Palaeoproterozoic island-arc-related mafic rocks of the Litchfield Province, western Pine Creek Orogen, Northern Territory

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CONTENTS

Abstract ........................................................................ iv
Introduction ........................................................................ 1
Regional geology ................................................................ 2
Pine Creek Orogen (PCO) .................................................. 2
Litchfield Province ......................................................... 3

Palaeoproterozoic mafic/ultramafic igneous rocks
of the Wangi Basics............................................................. 5
Geochronological and stratigraphic constraints of the
Wangi Basics...................................................................... 5

Petrography, geochemistry, Nd isotope chemistry
and a revised subdivision of the mafic/ultramafic

‘Wangi Basics’.................................................................. 6
Geochemistry and Petrography............................................. 6
Woolianna Gabbro............................................................ 9
High-Alumina gabbro and dolerite (HAG).......................... 10
Depleted Low-Ti gabbros (LTG).......................................... 12
Low-Ti dolerites (LTD) – south ...................................... 13
Low-Ti dolerites (LTD) – north ....................................... 15
Crustal-like mafic rocks (MCC) ........................................ 16
Benning Gabbro ............................................................... 17
High-Ti tholeitic gabbros (HTT) ....................................... 17
Keri Metamorphics ............................................................ 18
Metamorphosed noritic cumulates (MNC) ....................... 18
Metaferrogabbro (MFG) .................................................. 20
Lilyarba Mafics .................................................................. 21
Possible lamprophyric/shoshonitic association (LSS) ........... 21

Tectonomagmatic Affinity Discrimination
Diagrams .......................................................................... 22
Sm-Nd Isotope Geochemistry ............................................. 25

Discussion ........................................................................... 26
Woolianna Gabbro ............................................................ 26
Benning Gabbro ............................................................... 28
Keri Metamorphics ............................................................ 29
Lilyarba Mafics .................................................................. 29

Conclusions ........................................................................ 29

Acknowledgements .......................................................... 30
References ........................................................................ 31

Appendix I: Major and trace element results for Litchfield
mafic rocks (Excel chart)
Appendix II: Definitions of new stratigraphic units .......... 34

FIGURES
1. Location of Pine Creek Orogen ..................................... 1
2. Structural domains of Pine Creek Orogen ..................... 3
3. Interpretive geological map of Litchfield Province .......... 4
4. Field photographs of Litchfield Province
mafic rocks ...................................................................... 5
5. First vertical derivative magnetic image NT/1VDr
grey of Litchfield Province and environs ....................... 7
6. Geological map of Litchfield Province, showing new
mafic lithostratigraphic suites ........................................ 8
7. Chemical classification and nomenclature diagrams.
   (a) Total alkali–silica diagram (TAS) (b) SiO2 wt%
   versus K2O wt% ....................................................... 9
8. Detail of Woolianna Gabbro HAG outcrop ................. 10
9. Woolianna Gabbro HAG: photomicrographs ............ 11
10. Woolianna Gabbro HAG: Eu/Eu* vs Al2O3 wt%
diagram ......................................................................... 11
11. Woolianna Gabbro HAG: Harker diagrams ............. 12
12. Woolianna Gabbro HAG: chondrite-normalised and
    N-MORB-normalised diagrams .................................. 13
13. Woolianna Gabbro LTG: field photographs ............... 14
14. Woolianna Gabbro LTG: photomicrographs .............. 14
15. Woolianna Gabbro LTG: Eu/Eu* versus Al2O3 wt%
diagram ....................................................................... 15
16. Woolianna Gabbro LTG: chondrite-normalised and
    N-MORB-normalised diagrams .................................. 15
17. Woolianna Gabbro LTG-south: field photograph ....... 15
18. Woolianna Gabbro HTT: photomicrographs ............. 16
19. Woolianna Gabbro LTG-south: Eu/Eu* versus
    Al2O3 wt% diagram .................................................. 16
20. Woolianna Gabbro LTG-south: chondrite-normalised
    and N-MORB-normalised diagrams ......................... 17
21. Woolianna Gabbro LTG-north: field photograph ...... 17
22. Woolianna Gabbro LTG-north: photomicrographs .... 18
23. Woolianna Gabbro LTG -north: Eu/Eu* versus
    Al2O3 wt% diagram .................................................. 18
24. Woolianna Gabbro LTG-north: chondrite-normalised
    and N-MORB-normalised diagrams ......................... 19
25. Woolianna Gabbro MCC: chondrite-normalised and
    N-MORB-normalised diagrams .................................. 19
27. Benning Gabbro HTT: chondrite-normalised and
    N-MORB-normalised diagrams .................................. 20
28. Photomicrographs of Keri Metamorphics MNC .......... 20
29. Chondrite-normalised and N-MORB-normalised
diagrams for Keri Metamorphics MNC ......................... 21
30. Keri Metamorphics MFG: field photographs ............... 21
31. Keri Metamorphics MFG: photomicrographs ............ 22
32. Keri Metamorphics MFG: chondrite-normalised and
    N-MORB-normalised diagrams .................................. 23
33. Lilyarba Mafics: Eu/Eu* versus Al2O3 wt% diagram ....... 23
34. Lilyarba Mafics LSS: chondrite-normalised and
    N-MORB-normalised diagrams .................................. 24
35. Tectonomagmatic affinity discrimination
diagrams for global data. (a) Al2O3/TiO2
    versus Cr/FeOt (b) Al2O3/TiO2 versus Zr/Y ............. 24
36. Tectonomagmatic affinity discrimination
    diagrams for Litchfield Province mafic
    rocks. (a) Al2O3/TiO2 versus Cr/FeOt
    (b) Al2O3/TiO2 versus Zr/Y ........................................ 25
37. Al2O3/TiO2 versus CaO/Zr diagram for Litchfield
    Province mafic rocks .................................................. 26
38. Al2O3/TiO2 versus CaO/Zr diagram for Litchfield
    Province mafic rocks .................................................. 26
39. Tectonomagmatic affinity discrimination
diagrams for global data ................................................. 27
40. Tectonomagmatic affinity discrimination
diagrams for Litchfield Province mafic
    rocks. (a) Ti (ppm) versus CaO/TiO2
plitic whereas Cr/FeOt ............................................... 28
    (b) Ti (ppm) versus Al2O3/TiO2 .................................. 28

TABLE
1. Nd isotope data for Litchfield mafic rocks .......... 29
ABSTRACT

Palaeoproterozoic mafic and ultramafic rocks of widely scattered geographic extent in the Litchfield Province, western Pine Creek Orogen, Northern Territory have historically been grouped together in a single unit known as the Wangi Basics. Although these rocks all show variable overprinting by amphibolite facies metamorphism, their primary geochemical signatures have been preserved. Detailed geochemical investigations show that these rocks are chemically and isotopically diverse and can no longer be considered part of the same magmatic unit. Various categories of compositionally distinct mafic/ultramafic rocks can be recognised:

(i) High-alumina gabbro and dolerite (HAG).
(ii) Depleted low-Ti gabbro (LTG).
(iii) Low-Ti dolerite (LTD).
(iv) High-Ti tholeiitic gabbro (HTT).
(v) Metamorphosed noritic cumulate (MNC).
(vi) Metaferrogabbro (MFG).
(vii) Possible lamprophyric/shoshonitic association (LSS).
(viii) Crustally-contaminated mafic rocks (MCC).

The high-alumina gabbro and dolerite, depleted low-Ti gabbro and low-Ti dolerite are characterised by low TiO$_2$ contents, elevated Al$_2$O$_3$ and CaO abundances, and positive Sr and negative Nb and Ta anomalies relative to elements of similar compatibility. These chemical features are typical of Phanerozoic arc-related rocks, suggesting that these rocks originated in an analogous ancient Palaeoproterozoic island arc tectonic regime. The high-alumina gabbro, now amphibolite, was once dominantly a plagioclase-rich cumulate, but some compositions approach primitive high-alumina basalt typical of arc settings worldwide. The depleted low-Ti gabbro is characterised by negatively sloping REE patterns and other geochemical features that resemble Troodos low-Ti basalt (high-Ca boninite), implying derivation from a strongly depleted upper mantle source. Low-Ti dolerite from both the north and south of the Litchfield Province are chemically similar to known primitive island arc tholeiitic rocks. The depleted low-Ti gabbro and low-Ti dolerite have positive $\varepsilon_{Nd}$ isotopic values, indicating that they were derived from a depleted mantle source, consistent with the geochemical results. These rocks with arc-related chemical signatures (HAG, LTG, LTD) most likely represent tectonically disrupted slices of back-arc oceanic crust; the depleted low-Ti gabbro and low-Ti dolerite are interpreted to be mid-crustal-level feeder dykes to lavas that have since been removed, and the high-alumina gabbro probably represents a section through a former high-level magma chamber. The rocks show variable overprinting by amphibolite facies metamorphism. The high-Ti tholeiite is chemically similar to known rift tholeiitic rocks and most likely originated in a post-collisional magmatic event that postdated emplacement of the back-arc crust. In contrast, mafic/ultramafic rocks of the metamorphosed noritic cumulate and metaferrogabbro categories located in the north of the province do not share the arc-like chemical signature.

Recent U-Pb SHRIMP dating of two Wangi Basics samples yielded a magmatic age of 1860 Ma for a garnet-bearing metaferrogabbro from the north of the Litchfield Province and 1830 Ma for a probable lamprophyric/shoshonitic rock from the south of the province. A geochronological age has not yet been obtained for HAG samples, but stratigraphic relationships suggest an emplacement age pre-1855 Ma.

