1:100 000 GEOLOGICAL MAP SERIES

EXPLANATORY NOTES

SHORT RANGE 5659

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ABSTRACT

Three major Palaeoproterozoic sedimentary and volcano-sedimentary successions have been recognised in Short Range*. These are: (1) turbiditic Warramunga Formation; (2) Flynn Group, which is inferred to in part unconformably overlie Warramunga Formation, and (3) Tomkinson Creek Group. Flynn Group is a succession of predominantly subaerial rhyolitic and rhodacitic ignimbrite, lava and tuff, and associated volcaniclastic and clastic sedimentary rocks. Tomkinson Creek Group comprises sandstone together with subordinate volcanic and carbonate rocks. Palaeoproterozoic intrusive rocks include representatives of the Tennant Creek Supersuite, Treasure Suite and Devils Suite of Wyborn et al (1998a).

Warramunga Formation is confined in outcrop to the southeastern corner of Short Range and has a maximum age of sedimentation of 1860 Ma (Compston 1995). Intrusive representatives of Tennant Creek Supersuite are Tennant Creek Granite at Red Bluff and unnamed porphyries. These are also the local representatives of a widespread magmatic episode in northern Australia, the Barramundi Igneous Association of Etheridge et al (1987). The intrusive representatives of Tennant Creek Supersuite immediately post-date Warramunga Formation sedimentation and are broadly syn-tectonic with respect to the earliest deformation in the area, the Barramundi Orogeny. Broadly contemporaneous and consanguineous volcanic rocks are Warrego Volcanics and unnamed volcanic lithofacies within the dominantly sedimentary Wundirgi Formation. These volcanic-sedimentary rocks, together with Brumbree Formation, are the local succession of Flynn Group which is inferred to unconformably overlie Warramunga Formation. Wundirgi Formation is probably at least a partial correlative of a number of formations mapped elsewhere in TENTANT CREEK. It reflects the fact that paucity of outcrop inhibits a ready subdivision of Flynn Group in northern and western TENTANT CREEK.

Unnamed porphyry and monzodiorite/dolerite intrusions are representatives of the Treasure Suite of Wyborn et al (1998a). These rocks intrude Warramunga Formation, Brumbree Formation, and the contact between Wundirgi and Brumbree Formations.

A succession of sandstone, and subordinate carbonate and volcanic rocks comprise Tomkinson Creek Group. Stratiform mafic to intermediate rocks within the basal unit, Hayward Creek Formation, have generally been considered intrusive with extrusive rocks being subordinate except for Whittington Range Member, a mappable, substantially volcanic unit at the top of Hayward Creek Formation. These igneous rocks are, with a few exceptions, markedly conformable with the surrounding sedimentary rocks. It is suggested that they predate folding of Hayward Creek Formation although this has not been substantiated, and similarly the relative proportions of intrusive to intrusive rocks has not been resolved as many field relationships are poorly exposed or ambiguous.

Geochronological data indicate a substantial time break in the succession somewhere between uppermost Flynn Group and the base of Meerie Member of Hayward Creek Formation. There is also a discrete deformational event (called here the Murchison tectonic event) and consequent tectonic unconformity in this interval of stratigraphy although the precise position of this remains unclear. Correlation between the Davenport and Ashburton Provinces suggests the Murchison tectonic event immediately predates Manga Mauda Member of Hayward Creek Formation which is correlated with Unimbra Sandstone. A hiatus between Tin Fish Sandstone and Strzeleckie Volcanics and the overlying Illoqua Sandstone (BARROW CREEK) is interpreted to correspond lithostratigraphically with the Manga Mauda/Meerie Member boundary and is the favoured position of a significant time break (note that the spelling of Strzeleckie is taken from that of Mount Strzeleckie in BARROW CREEK, as per the Gazetteer of place names).

Treatre Suite felsic volcanic and intrusive rocks are essentially contemporaneous with both the second episode of deformation (Murchison tectonic event) in Short Range at about 1820 Ma and with gold-copper-bismuth mineralisation. The Murchison tectonic event may correlate with the similarly aged Stafford tectonic event in the northern and central Arunta Province, or it may be an early manifestation of the Strangways Orogeny (recognised throughout the Arunta Province).

Substantial volcanolithic detritus in Hayward Creek Formation suggests that either Treasure Suite represents part or the dominant source of this unit, or that equivalents of apparently minor volcanic intervals within Hayward Creek Formation were more widespread nearby. The latter raises the possibility that erosive activity was comparatively widespread during Hayward Creek Formation sedimentation. The stratiform igneous units mentioned above may therefore represent contemporaneous extrusive volcanic rather than later intrusive rocks. Compston (1995) recognised a significant component of Warramunga Formation age zircons in Hayward Creek Formation. This could mean either that Warramunga Formation was exposed at this time, or that the source of Warramunga Formation continued to be eroded.

Warrego Granite represents the local manifestation of a late episode of syntectonic felsic magmatism and has been assigned to the 1710-1720 Ma Devils Suite by Wyborn et al (1998a), although its age is equivocal and Compston (1995) favoured -1645 Ma as the intrusive age of this granite. Again, until relationships between the Tennant Inlier and Arunta Province are better constrained it is proposed that the associated deformation in the Tennant Inlier be called the Davenport Orogeny.

Previously mapped but unnamed sandstone members of Hayward Creek Formation are named and formalised here.

One outcrop of conglomerate in northeastern Short Range is currently assigned to Rising Sun Conglomerate. This remains equivocal and the outcrop may represent Gleeson Formation (Renner Group), which is otherwise confined in outcrop to HELEN SPRINGS.

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* Names of 1:250 000 and 1:100 000 map sheets in this report are shown in large and small capital letters respectively, eg TENTANT CREEK, SHORT RANGE.
Middle Cambrian stratigraphy of the Wiso Basin is represented by Montejinni Limestone and Point Wakefield beds. The former is generally silicified, and the latter is represented by only one outcrop at LU552626.

It is emphasised that short range was mapped and these notes essentially completed prior to the availability of new airborne geophysical data over TENNANT CREEK, released by AGSO in mid 1999.

KEY WORDS

Palaeoproterozoic, Warramunga Formation, Flynn Group, Tomkinson Creek Group, Tennant Creek Supersuite, Treasure Suite, Devils Suite, Barramundi Igneous Association, Davenport Province, Tennant Creek Province, Tennant Creek goldfield, Ashburton Province, Pine Creek Orogen, Arunta Province, Tennant Inlier, Davenport Orogeny, Barramundi Orogeny, Strangways Orogeny, Murchison tectonic event, Stafford tectonic event, Wiso Basin.
## CONTENTS

Abstract .......................................................................................................................... iii

Key words ....................................................................................................................... iv

Introduction ..................................................................................................................... 1
  Habitation and access ............................................................................................... 1
  Topography, drainage and vegetation ...................................................................... 1
  Climate ....................................................................................................................... 1
  Previous geological investigations ......................................................................... 1
  Present investigation .............................................................................................. 2

Palaeoproterozoic stratigraphy ................................................................................... 2
  Summary of revisions to stratigraphic units ............................................................. 2
  Warramunga Formation ........................................................................................... 4
  Possible Warramunga Formation equivalents ......................................................... 5
  Flynn Group ............................................................................................................ 5
  Wundiri Formation .................................................................................................. 6
  Warrego Volcanics ................................................................................................... 6
  Brumbre Formation .................................................................................................. 6
  Relationships of Flynn Group in Short Range ......................................................... 7
  Relationship between Flynn Group and Tomkinson Creek Group ......................... 8

Tomkinson Creek Group ............................................................................................ 9

Hayward Creek Formation ....................................................................................... 9

Morphett Creek Formation ...................................................................................... 12

Short Range Sandstone ............................................................................................ 13

Intrusive rocks ............................................................................................................ 13
  Tennant Creek Granite at Red Bluff ....................................................................... 14
  Warrego Granite ...................................................................................................... 14
  Unnamed granite ..................................................................................................... 15
  Porphyry ................................................................................................................... 15
  Dolerite and diorite ................................................................................................. 15
  Lamprophyre .......................................................................................................... 16
  Alteration .................................................................................................................. 16
  Geochemistry ......................................................................................................... 20
  Mafic intrusive rocks ............................................................................................... 20
  Felsic intrusive and extrusive rocks ....................................................................... 20

Phanerozoic stratigraphy ............................................................................................ 22

Palaeozoic ................................................................................................................... 22
  Cambrian .................................................................................................................. 22

Mesozoic ..................................................................................................................... 22
  Cretaceous? ............................................................................................................ 22

Cainozoic ..................................................................................................................... 23

Structure ....................................................................................................................... 24
  Folding ..................................................................................................................... 24
  Timing of deformational events ............................................................................. 28
  Faulting .................................................................................................................... 29

Geological history ....................................................................................................... 29
  Summary of Proterozoic events ............................................................................ 29
  Discussion ............................................................................................................... 30

Regional correlations .................................................................................................. 31

Economic geology ....................................................................................................... 33
  A brief history of mining and exploration ............................................................... 33
  Tennant Creek style ironstone-associated gold-copper-bismuth mineralisation and its
genesis ....................................................................................................................... 35
  Analagous for Tennant Creek type mineralisation? ............................................... 36

Acknowledgements .................................................................................................... 37

References .................................................................................................................... 37
TABLES

Table 1  Palaeoproterozoic stratigraphy of Short Range ................................................................. 3
Table 2  Geochemical analyses of monzodiorites and diorites from DDH6, 7 and 7a, Short Range .......... 24
Table 3  Geochemical analyses of representative and average granitic rocks from Tennant Creek .......... 25
Table 4  Shear orientations for the Tennant Creek one-mile sheet ..................................................... 26
Table 5  Working structural history of the Tennant Inlier ..................................................................... 28

FIGURES

Figure 1  Schematic summary of the Palaeoproterozoic stratigraphy of Tennant Creek Province .......... 7
Figure 2  Possible context of Warramunga Formation, and Flynn/Ooradidgee Group sedimentation .......... 8
Figure 3  QF cationic plot for Tennant Creek felsic igneous rocks ...................................................... 16
Figure 4  Photomicrographs of alteration in selected igneous rocks from Tennant Creek .................... 17
Figure 5  K2O versus Na2O for various Tennant Creek igneous rocks ................................................. 18
Figure 6  Alumina-saturation classification plot for Tennant Creek felsic igneous rocks .................... 18
Figure 7  Total alkalis versus silica (TAS) classification diagrams ..................................................... 19
Figure 8  Classification based on K2O versus SiO2 for Tennant Creek felsic igneous rocks ................ 19
Figure 9  Ternary plots showing the tholeiitic character of diorite and monzodiorite from Short Range ........ 20
Figure 10  REE plots for diorite and monzodiorite intruding Flynn Subgroup and for Kudina Basalt ........ 20
Figure 11  Ce versus Nd for diorite and monzodiorite from Short Range and for Kudina Basalt ............ 21
Figure 12  Spider diagram of incompatible elements for diorite and monzodiorite from Short Range ........ 21
Figure 13  Sr/Ce versus Ce and La versus Ce for diorites, Kudina Basalt and Murchison dolerites .......... 21
Figure 14  Upper continental crust (UCC) normalised spider diagrams for various granites .................. 22
Figure 15  REE plots for Tennant Creek Granite, Mumbilla Granodiorite, and Warrego Granite ............ 22
Figure 16  Histogram of Ti/Zr ratios for granites and porphyries ..................................................... 23
Figure 17  Histogram of Ti/Zr ratios for the Newlands Volcanics, Davenport Province .......................... 23
Figure 18  Histogram of Ti/Zr ratios for the Mumbilla Granodiorite .................................................. 23
Figure 19  Comparison of stratigraphy of Tennant Inlier with that of Pine Creek Orogen and McArthur Basin ............... 32
Figure 20  Postulated relationships between Tennant Inlier and northern Arunta Province .................. 34

APPENDICES

Appendix 1  Stratigraphic name definitions ...................................................................................... 43
Appendix 2  Data sources and notes for Figures 19 and 20 ................................................................. 44
INTRODUCTION

Short Range covers an area of about 2 885 km² between latitudes 19° 00’S and 19° 30’S and longitudes 133° 30’E and 134° 00’E in northeastern TENNANT CREEK. The area encompasses only six prospects with recorded production, compared to a total of 130 in the Tennant Creek goldfield. However, these include the largest tonnage mine, Warrego, which also has the distinction of being a significant copper orebody and the major producer of bismuth in the goldfield. The other significant mine in SHORT RANGE is the comparatively low tonnage but high grade White Devil.

Habitation and access

A sealed road joins the former Warrego mine and township to Tennant Creek. This road continues as a formed earth road into GREEN SWAMP WELL. Tennant Creek has a population of 3860 at the time of writing and is 505 km north of Alice Springs on the Stuart Highway, the main road link between Adelaide, Alice Springs and Darwin. The Barkly Highway, connecting to Mt Isa, joins the Stuart Highway about 25 km north of Tennant Creek. A good track runs north from Warrego to Last Hope and provides ready access via a number of tracks to Short Range. Kalumpulu on the northern boundary of the eastern map area is reached via an unsealed road which joins the Stuart Highway a short distance north of Churchill’s Head in HELEN SPRINGS. A large part of SHORT RANGE is covered by Phillip Creek pastoral lease, with a small portion of Banka Banka pastoral lease in the northeast. The remainder is part of the Karlantijpa North Aboriginal Land Trust. The area is crossed north-south by the gas pipeline and Alice Springs to Darwin railway corridor.

Topography, drainage and vegetation

Short Range extends east-west across the central eastern map area. This range is a remnant of the Ashburton Surface and rises to a maximum height of 426 m, whilst the surrounding plain (Tennant Creek Surface) varies between about 300 and 350 m above sea level. A slight topographic elevation is associated with good outcrop in the extreme northwest of the map area.

In the Murchison and Davenport Ranges, the Ashburton Surface is interpreted to be an early Cambrian or older planation surface, dissected during lower Middle Cambrian times (Stewart et al 1986). Previous authors have emphasised the antiquity of this planation surface, Hays (1967) correlated it with King’s (1950) Gondwana Surface and recognised that it predated the Cretaceous. Twidale (1997) pointed out that the Gondwana land surface was complex and included isolated remnants of a Proterozoic land surface in BARROW CREEK. A sub-Torridonian land surface in northwest Scotland (Williams 1969, Stewart 1975) is Proterozoic in age and constitutes another example of an exhumed old land surface.

Hays (1967) recognised an old, vestigial weathering profile on erosional remnants of the Ashburton Surface and also underlying the Cabbage Gum Basin which itself underlies the Tennant Creek Surface to the south of Tennant Creek township. The Tennant Creek Surface is part of a stable Cainozoic land surface and has a thin cover of colluvium (some dissected), alluvium, sheet sand, or residual soil. Hays (1967) pointed out that the Tennant Creek Surface predated lateritisation, and correlated the lateritisation beneath the Cabbage Gum Basin with that seen in the McDouall Ranges and Mount Cleland area. This represents the more or less dissected remnants of the more continuous Ashburton Surface preserved in the Ashburton, Murchison and Davenport Ranges. The lateritisation predates the mid-Miocene and may have started immediately after Lower Cretaceous sedimentation (Hays 1967). It could therefore immediately predate either the Morney or Canaway duricrusts of western Queensland that were described and dated by Idnurm and Senior (1978).

Refer to Stewart et al (1954) and Perry and Christian (1954) for details of vegetation. The Tennant Creek Surface supports shrublands of Eucalyptus spp and Acacia spp; Eucalyptus spp woodlands; and gummy spinifex and turpentine grasslands. Eucalyptus spp and Acacia spp provide a light tree and shrub cover on the Ashburton Surface with a denser cover on the more gentle slopes. Kerosene grass and gummy spinifex are the main grass species.

Creeks in SHORT RANGE are predominantly dry and only flow for short periods after rain.

Climate

The area has an arid, tropical climate with long, hot summers and short, mild winters. A summary of salient temperature and rainfall data for Tennant Creek provided by the Bureau of Meteorology was presented in Donnellan et al (1995).

Previous geological investigations

The first major study of the geology and ore deposits of the Tennant Creek goldfield was that of Ivanc (1954), whose map and report included part of SHORT RANGE. 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 map compiled by Mendum and Tonkin (1971) and later published together with explanatory notes compiled by Dodson and Gardener (1978). An important contribution to the understanding of SHORT RANGE geology is the 1:100 000 preliminary edition WARREGO SPECIAL map (Mendum and Tonkin 1974) that included information from Geopeko NL mapping.

Geopeko mapped EL214 on behalf of Peko Mines Ltd. This mapping was undertaken using 1:12 000 black and white aerial photographs. A preliminary 1:250 000 interpretive solid geology map based on this work was included in an annual report for EL214 (Love 1974), and was reproduced at 1:500 000 scale in Le Messurier (1976). A refinement of this map based on BMR and company mapping, and geophysical interpretation was presented by Le Messurier et al (1990).

The importance of magnetic prospecting at Tennant Creek was recognised early and has remained the major exploration tool. Daly (1957) reported that a lack of geological data, together with the known association of gold with ironstone bodies, prompted ground-based geophysical surveys by the Aerial, Geological and Geophysical Survey of Northern
Australia (AGGSNA) in the Tennant Creek field in 1935, 1936 and 1937. Further impetus for geophysical surveys came in 1950 with the discovery of a copper resource at depth at Peko, and consequent indications for significant base metal potential in the goldfield. Data from early aeromagnetic surveys (BMR 1956, 1960) were important in the discovery of the Warrego deposit.

Results of the AGGSNA surveys were reported by Rayner and Nye (1936), Richardson and Rayner (1937a,b), Richardson et al (1936) and Daly (1957). To facilitate interpretation of these data, an airborne magnetometer and scintillometer survey was undertaken by BMR in 1956 in order to delineate the regional anomalies. The area surveyed included all known mine workings, and the results were published as a 1:126 720 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 maps (BMR 1962a-d) and a 1:250 000 map of total magnetic intensity (TMI) and radioactivity (BMR 1968). Preliminary edition 1:100 000 TMI contour maps for the six 1:100 000 map areas that comprise TENNANT CREEK (including SHORT RANGE) were published by AGSO in 1998.

Present investigation

The first edition SHORT RANGE map and notes are based on field mapping by NTGS during the winter months of 1991-1993 as part of its program of geological mapping at TENNANT CREEK over the 1989-1993 field seasons. Mapping was undertaken using 1:25 000 colour aerial photographs taken during a joint flying project in 1988 and subsequently by NTGS contracting with AirResearch Mapping for Flynn North (flown April 1989) and Short Range (flown April 1990).

An unpublished, interpretative TENNANT CREEK map based on BMR gravity and aeromagnetic data, together with NTGS geological mapping, was produced by Farrar (1994). Farrar integrated this with available solid geology maps, appropriately modified, to produce a 1:1 250 000 interpretative map of the Tennant Inlier that appeared on the second edition TENNANT CREEK sheet (see Donnellan et al, 1999 for details).

AGSO contracted with Kevron to fly a low level aeromagnetic and radiometric survey (200 m line spacing) over the entire TENNANT CREEK map area in 1998. The data were released in mid 1999 but were not available at the time of mapping and this report was largely written prior to its release. NTGS are currently interpreting these data. Consequently, the insights these data allow into the geology of SHORT RANGE will be addressed elsewhere (Donnellan et al in prep).

PALAEOPROTEROZOIC STRATIGRAPHY

Summary of revisions to stratigraphic units

The Palaeoproterozoic stratigraphy of SHORT RANGE is summarised in Table 1, and discussed in more detail below. Some significant stratigraphic revisions are briefly summarised here for the reader's convenience. An unconformity in rocks mapped as Warramunga Group by Mendum and Tonkin (1971) was recognised by Owen (1940), Ivanac (1954) and Blake (1984). This, together with the fact that the group comprised distinct successions of tuffaceous/volcaniclastic turbidites and predominantly subaerial volcanic and associated shallow water sedimentary rocks, led Donnellan et al (1995) to divide the group. Thus, they mapped a turbidite succession (Warramunga Formation) and a volcano-sedimentary succession (Flynn Group). These were considered valid lithostratigraphic units but the potential for them to overlap in time was recognised. It was also recognised that Flynn Group rocks were less deformed than those of the Warramunga Formation. Despite possible confusion it was considered historically important to retain the name Warramunga for the unit from which the majority of gold in TENNANT CREEK has been recovered. Hence, the old group name was retained for one of the constituent lithologies, specifically the turbidite sequence, which was given formation status.

The Flynn Group represents an analogous succession to Ooradidgee Subgroup in the Davenport province. However, the Flynn Group was named separately because both units show marked lateral facies variations which tend to preclude a direct correlation between individual constituent formations.

In common with a number of previous authors (e.g Ivanac 1954, Mendum and Tonkin 1976), Donnellan et al (1995) considered the relationship between the then Flynn Group and overlying rocks of Tomkinson Creek beds to be transitional. A difference in fold style between these two units was attributed to a disharmonic relationship rather than to an angular unconformity as proposed by Dunnet and Harding (1967) and Blake (1984). The Tomkinson Creek beds were redefined as a subgroup and combined with the Flynn Group into the Churchills Head Group (Donnellan et al 1995).

Two considerations indicate a major stratigraphic division within both the Churchills Head Group and its correlate to the south, the Hatches Creek Group. Firstly, there is a lithostratigraphic distinction between the volcano-sedimentary lower succession of both groups (with pronounced lateral facies variations and discrete volcanic centres), and the overlying, layer cake stratigraphy. The latter comprises clastic, carbonate and generally subordinate volcanic rocks but includes a regionally extensive flood basalt sequence (Kudinga Basalt and the correlative Whittington Range Member).

