm in diameter in a dolopseudospar mosaic (Figure 3D), and ribbon limestone comprising centimetre-scale interbeds of light grey bioclastic dolomudstone and darker grey silstone (Figure 3E). These may be locally mottled or bear dark grey silt laminations and styololites. Thin maroon and grey mudstone interbeds, chert nodules, and evaporite nodules up to 4 cm in size within associated bedding-subparallel gypsum veins, are also present. Common bioclasts include hyoliths (which occasionally provide the nuclei for scattered onkoids), brachiopods or molluscs, and possible trilobites.

In thin section, typical dolostone consists of a background of secondary dolomite to dolomicrospar mosaic with up to 2% interstitial iron oxides and/or clay minerals. These latter mineral groups are concentrated as cumulate within the styololites. Despite patchy coarser dolomitisation, original sedimentary structures are preserved with a fair degree of fidelity. Calcite (up to 5%) tends to be a later pore or vein filling. Scattered nodular or silt-size detrital quartz may also be present.

Siliciclastic grey, yellow-grey and maroon mudstone intervals (C, E) bear minor thin stylolitic dolostone interbeds, some of which show sedimentary boudinage. The mudstone may be locally brecciated or brecciated (Elliott 1965) following evaporite dissolution. Evaporites are preserved as nodules, thin beds (less than 1 cm thick) or as matrix to dolostone flat-pebble breccias.

The Montejinni Limestone crops out in TENNANT CREEK as low, rubble-covered rises. As with the Gum Ridge Formation, these exposures are extensively silicified and lateritised, but equivalent massive limestone and bedded lime mudstone/marl lithotopes can be recognised.

Sedimentary structures indicate a range of depositional environments in the Montejinni Limestone, including restricted shelf marine (bioclastic limestones), shallow subtidal (onkoid limestones) and peritidal (nodular evaporites, cryptomicrobial laminates and flat-pebble breccias).

Hooker Creek Formation (Emh)

The Hooker Creek Formation does not crop out in TENNANT CREEK, but is intersected in Geopeko cored drillholes in the southwestern corner of TENNANT CREEK and adjoining areas. In these, it spans intervals informally designated G to K (Figure 2).

Maroon silstone or grey dolomitic mudstone (intervals G, I, K) dominate. The maroon silstone may display fine-scale brecciation due to evaporite dissolution, but both this and the grey mudstone otherwise show vague lamination. Thin dolostone interbeds include yellow-grey cryptomicrobial dololaminite and grey, mottled or laminated dolostone with darker olive green or grey-black, bedding-parallel silt laminations and styololites. Hyoliths are locally visible in cores. Dolostone flat-pebble conglomerates are rare (Figure 3F).

Interval J is a yellow-brown, fine dolomitic quartziferous sandstone, clayey in parts, in the upper part of the formation. Huleatt (1977) and Kennewell (1977) record hyoliths ('Biconulites', Acrotreta, Acrothele and lingulid brachiopods, echinoderm ossicles, and Redlichia and ptychopariid trilobites from Hooker Creek Formation. Acetic acid digestion of dolostone from the Geopeko drillholes here confirms the presence of lingulate brachiopods, hyoliths, echinoderm plates and fragmentary trilobites. The fauna indicates an Ordian-early Templetonian (early Middle Cambrian) age.

Among the Geopeko drillholes, Hooker Creek Formation attains a maximum 88 m thickness in Explorer 108 (GREEN SWAMP WELL). In that sheet, the stratotype BMR drillhole Green Swamp Well 6 intersects 162 m of the formation - its greatest known thickness (Kennewell and Huleatt 1980:56).

The Hooker Creek Formation was deposited under peritidal to restricted marine conditions.

Point Wakefield beds (Emp)

Outcrops of Point Wakefield beds in the central and eastern Wiso Basin are typically rubble-strewn slopes and small scarp on the margins of low rises. The rises are commonly capped by calcrete. The unit is transgressive over the Ordian-early Templetonian formations of the Wiso Basin, as in BMR drillholes Green Swamp Well 1, 2 and 3 it directly overlies the Montejinni Limestone, Hooker Creek Formation and Lothari Hill Sandstone respectively. The maximum attributed thickness is 54 m, in BMR drillhole Lander River 5 (Kennewell and Huleatt 1980:60).

Two subunits have been recognised (Kennewell 1978; Kennewell and Huleatt 1980): a brown and white calcareous claystone, silty in part (Emp), and a possibly overlying subunit of interbedded well sorted sandstone and laminated claystone (Emp). The latter subunit includes silicified linked bulbous stromatolites at one locality in GREEN SWAMP WELL, but these are not diagnostic of age.

In TENNANT CREEK, only one outcrop area of Point Wakefield beds is known, on the western slope of Short Range at GR LU5564. This locality was designated TC1 by Kennewell and Huleatt (1980:15), and represents subunit Emp. Here, tabular beds of tan and white silt claystone, in some cases tinged red-brown, crop out beside small gutters on the flats adjacent to the ridgeline outcrop of the Hayward Creek Formation. A fauna of ptychopariid trilobites, obolid
Figure 3  Photomicrographs of Middle Cambrian lithotopes, southwestern TENNANT CREEK. A-E, Montejinna Limestone. A, lithic greywacke conglomerate of basal interval A; 137.5 m depth in drillhole Rover 14 (DDH2). B, moroon ferruginous sublitharenite of upper interval A; 116.9 m depth in drillhole Rover 1 (DDH1). C, fenestral intraclast dolarenite of interval BD; 120.0 m depth in drillhole Rover 14 (DDH2). D, onkoid dolostone of upper interval BD; 114.4 m depth in drillhole Rover 14 (DDH2). E, bioclastic dolomudstone of upper interval BD: here with paler silicified bed bearing calcite brachiopod, hyolith, chancellorid, sponge spicule and ?mollusc biofragments; 107.8 m depth in drillhole Rover 14 (DDH2). F, Hooker Creek Formation; flat pebble conglomerate in grey dolomudstone (top) of interval 1: here with pebbles of dolomitic quartz sandstone; 62.6 m depth in drillhole Rover 13 (DDH1). Width of each field 30 mm.
brachiopods, hyoliths and sponge spicules from these beds has been assigned a Templetonian (early Middle Cambrian) age (Jell in Kennewell 1978). The psychoparid is identified by Kruse (1998) as Xingrenaspis alioiensis (Etheridge), and the brachiopods as Lingulaella sp., Karatehe kartuja Kruse and an obolind, indicating a late Templetonian-Floran age.

CAINozoIC

Map symbols Ts and Tl are used for silcrete and ferricrete respectively. These duricrusts probably developed over a significant time span from the Cretaceous to the Neogene (mid-Miocene). Kennewell and Hulett (1980) suggest that there are possible correlatives of both the Morney (early Eocene) and Canaway (late Miocene) deep weathering profiles, developed in Queensland and dated by Idnurm and Senior (1978), in TENNANT CREEK. Certainly these duricrusts postdate the development of the Tennant Creek Surface on FLYNN and TENNANT CREEK. Much of the Cambrian Montejinim Limestone in the northwest of TENNANT CREEK is intensely silicified. Similarly the Anthony Lagoon beds in the northeast are predominantly lateritised. The relevant outcrops are designated by the appropriate Cambrian stratigraphic unit followed by either Ts or Tl. In these instances the parent rock type is recognisable or can be fairly reliably inferred. The map symbol Ta has been used in only one instance. It indicates deeply weathered rock; parent rock not recognisable.

Colluvial deposits are designated Czc, and, where quartz-rich, Czq. The more fine-grained and often more distal colluvium and wash is designated Czs. These deposits either underlie more recent colluvium (Qc, Qcq), sands (Qs; sheet and dune sands: Qa and Qas; extant and abandoned watercourses) and soils (Qr, Qar) or are clearly dissected by active or recently active watercourses. Qp is used for the local development of clay-rich detritus in floodouts or local depressions in watercourses. Qcq is mainly colluvial vein quartz whilst Czq comprises both vein quartz and silcrete detritus.

STRUCTURE

The Warramunga Formation turbiditic flysch sequence was folded contemporaneously with the Barramundi Orogeny (D1) of Etheridge et al. (1987) about 1845 Ma. These first generation folds (F1) are moderate to tight, and upright with east or east-southeast trending fold axes and a well developed axial planar slaty cleavage (S1). The 'early' granites in TENNANT CREEK are syntectonic with the Barramundi Orogeny. This is evidenced by, for example, an easterly foliation in the Tennant Creek Granite and, to a lesser extent, in the Mumbilla Granodiorite. The time of emplacement of these 'early' granites may be coincident with the change from transpression to transtension in an on-going dextral shear and with the waning of the Barramundi Orogeny and the onset of Flynn Subgroup deposition. A number of authors (e.g. Rattenbury 1994) have postulated a broadly strathabound, sheet-like form for the intrusive porphyries. These bodies were, however, probably deformed during the second deformation (D2) and not the Barramundi Orogeny. Reference to the solid geology map (see mapface) indicates that the distribution of the intrusive porphyry may correspond with an en echelon arrangement of tension gashes.

On-going dextral shear resulted in reactivation of the early tectonic fabric in the Warramunga Formation, probably coeval with the gold-copper-bismuth mineralisation which has been dated at about 1.82 Ga by Compston and McDougall (1994). At this time S1 in the Warramunga Formation propagates locally into the unconformably overlying Flynn Subgroup rocks. Disharmonic folding between the Flynn and Ooradidge Subgroups and the overlying Tomkinson Creek and Wauchope Subgroups may in part relate to this minor tectonic event rather than entirely to the subsequent Stranges Woyrageny (D2). However, a regional unconformity is not evident at this level in the stratigraphy. There is a transitional, apparently conformable, contact between the Flynn Subgroup and the Tomkinson Creek Subgroup at the boundary between the Tennant Creek and Ashburton provinces in the north; and between the Flynn Subgroup and Wauchope Subgroup at the boundary of the Tennant Creek and Davenport provinces in the south.

Two pervasive cleavages were developed in the Warramunga Formation during the Stranges Woyrageny (D2). These cleavages are orientated northwest (S1) and northeast (S2) and are predominantly crenulation, or local fracture or slaty cleavages. These two cleavages remain essentially orthogonal; S2 generally antedates S2' although locally the converse is true indicating that this is a genuine, conjugate deformation as thought by Dunnet and Harding (1967). These cleavages are also well developed in the Flynn and Ooradidge Subgroups but only generally recognisable as spaced fractures in the more competent Tomkinson Creek and Wauchope Subgroups.

Folding (F2/F2') associated with the Stranges Woyrageny is well exposed on a regional scale in the Davenport province. These folds are upright, concentric domes and basins (Stewart 1987) arranged en echelon with predominately northwest trending fold axes. The Tomkinson Creek Subgroup describes a large northwest plunging synclinal fold with superposed north-northwest to north trending shorter wavelength folds.

The style of folding produced in D2/D2' in the Warramunga Formation is well represented on the mesoscale. Excellent examples of these folds are to be found in the Mary Lane shear zone (Figure 4). Mesoscale anticlinal folds include symmetric and asymmetric chevron folds; asymmetric, box and doubly peaking anticlines; and symmetric doubly peaking anticlines ('M' folds). Mesoscopic synclinal folds are predominantly concentric. However, there are examples of concentric anticlinal folds; symmetric and asymmetric synclinal chevron folds; and asymmetric, box and doubly peaking synclines. The entire outcrop area of the Warramunga Formation is interpreted to define a regional scale doubly plunging anticlinal box fold with large-scale chevron folds developed in zones of high-strain (kink bands).

Reconnaissance fieldwork indicates that the Mount Bonnie Formation, the Burrell Creek Formation and the Lander Rock beds show the same association of cleavages as the Warramunga Formation, suggesting deformation in both the Pine Creek geosyncline and the northern Arunta Inlier comparable to that seen in the Tennant Creek Inlier. The association of tight to isoclinal, upright folds with an axial planar slaty cleavage, and conjugate kink folds with associated
crenulation cleavages is typical of ‘slate belts’ which merge with polydeformed belts as the scale of the second generation folding increases and becomes regionally significant (Hobbs et al 1976).

Major faults in the Tennant Creek province form an anastomosing array which may, at least locally, show offsets of the order of 10 km. Blake et al (1987) suggested that in the Davenport province synsedimentary normal faults were reactivated as reverse faults during folding and that curved axial surfaces of major folds may have resulted from strike-slip movement on pre-existing transfer faults. Reading (1980) stated that en echelon folds are a good indication of strike-slip at depth.

The style of deformation seen in the Tennant Creek province and throughout the Inlier can be reconciled with simple shear produced by an initial, approximately northwest orientated dextral shear couple (cf. Michell and Reading 1978). As the regime evolved from dominantly transtensional to dominantly transpressional, second generation folds rotated to near parallelism with the conjugate northwest and northeast-orientated strike-slip faults and a flexural-slip component is imposed on the first generation east-oriented folds. It is plausible that the northern Arunta Inlier and Pine Creek geosyncline deformed in a similar manner to the Tennant Creek Inlier.

A spaced, north orientated cleavage (S3) is recognisable throughout the Warramunga Formation. This may result from easterly compression associated with the 1590-1500 Ma Isan Orogeny in the Mount Isa terrain (O’Dea et al 1997). Open north-orientated folds are developed in the Namerinni Group on HELEN SPRINGS (Hussey et al in prep).

**GEOPHYSICS**

Interpretive 1:100 000 scale solid geology maps of both FLYNN and TENNANT CREEK, and a 1:250 000 TENNANT CREEK map (Farrar 1994), were based on BMR gravity and aeromagnetic survey data in conjunction with NTGS geological mapping. These maps have been synthesised with somewhat modified 1:1 000 000 solid geology maps of the Davenport Ranges (DEVILS MARBLES REGION, KURUNDI, HATCHES CREEK and ELKEDRA; Wyche et al 1987, Stewart and Blake 1986, Blake et al 1986 and Blake and Horsfall 1986 respectively), and the 1:1 000 000 solid geology maps of BONNEY WELL (Wyche and Simons 1987) and BARROW CREEK (Haines et al 1991). Similarly, the area of coverage has been extended northwards to include western HELEN SPRINGS. The solid geology map for HELEN SPRINGS is based on recent NTGS mapping (1995-1997) (Hussey et al in prep) and preliminary geophysical interpretation of western HELEN SPRINGS. The result is a 1:1 250 000 solid geology map over the exposed portion of the Tennant Creek Inlier which appears on the map face of TENNANT CREEK.