These significant chemical and geochronological differences have led to the introduction of the following new lithostratigraphic units: Woolianna Gabbro, Benning Gabbro, Keri Metamorphics and Lilyarba Mafics. The umbrella term Wangi Basics for these mafic/ultramafic rocks is hereby discontinued.
INTRODUCTION

The North Australian Craton (NAC) of Plumb (1979) is one of three major Precambrian tectonic units of Australia (Myers et al. 1996). Tectonic processes contributing to the formation of the NAC have long been the subject of considerable debate, with much of the understanding largely influenced by tectonic regimes involving ensialic processes (e.g. Etheridge et al. 1987). Two contrasting models have been proposed for the tectonic evolution of the NAC, the first involving intraplate, intracratonic processes (e.g. Hancock and Rutland 1984, Etheridge et al. 1987) and the second favouring regimes more analogous to recent plate tectonic processes (e.g. Tyler et al. 1995, Sheppard et al. 1999, Griffin et al. 2000).

Hancock and Rutland (1984) proposed a model for the tectonic evolution of the Halls Creek Orogen (HCO) in the Kimberley region of northwestern Australia (Figure 1) which involved lithospheric extension followed by oblique convergence, resulting in subduction of thin continental crust prior to crustal shortening. This convergence was thought to be responsible for the generation of high-temperature metamorphism and plutonism. This was based in part on the apparent observation that orogenic belts in this region lacked evidence for an island-arc complex, such as paired metamorphic belts diagnostic of oceanic subduction. These authors therefore concluded that lithospheric extension and convergence did not involve subduction of oceanic crust. Their model was expanded upon by Etheridge et al. (1987) who, again citing the apparent absence in Proterozoic northern Australia of features diagnostic of modern orogeny (for example, ophiolites), proposed an intraplate extensional model involving contemporaneous small-scale mantle convection which initiated mantle melting, underplating and continental extension. This model was further reinforced by Wyborn (1988), who suggested that between 2300 Ma and 2000 Ma, large volumes of mantle-derived material accreted to the base of the lower crust.

Figure 1. Geological map of northern Australia showing orogenic domains, Neoarchaean basement and northern Australian basins. Dashed inset box details location of Pine Creek Orogen. The red hatched area shows the location of the Litchfield Province.
The underplated material was subsequently remelted during 1880–1840 Ma to produce compositionally uniform felsic volcanic and I-type granites throughout Proterozoic Australia. The proposed tectonic regime involved generation of new crust by vertical accretion in an intracontinental environment and did not require subduction of oceanic crust. However, modern analogues for such a process are unknown.

The intraplate models proposed by these previous authors contrast with more recent plate tectonic models that involve analogies with modern tectonic regimes (Myers et al 1996, Cawood and Korsch 2008). Within the HCO, Tyler et al (1995) identified three distinct tectonostratigraphic terranes, which they considered were once geographically separate but were subsequently tectonically juxtaposed to their present position. Based on geochemical observations, Sheppard et al (1999) suggested that the tectonic setting in the Central Zone of the HCO was more reminiscent of an oceanic island arc/back-arc system analogous to modern subduction processes. Griffin et al (2000) further considered that the genesis of high-K granites and volcanic rocks in the HCO occurred in a postcollisional tectonic setting related to an island arc regime or ensialic marginal basin.

Historically, the westernmost portion of the Pine Creek Orogen (PCO), known as the Litchfield Province (Figure 1), has been considered to represent a tectonic continuation of the HCO into the Northern Territory (Traves 1955, Morgan et al 1970, Hancock and Rutland 1984). More recently, Carson et al (2008) suggested that metamorphism in the Litchfield Province at 1855–1853 Ma (Litchfield Event) correlates directly with a similar event at 1855 Ma in the Western Zone of the HCO. Although the Central Zone of the HCO similarly experienced localised crustal anatexis at 1855 Ma, it also underwent a subsequent 1845–1835 Ma tectonometamorphic event which to date has not been identified in the Litchfield Province. This led Carson et al (2008) to suggest that if a continental suture of this age (1840 Ma) exists in the HCO, then it does not extend into the Litchfield Province.

**REGIONAL GEOLOGY**

**PINE CREEK OREGEN**

The Pine Creek Orogen (PCO), known as the Litchfield Province (Figure 1), and constitutes one of the most mineralised regions in Australia. The regional geology and stratigraphy of the PCO has been described previously by various authors (eg Walpole et al 1968, Needham et al 1980, Stuart-Smith et al 1980, Ahmad 1988, Needham et al 1988, Needham and De Ross 1990, Ahmad et al 1993).

The PCO is dominated by a series of deformed and metamorphosed Palaeoproterozoic siliciclastic, carbonate and carbonaceous sedimentary and volcanicogenic successions (Worden et al 2008b) that unconformably overlie small inliers of crystalline (granite and gneiss) basement of Neoarchaean age (2700–2500 Ma; Cross et al 2005, Hollis et al 2009a, Glass et al 2010). These successions are extensively intruded by syn- to post-tectonic granitoids. To the east, they are unconformably overlain by the Palaeo- to Mesoproterozoic McArthur Basin, to the west by the Neoproterozoic Victoria Basin and to the southwest and northwest by Cambrian-Ordovician and Mesozoic successions (Daly and Bonaparte basins). Bimodal (volcanic and intrusive) igneous rocks are recognised throughout the PCO.

Needham et al (1988) broadly subdivided the PCO into three major geological domains based on lithostratigraphic, tectonic and metamorphic criteria. These comprise the amphibolite to granulite facies Litchfield Province in the western PCO, the greenschist facies Central Domain (including Rum Jungle region and South Alligator valley) and the amphibolite facies Nimbuwah Domain to the northeast (Figure 2). Within the Central Domain, Archaean basement is represented by the subsurface 2674 Ma Woolner Granite (Williams and Compston 1983, Glass et al 2010) and the 2545–2521 Ma Rum Jungle Complex (Cross et al 2005). The Central Domain has the best preserved stratigraphy in the PCO and ranges from 2 km to 18 km in thickness, generally increasing to the east (Ahmad et al 1993). It is further subdivided into the 2020 Ma Woodcutters Supergroup and the 1860–1840 Ma Cosmo Supergroup, these separated by an unconformity representing at least 160 million years (Ahmad and McCready 2001, Ahmad et al 2006, Worden et al 2008a, b). Both Supergroups are dominated by carbonate, carbonateaceous, siliciclastic and volcanioclastic sedimentary rocks, with subordinate mafic and felsic volcanic rocks. The sedimentary successions of the Central Domain are intruded by post-tectonic granitoids of the 1830–1800 Ma Cullen Supersuite.

The Nimbuwah Domain includes Neoarchaean gneissic basement consisting of the 2671 Njibinjibinj Gneiss (Hollis et al 2011), the 2640 Ma Arrarra Gneiss (Hollis et al 2009a, b), the 2520 Ma Nanambu Complex [Hollis et al (2009b); previously dated at 2470 ± 47 Ma by Page et al (1980)], and the 2527–2510 Ma Kukalak Gneiss (Hollis et al 2009a, b). Neoarchaean basement in the Nimbuwah Domain is overlain by Palaeoproterozoic amphibolite facies metamorphosed rocks. The heat source thought to be responsible for mid-amphibolite facies metamorphism is attributed to emplacement of the 1867–1862 Ma Nimbuwah Complex, comprising granitic, granodioritic and subordinate tonalitic gneiss (Hollis et al 2009a, b).

The Litchfield Province is located on the western perimeter of the PCO and consists of poorly exposed Palaeoproterozoic amphibolite to granulite facies metamorphosed rocks, dominantly S-type Palaeoproterozoic granitoids and mafic and ultramafic rocks. Unlike in the Central and Nimbuwah Domains, Archaean rocks have not been identified in the Litchfield Province.

In general, correlation of strata between the three domains is largely hindered by lack of exposure and differing styles of structure and metamorphic grade. However, detrital zircon dating by Hollis et al (2009c) showed that Palaeoproterozoic metasedimentary rocks of the Nimbuwah Domain were derived from a different source material to similarly aged rocks in the Central Domain and Litchfield Province. The occurrence of 2670 Ma and 2500 Ma granitic and gneissic rocks in both the Central and Nimbuwah Domains (Cross et al 2005, Hollis et al 2009a, b, Glass et al 2010) may
indicate contiguous Neoarchaean basement under surficial cover. However, recent Nd isotope studies (Glass et al 2010) highlight differences in Nd isotopic character for the two 2670 Ma rock bodies. Additional data are needed to evaluate this hypothesis.

Widespread regional deformation took place during the Palaeoproterozoic and was historically termed the “Barramundi Orogeny” (eg Etheridge et al 1987, Page and Williams 1988). However, recent geochronological studies have revealed that deformation in the PCO was not restricted to a single synchronous widespread event, but a series of tectonically distinct events at 1865 Ma, 1855 Ma and 1813 Ma (Carson et al 2008).

**Litchfield Province**

Situated on the westernmost margin of the PCO (Figure 2), the Litchfield Province comprises an elongate northnortheast-trending belt of poorly exposed Palaeoproterozoic metamorphic and igneous rocks (Figure 3; Berkman 1980, Pietsch and Edgoose 1988). The Province has been previously designated the Litchfield Block (Sweet 1977), Litchfield Complex (Needham et al 1980) and Litchfield Domain (Needham 1988). The name Litchfield Province is adopted here as described by Berkman (1980) and Pietsch and Edgoose (1988). The Litchfield Province is separated from the Central Domain of the PCO to the east by the southerly portion of the north-trending Giants Reef Fault and bounded to the west by the overlying Palaeozoic-Mesozoic Bonaparte Basin.