Secondly, a structural break occurs between rocks of the Ooradidgee and Wauchope Subgroups, attributed here to the Murchison tectonic event. A corresponding, but not precisely identified break is inferred between the Flynn and Tomkinson Creek successions. Lithostratigraphic correlations between the Churchills Head and Hatches Creek Groups place the break at the base of Hayward Creek Formation. The Flynn, Tomkinson Creek and Ooradidgee Subgroups are therefore redefined here as Groups. The Churchills Head Group is thus redundant and the Hatches Creek Group now only comprises the Wauchope and Hanlon Subgroups.

It is probable that the Tomkinson Creek Group will ultimately be included in the Hatches Creek Group. Recent aeromagnetic data support stratigraphic continuity between the Ashburton and Davenport provinces, corroborating
<table>
<thead>
<tr>
<th>UNIT, MAP SYMBOL AND THICKNESS</th>
<th>LITHOLOGY</th>
<th>STRATIGRAPHIC RELATIONSHIPS</th>
<th>DEPOSITIONAL ENVIRONMENT</th>
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<tbody>
<tr>
<td>TOMKINSON CREEK GROUP</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Short Range Sandstone (Pths)</td>
<td>Quartz arenite, sublithic and lithic arenite, feldspathic sublitharenite</td>
<td>Conformably underlies Attack Creek Formation in Flynn and conformably overlies Morphett Creek Formation</td>
<td>Littoral to sublittoral marine</td>
</tr>
<tr>
<td>Upper sandstone lithofacies (Pths) Top not exposed in SHORT RANGE, -400 m in Flynn</td>
<td>Quartz arenite, sublitharenite and feldspathic sublitharenite; locally trough crossbedded near base, predominantly planar bedded with parallel laminated to thin bedded units arranged in medium to massive sets. Ripples, rhysolitrope and desiccation cracks at various levels</td>
<td>Channeled contact with lower sandstone interval locally, although predominantly faulted. A probable siltstone interval has been largely faulted out</td>
<td>Intertidal/beach</td>
</tr>
<tr>
<td>Lower sandstone lithofacies (Pths) -625 m</td>
<td>Quartz arenite, sublitharenite, feldspathic sublitharenite and siltstone; medium to coarse grained, tabular; well developed bidirectional tabular crossbedding; extensively rippled</td>
<td></td>
<td>Predominantly shallow marine, sublittoral, with intertidal sedimentation in at least two intervals</td>
</tr>
<tr>
<td>Deagan Member (Pths) ≤ 500 m?</td>
<td>Quartz arenite, pebbly sandstone, conglomeritic and siltstone</td>
<td>Conformable with, and partial lateral facies equivalent of Short Range Sandstone and Morphett Creek Formation</td>
<td></td>
</tr>
<tr>
<td>(Pths)</td>
<td>Siltstone; thin bedded with subordinate interbedded sandstone</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>Conglomerate and sandstone</td>
<td></td>
<td></td>
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<tr>
<td>Morpheap Creek Formation (Ptm) -1500 m maximum thickness in SHORT RANGE, −2500 m in Flynn</td>
<td>Sublithic and lithic arenite; feldspathic litharenite; siltstone; green chert interval (tuff); dolostone, quartzitic dolostone</td>
<td>Conformable with Hayward Creek Formation below and Short Range Sandstone above. Partial lateral facies variation with Deagan Member near top of succession. Lowermost succession exposed in northeast and topmost succession in northwest SHORT RANGE</td>
<td>Fluvial, intertidal and shallow marine</td>
</tr>
<tr>
<td>Hayward Creek Formation (Pth)</td>
<td>Lithic and sublithic arenite; feldspathic sublitharenite; pebbly sandstone; siltstone; volcanic rocks</td>
<td>Conformable with Morpheap Creek Formation above, and an apparent transitional contact with Brumbree Formation below. Local channeling at both top and bottom contacts. Conformable, locally channelled, transitional contacts between constituent lithofacies. Intruded by dolerite sills</td>
<td>Fluvial, intertidal and shallow marine</td>
</tr>
<tr>
<td>Whittington Range Member (Pthw) -300 m</td>
<td>Anisitic vesicular volcanic rock, interbedded leached white and pink siltstone and fine sandstone; quartz arenite; green mudstone; chertified stromatolitic biolrns</td>
<td>Poorly exposed in SHORT RANGE</td>
<td>Shallow marine?</td>
</tr>
<tr>
<td>Coodna Member (Pthw, interbedded siltstone lithofacies Pths) -930 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 crossbeds; beds show lateral persistence; rippled. Minor conformable siltstone, shale and fine sandstone in middle</td>
<td></td>
<td>Mainly fluvial</td>
</tr>
<tr>
<td>Meerie Member (Pthw) -870 m, includes −770 m of mainly sandstone overlain by −100 m of volcanic rocks at top (Pths)</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. Weathered and ferruginised felsic to intermediate volcanic rocks at top - laterally discontinuous</td>
<td></td>
<td>Predominantly intertidal/shallow marine. Subaerial? volcanics at top</td>
</tr>
<tr>
<td>UNIT, MAP SYMBOL AND THICKNESS</td>
<td>LITHOLOGY</td>
<td>STRATIGRAPHIC RELATIONSHIPS</td>
<td>DEPOSITIONAL ENVIRONMENT</td>
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</tr>
<tr>
<td>Manga Mauda Member (Pd/n) ~1000 m, includes 900 m of mainly sandstone overlain by ~100 m of silstone at top (Pd/n). Discontinuous volcanic interval (Pd/n) in middle of Member</td>
<td>Lithic and sublithic arenite and pebbly arenite. Predominantly medium grained; medium to thick bedded; planar and shallow angular crossbedded. ~100 m of silstone and fine grained sandstone (thin and planar bedded) 450 m above base and a further ~100 m at top. Minor weathered and ferruginised felsic to intermediate volcanic rocks</td>
<td>Conformable and transitional with underlying Wundirgi Formation and overlying Hayward Creek Formation. Locally faulted contact with Hayward Creek Formation</td>
<td>Predominantly fluvial</td>
</tr>
</tbody>
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**FLYNN GROUP**  
Northern and northwestern (SHORT RANGE) succession

<table>
<thead>
<tr>
<th>Formation/Epoch/Stage</th>
<th>Description</th>
<th>Stratigraphic Relationship</th>
<th>Depositional Environment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brunswick Formation (Par) ~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>Correlates in large part with Bernborough Formation and with upper parts of Wundirgi and Yungkulungu Formations in TENNANT CREEK</td>
<td>Subaerial felsic pyroclastics and waterlain (shallow marine?) reworked equivalents</td>
</tr>
<tr>
<td>Warrego Volcanics (Ero) ~550 m in type area</td>
<td>White, pink, mave, grey and green silstone, chert and felsic tuff and possible ignimbrite interbedded with fine to medium grained lithic arenite</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wundirgi Formation (Pzw) ~3000 m by analogy with Monument Formation</td>
<td>Thin to medium bedded, fine to coarse-grained sublithic and lithic arenite; thin bedded silstone; minor conglomerate and breccia; felsic volcanic rocks</td>
<td>Conformable transitional contact with Brunswick Formation. Competency contrast results in an apparent unconformable relationship between these units locally. In part a lateral facies equivalent of Warrego Volcanics, Whipper Sandstone Member and Monument Formation of FLYNN. Probably equivalent in large part to Yungkulungu Formation in TENNANT 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>UNGROUPED</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Warramunga Formation (Ew) ~3000 m</td>
<td>Lithic arenite, volcanic litharenite and wacke, silstone, shale and phyllite; banded ironstone ('chaenomeple 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>Flynn</td>
</tr>
</tbody>
</table>

Blake's (1984) original correlation. There is a hiatus in the Wauchope Subgroup of the Hatches Creek Group at the base of the Coulter's Sandstone, and a corresponding unconformity is inferred in the Tomkinson Creek Group at the base of the shallow marine Meerie Member of the Hayward Creek Formation.

**Warramunga Formation (Pzw)**

The Warramunga Formation is a polydeformed turbiditic succession of lithic and sublithic arenite, wacke and silstone, terrigenous mudstone and argillaceous banded ironstone. In TENNANT CREEK and FLYNN (Donnellan et al. 1995), and TENNANT CREEK (Donnellan et al. 1999), the Warramunga Formation was divided into two mappable lithological units. These units are a sandstone lithofacies (sandstone greater than silstone) and a silstone lithofacies (sandstone less than silstone). The sandstone lithofacies is generally medium to thickly bedded or massive, whereas the silstone lithofacies is laminated or thinly to medium bedded. Recognisable bedding does not necessarily coincide with individual Bouma sequences. Sandstone or silstone intervals of the Bouma sequence give a false impression of an alternating succession of sandstone and silstone beds.

Outcrop of Warramunga Formation is confined to the southeastern corner of SHORT RANGE. Outcrop of former Warramunga Group over the remainder of SHORT RANGE is now largely assigned to the Flynn Group which is interpreted to unconformably overlie the Warramunga Formation. The distinction is thus made between a deep water sedimentary succession of tuffaceous/volcaniclastic arenite and wacke, and a succession of largely subaerial pyroclastic rocks which give way upwards to a succession dominated by shallow water clastic and epiclastic rocks. Furthermore, Warramunga Formation turbidites are more deformed than rocks of the Flynn Group and SHRIMP U-Pb zircon dating by Compston (1995) confirms that the Warramunga Formation is older than the Flynn Group in TENNANT CREEK. In SHORT RANGE,
all outcropping Warramunga Formation is mapped as siltstone lithofacies with the exception of one area which is intensely intruded by porphyry and is undifferentiated on the map.

Lithic clasts are predominantly of felsic volcanic derivation. Comparable ages (~1.86 Ga, for zircon populations in greywacke from White Devil and Eldorado, and from an altered felsic tuff from Gecko) led Compston (1995) to conclude that Warramunga Formation turbidites were rapidly derived from a penecontemporaneous volcanic source. It is suggested that a large proportion of the Warramunga Formation is tuffaceous. However, Compston (1995) found a mixed provenance for the Formation and recognised a second zircon population with more heavily abraded and rounded grains. Furthermore, many zoned euhedral zircons had rounded cores indicating inheritance. Detrital zircons include grains with ages between 3 and 2 Ga. Zircons with ages of ~1.91 Ga and 1.93 Ga are also present. Compston stated that sources of detritus with these ages have not yet been identified in outcrop. Provenance studies of the Warramunga Formation and similar turbiditic successions in central and northern Australia (eg Lander Rock beds, Mount Bonnie Formation, Burrell Creek Formation, Killi Killi beds) therefore represent an important potential source of information on the origin and tectonic context of these successions and the early Palaeoproterozoic geological history of the North Australian Craton.

Subordinate rock types in the Warramunga Formation are "haematite shale" and thinly interbedded jasperoid and magnetite/haematite rocks. Haematite shale is a local name for an argillaceous banded ironstone (Le Messurier et al. 1990). This consists of laminae or thin beds of fine grained, graded siliciclastic and iron rich detritus, and is interpreted as being of turbiditic origin.

Massive ironstones (magnetite, haematite and maghemite together with quartz) include apparently stratiform as well as discordant bodies, although the latter predominate. Over 600 ironstone bodies have been identified in the Tennant Creek goldfield with the majority being apparently associated with the Warramunga Formation. Most of the gold mineralisation identified to date is associated with these ironstones, although only a small proportion of ironstones carry significant gold.

Possible Warramunga Formation equivalents

A problem associated with the Warramunga Formation is that its volcanic source is apparently not exposed in the vicinity of TENNANT CREEK. Proximal volcano-sedimentary facies corresponding to the medium grained turbidite sedimentation represented by the Warramunga Formation are also not exposed. Possible candidate rocks were intersected during drilling by Occidental (Swingle 1982) on the southwestern margin of TENNANT CREEK. These include volcanolithic debris flow deposits. However, these rocks were assigned to Flynn Group by Donnellan et al (1995).

Felsic volcanic rocks mapped as (former) Warramunga Group in northeastern BONNEY WELL are probable chronostratigraphic correlatives of Warramunga Formation. Smith (1999) dated a sample of Warramunga Group volcanics at 1862 Ma using the SHRIMP U-Pb zircon method. These volcanic rocks were probably deposited under subaerial conditions. They are associated with interbedded sandstone and siltstone (heterolithic facies) that are interpreted as marginal marine rather than deep-water turbidite deposits. These rocks may therefore represent a proximal equivalent and penecontemporaneous source for the Warramunga Formation turbidite sequence.

Another probable correlative is the Junalki Formation, which immediately underlies the Unimbra Sandstone (Wauchope Subgroup, Hatches Creek Group) north of the Murchison syncline in TENNANT CREEK. This formation consists of rhodacitic to rhyolitic crystal-lithic tuff, and minor andesitic to dacitic lava which occurs near its top. Lithologies change from mostly interbedded tuffaceous volcanic and volcaniclastic rocks at the base to predominantly volcanolithic sandstone and siltstone up-section. The Junalki Formation was previously correlated with the 1849 Ma Yungkulungu Formation, which similarly varies from a lower, predominantly volcanic, to an upper predominantly sedimentary succession (Donnellan et al 1995). However, Donnellan et al noted similarities between the Junalki Formation and undifferentiated former Warramunga Group rocks in northeastern BONNEY WELL (see above), and recent geophysical data indicate lateral continuity between them. Thus, the Junalki Formation is extended to include some of the former Warramunga Group rocks in BONNEY WELL. Given that the formation is a possible time equivalent to the Warramunga Formation, it can be concluded that there might be a substantial time interval (~65 my) of stratigraphy missing between the Junalki Formation and Unimbra Sandstone on the northern margin of Murchison Range.

FLYNN GROUP

The Flynn Group comprises volcano-sedimentary rocks previously assigned to the Warramunga Group (Mendum and Tonkin 1976, Dodson and Gardner 1978) but excludes a thick sequence of turbidite, the Warramunga Formation, which hosts gold-copper-bismuth mineralisation associated with ironstone. Three spatially discrete successions have been mapped in the Flynn Group in TENNANT CREEK although correlations between them have been proposed by Donnellan et al (1995, 1999). The Flynn Group in SHORT RANGE is assigned to the northern and western succession. These are predominantly sedimentary rocks and subordinate volcanic rocks comprising the Warrego Volcanics and the Wundirgi and Brumbreu Formations.

The Warrego Volcanics include both subaerial and subaqueous tuffaceous rocks, including accretionary and rim-type lapillii-bearing tuff, some parts of which show a degree of welding. The Warrego Volcanics probably correlate with subaerial tuffaceous rocks of the Wundirgi Formation. They are also interpreted to be more distal equivalents of the ignimbrite, tuff and minor probable lava (plus siltstone, shale and chert) that constitutes the Bemborough Formation of the central succession (Donnellan et al 1999).

Sedimentary rocks of the Wundirgi and Brumbreu Formations have a substantial epiclastic component. The Wundirgi Formation is a monotonous succession of interbedded sandstone and shale with the ratio of sandstone to shale increasing upwards across a transitional contact with
the Brumbreu Formation. The Brumbreu Formation includes subordinate lava and pyroclastic rocks.

From the Warrego Volcanics upward, the Flynn Group in SHORT RANGE shows a progression from subaerial and subaqueous, predominantly volcanic rocks, through off-shore marine, to littoral and finally fluviatile sedimentary rocks at the contact with the overlying Tomkinson Creek Group.

**Wundirgi Formation (Enw)**

The Wundirgi Formation comprises volcanolithic arenite and siltstone, and subordinate volcanic rocks. Over much of its apparent extent in TENNANT CREEK, the Wundirgi Formation is non-outcropping and this has precluded an effective subdivision of the northern and western successions of the Flynn Group. Thus, the Wundirgi Formation may be a correlative of a substantial proportion of the Flynn Group succession elsewhere. Outcrop is comparatively good but discontinuous in SHORT RANGE, where the succession is a monotonous one of interbedded sandstone and shale. The thickness of the formation is difficult to estimate due to discontinuous and folding and faulting. It was previously estimated to be 600 m in the east, thickening to 1500 m in the west (Donnellan et al 1995), but this estimate may be too thin.

The Wundirgi Formation conformably overlies the Warrego Volcanics (eg LU998530) in FLYNN. A pale green chert at the top of the Warrego Volcanics has a sharp contact with interbedded, medium to thickly bedded sandstone and shale. Up-section, the Wundirgi Formation is more thinly to medium bedded and beds become very planar. The ratio of sandstone to shale increases upward across a transitional contact with the Brumbreu Formation.

In SHORT RANGE (LU862608), a 100 m succession of medium to thickly bedded, crossbedded, heavy mineral-bearing lithic arenite, rippled lithic arenite and minor quartz pebble conglomerate underlies a sequence of volcanic rocks and is correlated with the Whippet Sandstone Member. There is a thick east-trending sequence of very thinly to thickly bedded, accretionary lapilli-bearing surge and possible fall deposits in the Wundirgi Formation cropping out at LU780659. This interval is correlated with the Bernborough Formation and Warrego Volcanics.

Several very thickly bedded, graded breccia deposits with mudstone or siltstone clasts occur at LU863612. These are interpreted as fluidised flows and may be the result of surges or ignimbrites entering water. Alternating sandstone and shale beds at the top of the succession show high lateral bedding persistence and are probable storm deposits. The sedimentary succession is interpreted as shallow marine to intertidal. However, the volcanics are mainly subaerial, although subaqueous mass flow deposits are also present. Similar mass flow deposits were intersected in drill core by Occidental (Swingler 1982) in southwestern TENNANT CREEK.

An 1821 Ma date for the marginal monzodiorite phase of a diorite sill intruding Wundirgi Formation in SHORT RANGE provides a minimum age of sedimentation (Compston 1995). Moderately foliated to mylonitic felsic schists to the southwest of Tennant Creek township in TENNANT CREEK have been interpreted as sheared granite or porphyry, and granophyric volcanic rocks from this area have been dated at 1829 ± 8 Ma and 1827 ± 9 Ma (Compston 1995). These volcanic rocks are interpreted to be part of the Wundirgi Formation and the dates therefore provide an age for the formation.

An original Rb-Sr date of 1920 ± 60 Ma for 'amphibolites' from the BMR3 area, southwest of Tennant Creek township, was interpreted as the age of metamorphism and led to the conclusion that rocks in this area must be basement to the then Warramunga Group (Black 1977). Subsequent Sm-Nd systematics (Black and McCulloch 1984) were interpreted as indicating a late Archaean to earliest Proterozoic mantle segregation age. The material sampled for geochronology was interpreted by Donnellan et al (1995) as monzodiorite showing similar alteration mineralogy to that described below for diorites and monzodiorites from SHORT RANGE. These rocks are considered part of the Treasure Suite rather than basement. This interval of stratigraphy may broadly correlate with the Bullion Schist in BARROW CREEK.

**Warrego Volcanics (Eno)**

The most extensive outcrops of Warrego Volcanics are in the Great Western syncline. Warrego Volcanics also crop out in southwestern FLYNN. The succession is best described as tephra. Primary structures are poorly preserved and much of the outcrop comprises white, pink, mafic and grey siltstone, laminated chert, and fine to medium grained lithic sandstone and wacke. Primary volcanic textures are locally preserved. Accretionary lapilli-bearing tuffs have been recognised in FLYNN (LU992532). Some tuffs show a degree of welding and are interpreted as subaerial surge and fall deposits. Otherwise the proportion of primary volcanic to reworked epiclastic rock is difficult to determine.

Warrego Volcanics outcropping in SHORT RANGE are interpreted as predominantly epiclastic. The sandstone includes a range of exotic material together with embayed quartz and volcanolithic clasts. Exotic material is predominantly of polycrystalline quartz showing a variety of textural characteristics that reflect dynamic recrystallisation. These include inequigranular and seriate-interlobate fabrics. Quartz veins tend towards equigranular polygonal fabrics. Many lithic clasts have well defined intersecting cleavages; these are continuous with but are generally better defined than those in the surrounding rock. Similar grain types are common in the Brumbreu Formation although this unit is predominantly more coarse grained and cleavage, defined by fine sericite in lithic fragments, does not extend beyond grain boundaries. This is suggestive of reworked material, and a possible hiatus in the succession.

The Warrego Volcanics may partially correlate with volcanic rocks near the top of the Wundirgi Formation.

**Brumbreu Formation (Ebr)**

The Brumbreu Formation overlies the Wundirgi Formation and comprises lithic arenite, predominantly volcanic litharenite, heavy mineral-bearing quartz arenite, granule- and pebble-bearing sandstone, felsic tuff, silicified felsic tuff (chert) and shale in outcrop. The type section for this formation is in SHORT RANGE where 900 m of section are exposed between LU862632 (base) and LU868644 (top).
Mendum and Tonkin (1976) measured 1450 m of Brumbyre Formation to the north of Last Hope. Westward thickening of Brumbyre Formation may be a consequence of fault repetition.

The Brumbyre Formation crops out discontinuously along the southern margin of SHORT RANGE as rounded strike ridges separated by narrow valleys. It is broadly equivalent to the unnamed unit Pw, of the former Warramunga Group as mapped by Mendum and Tonkin (1976). These authors divided the Warramunga Group into seven unnamed lithostratigraphic units (Pw, ,.) together with the Warrego and Gecko Volcanics, Bemborough Formation and Whippet Sandstone Member. Blake (1984) correlated unit Pw, with the Ooradiddlee Group. Blake recognised an unconformity (LUB51609) between units Pw and Pw of the former Warramunga Group which he correlated with the unconformity between the Warramunga Group (of previous usage) and the Hatches Creek Group (Wauchope Subgroup) in the Murchison Range.

Donnellan et al (1995) mapped a planar, conformable contact between the Brumbyre and Wundirgi Formations at LU808637. Here a distinctive greyish-green, medium to thickly bedded, cross-beded sandstone at the base of the Brumbyre Formation overlies thinly bedded, rippled interbedded sandstone and siltstone of the Wundirgi Formation. The relationship appears transitional with interbedded sandstone and siltstone of the Wundirgi Formation becoming increasingly dominated by sandstone upward towards the contact with the Brumbyre Formation.