Warramunga Formation magnetic anomalies, produced by ironstones, can be distinguished from those related to magnetite-bearing fine-grained clastic rocks ('shale') of both the Warramunga Formation and the Flynn Subgroup, by the discrete character of the former. The exposed geology can be interpolated and extrapolated into areas of cover by tracing these magnetic trends.

Magnetic character tends to define two geological units, one within the Warramunga Formation and the other spanning the Flynn Subgroup/Tomkinson Creek Subgroup boundary. Between these units, a less magnetic Flynn Subgroup unit is distinguished from less magnetic Warramunga Formation by the occurrence of discrete, 'ironstone-type' anomalies in the latter. Thus, two geophysically mappable Warramunga Formation units (more- and less-magnetic) combine with two geologically defined and mapped lithofacies (sandstone and siltstone) to give a total of four units on the solid geology map.

The use of mapped, outcropping geology to subdivide geophysical units was also applied in the case of the Hayward Creek Formation to extrapolate into areas of non-exposure to the east of the Whittington Ranges.

Gravity character generally tends to distinguish granitic from non-granitic rocks. However, the coincidence of magnetic anomalies and mapped granite in areas without the gravity low which typically characterises granite, and low gravity values in areas of mapped Flynn Subgroup outcrop, suggests various degrees of assimilation of Flynn Subgroup rocks by a number of the different granites (e.g. Mumbilla Granodiorite, Cabbage Gum Granite, Tennant Creek Granite) in parts of TENNANT CREEK and BONNEY WELL.

Repetitive west-northwest striking geophysical features (WEST influence on Figure 5) define folding with a wavelength of the order of 25 km. These are modified by a geophysical character which reflects folding with north-northwest orientated (NORTH influence on Figure 5) fold axes and a wavelength of the order of 40 km. An east-northeast trend (EAST influence on Figure 5), which appears to be related to basement, provides a third regional influence. Although interference is evident, one trend is usually predominant. Shorter wavelength harmonics appear to give the folds a 'boxlike' form, with a more severe edge on the southern side. These harmonics also appear to have some relationship with the alignment and spacing of ironstones and ironstone groups. The regional geophysical character and trends relative to TENNANT CREEK are shown in Figure 5.

**GEOCHRONOLOGY**

Geological evidence suggests that the main Palaeoproterozoic sedimentary, igneous and tectonic 'events' in the Tennant Creek province occurred over a relatively brief time interval. Warramunga Formation sedimentation was followed by deposition of the Flynn Subgroup with little or no perceptible time break. In fact, Flynn Subgroup sedimentation could possibly have begun in one part of the basin, or in a contiguous overlapping basin before Warramunga Formation sedimentation was completed. It remains, however, that the Flynn Subgroup rocks lack the earliest (S1) fabric recognised in the Warramunga Formation. Similarly, Flynn Subgroup sedimentation was broadly coeval with intrusion and volcanism. Consequently, it is difficult to unravel the Palaeoproterozoic geological history of TENNANT CREEK by conventional geochronological methods.

Recent studies indicate two major cycles of Palaeoproterozoic sedimentation and volcanic activity in northern Australia, separated by an episode of tectonism (Barramundi Orogeny) and associated intrusive felsic magmatism (Page 1988). This Orogeny is dated at 1885±10 Ma
Figure 4 Examples of mesoscale folds resulting from D2/D2' and seen in outcropping Warramunga Formation in the Mary Lane Shear Zone (GR MU1433). A and B show changing fold profiles: Chevron, flexural-slip, and asymmetric doubly peaking anticlines; and chevron, doubly 'peaking' asymmetric and concentric synclines. C, asymmetric anticlinal box-fold, note the vertical change in fold profile.
Figure 5 Regional influences relative to Tennant Creek Inlier.
in the Mount Isa Inlier; 1885-1870 Ma in the Pine Creek Inlier; a little later in the Hall Creek Inlier (1854±67 Ma), and somewhat older in the Tennant Creek Inlier (1920-1870 Ma; Page 1988). Recent single-crystal zircon U-Pb SHRIMP dates of Compston (1995) constrain the age of the Barramundi Orogeny at TENNANT CREEK to 1800-1845 Ma.

Earlier geochronological studies of Black (1977 and 1984) and Sm-Nd isotopic systems (Black and McCulloch 1984) were summarised in Donnellan et al. (1995) to which the interested reader is referred.

A recent significant advance in geochronological studies of TENNANT CREEK rocks is the U-Pb single-crystal zircon ages determined by Compston (1991 and 1995) using the sensitive high-resolution ion microprobe (SHRIMP). These ages are sufficiently precise to contribute more reliably to unravelling stratigraphic problems. It is, however, stressed that the current stratigraphy is based entirely on the interpretation of field relationships but is corroborated by the geochronology.

Compston (1991) derived a U-Pb zircon age for the Bernborough Formation volcanic rocks of 1833±4 Ma which he subsequently refined (Compston 1995) to 1840±8 Ma and 1845±4 Ma. This is significantly younger than the current best estimates of the age of the Warramunga Formation. Compston (1991) dated detrital zircons from greywacke in the Warramunga Formation at 1862±10 Ma and 1884±13 Ma (revised to 1862±9 Ma and 1859±13 Ma; Compston 1994a). These ages are in close agreement with that for a highly altered tuff within the Warramunga Formation sedimentary succession. Blake and Page (1988) reported substantially older conventional Pb/Pb ages, 1922 Ma and 1916 Ma, from a single zircon analysis of each of two flow-foliated rhodacites from the ‘Warramunga Group’ to the east of the northern Murchison Ranges. These authors, however, recognised that these ages are substantially biased by inheritance, and are a blend of late Archaean zircon and zircon crystallising 1880-1870 Ma.

Contrary to previously published dates, Compston (1991) reported essential contemporaneity for the Tennant Creek Granite, ‘Red Bluff Granite’ (1850±7 Ma), Mumbilla Granodiorite (1850±6 Ma) and Cabbage Gum Granite (1848±7 Ma), Compston (1994) revised the age of the Tennant Creek Granite at Red Bluff to 1853±10 Ma.

The new age for the Bernborough Formation is younger than that of the Tennant Creek Granite (1858±12 Ma; Compston 1991). The Tennant Creek Granite intrudes the Warramunga Formation but has not been observed intruding the Bernborough Formation volcanic rocks, although these are compositionally very similar to the granite and likely to be part of the same episode of felsic magmatism. Compston (1995) gave an independent age of 1848±7 Ma for what he considered a separate, discrete northern pluton of the Tennant Creek Granite. Lack of outcrop precludes any firm field interpretation of the relationship between the northern and southern exposures of the Tennant Creek Granite.

Until recently the only published dates for the gold mineralisation at Tennant Creek were those of Black (1977). The favoured age for gold mineralisation was about 1810 Ma. This Rb-Sr age was determined for muscovite from the hydrothermal alteration associated with the Juno orebody. Identical or very similar Rb-Sr ages were determined for muscovite from level 10 of the Number 3 orebody, and level 5 of the Number 1 orebody at Warrego; muscovite from Nobles Nob mine (although this calculated age is dependant on the assumed initial ratio); muscovite from the Golden Forty mine; and muscovite from TC8 mine. Somewhat younger ages determined for muscovite (1757 Ma), sericite (1693 Ma) and biotite (1665 Ma) from the Warrego Mine were considered by Black (1977) as a record of a later thermal event, possibly the intrusion of the Warrego Granite. Compston and McDougall (1994) suggested a minimum age for mineralisation between 1825 and 1830 Ma based on 40Ar/39Ar analyses of hydrothermal muscovites from Peko, Argo, Nobles Nob and Juno.

Black and Page (1988) tentatively interpreted Rb-Sr whole-rock data from felsic volcanic rocks of the Ooradidgee and Wauchope Subgroups of the Hatches Creek Group as indicating a regional hydrothermal event at 1645±44 Ma which may be related to W and minor Cu, Bi and Mo mineralisation in the Davenport province.

GEOLOGICAL HISTORY

PALEOPROTEROZOIC TO NEOPROTEROZOIC

1. The Warramunga Formation turbidite flysch succession was rapidly deposited 1.86 Ga in a continental arc-related, dextral strike-slip pull-apart basin. The sediments were largely derived from the unconsolidated, penecontemporaneous felsic volcanic rocks of the arc. Detrital zircon (Compston 1995) and Nd isotopic data (εNd > -4.9) indicate an admixed component of Archaean to earlier Palaeoproterozoic rocks.

2. Syn-tectonic emplacement of felsic intrusive rocks (BIA) and deformation of the Warramunga Formation occurred during the Barramundi Orogeny (D1) 1.85 Ga. Mafic magmatism associated with the BIA is manifest in gabbro, and dolerite dykes, and diorite. On-going dextral shear generated dilatational (transitional) zones simultaneous with transpressional areas in an anastomosing array.

3. Extrusive subaerial volcanic activity and contemporaneous subaqueous volcanioclastic sedimentation of the Flynn Subgroup partially overlapped in time with granite emplacement. On-going mafic magmatism is manifest in dolerite dykes which post-dated the Barramundi Orogeny and have ages between 1.84 and 1.82 Ga. Incipient rifting was manifest in the generation of the bimodal volcanic and volcanioclastic rocks of the Ooradidgee Subgroup.

4. On-going dextral shear resulted in re-activation of early fabrics 1.82 Ga, essentially contemporaneous with Au-Cu-Bi mineralisation. Largely consolidated granite was remobilised into upper crustal dilatation zones. These events were probably simultaneous with the Yuendumu tectonic event in the northern Arunta Inlier.

5. Marine transgressive and regressive cycles and sedimentation of the clastic-carbonate Tomkinson Creek Subgroup occurred in a stable platform environment. There was contemporaneous sedimentation of the Wauchope and Hanlon Subgroups in a periodically reactivated failed-riift in the Davenport province.

6. Regional deformation (D2) occurred contemporaneously with the Strangways Orogeny of Collins and Shaw (1995) in the Arunta Inlier.
7. Post-tectonic magmatic activity was represented by granite intrusion, and minor ultramafic, calc-alkaline lamprophyre intrusion at about 1685.

8. A possible widespread hydrothermal alteration event at 1645±44 Ma was postulated for the Davenport province by Blake and Page (1988).

9. There was a substantial hiatus prior to latest Neoproterozoic to earliest Cambrian continental, rift-related red bed sedimentation manifest by the Rising Sun Conglomerate. This is a probable correlative of the Andagerra Formation of the Davenport province which in turn correlates with part of the Central Mount Stuart Formation.

GEORGINA AND WISO BASINS

The Georgina and Wiso Basins are erosional remnants of more widespread intracratonic platform deposition originally covering vast areas of central and northern Australia. This deposition had commenced in the Cryogenian (800 Ma; Lindsay in Jenkins et al. 1993:44) in the Amadeus, Ngalla and southern Georgina Basins of central Australia, but marine sedimentation did not extend into northern Australia (including TENNANT CREEK) until the Middle Cambrian. The principal developmental phases are:

1. Early Cambrian deposition of quartz sand and minor pebble conglomerate followed by extrusion of Helen Springs Volcanics, possibly related to limited continental break-up in east Gondwana (Veivers and Powell 1984).

2. Widespread transgression across the northern Australian craton occurred in Ordovician-early Templetonian (early Middle Cambrian) time, with deposition of carbonate-dominated peritidal to shallow marine sediments of sequence 1 (Shergold et al. 1988; Southgate and Shergold 1991): Gum Ridge Formation in the western Georgina Basin (Barkly Sub-basin) and Montejinni Limestone, Hooker Creek Formation and Lothari Hill Sandstone in the Wiso Basin. Transgression may have been due to crustal subsidence following cessation of volcanism.

3. Late Templetonian-Floran deposition of sequence 2 siliciclastic and carbonate sediments: Anthony Lagoon beds in the western Georgina Basin (Barkly Sub-basin), and Point Wakefield beds in the Wiso Basin. This phase terminated Middle Cambrian deposition in the area.

4. Following a long period of non-deposition, the region was blanketed by fluvialite to shallow marine cold-water siliciclastic platform sediments in Early Cretaceous time (Dunmarra Basin of Eupene 1990).

5. The region has been exposed since mid-Cretaceous time, with activity limited to continental processes of erosion and regolith, colluvium, black soil and local laterite, calcrete and silcrete development. Cretaceous rocks have been generally stripped from the area.

RELATIONSHIPS AND CORRELATIONS BETWEEN PALEOPROTEROZOIC UNITS

Many rocks formerly included in the Warramunga Group (Dunnet and Harding 1967; Mendum et al 1978) are now excluded from the Warrumunga Formation on both lithological and structural grounds (see Donnellan et al 1995, and Table 2). Some rocks of the former Warramunga Group mapped in the Davenport province on DONNYE WELL (Wyche et al 1987; Wyche and Simons 1987) and FREW RIVER (Blake et al 1986; Walley 1987) are here excluded from the Warrumunga Formation and are considered probable correlatives of the Flynn Subgroup.

The Warrumunga Formation comprises tuffaceous, turbiditic sedimentary rocks. Typical Flynn Subgroup is readily distinguished as a less deformed succession of primary volcanic rocks, predominantly pyroclastic but locally including lava, and shallow marine or lesser fluvialite epiclastic rocks. However, both the local propagation of a reactivated S1 cleavage from Warrumunga Formation into Flynn Subgroup rocks, the occurrence of deeper marine sediments with probable Bouma sequences in Flynn Subgroup rocks, and the close lithological similarity (tuffaceous lithic arenite) between sedimentary rocks of the two units can make the distinction extremely difficult locally. Combined lithological, sedimentological and structural criteria generally solve the problem in the field. Preliminary findings (Donnellan 1994; Donnellan et al 1995) indicate that rocks of the Warrumunga Formation and the Flynn Subgroup can be discriminated on geochemical criteria.