The Litchfield Province comprises Palaeoproterozoic, low- to high-grade metamorphic pelvic and psammitic metasedimentary rocks, syn- to post-tectonic granitoids, felsic volcanic and mafic intrusive rocks and rare basalt. Unlike in the Central Domain and Nimbuwah Domain, Archaean rocks have not been identified within the Province. Palaeoproterozoic metamorphic and igneous rocks include the mid-amphibolite to granulite facies Hermit Creek Metamorphics, the mid-amphibolite facies Fog Bay Metamorphics, the mid- to upper-amphibolite facies Welltree Metamorphics, greenschist to amphibolite facies Wangi Basics and syn- to post-tectonic Wagait Suite granitoids, and the dominantly S-type granitoids of the Allia Creek Suite (Figure 3). The Fog Bay Metamorphics are concealed beneath Mesozoic and Cenozoic cover in the northwest Litchfield Province and have only been identified in drillcore. They comprise garnet schist and gneiss, possible volcanogenic rocks, minor carbonate and quartzite (Pietsch and Edgoose 1988). The Hermit Creek Metamorphics comprise granulite-facies pelitic and psammitic schist, amphibolite, cordierite migmatite and rare calc-silicate rocks exposed in the southern part of the Litchfield Province. The Welltree Metamorphics consist of mid-upper amphibolite...
Facies garnet gneiss, schist and quartzite and have limited exposure east of the Tom Turners Fault in the northeastern Litchfield Province. The Wangi Basics comprise a grouping of poorly exposed mafic and ultramafic rocks predominantly bounded by the Tom Turners and Giants Reef Faults, but also including minimal outcrop west and east of these faults respectively. Palaeoproterozoic granites in the Litchfield Province are dominantly fractionated S-type granitoids and contain peraluminous minerals such as andalusite, cordierite and muscovite (Wyborn et al. 1997, Budd et al. 2002). The Litchfield Province is also host to felsic volcanic rocks.

The lack of contiguous outcrop of the various constituents of the Litchfield Province creates major uncertainties for lithostratigraphic correlation, both within the Province and with the well characterised Central Domain of the PCO immediately to the east (Carson et al. 2008). However, recently published geochronological data do provide some stratigraphic constraints. A U-Pb SHRIMP zircon date for the Fog Bay Metamorphics yields a maximum constraint on sedimentation at 2020 Ma (Carson et al. 2009), similar to the 2020 Ma maximum deposition age for the Wildman Siltstone of the Mount Partridge Group in the Central Domain (Worden et al. 2008a, b). In contrast, SHRIMP U-Pb studies of detrital zircons (Worden et al. 2008a) indicate that the mid-amphibolite to granulite facies Hermit Creek Metamorphics and Welltree Metamorphics correlate with younger detrital spectra of 1865 Ma for the Burrell Creek Formation of the Finniss River Group, a feature also noted by Hollis et al. (2009b). Felsic volcanism represented by the Warrs Volcanic Member and Berinka Volcanics has yielded crystallisation ages of 1860 Ma (Worden et al. 2006a, b).

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**Figure 3.** Interpretive geological map of Litchfield Province showing major Palaeoproterozoic metasedimentary and igneous units and superimposed outcrop locations of Wangi Basics. Modified from Carson et al. (2008).
Palaeoproterozoic syn- to post-tectonic, dominantly S-type granitoids in the Litchfield Province typically have ages in the range 1863–1850 Ma (Worden et al. 2008a). In contrast, a much younger maximum intrusion age of 1806 Ma was reported for the Allia Creek Granite, also an S-type granitoid in this region (Worden et al. 2008a).

The timing of peak metamorphism for the granulite facies migmatitic Hermit Creek Metamorphics and mid-amphibolite facies Fog Bay Metamorphics has recently been constrained by SHRIMP U-Pb monazite geochronology to 1855 Ma (Carson et al. 2008). This contrasts with a much later peak metamorphic SHRIMP U-Pb monazite age of 1813 Ma for the Welltree Metamorphics, which records a previously unrecognised tectonothermal event within the PCO (Carson et al. 2008). These authors speculated that the high-temperature advective heat source responsible for localised anatectic (partial melting) of the Hermit Creek Metamorphics may have been due to emplacement of the Wangi Basics, presumed to be synchronous with peak metamorphism at 1855 Ma. However, two samples of Wangi Basics from the northern and southern Litchfield Province yielded U-Pb SHRIMP zircon crystallisation ages of 1860 Ma (Carson et al. 2009) and 1830 Ma (Worden et al. 2008a) respectively. The difference between the two intrusion ages (within error) is about 30 million years. The apparent disparity in the geochronological data, combined with a distinct lack of reliable field mapping constraints (both discussed in more detail below), imply that these rocks (and perhaps other rocks mapped as Wangi Basics) are distinct lithostratigraphic units. These inconsistencies initiated a reappraisal of the Wangi Basics and became the focus of the present study.

### PALAEOPROTEROZOIC MAFIC/ULTRAMAFIC IGNEOUS ROCKS OF WANGI BASICS

The name *Wangi Basics* has historically been used as an umbrella lithostratigraphic term for a grouping of poorly exposed, variably metamorphosed, mafic and ultramafic rocks located within the Litchfield Province. They have been described previously by Dundas et al. (1987a), Pietsch and Edgoose (1988), Edgoose et al. (1989a, b) and Pietsch (1989).

The Wangi Basics have outcrop extent mostly bounded to the east by the Tom Turners Fault and to the west by the Giants Reef Fault, but also include minimal outcrop west and east of these faults (Figure 3). They comprise gabbro, leucogabbro, gabbronorite, hypersthene gabbro, augite norite, dolerite, ultramafic rocks (the majority of which have been metamorphosed to amphibolite facies) and rare basalt (eg Dundas et al. 1987a, Pietsch and Edgoose 1988, Edgoose et al. 1989a, b, Pietsch 1989). Local occurrences of troctolite (plagioclase-olivine cumulate), pyroxenite and anorthosite have also been documented (Edgoose et al. 1989a, b). Greenschist facies hydrous retrogression is relatively widespread throughout the province (Carson et al. 2008). Pillow basalts were reported by previous workers (eg Berger 1973, Poynter 1981), but the existence of these rocks has not been confirmed by subsequent field studies (Edgoose et al 1989b).

**GEOCHRONOLOGICAL AND STRATIGRAPHIC CONSTRAINTS OF WANGI BASICS**

The Wangi Basics have their greatest outcrop extent in the south of the Litchfield Province (Figures 3, 4a–b), where a large body of mafic rock about 50 km² in area is exposed on Wingate Mountains and Moyle (Edgoose et al. 1989a, b). Although field contact relationships of this large stock with surrounding rock units are not observed, Edgoose et al. (1989b) inferred that the stock most likely intruded nearby Hermit Creek Metamorphics, Burrell Creek Formation and Berinka Volcanics. Recent SHRIMP U-Pb detrital zircon geochronological data for the Hermit Creek Metamorphics yield maximum depositional ages of 1875 ± 4 Ma and 1868 ± 5 Ma, and for the Burrell Creek Formation, maximum depositional ages of 1868 ± 4 Ma and 1862 ± 3 Ma (Worden et al. 2008a). The Berinka Volcanics yield a crystallisation age of 1861 ± 4 Ma (Worden et al. 2006a). The presence of mafic igneous xenoliths (presumed to be Wangi Basics) within the adjacent Murra-Kamangee Granodiorite led Edgoose et al. (1989b) to suggest that this granodiorite intruded the stock. New U-Pb SHRIMP geochronological data for the Murra-Kamangee Granodiorite (Worden et al. 2008a) gave an intrusion age of 1854 ± 4 Ma. These

![Figure 4](image-url). Field photographs of Litchfield Province mafic rocks (a) View to west showing outcropping mafic rocks of HAG in foreground, Wingate Mountains. (b) Vista of undulating mafic hills of outcropping mafic rocks of HAG, Wingate Mountains.
data constrain emplacement of the mafic rock body to the range 1860–1855 Ma.

In the same region, immediately south of the large stock, a series of prominent linear sills of Wangi Basics (about 6 km long and 200 m wide; Edgoose et al 1989a, b) intrudes Burrell Creek Formation (maximum depositional age 1865 Ma) and nearby Chilling Sandstone. U-Pb SHRIMP geochronological data for the Chilling Sandstone yielded a maximum depositional age of 1861 ± 4 Ma (Worden et al 2008a), implying that the mafic sills must have been emplaced at 1860 Ma or later. In support of the above geochronological data, and based on field observations, Dundas et al (1987a) described Wangi Basics mafic rocks postdating deposition of the Burrell Creek Formation in DALY RIVER. Those authors further suggested that the Wangi Basics were comagmatic with the Palaeoproterozoic (preorogenic) Zamu Dolerite, which is exposed throughout the Central Domain of the PCO. However, the emplacement age of the Zamu Dolerite has not been adequately constrained.

In REYNOLDS RIVER, metamorphosed mafic and ultramafic dykes intrude the Welltree Metamorphics in drillcore (Pietsch 1989) but their affinity is unknown. A U-Pb SHRIMP maximum depositional age for the sedimentary protolith to the Welltree Metamorphics is interpreted to be 1865 ± 4 Ma (Worden et al 2006a), which is therefore the maximum constraint on the emplacement age of mafic/ultramafic dykes in this region.