A pale green chert at the contact between Brumbyre and Wundirgi Formations in SHORT RANGE (eg LU862632 and LU810633) is interpreted as a silicified tuff and is probably in situ. A similar chert at LU933638 is apparently stratigraphically higher in the Brumbyre Formation and is attributed to significant fault repetition within this formation. There is evidence for similar repetition in the area to the north and northwest of Last Hope.

Relationships of Flynn Group in SHORT RANGE

Rhyolitic and dacitic volcanic rocks, ignimbrite, and subordinate to minor lava of the Flynn Group are broadly coeval with the early granite and felsic porphyry that are widespread in TENNANT CREEK. The intrusive rocks are syn- to post-tectonic with respect to the earliest deformation that affected the Warramunga Formation (equivalent to the Barramundi Orogeny of Etheridge et al 1987). McPhie (1993) has demonstrated that, at least locally, the porphyries are peperitic and intruded into a wet sedimentary pile. Rattenbury (1992), following previous workers, considered that the porphyries formed an extensive stratiform sheet that was folded together with the Warramunga Formation. However, geochronological data of Compston (1995) confirmed that there are at least two episodes of porphyry intrusion, 1853 Ma and 1838 Ma. It is argued here that regional folding in the porphyries is due to a subsequent deformation event, which was close to coaxial with prior folding resulting from the Barramundi Orogeny. This later deformation (the Murchison tectonic event) may broadly correlate with the 1820 Ma Stafford tectonic event in the Arunta province.

Porphyry at White Devil clearly cuts folding and cleavage in the Warramunga Formation according to Nguyen (1987) and Edwards et al (1990). This porphyry was dated at 1853 Ma by Compston (1995) who concurred with McPhie (1993) that an older suite of felsic porphyries intruded a sequence of unlithified greywacke and was subsequently folded. A younger suite of porphyries from the Jubilee area in TENNANT CREEK was dated by Compston (1995) as 1838 Ma. Compston reasoned that the Warramunga Formation was rapidly redeposited from its felsic volcanic source rocks and that sedimentation was contemporaneous with volcanic activity. This is consistent with petrographic and geochemical considerations presented by Donnellan (1994) and Donnellan et al (1995). However, it is noted that volcanic activity penecontemporaneous with the
Warramunga Formation is spatially discrete. Warramunga Formation turbiditic rocks and contemporaneous volcanic rocks of the Junalki Formation are considered valid lithostratigraphic units. Partial time equivalence between the Warramunga Formation and Flynn Group was postulated by Donnellan et al. (1997) and is shown in Figure 1.

Blake et al. (1987), Wyche et al. (1987) and Wyche and Simons (1987) mapped an unconformity between the Warramunga Group and the Wauchope Subgroup of the Hatches Creek Group in Murchison Range in northern BONNEY WELL. The Ooradidgee Group in this area is only represented by a thin interval of Epenarra Volcanics. This is apparently consistent with deposition of the Ooradidgee Group in a number of fault-bounded basins associated with separate volcanic centres (Stewart 1987). Alternatively, the former undivided Warramunga Group in this area may represent: (1) Warramunga Formation, or volcano-sedimentary rocks contemporaneous with and representing a marginal facies to Warramunga Formation; or (2) correlatives of Flynn Group in TENNANT CREEK and/or Ooradidgee Group in the Davenport province.

An important question from an economic point of view is the regional extent of the Warramunga Formation basin of sedimentation. Is it part of a continuous basin extending from the Pine Creek Orogen to the northern Arunta province or is it a small, localised basin perhaps analogous to the Neogene Betic molassic basins of Spain? Compressional basins of the eastern Betic mountains are characterised by turbidite-dominated sedimentation (Debelmas and Masce 1998), and have a similar association of features to those recognised at TENNANT CREEK. Specifically, syn-sedimentary deformation occurred about vertical fold axes, particularly adjacent to strike-slip faults, resulting in an en echelon arrangement of folds. Two sets of conjugate transverse faults and reverse faults are also recognised in the Betic terrain. There is a close association between compressional and extensional basins in the Betic mountains, and there was substantial volcanic activity - particularly dacitic and rhyolitic (shoshonitic) ignimbrites attributed to crustal melting and with no relationship to subduction.

Thus, the situation envisaged in TENNANT CREEK is that classic turbidites (Warramunga Formation) accumulated in a compressional basin and deformed essentially contemporaneously with the accumulation of volcanic and volcaniclastic rocks (Flynn Group) in an adjacent, extensional basin on the other side of a strike slip fault (Figure 2). The lower part of the Flynn and Ooradidgee Groups may have accumulated contemporaneously with the Warramunga Formation.

Relationship between Flynn Group and Tomkinson Creek Group

The monzodioritic marginal phase of a Treasure Suite dolerite intruding the Wundirgi Formation (Flynn Group) was dated at 1821 Ma (Compston 1995). Similar monzonic and dioritic rocks intrude up to the lower part of the Brumbreu Formation. The basal unit of the Tomkinson Creek Group (Hayward
Creek Formation) has a maximum age of sedimentation of 1784 Ma for the base of Meerie Member (Compston 1995). This suggests the existence of a substantial time break somewhere between the Wundirgi Member (older than 1821 Ma) and the overlying Tomkinson Creek Group (younger than 1784 Ma). The precise location of the time break (and any corresponding unconformity) remains equivocal.

The favoured position for this hiatus is between the Manga Mauda and Meerie Members of the Hayward Creek Formation. This would correlate with the hiatus recognised by Haines et al (1991) between the Strzeleckie Volcanics and Illoqua Sandstone (equivalent to the Coutlers Sandstone) in BARROW CREEK.

Alternatively or additionally, the Hayward Creek Formation progrades across, and is unconformable on the Brumbree Formation. The base of the Hayward Creek Formation in this case is a sequence boundary and may represent a hiatus. Conglomerate is developed, or preserved, at least locally at this level and is mapped as the Blanche Creek Member (MU122857 in FLYNN).

The Unimbra Sandstone of the Wauchope Subgroup in the Davenport province was interpreted by Sweet (in Blake et al 1987) to be representative of a transgressive/regressive cycle. Sweet reported that the conglomeratic beds at the base of the Unimbra Sandstone in the Kurundi Region are a continuation of the Taragan Sandstone (of the Ooradidee Group). The fluviatile, lowermost member of the Hayward Creek Formation (Manga Mauda Member) may correlate with the Taragan Sandstone (and with fluviatile facies of the Treasure Volcanics). These relationships compound the problem of determining a precise lithostratigraphic horizon in the Tennant Inlier to correspond with the Murchison tectonic event.

Heavy mineral laminae in sandstone of Brumbree Formation contain abundant zircon with successive overgrowths and scarcely abraded crystal forms. Geochronological study of this material may further constrain the location of the time break and probable unconformity.

Hussey et al (1999) reported an eruptive age of 1819 Ma for the Strzeleckie Volcanics in BARROW CREEK. This date together with lithostratigraphic correlations between the Tomkinson Creek Group and Wauchope Subgroup, originally proposed by Blake (1984), would be consistent with a substantial hiatus between the Manga Mauda and Meerie Members of the Hayward Creek Formation. This would correspond with the unconformity between the Strzeleckie Volcanics and Tinfish Sandstone and the overlying Illoqua Sandstone, as recognised by Haines et al (1991) in BARROW CREEK.

In addition, Blake (1984) identified a possible angular unconformity towards the top of rocks mapped by Donnellan et al (1995) as the Wundirgi Formation. This would suggest that the break between the Flynn and Tomkinson Creek Groups is at the base, rather than at the top of the Brumbree Formation.

The relationship between the Tomkinson Creek Group and the underlying former Warramunga Group has been variously interpreted to be conformable, conformable and transitional, disconformable, an erosional unconformity or a tectonic unconformity (see Ivanac 1954, Dunnet and Harding 1967, Mendum and Tonkin 1976, Blake et al 1987, Compston 1995 and Donnellan et al 1995). An angular unconformity is now postulated within the Hatches Creek Group at the base of the Unimbra Sandstone and attributed to the Murchison tectonic event (see below under STRUCTURE). Correlation of the Unimbra Sandstone and the Manga Mauda Member of the Hayward Creek Formation suggests the corresponding tectonic break in the northern Tennant Inlier is between the Brumbree and Hayward Creek Formations.

**TOMKINSON CREEK GROUP**

**Hayward Creek Formation (Bth)**

The Hayward Creek Formation is a succession of medium to coarse grained sandstone, granule and pebble bearing sandstone and local pebble and cobble bearing conglomerate, together with subordinate fine grained sandstone, siltstone and volcanic rocks. The formation has a thickness of about 3 km in the type section in FLYNN (Appendix 1), where the Whittington Range Member adds an additional 300 m to the top of the formation. The Hayward Creek Formation is substantially thicker in SHORT RANGE, in part due to thick intervals of volcanic rocks intercalated with the sandstone but also (and predominantly) due to intrusive dolerite. The aggregate thickness of Hayward Creek Formation and the dolerites which intrude it is about 5 km in SHORT RANGE.

Sandstone includes lithic arenite, sublitharenite, quartz arenite and orthoquartzite. Lithic clasts are dominated by those of volcanic origin. There is a well defined laminated throughout the Hayward Creek Formation due to grain size variation between coarse and medium grained sandstone. This grain size variation is commonly reinforced by compositional variation between lithic-rich and lithic-poor sandstone. Furthermore, there is a colour lamination between pink and grey that probably reflects the relative proportion of clay to mineral cement.

The Hayward Creek Formation was divided into three mappable, but informal members in FLYNN (Donnellan et al 1995): the lower, middle and upper sandstone members. These were referred to as lithofacies rather than members in TENNANT CREEK (Donnellan et al 1999) in order to avoid any confusion that these were, at that stage, formal lithostratigraphic units. They are formally defined here, in ascending stratigraphic order, as the Manga Mauda, Meerie and Coodna Members (see Appendix 1). The type sections for these members are contiguous and are in FLYNN. The division is made principally on the basis of contrasting sedimentary characteristics, particularly bedding, which reflect palaeoenvironmental differences. The lower and upper units, Manga Mauda Member and Coodna Member respectively, are both interpreted as being predominantly fluviatile in origin. The middle Meerie Member is indicative of a peritidal (foreshore/shoreface) environment throughout both TENNANT CREEK and HELEN SPRINGS. The lateral persistence of this palaeoenvironment is remarkable.

Poorly outcropping and laterally persistent intervals of siltstone and volcanic rock separate the Manga Mauda and Meerie Members and a volcanic horizon separates the Meerie and Coodna Members, at least locally, in FLYNN. A further siltstone interval is locally mappable within the Manga Mauda Member. Four fining upward cycles are recognised in the type section in FLYNN (see Donnellan et al 1995).
and volcanic intervals are mapped separately where possible but are defined as part of the Manga Mauda and Meerie Members. A similar, but thicker and more readily mappable, interval of intermediate volcanic rocks, thinly bedded sandstone and siltstone, and locally outcropping silicified carbonate rocks showing cryptomicrobial lamination at the top of the Hayward Creek Formation was defined as the Whittington Range Volcanics by Mendum et al. (1978). It was redefined as a member of the Hayward Creek Formation by Donnellan et al. (1995). There is only one, equivocal, outcrop of Whittington Range Member in SHORT RANGE.

Volcanic and intrusive rocks apparently crop out more in the lower intervals of the Hayward Creek Formation in SHORT RANGE than in FLYNN. Geophysical data suggest that generally stratiform igneous rocks are widespread throughout the uppermost Hayward Creek Formation and persist to the top of the formation. Although they are broadly stratiform, these rocks show slight, to locally strong crosscutting relationships with sedimentary rocks of the Hayward Creek Formation. These igneous rocks probably include both intrusive equivalents of the volcanic rocks of the Whittington Range Member and volcanic rocks from lower in the Hayward Creek Formation. The implication is that there is significant ongoing magmatism post-dating the Treasure Suite.

*Manga Mauda Member (Ph*m)*

The Manga Mauda Member is a succession of medium to very coarse grained, medium to thickly bedded sandstone. It is granule and pebble bearing and has crossbedded sets up to 5 m thick. Its thickness is about 1 000 m in SHORT RANGE.

The contact with the underlying Brumbre Formation is apparently transitional and the base of the Manga Mauda Member is taken as the first significant pebble bed. There is local development of conglomerate at this stratigraphic level. For example, at LU774712, about 50 m of massive, poorly bedded, matrix supported pebble conglomerate crops out, although the underlying contact with Brumbre Formation is obscured by sand. This interval could correlate with conglomerate mapped as Blanche Creek Member in FLYNN at MU122856. However, a lack of lateral continuity suggests that the conglomerate is confined to local, discontinuous mega-channels and hence it has not been mapped separately in SHORT RANGE.

The more thickly bedded sandstone is generally coarse grained, poorly sorted and rounded, and may show grading. Conversely, medium bedded sandstone typically has uniform lamination and lower angle cross bedding, and grains are finer, better sorted and more rounded. An upward progression from coarse to medium grained sandstone, along with a corresponding change in bed thickness and the rounding and sorting of grains is suggestive of an overall fining upward cycle. Repeated fining upward cycles comparable to those recognised in the type section in FLYNN were not identified in SHORT RANGE. However, there is a return to coarse, thickly bedded sandstone with local pebble conglomerate part way up-section in the Manga Mauda Member (eg at LU795725), and this is accompanied by an upward change in bed thickness, grain size and sorting of sandstone, and is indicative of cyclicity. These variations may be consistent with a braided river system, which is possibly more proximal in the west.

Vein quartz is the dominant pebble and cobble material, but some pebble horizons and conglomerates are more polymictic and contain siltstone, chert, and jasper as additional clast types. Mendum and Tonkin (1976) described rare porphyry clasts from the Hayward Creek Formation in FLYNN (eg MU231710), and chert clasts are probably dominated by volcaniitic material. Rhyolite pebbles and porphyry clasts are also found at MU145790 and MU240700, again in FLYNN.

Opaque minerals define laminations in 'heavy mineral sandstone'. Iron minerals are also developed as surface coatings on mineral grains and may now be black, red or reddish-yellow (ie haematised or limonitised). These coatings are absent at point contacts between grains (particularly those between quartz and less stable lithic grains). Thus ‘reddening’ postdates sedimentation and initial compaction, but predate quartz overgrowths and clay cement. These ‘red beds’ are nearly synchronous with the oldest ‘true’ redbeds (~1.9 Ga). However, the latter are typically attributed to episodes of palaeosol development beneath major unconformities (Windley 1995) and reddening of detritus prior to sedimentation. Abundant weathered-out ‘shale’ clasts are almost a diagnostic feature of the Morphett Creek Formation. However, they are also locally abundant in the Hayward Creek Formation.

The lithic content of the sandstone is variable and although Manga Mauda Member is best described as sublithic arenite it does include both lithic and quartz arenite. Lithic clasts are dominated by those of volcanic origin and include readily identifiable, partially welded ignimbritic clasts, euhedral and embayed quartz phenocrysts in devitrified glass matrix, and cherty rock fragments some of which carry rutile needles and sericitised feldspar microlites. Quartz clasts include a wide variety of types. Strained and unstrained monocrystalline quartz includes euhedral and embayed grains as noted above. In addition, there are grains showing variable degrees of rounding. These include some grains that are well-rounded with similarly rounded quartz overgrowths that indicate a minor component of reworked, polycyclic grains. Polycrystalline quartz grains include those with sutured or interlobate, polygonal, and castellated textures all suggesting derivation from statically recrystallised source rocks. Polycrystalline grains with a marked preferred orientation of elongated subgrains attest to source rocks having experienced dynamic recrystallisation.

The indications are for a mixed provenance. Geochronological studies of a sample taken from the Meerie Member in FLYNN by Compston (1995) showed three age populations of zircon. These populations are 1784 Ma (the maximum age of sedimentation), 1823 Ma and 1862 Ma; individual older grains range to ~2650 Ma and a group of three zircons is dated at 1962 Ma. These dates are consistent with derivation of the Hayward Creek Formation from a provenance that experienced prior and penepencontemporaneous volcanic activity. Probable source rocks include the Treasure Suite and the Warramunga Formation or its source volcanics. Evidence for the Tennant Creek Supersuite being a significant contributor to the Hayward Creek Formation is apparently lacking in the zircon data. This is difficult to reconcile with significant exposure of the Warramunga Formation at the time of deposition of the Hayward Creek
Formation and indicates that the felsic volcanic source of the Warramunga Formation may still have been exposed during Tomkinson Creek Group sedimentation. These sources are in addition to material from the uppermost Flynn Group and from subsequent felsic volcanic rocks aged ~1784 Ma. These data indicate that detailed petrographic studies of the Hayward Creek Formation may be a powerful tool in unravelling the regional tectonic context and structural history of the Tennant Creek province.

Locally, the top of the Manga Mauda Member is difficult to distinguish from the basal Meerie Member. Near the top of the Manga Mauda Member at LU846687, a grain size laminated sandstone has thin to thick beds, well sorted and rounded grains and a wide range of ripple types. These include straight and sinuous, parallel and bifurcating, and symmetric to slightly asymmetric ripples. There are ripples with rounded or pointed crests, including oscillation ripples, together with interference, cusptate and linguoid forms. Successive beds typically show ripples in different orientations. These characteristics are comparable with typical Meerie Member. Immediately above this locality, an interval of fine grained, thinly bedded sandstone and siltstone is a probable correlate of the siltstone that occurs at the top of the Manga Mauda Member in FLYNN. The base of the Meerie Member is immediately above this interval (e.g. LU862686) and is characterised by a thinly to medium bedded pebble conglomerate overlain by a tabular, parallel laminated, medium grained sandstone. Pebble conglomerate also marks the base of the Meerie Member along strike at LU845698.

**Meerie Member (Pth.)**

The Meerie Member is about 870 m thick. It is characterised by repeatedly grain size laminated, well rounded and well sorted sandstone, which has very low angle cross bedding in medium bed sets that show good lateral persistence. Meerie Member sandstone is generally less lithic than that of the Manga Mauda Member, and is typically a quartz or sublithic arenite. However, the Meerie Member also includes sandstone that shows poor sorting and rounding of clasts, and some lithic arenite verges on lithic wacke in that it has abundant recrystallised matrix. These more lithic rocks are probably a consequence of intermittent penecontemporaneous volcanic activity and rapid epiclastic sedimentation, as discussed above. The greater overall compositional and textural maturity of sandstone of the Meerie Member in contrast with that of both the Manga Mauda and Coodna Members probably resulted from its peritidal depositional setting as opposed to the fluviatile settings of the other members.

Trough crossbedded pebble and cobble conglomerate, and pebble and granule bearing sandstone, which is about 6 m thick at LU440810, was previously assigned to the ‘middle sandstone member’ of the Hayward Creek Formation by Donnellan et al. (1995). It is now considered part of the Short Range Sandstone (see below).

Ripple marks are well represented in the Meerie Member. At LU830725, lunate, pointed crested symmetric and slightly sinuous crested ripple marks occur. Nearby at LU835720, ripple marks are bifurcating and are rounded or truncated. Abundant ripple marks at LU849706 indicate significant lateral continuity of an intensely ripple marked interval of Meerie Member immediately below the contact with the Coodna Member. At this level, Meerie Member sandstone also becomes a thinly to very thinly bedded fine sandstone and siltstone (e.g. LU833724) suggesting lateral continuity of the siltstone lithofacies marking the topmost Meerie Member in FLYNN. Local lateral variation between siltstone and volcanic lithofacies seen in FLYNN at this stratigraphic level has not been identified in SHORT RANGE.

The Meerie Member is typically much more dissected than the upstanding, silicified ridges of the Manga Mauda and Coodna Members. Exposures are typically tabular although the member also outcrops as boulders (e.g. LU826717). Similar bouldery outcrop of Meerie Member is seen in HELEN SPRINGS at LV065015.

**Coodna Member (Pth.)**

The Coodna Member is very similar to the Manga Mauda Member. It mainly consists of medium to very coarse grained, medium to thickly bedded sandstone that is granule and pebble bearing. Crossbed sets up to 5 m thick occur. The lowermost, medium to thickly bedded, trough crossbedded sandstone of the Coodna Member has a substantial volcanolithic component (e.g. LU830728). The thickness of the member is about 930 m in SHORT RANGE. Like the Manga Mauda Member, the Coodna Member is considered to have been deposited in a fluviatile environment.

**Whittington Range Member (Pth.)**

Formerly known as the Whittington Range Volcanics (Mendum et al. 1978), the Whittington Range Member was included in the Hayward Creek Formation by Donnellan et al. (1995). It is inferred to occur at only one locality in SHORT RANGE (LU920810), where the outcrop is deeply weathered. Recent geophysical data corroborates this inference. As mapped in FLYNN and BRUNCHILLY, the Whittington Range Member is up to ~300 m thick and includes mudstone/siltstone, fine sandstone, silicified cryptomictobically laminated rock (originally ?dolostone), and volcanics (Donnellan et al. 1999). Mendum et al. (1978) reported a 347 m thick type section. The clastic sedimentary rocks are thinly bedded and have ripple marks. They suggest a protected, shallow water to intertidal environment.