ECONOMIC GEOLOGY

TENNANT CREEK hosts the Tennant Creek goldfield which has produced 156 t of gold, 345000 t of copper, 14,000 t of bismuth, 220 t of selenium and 56 t of silver from 130 mines. Most production, however, has been from 12 deposits (Table 4). Gold was first discovered in the district in 1874 (Northern Territory Times and Gazette, October 1881), however, significant mining and prospecting did not take place until 1932 when two small batteries were constructed near the present town site. Table 5 lists chronologically important discoveries and mining developments in the Tennant Creek goldfield. More details on the history of mining and production can be obtained from Ivanac (1954), Balfour (1989) and LeMessurier et al (1990).

Since the early gold discoveries, the district has been the focus of a considerable amount of mineral (mainly gold) exploration, particularly from the 1970s onward. Some 1400 company reports have been lodged with the Northern Territory Department of Mines and Energy.

The geology and related mineralisation within the Tennant Creek goldfield has been the subject of a number of investigations and studies by government organisations (CSIRO, BMR and NTGS) and Australian universities over the last fifty years. The earliest detailed report was completed by Ivanac (1954).


Significant publications on the ore deposits and controls of mineralisation within the Tennant Creek goldfield include: McKeown (1942), Edwards (1955), Elliston (1966), McNeil
<table>
<thead>
<tr>
<th>Mine</th>
<th>Ore (Mt)</th>
<th>Ore grades</th>
<th>Metal Produced</th>
</tr>
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<tbody>
<tr>
<td>Warrego</td>
<td>4.95</td>
<td>8.5% Au</td>
<td>41 280kg Au</td>
</tr>
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<td></td>
<td></td>
<td>2% Cu</td>
<td>91 500t Cu</td>
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<tr>
<td></td>
<td></td>
<td>0.3% Bi</td>
<td>~12 000t Bi</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>~5 500kg Ag</td>
</tr>
<tr>
<td>Nobles Nob</td>
<td>2.14</td>
<td>17% Au</td>
<td>34 580kg Au</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>~1 730kg Ag</td>
</tr>
<tr>
<td>Juno</td>
<td>0.45</td>
<td>59% Au</td>
<td>26 130kg Au</td>
</tr>
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<td></td>
<td>7% Ag</td>
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<td></td>
<td></td>
<td>0.4% Cu</td>
<td>1 439t Cu</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.6% Bi</td>
<td>2 293t Bi</td>
</tr>
<tr>
<td>White Devil</td>
<td>1.3</td>
<td>15.2% Au</td>
<td>19 800kg Au</td>
</tr>
<tr>
<td>Peko</td>
<td>3.1</td>
<td>3.5% Au</td>
<td>7 481kg Au</td>
</tr>
<tr>
<td></td>
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<td></td>
<td></td>
<td>4.1% Cu</td>
<td>117 465t Cu</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.2% Bi</td>
<td>7 350t Bi</td>
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<tr>
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<tr>
<td></td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>0.1% Bi</td>
<td>320t Bi</td>
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<tr>
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<td>0.21</td>
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<td>Argo</td>
<td>0.29</td>
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<tr>
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<td>3.0</td>
<td>1.2% Au</td>
<td>3 450kg Au</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4.0% Cu</td>
<td>122 700t Cu</td>
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<tr>
<td>Golden Forty</td>
<td>0.15</td>
<td>12% Au</td>
<td>1 762kg Au</td>
</tr>
<tr>
<td>TC8</td>
<td>0.08</td>
<td>18% Au</td>
<td>1 420kg Au</td>
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<td>12% Ag</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>3% Cu</td>
<td>8 905t Cu</td>
</tr>
</tbody>
</table>

Au (±Cu, Bi) deposits, with only three quartz vein-hosted gold occurrences.

**Ironstone-related Au (±Cu, Bi) deposits**

The ironstone-related Au (±Cu, Bi) mineralisation on TENNANT CREEK may be classed as polymetallic hydrothermal replacement deposits. The mineralisation is closely associated with magnetite-haematite bodies within terrigenous clastic metasediments of the Warramunga Formation. About 80% (122 t) of the gold produced to December, 1998 has been derived from four deposits: Warrego, Nobles Nob, Juno and White Devil, which are quite different in size, metallic content and grade, but have very similar geological setting, host rock and age (1830 Ma).

**Ironstones**

These replacement bodies are irregular ellipsoidal lenses to flattened pipe-like in shape, and range in size from a few tonnes to over 15 million tonnes (LeMessurier et al 1990). Over 700 ironstone bodies have been recorded throughout the field, but fewer than 200 are known to contain significant mineralisation, and only 25 contained more than 100 kg of gold (Figure 6).

Most of the ironstone bodies are discordant to stratigraphic layering, with only a few near concordant. Orientation of the lodes is usually in the plane of the easterly trending S1 and S2 cleavages, with their long axis near vertical. Some ironstones have been subsequently reoriented by post-D2 tectonic activity such as faulting, folding and granite intrusion.

In the oxidised zone, which commonly extends 100 m below the surface, ironstones consist of haematite with minor remnant magnetite, goethite, quartz, sericite and clay minerals. Hypogene ironstones consist of magnetite (50-80%), quartz (0-60%) and chloride (5-40%) with minor amounts of pyrite, talc, dolomite, muscovite and calcite (Wedekind et al 1989).

The magnetite in the ironstone pods is typically in the form of massive fine grained (0.02-0.5 mm) sutured aggregates which are brecciated and infilled with chloride and quartz (zololomite, talc, muscovite, chloropyrite, pyrite, bismuthinite and gold). Magnetite commonly displays colloform textures in the form of mammillary bands and spherulitic aggregates with chloride. Platy and acicular grains of magnetite are considered to be pseudomorphs after primary haematite (Large 1975). The intimate association of haematite and magnetite at Golden Forty suggests that the oxygen fugacity at the time of deposition was close to the magnetite-haematite buffer (Hargreaves 1974).

Magnetite veins and disseminations in highly chloritised sediment breccia and stringer zones are commonly encountered adjacent to and below the ironstone bodies respectively. The stringer zones and leached sediments located below the ironstones are considered to represent the hydrothermal channel (Large 1975).

Trace element and mineralogical studies demonstrated significant enrichment of W and Mo in the ironstones compared to the haematite shales (Horvath 1988; Large and Robinson 1987) and that the magnetite from the Golden Forty orebody is pure Fe₂O₃ and has the same cell dimensions as magnetite in the surrounding metasediments (Hargreaves 1974).
Table 5  Chronological list of important discoveries and mining developments in TENNANT CREEK.

1874  Gold reported from the Last Hope area 48 km NW of the Old Telegraph Station
1894  Gold panned from Bishops Creek
1925  High copper and gold ore samples obtained from shaft sunk 9 km SW of the Old Telegraph Station
1932  Payable gold located at abandoned workings (Great Northern) 9 km S of the Old Telegraph Station
1933-34 Discovery of numerous deposits including Nobles Nob, Eldorado, Golden Forty, Lone Star, Pinnacles, Wheat Doria, Northern Star, Hammerjack, Rising Sun and Blue Moon
1936  Fifty small gold mines in operation
1938  Seventy small gold mines in operation
1939  Whippet mine is brought into production
1943  All mines (except Eldorado) are closed down during the Second World War
1944  Enterprise mine reopens and by 1947 twenty five mines are operating
1950  Discovery of high grade copper ore beneath the Peko mine
1952  Only eight mines operating
1962  Orlando mine is brought into production
1965  Ivanhoe mine is brought into production
1967  Juno mine is brought into production
1972  Warrego mine is brought into production
1973  Gecko mine is brought into production
1974  Golden Forty mine is reopened
1986  Argo and TC8 mines are brought into production
1987  White Devil mine is brought into production
1989-91  Retreatment of old tailings at Eldorado
1992  Opencut mining at Eldorado
1994  Opencut mining at Orlando East and retreatment of Warrego tailings
1995  Recommencement of mining at Gecko
1998  Gecko placed on care and maintenance

Many workers in the goldfield have recognised several significant 'lines of lodes' which can be traced discontinuously along west trending directions subparallel to the Mary Lane Shear Zone, particularly in the southern half of the goldfield. A number of structural and lithological elements, often in combination, are found to control the distribution of mineralised ironstones within the Warramunga Formation.

The relative importance of stratigraphy and structure is still debatable. Both contribute to provide the conditions favourable for iron oxide precipitation.

Stratigraphic Controls

Stratigraphic controls on ironstone distribution, particularly the association of 'haematite shales' and quartz-feldspar porphyries, have been recognised by numerous authors. Rattenbury (1992) identifies three main stratigraphic levels of ironstone in the southeastern part of the goldfield, and suggests that the ironstone bodies occur at discrete stratigraphic levels in association with haematite shale beds.

A close surface correlation between mineralised ironstones and 'haematite shale' beds is present along the line of lodes from Mount Samuel to Rising Sun in the southern part of the field. In subsurface the ironstones at Nobles Nob, Juno and TC8 centre on and partially replace haematite shale beds. There are numerous deposits, however, which are not associated with haematite shales or porphyry intrusions which suggests that neither are critical for ironstone formation. The mineralised ironstones are exclusively located within or near iron oxide enriched metasediments of the Warramunga Formation which suggests the latter probably supplied some of the iron oxides.

Early studies (Ivanac 1954; Whittle 1966) have identified that the ironstones are commonly hosted within argillaceous lithologies, which is very apparent in the smaller deposits (e.g. Whippet mine). The mudstone and shale hosts are more strongly cleaved and fractured than the coarser arenite units, which appears to make the former more susceptible to replacement by chlorite and magnetite. The importance of sediment chemical composition, for example carbonaceous (Reveleigh 1977) or iron-enriched (Wedekind et al 1989) components, acting as a reductant in triggering initial deposition of iron oxides, is uncertain.

Other local lithological controls may also include preferential ironstone replacement along contacts between sediments and quartz porphyry intrusions (e.g. Warrego and Jubilee) or within intraformational sedimentary breccias or slump structures (e.g. Gecko An3 and Peko), which were recognised by Ellision (1960).

Structural controls

Several structural controls are evident on both regional and local scales. The regional slaty cleavage (S1) and shears parallel to S1 which coincide with the moderate to tight, doubly plunging F1 folds are responsible for the east alignment of the majority of ironstone lodes.

There are three significant trends of ironstone-bearing shear zones and faults which were first recognised by Crohn and Oldershaw (1965). The east (090°-100°) trend is most predominant, generally coinciding with the bedding and the penetrative S1 cleavage orientation. Southeast (130°) and east-northeast (070°) orientations are possibly riedel shears related
Figure 6: Tennant Creek goldfield production graph.
to the D1 event, and are responsible for the irregular *en echelon* pattern of ironstones developed due to shear-bedding or shear-S$_1$ intersections.

Some ironstones are subparallel to bedding, and can be traced through several gentle folds 1.5 km northwest of the Memshibah mine (Crohn and Oldershaw 1965) and in subsurface at the Gigantic mine (Giants Reef Mining NL 1993). The main ironstone host bodies at Argo and Peko exhibit both concordant and discordant relationships with the enclosing metasediments (Meade 1986), hence a concordant relationship probably indicates favourable replacement of a bed along a lithological contact, rather than being evidence for syndepositional ironstone formation.

Major shear zones are generally barren, the exception being the Mary Lane Shear which hosts a number of small mineralised ironstones (e.g. Mascot, Hidden Mystery and Mary Ann) including the Ivanhoe deposit which appears to be located at the intersection of the Mary Lane Shear and a northeast trending quartz-filled shear. Many deposits (e.g. White Devil, Black Angel, Argo, Lone Star) are located in smaller east trending brittle-ductile shear zones and faults. Orlando, however, appears to be hosted within a shear which deformed the adjacent sediments in a more brittle manner.

Both Ivanac (1954) and Whittle (1966) noted that many of the gold-bearing ironstones were located at positions of pitch reversal within faulted antilines or drag folds. These tight, parasitic F1 anticlinal folds are often doubly plunging (20-40°) in nature due to the shearing component which accompanied D1. Several larger subsurface deposits were also found to be situated in anticlinal structures (e.g. Juno, White Devil, Gecko, Peko and Argo), which highlights these as favoured loci for ironstone emplacement.

Post-ore thrust faulting with displacements up to 170 m have been encountered in several deposits (e.g. Eldorado, Northern Star, Golden Forty and Lone Star). Other minor faults displace and brecciate the ironstone pods which allowed entry of later Au-Cu-Bi bearing hydrothermal fluids and oxidised meteoric waters.

**Au (±Cu, Bi) mineralisation**

All mined deposits contained economic accumulations of gold, however only six had economically mineable copper and bismuth grades. These latter deposits also produced silver; and minor selenium was obtained from Warrego, Juno and Gecko.

The Au (±Cu, Bi) mineralisation has been found within the ironstone pods and the altered metasediments above, adjacent to and below the ironstones. The ore zones within the ironstone bodies may vary between 10% (e.g. Golden Forty) to greater than 70% (e.g. Nobles Nob) of the volume. Studies on the small to medium sized deposits have shown that ore zonation patterns may be well developed within some ironstones (Figure 7) and absent in others.

Primary gold is commonly concentrated towards the base or in the footwall of the ironstone in a magnetite-chlorite+muscovite-sericite ganguage assemblage. In many of the smaller deposits the gold ore was located along the brecciated ironstone-sediment contact. The gold is typically fine grained and varies from a few microns to 1 mm in size and is closely associated with bismuth. Gold grades are variable, but average 20 g/t (Figure 6) and gold fineness is high (900-1000), except when present in copper orebodies (Wedekind 1990).