Overall, the absence of contiguous outcrop and lack of contact relationships within the Litchfield Province have made lithostratigraphic correlation between individual rock units difficult. This is further exemplified when attempting regional lithostratigraphic correlation with the well documented stratigraphy of the Central Domain of the PCO, immediately to the east. Although exposure of the Wangi Basics is poor, regional magnetic imagery (Clifton 2008) indicates that exposed mafic rocks in the Litchfield Province are more extensive in the subsurface (Carson et al 2006, Glass 2007; Figure 5a). Long linear dykes and an area of high magnetic response can be seen subsurface on MOYLE and WINGATE MOUNTAINS (Figure 5b).

Geochronological studies of two samples of Wangi Basics, from the northern and southern Litchfield Province, yielded U-Pb SHRIMP zircon crystallisation ages of 1860 Ma (Carson et al 2009) and 1830 Ma (Worden et al 2008a) respectively. The difference between the two intrusion ages (within error) is about 30 million years. Based on the above stratigraphic observations, and in light of the U-Pb SHRIMP zircon age discrepancy between two mapped Wangi Basics units (located at either end of the Litchfield Province), the present study was initiated to investigate the relationships between these mafic rocks, in an attempt to determine whether they could be distinguished and/or classified by chemical means, and if necessary, to redefine the lithostratigraphic nomenclature. To facilitate this study, samples of Wangi Basics were collected during the 2006 and 2008 field seasons in conjunction with samples collected by earlier workers. Locations of each sample are detailed in Appendix 1.

Petrography, Geochemistry, Nd Isotope Chemistry and Revised Subdivision of Mafic/Ultramafic ‘Wangi Basics’

Geochemistry and Petrography

Sample locations and major and trace element geochemical data, including historical Northern Territory Geological Survey (NTGS) data, are available for a number of mafic/ultramafic samples of Wangi Basics from the Litchfield Province (see Appendix 1). All samples collected are referenced to GDA 94, Zone 52L.

Chemically, the Litchfield mafic rocks show considerable trace element heterogeneity (Glass 2007), and on the basis of their rare earth element (REE) patterns, trace element abundance patterns, and various trace element ratio diagrams (discussed in greater detail below), they have been subdivided into eight geochemical categories. Six geochemically distinctive categories are well defined and their derivation explained in detail further in the text. These are:

(i) High-alumina gabbro and dolerite (HAG)
(ii) Depleted low-Ti gabbro (LTG)
(iii) Low-Ti dolerite (LTD)
(iv) High-Ti tholeiitic gabbro (HTT)
(v) Metamorphosed noritic cumulate (MNC)
(vi) Metaferrogabbro (MFG)

Two additional, chemically less well defined categories have also been recognised:

(vii) Possible lamprophyric/shoshonitic association (LSS)
(viii) Crustally contaminated mafic rocks (MCC)

These various geochemical categories can be further amalgamated according to shared chemical tectonic affinities (discussed in detail in text), and four new stratigraphic units replace the former umbrella term ‘Wangi Basics’. The new stratigraphic names are:

1. Woolianna Gabbro
   High-alumina gabbro (HAG)
   Depleted low-Ti gabbro (LTG)
   Low-Ti dolerite (LTD) – south
   Low-Ti dolerite (LTD) – north
   Crustally contaminated mafic rocks (MCC).

2. Benning Gabbro
   High-Ti tholeiitic gabbro (HTT).

3. Keri Metamorphics
   Metamorphosed noritic cumulate (MNC)
   Metaferrogabbro (MFG).

4. Lilyarba Mafics
   Possible lamprophyric/shoshonitic association (LSS).

Figure 6 shows the spatial distribution of these newly defined geochemical categories and lithostratigraphic
units within the Litchfield Province. The HAG, HTT, MCC and LSS are confined to the south of the province, LTD to the north and south of the province, LTG forms a linear belt in the centre and MNC and MFG are located in the extreme north. Mafic rocks to the immediate west and east of Tom Turners Fault (Figure 6) have not been sampled due to land access issues and given their proximity to Woolianna Gabbro rocks and based on previous descriptions by Dundas et al (1987b) are tentatively assigned to that suite.

Figure 7a shows the newly defined units plotted on the total alkali–silica (TAS) chemical classification diagram. The majority of samples lie within the basalt (gabbro) field, with a small number plotting in the basaltic andesite (diorite) field. Some samples have higher total alkali contents (explained further in the text) compared with the bulk of the data. Similar trends are shown in Figure 7b, where SiO$_2$ wt% is plotted against K$_2$O wt%.
In this diagram, a number of samples plot within the high-K basalt (gabbro) field, with two potassic samples plotting within the absarokite (a more primitive potassic basaltic rock) field of the shoshonitic rock series as defined by Rock (1991).

The petrography and chemistry of each unit are described below. In order to highlight the chemical characteristics of individual samples, selected trace elements are plotted on normal mid-ocean ridge basalt (NMORB) and chondrite-normalised diagrams.
using normalisation values of McDonough and Sun (1995). NMORB was chosen to directly compare the data with the most abundant basaltic rocks on Earth.

**Woolianna Gabbro**

The Woolianna Gabbro embraces a variety of rocks with distinctive island-arc geochemical characteristics. These
include the following categories: high-alumina gabbro and dolerite (HAG), depleted low-Ti gabbro (LTG), low-Ti dolerite (LTD)-south, low-Ti dolerite (LTD)-north and tentatively the crustally contaminated mafic rocks (MCC), rare mafic cumulate and unassigned mafic ‘Wangi Basics’ rocks east and west of Tom Turners Fault (Dundas et al. 1987b).

The Woolianna Gabbro is exposed sporadically east and west of Tom Turners Fault and west of Giants Reef Fault, (Figure 6). Based on stratigraphic relationships discussed earlier, the large stock (HAG) of the Woolianna Gabbro is thought to have an age in the range 1860–1855 Ma, although this age is poorly constrained given the paucity of contact relationships.

High-alumina gabbro and dolerite (HAG)

The HAG category is restricted to a large igneous stock in the southern part of the province (northeastern MOYLE and northwestern WINGATE MOUNTAINS) immediately west of Giants Reef Fault (Figures 4a–b, 6). It comprises an association of gabbro, leucogabbro, gabbronorite, cumulus hypersthene gabbro, augite norite and dolerite (some variably recrystallised). Probable compositional layering (strike 290°) showing centimetre-scale mafic and felsic segregations is visible in some rocks (Figure 8). Relative to surrounding strata, HAG show a stronger aeromagnetic response (bright elliptical area north of Giants Reef Fault in Figure 5b).

Representative samples of HAG are typically medium to coarse grained, variably altered, equigranular rocks including gabbro, hypersthene gabbro and microgabbro to coarse-grained dolerite, most of which are metamorphosed to greenish schist facies. They are typically composed of abundant polysynthetic-twinned calcic plagioclase (zoned cumulus plagioclase), granular to subophitic orthopyroxene and clinopyroxene (Figure 9a). Clinopyroxene crystals commonly show exsolution textures of Ca-poor pyroxene (orthopyroxene; Figure 9b). Pyroxenes are typically rimmed with pale green to pale brown secondary, strong to weakly pleochroic hornblende, however relict primary igneous textures are preserved (Figure 9c). Localised samples show abundant uralitic and fibrous tremolite-actinolite replacing orthopyroxene and clinopyroxene (Figure 9d), commonly with opaque oxides rimmed by clinzoisite.

Chemically, HAG samples have dominantly quartz-hypersthene normative compositions but a few olivine normative compositions have been identified. SiO₂ contents are in the range 48.8–52.3 wt%. Compared to MORB, HAG samples have extremely low TiO₂ abundances, in the range 0.08–0.40 wt% with a mean value of 0.19 wt%. They are highly aluminous, with Al₂O₃ typically >17 wt% and as high as 22 wt%. The majority of samples also have high CaO (10.9–15.6 wt%). Average Fe₂O₃ (total FeO as FeO) is approximately 6 wt%. MgO values are variable, in the range 4.1–11.3 wt% with a mean of 8.4 wt%. Mg number (Mg#) ranges from 57 to 82; Mg# = molar100*(Mg/(Mg+Fe²⁺)) for (Fe₀.9O₋₁/FeO = 0.15).

Figure 10 shows Eu anomaly [Eu/Eu* = Eu₉/ (Sm₉⁺*Gd₉⁻⁺)] versus Al₂O₃ wt% for HAG data. This diagram distinguishes samples according to their degree of plagioclase accumulation or fractionation and differentiates primary liquid compositions relative to Mg#. Potential parental (primary) liquid compositions are defined by Eu/Eu* values ≥0.9 to ≤1.1, Mg# >65 to ≤74 and Al₂O₃ <19 wt%. Primary liquid compositions do not have a significant Eu anomaly, indicating that they have not accumulated or fractionated extensive amounts of plagioclase. Probable parental liquid compositions differ from potential parental compositions in having Mg# <65. Plagioclase accumulative compositions have Eu/Eu* values >1.1 and plagioclase fractionated liquid compositions have Eu/Eu* values <0.9. The majority of HAG have strong positive Eu anomalies (blue dots), ie Eu/Eu* >1, indicating that they are plagioclase accumulative. However, some samples have Eu/Eu* ~1 and Mg# ~67, indicating that they are candidates for parental liquid compositions to the HAG category (represented by red dots). Probable (fractionated) liquid compositions with Eu/Eu* ~1 and lower Mg# (Mg#<65) are shown as green dots.