Mendum and Tonkin (1976) described the volcanic rocks of the Whittington Range Member from fresh material obtained in drill core (BMR3; MU078929). The volcanics are amygdaloidal basalts of tholeiitic affinity that bear andesine laths together with augite and pigeonite in a groundmass of magnetite, haematite, chlorite and clay minerals. Minor spherolithic rhyolites are also recognised as are fine to medium grained quartz arenite and subarkose with accessory bluish-green tourmaline, and micaceous siltstone. Material analysed from MU060758 is andesitic. Here two flows of porphyritic andesite, each about 50 m thick, crop out immediately below the contact with the overlying Morphett Creek Formation. These two flows are separated by 10 m of medium grained, medium and planar bedded sandstone.
Morphett Creek Formation (Ptm)

A significant portion of northern SHORT RANGE may be underlain by the Morphett Creek Formation but is covered by Cambrian strata of the Wiso Basin and Cainozoic detritus. Outcrop of this unit is largely restricted to a small area in extreme northeastern SHORT RANGE, although there is some outcropping Morphett Creek Formation in the central west. The Morphett Creek Formation is better exposed in FLYNN, where it comprises a succession of sandstone, siltstone, mudstone and carbonate rocks. Four lithofacies were recognised in the Morphett Creek Formation in FLYNN by Donnellan et al (1995). These are: (1) a lower sandstone lithofacies with a local development of; (2) a basal conglomeratic lithofacies; (3) a middle mixed siliciclastic/carbonate lithofacies; and (4) an upper sandstone/siltstone lithofacies. Poor outcrop and structural complexity, particularly associated with later faulting, frustrate attempts to map these lithofacies individually in SHORT RANGE. However, they are widespread in FLYNN and show good lateral continuity into southern HELEN SPRINGS where the best exposures of the formation are to be found.

Lower sandstone lithofacies

Two mappable units are recognisable in the lower sandstone lithofacies in FLYNN, BRUNCHILLY and MUCKATY. The lower interval of this sandstone lithofacies is about 500 m thick and consists of interbedded fine grained sandstone and siltstone. Although quite quartzose near its base, this lower sandstone becomes more lithic and micaceous upward. Numerous, rounded sandstone pebbles indicate that conglomerate probably occurs locally near the base (eg MV038018). Abundant weathered-out shale clasts are indicative of substantial intraformational detritus. This lower interval is distinguished by its dark weathering characteristics and phototones, together with a rounded, dissected topographic expression.

In contrast, there is a markedly laterally persistent, bench character to the overlying quartz arenite, which constitutes the upper ~1000 m of the lower sandstone lithofacies. This sandstone is well rounded and sorted and has a sugary texture. Fine grained sandstone and siltstone interbeds become more abundant towards the top of the upper sandstone interval.

Both sandstone intervals show repeated grain size lamination, are medium bedded with tabular crossbeds and have a transitional relationship. Abundant ripple marks near the base of the lower sandstone interval include interference and sinuous crested, asymmetric forms. Desiccation features are found in fine grained sediments of both the lower and upper sandstone intervals.

Mixed siliciclastic/carbonate lithofacies

The mixed siliciclastic/carbonate lithofacies comprises a cyclic succession of thin to medium bedded sandstone; laminated siltstone and microbial and stromatolitic boundstone. Both types of boundstone are intensely silicified and commonly outcrop as green and blue-grey chert, including ribbon chert, particularly in HELEN SPRINGS. Stromatolites include large domical forms with diameters of the order of 10 m that locally form aggregations up to 100 m in diameter (eg MV030080).

Ripple marks and locally abundant pseudomorphs after evaporite minerals (halite casts and cauliflower chert) are widespread in HELEN SPRINGS as reported by Randal et al (1966) but are apparently not recognised in TENNANT CREEK. There may therefore be a progressive change in rock type and in corresponding palaeoenvironment within this mixed siliciclastic/carbonate lithofacies between FLYNN, and BRUNCHILLY and MUCKATY. Dolomudstone, coarser dolostone and quartzitic dolostone are additional rock types outcropping in this mixed lithofacies. A distinctive, ooid-bearing quartzitic dolostone is found near Kuerschner Creek (eg MV055225) in BRUNCHILLY, and is correlated with a similar rock at MU054929 in FLYNN. This supports a model of lateral facies equivalence between the mixed siliciclastic/carbonate lithofacies in HELEN SPRINGS and the recessive middle unit of the Morphett Creek Formation in FLYNN.

Upper sandstone/siltstone lithofacies

The upper sandstone/siltstone lithofacies comprises planar, thinly to medium bedded, fine to medium grained sandstone and siltstone. The sandstone is markedly laterally persistent. It consists of lithic and sublithic arenite, but becomes finer grained, better sorted and less lithic and feldspathic upward. Angular quartz grains and the prevalence of chert among the lithic material suggest that some of the sandstone and siltstone may be tuffaceous. The unit is markedly micaceous. Intraformational clasts, and weathered-out shale clasts are widespread. Halite pseudomorphs, nodular cauliflower chert and ribbon chert suggest a similar association of rock types as in the middle, mixed siliciclastic/carbonate lithofacies but with a greater siliciclastic component. Vertical lithofacies variations between the middle and upper lithofacies are probably paralleled by similar lateral facies variations within these two lithofacies. Sandstone in the upper interval of the stratigraphy is better sorted, contains more rounded grains, and is more compositionally mature in HELEN SPRINGS where the distribution of lithic arenite is localised.

Although they immediately overlie the Hayward Creek Formation, rocks of the Morphett Creek Formation in northeast SHORT RANGE are lithologically more typical of the upper part of the Morphett Creek Formation in FLYNN, and HELEN SPRINGS. They comprise planar, thinly to medium bedded, laterally persistent, fine to medium grained, markedly micaceous sandstone and siltstone.

Rocks mapped as undifferentiated Morphett Creek Formation in central-western SHORT RANGE could be assigned to a number of lithostratigraphic units within the Tomkinson Creek Group. They consist of medium to coarse grained, laminated and crossbedded sandstones that are thinly to medium bedded and locally granule-bearing. Their geological context indicates that they probably occur towards the top of the Morphett Creek Formation. They bear comparison with an unnamed sandstone unit at the base of the Short Range Sandstone mapped by Donnellan et al (1995) as 'unit A of the lower sandstone lithofacies'. These rocks are now included in the Deagan Member (see Hussey et al 2001). This unit comprises rocks in FLYNN and southern
HELEN SPRINGS that are correlatives of part of both the upper portion of the Morpnett Creek Formation and the lower interval of the Short Range Sandstone. The Deegan Member appears to thicken to the north and east in HELEN SPRINGS, probably largely at the expense of the Morpnett Creek Formation rather than the Short Range Sandstone.

There is a probable disconformity at the bases of both the Morpnett Creek Formation and the Short Range Sandstone. The uppermost Morpnett Creek Formation shows chevron folding in FLYNN, SHORT RANGE and BRUNCHILLY and is folded disharmonically with respect to the overlying Short Range Sandstone. This is probably due to a competency contrast between interbedded sandstone and siltstone of the upper Morpnett Creek Formation and sandstone of the lowermost Short Range Sandstone.

**Short Range Sandstone (Pts)**

The Short Range Sandstone predominantly comprises medium to coarse grained quartz arenite, lithic and sublithic arenite, and feldspathic arenite. These lithologies suggest a mixed provenance that may include a variable proportion of penecontemporaneous reworked volcanic detritus. Two lithofacies are recognised in the Short Range Sandstone in FLYNN on the basis of bedding characteristics and sedimentary structures. They are similarly recognisable and mappable in SHORT RANGE. The lower sandstone lithofacies contains bidirectional, tabular, high-angle crossbeds arranged in medium to thick bed sets. Prolific and varied ripple marks are a characteristic feature of this interval, particularly in the northwestern outcrop area. These include straight crested symmetrical, asymmetrical, slightly sinuous, lunate interference, and oscillation ripples. Shrinkage cracks are also apparently quite widespread (eg LU436890, LU438806). The upper sandstone lithofacies has a more massive appearance. It has parallel, planar, or very shallow angle crossbeds and laterally persistent thin beds arranged in thin, medium or more typically, thick to massive bed sets.

Outcrop of Short Range Sandstone is restricted to the northwestern corner of SHORT RANGE. Rocks in this area were previously mapped as Hayward Creek Formation (Mendum and Tonkin 1971). The present reinterpretation is corroborated by recent AGSO geophysical data. Outcrop defines a partially exposed, north orientated, northerly plunging synclinal fold showing significant elongation parallel to the fold axis, which has a total length of 25 km. On the western limb of this fold, the lower sandstone lithofacies shows folding of a shorter wavelength and faulting out of anticlinal folds by north orientated faults. The lower sandstone lithofacies probably defines a partially exposed, corresponding, north plunging anticlinal fold.

**Deegan Member (Pts)**

The Short Range Sandstone has a transitional contact with the Morpnett Creek Formation. The transition is encompassed by the Deegan Member which was first mapped separately in HELEN SPRINGS although Donnellan et al (1995) recognised it as a discrete lithostratigraphic interval (and included it in the lower sandstone lithofacies) of the Short Range Sandstone in FLYNN. The Deegan Member was defined by Hussey et al (2001). Three lithofacies are shown on the map and are dominated respectively by: quartz arenite and minor pebbly sandstone; conglomerate and coarse sandstone; and siltstone with lesser sandstone interbeds.

Locally, the Deegan Member comprises a pebble to boulder conglomerate with a matrix of coarse sand and granules. This conglomerate has laterally persistent, planar beds and is interbedded with minor sandstone. It has a maximum thickness of 8 m at LU439814. At this locality, a progressive upward change from conglomerate to planar bedded, laterally persistent quartz sandstone, gritstone and pebble conglomerate is exposed.

Granule and pebble bearing sandstone and granule conglomerate are found in the lower sandstone lithofacies of the Short Range Sandstone. This is in marked contrast with FLYNN and may have contributed to the original assignment of these outcrops to the Hayward Creek Formation by Dodson and Gardener (1978). The Deegan Member is apparently in part laterally equivalent to both the upper Morpnett Creek Formation and, to a lesser extent, the lower sandstone lithofacies of the Short Range Sandstone.

**INTRUSIVE ROCKS**

A large part of the Tennant Creek province is occupied by granite although outcrop is generally poor. A large number of individual granites were mapped in the first edition TENNANT CREEK (Mendum and Tonkin 1971) due to geographic isolation and minor petrographic variations. Donnellan et al (1995) recognised that many Palaeoproterozoic granitic rocks in TENNANT CREEK have strikingly similar mineralogy, petrography and geochemistry and consequently tried to minimise unnecessary subdivision.

The oldest exposed granitic rocks in TENNANT CREEK are part of a widespread 1880-1840 Ma felsic volcano-plutonic suite (Barramundi Igneous Association) which is syn- to immediately post-tectonic with respect to the widespread Barramundi Orogeny of Etheridge et al (1987). These 'early' felsic volcano-plutonic rocks in TENNANT CREEK are included in the ~1850 Ma Tennant Creek Supersuite of Wyborn et al (1998). Local representatives in SHORT RANGE are the Tennant Creek Granite (at Red Bluff), the Warrego Volcanics and probable unnamed correlatives in the Wundirgir Formation, and representatives of the first of two episodes of porphyry intrusion.

The ~1820 Ma Treasure Suite is restricted in outcrop to felsic and intermediate volcanic rocks, and granophyre, porphyry, and diorite to monzodiorite intrusive rocks. However, a gravity low beneath the Tennant Creek goldfield that was modelled by Rattenbury (1994) is probably better reconciled with granite of the Treasure Suite rather than the Tennant Creek Supersuite, given their respective densities (Wyborn et al 1998a). In SHORT RANGE, outcropping representatives of the Treasure Suite include unnamed diorite and monzodiorite that intrude the Wundirgir and Brumbree Formations, and possibly the younger of two intervals of porphyry intrusion, although the latter may relate to the closing stages of the Tennant Creek Supersuite or a discrete episode of magmatism. Felsic and intermediate volcanic rocks in the Hayward Creek Formation and dolerite that intrudes this unit are probably younger than the Treasure
Suite and may therefore represent a separate episode of igneous activity. Wyborn et al. (1998a) pointed out that the bimodal Treasure Suite has its more mafic end members preserved in the northwest in the Tennant Creek province, whereas the more felsic and fractionated end members occur to the southeast in the Davenport province.

A final episode of igneous activity is represented in SHORT RANGE by the Warrego Granite. This is probably a member of the ~1710 Ma Devils Suite of syn-to post-tectonic granite. Lamprophyre dykes intrude the Tennant Creek province along a northwesterly-oriented zone from the vicinity of Gosse River to Warrego. These dykes are broadly contemporaneous with the Warrego Granite.

**Tennant Creek Granite at Red Bluff (Pgt)**

This granite was included in the informal Tennant Creek granite complex of Crohn and Oldershaw (1967) and was subsequently referred to as Red Bluff granite by Mendum and Tonkin (1976). Morrison (in Donnellan et al 1999) defined the granite outcrops at Red Bluff as part of the Tennant Creek Granite. As it is part of a granite body outcropping over an area of about 50 km² in southwestern SHORT RANGE, northwestern Kelly and northeastern TENNANT CREEK that is spatially separated from the main outcrop area of Tennant Creek Granite, it is now referred to as the Tennant Creek Granite at Red Bluff (Donnellan et al 1995).

The Tennant Creek Granite at Red Bluff is a biotite-bearing granite predominantly composed of alkali feldspar (microcline and orthoclase), sodic plagioclase (oligoclase), strained quartz (commonly ovoid, blue and opalescent), and red-brown biotite. Accessory minerals include magnetite, sphene, zircon, muscovite, ilmenite, fluorite and rare amphibole. Secondary alteration products include chlorite, epidote, and muscovite resulting from the saussuritisation of feldspar and alteration of biotite. Marginal and fractured zones of the granite show sodic and potassic metasomatism and tourmalination. Blue opalescent quartz is probably a deformation/alteration feature and is a widespread characteristic of Palaeoproterozoic granites of northern Australia.

The granite is seriate porphyritic to equigranular and has foliated and mylonitised zones. Foliated granite has orientated red-brown biotite, stretched quartz crystals with undulate extinction and elongate feldspar phenocrysts, whereas non-foliated granite shows minor rapakivi texture. Rapakivi or incipient rapakivi texture in the Barramundi Igneous Association at TENNANT CREEK may be attributable to subsolvus exsolution of sodic plagioclase from early crystallised alkali feldspar by analogy with studies of the development of this texture in the Wilbog Batholith in Finland (Dempster et al 1994). Dempster et al emphasised the importance of high fluorine fugacity in facilitating mobility of the mantling feldspar component and in lowering liquidus temperatures. The consequence of this is that even high-level intrusions can become subsolvus. Boron may have similar effects and is known to lower the liquidus temperature in granitic compositions (Pichavant and Manning 1984). Dempster et al (1994) suggested that there may be substantial low temperature recrystallisation of quartz in rapakivi granites. This probably has a bearing on the ovoid shape of blue quartz in the Tennant Creek Granite at Red Bluff.

Compston (1995) reported ages of 1853 ± 10 Ma and 1849 ± 7 Ma for samples from Tennant Creek Granite at Red Bluff in TENNANT CREEK and Kelly, respectively.

**Warrego Granite (Pgw)**

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

The Warrego Granite is a peraluminous granite. It comprises feldspar 1-3 cm in diameter, muscovite and quartz together with accessory corundum, apatite, and minor sphene and zircon. Muscovite books 0.5-1 cm in diameter are undeformed. Feldspar is extensively sericitised in outcrop, and the relative proportions of feldspar compositions cannot be determined. Drill core samples (BMR-NTGS DHD7) have microcline as the sole alkali feldspar, whereas plagioclase is slightly zoned with sericitised andesine or oligoclase cores and unaltered albite rims. Iron-rich chlorite replaces primary biotite. Mendum and Tonkin (1976) reported minor hornblends in the type area which is centred around a low hill on the eastern margin of the granite at LU714556.

There is intense alteration over a distance of up to 400 m at the eastern contact of the granite where country rock has been metamorphosed to a knotted quartz-muscovite schist and the granite is metasomatised to a dark grey, medium grained quartz-muscovite rock. The contact zone is marked by abundant small quartz veins.

Xenoliths are restricted to contact metamorphosed Flynn Group metasediments, and reincorporated clasts of medium to fine grained quartz-muscovite rock from the metasomatised granite margin within coarse grained equigranular granite. Large 1-3 m wide, north orientated quartz veins intrude the granite, together with smaller dykes and lenticular pods of quartz-feldspar pegmatite.

The age of the Warrego Granite is uncertain. Black (1977) reported a whole-rock isochron date of 1703 ± 100 Ma; the large error was a consequence of a small range in Rb/Sr⁸⁷ ratios. The selective inclusion of a chloride analysis resulted in a date of 1662 ± 20 Ma. The concordancy of three muscovite separates with the whole-rock chlorite isochron led Black to conclude that the Warrego Granite is ~1690 Ma. Single crystal zircon U-Pb dating using SHRIMP by Compston (1995) resulted in 1857 ± 12 Ma and 1844 ± 20 Ma dates for inherited xenocrysts, and clusters of dates at ~1650 Ma and ~1800 Ma. Rim growth on pre-existing grains was dated at ~1650 Ma. This younger date is the preferred age of crystallisation of the Warrego Granite although Compston (1995) pointed out that the population of low-U zircons may indicate that the granite crystallised at ~1800 Ma.
Wyborn et al (1998a) included the Warrego Granite, along with the Devil's Marbles Granite and the Elkedra Granite, in the ~1710 Ma Devils Suite, which was considered to comprise undeformed, fractionated, peraluminous granites of the I-granodiorite type. The Elkedra Granite clearly postdates folding in the Rooneys Formation, which it intrudes (Blake et al. 1987). However, this granite is deformed with mafic minerals in several preferred orientations and locally, quartz-tourmaline rock also shows consistent trends. It is suggested that the Elkedra Granite postdates early deformation (Murchison tectonic event) of the Oradig (and Flynn) Group(s), but is probably syn-tectonic with respect to later deformation (Davenport and Orogeny).

The Warrego Granite has contact metamorphosed the Warrego Au-Cu-Bi deposit (Weckkind and Love 1990). Wyborn et al (1998a) pointed out that, consequently, the granite could not be responsible for the mineralisation, contrary to the suggestion of Stolz and Morrison (1994).

Unnamed granite (Pg)

This granite was mapped as part of the Warrego Granite by Mendum and Tonkin (1976). However, it has a different composition (orthoclase, plagioclase, blue opalescent quartz, chloritised biotite) and a prominent east to northeast orientated foliation. This unit is considered to be a probable equivalent of the Tennant Creek Granite or the Cabbage Gum Granite. It outcrops at only one locality in SHORT RANGE (LU550496).

Porphyry (Pp)

Felsic porphyry is a minor but ubiquitous component of the Tennant Creek goldfield. It is restricted in outcrop to the southeast in SHORT RANGE. Porphyry at White Devil cuts the foliation in the Warramunga Formation (Nguyen 1987). Compston (1995) determined the age of this porphyry as 1853 ± 8 Ma, and that of porphyry in the vicinity of Jubilee in TENNANT CREEK as 1838 ± 9 Ma. Porphyry has been the focus of some interest at TENNANT CREEK given its apparent spatial relation to areas of gold mineralisation, with quartz-magnetite bodies often bordering porphyry margins. Porphyry apparently antedates gold mineralisation and any genetic relationship is therefore precluded. However, sheared and metamorphosed granite or felsic porphyry intersected in drill core to the south of Tennant Creek has been dated as 1829 Ma (Compston 1995). It is thus part of the Treasure Suite rather than the Tennant Creek Supersuite of Wyborn et al 1998, and is close to contemporaneous with the gold mineralisation. There are therefore possibly three episodes of porphyry intrusion at TENNANT CREEK.

Porphyry in TENNANT CREEK has many mineralogical and textural characteristics in common with the Tennant Creek Granite. These include ovoid, blue opalescent quartz and concentrically zoned, pink to white alkali feldspar with weakly developed mantles of green plagioclase. Porphyry also shows similar alteration characteristics and a similar chemistry to the Tennant Creek Granite, although it shows a wider range of composition, mainly due to pervasive potassic metasomatism.

McPhie (1993) demonstrated peperitic texture in porphyry intruding greywacke in the vicinity of the smelter on the Warrego road (LU875483). Donnellan et al (1995) noted passive, irregular intrusive contacts in less foliated porphyries with subsequent localised shearing along such contacts resulting in 'enclaves' of porphyry in the host metasediments and conversely, metasediment 'xenoliths' in the porphyry. A lack of significant contact-related, low-temperature alteration was regarded as implying a relatively anhydrous environment of intrusion at elevated temperatures.

Several authors have indicated probable folding of porphyry together with the Warramunga Formation on a regional scale (LeMessurier et al. 1990, McPhilie 1993, Rattenbury 1992). Small intrusive bodies are commonly well cleaved, with the development of foliation or flow banding parallel to the regional, west orientated (S) fabric in the host (Warramunga Formation). Some of the larger bodies show similar flow banding, and have northwest orientated shears and kink folds. Geophysical interpretation suggests an en echelon arrangement of porphyry in interference folds trending northwest across TENNANT CREEK. Porphyry intruding the Flynn Group and at the contact between the Warramunga Formation and Flynn Group suggests the plausibility of at least two generations of felsic porphyry, which is consistent with geochronological data (see above).

Dolerite and diorite (Bd1)

A dolerite dyke intruding the Tennant Creek Granite at Red Bluff was dated at 1858 Ma (Compston 1995), which is, within error, the age of the Tennant Creek Granite and the Tennant Creek Granite at Red Bluff. Compston (1995) pointed out that field relationships indicate that the dolerite intrudes granite, and that different zircon chemistry militates against zircons in the dolerite being inherited from the granite.