Supergene enrichment of gold has played an important part for most of the surface deposits, producing high grade (up to 1500 g/t Au at Nobles Nob) zones above the water table containing small nuggets and coarse flakes disseminated in altered (clay/sericite) and brecciated ferruginous mudstones or in quartz-haematite. Gold flakes and grains on cleavages and bedding planes are also common (Ivanac 1954). The supergene zone is overlain by a leached barren zone which commonly extends 2-3 m below ground level.

Bismuth mineralisation in the primary zone predominantly consists of bismuthinite and minor sulphides (wittichenite, emplitcite, aikinite) and minor seleniferous bismuth sulphosalts (junoite, wittite, guanajuitite) often partially within or above the gold zone in a magnetite-chlorite+muscovite/sericite+talc ganguage. Bismuthite (BiO$_2$CO$_3$) and bismite (Bi$_2$O$_3$) are commonly encountered in the oxide zone of bismuth-bearing deposits.

Bismuthinite may form anhedral aggregates or discontinuous veinlets intergrown with sulphides, silicates and/or carbonates infilling 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 mine) to 1% (Jubilee mine) and averaged 0.3% in the largest bismuth-bearing deposit at Warrego.

Copper mineralisation in the primary zone largely consists of fine to medium grained chalcopyrite which may occur in zones which overlap with that of gold (e.g. Warrego and Orlando), or form relatively discrete zones within a talmagnetite-dolomite ganguage (e.g. Juno, Golden Forty and TC8), or be relatively evenly distributed throughout the massive magnetite with very low grade gold (e.g. Gecko).

Chalcopyrite commonly replaces and infills fractures in the massive magnetite and early formed pyrite. In other cases chalcopyrite is intergrown with magnetite and quartz suggesting co-precipitation of these three minerals (Large 1974). Veinlets of chalcopyrite may also be present within the alteration pipe below the ironstone pod. Bornite occurs as a minor phase, although a bornite-rich copper lode within a talc-dolomite zone has been delineated at TC8 (Giants Reef Mining NL 1993).

Chalcocite and minor covellite are commonly encountered in the supergene ore of copper-bearing ironstones (e.g. Gecko, Peko and TC8) replacing primary chalcopyrite. Malachite and occasionally native copper and chrysocolla are present on surface exposures. Copper grades are generally moderate; grading 2 to 4% Cu.

Other sulphides present in minor to trace amounts include: galena and sphalerite (Orlando, Juno, Peko, Gecko, Ivanhoe); cobaltite (Peko, Gecko, Orlando); molybdenite (Gecko, Peko, White Devil, Golden Kangaroos); tetrahedrite (Peko, Gecko); and enargite (Nobles Nob, TC8).

Pyrite is common within the mineralised ironstones, forming disseminated subhedra or veinlets replacing massive magnetite. Pyrite-rich (up to 90%) zones may form adjacent to (e.g. Argo) or within (e.g. Peko and Gecko) the ironstone lode and can occasionally contain economic concentrations of copper and gold. Pyrrhotite and arsenopyrite were significant
Figure 7  Cross sections showing ore and gangue mineral zonation in the Juno (modified after Large, 1975), TC8 (Hill, 1990), Warrego (modified after Wedekind and Love, 1990), and Nobles Nob (modified after Reveleigh, 1977) orebodies.
sulphide phases in the Peko and West Peko orebodies, but are minor in other deposits.

Uraninite has been identified in several deposits (e.g. Juno, Northern Star, Warrego and Gecko). At Juno, submicroscopic grains of uraninite occur in the magnetite-chlorite pod on the outer edge of the gold zone (Large 1974), while at Northern Star disseminated fine grained (0.02 mm) secondary uraninite is located within chloritised thrust faults (Edwards 1987). Traces of cassiterite and wolframite have been recorded in the stringer zone at Juno (Large 1974) and scheelite in the deeper parts of Argo (Meade 1986).

Early investigations undertaken on the small surface mines concluded that iron oxides deposited first and acted as a chemical trap for later Au-bearing fluids (Woolnough 1936; Owen 1940). The first mineral paragenetic studies on Tennant Creek deposits were completed by Pontifex (1964) and Whittle (1966), both of whom concluded that the mineralisation involved a two stage process with magnetite (±quartz-chlorite-pyrite) pod formation followed by precipitation of Au-Bi-Cu minerals. Most of the studies completed since this time supported two stage paragenesis model, however, some workers have proposed a one stage mineralisation phase (Large 1974; Reveleigh 1977), while others have invoked more than two stages (Wright 1965; Meade 1986; Edwards 1987; Huston et al 1993).

Ore textural relationships and fluid inclusion data (Horvath 1988, Nguyen et al 1989, Huston et al 1993) suggest two distinct hydrothermal phases were necessary to produce the ironstone related Au-Cu-Bi mineralisation. Initially, haematite formed lath-like crystals which were subsequently replaced by fine grained massive magnetite, accompanied by fine grained chlorite, quartz, and minor pyrite also formed at this time. The second phase is dominated by sulphide minerals with Mg-rich and Fe-rich chlorite, muscovite and gold. A minor, late carbonate stage is recognised at White Devil and Gecko (Huston et al 1993), Peko (Wright 1965) and Argo (Meade 1986). Figure 8 summarises the typical mineral paragenesis of the Au (Cu-Bi) deposits.

### Hydrothermal alteration

Many of the Au-Cu-Bi deposits are characterised by intensive chloritisation and varying degrees of dolomite-talc alteration and sericitisation. Minor tourmalisation has been described at Peko Mine (Whittle 1966) and iron-silicate (stilpnomelane-minnesotite-greenalite) alteration phases at West Peko (Skirrow 1993). The alteration exhibits distinct vertical and lateral distribution away from the massive magnetite-chlorite core in the form of an outer envelope of quartz-magnetite-chlorite (e.g. Warrego, White Devil, Gecko) or talc and/or carbonate (e.g. Juno, TC8, Argo) according to Large (1991).

### Chloritisation

Chloritic alteration accompanies development of both the ironstone lodes and Au (Cu-Bi) mineralisation (Wedekind et al 1989; Huston et al 1993). The earlier, fine-grained, foliated chlorite (rippedolite variety) is generally found throughout the ironstone bodies and within the metasediments adjacent to and below the ironstones. The later-formed chlorite is coarser grained, non-foliated and confined to gold zones and in altered metasediments adjacent to the dolomite envelope. Hargreaves (1974) found that chlorite in metasediments was typically Mg-rich, while Fe- and Mg-rich chlorites were present in the Golden Forty orebody, with Fe-rich chlorite common in the upper portion of the chlorite-magnetite zone and in the quartz-haematite zone.

<table>
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<th>MINERAL</th>
<th>OXIDE STAGE</th>
<th>SULPHIDE STAGE</th>
<th>CARBONATE STAGE</th>
<th>SUPERGENE</th>
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<td>Magnetite</td>
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<tr>
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</table>

**Figure 8** Generalised mineral paragenesis for ironstone related Au (Cu-Bi) deposits.

### Dolomite-talc alteration

Dolomite-talc alteration is usually associated with mafic-ultramafic hosted hydrothermal gold deposits (e.g. Vubachikwe mine area, South Africa) or replacement deposits within an iron-magnesium bearing carbonate bed (cf. Homestake mine, USA) rather than deposits hosted within a flysch sequence. In the Tennant Creek deposits, dolomite-talc alteration can be present as discrete envelopes up to 15 m wide, above and adjacent to the massive ironstone pods (e.g. Juno, Argo, TC8, Golden Forty, Northern Star and Gecko An3) or as irregular zones adjacent to the main ore zone (e.g. Orlando Ivanhoe, White Devil and Peko).

Fine grained foliated aggregates of talc with fine grained disseminated magnetite commonly form the talc-magnetite zone which tends to form above and adjacent to the massive magnetite-chlorite (Juno, TC8, Argo) or magnetite-quartz
zone (Golden 40, Nobles Nob). Anthophyllite is present 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). The talc (anthophyllite) appears to be the further
alteration product of early hydrothermal chloride which
experienced later intense magnesian alteration and partial
desilicification.

Dolomite-rich lithologies completely surround the talc-
magnetite zone to form an outer alteration shell which
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,
is typically coarse grained and forms late cross-cutting veins,
massive aggregates and breccias replacing wallrocks.
Dolomitic zones are best developed adjacent to ‘haematitic
shale’ units (e.g. Argo, Juno and Gecko An 3) and appear to
form by the carbonation and desilicification of talc-rich
lithologies.

**Sericite-muscovite alteration**

Sericite-muscovite alteration is common in gold zones.
Disseminations, irregular patches and veinlets of fine to
course grained sericite, are common in oxidised orebodies
(e.g. Nobles Nob, Rising Sun, Patties, Joker, Kiora), while
disseminated, non-foliated coarse grained muscovite flakes
within massive magnetite-chlorite predominates at depth (e.g.
Warrego, TC8, Golden Forty, Orlando).

**Ore genesis**

**Previous models**

There have been at least six different genetic models proposed
for the ironstone-related Au (Cu-Bi) mineralisation at Tennant.
Creek. The earliest theories suggested that both iron oxides
and Au-Cu-Bi metals were magmatic in origin and probably
derived from granitic and porphyry intrusives (Woolnough
1936; Owen 1940; Ivanac 1954; Crohn and Oldershaw 1965).
Elliston (1966) proposed that the ore-forming metaliferous
brines were derived from de-watering and remobilisation of
flysch sediments during diagene.

Pontifex (1964), Whittle (1966) and Dunnet and
Harding (1967) suggest that basic intrusives (gabbro and
dolerite) are the source of the mineralising fluids. Revelegh
(1977) favours metal-rich hydrothermal fluids derived from
a series of blind intrusions which also produced the
lamprophyre dykes. Large (1974, 1975) believed that the
mineralising fluids were derived from connate water released
from argillaceous sediments in the vicinity of granitic and
porphyry intrusives. Norris (1980), Main et al (1990) and
Goulevitch in Giants Reef Mining NL (1993) suggest that
the mineralised ironstones may represent remobilised,
sediment host, massive oxide deposits which were
originally formed at or close to the sea floor from metal-
rich solutions.

Wedekind et al (1989), Nguyen et al (1988), Wall and
Valenta (1990) and Skirrow and Walshe (1993) suggest a two-
stage process involving early ironstone formation from
connate brines followed by the introduction of hydrothermal
sulphur-bearing Au (Cu-Bi) fluids. Several theories on the
nature, source and the precipitation controls of the ironstone
and Au (Cu-Bi) fluids within the two-stage model are proposed.

Huston et al (1993) recognised three paragenetic stages in
a study of the Gecko and White Devil deposits involving:
(1) early syn-deformational ironstone formation stage from
low temperature (250°C) connate brines; (2) introduction of
syn- to post-deformational higher temperature (350°C)
sulphide-bearing Au-Cu-Bi fluids with variable magmatic and
connate components; and (3) a late, minor carbonate stage.

**Fluid inclusion studies**

Fluid inclusion studies have been undertaken by various
workers on several deposits as shown in Table 6. There are
substantially different interpretations on the temperature of
the magnetite stage fluids and the salinity of sulphide fluids.
suggest that the oxide stage fluids were relatively lower
temperature (200-250°C) and moderately saline (~20 wt%
NaCl eq) compared to the sulphide stage fluids which were
higher in both temperature (300-350°C) and salinity (~20-
40 wt% NaCl eq). In contrast, Nguyen et al (1989) and
Skirrow and Walshe (1993) suggest that magnetite stage fluids
were relatively higher in temperature and salinity compared
to sulphide stage fluids.

Quartz-magnetite O-isotope geothermometry has been
used by both Skirrow and Walshe (1993) and Huston et al
(1993) to support their fluid inclusion temperatures for
ironstone formation. Gas analysis of vapour-rich inclusions
from Juno, TC8, Gecko and Warrego ore zones indicate the
presence of N2, CO and CH4 (Zaw et al 1994a and b). Vapour-
rich inclusions from West Peko contain significant amounts of
N2 and CH4 (Skirrow and Walshe 1993).

**Stable isotope studies**

Oxygen-hydrogen isotope studies (Large and Wedekind 1987;
have been undertaken on several mines in order to identify
the source of the mineralising fluids (Figure 9). The data
suggests that the ‘barren’ ironstones formed from formational
waters, and a second fluid source, either metamorphic or
magmatic, was responsible for the economic mineralisation

Large and Wedekind (1987) and Wedekind (1989) have
documented the presence of narrow δ18O and δD depletion
haloes around the Argo and Warrego orebodies, and the δ18O
and δD depletion within a ‘barren’ ironstone (Explorer 28).
Oxygen isotope geothermometry on quartz-chlorite pairs
from mineralised ironstone (Wedekind 1989) gave
temperatures of around 300-350°C, which is consistent with
temperatures obtained via fluid inclusion. Temperatures
determined from chalcopyrite-bismuthinite pairs gave a range
of 330 to 430°C (Wedekind and Adrichem 1987; Huston et
al 1993).

Carbon-oxygen isotope studies on carbonates from Juno
(Large 1974), White Devil and Argo (Huston 1991) mines
indicate large variations in carbon and oxygen isotope ratios,
but a positive trend is seen in late stage calcite from Argo
(Figure 10) which may indicate mixing of multiple δ13C and
δ18O sources. Huston (1991) suggests that mixing involved a
magmatic fluid enriched in δ13C and depleted in δ18O, with a
metamorphic fluid depleted in $\delta^{13}$C and enriched in $\delta^{18}$O.

Sulphur isotope studies have been conducted on several mines, including Juno, White Devil, Gecko, Argo and Warrego (Large 1974; Nguyen 1987; Wedekind and Adrichem 1987; Wedekind 1988 and Huston et al. 1993). The variation of $\delta^{34}$S values is significant in most deposits (Figure 11) but strong modes are apparent at Gecko and Argo (between -1 and 1%), Warrego (2-3%), and at White Devil (2.5-4.5%) which is compatible with a probable magmatic source for at least some of the sulphur in these deposits. The variation in $\delta^{34}$S values in the deposits suggests mixing of connate $\text{SO}_4$ and magmatic $\text{H}_2\text{S}$ (Large 1991), or fractionation during either reduction of $\text{SO}_4$ (Huston et al. 1993), or oxidation of $\text{H}_2\text{S}$ in ore fluids (Skirrow 1993).