Figure 11 presents modified Harker diagrams using MgO wt% as an index of differentiation and show data for selected elemental oxides and trace elements for HAG. The colours are as in Figure 10. Vectors showing compositional trends for olivine, clinopyroxene and plagioclase addition to a 9 wt% MgO composition are shown in Figure 11b. In all diagrams, the line of magmatic differentiation (dotted line) is shown by the array of green and red dots which represent inferred liquid compositions as defined in Figure 10. With the exception of one sample, the potential parental liquid compositions (red dots), which are rare HAG samples free of accumulated crystals, have most likely differentiated by crystal fractionation of pyroxene ± olivine to give rise to evolved compositions represented by the green dots at MgO <9 wt%. The scatter of blue dots above the magmatic differentiation line indicates that these compositions are mixtures of evolved liquids plus accumulated plagioclase and ferromagnesian minerals, ie pyroxene (clinopyroxene and orthopyroxene) and to a lesser degree, olivine. In Figure 11c–d, the majority of data for TiO₂ wt% and the trace element Y (ppm) are offset to lower values below the magmatic differentiation line by the dilution of accumulated plagioclase (blue dots). However, in Figure 11e, some samples have higher values due to
pyroxene ± spinel accumulation. In Figure 11e–f, the trace elements Cr and Ni show strong depletion with decreasing MgO wt%. Elevated Cr above the magmatic trend for some samples suggests accumulation of Cr-diopside ± Cr-spinel. Generally low Ni contents in the inferred parental liquids (<50 ppm Ni; Figure 11f) suggest that these compositions evolved by early olivine fractionation from more primitive precursors; the scatter to higher Ni contents in higher MgO samples is consistent with ferromagnesian mineral accumulation. It should be noted, however, that low Ni/Cr is a characteristic feature of boninitic magmas.

Figure 12a–d shows REE chondrite-normalised and NMORB-normalised trace element abundance diagrams for HAG rocks. Figure 12a shows patterns for compositions with a strong positive Eu anomaly, which is attributed to plagioclase accumulation. REE abundances are typically below 20x chondrite. The same samples are plotted on an NMORB-normalised plot (Figure 12b), where they show marked depletions in the middle-heavy rare earth elements (MREE and HREE) and strong enrichment in Sr. In contrast,
HAG samples in Figure 12c show a range of examples with smooth (flat) Eu patterns. The colours and samples represented in the diagram are the same as in Figure 10, where potential parental liquids are shown in red and probable fractionated liquids in green. Again, the samples have characteristically low REE. The same samples are plotted on an NMORB-normalised diagram (Figure 12d) and show similar depletions for MREE and HREE relative to NMORB and positive Sr anomalies.

**Depleted low-Ti gabbro (LTG)**

The LTG has limited outcrop extent within the central Litchfield Province and is restricted to areas in DALY...
River (Figure 6). It denotes a grouping of metamorphosed gabbronorite (amphibolite) and ultramafic rocks. Earlier researchers (eg Dundas et al 1987a) recorded the presence of metaperidotite, metapyroxenite and metaharzburgite, most of which are strongly altered. Figure 13a shows detail of outcropping LTG rocks and Figure 13b, natural exfoliation of an exposed boulder.

Metagabbronorite is inequigranular and consists of polysynthetically twinned and partially saussuritised (decussate and commonly fragmented) plagioclase and abundant green to pale green hornblende after former pyroxene (clinopyroxene and orthopyroxene; Figure 14a–b) which, in some rock types, define the metamorphic fabric. In localised samples amphibole is zoned, with more fibrous cores and uralitic rims. Minor primary phases include late magmatic brown hornblende and opaque oxides. Accessory minerals include secondary metamorphic biotite (of subsolidus origin rimming primary opaque oxides) and clinozoisite (after plagioclase).

Compositionally, these rocks are quartz-hypersthene and olivine normative. SiO₂ values are in the range 48.5–52.5 wt% and TiO₂ abundances are characteristically low, with values in the range 0.25–0.60 wt%. Al₂O₃ values range from 13.7 wt% to as high as 19.1 wt%, coupled with high CaO values in the range 10.8–13.7 wt%. FeO₂ averages around 9.0 wt% and MgO values are in the range 6.3–10.7 wt%. Average Mg# is ~60.

Of the seven LTG samples, two (green dots in Figure 15) are probable (fractionated) liquid compositions, with Eu/Eu* ~1. The other samples are plagioclase accumulative (blue dots).

Figure 16a shows chondrite-normalised REE abundances and Figure 16b, trace element abundances normalised to NMORB. Shown for comparison are data for the Troodos (Cyprus) high-Ca boninite association (discussed further in text). LTG has distinctive negative-sloping REE patterns (Figure 16a) with slight enrichment in La and Ce, the light rare earth elements (LREE). Two samples (probable liquid compositions) lack an Eu anomaly and are shown in green. MORB-normalised diagrams (Figure 16b) are also distinctive in that they show strong positive Sr anomalies coupled with low relative Ta-Nb. In comparison to NMORB, LTG shows marked MREE to HREE depletion.

Low-Ti dolerite (LTD) – south

Southern LTD comprises dolerite, amphibolite (metadolerite), pyroxenite and metabasalt and is exposed on WINGATE MOUNTAINS and MOYLE (Figures 6, 17). The

![Figure 12](A09-283.ai)

Figure 12. Chondrite-normalised and N-MORB-normalised diagrams for Woolianna Gabbro HAG. (a) Chondrite-normalised diagram showing REE patterns for HAG with positive Eu anomalies. (b) Same data plotted on an NMORB-normalised diagram. (c) Chondrite-normalised diagram showing REE patterns for HAG with smooth (flat) Eu. (d) Same data plotted on an NMORB-normalised diagram.
The age of these rocks has not yet been determined and reliable contact relationships with surrounding rock units are not observed.

LTD-south rocks are mostly metamorphosed, medium-to fine-grained dolerite and rare vesicular basalt, which occurs on Wingate Mountains near outcropping Berinka Volcanics. Individual samples consist of decussate (randomly oriented) plagioclase laths of <0.5 mm size (commonly albitised or saussuritised) which are poikilitically enclosed within larger oikocrystic (the enclosing mineral) amphibole crystals (the latter typically 2 mm, but locally as large as 30 mm), which replace primary ophitic clinopyroxene (Figure 18).

LTD-south includes quartz-hypersthene normative rocks with minor olivine normative compositions. SiO$_2$ values are in the range 48.8–51.7 wt%, TiO$_2$ abundances 0.42–0.81 wt%, Al$_2$O$_3$ values 13.1–16.7 wt% and CaO 8.1–12.1 wt%. Total FeO (FeO$_t$) averages 10 wt%.

Figure 13. Field photographs of Woolianna Gabbro LTG. (a) LTG outcrop near sample area PC05CJC029. Livistona species typically grow on soils derived from these mafic rocks. 674042mE 8468474mN, GDA 94, Zone 52L, Daly River (b) Natural exfoliation of a boulder outcrop revealing plagioclase phenocrysts enhanced by weathering. 674262mE 8466896mN, GDA 94, Zone 52L, Daly River.

Figure 14. Photomicrographs of Woolianna Gabbro LTG. (a) Plane-polarised light photomicrograph of sample PC06LMG002 metamorphosed inequigranular gabbronorite showing polysynthetically twinned plagioclase (Pl) and hornblende (Hbl). (b) Cross-polarised light photomicrograph of same field of view.
and MgO abundances are in the range 6.9–12.1 wt% (average Mg# ~63). Sample PK05CJC005 represents a mafic cumulate composition with SiO$_2$ 45.9 wt%, MgO 17.5 wt% and CaO 9.2 wt%. Cr and Ni abundances are high: 1600 ppm Cr and 650 ppm Ni.

**Figure 19** shows that the majority of LTD-south samples are probable (fractionated) liquid compositions with Eu/Eu* ~1 and lower Mg# (Mg# <65; green dots). However, the two most primitive LTD samples (Eu/Eu* ~1 and Mg# ~72) may be parental (and also primary) liquid compositions to these rocks (red dots).

**Figure 20** shows the data plotted on chondrite-normalised REE and NMORB-normalised diagrams. Shown for reference (grey boxed areas) are fields for worldwide primitive arc tholeiitic rocks (see Tectonomagmatic affinity discrimination diagrams). In **Figure 20a**, the REE data for the southern LTD are relatively flat and in **Figure 20b**, the data show positive Sr anomalies, coupled with moderate Nb-Ta anomalies and Ba enrichment relative to Th. Relative to NMORB, all LTD samples show HREE depletion.

**Low-Ti dolerite (LTD) – north**

LTD-north comprises dolerite, amphibolite (metadolerite) and rare gabbro located in the north of the province, on

![Figure 17](image-url) Field photograph showing rounded boulders of Woolianna Gabbro LTD-south, sample PC08LMG004. 674186mE 8465676mN, GDA 94, Zone 52L, DALY RIVER.

![Figure 15](image-url) Eu/Eu* versus Al$_2$O$_3$ wt% diagram for Woolianna Gabbro LTG samples. Boxed area highlights probable (fractionated) liquid compositions.

![Figure 16](image-url) Chondrite-normalised and N-MORB-normalised diagrams for Woolianna Gabbro LTG. Shown for comparison are data for upper pillow lavas (high-Ca boninite suite) from Troodos ophiolite (data from Smewing and Potts 1976, Simonian and Gass 1978, Cameron 1985, Thy _et al_ 1985, Flower and Levine 1987 and Rogers _et al_ 1989; compiled by T Falloon). (a) Chondrite-normalised diagram showing REE patterns for LTG. (b) Same data plotted on an NMORB-normalised diagram.
REYNOLDS RIVER (Figure 6). Scattered debris sourced from dolerite cropping out further uphill is shown in Figure 21.