A later phase of dolerite emplacement is evident to the north of Warrego. As described above, a monzodioritic marginal phase of dolerite that intrudes the Wundirgi Formation has been dated at 1821 Ma (unpublished data of D Compston reported in Compston and McDougall 1994). Dolerite sills also intrude the Coodna Member near the top of the Hayward Creek Formation, as is evident at LU685790 in SHORT RANGE and MU027730 in FLYNN, and as is clearly shown in geophysical data. These sills must postdate the 1784 Ma maximum age of sedimentation for the Meerie Member as determined by Compston (1995). This probably indicates a later phase of mafic magmatism in SHORT RANGE that postdates the Treasure Suite, and this is possibly related to the Whittington Range Member volcanic rocks.

Wyborn et al (1998) considered that their Treasure Suite may be genetically related to the mineralisation at Tennant Creek and the mafic members of the suite are of particular interest in this regard, as was originally suggested by Dunnet and Harding (1967). These rocks show subophitic textures, and quartz-bearing varieties show graphic intergrowths of quartz and alkali-feldspar. Plagioclase feldspar may be strongly zoned and is more or less intensely sericitised. Clinopyroxene is typically extensively replaced by chlorite and actinolite and these minerals also replace minor, reflet primary hornblende, and biotite. Lesser constituents include magnetite, ilmenite, epidote (replacing biotite), talc, apatite and sphe, together with leucoxide, haematite and carbonate. There is local haematite and chlorite-carbonate veining.
Lamprophyre

In TENNANT CREEK, lamprophyre sills, dykes and laccoliths (up to 12 m thick) intrude the Warramunga Formation, felsic volcanic rocks of the Yungkulungu Formation (Donnellan et al 1999), and Wundiri Formation sedimentary rocks. Surface outcrop is scant and weathered although lamprophyre dykes are seen in outcrop at White Devil in SHORT RANGE. Duggan and Jaques (1996) emphasised that an apparent close spatial association with gold-copper-bismuth mineralisation is probably an accidental consequence of the positioning of drill holes rather than a true reflection of the distribution of lamprophyres. Thus, not only is any spatial association with mineralisation almost certainly spurious, but the marked northerly strike of known lamprophyres does not necessarily indicate a pronounced structural control.

Crohn and Oldershaw (1965) reported the occurrence of rare amphibole- and pyroxene-bearing lamprophyre intruding the Warramunga Group. Jaques et al (1985) classified the majority of lamprophyres at TENNANT CREEK as magnesian minette, consisting of plagiopogene phenocrysts in a biotite-rich groundmass, and with high magnesium, chromium and nickel contents. Duggan and Jaques (1996) stated that the most magnesian lamprophyre in TENNANT CREEK is olivine-bearing, with or without chromite, and that the olivine is replaced by talc and serpentine. Refer to these studies for further details of mineralogy, geochemistry and petrogenesis.

Duggan and Jaques (1996) reported two groups of lamprophyre in TENNANT CREEK. Both belong to Rock’s (1991) calc-alkaline (shoshonitic) lamprophyre (CAL) group but are readily distinguished on the basis of Zr/Nb ratios. Those with low Zr/Nb (<12) are confined to the southeastern extremity of the known distribution of lamprophyre at TENNANT CREEK and are apparently associated with Flynn Group rocks. In contrast, the Warramunga Formation hosts those with higher Zr/Nb ratios (>20). This is not of any obvious petrogenetic significance.

Lamprophyre has a $^{87}$Rb/$^{86}$Sr age of 1664 ± 16 Ma (Black 1977); and a K/Ar age of 1690 ± 35 Ma and a U-Pb zircon SHRIMP age of 1685 Ma (Compston 1994, Compston and McDougall 1994). The Rb/Sr age is based on a whole rock isochron that includes samples from East New Hope and Ivanhoe mine, and the K/Ar on biotite and U-Pb SHRIMP age are for a lamprophyre from the Explorer 50 prospect, 15 km west of Tennant Creek.

ALTERATION

Brief mention was made above of alteration in the Tennant Creek Granite. In their discussion of the geochemistry of felsic intrusive and extrusive rocks of TENNANT CREEK, Donnellan et al (1995) tabulated the qualitative effects of alteration on the geochemistry of felsic intrusive rocks. Here, a brief attempt is made to present some of these effects graphically. The approach is based on that of Bowden and Kinnaird (1984) and uses plots of two cationic functions Q and F (see Figure 3 for details). The consequences of alteration must obviously be understood prior to using geochemical data for petrogenetic considerations. Furthermore, any attempt

![Figure 3](a) QF cationic plot for Tennant Creek Granite (triangles) and Tennant Creek Granite at Red Bluff (squares). Filled symbols are used for samples interpreted to show few or no geochemical consequences of alteration (ie minor deuteric alteration versus metasomatism); open symbols are used for altered samples. Filled and unfilled symbols are used in this way in Figures 3a-e, and retained for Figures 5 to 8 inclusive. Q = Si/3 - (K + Na + 2Ca/3) and F = K - (Na + Ca) (see Bowden and Kinnaird 1984); (b) QF cationic plot for TENNANT CREEK felsic porphyries. The field for “unaltered” Tennant Creek Granite from Figure 3a is shown for comparison; and (e) QF cationic plot for Flynn Group felsic volcanic rocks from TENNANT CREEK. Field delimits samples probably reflecting differentiation as opposed to metasomatism, and field for “unaltered” Tennant Creek Granite from Figure 3a is shown for comparison.

16
to correlate rocks from the Tennant Intler with those of the northern Arunta province must consider possible regional hydrothermal alteration of protolith prior to metamorphism.

Alteration includes a range of mineralogical and chemical changes which cover a variety of possible processes from subsolus (e.g. rapakivi texture), deuteric (e.g. saussuritisation), hydrothermal/metasomatic (e.g. potassic, phyllic and propylitic alteration) and metamorphic (sub to lowermost greenschist facies). These are not necessarily clear distinctions between these processes. Thus, high temperature deuteric saussuritisation may merge into potassic alteration with the formation of microcline and distinctive green hydrothermal biotite, and progressively into phyllic (sericitic) alteration, greisenisation and boron metasomatism (with the formation of tourmaline/luxullianite), with decreasing temperature.

There is similarly a trend to propylitic alteration, sodic metasomatism (albitisation) and chloritisation (with minor actinolite). There is also minor haematitisation. Silicification is demonstrated by the widespread occurrence of blue, opalescent quartz in felsic igneous rocks in TENNANT CREEK (and is also found in granitic rocks from the Pine Creek Orogen and Arunta province). The reddish colour of many granites reflects widespread potassic alteration with haematitisation of feldspar. This is a common characteristic of many so-called anorogenic granites, as is rapakivi texture and an association with porphyry and
Figure 5  K₂O versus Na₂O for: (a) Tennant Creek Granite; (b) intrusive porphyries from TENNANT CREEK; (c) Flynn Group felsic volcanic rocks from TENNANT CREEK; and (d) porphyries from the (former) 'Warramunga Group' in BONNEY WELL (data from Blake et al 1987). Symbols as for Figure 3 except for 5d. Box shows field for "unaltered" (ie non-metasomatized) samples and is based on Wyborn et al (1998b).

Figure 6  Alumina-saturation classification diagram (after Shand 1947) for Palaeozoic felsic igneous rocks from TENNANT CREEK. Symbols as for Figure 3.

Rhyolitic ignimbrite, although these characteristics may simply reflect the epizonal character of granite.

Alteration varies from selective in the granites to pervasive in some porphyries, and from relatively localised (eg marginal albitionisation) to widespread (eg silicification). Some of the variety of styles and intensity of alteration affecting felsic rocks from TENNANT CREEK is illustrated in Figure 4.

Although alteration is widespread in granitic rocks of the Barramundi Igneous Association at TENNANT CREEK, the plots presented here corroborate previous conclusions that most analyses represent igneous compositions fairly reliably. This is a consequence of the local redistribution of elements during deuteric alteration (eg saussuritisation) without significant metasomatism.
However, a number of samples of both the Tennant Creek Granite and the Tennant Creek Granite at Red Bluff show a trend towards significant alkali metasomatism including both sodic metasomatism (albitisation) and potassic metasomatism (microcrystallisation; Figure 3a). Potassic and silicic metasomatism is also widespread and quite intense among the felsic porphyries and felsic volcanic rocks in TENNANT CREEK (Figure 3b,c).

Geochemical effects of alteration are comparatively minor in the Tennant Creek Granite (Figure 5a), but are marked in porphyries and volcanic rocks (Figure 5b,c). Figure 5d illustrates that porphyries associated with the "Warramunga Group" in northern BONNEY WELL show few geochemical effects of alteration, in marked contrast to those from TENNANT CREEK. Also plotted is the aluminasaturation diagram of Shand (1947; Figure 6a-c) and the classification of Middlemost (1985; see Figure 7a-c), which further illustrate the geochemical consequences of the alteration identified in Figures 4a-c. These diagrams also confirm the conclusions previously reached by Donnelan et al (1995) that the Palaeoproterozoic early granite rocks at TENNANT CREEK are high-K, predominantly peraluminous, and subalkaline (Figure 8a-c).

Alteration in diorites and monzodiorites of the Treasure Suite predominantly resulted in the replacement of clinopyroxene (augite). However, it also resulted in the
replacement of hornblende and biotite by chlorite and actinolite, the sericitisation and epidotisation of plagioclase, and in haematite and chlorite-carbonate veining.

GEOCHEMISTRY

Mafic intrusive rocks

Diorites and monzodiorites from SHORT RANGE are tholeitic (Figure 9) with low M-numbers (100 MgO / MgO + FeO total) around 32. They have REE patterns that show slight enrichment in LREE (light rare earth element), (La/Sm)N=1.7-2.1; flat HREE (heavy rare earth element) patterns, (Gd/Yb)N=1.1-1.3; and little or no Eu anomaly, Eu/Eu*=1-1.5 (Figure 10). However, Ce/Nd ratios are close to chondritic (Figure 11). A primordial mantle-normalised plot of incompatible elements (Figure 12) shows a relatively flat pattern but with enrichment of highly incompatible LILE (large ion lithophile elements) relative to HFSE (high field strength elements), a marked negative Nb anomaly and slight negative Ti and P anomalies; ie a typical ‘continental’ signature (Tarney 1992, Martin 1992).

These rocks also show a marked negative Sr anomaly, and a Sr/Ce versus Ce plot (Figure 13a) indicates the possibility of plagioclase fractionation. However, significant plagioclase fractionation is difficult to reconcile with Eu anomalies that are absent to slightly positive. A correspondence between Rb and Sr suggests that alteration is probably not the factor resulting in Sr depletion. Dolerite from the Tennant Inlier has La/Ce (Figure 13b) ratios close to the chondritic ratio (average 0.41, compared to 0.39 for chondrites), whereas diorites from SHORT RANGE have more fractionated ratios (av. 0.52). Analyses of diorite from SHORT RANGE are presented in Table 2.

Felsic intrusive and extrusive rocks

Major, minor and trace element geochemistry of representative samples of Tennant Creek Granite, Tennant Creek Granite at Red Bluff, Warrego Granite and Mumbilla Granodiorite are presented in Table 3. These samples were chosen on the bases of apparently lacking significant geochemical disruption from alteration, and of having SiO₂ content closely comparable with those of unfractured I- and S-type granites from the Lachlan Fold Belt (data of Chappell and White 1992). A plot normalised to upper continental crust (UCC) for these samples is presented in Figure 14 using the UCC values of Taylor and McLennan (1985) and the element order proposed by Sylvester (1994), which reflects increasing bulk solid/calc-alkaline granitic melt partition coefficients from left to right. Corresponding REE plots are presented in Figure 15.

Histograms of Ti/Zr of Tennant Creek Granite, Tennant Creek Granite at Red Bluff and porphyry are shown in Figure 16. These distributions are close to normal and the average closely approximates that of the average unfractured I-type granite (11.9) from the Lachlan Fold Belt. This is significantly lower than that of UCC (15.8), which is comparable with the Ti/Zr of the average unfractured S-type granite from the Lachlan Fold Belt (15.0; Chappell and White 1992). Interestingly, a small number of porphyries from the ‘Warramunga Group’ in BONNEY WELL have a Ti/Zr distribution suggesting two populations; one has lower and one has higher Ti/Zr ratios than the porphyries from TENNANT CREEK. A similar characteristic (but different ratios) is shown by the Newlands (and Arabulja) Volcanics from the Davenport province (Figure 17) where the lower ratio is comparable with that of felsic rocks from TENNANT CREEK and the higher ratio somewhat greater than UCC. Similarly, the Mumbilla Granodiorite from TENNANT CREEK and the Hill of Leeders Granite from BONNEY WELL have comparable Ti/Zr ratios (18.2 and 19.9 respectively; Figure 18).
Figure 11 (a) Ce versus Nd for diorite and monzodiorite from SHORT RANGE. Average Ce/Nd is 1.52 for these rocks by comparison with the chondritic ratio of 1.31 (data from Sun and McDonough 1989). (b) Ce versus Nd for the Kudinga Basalt (filled squares) and 'late' dolerites from the Davenport province. Average Ce/Nd = 2.1, the typical value for Proterozoic dolerites, although smaller degrees of partial melting will increase this ratio (see Ahmad and Tarney 1991). Dolerite data from Blake et al (1987).

Figure 12 Field for 10 samples of diorite and monzodiorite from SHORT RANGE showing incompatible elements normalised against the primordial mantle values of Wood et al (1979).

Figure 13 Sr/Sm versus Ce for (a) diorites and monzodiorites from SHORT RANGE, and (e) Kudinga Basalt (filled squares) and dolerites from the Davenport province, illustrating probable plagioclase fractionation. (b, d) Corresponding plots for La versus Ce. Davenport dolerite data from Blake et al (1987).
Currently available geochemical data from felsic igneous rocks of the Tennant Inlier indicate that Ti/Zr ratios are close to normally distributed in the individual intrusive and extrusive units and are predominantly either ~10-12, or ~20. However, there is an indication of a fairly widely distributed and apparently discrete population with a mean Ti/Zr of around 9. The integrity of this population requires further close scrutiny as more data become available. At this stage, it appears as one of two populations in felsic igneous rocks of the Treasure Volcanics, the Newlands Volcanics and, on the basis of very limited data, in the Arabulja Volcanics from the Davenport province. It was noted above that two populations are similarly probably represented in porphyries from the ‘Warramunga Group’ in BONNEY WELL, and this is again the case in granophyre from the Davenport province. Analyses of the Warrego Granite from SHORT RANGE, and of the Devils Marbles and Elkedra Granites (late granites of the Davenport province) all show low Ti/Zr. Plausibly these different ratios could reflect broadly infracrustal and supracrustal source compositions.

**PHANEROZOIC STRATIGRAPHY**

**PALAEOZOIC**

**Cambrian**

The Cambrian geology of TENNANT CREEK, including SHORT RANGE, has been described in detail by Kruse in Donnellan et al (1999). The Montejinni Limestone and Point Wakefield beds outcrop in SHORT RANGE with the latter confined to one outcrop at LU551625. In northern SHORT RANGE, the Montejinni Limestone is largely replaced by either silcrete, or calcrete and silcrete. This has been distinguished on the map as it may have significance with the original distribution of lithologies within the unit.

**MESOZOIC**

**Cretaceous? (K1)**

Mesozoic sediments are confined in outcrop to a few small mesas in extreme northeastern SHORT RANGE. They comprise medium bedded and cross-laminated sandstone and interbedded siltstone. Plant macrofossils including probable stem and root material have been recognised in this unit in FLYNN (eg LU953968).

These sedimentary rocks are most probably Unit A of the ‘Mullamud Beds’ succession of the Inland Belt described by Skwarko (1966, 1973) and further described from Wiso Basin by Kennewell and Hulett (1980). Beds of pebble and cobble conglomerate within Unit A that were described by...
Figure 16 Histogram of Ti/Zr ratios for: (a) Tennant Creek Granite (including Tennant Creek Granite at Red Bluff); and (b) intrusive porphyries from TENNANT CREEK. Mean Ti/Zr ratios are 11.8 and 12.6 respectively. These averages are comparable with that of the average unfractionated I-type granite (11.9), whilst the average unfractionated S-type has a ratio of 15.0. Data on unfractionated I- and S-type granites are for granites from the Lachlan Fold Belt and based on the data of Chappell and White (1992).

Figure 17 Histogram of Ti/Zr ratios for 24 samples from Newlands Volcanics of the Davenport Province (data of Blake et al 1987). The distribution is bimodal with one population having Ti/Zr ratios of ~9 and the other ~22.

Figure 18 Histogram of Ti/Zr ratios for Mumbilla Granodiorite.

Skwarko (1973) and Kennewell and Huleatt are not seen in either SHORT RANGE or FLYNN.

The precise age of these rocks is equivocal. White (in Skwarko 1973) assigned Unit A an Early Cretaceous age on the basis of its plant fossils. Skwarko (1966) considered these sediments to be early Aptian, and it was thought possible their deposition started in the late Neocomian. Hughes (in Kennewell and Huleatt 1980) considered Unit A to be equivalent to the Petrel Formation and therefore of Upper Jurassic to Neocomian age.

Three featureless outcrops of silcrete near LU865900 have been interpreted on the map as possible silicified Montejinni Limestone. It is also possible they could be totally silicified Mesozoic sediments. Other equivocal outcrops include a number of mesas, capped by silcrete and ferricrete, that occur along major valleys and are developed on recessive units of the Tomkinson Creek Group (particularly the Morphett Creek Formation) in FLYNN. These were interpreted as Palaeoproterozoic rocks by Donnellan et al (1995) although these authors noted the possibility that some may be Mesozoic.

CAINOZOIC

Czi and Czr are the map symbols used for silcrete and ferricrete, or silicified and ferruginised rock, respectively. These duricrusts probably developed over a significant time span from Cretaceous to Neogene (mid Miocene). Kennewell and Huleatt (1980) suggested that they are possible correlatives of the Morney and Cannaway deep weathering profiles in Queensland that were dated as early Eocene and late Miocene, respectively, by Idnurm and Senior (1978).

Colluvial deposits are designated Czr and quartz rich colluvial deposits are designated Czq. Qc is mainly colluvial vein quartz whereas Czq comprises both vein quartz and silcrete detritus. Finer grained and generally more distal deposits of colluvium and wash are labelled Czs. These deposits either underlie more recent colluvium (Qc, Qcq), sands (Qs, sheet and dune sands; Qu 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.
Table 2 Geochemical analyses obtained by NTGS in the 1990s for samples of monzodiorite and diorite from NTGS/BMR drill holes DDH 6, 7 and 7a, Area 3, SHORT RANGE (Dalry 1970, Lau 1971, Mines Branch 1972). Major and minor oxides are shown as weight percent, and trace elements as parts per million by weight. Note: sample numbers show the drill hole and depth sampled in feet; LOI indicates loss on ignition; and M-number = 100 MgO / MgO + FeO total

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STRUCTURE

Bates and Jackson (1987) emphasised that there are no necessary close genetic or temporal relationships between deformation in fold belts and the development of mountainous topography. In this context, it is emphasised that the Tennant Inlier comprises sub- to lower-greenschist facies rocks and may not represent a deeply dissected, mountainous terrain.

Folding

The structure of Short Range is best considered in a regional context. The following account is presented in broadly chronological order of individual studies at Tennant Creek.

Early mapping

Ivanac (1954) recognised two deformations in the Tennant Creek goldfield. The first produced westerly trending folds and the second superimposed folding about northeasterly trending axes. Ivanac also noted that the strike of bedding was westerly in the south and tended more northeasterly in the north of the goldfield. Dunnet and Harding (1967) reported the results of structural analysis of the Mount Woodcock one-mile sheet. These authors agreed that the dominant phase of folding was east-west and was associated with a well-developed axial planar slaty cleavage, defined by mica and chlorite and developed during regional metamorphism. However, these westerly folds were considered to have resulted from the second phase of folding (D₂) to have affected the Warramunga Group.

A prior phase of folding (D₁) in the Warramunga Group was inferred from its unconformable relationship with the overlying Tomkinson Creek beds, rapid plunge reversals of mesosome (D₂) folds and the S₁/S₂ intersection lineation, and a symmetrical distribution of poles to bedding about a horizontal northeasterly trending fold axis. Dunnet and Harding (1967) did not consider this fold axis to be parallel to either D₁ (westerly) or D₂ (northeasterly) phases of folding.
Table 3: Geochemistry of representative and average granitic rocks from TENNANT CREEK. Major and minor oxides are shown as weight percent, and trace elements as parts per million by weight. Sample locations: DDH4-70 (BMR/NGTS), Tennant Creek Granite MU265621; 2503, Mumbilla Granodiorite MT329957; av Pgt, average ('fresh') Tennant Creek Granite, n = 47; except La, Ce and Nd where n = 40; MnO, Rb, Th, U and Nb where n = 34; and Cr where n = 29; av Pgm, average ('fresh') Mumbilla Granodiorite, n = 17; except La, Ce and Nd where n = 10; MnO where n = 12; Cr where n = 13; and Rb, Th, U and Nb where n = 16; DDH7-270, Warrego Granite; I-type, average unfractuated I-type granite from the Lachlan Fold Belt, data from Chappell and White (1992, Table 4), n = 131; S-type, average unfractuated S-type granite from the Lachlan Fold Belt, data from Chappell and White (1992, Table 4), n = 160

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The third deformation started at the close of D₃ and is represented by conjugate shears with an associated fracture or crenulation cleavage (northwest trending S₃) or a crenulation cleavage (northeast trending S₃). Associated folds are variable depending on the relative degree of shearing, but an open, chevron style of folding is common. Dunnet and Harding (1967) recognised conflicting timing relationships between these conjugate structures. One or other of these structures is dominant in any given area.