A consistent zonation is also apparent with lower $\delta^{34}$S in the Au-rich zones and higher $\delta^{34}$S within Cu-rich zones. At Warrego $\delta^{34}$S increases from the footwall gold pod to the outer hangingwall margin of the orebody, reflecting the temperature gradient of the hot solutions passing through the core of the orebody (Wedekind 1988). An antipathetic correlation between gold grade and $\delta^{34}$S, and the co-variation of pyrite and chalcopyrite with gold at Warrego suggests contemporaneous deposition of gold with sulphides (Wedekind 1988).

Lead isotope analyses show a significant difference in the $^{206}$Pb/$^{207}$Pb signature of Au-bearing ironstone and haematite shales which suggests that magnetite-haematite shales is not the local source of the economic mineralisation (Gulson et al. 1987).

**Age of mineralisation**

The slaty S1 cleavage, tight F1 antilines and shears related to these structures control the location of ironstones. Chlorite within the alteration envelope associated with ironstone emplacement is commonly foliated and the ironstone pods have undergone varying degrees of brittle-ductile deformation which suggests emplacement syn-D1. Chlorite and muscovite closely associated with Au (Cu-Bi) are commonly non-foliated, suggesting a late or post-D1 emplacement. Structural evidence at White Devil (Nguyen 1987) suggests that the mineralisation accompanies D2.

![Figure 9](image_url)  
**Figure 9** $\delta^{18}$OSMOW-$\delta^{18}$OSMOW diagrams for chloride separates from Au (Cu-Bi) deposits in Tennant Creek (modified after Large, 1997)  
Black (1977) was able to date muscovite from Juno, Warrego, Golden Forty and Nobles Nob using Rb-Sr methods which suggested a mineralisation age of 1810 Ma. More recent $^{40}$Ar/$^{39}$Ar analyses of hydrothermal muscovite from Peko, Argo, Nobles Nob and Juno suggest a minimum age for mineralisation between 1825-1830 Ma (Compston and McDougall 1994).

For isotopes from Juno, Argo, Gecko and Peko gave model ages of 1819-1834 Ma (Warren et al. 1995). Significant igneous activity in the region about this time is recorded in the small unnamed dioritic intrusives (1821±7 Ma, SHRIMP U-Pb) northwest of Tennant Creek, metamorphosed and highly deformed intrusives (1829±8 Ma and 1827±9 Ma, SHRIMP).

![Figure 10](image_url)  
**Figure 10** $\delta^{13}$CPDB-$\delta^{18}$OSMOW diagrams for carbonate separates from Au (Cu-Bi) deposits in Tennant Creek (modified after Large, 1991).
the Pine Creek Inlier implies that the turbidite sequence overlies carbonate-bearing sequences which could generate saline iron-bearing brine during diagenesis. The iron oxides precipitated in dilution zones and commonly replaced highly strained and chemically reactive shale units to form irregular massive pods and pipes (Figure 12).

The Au-Cu-Bi minerals and related alteration minerals are late-tectonic and infill fractures and replace zones in the ironstone. The ore forming fluids were mesothermal and predominantly metamorphic in character. Variations in ore fluid chemistry and ore types in the district could be due to local geological conditions (e.g. presence of carbonaceous shale or distance from ‘syn-ore’ magmatic intrusives) which influenced the degree of mixing between deeper, possibly magmatic derived ore fluids and regional connate brines.

Comparisons

The Tennant Creek style of Au-Cu-Bi mineralisation is quite unique, with its close relationship with the ironstones. This style, however, does share some similarities with Proterozoic iron oxide (Cu-U-Au-REE) deposits, Precambrian BIF-hosted gold deposits and syenitic felsic-hosted Au-bearing replacement type deposits (Perenzi 1994).

The Palaeoproterozoic (1900 Ma) hard iron ores of central Michigan (Cannon 1976) appear to have formed by similar processes to those which produced the ironstones at Tennant Creek. In this case, the massive magnetite bodies have concentrated where the upper jasperite unit of the Negaunee Iron Formation has oxidised iron-bearing metamorphic fluids. Flow of the fluids was concentrated along structurally and stratigraphically controlled channelways, and the iron ores are now found in favourable structural (e.g. along crests of plunging anticlines at the Greenwood mine) and stratigraphic traps.

The Hail gold mine in South Carolina, USA (Hayward 1992), Fortnum gold mine in Western Australia (Hill and Cranney 1990), Starr Au-Cu deposits in northwestern Queensland (Rotherham 1997) and Peak gold mine in Cobor New South Wales (Hillman and Scott 1990) are examples of felsic-hosted Au-bearing replacement-type deposits, which appear to represent the closest genetic analogs to the Tennant Creek deposits. These deposits are located in extensional cratonic basins within a felsic sequence which has undergone multiple deformation and greenschist metamorphism.

A combination of structural and stratigraphic controls have produced competency and chemical contrasts between host and adjacent lithologies which triggered the precipitation of Au-bearing fluids. Magnesium (chloritic) and potassium (sericite) hydrothermal alteration events accompanied the introduction of ore fluids which were probably derived from both metasediments and felsic magma at depth.

Potential therefore exists for Au (+Cu,Bi) mineralisation in the Tennant Creek goldfield to be hosted within lithologies other than ironstone. For example, early phases of the felsic porphyry intrusions which have undergone some brittle deformation during D1 and are located near major faults.

Au-bearing vein quartz deposits

There are only three known Au-bearing vein quartz deposits in TENNANT CREEK. The Last Hope mine (LU 8063) has

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Figure 11 Histograms showing the variation in $\delta^{18}$CDT for some ironstone-related Au (Cu-Bi) deposits (modified after Large, 1991).

U-Pb) within Wundiri Formation southwest of Tennant Creek and felsic volcanic (1818 ± 10 Ma, SHRIMP U-Pb) and granophyre intrusives within the Davenport province (age dates from AGSO OZCHRON database).

Genetic model

The preferred model presented here is based on previous models (Nguyen et al 1989; Wedekind et al 1989; Wall and Valenta 1990; Huston et al 1993) and recent regional metallocenic work conducted in the Davenport province by NTGS. The ironstone related Au-Cu-Bi mineralisation appears to be the product of a two stage hydrothermal process involving an early iron oxide stage followed by a Au-bearing sulphide stage (Figure 12).

Field relations, fluid inclusion and stable isotope studies suggest that the ironstones formed during the deformation and metamorphism of the Warramunga Formation from moderately saline connate brines. Regional equivalence of the Warramunga Formation and Mount Bonnie Formation in
OXIDE STAGE: During diagenesis and early deformation iron oxides were remobilised from sediments and magmatic intrusives, then concentrated in structural and stratigraphic traps to form massive pods and pipe-like bodies.

SULPHIDE STAGE: Development of extension fissures in ironstones within ductile chloritic shear zones. Au-Cu-Bi bearing fluids derived from granites precipitate within fractured ironstones and adjacent altered metasediments.

Figure 12 Sketch illustrating the development of ironstone-related Au (Cu-Bi) mineralisation at Tennant Creek (modified after Huston et al. 1993).
produced 12.9 kg Au derived from bedding-parallel quartz veins located at the contact between metasediments of the Wundirgi Formation and a dolerite sill (Ivanac 1954). The Bull Pup mine (LU 8162) has produced 1.7 kg Au from quartz veins in faulted arcnite of the Wundirgi Formation (Tapp 1966). At the Dolomite mine (MU 1725; previously Pinnacles Extended) about 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 vein quartz deposits in the Last Hope, Bull Pup and Dolomite mine areas. At the Last Hope mine (also known as Moonlight Rockhole) gold was discovered in 1874 and is in the form of small grains and nuggets up to 32 ounces (~1 kg) in the eluvials and alluvials near the hard-rock workings (Ivanac 1954). The alluvial field was re-discovered in 1936 and some 16.7 kg Au was extracted by prospectors in the subsequent two years (Balfour 1989). Gold slugs 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 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 Tasman (47 g) according to Balfour (1989) and NTDME mineral production records.

**NOTES ON GROUNDWATER OCCURRENCE**

**Introduction**

Cambrian rocks of the Georgina and Wiso Basins contain significant aquifers. Important aquifers also occur as Cainozoic palaeo-channels incised into Palaeoproterozoic rocks at Kelly Well. Over 700 bores are known to have been drilled throughout the sheet. In some areas there has been relatively intense drilling for water supply investigation. In addition there are scattered bores drilled for pastoral, mine and Aboriginal water supply. Locations are shown in Figure 13.

**Rainfall**

Rainfall occurs mostly in the summer months. The most notable feature of the rainfall is its variability. In all months the standard deviation is about the same as or greater than the mean. Rainfall statistics for Tennant Creek Post Office are summarised in Table 7, p41 and Figures 14 and 15.

**Surface Drainage**

Numerous minor streams drain from the low hills in the central part of the sheet and form large drainages such as Tennant Creek, Phillip Creek and Gosse River. These creeks flow for only a short time after rain and are dry for most of the year. The only gauging station in the area is on Kelly Creek. This has not been rated but a useful indication of the frequency of large flows is given by plotting the time for which flows exceed 2 m (Figure 16). It can be seen that large flows occur at intervals of some years in the period January to March.

**PALAEOPROTEROZOIC**

The Palaeoproterozoic rocks are generally poor aquifers. There is insufficient data to report drilling results for each unit. In general the yield of a particular bore will be determined by the structural setting and lithology rather than its stratigraphic position. Hydrogeological characteristics of the Proterozoic rocks are summarised in Table 8, p41.

Some sandstone units (such as Short Range Sandstone) are good aquifers where conditions are right to produce open joints.

**Warramunga Formation and Flynn Subgroup**

Bores in these rocks are mostly saline, with values over 5,000 mg/L, although salinities as low as 200mg/l are known from near the Old Telegraph Station. Yields are generally small. The fact that the Peko Mine, with several kilometers of shafts and drives, was pumped at less than 5.3l/s (Bracewell et al 1962) demonstrates low permeability of the Warramunga Formation.

**Granites**

As expected granites have very low permeability. In the headwaters of Gosse River extensive drilling has yielded little water. Where the granites are deeply weathered, as in the Kelly Well and Cabbage Gum areas, the weathered zone may be a minor aquifer.

**PALAEOZOIC**

Most knowledge of the Wiso Basin is derived from the Tennant Creek West investigation (see below). Peko-Wallsend formerly extracted water from a borefield on the eastern margin of the Basin. Aquifers are summarised in Table 9, p41.

Little drilling has been done in the Georgina Basin on TENNANT CREEK, largely because much of it has been Vacant Crown Land until recently. The stratigraphy of the Georgina Basin is described by Smith (1972) and this report.

Water quality is generally good and substantial supplies are available where there is sufficient thickness of saturated limestone. Knowledge of the Basin is summarised in Table 10, p41.

**CAINozoIC**

The aquifers that supply Tennant Creek township are of Cainozoic age. Except for unweathered sandstone and siltstone underneath Cainozoic sediments at Kelly Well, Cainozoic units generally are highly weathered and any primary permeability has been destroyed. Permeability is due to vugs in silcrete and silicified siltstone. As noted above some aquifers in Palaeoproterozoic rocks are a result of weathering and might be better classified as Cainozoic aquifers. Cainozoic aquifers
have been found in poorly defined drainages at Kelly Well and Cabbage Gum, but not associated with the Gosse River.

**TENNANT CREEK WATER SUPPLY INVESTIGATIONS**

From 1955 onwards a series of investigations from Tennant Creek water supply have been conducted.

**Cabbage Gum Basin**

This is a small basin of 6.5 km² and a saturated thickness of 16 m. The following account is summarised from Bracewell et al (1962). Development commenced with well-sinking in 1955. Aquifers occur both in the sediments and in fractured parts of the underlying weathered zones. With one exception weathered basement aquifers occur only beneath Cainozoic aquifers. A block of Flynn Subgroup is associated with higher than normal salinity. The best aquifers occur in Cainozoic sediments. These are bounded on the northwest by the shatter belt.

**Kelly Well Borefield**

This area has been investigated since 1965. Presumed Cainozoic sediments occupy a palaeochannel incised into Palaeoproterozoic rocks. Both sediments and weathered basement have been silicified, kaolinised and ferraruginised (Lau 1993). The two silcrete layers in sediments include high-yielding aquifers (Lau 1993). Lau (1993) has interpreted these as groundwater silcrete, whereas much of the overlying material is pedogenic silcrete.

**Gosse River Investigation**

In 1975 an investigation was conducted in the valley of the Gosse River (Verhoeven 1976). About 12 km of seismic refraction was run and 19 bores drilled. The highest yield obtained was 1 l/s (RN11165) from weathered Flynn Subgroup. One bore (RN11048) produced potable water from deeply weathered Flynn Subgroup detected by the seismic work. The investigation found only minor aquifers in weathered Flynn Subgroup and granite.

**Tennant Creek West**

This area was investigated in 1977-8 for a possible expanded water supply for Tennant Creek (Verhoeven and Knott 1980). Aquifers identified were a sandstone unit in the Point Wakefield Beds, the Montejinni Limestone and a sandstone unit of uncertain age. Correlation between this area and Kelly Well is uncertain.

**Eastern Wiso**

Peko Mines NL investigated the eastern edge of the Wiso Basin 30 km west of Warrego Mine. Large supplies were obtained from the Montejinni Limestone, which had a transmissivity in excess of 150 m²/day (Verhoeven and Knott 1980).

**RECHARGE**

Information about recharge is limited to observations on the Kelly Well Borefield. Figure 16 shows a hydrograph for an observation bore in the Kelly Well Borefield. It can be seen that in 11 years of recording nearly all recharge occurred in two events 1976 and 1977, with minor events in 1981 and 1993. Flows in Kelly Creek are plotted on the same graph and it can be seen that recharge events correlate with large flow events.

Childs (1989) proposed the following mechanism: Flows less than 2.28 m at the gauging station dissipate before reaching the borefield. The longer flows exceed this height the more water will flood across the borefield.