LTD-north rocks are mostly medium- to fine-grained dolerite with a metamorphic overprint. Amphibole occurs as decussate pale tremolite/actinolite, colourless cummingtonite and pale green to brown hornblende (in some cases uralitised). Plane-polarised and crossed-polarised light microphotographs of sample PC06LMG010 (Figure 22) show detail of a quartz-cummingtonite-hornblende-plagioclase amphibolite. The rock has weak compositional layering with quartzofeldspathic and amphibole-rich lamellae. Minor disseminated sulfide (mostly pyrrhotite) occurs in lamellae parallel to foliation. Fine-grained opaque oxides are also disseminated throughout.

LTD-north is quartz-hypersthene normative in composition. SiO$_2$ values are in the range 49.3–55.4 wt%. TiO$_2$ abundances are in the range 0.5–0.9 wt%, Al$_2$O$_3$ values 11.4–16.7 wt% and CaO values 8.1–11.7 wt%. Total FeO (FeO$_{tot}$) averages 10.7 wt%. The majority of LTD-north has MgO wt% abundances in the range 4.2–12.4 wt% MgO (average Mg# ~60). On the basis of major elements these rocks are similar to LTD-south.

Figure 23 shows that the majority of LTD-north samples are probable (fractionated) liquid compositions with Eu/Eu* ~1 and lower Mg# (Mg# <65; green dots). However, the most primitive LTD-north sample (Eu/Eu* ~1 and Mg# ~72) may represent a parental (primary) liquid composition to the category (red dots).

Figure 24a shows the data plotted on chondrite-normalised REE and NMORB-normalised diagrams. The data show slight enrichment in LREE relative to HREE. Relative to NMORB, LTD-north is enriched in the more incompatible elements and shows HREE depletion (Figure 24b). These rocks are subtly different from LTD-south in that they lack a positive Sr anomaly but have a weak Nb-Ta anomaly similar to that of the southern subcategory.

Figure 18. Photomicrographs of Woolianna Gabbro LTD-south (a) Plane-polarised light photomicrograph of metabasalt sample FE06LMG012. (b) Cross-polarised light photomicrograph of same field of view. Both images show decussate (randomly oriented), >0.3 mm-long, albitised/saussuritised plagioclase laths (Pl) poikilitically enclosed within larger (30–35 mm long and 15 mm wide) oikocrystic amphibole crystals (Am). Amphibole most likely replaces primary ophitic clinopyroxene. The amphibole has been partially replaced by minor tremolite/actinolite. Very minor microcrystalline opaque oxide is disseminated.

Figure 19. Eu/Eu* versus Al$_2$O$_3$ wt% diagram for Woolianna Gabbro LTD-south samples. Boxed area highlights potential parental and probable (fractionated) liquid compositions.

Crustal-like mafic rocks (MCC)

Three samples (FE05CJC021, 025 and 026) are located at the northern perimeter of the HAG outcrop area (Figure 6), immediately adjacent to Ti-Tree Granophyre in WINGATE MOUNTAINS. These samples are coarse-grained, dioritic in composition (one sample with abundant quartz), have saussuritised plagioclase, uralitised amphibole (possibly after orthopyroxene and/or clinopyroxene), pale green hornblende with dark green edges and exsolution in orthopyroxene, are partly chloritised and have minor black opaque oxides.

SiO$_2$ values are in the range 51.2–56.9 wt%, and TiO$_2$ is low, in the range 0.5–0.9 wt%. Al$_2$O$_3$ is in the range 11.5–15 wt% and MgO values 4.6–5.4 wt%. Relative to NMORB, the grouping has distinctive trace element
chemistry, with extreme enrichment in the incompatible elements, eg Th and REE and low relative high field strength element abundances (Ti, Ta, Nb) relative to the incompatible elements (Figure 25). This geochemical signature has similarities to felsic crustal rocks, suggesting that the mafic rocks are strongly crustally contaminated (eg Glass 2002).

**Figure 20.** Chondrite-normalised and N-MORB-normalised diagrams for Woolianna Gabbro LTD-south. Shown for comparison (grey shaded areas) are fields for worldwide primitive arc tholeiitic rocks, compiled by WR Taylor. (a) Chondrite-normalised diagram showing REE patterns for LTD-south. (b) Same data plotted on an NMORB-normalised diagram.

Benning Gabbro

**High-Ti tholeiitic gabbro (HTT)**

In WINGATE MOUNTAINS and MOYLE and southwest of the HAG, high-Ti tholeiitic gabbro (HTT) comprises a series of dominantly southwest-trending linear sills, altogether about 6 km long and 200 m wide (Edgoose et al 1989a, b; Figures 5b, 6). In WINGATE MOUNTAINS, three samples intrude metasedimentary Burrell Creek Formation and one sample intrudes Chilling Sandstone. A single fine-grained mafic sample (most likely a doleritic chilled margin) proximal to a fault zone was sampled on MOYLE. A series of mafic sills also occurs to the southeast within Chilling Sandstone. However, access to these sites was restricted due to the difficult nature of the terrain.

Four HTT samples on WINGATE MOUNTAINS are coarse-grained and quartz-hypersthene normative, whereas the single chilled margin sample is olivine normative. Three of the coarse-grained samples are metamorphosed equigranular assemblages consisting of quartz, and plagioclase feldspar with highly saussuritised cores and often prominent (?K-feldspar) rims (Figure 26a). Pale to dark green to brown pleochroic hornblende, fibrous (acicular) actinolite and uralitised amphibole are common. Minor symplectic intergrowths of feldspar and quartz occur in interstices and opaque oxides (often tabular) are also present. Sample FE06LMG025 shows detail of relict primary clinopyroxene with minor uralitisation around the margins (Figure 26b). The fine-grained chilled margin sample (PK06LMG019) is dominated by decussate brown hornblende and saussuritised (albite-sericite-clinozoisite) altered feldspar. Fine-grained opaque oxide is disseminated throughout.

A characteristic feature of HTT is that all constituents show some degree of alkaline enrichment. HTT has higher total alkalis compared to the other mafic rock categories (apart from LSS) and in Figure 7b, four HTT samples plot...
in the high-K field as defined by Rock (1991), the exception being the chilled margin sample. Sample PK05CJC018 is the most alkalic sample, with ~2.6 wt% K₂O.

For HTT, SiO₂ is in the range 47.3–54.6 wt%, the chilled margin sample on MOYLe being the least siliceous. The samples have higher Ti abundances than other mafic rocks in the Litchfield Province, with TiO₂ values in the range 1.9–4.2 wt%, average 2.3 wt% TiO₂. HTT characteristically has lower alumina abundances compared to HAG and LTG, with Al₂O₃ in the range 13.6–15.1 wt%. Compared to other Litchfield Province mafic rocks, total Fe as FeO t is high, in the range 11.5–14.5 wt%, and MgO is correspondingly low, averaging about 5 wt% MgO (Mg# ~42). CaO values are in the range 7.2–12.1 wt%. The least evolved (most primitive) sample is of the chilled margin rock on MOYLe. This sample shows no signs of chemical (wall-rock) modification (trace element enrichment) and is also chemically pristine (LOI = 0.8).

HTT data are plotted on chondrite-normalised and NMORB-normalised diagrams in Figure 27. Shown for reference (grey boxed area) are data for mafic rocks from the Arthur Lineament and Smithton Trough, Tasmania (Crawford and Berry 1992, Holm et al 2003), discussed later in text. HTT typically has moderately elevated LREE and positively sloping REE patterns. Relative to NMORB, it has similar HREE abundances, more pronounced Nb-Ta depletions and incompatible element enrichment.

Keri Metamorphics

**Metamorphosed noritic cumulate (MNC)**

MNC is a metamorphosed mafic/ultramafic category that outcrops as low, rounded boulders restricted to a small area in the north of the Litchfield province and northwestern REYNOLDS RIVER. However, magnetic imagery (Figure 5a) indicates a greater distribution under cover. Three samples were submitted for analysis.

Two MNC samples are quartz-hypersthene normative and one is olivine normative. The quartz-hypersthene normative samples possibly represent metamorphosed augite norite (formerly orthopyroxene-rich cumulate) with all of the pyroxene (orthopyroxene and clinopyroxene) being replaced by amphibole. Abundant fibrous amphibole (tremolite-actinolite) is interlaminated with chlorite and is most likely replacement products of primary orthopyroxene, whereas uralitic amphibole is most likely derived from granular clinopyroxene (Figure 28). Some of the uralitic amphibole has schiller-like inclusions of opaque oxide. Residual partly seritised (± clinozoisite) platy plagioclase (up to 2 mm in size) has in part been overprinted.

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**Figure 22.** Photomicrographs of Woolianna Gabbro LTD-north. (a) Plane-polarised light photomicrograph of metadolerite sample PC06LMG010 showing plagioclase (Pl), colourless cummingtonite (Cum) and green hornblende (Hbl). (b) Crossed-polarised light photomicrograph of same field of view showing quartzofeldspathic and amphibole-rich lamellae which form weak compositional layering (not evident in photomicrograph). Quartz appears as very small interstitial grains. Larger grains of amphibole replace ophitic pyroxene. Disseminated opaque oxide can be seen in both images.

**Figure 23.** Eu/Eu* versus Al₂O₃ wt% diagram for Woolianna Gabbro LTD-north samples. Boxed area highlights potential parental liquids and probable (fractionated) liquid compositions.
Figure 24. Chondrite-normalised and N-MORB-normalised diagrams for Woolianna Gabbro LTD-north. (a) Chondrite-normalised diagram showing REE patterns for LTD-north. (b) Same data plotted on an NMORB-normalised diagram.

Figure 25. Chondrite-normalised and N-MORB-normalised diagrams for Woolianna Gabbro MCC. (a) Chondrite-normalised diagram showing REE patterns for MCC. (b) Same data plotted on an NMORB-normalised diagram.