In the Quartz Hill subarea, an S₃ cleavage was recognised and interpreted as either synchronous with, or post-dating S₂. In addition to the quartz filled, northwesterly trending Quartz Hill–Rocky Range Fault and complementary northeasterly orientated shears in the Tennant Creek one-mile area, Crohn and Oldershaw (1965) recognised a number of consistent orientations of shear zones, faults, ironstone and quartz veins (Table 4). They concluded that mineralised shears, ie those hosting ironstone ± gold-copper-bismuth, predominantly trend westerly, but also trend west-northwesterly or east-northeasterly. However, the most prominent shears lack significant mineralisation, trend northwesterly or northeasterly and are typically quartz-filled. Additional minor sets of shears trend north-northwesterly and north-northeasternly.

Mendum and Tonkin (1976) extended structural studies into the Marion Ross 1:50 000 map area. They refuted the first phase of folding (D₃ above) recognised by Dunnet and Harding (1967). They attributed the relationships described by Mendum and Tonkin (1976) to the result of D₅/D₆ being superimposed on D₂ and they considered D₃ and D₄ to be
Table 4 Shear orientations for the Tennant Creek one-mile sheet (data from Crohn and Oldershaw 1965)

<table>
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<th>Shear orientation</th>
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<td>120° - 130°</td>
<td>Quartz Hill – Rocky Range trend, quartz filled</td>
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<tr>
<td>105° - 110°</td>
<td>Complementary / conjugate set to above, quartz filled</td>
</tr>
<tr>
<td>70°</td>
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</tr>
<tr>
<td>320° - 340°</td>
<td>Mineralised and quartz filled</td>
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<td>20° - 30°</td>
<td>Mineralised and quartz filled</td>
</tr>
<tr>
<td>90° - 100°</td>
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</tbody>
</table>

essentially synchronous. They equated the first phase of folding to have affected the Warramunga Group with the first deformation in the Tomkinson Creek beds (recognising a westeiy orieented fracture cleavage in the latter) and correlated this deformation with D2 of Dunnet and Harding (1967).

Interestingly, Mendum and Tonkin (1976, p84) also seemed to question the validity of the unconformity recognised between the Warramunga Group and the Hatches Creek Group by Smith et al (1961) in the Murchison Ranges. They suggested that the 'unconformity' must have been a detachment surface in order to accommodate the different styles of folding above and below it in the sequence. However, Blake et al (1987) mapped an unconformity between the Warramunga Group and the Hatches Creek Group, as originally proposed by Smith et al (1961). Furthermore, Blake (1984) recognised an unconformity between the Warramunga Group and the Tomkinson Creek beds in SHORT RANGE (LU852609). Blake and Stewart (1987) stated that the Hatches Creek Group suffered two phases of concentric folding; ie northwesterly orientated folds are superimposed by northeasterly trending folds resulting in classic interference patterns. However, they did not provide any details of the temporal separation of these two events, which may have been progressively or close to synchronous? These fold phases could correspond with the second, close to synchronous and conjugate, deformation to have affected the Warramunga Formation as recognised by Dunnet and Harding (1967), Mendum and Tonkin (1976) and Donnellan et al (1995). An alternative possibility is outlined below.

Structural studies by Rattenbury (CODES)

Rattenbury (1992) reported the results of a structural study in the southern and western Tennant Creek goldfield in the vicinity of the McDouall Ranges, Nobles Nob and Mount Samuel (TENNANT CREEK) areas and the Black Angel and White Devil (SHORT RANGE) areas, respectively. This was a summary and interpretation of his work on behalf of CODES (based at the University of Tasmania) and was previously reported by Rattenbury (1988a and b, 1989a and b, 1990a and b). The principal conclusions of this work confirmed that on a domainal scale, westerly trending, open to close cylindrical folds that have horizontal fold axes dominate the Warramunga Formation. Rattenbury (1992) calculated bedding-cleavage intersection lineations to investigate fold plunge variability on a smaller scale and concluded that in the southern goldfield, superimposed folding was unlikely to have rotated fold axes without deforming cleavage, which remained planar.

Conversely, he suggested that the conical distribution of bedding reported by Dunnet and Harding (1967) in the northern field may reflect superimposed strike-slip deformation with steeply northwesterly dipping fold axes. A possible complication here is that Dunnet and Harding (1967) probably measured bedding in both the Warramunga Formation and Flynn Group. Furthermore, Rattenbury (1992) recognised only one cleavage as being widespread throughout the Warramunga Formation. Consequently, there may be the possibility of confusion where S2 or S3' are slaty cleavages. Northwesterly orientated folding is well developed in the Orlando and Queen of Sheba areas where Dunnet and Harding (1967) further recognised a change from northwesterly to southeasterly plunges. They attributed this to possible superimposition of northwesterly on westerly orientated phases of folding.

Wedekind et al (1988), building on the work of Goulévitch (1975), refuted the 'mega-kink model' of Le Messurier et al (1990) for the reorientation of the Warrego orebody. They attributed it to displacement of ironstone, originally contained within an westerly orientated fold, about a southeasterly trending, reclined fold axis that was contemporaneous with the emplacement of the Warrego Granite. This would imply a folding event at around 1690 Ma, which is broadly consistent with localised deformation in the Elkedra Granite.

NTGS second edition mapping

Results of an independent structural analysis of the Warramunga Formation were reported by Donnellan et al (1995). Lower hemisphere equal area projections of data collected were presented in their Figure 28 with the corresponding subareas presented in their Figure 29 (Donnellan et al 1995 p38, 59). Data for three regionally mappable cleavages were presented in these plots. It was recognised that a fourth, northerly orientated cleavage is widespread but it was not regularly measured as it did not appear to vary. Furthermore, the second deformation was considered progressive. Locally incremental cleavages were recognisable but were not routinely measured given that the three cleavages presented appeared to encompass...
the major elements of the structural history of the Warramunga Formation (at that time).

A similar situation was recognised in the Quartz Hill area by Mendum and Tonkin (1976). These authors considered that $S_2$ was locally obliterated by $S_3$: this was not apparent to Donnellan et al (1995) although they did recognise that $S_3$ is locally a well developed slaty cleavage. Incremental cleavage development was attributed to the progressive nature of $D_2$. An example of this may be two northwesterly orientated cleavages mapped in the Olive Wood area in FLYNN by Mendum and Tonkin (1976).

The work of Donnellan et al (1995) largely confirms that of Rattenbury (1992) and Mendum and Tonkin (1976). Thus, the Warramunga Formation was folded into upright, easterly orientated open to close folds with a well developed axial planar cleavage. Subsequent deformation was in response to ongoing dextral strike-slip. This resulted in superimposed, predominantly coaxial folding with the fold axis bisecting the acute angle between the two associated, close to orthogonal crenulation cleavages ($S_3$ and $S_4$). $D_2$ is represented by major northwesterly and northeasterly striking kink bands, which may define an asymmetric box arrangement.

Many of the equal area projections, but particularly those adjacent to the Quartz Hill–Rocky Ridge trend (eg Iris area and Olive Wood–Orlando area) show reorientation of $S_2$ and $S_3$ consistent with superimposed northwesterly plunging folds as recognised by Dunnet and Harding (1967) in the northern goldfield. A similar effect was recognised at Warrego by Goulevitch (1975). Subarea 9 in the extreme southeast of the Warramunga Formation area of outcrop (Donnellan et al 1995, p59) shows the effects of superimposed northeasterly plunging folds. This is consistent with the northeasterly orientated cross-folding originally recognised by Ivanac (1954). Thus, Donnellan et al (1995) recognised a first phase of westerly orientated folds with a superimposed phase of northwesterly and northeasterly orientated folding. This second deformation was considered conjugate and close to synchronous. Locally, there is evidence for conflicting timing relationships between northeasterly and northwesterly orientated crenulation cleavages, although generally the northwesterly cleavage predates the northeasterly cleavage and the northwesterly trend is generally dominant.

Conflicting relationships were also recognised by Mendum and Tonkin (1976; see above) who suggested synchrony between their $S_3$ and $S_3'$ ($S_3$ and $S_4'$ of Donnellan et al 1995). Small scale chevron folding associated with $D_2$ is well preserved in the Mary Lane shear zone, for example, as are asymmetric box folds. It is suggested that macroscale box folds are developed in the Warramunga Formation but are not readily mappable. Such macroscale box folds, defined by megakinks, are recognised in the 1999 AGSO geophysical data, and affect both the Warramunga Formation and Flynn Group. The long axes of box folds are close to coaxial with $D_2$ fold axes but there is a component of flexural slip resulting in modification of the profiles of $F_2$ folds.

The east-southeasterly and west-northwesterly orientated shear zones may reflect an early incremental step of the second deformation. A further increment may be reflected in major northwesterly and northeasterly orientated (eg Quartz Hill and Bernborough) fault systems. This later stage is typically associated with quartz veining. A final stage may be manifested in the north-northwesterly and north-northeasterly orientated structures recognised by Crohn and Oldershaw (1965). However, whether these are progressive elements of a single deformation or separate events is debatable. An interpretation suggesting two separate fold events about close to coaxial conjugate axes is favoured at this stage (see below).

**Postulated regional structure of Tennant Inlier**

The Hatches Creek Group and Tomkinson Creek Group were deposited later and hence not deformed during $D_2$, (westerly folds in the Warramunga Formation). Folding in the Hatches Creek Group is manifested as concentric, en echelon dome and basin folds with a dominant northwesterly trend. However locally, particularly in the Ooradidgee Group, a northeasterly trend was apparently generated in response to a similar stress field to that responsible for superimposed $D_2$ and $D_3$ folding in the Warramunga Formation.

However, evidence is emerging that the structural history of Tennant Inlier is more complicated than suggested above. There is local evidence in existing mapping for at least a third phase of folding in, for example, the Froidland syncline and possibly also the Errolola syncline in the Davenport province. West to west-northwesterly orientated folds are recognised in, for example, the Bullion Schist in the vicinity of Home of Bullion in BARROW CREEK, in the Ooradidgee Group in the Devils Marbles anticline in BARROW CREEK, and in other Ooradidgee Group (formerly Warramunga Group) in the Murchison Ranges.

The Flynn Group is similarly predominantly folded about westerly orientated axes, eg the westerly orientated and plunging Warrego syncline. Evidence from the Ooralingie Granite in BARROW CREEK (see below) indicates that northwesterly and northeasterly orientated structures may also have developed during this phase of deformation (Murchison tectonic event). Wedekind et al (1988) suggested reorientation of an originally west striking fold containing the Warrego orebody about a northeasterly trending fold generated contemporaneously with the intrusion of the Warrego Granite. This implies another phase of folding at about 1690 Ma.

Additional cleavages (to the 3 routinely mapped by Donnellan et al 1995) are recognisable in the Warramunga Formation (see above). These have previously been interpreted as incremental steps in the second major conjugate deformation superimposed on the earliest westerly orientated fold event. However, it is possible that they represent additional deformation recognisable locally but not currently mapped throughout the Warramunga Formation, Flynn Group and, as previously stated, possibly also the Ooradidgee Group. Corresponding cleavages have been recognised in the Ooradidgee Group during recent fieldwork.

A working hypothesis is that the Flynn and Ooradidgee Groups were deformed by a conjugate deformation during the Murchison tectonic event (about 1830-1800 Ma), with a significant westerly orientated component (ie coaxial with the earlier Barramundi Orogeny in the Warramunga Formation). They were subsequently deformed in the Davenport Orogeny (about 1700 Ma), together with the
Table 5 Working structural history of the Tennant Inlier

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<td>North orientated faults and folds</td>
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<td>Devils Suite in part (eg Elkedra Granite, ?Warrego Granite)</td>
<td>Isan Orogeny?</td>
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<td>Northwest and northeast orientated shears, faults and folds</td>
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<td>Flynn Group, Ooradigee Group, Bullion Schist</td>
<td>Treasure Suite, Ooralingie Granite, ‘Late’ porphyries</td>
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<td>West trending folds and faults</td>
<td>Warramunga Formation</td>
<td>Tennant Creek Supersuite, including ‘early’ porphyries</td>
<td>Barramundi Orogeny c1850 Ma</td>
</tr>
</tbody>
</table>

Wauchope and Hanlon Subgroups and the Tomkinson Creek Group, about close to coaxial conjugate axes. A manifestation of the earlier of these two, close to coaxial deformations may have been predominantly westerly orientated folding. Northwesterly trending folds of the Davenport fold belt necessarily developed in the later deformation (ie after Wauchope and Hanlon Subgroup sedimentation) and were associated with northeasterly orientated, superimposed folding.

Northerly orientated folding in the Bullion Schist to the west of the Stuart Highway in BARROW CREEK might be conjugate with respect to the early, westerly orientated folds (Murchison tectonic event) noted above in the Flynn and Ooradigee Groups and the Bullion Schist. However, this would appear to necessitate a further, late, northerly orientated deformation to account for fold orientations seen locally in the Wauchope and Hanlon Subgroups (eg Bonney Syncline) and widespread in the Tomkinson Creek Group. It is noted in passing that the J-Fold in the Bonya Schist at Jervois in HUCKITTA is a north trending structure.

A working structural history for the Tennant Inlier is proposed in Table 5. D₄/D₄' of Donnellan et al (1995) is now considered to be probably D₂/D₂' with respect to the Tennant Inlier (Davenport Orogeny), and to post-date the Hatches Creek Group. A prior, conjugate, deformation (Murchison tectonic event) resulted in close to westerly orientated folding in the Flynn Group, and broadly westerly and northerly orientated structures in the Ooradigee Group and the Bullion Schist. This deformation also resulted in west-northwesterly to east-southeasterly, and north-northeasterly to north-northwesterly orientated (locally mineralised) structures in the Warramunga Formation.

Timing of deformational events

The age of the first phase of folding (Barramundi Orogeny) in the Warramunga Formation can be constrained by the maximum age of the Warramunga Formation (~1860 Ma), by the associated syn-tectonic emplacement of the Tennant Creek Supersuite (1850 Ma), and by the 1855 Ma date for a porphyry which cuts the foliation at White Devil mine. The Barramundi Orogeny is thus ~1855 Ma at TENNANT CREEK. The gold-copper-bismuth mineralisation has a minimum age of 1825 Ma according to Compston and McDougall (1994). Compston (1995) suggested that D₄ may immediately post-date the Flynn Group and would thus be essentially contemporaneous with mineralisation. Donnellan et al (1995) considered that D₄ must post-date the Hatches Creek Group and suggested that the mineralisation may have been contemporaneous with reactivation of D₂'.

Compston (1995) postulated that a phase of deformation post-dated the Flynn Group and pre-dated the Tomkinson Creek Group. This is consistent with the Murchison tectonic event which is now recognised between the Ooradigee Group and Wauchope Subgroup of the Hatches Creek Group. It is not clear whether D₂/D₂' mapped by Donnellan et al (1995) in the Warramunga Formation corresponds with the Murchison tectonic event and/or the Davenport Orogeny. It may include cleavages relating to both of these periods of deformation.

The only other age constraints available on this second phase of deformation were that it predated the Elkedra Granite (~1720 Ma, OZCHRON database; Blake et al. 1987) and post-dated the Barramundi Orogeny (~1855 Ma at TENNANT CREEK). Data presented on syn-tectonic granite from BARROW CREEK by Hussey et al (1999) suggested that this deformation may in fact be ~1805 Ma in that area. At the locality from which the samples for geochronology were taken, this deformation results in a northwesterly orientated mylonitic fabric in the Ooralingie Granite. This mylonitic fabric is itself deformed and shows a well developed, east-northeasterly trending crenulation. In addition, more or less easterly plunging crenulation folds are developed locally and are associated with a northerly reorientation of the mylonitic fabric.

We concur with Compston (1995) and favour discrete episodes of deformation immediately after the Flynn (and Ooradigee) Group(s), and again after the Tomkinson Creek Group and and the Hanlon Subgroup. Further implications are that D₂ may be diachronous and/or that deformation of the Warramunga Formation, Flynn and Ooradigee Groups may have been progressive over the time interval ~1830-1800 (Murchison tectonic event). Currently available geochronological data (OZCHRON database, R Page pers comm 1999) suggest that the Wauchope Subgroup may in part be contemporaneous with this deformation although it appears to have escaped its consequences.

On the basis of the available age constraints as outlined above, the third deformation in the Tennant Inlier (Davenport Orogeny) is not contemporaneous with the late Strangways Orogeny (1745-1730 Ma) of Collins and Shaw (1995) in the Arunta province. Similarly, the early Strangways Orogeny (1780-1770 Ma) may not be represented in the Tennant Inlier, or is much earlier
(-1830-1805 Ma). It is noted that in the Arunta province, tectonism is evident in the northern and central regions during the early Strangways Orogeny (Weldon, Wabudali and Ongeva tectonic phases) but is not substantiated in the late Strangways Orogeny (Collins and Shaw 1995). Furthermore, the regional extent of the Stafford tectonic event is uncertain and it is the early Strangways Orogeny that is associated with widespread syn-tectonic granite emplacement in the northern Arunta province (Collins and Shaw 1995). Thus, orogeny may have started earlier in the Tennant Inlier (Murchison tectonic event), and closed later (Davenport Orogeny), than in the Arunta province. Given that D$_2$ in the Tennant Inlier does not correlate chronostratigraphically with either the Stafford tectonic event or the early Strangways Orogeny it is proposed, as already discussed, to refer to this deformation as the Murchison tectonic event.

The timing of the northerly orientated deformation is not known but would appear to be late. However, northerly oriented folds predominate in the Bullion Schist west of the Stuart Highway in BARROW CREEK and these appear to be early (ie D$_2$, with respect to the inlier), and apparently parallel to the northerly orientated schistosity in this area, which is crenulated by a northwesterly orientated cleavage (eg LS759278). Elsewhere in this vicinity (eg LS755301), northeasterly and northwesterly trending cleavages are crenulated by a more or less northerly orientated cleavage and this suggests that conversely, the northerly orientated deformation overprints a prior northeasterly and northwesterly orientated fabric. At LS764317, a west-northwesterly trending schistosity is intensely crenulated by a westerrnly orientated cleavage and weakly by a north-northwesterly cleavage. The west-northwesterly trending folds in the Bullion Schist in the vicinity of the Home of Bullion trend more northwesterly further to the east and west and Haines et al (1991) suggested that this is attributable to refolding of west-northwesterly trending folds about northerly or northeasterly trending fold axes. The same can be said for the Ooradilee Group and Wauchope Subgroup in the Devils Marbles anticline.

Conversely, the northeasterly trending Homestead anticline in ELKEDRA is apparently mildly refolded about a northerly or north-northwesterly fold axis. In the vicinity of MS118224, the Bullion Schist has andalusite developed in S$_2$ and S$_3$ crenulation cleavages, although this is predominantly developed in the northwesterly orientated S$_2$ schistosity. Andalusite is attributed to contact metamorphism developed in the vicinity of outcropping porphyry and proximal to the Ali Curung Granite. Three relationships tend to confirm the relative timing of fold phases in the vicinity of Home of Bullion as suggested by Haines et al (1991). The northerly and westerly orientation of (micaceous) schistosity to the west and east of the Stuart Highway, respectively, suggests that these orientations probably relate to essentially the same episode of deformation. This topic will be discussed further elsewhere (Donnellan et al in prep).

Faulting

Faults in TENNANT CREEK are discontinuous in outcrop but have much greater continuity as is evident in recently acquired geophysical data. Faults are sub-parallel to the principal cleavage orientations. Easterly, northwesterly and northeasterly orientated faults are widespread. Rattenbury (1992) recognised a reverse sense of movement on many of the easterly orientated, bedding sub-parallel faults and inferred from this and the disharmonic character of the folding, that the deformation is relatively thin-skinned and that shortening is achieved at depth by thrusting. Rattenbury projected blind thrusts into the axial zones of the anticlinal folds and suggested that they are an important structural control on the distribution of mineralisation. Strike-slip faulting is associated with D$_2$ and major faults trend northwest (eg Quartz Hill - Rocky Ridge, Bernborough, and Navigator Faults, and Northern Star shear zone). Multiple phases of movement are suggested for many of these faults, with a net component of movement in a subhorizontal and dextral sense (Mendum and Tonkin 1976). There are conflicting timing relationships between the northwesterly trending Northern Star shear zone and the northwesterly trending Quartz Hill and Bernborough Faults, and this is taken to indicate synchronocity (Mendum and Tonkin 1976).

Mendum and Tonkin (1976) discuss northerly trending faults that are predominantly dextral strike-slip faults with up to 5 km of horizontal movement. Some have little or no vertical component of movement. These are predominantly confined to northern TENNANT CREEK with the notable exception of a northerly trending fault at the Peko mine. Some faults show the opposite, ie sinistral, sense of movement. Mendum and Tonkin (1976) suggested that with the exception of these north-striking faults the structure of TENNANT CREEK could be reconciled with a principal stress direction orientated north-northeast. They attribute the northerly orientated faults to reactivation of pre-Warramunga Formation basement structures. A model for oblique orogeny presented by Mitchell and Reading (1978) can readily accommodate northerly orientated normal faults in such a stress field. Normal faulting is prevalent further north, particularly in the Namerinni Group in HELEN SPRINGS, although those structures are likely to have resulted from a later stress field than that presently being discussed. The late faults are responsible for substantial vertical offset in the Namerinni Group and may have a syn-sedimentary component of movement.

Syn-sedimentary normal and transfer faults in the Davenport province were recognised by Stewart (in Blake et al 1987) and Stewart 1987 on the basis of abrupt changes in thickness of lithostatigraphic units (eg Kurinelli Sandstone).

Northeasterly trending faults can be seen to curve into northwesterly trending faults, eg Stuart Highway Fault curves into the Quartz Hill - Rocky Range Fault. The sense of movement on both of these faults is dextral. The sense of movement between a group of these curved, mega-faults is however sinistral. These major fault systems are further organised into a system of regional, en echelon faults with a dextral sense of shear.

GEOLOGICAL HISTORY

Summary of Proterozoic events

1. Post 1890 Ma: development of an ensialic (transitional) pull-apart basin.

3. About 1855 Ma: the Barramundi Orogeny resulted in the earliest, approximately east-west orientated phase of folding which affected the Warramunga Formation.