Elsewhere, information on recharge is more due to speculation than observation. Substantial recharge is likely to occur on other flood-outs similar to Kelly Creek. As suggested by Randal (1973) recharge from rainfall may occur through sandplain and light-textured soils. Minor recharge may occur to the Palaeoproterozoic aquifers directly through jointed outcrops.

**HYDROCHEMISTRY**

Figure 17 shows contours of total dissolved solids. It can be seen that highest salinities occur in Palaeoproterozoic rocks. Durov plots were prepared using all analyses on the sheet (Figure 18). Plots for individual areas are broadly similar. All the anion plots are close to a curved line starting from near the bicarbonate corner and trending toward 25% sulphate, 75% chloride. This is similar to tri-linear plots presented by Randal (1973). The cations trend from a roughly equal mix of calcium and magnesium toward the sodium corner. Unlike Randal’s (1973) plot the analyses do not plot on the “dolomite line”, but on the magnesium side of it. This is probably a consequence of the higher salinities on TENNANT CREEK causing calcium carbonate to precipitate.
Figure 13  Bores on Tennant Creek.

Figure 14  Monthly rainfall at daily read gauge 15087 (Post Office) 1874 to 1993, omitting years for which data is missing.
Figure 15  Annual rainfalls at Tennant Creek (DR15087 - Post Office, DR15135 - Airport).

Figure 16  Hydrograph in the Kelly Well Borefield and creek flows.
Figure 17
Contours of Total Dissolved Solids in mg/l

- Bores with TDS values

Note that contours are also based on bores up to approx 27 km outside the map boundaries.
868 analyses
Analyses with ionic imbalances above 5% were deleted

Each analysis is represented by four points on the diagram. One on the triangular field on the left of the diagram shows the relative proportions of the three major anions. The triangular field at the top of the diagram shows the proportions of the major cations. Chloride is plotted against calcium on the square field adjacent to the two triangular fields. On the rectangular field below this total ions are plotted against calcium, to allow the trends in the two triangular fields to be related to salinity.

Figure 18  Durov Plot for Tennant Creek Sheet. This plot shows all suitable analyses for bores on the Tennant Creek sheet.
### Table 7  Rainfall at Post Office in mm, 1874 to 1993, omitting years with incomplete record.

<table>
<thead>
<tr>
<th>Month</th>
<th>Mean</th>
<th>Median</th>
<th>Minimum</th>
<th>Maximum</th>
<th>25th percentile</th>
<th>75th percentile</th>
<th>Standard deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jan</td>
<td>90</td>
<td>62</td>
<td>0</td>
<td>390</td>
<td>17</td>
<td>145</td>
<td>85</td>
</tr>
<tr>
<td>Feb</td>
<td>85</td>
<td>61</td>
<td>0</td>
<td>380</td>
<td>15</td>
<td>130</td>
<td>88</td>
</tr>
<tr>
<td>Mar</td>
<td>51</td>
<td>20</td>
<td>0</td>
<td>373</td>
<td>6</td>
<td>60</td>
<td>74</td>
</tr>
<tr>
<td>Apr</td>
<td>14</td>
<td>2</td>
<td>0</td>
<td>196</td>
<td>0</td>
<td>14</td>
<td>29</td>
</tr>
<tr>
<td>May</td>
<td>12</td>
<td>0</td>
<td>0</td>
<td>172</td>
<td>0</td>
<td>9</td>
<td>27</td>
</tr>
<tr>
<td>Jun</td>
<td>7</td>
<td>0</td>
<td>0</td>
<td>83</td>
<td>0</td>
<td>6</td>
<td>15</td>
</tr>
<tr>
<td>Jul</td>
<td>6</td>
<td>0</td>
<td>0</td>
<td>94</td>
<td>0</td>
<td>0</td>
<td>16</td>
</tr>
<tr>
<td>Aug</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>83</td>
<td>0</td>
<td>1</td>
<td>9</td>
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<tr>
<td>Sep</td>
<td>7</td>
<td>0</td>
<td>0</td>
<td>71</td>
<td>0</td>
<td>5</td>
<td>14</td>
</tr>
<tr>
<td>Oct</td>
<td>15</td>
<td>10</td>
<td>0</td>
<td>78</td>
<td>1</td>
<td>21</td>
<td>18</td>
</tr>
<tr>
<td>Nov</td>
<td>27</td>
<td>20</td>
<td>0</td>
<td>106</td>
<td>8</td>
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<td>24</td>
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<td>Dec</td>
<td>50</td>
<td>39</td>
<td>0</td>
<td>216</td>
<td>16</td>
<td>70</td>
<td>46</td>
</tr>
<tr>
<td>Yearly (1)</td>
<td>367</td>
<td>323</td>
<td>112</td>
<td>851</td>
<td>226</td>
<td>485</td>
<td>169</td>
</tr>
</tbody>
</table>

(1) Based on a September to August water year.

Note: The earlier part of the record is presumably for the Telegraph Station.

### Table 8  Hydrogeology of Proterozoic Rocks.

<table>
<thead>
<tr>
<th>Unit</th>
<th>Lithology</th>
<th>Hydrogeological Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Attack Creek Formation</td>
<td>Sandstone, feldspathic sandstone, siltstone, shale</td>
<td>2 failures 120 m deep</td>
</tr>
<tr>
<td>Short Range Sandstone</td>
<td>Felspatic sandstone, siltstone and shale</td>
<td>3 successes out of two attempts</td>
</tr>
<tr>
<td>Morphett Creek Formation</td>
<td>Quartz sandstone, feldspathic sandstone, basalt</td>
<td>1 success, 1 attempt</td>
</tr>
<tr>
<td>Hayward Creek Formation</td>
<td></td>
<td>6 failures out of six attempts</td>
</tr>
<tr>
<td>Granites</td>
<td></td>
<td>Very low yields from fresh granite. Weathered granite may be an aquifer where the kaolin content is relatively low (2)</td>
</tr>
<tr>
<td>Warramunga Formation</td>
<td>Siltstone and greywacke</td>
<td>Very low permeability. Bores yield small supplies of saline water. (2) (Bracewell et al. 1962)</td>
</tr>
</tbody>
</table>

### Table 9  Wiso Basin Hydrogeology.

<table>
<thead>
<tr>
<th>Unit</th>
<th>Lithology</th>
<th>Hydrogeological Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Point Wakefield Beds</td>
<td>Siltstone and sandstone</td>
<td>The middle sandstone unit is one of the major aquifers in the Tennant Creek West area. Primary permeability (1). The sandy silstones contain minor aquifers</td>
</tr>
<tr>
<td>Lothari Hill Sandstone</td>
<td>Sandstone</td>
<td>Good aquifer (1)</td>
</tr>
<tr>
<td>Hooker Creek Formation</td>
<td>Dolomitic siltstone, siltstone, silty dolomite</td>
<td>Minor aquifers in the dolomitic siltstone (1)</td>
</tr>
<tr>
<td>Montejinni Limestone</td>
<td>Limestone</td>
<td>Good aquifer (3)</td>
</tr>
<tr>
<td>Gun Hill Ridge Formation</td>
<td>Chert, chert breccia, limestone</td>
<td>Moderate aquifer in the Georgina Basin, not known to have been tested in the Wiso Basin</td>
</tr>
<tr>
<td>? Proterozoic</td>
<td>Reddish purple sandstone</td>
<td>Good aquifer, limited extent (2) (2)</td>
</tr>
</tbody>
</table>

(1) From Verhoeven and Knott (1980)  
(2) From Verhoeven and Russell (1981)  
(3) Randell (1973)  

### Table 10  Georgina Basin Hydrogeology.

<table>
<thead>
<tr>
<th>Unit</th>
<th>Lithology</th>
<th>Hydrogeological Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anthony Lagoon Beds</td>
<td>Chert, chert breccia, limestone</td>
<td>Probably above water table in this area</td>
</tr>
<tr>
<td>Gun Hill Ridge Formation</td>
<td>Basalt</td>
<td>Moderate aquifer</td>
</tr>
<tr>
<td>Helen Springs Volcanics</td>
<td></td>
<td>Too thin and weathered to be an aquifer</td>
</tr>
<tr>
<td>Rising Sun Conglomerate</td>
<td></td>
<td>Not known to be an aquifer</td>
</tr>
</tbody>
</table>


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APPENDIX

DEFINITIONS OF EXISTING STRATIGRAPHIC UNITS

Definitions of all existing Cambrian lithostratigraphic units in the Wiso Basin are given below. Although a unit of long standing, the Montejenni Limestone is only now formally defined here. For the remaining units, the unpublished definitions of P.J. Kennewell, held by the Central Register of Australian Stratigraphic Names, Australian Geological Survey Organisation (AGSO), Canberra, are published here for the first time (with stylistic modifications only).

MONTJEJNI LIMESTONE (P.D. Kruse, after Traves 1955)

Derivation of name: ‘Montejenni’ homestead (lat. 16°39'S, long. 131°46'E on VICTORIA RIVER DOWNS), near which the limestone is exposed in hills 7-10 m high.

Distribution: Throughout Wiso Basin. Outcrop in DELAMERE, VICTORIA RIVER DOWNS, DALY WATERS, WAVE HILL, BEETALOO, BIRRINDUWU*, WINNECKE CREEK, SOUTH LAKE WOODS, HELEN SPRINGS, TANAMI*, TANAMI EAST*, GREEN SWAMP WELL*, TENNANT CREEK, MOUNT SOLITAIRE* (* as undifferentiated Montejenni Limestone and Hooker Creek Formation only). Subcrop proven or inferred in LARRIMAH, NEWCASTLE WATERS, LANDER RIVER, BONNEY WELL.

Partial type section: Base (boundary stratotype) exposed in a partial section at 'Montejenni' homestead (lat. 16°39'S, long. 131°46'E on VICTORIA RIVER DOWNS; Traves 1955), at base of 7-10 m high limestone hills resting unconformably on Antrim Plateau Volcanics (Lower Cambrian).

Reference section: Top (boundary stratotype) at 185.9 m depth in a near-complete section in BMR drillhole Green Swamp Well 6 (GREEN SWAMP WELL; Kennewell and Huleatt 1980; lat. 19°20'S, long. 132°59'E),

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at top of grey-buff dolostone. Boundary coincides with
defined base of conformably overlying Hooker Creek
Formation. Cores and cuttings stored at the Australian
Geological Survey Organisation, Canberra.

Lithology: Grey limestone and dolostone (laminated, stylolitic,
mottled, bioclastic, ooid, ribbon, may include nodular
chert); yellow-grey cryptomicrobial laminitae; grey
calcareous mudstone; maroon siltstone. Nodular
evaporites in several lithotypes. In places, basal breccia
of reworked clasts in dolomitic matrix. At surface: grey
chert and quartzite, tabular brown chert, silicified
bioclastic coquina, silicified nodular evaporite.

Thickness: Maximum 151.2 m in a near-complete section
in BMR drillhole Green Swamp Well 6 (Kennewell
and Huleatt 1980).

Relationships and boundary criteria: Unconformably
overlies Antrim Plateau Volcanics or its equivalents
(Lower Cambrian), or where this is absent, various
Proterozoic units. Basal beds are limestone, or breccia
of reworked clasts in carbonate-bearing matrix.
Conformably overlain by Hooker Creek Formation, or
where this is absent, unconformably overlain by Point
Wakefield beds (late Templenoton-Floran, Middle
Cambrian) in eastern Wiso Basin, or undifferentiated
Lower Cretaceous rocks in northern Wiso Basin.
Boundary with Hooker Creek Formation is a contact
between grey dolostone below and maroon siltstone
above.

Age and evidence: Fauna includes trilobites Redlichia
and Xystroida, hyoliths, lingulate (includingacrothelid)
and orthide brachiopods, echinoderm plates, sponge
spicles, chancellorids, molluscs and problematic
Redlichia together with Xystroida indicates an
Ordovician-early Templenoton (early Middle Cambrian)
age (Travis 1955; Milligan et al. 1966; Randal
and Brown 1967; Randal 1973).

Synonymy: Chewings (1931) included the formation in the
Winnecke Creek Tabeland formation. Previously
mapped as Gum Ridge Formation by Milligan et al.
(1966), Brown and Randal (1969), Randal and Brown
(1969), Mendum and Tonkin (1976) and Dodson
and Gardner (1978) in the eastern Wiso Basin; the
Gum Ridge Formation is now restricted to the Georgina
Basin. Montejinni limestone of Schmidt et al. (1976);

HOOKER CREEK FORMATION (P.J. Kennewell 1977)

Derivation of name: Hooker Creek community, lat. 18°35'S,
long. 130°37'E, WINNECKE CREEK.

Distribution: Exposed over large areas of WINNECKE
CREEK and extending in the subsurface under large
parts of SOUTH LAKE WOODS, GREEN SWAMP
WELL and TANAMI EAST. Distribution in the northern
Wiso Basin is not known. Its extent cannot be defined
exactly, as it is impossible to distinguish dolostone of
this formation from the Montejinni Limestone in some
areas.

Type section: In stratigraphic drillhole BMR Green Swamp
Well 6 (lat. 19°20'S, long. 132°39'E) between 24.4
and 185.9 m (Kennewell and Huleatt 1980). Four cores
and cuttings at 3 m intervals from this section are stored
at the Australian Geological Survey Organisation,
Canberra. The log of the type section is as follows:
24.4-30.5 m: calcareous siltstone: grey, grey quartz grains,
grades to slightly calcareous in parts, siliceous matrix.
30.5-57.9 m: sandstone: white, quartzose, very fine-
to fine-grained, subangular to subrounded, dolomitic
or siliceous matrix; interbedded with siltstone: red-brown,
grey-green or white-grey, micaceous or dolomitic in parts,
siliceous.
57.9-86.8 m: dolostone: buff-brown, finely crystalline;
interbedded with siltstone: dolomitic, red to grey,
micaceous in parts.
86.8-137.5 m: siltstone: dolomitic to slightly
dolomitic, red-brown, red, pink or grey, micaceous;
more interbeds of dolostone: cream, very fine-grained.
137.5-146.9 m: dolostone: grey-white, finely
crystalline.
146.9-185.9 m: siltstone: dolomitic, red or buff-
brown, micaceous.