Figure 26. Photomicrographs of Benning Gabbro HTT. (a) Cross-polarised light photomicrograph of sample FE06LMG022 showing plagioclase (Pl) crystals with prominent unaltered rims surrounding saussuritised cores. (b) Cross-polarised light photomicrograph of sample FE06LMG025 showing relict primary clinopyroxene (Cpx) with minor uralitic amphibole (Am) surrounding crystal.
by recrystallised amphibole. Rare brown hornblende, biotite and quartz are accessory phases and minor microcrystalline disseminated opaque oxide is also present.

MNC is typically low in Ti, with values in the range 0.3–0.4 wt% (mean 0.37 wt% TiO₂) and highly magnesian: MgO values are in the range 15.9–22.1 wt%. The high MgO value for sample PC06LMG024 (Mg# ~78) reflects its cumulate status. SiO₂ values are in the range 45.6–52.9 wt%. Al₂O₃ values are low relative to other Litchfield Province mafic rocks, in the range 7.7–10.0 wt%. FeO t is 9.3–12.4 wt% and CaO is 4.7–7.5 wt%.

**Figure 29** shows chondrite-normalised REE and NMORB-normalised plots. All samples show slight negative Eu anomalies, indicating plagioclase fractionation. Relative to NMORB, they show HREE depletion and moderate LREE enrichment. All three samples show moderate enrichment in the most incompatible elements, which is at variance with their mafic/ultramafic status. The slightly altered sample has Sr depletion, which may reflect post-emplacement element mobility resulting in Sr loss.

**Metaferrogabbro (MFG)**

MFG is a garnet-bearing amphibolite (metaferrogabbro) that crops out near MNC rocks on REYNOLDS RIVER. Its constituents form well rounded boulders (**Figure 30a**) and are only found within a small defined area. In the field, they are characterised by garnet porphyroblasts up to and greater than 10 mm diameter, which commonly amalgamate to form linear segregations in an amphibole-rich groundmass (**Figure 30b**).

Petrographically, MFG has poikilitic garnet porphyroblasts which enclose abundant amphibole (hornblende and grunerite), minor carbonate, quartz, apatite and ilmenite (**Figure 31**). Porphyroblasts are enclosed in a granular amphibolitic groundmass containing abundant plagioclase, local biotite, and green hornblende ± grunerite. Opaque oxide minerals are ilmenite.

Chemically, garnet-rich segregations dominate the major elemental oxide signatures for three of the garnet amphibolite samples. This is reflected in low SiO₂...
values, in the range 38.9–46.5 wt%. These are high-Ti rocks, with values in the range 1.9–2.5 wt% TiO$_2$, high alumina (16.8–18.2 wt% Al$_2$O$_3$) and very high FeO (18.8–23.2 wt%), with correspondingly lower MgO (2.6–3.5 wt%). CaO values are in the range 7.6–9.8 wt% and P$_2$O$_5$ is 0.44–0.55 wt%. In contrast, sample PC06LMG017 has higher SiO$_2$ (50.3 wt%) and lower TiO$_2$ and P$_2$O$_5$ contents, suggesting a less modal percentage of garnet (ie garnet does not dominate the overall chemical signature).

MFG is strongly plagioclase-accumulative (Eu/Eu* ~1.5–1.6), with positive sloping REE chondrite-normalised patterns and positive Eu anomalies (Figure 32), indicating that they are metamorphosed plagioclase-pyroxene cumulate rocks.

The age of MFG is constrained by Carson et al (2009), in which for sample PC06LMG013, those authors determined a weighted mean $^{207}$Pb/$^{206}$Pb SHRIMP age of 1860 ± 6 Ma (95% confidence level), interpreted to represent the magmatic crystallisation age for this sample.

**Lilyarba Mafics**

**Possible lamprophyric/shoshonitic association (LSS)**

Two fine-grained (altered) mafic samples were collected prior to the initiation of this study from a remote area only accessible by helicopter, located southwest of the main HAG outcrop area, east of Giants Reef Fault in central Wingate Mountains (Figure 6). The samples have distinctive potassic signatures, with K$_2$O values of 1.7 wt% and 1.8 wt%. Silica values are low (47.8 wt% and 48.2 wt% SiO$_2$), alumina high (17.3 wt% and 18.5 wt% Al$_2$O$_3$), and 4.4 wt% and 8.6 wt% MgO. Texturally, both samples show some degree of sericite/ saussurite alteration of primary feldspar.

Sample FE04JHL002 is strongly plagioclase accumulative, whereas FE04NJ005 is most likely a primary liquid composition (Figure 33, 34). Both samples have chemical signatures enriched in the most incompatible elements (Figure 34b), however, sample FE04JHL002 has a pronounced positive Eu anomaly (Figure 34a),

![Figure 29](Plagioclase (fractionated) liquid)

**Figure 29.** Chondrite-normalised and N-MORB-normalised diagrams for Keri Metamorphics MNC. (a) Chondrite-normalised diagram showing REE patterns for MNC. (b) Same data plotted on an NMORB-normalised diagram.

![Figure 30](PC06LMG013)

**Figure 30.** Field photographs of Keri Metamorphics MFG. Open compass, for scale, is ~18 cm long. (a) Sample PC06LMG013 showing garnets enhanced by weathering. 670455mE 8548345mN, REYNOLDS RIVER (b) Sample PC06LMG011A in which garnets appear to be aligned in flow texture. 670541mE 8547875mN, REYNOLDS RIVER.
reinforcing the plagioclase-accumulative signature for this sample. Chemically, both samples appear to be of broadly shoshonitic affinity, although additional work to confirm the alkaline signature is clearly required for these rocks.

Worden et al. (2008a) reported a $^{207}$Pb/$^{206}$Pb SHRIMP date of 1829 ± 4 Ma for sample FE04JHL002, which is interpreted to represent the crystallisation age for this sample. This age is typical for lamprophyres and other alkaline rocks in northern Australia (WR Taylor pers comm 2007). For example, Sheppard and Taylor (1992) reported a Pb-Pb isochron date of 1830 ± 39 Ma for olivine-mica-K-feldspar lamprophyre dykes, syenite and granite at Mount Bundey, in the PCO. They further reported that the granite was dated more precisely, yielding a U-Pb zircon date of 1831 ± 6 Ma, which by implication also provides an age for the lamprophyres. In addition, Hanley (1996) determined a SHRIMP zircon crystallisation age of 1830 ± 7 Ma for a trachyandesite (an alkaline volcanic rock) from the Murphy Inlier.

**Figure 31.** Photomicrographs of Keri Metamorphics MFG. (a) Plane-polarised light photomicrograph of sample PC06LMG016 detailing sharp-edged garnet porphyroblast (Grt) with groundmass amphibole (Am) and plagioclase (Pl). (b) Cross-polarised light photomicrograph of sample PC06LMG011A showing poikilitic garnet porphyroblast (Grt) enclosing amphibole (Am), and plagioclase (Pl). (c) Plane-polarised light photomicrograph of sample PC06LMG016 showing detail of granular amphibolite groundmass with plagioclase (Pl), amphibole (Am) and grunerite (Gru). (d) Cross-polarised light photomicrograph of same field of view highlighting amphibole (hornblende and grunerite (Gru)) and plagioclase (Pl) in granular amphibolite groundmass.

**TECTONOMAGMATIC AFFINITY DISCRIMINATION DIAGRAMS**

A number of the above rocks that have demonstrably liquid compositions (excluding plagioclase cumulate samples) also have compositions reminiscent of modern island arc magmatism. These include compositions with positive Sr peaks coupled with low relative Nb-Ta depletions and negatively sloping REE patterns (as seen for LTG). To further validate these observations, the data are plotted on tectonomagmatic discrimination diagrams (defined by large global datasets) which serve to discriminate between different tectonic environments for mafic igneous rocks (WR Taylor pers comm 2006). **Figure 35** depicts bivariate diagrams with $\text{Al}_2\text{O}_3$/TiO$_2$ versus Cr/FeO (total Fe as FeO) and Zr/Y. The field types represented include, for example, MORB, ocean island basalt (OIB), high-Ca boninite, boninite-associated low-Ti tholeite, primitive arc tholeite and rift tholeite. To minimise the effects of fractionation and potential
cumulate compositions, only samples with Mg# <80 and >40 are considered.

Global reference data for which these fields serve to discriminate are shown in Figure 35 and include data for the Troodos ophiolite (high-Ca boninite), boninite-associated low-Ti tholeiite and high-Ti rift tholeiite, Tasmania), global primitive arc-tholeiite, and Mariana Trench and Lau back-arc basin basalt (BABB; Pearce et al. 1995b). Some high-Ca boninite rocks demonstrate the effects of crystal fractionation and plot in the low-Ti tholeiite (boninite-related) field. BABB data plot within the N-MORB and high-Ti rift tholeiite fields, with some overlap with primitive arc tholeiite. The vectors on Figure 35a indicate directions for plagioclase accumulation and olivine and pyroxene fractionation. Figure 36 shows the distribution of Litchfield Province mafic data plotted on these diagrams and differentiated according to geochemical classification and newly identified suites introduced above. As with Figure 35, only samples with Mg# <80 and >40 are considered. In both figures, HAG and LTG plot dominantly in the low-Ti tholeiite (boninitic-related) field, reflecting both low TiO$_2$ and high Al$_2$O$_3$ wt% abundances. Their distribution trends reflect crystal fractionation, but in the case of HAG, accumulation by plagioclase shifts the compositions towards higher aluminium contents. In Figure 36a, LTD north and south define a linear vertical trend (crystal fractionation related) within the field defined by worldwide primitive arc tholeiite, whereas samples from HTT form a restricted spread within the field defined by high-Ti rift tholeiite. MNC and MFG plot in the field defined for high-Mg basalt and komatiite, however these rocks are cumulates and their position on this diagram has little meaning in a tectonic sense. These diagrams serve to link mafic rocks of the newly defined suites and compositionally distinct groups to distinct tectonic environments.