4. About 1850 Ma: melting of the lower crust and subsequent emplacement of dry granodioritic magma (e.g., Mumbilla Granodiorite) in the upper crust, followed by limited in situ fractionation culminating in granitic magmatism (e.g., Tennant Creek Granite).

   These felsic intrusive rocks constitute the 'early granites' of the Tennant Inlier, and are also referred to as part of the Barramundi Igneous Association. They are synto immediately post-tectonic with respect to the Barramundi Orogeny. This felsic magmatism was associated with contemporaneous mafic magmatism, although the latter is volumetrically minor at the present level of exposure.

5. Post 1850 Ma: the volcano-sedimentary Flynn Group was deposited immediately following intrusive activity.

   Volcanic rocks of this group were probably derived from subjacent, consanguineous intrusive magmas and are exclusively rhyodacitic to rhyolitic at the current level of exposure. Flynn Group rock units post-dated and/or escaped deformation during the Barramundi Orogeny. Flynn Group rocks change progressively upward from subaqueous clastic sedimentary rocks to subaerial volcanic rocks (pyroclastic and epiplectic rocks and minor lavas).

   Probable correlatives of the Flynn Group (Ooradidgee Group and part of the former Warramunga Group in northern BONNEY WELL) are bimodal and include mafic volcanics and intrusive gabbro, dolerite and diorite. These Treasure Suite rocks are contemporaneous with the Murchison tectonic event.

6. ?1820-1810 Ma: a second phase of deformation post-dated Flynn Group sedimentation and was responsible for the first regional deformation in the Davenport province, together with refolding in the Warramunga Formation. This deformation, here called the Murchison tectonic event, is also essentially coeval with Tennant Creek gold-copper-bismuth mineralisation, and the syn- to post-tectonic Treasure Suite.

7. About 1785 Ma: post-Murchison sedimentation continued with deposition of the Tomkinson Creek Group. There was an apparent decrease in the direct volcanic contribution to sedimentation at this time and a change to shallow marine/intertidal and continental sedimentation. The Tomkinson Creek Group marks the inception of mixed, cyclic clastic and carbonate sedimentation which continued to the north in HELEN SPRINGS until well into the Mesoproterozoic.

8. ?1730-1700 Ma: a third episode of tectonism, the Davenport Orogeny, post-dated Tomkinson Creek Group sedimentation.

9. Post 1700 Ma: a phase of granitic magmatism is syn- to post-tectonic with respect to the Davenport Orogeny and probably includes the Warrego Granite in SHORT RANGE. These 'late granites' are roughly contemporaneous with minor ultramafic, calc-alkaline, lamprophyric magmatism at about 1685 Ma. (Note: the precise age of the Warrego Granite remains equivocal – it may be closely related in time to a possible regional hydrothermal alteration event at 1645 ± 44 Ma that was postulated for the Davenport province by Blake and Page 1988).

Discussion

The oldest rocks exposed in SHORT RANGE are 1860 Ma lithic arenite, wacke and siltstone of the turbiditic Warramunga Formation. Analogy with the Betic mountains in Spain (Montenat et al. 1987, Debelmas and Masle 1998) suggests that the Warramunga Formation may have been deposited in a relatively small basin or possibly a series of small, contemporaneous basins (depending on the final interpreted regional extent of the Warramunga Formation). Although comparable sedimentary rocks are widespread and may be penecontemporaneous throughout northern Australia, from the Pine Creek Orogen to the Tennant Inlier, the northern Arunta province and the Tanami Region, they were not necessarily deposited in regionally extensive basins, and may represent a variety of tectonic settings. There is evidence for a prior episode of turbiditic sedimentation in northern Australia, e.g., the Mount Bonnie Formation in the Pine Creek Orogen. Subsequent turbiditic sedimentation is also manifested locally in the Flynn Group and in the northern Arunta province.

The early turbiditic succession at TENNANT CREEK was deformed during the Barramundi Orogeny contemporaneously with the emplacement of I-type granitic rocks at about 1850 Ma. This deformation produced upright, open to closed, westerly orientated folds in the Warramunga Formation. As previously noted, a porphyry at White Devil cuts cleavage in the Warramunga Formation and has an age of 1853 Ma. This early phase of felsic intrusive activity in SHORT RANGE is represented by the Tennant Creek Granite (at Red Bluff) and porphyry. Probable consanguineous felsic volcanic activity is represented by the Warrego Volcanics and volcanic intervals in the Wundirgi Formation, and is widespread in TENNANT CREEK. Both of these units are part of the Flynn Group which is inferred to unconformably overlie the Warramunga Formation as it was not deformed during the Barramundi Orogeny.

It is plausible that the Flynn Group does not strictly overlie the Warramunga Formation but was deposited in a separate, closely spatially related basin or basins, which only partially overlapped in space (and time?) with the basin or basins in which the Warramunga Formation accumulated. It is therefore plausible that the lowermost Flynn Group rocks may overlap in time with the Warramunga Formation, but escaped deformation due to deposition in an extending basin while the adjacent Warramunga basin was undergoing contemporaneous compression. These relationships can be reconciled with a transcurrent system. Nonetheless, the distinction remains that the Warramunga Formation is a turbiditic succession with classical Bouma sequences and is regionally more deformed than the volcano-sedimentary
Flynn Group, which is a more proximal and, at least in part, subaerial succession. Presently available geochronological data indicate that the Warramunga Formation is older than the Flynn Group.

Volcano-sedimentary rocks of the Flynn Group followed turbiditic sedimentation and granite intrusion. As noted above it is likely that rocks of the early Flynn (and Ooradiggee) Group(s) may be found to overlap in time with the Warramunga Formation and with intrusive activity associated with the Barramundi Orogeny. Recent geochronological data reported by Smith (1999) indicate this. Thus, as discussed above, volcanic rocks from the undifferentiated former Warramunga Group in northern BONNEY WELL are dated at 1862 Ma. These rocks are correlated, and are, on geophysical images, continuous with the Junalki Formation in southern TENNANT CREEK. It is debatable whether these rocks, all now referred to as Junalki Formation, should be excluded from the Flynn Group.

Donnellan et al (1995, 1999) favoured reactivation of D, contemporaneous with gold mineralisation at around 1820 Ma. Compston (1995) indicated the possibility of this being a discrete deformation, D,. Current evidence suggests that this is indeed the case. This second deformation was a progressive conjugate deformation, probably at about 1820-1810 Ma, which effected superimposed folding in the Warramunga Formation and folded the Ooradiggee Group (and the Bullion Schist) about westerly to west-northwesterly, and northerly orientated axes.

The age of the Hayward Creek Formation (maximum age of sedimentation 1784 Ma) precludes deformation in the Tomkinson Creek Group correlating with deformation at 1820 Ma (Murchison tectonic event). The Tomkinson Creek Group and Waunchope and Hanlon Subgroups (Hatches Creek Group) were deformed at about 1730-1700 Ma: this deformation (D, ) was close to coaxial with D, and was similarly conjugate.

A fourth deformation is manifested in the Ashburton province where the Renner Group unconformably overlies the Namerimi Group in HELEN SPRINGS and is deformed into broad, open folds. This deformation may be represented in the Warramunga Formation and Flynn Group as a spaced, north orientated cleavage, and it may broadly correlate with the Isan Orogeny.

Evidence for ongoing felsic to intermediate magmatism (ie younger than 1800 Ma) comes from volcaniarcic detritus in the Hayward Creek Formation and the Whittington Range Member together with mafic to intermediate rocks intruding the Hayward Creek Formation. The Tomkinson Creek Group represents a change to possible foreland basin/intermontane basin sedimentation that was succeeded by stable platform sedimentation.

The post-tectonic Warrego Granite and the penecontemporaneous lamprophyre dykes are apparently genetically unrelated, and the volume of the lamprophyre is inadequate to suggest a heat source for generation of the Warrego Granite (and other members of the Devils Suite) according to Duggan and Jaques (1996). These authors suggested that the geochemical data indicate contamination of a subcontinental lithospheric source for lamprophyres by probable subduction-derived crustal material not long prior to their generation. However, this is difficult to reconcile with the apparent intraplate setting at this time.

It is noted in passing that the 'andesitic' character of volcanic rocks in the Whittington Range Member also requires explanation. Donnellan et al (1997) postulated that possible subduction occurred in TENNANT CREEK immediately prior to Warramunga Formation sedimentation. Similarly, intermediate volcanic rock compositions of the Treasure Suite in both the Tennant Creek and Davenport provices merit further petrogenetic study. Subduction related magmatism is evident in the 1879 Ma Atmarpa Igneous Complex of the southern Arunta province, which is interpreted as a cordilleran margin (Zhao and McCulloch 1995). However, much has yet to be learned concerning the Arunta province, its internal structure, which does appear to involve evidence for lithospheric boundaries of some sort; its relationship to the Tennant Inlier; and the general make-up of the north Australian craton and in particular, its early (Late Archaean to earliest Palaeoproterozoic) history. Continued work on the regional geological framework must precede any tectonic models. Likewise, studies of the geochemistry of mafic rocks are considered to be critical for advancing understanding of the Arunta province and Tennant Inlier.

Finally, it is noted there may be some younger units exposed in SHORT RANGE. An isolated outcrop of conglomerate and sandstone in northeastern SHORT RANGE is tentatively assigned to the Neoeproterozoic or lowermost Cambrian Rising Sun Conglomerate, which has previously been confined to the Georgina Basin (ie in southern TENNANT CREEK). This outcrop is equivocal and might alternatively represent the Gleeson Formation of the Renner Group mapped in HELEN SPRINGS. The Rising Sun Conglomerate has been correlated with the Andaemma Formation in the Davenport province. These rocks together with the Central Mount Stuart Formation in BARROW CREEK indicate a major episode of redbed sedimentation at the close of Proterozoic time.

REGIONAL CORRELATIONS

Historically, the Tennant Inlier is geographically well defined. It includes the outcrop extent of Palaeoproterozoic rocks in the Davenport and Murchison Ranges of the Davenport province in the south, and the Short, Whittington and Ashburton Ranges of the Ashburton province in the north. The central part of the inlier, the Tennant Creek province, is generally more recessive but does include dissected remnants of a regionally extensive penneplain, the Ashburton Surface, which includes Mount Samuel and the McDouall and Honeymoon Ranges.

The Taylor and Crawford Ranges (in BARROW CREEK) represent an obvious extension of the inlier, and aeromagnetic data indicate that its stratigraphy extends over a much wider area. This geophysical continuity is obscured in outcrop by Palaeoproterozoic to Mesoproterozoic rocks, which crop out in the northernmost Ashburton Ranges (in HELEN SPRINGS). These rocks are equivalent to the McArthur and Roper Groups of the McArthur Basin. Neoeproterozoic to Palaeozoic rocks of the Georgina and Wiso Basins conceal Palaeoproterozoic geology to the east.
and west, respectively, and there is also widespread surficial cover.

A proposed structural framework is presented in Table 5. It includes components of two orogenic cycles, the Barramundi and Davenport Orogenies. The Barramundi Orogeny is regionally widespread in northern Australia, and associated rift, sag and syn-orogenic turbiditic flysch phases of sedimentation were recognised by Etheridge et al. (1987). However, only the flysch phase of this orogenic cycle is represented in outcrop in the Tennant Inlier (i.e. the turbiditic, tuffaceous Warramunga Formation).

Synth to post-tectonic intrusive and extrusive ignimbritic rocks, predominantly of dacite to rhyolitic composition, are well represented in the central Tennant Inlier. They have been called the Tennant Creek Supersuite by Wyborn et al. (1998a), and locally represent the Barramundi Igneous Association. These volcanic and associated sedimentary rocks in TENTANN CREEK are called the Flynn Group. They are generally younger and less deformed than the Warramunga Formation.

The Flynn Group is analogous to the Ooradiggee Group, and both groups are characterised by complex lateral facies associations and interfering relationships between formations. Complex interfering relationships continue upward, at least locally, into the lower Wauchope Subgroup. Blake et al. (1987) recognised: (1) partial lateral equivalence between the Unimbra Sandstone (Wauchope Subgroup) and the Treasure and Epenarra Volcanics (Ooradiggee Group); (2) local upward continuation of the fluvialitic Taragan Sandstone of the Ooradiggee Group in conglomeratic facies at the base of the Unimbra Sandstone; and (3) interfering relationships and partial lateral equivalence between the Yeeradgi Sandstone, Arabulja Volcanics and Newlands Volcanics (all of the Wauchope Subgroup). North-northeast of Juggler Mine, the Unimbra Sandstone is thin and the Newlands and Treasure Volcanics may partially overlap chronostratigraphically as is indicated by currently available, but unpublished geochronological data (OZCHRON data base, R Page pers. comm).

The foregoing suggests that a major break in the stratigraphy occurs at the base of the Coulters Sandstone, which is a correlate of the Meerie and Coodna Members of the Hayward Creek Formation in SHORT RANGE. However, this time break is only manifested in the field by a local unconformity. Haines et al. (1991) suggested a lithostratigraphic correlation between the Strzeleckie, Arabulja and Newlands Volcanics. A recent SHRIMP U-Pb date of 1819 ± 9 Ma for the Strzeleckie Volcanics has been reported by Hussey et al. (1999). The lowermost Meerie Member is dated at 1784 Ma (Compston, 1995). Hence, the inferred time breaks between these volcanic rocks and the Coulters Sandstone is probably of the order of 30 my, and a similar time break is implied between the Manga Mauda and Meerie Members of the Hayward Creek Formation in SHORT RANGE.

Haines et al. (1991) indicated a major disconformity between the Strzeleckie Volcanics and the Illloquara Sandstone; these are correlatives of the Arabulja/Newlands Volcanics and the Coulters Sandstone respectively. Given a major disconformity at this level in the stratigraphy, correlation of the Coulters Sandstone and the Hayward Creek Formation (Blake 1984) remains likely despite the contrary assertion by Hussey et al. (1999).

Structural considerations indicate a tectonic break (Murchison tectonic event) at the top of the Ooradiggee Group, which shows the same conjugate deformation seen in the Flynn Group (ie the second deformation in the Warramunga Formation). These rocks were subsequently refolded (Davenport Orogeny), together with the Wauchope and Hanlon Subgroups (Hatches Creek Group), about close to coaxial conjugate fold axes. This resulted in the disharmonic relationship between the Ooradiggee Group and the Wauchope Subgroup. The base of the Unimbra Sandstone is considered to define a tectonostratigraphic break whereas the base of the Coulters Sandstone represents a major disconformity and lithostratigraphic break. These correlate with a tectonostratigraphic break at the base of the Manga Mauda Member and a hiatus at the base of the Meerie Member (both of the Hayward Creek Formation) in SHORT RANGE.

A broad litho/tectono-stratigraphic framework for the Tennant Inlier is presented in Figure 19. Postulated correlations are shown between the Tennant Inlier and the adjacent northern Arunta province (Figure 20), and Pine Creek Orogen (Figure 19). It is stressed that the correlations proposed in these figures may be liable to revision in the light of ongoing work.

ECONOMIC GEOLOGY

A brief history of mining and exploration

The first record of gold in TENTANN CREEK is an 1874 report of its occurrence in the Last Hope area in SHORT RANGE referred to in the Northern Territory Times and Gazette of October 1881. Subsequent to this, Brown (1895) reported panning gold from Bishops Creek. Davidson (1905) sampled quartz reefs and downgraded the area’s potential. However, when prospectors turned their attention to quartz-haematite (ironstone) bodies, high grade gold (and copper) mineralisation was discovered 9 km south-southwest of the Old Telegraph Station (Great Northern), and payable gold was located beneath the abandoned workings in 1932. Numerous deposits were found in the early 1930s including Nobles Nob and Eldorado, although payable gold was not found at Nobles Nob until 1939. Ivanac (1954) reported that immediately prior to the Second World War a total of one hundred and thirteen mines were in operation. During the war all mines closed except Eldorado (Le Messurier et al. 1990). By 1947, 25 mines were again operating but the number had dropped to eight by 1952. Nevertheless, gold production rose sharply from the late 1940s until the early 1970s and the first copper was produced in the mid 1950s.

Despite the large number of prospects that are mineralised (130 have recorded production) they represent only about 20% of the known ironstone occurrences. Furthermore, 94% of the gold (∼160 t produced to 2000) was contained in eleven mines (NTGS MODAT database). Warrego (41.3 t Au recovered), Nobles Nob (34.6 t Au recovered) and Juno (26.1 t Au recovered) accounted for approximately 64% of total gold production. Warrego (in SHORT RANGE) has also produced a substantial amount of copper (91 500 t), equivalent to ∼80% of the amount of
Figure 20 Schematic representation of postulated lithostratigraphic and tectonostratigraphic relationships between the Tennant Inlier and northern Arunta Province. Data sources and additional notes are presented in Appendix 2.
copper produced from the predominantly copper-bearing Peko orebody close to the eastern extremity of the goldfield (117 465 t Cu and 7.5 t Au recovered). In addition to Warrego, SHORT RANGE hosted the rich White Devil deposit which produced 23.4 t of Au before closure in September, 1999. Immediately west of White Devil, the Black Angel mine produced 176 kg of Au from 25 900 t of ore in two periods of production from 1936-1964, and from 1985-1986.

Many aspects of the genesis of ironstone-associated gold-copper-bismuth mineralisation in TENNANT CREEK remain unresolved. Initially this might be attributed to the well-defined exploration target represented by the association of economic mineralisation and massive ironstone bodies (magnetite-haematite lodes), with the advent of the first ground based magnetic surveys (AGGSA 1935-1937), and subsequently aeromagnetic surveys (BMR 1956-1960). These first generation aeromagnetic surveys are directly credited with the discovery of Warrego (SHORT RANGE), and Gecko and Ivanhoe (TENNANT CREEK). Low level aeromagnetic surveys, started in 1964 and continued in 1965 and 1967, identified a number of new ironstone-related anomalies and in turn stimulated company-funded surveys. The latter included a 1984 Austrex aeromagnetic survey (200 m line spacing, 80 m terrain clearance) over 3 400 km² and a comparable standard of survey extended over 1 500 km² to the southeast of the goldfield by Peko in the late 1980s. This generation of aeromagnetic survey identified even largely oxidised shallow ironstones. In 1998 AGSO contracted Kevron to fly a low level, 200 m line spaced aeromagnetic and radiometric survey over the entire TENNANT CREEK map area. In 1999, the NTGS-contracted Australian Geophysical Surveys Pty Ltd and extended 200 m coverage over CHALUBA, BONNEY WELLM, EPEARRA in FREW RIVER and HANSON in LANDER RIVER.

Farrar (1979) described Richardson and Kirkpatrick's mathematical model to analyse ellipsoidal magnetic anomalies associated with pipe-like, flattened 'ironstones' in TENNANT CREEK. Farrar further discussed how the model was successfully applied in targeting the Warrego orebody and in identifying a residual anomaly associated with a satellite body immediately to the north. Downhole magnetics were first applied to exploration at Tennant Creek in 1984, according to Williams (1987) who provided a history of exploration at Tennant Creek.

In 1996 the Northern Territory Department of Mines and Energy contracted World Geoscience to undertake a low level, closely spaced airborne radiometric survey over a small area in the Tennant Creek goldfield. The philosophy behind this exercise was to test the method as an exploration tool for economic mineralisation using U as a radiogenic pathfinder. An association between gold and uranium was known in at least some of the Tennant Creek gold deposits suggesting this was a potential testing ground for the method. There proved to be a very high correlation between the magnetic signal and a high U signal in eight existing ironstone prospects and the radiometric survey identified a similar number of prospective targets in the test area. These targets are currently untested.

**Tennant Creek style ironstone-associated gold-copper-bismuth mineralisation and its genesis**

Tennant Creek gold-copper-bismuth mineralisation is apparently unique with respect to its association with massive magnetite-quartz or haematite-quartz (ironstone) bodies. Haematite is probably a near-surface oxidation product, given that the depth of weathering is of the order of 100 m. However, Large (1975) has interpreted platy and acicular grains of magnetite as pseudomorphs after primary haematite. The ironstones range in size from a few tens of tonnes to more than 15 Mt at Warrego (Le Messurier et al 1990). Davidson and Large (1998) included the Tennant Creek ironstone-associated ore bodies in a rather loose class of 'Proterozoic Cu-Au deposits', which also includes Olympic Dam and Ernest Henry. Olympic Dam is three orders of magnitude larger in tonnage, and has approximately thirty times more contained gold than Nobles Nob, whereas conversely the gold grade at Nobles Nob is approximately thirty times that of Olympic Dam.

Ferenczi (1994) also recognised some affinities with Precambrian BIF-hosted, and flysch-hosted gold mineralisation. Large (1991) attributed Proterozoic Cu-Au iron oxide deposits to the production of oxidised, saline, high temperature, magmatically derived fluids which can transport gold, copper and rare metals as chloride complexes in a variety of magmatic and exhalative environments. A direct magmatic contribution to the syn-tectonic Tennant Creek style deposits has remained difficult to substantiate in the apparent absence of contemporaneous magmatic activity. However, Dunnet and Harding (1967) suggested that mafic dikes, now included in the Treasure Suite by Wyborn et al (1998), may be related to mineralisation. They are of a comparable age to the mineralisation, ~1820 Ma.

Critical aspects of the debate on the genesis of Tennant Creek mineralisation have focused on the timing of ironstone and gold mineralisation, whether the ironstones represent replacement or open space fill, and the nature of chemical triggers for the precipitation of ironstone and economic gold-copper mineralisation. Many of these issues are relevant to evaluating the potential of the area for non-ironstone related gold mineralisation, for host lithologies other than the Warramunga Formation turbiditic sediments and for the relative importance of structural and lithological controls on mineralisation. Related issues include the genetic implications of the spectrum of deposits from zoned gold-rich deposits (eg Juno, White Devil, TC8, Warrego and Nobles Nob) to copper dominated mineralisation (eg Gecko).