Lithology: Siltstone: dolomitic, red, laminated, bioturbated,
micaceous; dolostone: white, finely crystalline, hard,
microbial structures in parts; rare sandstone: red-
brown, fine-grained, silty and clayey. Typical red-brown
colour in outcrop probably due to weathering.

Thickness: Maximum recorded thickness 161.5 m in type
section BMR Green Swamp Well 6.

Relationships and boundary criteria: Conformably
overlies Montejinni Limestone with gradational
contact. Conformably overlain by Lothari Hill Sandstone
with gradational contact. May form lower
level of upper Montejinni Limestone.

Age and evidence: Fauna includes hyoliths; Acrotreta,
Acrothela and lingulate brachiopods; echinoderm
ossicles; and Redlichia and psychoparid trilobites.
Numerous small onkoids also present. The fauna
indicates an early Middle Cambrian (Ordovician-early
Templenoton) age (J. Gilbert-Tomlinson, BMR, pers.
comm. 1976).

Synonymy: Chewings (1931) included the formation in the
Winnecke Creek Tabeland formation. Milligan et al.
(1966) included the formation in the Merrina Beds.

LOTHARI HILL SANDSTONE (P.J. Kennewell 1977)

Derivation of name: Lothari Hill, lat. 18°50'12"S, long.
131°29'06"E, WINNECKE CREEK.

Distribution: Poorly exposed over northern, central and
southwestern TANAMI EAST, the extreme south of
WINNECKE CREEK and the northern half of GREEN
SWAMP WELL. Its southwestern extent into the Lander
Trough on LANDER RIVER is not known.

Type section: In stratigraphic drillhole BMR Green Swamp
Well 4 (lat. 19°16'5", long. 132°39'E), from the surface
to 94 m depth (Kennewell and Huleatt 1980). One core,
and cuttings at 3 m intervals are stored at Australian
Geological Survey Organisation, Canberra. The section
Lithology: Sandstone: typically red-brown in outcrop (probably due to lateritisation), white in parts, poorly sorted, fine-grained, clayey, grades to clayey siltstone and claystone in parts, contains vertical burrows, desiccation cracks, and although thickly bedded and even-textured, some low-angle cross-bedding is present.

Thickness: Maximum recorded thickness 94 m in BMR Green Swamp Well 4.

Relationships and boundary criteria: Conformably overlies Hooker Creek Formation with gradational contact, as shown by cuttings from BMR stratigraphic drilling and as exposed on Lothari Hill. Unconformably overlain by Point Wakefield beds in BMR Green Swamp Well 3, by Lake Surprise Sandstone in southwestern TANAMI EAST and by Buchanan Hills beds at Buchanan Hills. Upper contact otherwise eroded and covered by Cainozoic deposits throughout most of the Wiso Basin.


POINT WAKEFIELD BEDS (P.J. Kennewell 1977)

Derivation of name: Point Wakefield, lat. 19°59'S, long. 133°21'E, GREEN SWAMP WELL.

Distribution: Poorly exposed in low rises in northern GREEN SWAMP WELL and SOUTH LAKE WOODS. May extend as belt about 25 km wide around northern Lander Trough, concealed beneath Cainozoic deposits including extensive calcarete on BONNEY WELL, GREEN SWAMP WELL and TANAMI EAST. Its extent in the northern Wiso Basin, and in the Lander Trough, where it is concealed by younger sediments, is not known.

Reference section: BMR Green Swamp Well 1 (lat. 19°25'S, long 133°30'E), from 0.7 to 25.9 m depth. Brown and white claystone, calcareous in parts, silty in parts, is the dominant rock type, with a few chert beds (possibly resulting from weathering).

Lithology: Claystone: calcareous in many places, white to brown, soft to hard, chaledonic in parts, silty in parts, may contain quartz grains; sandstone: red to white, generally fine-grained, angular, well sorted, typically micaceous, bioturbated in parts, low-angle cross-bedding in parts; siltstone: red-brown, sandy in parts, micaceous; claystone: red-brown and white, silty laminae in parts, typically laminated, bioturbated and micaceous; 2 m of conglomerate, possibly basal, crops out at lat. 18°22'S, long. 132°57'E.

The term ‘beds’ is proposed for this rock unit as it commonly crops out as thin deposits preserved in topographically higher areas, and its lateral continuity is difficult to demonstrate, particularly as fossils have been found at only one locality. It is postulated that calcareous claystone is a major component of the beds but does not crop out due to its soft nature; when incised, this rock type develops a thin capping of calcrite. Two distinct rock units may be present in the Point Wakefield beds: an upper sandstone, siltstone and claystone sequence typified by outcrops at Point Wakefield, and a lower calcareous siltstone sequence which is commonly capped by calcrite.

Thickness: Maximum recorded thickness is 54 m in BMR Lander River 5 (lat. 20°14'S, long. 133°28'E). It is 37.5 m thick in stratigraphic drillholes BMR Barrow Creek 18 (lat. 21°09'S, long. 145°1'1'E), 26.2 m in Green Swamp Well 3 (lat. 19°20'S, long. 133°03'E) (Kennewell and Huleatt 1980). Greatest known thickness in outcrop is 22 m at Point Wakefield. Total thickness of the Point Wakefield beds is probably much greater than thickness recorded here.

Relationships and boundary criteria: Cuttings from stratigraphic drillholes BMR Green Swamp Well 1, 2 and 3 (lat. 19°25'S, long. 133°30'E; lat. 19°24'S, long. 133°16'E and lat. 19°20'S, 133°03'E respectively) show the Point Wakefield beds overlying the Montejinni Limestone, Hooker Creek Formation and Lothari Hill Sandstone respectively (Kennewell and Huleatt 1980). In SOUTH LAKE WOODS the beds overlie the Proterozoic Churchill Head Group. Hence the basal contact is unconformable.

At Point Wakefield astronomical station (lat. 19°59'S, long. 133°21'E), sandstone, possibly of the Hanson River beds, overlies the Point Wakefield beds, but the contact is not exposed and its nature not known. Elsewhere, the Buchanan Hills beds or Cainozoic units overlie the Point Wakefield beds.

Age and evidence: Stratigraphic position indicates an age between the limits of early Middle Cambrian (Ordian-early Templetonian) and Early Ordovician ( Arenig). White silty claystone at locality TCI (lat. 19°20'S, long. 133°37'E) contains the ptychopariid trilobite Xingrenaspis alroiensis, from which a late Templetonian-Florian (early Middle Cambrian) age has been determined (Kruse 1998).

Synonymy: Included in Chewings’ (1931) Winnecke Creek Tableland formation. Milligan et al. (1966) included these
DEFINITIONS OF NEW STRATIGRAPHIC UNITS

TENNANT CREEK GRANITE (R.S. Morrison)

**Symbols:** Btg - Tennant Creek Granite; Bgt - Tennant Creek Granite at Red Bluff; Bgt_n Tennant Creek Granite north of the Barkly Highway.

**Derivation of name:** After Tennant Creek township (GR MU2715) and Tennant Creek (GR MU3822) on TENNANT CREEK.

**Synonymy:** The Tennant Creek Granite has also been described informally as ‘Tennant Creek Granite complex’ (Crohn and Oldershaw 1965). Parts of this complex were subsequently referred to as the ‘Red Bluff Granite’ (GR LU4295) and ‘Tennant Creek Granite’ (GR MU3814) (Mendum and Tonkin 1976).

**Distribution:** The Tennant Creek Granite occurs as scattered outcrops over a 60 km east-west topographic high in central TENNANT CREEK. The largest single outcrop is roughly circular, 7 km in diameter, and centred on GR MU3912, and is known locally as ‘Devils Pebbles’. Spatially separate additional major outcrops (30 km²) are centred around ‘White Hill’ (GR MU4328), as scattered outcrops covering approximately 50 km² in the vicinity of ‘Red Bluff’ (Bgt - GR LU4295), and in a 280 km² area north of the Barkly Highway centred on GR MU3055 (Bgt).

**Surface expression:** This unit forms large tors and whalebacks (particularly at the Devils Pebbles locality), or low hills and rises (particularly at the White Hill locality).

**Type area:** Devils Pebbles locality; GR MU3814.

**Lithology:** Composed of foliated to mylonitised biotite or biotite-bearing granite within less foliated or non foliated seriate porphyritic to equigranular biotite granite. Foliated granite commonly has oriented reddish-brown biotite flakes, stretched quartz crystals and elongated feldspar phenocrysts. The less foliated or non foliated phase has minor rapakivi texture and ovoid quartz crystals 0.5-1 cm in diameter with (1.5-3 cm) subhedral alkali feldspar phenocrysts (microcline and microperthitic microcline) and (2-3 mm) oligoclase. Equigranular granite commonly has anhedral quartz. Minor mafic constituents include muscovite, and in one sample, amphibole. Accessories include sphene, fluorite, magnetite, ilmenite, rutile, leucoxene and relatively abundant zoned zircon. Secondary alteration products include chlorite, epidote and muscovite, formed from saussuritisation of feldspar and alteration of biotite. Marginal and more highly fractured zones of the Tennant Creek Granite are often extensively altered with both sodic and potassic metasomatism accompanied by tourmalinisation (luxullianite).

**Relationships and boundary criteria:** The Tennant Creek Granite concordantly intrudes the Warramunga Formation. Crohn and Oldershaw (1965) reported overturned drag folds and apparent divergence of metasedimentary beds around the intrusion at the Devils Pebbles. The southern contact margin is characterised by a 100 m thick contact aureole of spotty hornfels (quartz and chlorite porphyroblasts) in Warramunga Formation metapelite. The eastern margin intrudes undifferentiated Flynn Subgroup metasediments. The ‘Tennant Creek Granite at Red Bluff (Bgt)’ is separated from the main outcrop of Tennant Creek Granite at the Devils Pebbles by 8 km of Warramunga Formation, while the Tennant Creek Granite north of the Barkly Highway (Bgt) is separated by 2 km of undifferentiated Flynn Subgroup rocks.

**Xenoliths and dykes:** Warramunga Formation metasediment xenoliths are commonly elongated or streaked out parallel to foliation, and up to 1 m in length. The centre of the Devils Pebbles locality contains numerous Warramunga Formation xenoliths (up to 30% of the total mass). Prevalent at the Devils Pebbles locality are abundant rounded or ovoid autoliths of porphyritic granodiorite, quartz monzonite or quartz diorite. Accidental inclusions of altered metasediments are prevalent along the eastern margin (GR MU3344). Dykes of dolerite (Edl) intrude the Granite at Devils Pebbles in an east-west orientation (GR MU1238). Minor (approximately 10 cm wide) aplitic dykes, and small veins and pods intrude the Granite.

**Distinguishing or identifying criteria:** Rapakivi texture, non foliated to strongly foliated, felsic porphyritic autoliths and Warramunga Formation xenoliths.

**Structural attitude:** At the Devils Pebbles, the Tennant Creek Granite is dominated by east-west foliation to mylonitisation in narrow (10 m) zones, conformable to the regional structure and retaining a diffuse contact with contiguous less deformed Granite. Narrow shear zones occasionally occur through the granite in north-south and northwest-southeast orientations.

**Correlations:** Page (1988) correlates the Tennant Creek Granite with other felsic intrusives (e.g. Grace Creek Granite, Kalkadoon Granite) associated with the 1880-1850 Ma Barramundi Orogeny affecting the Pine Creek, Litchfield-Arnhem and Mount Isa Inliers in northern Australia. The Tennant Creek Granite may represent the source material to narrow, lenticular bodies of felsic porphyries on TENNANT CREEK, and may be equivalent to the smaller Channingum Granite, and to the Cabbage Gum Granite to the south.

**Age and evidence:** Compston (1991) obtained an ion microprobe date of 1858±12 Ma for the Tennant Creek Granite.

CHANNINGUM GRANITE (R.S. Morrison, after Mendum and Tonkin 1976)

**Symbols:** Pgc - Channingum Granite; Pgc - strongly foliated or sheared Channingum Granite; Pgc_l - leuocratic, albited Channingum Granite; Pgc_p - porphyritic Channingum Granite.

**Derivation of name:** Named after Channingum Creek, which is a tributary of the Gosse River on TENNANT CREEK (GR MU1648).
Synonym: Previously referred to as the New Hope Granite (e.g. GR MU1845) and the Channingham Granite (e.g. GR MU2052) (Mendum and Tonkin 1976).

Distribution and surface expression: The Channingham Granite forms six small plutons, the largest of which measures 2.6 km in diameter. They occur mainly as tors, or as low rises on central-eastern TENNANT CREEK. Individual outcrops are separated by sheet flood sands. The largest tors occur in an area 1 km in diameter, centred around GR MU2243. Smaller tors occur in an area 1 km in diameter centred around GR MU1845. Other outcrops occur as low rises on and in the immediate vicinity of GR MU2145, and extending 3.5 km north-south and 2.7 km east-west as isolated tors and low rises in an area centred around GR MU2052.

Type area: Small tors of rapakivi granite with quartz-tourmaline clots, leucocratic albised and marginal porphyritic phases are located at GR MU1845.

Lithology: The Channingham Granite is a medium to coarse grained (0.5-2 cm diameter grains) granite (sensu stricto) with an equigranular to seriate porphyritic texture. It is primarily composed of alkali feldspar phenocrysts (microcline and microcline microperthite), oligoclase and quartz, displaying moderately developed rapakivi texture in places. This granite is characterised by 0.5-1 cm rounded quartz crystals and rounded clots of tourmaline-quartz up to 8 cm in diameter (luxullianite). Mafic minerals include coarse grained brown biotite, with minor muscovite and magnetite. Zircon, apatite and relic fayalite (iddingsite) are the accessory phases. The Channingham Granite commonly exhibits weak subvertical northwest-southeast to east-west foliation defined by biotite orientation. Outcrops adjacent to faults (GR MU2346 and MU2244) are intensely foliated or sheared (Eg c) and extensively altered (chloritised, saussuritised), including the localised development of leucocratic quartz-bearing albite (Pgc).

Relationships and boundary criteria: In the type area, the northern contact grades into 50 m of felsic quartzfeldspar porphyry (Eg c) which has an irregular, passive intrusive contact with surrounding clastic sediments of the Yungkulungu Formation (GR MU1845). Minor contact metamorphism, with the localised development of muscovite or sericite. The southern contact is covered by recent sheet flood sands, but probably intrudes Warramunga Formation metasediments.

Enclaves and dykes: Enclaves include xenoliths of Warramunga Formation hornfelsed metasediments (5-10 cm in diameter), and rare rounded felsic porphyry autoliths. Minor late-stage magmatic aplite dykes intrude the granite.

Distinguishing or identifying features: Characteristic rapakivi biotite granite with marginal porphyritic and mylonitised phases, minor fayalite (iddingsite) and luxullianite.

Structural attitude: Occurrence of stocks and bosses with marginal porphyritic, sheared and altered phases indicate a very high level of emplacement, perhaps as part of a feeder system to the felsic volcanic rocks of the Flynn Subgroup.

Correlation: Mineralogy, texture, style of intrusion and alteration suggest that the Channingham Granite represents the eastern equivalent of the oval quartz-bearing phase of the Tennant Creek Granite. The marginal quartz-feldspar porphyry may be equivalent to felsic porphyries found elsewhere on TENNANT CREEK based on similar criteria.

Age and evidence: The Channingham Granite intrudes the Yungkulungu Formation of the Flynn Subgroup (1833±4 Ma; Compston 1991). Due to petrological and geochemical similarities, the Channingham Granite is probably synchronous with the intrusion of the Tennant Creek Granite (1858±12 Ma; Compston 1991) and/or the Cabbage Gum Granite (1848±7 Ma; Compston 1991).

MUMBILLA GRANODIORITE (R.S. Morrison)

Symbols: Eg m - Mumbilla Granodiorite; Eg m, - strongly foliated or sheared Mumbilla Granodiorite; Eg m, - leucocratic, albised Mumbilla Granodiorite; Eg m, - porphyritic phase of the Mumbilla Granodiorite.

Derivation of name: Named after Mumbilla waterhole, located on the Gosse River (GR MU0043).

Synonym: The Mumbilla Granodiorite was previously referred to by Mendum and Tonkin (1976) as the Gosse River Adammellite, the Gosse River South Adammellite, the Gosse River North Granite, North Seismic Adammellite, South Gosse Adammellite and (in part) the Gosse River East Granite.

Surface expression and distribution: The Mumbilla Granodiorite commonly forms tors separated by recent sheet flood sands. More weathered outcrop form low hills or rises. Deeply weathered Mumbilla Granodiorite crops out along the Gosse River and its tributaries. The pluton has a minimum width of 16 km in a northeast-southwest orientation, and extends over 36 km in a southeast-northwest orientation, centred on GR MU0237. A probable northern extension is represented by a pluton, 5 km in diameter, cropping out along the Gosse River and as large tors both to the east and west of the river centred around GR MU5819.

Type area: At GR MT9533.

Lithology: The predominant phase is biotite-bearing to biotite granodiorite, but ranges from granodiorite to granite with variations of relative proportions of megacrystic alkali feldspar (up to 8 cm) and plagioclase (1 cm laths) associated with coarse grained anhedral quartz. Plagioclase is often zoned with labradorite cores and oligoclase rims. Mafic constituents are dominated by reddish brown biotite (0.5 cm) and include relic fayalite (iddingsite) and minor spheroids. Accessory minerals include magnetite, ilmenite, fluorite and relatively abundant zircon. Minor tourmaline-bearing pegmatitic segregations occur, but seldom form intrusive dykes. Quartz-tourmaline was also noted filling veins and fractures.

Minor phases include an equigranular medium to coarse grained quartz-veined leucocratic quartz-bearing and veined albitite with tourmaline (luxullianite)
(GR MU0731) (Pgm.), while the northeastern extension of the Mumbilla Granodiorite (GR MU5819) is porphyritic with 1-2 cm laths of alkali feldspar, 0.5 cm quartz and plagioclase and 0.2 cm biotite crystals in a medium to fine grained felsic groundmass (Pgm.). Narrow but mappable northeast-southwest and northwest-southeast shear and mylonite zones occur through the pluton (Pgm.).

Distinguishing and identifying features: The Mumbilla Granodiorite is characterised by alkali feldspar megacrysts, fayalite, zoned plagioclase with calcic cores, and an abundant and varied enclave population. Margins are commonly more strongly foliated and/or sheared and granitic rather than granodioritic in composition.

Relationships and boundary criteria: In the south (e.g. GR MT9332), Mumbilla Granodiorite passively intrudes the Flynn Subgroup (Junalki Formation). To the north (e.g. GR MU1334), the Granodiorite becomes progressively finer grained and ultimately aplite over a distance of ~500 m, and is faulted against felsic volcanics of the Flynn Subgroup (Yungkulgungu Formation). The north-eastern contact (e.g. GR MU5819) is both faulted against, and intrusive with, sediments and volcanics of the Yungkulgungu Formation, while to the east the Granodiorite intrudes foliated Yungkulgungu Formation volcanics (e.g. GR MT5105). The western contact is covered by recent sediments, but probably intrudes the Junalki Formation or either merges into or intrudes the Cabbage Gum Granite.

An amphibole-rich quartz diorite plug approximately 20 m in diameter (GR MU1231) with irregular, passive and baked margins intrudes into the Granodiorite.

Enclaves and dykes: Accidental xenoliths include Warramunga Formation metasediments and Flynn Subgroup sediments; and autoliths include rare dolerite (and gabbro) and possible biotite lamprophyre, and biotite- and amphibole-rich cumulate enclaves. The most abundant enclaves are autoliths of rounded or lobate porphyritic granodiorite to quartz diorite, up to 2 m in diameter. Autoliths composed of slightly porphyritic red granite displaying rapakivi texture may have originated from the Cabbage Gum Granite, the Tennant Creek Granite or the Channingum Granite. Subvertical dykes of dolerite up to 10 m wide intrude the granodiorite in north-south and northwest-southeast orientations (Pdl), as well as dykes of late-stage aplite or quartz diorite up to 1 m wide. The quartz diorite dykes may be associated with the development of felsic porphyritic enclaves.

Structural attitude: The pluton is generally either massive, displaying no discernable internal structures apart from rare sub-horizontal biotite schlieren, or moderately foliated with biotite forming an east-west foliation.

Correlations: Probable northern extension of the Hill of Leaders Granite on BONNEY WELL. However, these granite bodies cannot be precisely correlated as they are separated by 10 km of 'unnamed granite' on BONNEY WELL.

Age and evidence: Compston (1991) obtained an ion microprobe date of 1850±6 Ma.

CABBAGE GUM GRANITE (R.S. Morrison, after Crohn and Oldershaw 1965)

Derivation of name: Named after the Cabbage Gum Basin; which consists of a shallow topographic depression centred around the Cabbage Gum Bore (GR MU1612).

Synonym: None.

Surface expression and distribution: Restricted in outcrop to small (0.5 m) tors at the northeast margin of the granite body (GR MU1618). It also occurs as an excavated subcrop in an area of a slight topographic high 10 km south of Tennant Creek (GR MU1517), otherwise it is known almost entirely from drill hole intersections. The Cabbage Gum Granite has been intersected 31 km south-southeast of Tennant Creek (GR MT1217), representing the known southern limit of the granite body. It has also been encountered in drill core 5.5 km northeast of the Cabbage Gum Bore (GR MU2015) and 30 km west-southwest of Tennant Creek (GR LU8814).

Type area: At the only known outcrop location, 9 km south of Tennant Creek (GR MU1618).

Lithologies: Crohn (1961) identified at least five different phases of the Cabbage Gum Granite; a medium grained granite, an augen gneiss, a quartz-feldspar porphyry (cf. Flynn Subgroup volcanic rocks), a fine grained granite, and a medium grained gneissic granite. At the type locality, the Cabbage Gum Granite consists of a massive seriate porphyritic biotite-bearing rapakivi granite composed of rounded 1-2 cm mantled alkali feldspar, finer grained sodic plagioclase, rounded quartz and reddish brown biotite. Accessory minerals include apatite, fayalite (iddingsite), magnetite, fluorite, zircon and sphene.

Relationships and boundary criteria: No contacts are exposed. To the immediate east of the Cabbage Gum Granite lies the Mumbilla Granodiorite. Drill hole information (Verhoeven and Russell 1981) in the Kelly Basin along the southern contact of the known extent of the Cabbage Gum Granite has intersected Granite showing an intrusive contact relation with Flynn Subgroup sediments. In this area (GR MT1794), the Granite is also overlain by Palaeo-protorozoic sedimentary rocks of the Hatches Creek Group. The western contacts are largely unknown, but may involve a complex inter-association with Warramunga Formation metasediments, Flynn Subgroup sedimentary and volcanic rocks, Tennant Creek Granite at Red Bluff and the Warrego Granite.

Enclaves and dykes: Small (2-10 cm), stretched, silicified xenoliths of probable Warramunga Formation metasediments or Flynn Subgroup derivation. Xenoliths seen in outcrop show only minor stretching, but this can be quite pronounced in more strongly foliated cored sections. Crohn (1961) described a roof pendant of extensively sheared and silicified metasediments approximately 1.6 km wide and 8 km in length from bore hole and drill core data. Other such roof pendants have been intersected by drilling in the Granite body, and probably represent rafts of Flynn Subgroup material.
Drill core from the southern margin of the Granite (GR MT1495) show intrusive dolerite dykes (Pd).

Structural attitude: A major quartz-veined shear zone crosscuts the Cabbage Gum Granite in the vicinity of Cabbage Gum Bore (GR MU2015) in a northeasterly orientation and may represent a major structural feature in the region (Mendum and Tonkin 1976).

Correlations: Textural, geochemical and geochronological evidence indicate that the Cabbage Gum Granite is an extension of the Tennant Creek Granite to the north, and the Channing Granite to the east. Similarly, the Cabbage Gum Granite may represent the western extension of the Mumbilla Granodiorite.

Age and Evidence: Compston (1991) reported a U-Pb ion microprobe date of 1848±7 Ma for the Cabbage Gum Granite.

WARREGO GRANITE (R.S. Morrison after Mendum and Tonkin 1976)

Symbols: Egw - Warrego Granite.

Derivation of Name: Named after the Township of Warrego, located 44 km ENE of Tennant Creek, Northern Territory (GR LU7749).

Synonymy: None

Distribution and Surface Expression: The Warrego Granite crops out as small hills and low rises, and along recent water courses. Small hills are often capped by silcrete. Most outcrops of Warrego Granite are extensively weathered. Surface outcrops indicate the pluton extends approximately 7 km east-west and for at least 15 km NNW from Warrego, centred around GR LU7155.

Type Area: Centred around a low hill along the eastern margin of the granite (GR LU7259) where contact relations and textural variations are clearly seen.

Lithologies: The main granite lithology is a massive coarse grained equigranular muscovite granite or muscovite granodiorite with 1-3 cm diameter feldspar, muscovite and quartz crystals. At surface, feldspar crystals are extensively sericitised, preventing an accurate count of relative feldspar proportions. In drill core samples (BMR-NTGS DDH7), 3 mm long books of iron-rich chlorite appear to be replacing primary biotite. Microcline is the sole alkali feldspar, and plagioclase is slightly zoned with andesine or oligoclase cores and albite rims. Accessory minerals include corundum and apatite with minor sphene and zircon. Muscovite books 0.5-1 cm in diameter show no evidence of deformation. Mendum and Tonkin (1976) reported the occurrence of minor hornblende in the type area of the Warrego Granite.

Relationships and Boundary Criteria: The eastern exposed contact is characterised by a 200-400 m wide zone of intense high temperature hydrothermal alteration (GR LU7259). The contiguous Flynn Subgroup sediments, into which the granite intrudes, have been metamorphosed to a knotted quartz-muscovite schist. The granite has been metasomatized to a dark grey medium grained quartz-muscovite greisen. The contact zone is marked by an abundance of small quartz veins. Elsewhere, the contacts are covered by recent sheet flood sands. To the south, the Granite contact with metasediments is exposed in a shallow pit (GR LU7648), showing passive intrusive characteristics in sheared metasediments. To both the north and the west, the Warrego Granite is surrounded by sedimentary and volcanic rocks of the Flynn Subgroup.

Enclaves and Dykes: Xenoliths are restricted to contact metamorphosed Flynn Subgroup sedimentary rocks and reincorporated clasts of medium to fine grained dark grey quartz-muscovite rock from the metasomatized granite margin within coarse grained equigranular granite. Xenoliths are more prevalent closer to the granite margin. Large 1-3 m wide quartz veins intrude the granite in a north-south orientation. Smaller dykes and lenticular pods of quartz-feldspar pegmatite were noted.

Distinguishing or Identifying Features: The Warrego Granite is readily distinguished from other intrusives on the Tennant Creek 1:250 000 sheet area by its two mica, corundum-bearing composition, the relative abundance of pegmatitic segregations, and the development of a quartz-biotite contact metamorphic aureole.

Correlation with Other Units: None. One of Mendum and Tonkin's (1976) three units for the Warrego Granite (Egx) is now considered to be in part coarse grained felsic volcanic rocks of the Flynn Subgroup (this study). Where intrusive, this unit (Egx of Mendum and Tonkin 1976) may be equivalent to the Palaeoproterozoic Tennant Creek Granite or Cabbage Gum Granite due to its location (separated by felsic volcanics of the Flynn Subgroup: GR LU5856 and LU5550), different composition (orthoclase, plagioclase, blue opalescent quartz and chloritised biotite) and structure (prominent east-west to NE-SW foliation).

Age and Evidence: The Warrego Granite intrudes Palaeoproterozoic volcanics and sedimentary rocks of the Flynn Subgroup. Black (1977) reported an Rb-Sr date of 1662±20 Ma with an initial ratio of 0.702±0.008.