However, the ironstones are now generally considered syn-D$_1$ (ie Barramundi Orogeny). They have undergone brittle-ductile deformation and are associated with foliated chloritic alteration. Ironstone formation is therefore ~1850 Ma, whereas $^{40}$Ar/$^{39}$Ar data for muscovite associated with the economic mineralisation at Peko, Juno, Argo and Nobles Nob indicate a minimum age for sulphide stage mineralisation of ~1825 Ma (Compston and McDougall 1994). Pb model ages for galena from Peko, Juno, Argo and Gecko are 1819-1834 Ma (Warren et al 1995). Nguyen (1987) provided structural evidence for gold mineralisation associated with D$_2$. Thus, there is probably a substantial time break between ironstone and gold-copper-bismuth mineralisation, despite the suggestions of Huston et al (1993) and Skirrow (1993) that they are contemporaneous. Skirrow (1993) indicated that gold-copper-bismuth mineralisation at West Peko is late in D$_3$, or D$_4$. This raises the aspect of the possible progressive character of deformation in TENNANT CREEK.

**Fluid inclusion and stable isotope studies**

These studies have been used by several workers on a number of important Tennant Creek orebodies in an attempt to characterise mineralising fluids and identify their sources. In particular, fluid inclusion studies have been undertaken on Eldorado (Horvath 1988, Khin Zaw et al 1994), White Devil (Nguyen et al 1989, Huston et al 1993), Gecko (Huston et al 1993, Khin Zaw et al 1994), West Peko (1994), and Juno and TC8 (Khin Zaw et al 1994). Conflicting lower temperature estimates (~250°C, eg Huston et al 1993) and higher temperature estimates (~350-400°C, eg Skirrow and Walshe 1994) for oxide stage fluids, which all studies suggest are of moderate salinity (~20 wt% NaCl eq), can probably be reconciled. For example, Skirrow (1993) stated that quartz-magnetite O-isotope geothermometry indicated it was necessary to apply a substantial pressure correction (2.5-3.5 kb) to oxide stage fluids at West Peko and Eldorado. However, Huston et al (1993) estimated a lower pressure correction of 850 bars for oxide stage fluids they studied. They also estimated a pressure correction based on quartz-magnetite O-isotope geothermometry on barren ironstones unrelated to the ore deposits they studied.

Controversy with respect to the sulphide stage of mineralisation is more fundamental (see Ferenezi and Ahmad 1998). All workers have suggested that sulphide stage, heterogeneously trapped fluids had a temperature around 300-350°C with N$_2$ and CH$_4$ + CO$_2$ in vapour-rich inclusions. Whereas Nguyen et al (1989) and Skirrow and Walshe (1994) indicated that these fluids were of low to moderate salinity, all other workers indicated that they had high salinities. More importantly, different studies have attributed the range of δS$^{34}$ values to fractionation during the reduction of SO$_2$ (Huston et al 1993) or the oxidation of H$_2$S in ore fluids (Skirrow 1993), whereas Large (1991) took the middle ground and suggested variable mixing between connate SO$_2$ and magmatic H$_2$S. Skirrow (1993) did not dispute the validity of high temperature, high salinity fluids but he did not consider oxidised, probable basinal brine to be responsible for mineralisation, with the exception of minor uranium.

Reaction of gold-bearing fluid with ironstone and with contemporaneous oxidising fluid was cited by Skirrow (1993) as the probable agent obscuring isotopic differences between pristine fluids. Skirrow also found evidence in δC depletion of carbonate associated with the mineralisation, together with N$_2$ and CH$_4$ for an organic fluid component. He concluded that the ironstone-forming oxidised basin brines, and the reduced gold-copper-bismuth bearing fluids were discrete and did not progressively evolve one from the other. Furthermore, he suggested that: (1) the interaction of reduced, gold transporting fluid with ironstone or with post-ironstone, oxidising basinal fluids is an effective trigger for gold-copper-bismuth mineralisation; (2) it allows for a spectrum of gold-rich oxidised and copper sulphide-rich (pyrrhotite-bearing) reduced deposits; and (3) fluid sources and the mineralisation may be more closely akin to gold mineralisation in the Pine Creek shear zone than haematite-rich deposits of the gold-copper-iron oxide association.

Wyborn et al (1998) suggested the ~1820 Ma Treasure Suite as a possible magmatic source for gold-copper-bismuth and a wide range of other minor, rare metals including Se, Co, W, Sn and Mo in TENNANT CREEK. This suite comprises apparently only minor mafic to intermediate rocks in the Tennant Creek province, but Dunnet and Harding (1967) nonetheless suggested mafic diorites now included in this suite may have been related to Tennant Creek gold mineralisation. Widespread predominantly felsic rocks in the Davenport province are assigned to the Treasure suite, and Wyborn et al further point out that granite modelled under the Tennant Creek goldfield (see Rattenbury 1994) might be attributed to this suite.

**Analogue for Tennant Creek type mineralisation?**

Rutland and Drummond (1997) presented extended abstracts exploring possible geological and metallogenic parallels between the Palaeoproterozoic of northern Australia and Fennoscandia. In the context of the Tennant Inlier, some comparisons can be drawn with the Kiirunavaara and Skellefte deposits in northern Sweden. The Kiirunavaara deposit consists of a magnetite orebody, dated at 1.89 Ga, which is contemporaneous with the host acid volcanic rocks (rhyolitic ignimbrite referred to as the Kiruna porphyries) and some 0.4 Ga older than associated pyrite-chalcopyrite mineralisation, which is attributed to a later low temperature hydrothermal event (Cliff et al 1990, Cliff and Rickard 1992). The Skellefte district is seen by Par& (1991) as geologically continuous with the Kiruna district, and hosts pyritic volcanicogenic massive sulphide (some gold-rich) deposits in felsic volcanic rocks of Skellefte Group (Allen et al 1997, Weihed 1997). It is pertinent that Allen et al (1997) pointed out that the Skellefte Group comprises mafic, intermediate and felsic volcanic rocks but that sulphide mineralisation is mainly associated with subaqueous, tuffaceous rhyolitic cryptodomes, often as sub-seafloor rather than exhalative deposits but also as possible subaerial replacement deposits. Hitzman et al (1992) considered the 'Kiruna-type' deposits to be part of a larger class of Proterozoic iron oxide (Cu-U-Au-REE) deposits. In a recent review, Hitzman (2000) interpreted the Kiruna-type magnetite-apatite and the iron oxide-copper-gold deposits as end members of a continuum. Carson (2000) stated that the Kiruna-type deposits contain varying proportions of magnetite, haematite, apatite and
actinolite. According to Carlson, there are magnetite-apatite, magnetite-actinolite, and magnetite-haematite-apatite bodies although the ores also include massive magnetite essentially devoid of apatite. Hitzman (2000) reported that magnetite-apatite deposits may grade upwards into haematite-rich bodies with a corresponding change from sodic or sodic-calcic to potassic or hydrolytic alteration.

Additional important considerations presented by Hitzman (2000) are that iron oxide-copper-gold mineralisation (which may be associated with magnetite-apatite deposits) may result from similar, but cooler fluids to those forming the iron ore (ie oxidised, sulphide-poor and saline). Alternatively, the copper-gold mineralisation may result from interaction of the magnetite-apatite depositing fluid with a cooler, relatively sulfate-rich meteoric or basinal fluid carrying copper and gold, or directly from a oxidised, saline, probably sulfate-bearing fluid.

Skirrow (2000) recognised a spectrum of ‘ironstone’ associated gold-copper-bismuth deposits in TENNANT CREEK, which vary between reduced, copper-rich deposits and oxidised gold-rich deposits. He stated that the former have a narrow, and the latter a wider range of δ^34S_isotope values. Skirrow (1993, 2000) suggested that interaction of low or moderately saline, relatively reduced fluids carrying Au-Bi ± Cu with magnetite-haematite (‘ironstone’), and a greater or lesser overprint from a second oxidised, saline fluid at a late stage of, or post-dating, mineralisation can account for the known fluid characteristics of the Tennant Creek deposits and the range of deposit types.

According to Hitzman (2000), iron oxide-copper-gold (and magnetite-apatite) deposits form in a number of tectonic environments. These are: (1) intra-continental, both orogenic collapse and anorogenic magmatic settings; and (2) extensional settings associated with subduction at continental margins. The Gawler province, which hosts the Olympic Dam deposit, is assigned to an anorogenic magmatic setting. The Cloncurry District, which hosts the Ernest Henry deposit, is assigned to an orogenic basin collapse setting.

With respect to Tennant Creek, it is noted that Hitzman (2000) pointed out that the anorogenic magmatic setting is characterised by extrusive and intrusive igneous rocks, which are variably of felsic (eg granite intruding consanguineous volcanics) to mafic composition. In general, it hosts subaerial volcanics, particularly welded rhyolitic rocks, together with coarse volcanioclastic sedimentary rocks. ‘Red granites’ reflect pervasive hydrothermal, haematitic alteration of feldspar. Potassic or sodic alteration is also common. The igneous rocks are intracrustal melts consequent on underplating.

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**APPENDIX 1**

**Stratigraphic name definitions**

MANGA MAUDA, MEERIE AND COODNA MEMBERS of Hayward Creek Formation (new names).

**Proposer:** N. Donnellan.

**Derivation of names:** Manga Mauda (lat. 19°16'48", long. 134°13'29" E), Meerie (lat. 19°15'0"0, long. 134°14'56" E), and Coodna (lat. 19°16'57", long. 134°13'58" E) waterholes in FLYNN.

**Distribution:** All three members are exposed in FLYNN and SHORT RANGE (TENNANT CREEK); Meerie and Coodna Members in MOCKATY and BRUNCHILLY (HELEN SPRINGS), and probably Manga Mauda and Meerie Members in BARKLY (TENNANT CREEK).

**Type Section:** The three members form a continuous section from lat. 19°09'44" long. 134°08'41" (base) to lat.19°09'10" long. 134°07'05" (top). The Manga Mauda Member extends from the base of the section to 134°08'04" from where the member continues with a recessive, mapped siltstone lithofacies which extends to the base of the Meerie Member at 134°08'00". The Meerie Member extends upward to 134°07'16" and is overlain by a recessive, discontinuous volcanic lithofacies included within the member and which extends to the base of the Coodna Member at 134°07'32". The Coodna Member extends to the top of the section.

Note that a fourth member overlays these three members: the Whittington Range Member (formerly Whittington Range Volcanics), which is dominantly volcanic. It was defined by Mendum et al (1978) and renamed as part of the Hayward Creek Formation by Donnellan et al (1995). These four Members together make up the entire Hayward Creek Formation.

**Thickness:** The Manga Mauda Member is ~1,000 m thick (~900 m of sandstone plus ~100 m of siltstone at the top); the Meerie Member is ~870 m (~770 m of sandstone plus ~100 m of volcanic rocks at the top); and the Coodna Member is ~930 m thick. The Whittington Range Member is 347 m thick in its original type section (Mendum et al 1978).

**Lithology:** All Members comprise predominantly lithic, sublithic and quartz arenite with subordinate to minor monomictic and polymictic orthoconglomerate. The Meerie Member is distinguished from the underlying Manga Mauda and overlying Coodna Member by sandstone composition and bedding characteristics. Thus, the Meerie Member predominantly
comprises well sorted, thin bedded sandstone with well rounded grains in thin to medium bed sets showing very low angle cross bedding to planar, parallel, laterally persistent beds. Sandstone compositions include quartz arenite together with sublithic and lithic arenite, some of which show poor sorting and rounding of clasts, and some vugging on wacke, in that they have abundant recrystallised matrix. The Manga Mauda and Coodna Members generally comprise more poorly sorted sandstone with less rounded grains, pebble-bearing sandstone and pebble conglomerate. They have thin to medium beds arranged in thick bed sets that show trough and tabular cross bedding.

**Structural attitude:** Moderate to steeply dipping and locally overturned beds folded into broad domes and basins.

**Relationships and boundary criteria:** A conformable, transitional relationship exists between the Manga Mauda Member and the underlying Brumbree Formation. The contact is taken as the onset of pebble-bearing sandstone. There is similarly a conformable contact between the top of the Coodna Member and thinly interbedded fine sandstone and siltstone of the overlying Whittington Range Member. To the north, and particularly in HELEN SPRINGS, there is a conformable contact between the Coodna Member and a mapped, informal interval of intensely silicified sandstone (orthoquartzite) which in turn underlies volcanic rocks and silicified, stromatolitic, calcareous siltstones (?) of the Whittington Range Member.

**Age and evidence:** The Hayward Creek Formation has a maximum age of sedimentation of 1784 ± 9 Ma which is the age of the youngest detrital zircon population recognised by Compston (1995).

**Synonymy:** The Manga Mauda, Meerie and Coodna Members are respectively synonymous with the informal lower, middle and upper sandstone members of the Hayward Creek Formation of Donnellan et al (1995) and the lower, middle and upper sandstone lithofacies of Donnellan et al (1999).

**Correlatives:** The Hayward Creek Formation was correlated with the Unimbra, Yeeradgi and Coulters Sandstones together with the Frew River Formation (Wauchope Subgroup, Hatches Creek Group, Davenport province) by Blake (1984). These three Sandstones would therefore correlate with the Manga Mauda, Meerie and Coodna Members respectively.

An alternative correlation was suggested by Donnellan et al (1995) who correlated the Hayward Creek Formation with the Taragon, Unimbra and Yeeradgi Sandstones. However, their revised correlations are difficult to reconcile with new age constraints (eg Compston 1995, Smith 1999). Also, the probable regional distribution of a basal sandstone unit following a hiatus in sedimentation suggests at least partial equivalence of the Hayward Creek Formation with the Coulters Sandstone, because a hiatus is also inferred at the base of the Meerie Member. Hence a correlation similar to that of Blake (1984) is now preferred, whereby the Manga Mauda Member is correlated with the Unimbra and Yeeradgi Sandstones, and the Meerie and Coodna Members with the Coulters Sandstone.

The Hayward Creek Formation may also correlate with part of the Yiyintyi Sandstone of the Tarawarra Group (McArthur Basin).

**APPENDIX 2**

**Data sources and notes for Figures 19 and 20 (see also reference list)**


**Figure 20** Schematic representation of postulated lithostratigraphic and tectonostratigraphic relationships between the Tennant Creek and northern Arunta Inliers. Dates are from the following sources.

1 Young et al (1995). The Ngadarunga Granite is an S-type, and 1880 ± 5 Ma was interpreted as an igneous crystallisation age. However, the authors acknowledge the age could reflect inheritance and that the crystallisation age (and hence the Yuendumu tectonic event) may be younger than 1880 Ma. The date for the Patmunugala beds is an interpreted igneous crystallisation age but again the authors acknowledge these rocks could be younger. The date for the Nicker beds is a preferred crystallisation and eruptive age. The date for the Carrington Granite Suite is an interpreted igneous crystallisation age for a granodiorite from near Mount Hardy. The age inferred for the Lander Rock beds is a minimum age given that they are intruded by the Ngadarunga Granite.

2 Collins and Williams (1995). The date of 1780 Ma for the Napperby Gneiss is an inferred age for its granitic protolith. The preferred emplacement age for the Warrimbi Granite is 1785 ± 22 Ma, whereas 1868 ± 12 Ma is interpreted to result from inheritance given that the Granite intrudes the Reynolds Range Group. The Hawthorn Granite and Mount Stafford Granite are S-types and both have an interpreted emplacement age of 1818 Ma. The Warrimbi Granite and Mount Stafford Granite were partially melted from a 1870-1860 Ma protolith.

3 Unpublished data of Collins and Williams, quoted by Collins and Williams (1995). The probable age range of the Reynolds Range Group is 1820-1780 Ma given that it unconformably overlies the Mount Stafford terrane and is intruded by the Warrimbi Granite. 1870 Ma is an inferred maximum age for the Lander Rock beds based on zircon populations in metasedimentary xenoliths from the Mount Stafford Granite and Warrimbi Granite. A possible minimum age for the Lander Rock beds is 1850-1820 Ma if the dominant zircon population in the S-type Ngadarunga Granite (Young et al 1995) is inherited.

4 Warren and Shaw (1995). These authors suggested that the Narwinietooa Metamorphic Complex (NMC) probably has two components. They reported that the NMC was deformed, metamorphosed and intruded by syntectonic granite.
during the Strangways Orogeny (1760-1750 Ma). Black and Shaw (1992) dated non-foliated microgranitic phases of the Forty Five Augen Gneiss at 1760 ± 11 Ma, and gneiss at 1754 ± 9 Ma. Warren and Shaw (1995) inferred a protolith age of ~1770 Ma for the felsic and intermediate gneisses of the NMC on the basis of a geochemical correlation with the Randall Peak Metamorphics. They further suggested that geophysical data indicates that the higher metamorphic grade rocks of the NMC extend northwest to underlie the Lander Rock beds which may be >1880 Ma (at least locally).

5 Nunn (1999) reported a maximum depositional date of 1639 Ma for an epiclastic tuffaceous unit from the Shillinglaw Formation (Namerinni Group). Similar ages have been reported for parts of the McArthur Group in the McArthur Basin (Page et al 2000).

6 A depositional age of 1492 ± 4 Ma was reported for the Mainur Formation, lower Roper Group, McArthur Basin (Jackson et al 1999). Hussey et al (2001) correlated the Renner Group (Ashburton province, Tennant Inlier) with the Roper Group.

7 Compston (1995). The age of the S-type Warrego Granite is equivocal. Compston favoured the youngest U-Pb analyses (~1650 Ma) as the probable crystallisation age of the granite, although he noted that this may alternatively be as old as ~1800 Ma. Compston and McDougall (1994) gave a 40Ar/39Ar muscovite date of 1677 ± 4 Ma for a thermal event which affected the Warrego Granite. The Wundirgi Formation has a minimum age of 1827 ± 9 or 1827 ± 8 Ma, the date of probable metamorphosed intrusive rocks within the formation, and a metamorphic date of 1696 ± 4 Ma (Compston and McDougall 1994). The monzodioritic marginal phase of a diorite intruding the Wundirgi Formation in SHORT RANGE has been dated at 1821 Ma (Compston 1995).

8 Blake and Page (1988) reported 1820 Ma as their preferred age for the Epenarra Volcanics, and 1813 Ma for the Treasure Volcanics, although both sets of zircon data are complicated by inheritance and/or lead loss.

9 Wyborn et al (1998a, b) recognised three suites of felsic (with or without intermediate and mafic) igneous rocks in the Tennant Creek and Davenport provinces: (a) the ~1850 Ma Tennant Creek Supersuite; (b) the ~1820 Ma Treasure Suite; and (c) the ~1710 Ma Devils Suite. The age of the Tennant Creek Supersuite is well constrained by dates of Compston (1995). North and south plutons of the Tennant Creek Granite are 1848 Ma and 1858 Ma respectively. The Tennant Creek Granite at Red Bluff is 1853 Ma (and 1849 Ma at western Red Bluff). Additional dates for members of the Supersuite from Compston (1995) are: Mumbilla Granodiorite 1850 Ma, White Devil Porphyry 1853 Ma, Cabbage Gum Granite 1848 Ma, and associated dolerite intruding the Tennant Creek Granite 1858 Ma. Dates for the Channingum Granite (1840 ± 9 Ma), Bernborough Formation (1840 ± 8 Ma and 1845 ± 4 Ma) and an unnamed porphyry (1838 ± 9 Ma). These ages bridge the time gap between the Tennant Creek Supersuite and the Treasure Suite which Wyborn et al (1998a, citing Blake and Page 1988) suggested ranges from 1829-1816 Ma.

The 1829-1816 Ma range for the Treasure Suite is consistent with Compston’s (1995) and Compston and McDougall’s (1994) dates for rocks intruding the Wundirgi Formation (see above), and also with a 1819 ± 9 Ma date for the Strzeleckie Volcanics reported by Hussey et al (1999). A maximum age of 1784 Ma (Compston 1995) constrains sedimentation of the Hayward Creek Formation (Meerie Member). This may be consistent with a discrete episode of magmatism contemporaneous with the Kudinga Basalt in the Davenport province, ie post-dating and unrelated to the Treasure Suite. However, given a substantial time break at the base of the Coulters Sandstone and Meerie Member of the Hayward Creek Formation (see discussion in text) then magmatism in the lower Wauchope Subgroup and the Manga Mauda Member of the Hayward Creek Formation is contemporaneous with the Treasure Suite. The Devils Suite comprises the Devils Marbles, Elkedra and Warrego Granites and probably also the Gosse River East Syenite and possibly part of both the Ali Curung Suite and the Barrow Creek Granite Complex.

10 Hussey et al (1999) reported magmatic ages of 1809 and 1803 Ma for the Ooralingie and Bean Tree Granites respectively of the Barrow Creek Granite Complex. They considered that these ages bracket the time of the Murchison event. Warren (1989) noted the physical and geochemical similarities between the relatively undeformed granite of the Barrow Creek Granite Complex and the late, two-mica, granites of the Devils Suite. It is possible that the Barrow Creek Granite Complex and the Ali Curung Suite may include representatives of both the Treasure and Devils Suites. Zhao and McCulloch (1995) in their subdivision of granites of the Arunta Inlier included the Barrow Creek Granite Complex in their 1730-1710 Ma high heat production group, and the Ali Curung Suite in their low-Al type Main Group granites which also include the Napperby Main Suite and Dnieper Granite. Zhao and Bennett (1995) reported a 1771 Ma crystallisation age for the Dnieper suite.

11 Zhao and Bennett (1995).


13 Scrimgeour and Smith (pers comm 1999), and Smith (1999).