Figure 37 is a diagram of Al$_2$O$_3$/TiO$_2$ versus CaO/Zr and shows the distribution of the same reference global data as in previous diagrams. Again, only data with Mg# <80 and >40 are considered. The Litchfield Province mafic data are plotted in Figure 38. There is good agreement for these data when compared with the global compilation, for example, LTG plots similarly to Troodos high-Ca boninite, LTD mirrors the distribution of primitive arc tholeiite and HTT plots in the region defined for high-Ti rift tholeiite.

Figure 39 shows plots of Ti (ppm) abundance against the major element ratios CaO/TiO$_2$ and Al$_2$O$_3$/TiO$_2$ (after Sun and Nesbitt 1978). Mantle and crustal reservoir fields are shown for reference and include pyrolite (ie fertile mantle peridotite), MORB, BABB, komatiite and high-Mg basalt, ophiolite and island arc magmas (Sun and Nesbitt 1978). In Figure 39 the distribution of the same reference global data used in Figure 35 is shown. As in previous diagrams, only samples with Mg# <80 and >40 were used. High Al$_2$O$_3$/TiO$_2$ and CaO/TiO$_2$ ratios are characteristic of both low-Ti ophiolitic (ie boninitic) and primitive arc magmas (Sun and Nesbitt 1978), and this is shown by the distribution of Troodos high-Ca boninite (Figure 39a–b). Tasmanian rift tholeiite (Figure 39a–b) show a dominant clustering at low CaO/TiO$_2$ ratios and high-Ti abundances.
Ellipsoids in Figure 39c–d, highlight the dominant cluster for primitive arc tholeiite. Mariana Trench and Lau BABB (Figure 39e–f) plot as expected, within the field for MORB and BABB.

The Litchfield Province mafic data are shown for comparison in Figure 40. HAG shows a dominant population with abundances <1500 ppm Ti (<0.25 wt% TiO₂), coupled with extreme CaO/TiO₂ and Al₂O₃/TiO₂ values, both ratios in excess of 40 and as high as ~120. The extreme elevated major element ratios reflect their cumulate status, however, some HAG samples overlap with Troodos low-Ti basalt and boninite. LTG samples are also low-Ti and plot in the same region as the Troodos data. LTD shows a strong overlap with global primitive arc tholeiite (boninite-related).

**Figure 34.** Chondrite-normalised and N-MORB-normalised diagrams for Lilyarba Mafics LSS. (a) Chondrite-normalised diagram showing REE patterns for the two possible alkaline LSS samples. (b) Same data plotted on an NMORB-normalised diagram.

**Figure 35.** Tectonomagmatic affinity discrimination diagrams; diagrams and fields defined by WR Taylor pers comm 2006. Data for high-Ca boninite of Troodos ophiolite (Smewing and Potts 1976, Simonian and Gass 1978, Cameron 1985, Thý et al 1985, Flower and Levine 1987, Rogers et al 1989; compiled by WR Taylor); global primitive arc tholeiite (Crawford and Berry 1992, Holm et al 2003); Lau back-arc basin basalt (BABB; Pearce et al 1995b); Mariana Trench BABB data extracted from PETDB (Lehnert et al 2000; [http://www.petdb.org/](http://www.petdb.org/)); low-Ti tholeiite (Brown and Jenner 1989). Pl = plagioclase; Ol = olivine; Px = pyroxene; M = meimechite; N/BK = NMORB and basaltic komatiite; OIB = Oceanic island basalt; PA = primitive arc tholeiite including some picrite and ankaramite; S/K = siliceous high-Mg basalt and komatiite. (a) Al₂O₃/TiO₂ versus Cr/FeO (total Fe as FeO). (b) Al₂O₃/TiO₂ versus Zr/Y.
island arc tholeiite data as defined by the ellipsoid in Figure 39c–d.

For the majority of the mafic Litchfield Province rocks, TiO$_2$ abundances are less than 1.0 wt%. HTT, however, has very low CaO/TiO$_2$ and Al$_2$O$_3$/TiO$_2$ ratios coupled with high-Ti abundances (typically in the range 1.5–~2.0 wt% TiO$_2$), and mirrors the distribution of known high-Ti rift tholeiitic rocks.

These trace element ratio discrimination diagrams clearly demonstrate that the Litchfield Province mafic data replicate observed abundances of the natural reference data for low-Ti boninite-related tholeiite, BABB, primitive arc tholeiite and high-Ti rift tholeiite.

**SAMAR IUM-NEODYMI UM ISOTOPE GEOCHEMISTRY**

Ten mafic samples were submitted for Nd isotope analysis. Samarium and neodymium are MREE and are moderately incompatible during mantle melting. Relative to Sm, Nd is concentrated in the melt, such that crustal rocks are characterised by low Sm/Nd compared to mantle compositions. The radiogenic parent nuclide $^{147}$Sm alpha-decays to the stable daughter nuclide $^{143}$Nd with a half-life of 1.06 x 10$^{11}$ years (Lugmair and Marti 1978), such that:

$$\frac{^{143}Nd}{^{144}Nd\text{ today}} = \left(\frac{^{143}Nd}{^{144}Nd\text{ initial}}\right) + \frac{^{147}Sm}{^{144}Nd} \left(e^{\lambda t} - 1\right)$$

where $\lambda$ is the decay constant (6.54 x 10$^{-12}$ year$^{-1}$), $t$ = time and $^{144}$Nd is the unradiogenic reference isotope (eg Dicken

![Figure 36](image-url)  
*Figure 36. Tectonomagmatic affinity discrimination diagrams showing data for Litchfield Province mafic lithostratigraphic units and constituent chemical categories. Fields as for Figure 35. (a) Al$_2$O$_3$/TiO$_2$ versus Cr/FeO (total Fe as FeO). (b) Al$_2$O$_3$/TiO$_2$ versus Zr/Y.*

![Figure 37](image-url)  
*Figure 37. Al$_2$O$_3$/TiO$_2$ versus CaO/Zr diagram for Troodos high-Ca boninite, Mariana Trench and Lau BABB, primitive arc tholeiite Tasmanian low-Ti tholeiite and Tasmanian high-Ti rift tholeiite. Data and references as for Figure 35. Pl = plagioclase, Cpx = clinopyroxene. Average NMORB (black diamond) is shown for comparison (data from Geochemical Earth Reference Model (GERM); [http://earthref.org/], Hauri and Hart 1997, Hofmann 1988, Smith et al 1995 and Ito et al 1987). Red lines separate fields for rift tholeiite, primitive island arc tholeiite and boninite.*
100

HTT

Ito

Wasserburg (1979) where:

are normalised to 146Nd/145Nd = 2.0719425 (equivalent to a CETAC ARIDUS desolvating nebuliser. Nd isotope ratios are conducted using an NU Plasma MC-ICPMS coupled to resins (Pin and Santos-Zalduegui 1997). Isotopic analyses by extraction of Nd and Sm using EICHROM RE and LN 149Sm-150Nd spike are dissolved at high pressure, followed

org/

Geochemical Earth Reference Model (GERM);

NMORB (black diamond) is shown for comparison (data from categories. Pl = plagioclase, Cpx = clinopyroxene. Average Province mafic lithostratigraphic units and constituent chemical

Figure 38

of Melbourne, following procedures described in Maas


1997). Alternatively, isotopic data can be presented using epsilon notation for Nd (eNd) developed by DePaolo and Wasserburg (1979) where:

\[ \epsilon_{\text{Nd}} = \left( \frac{143\text{Nd} / 144\text{Nd}}{143\text{Nd} / 144\text{Nd}_{\text{CHUR}}} - 1 \right) \times 10^4 \]

where t = time and CHUR = CHondritic Uniform Reservoir.

Sm-Nd isotopic analyses were carried out at University of Melbourne, following procedures described in Maas et al (2005). Briefly, sample powders spiked with mixed 149Sm,150Nd spike are dissolved at high pressure, followed by extraction of Nd and Sm using EICHROM RE and LN resins (Pin and Santos-Zalduegui 1997). Isotopic analyses are conducted using an NU Plasma MC-ICPMS coupled to a CETAC ARIDUS desolvating nebuliser. Nd isotope ratios are normalised to 146Nd/144Nd = 2.0719425 (equivalent to the more familiar 146Nd/144Nd = 0.7219; Vance and Thirlwall 2002) using the exponential law. All Nd isotope ratios are reported relative to La Jolla Nd = 0.511860. Internal and external precisions for 143Nd/144Nd are \( \pm 0.000012 \) (2se) and \( \pm 0.000020 \) (2sd) respectively. USGS standard BCR-1

is 0.512624-0.512645 and JNd-1 is 0.512113 \( \pm 22 \) (2sd), indistinguishable from TIMS reference values. \( \epsilon_{\text{Nd}} \) and \( T_{\text{DM}} \), model ages are calculated using 147Sm/144Nd = 0.1967 and 146Nd/144Nd = 0.512638 for modern CHUR, and 0.2136 and 0.513141 for modern depleted mantle (DM) respectively.

Sm and Nd whole-rock isotope data for this study are presented in Table 1. \( \epsilon_{\text{Nd}} \) values are calculated assuming that all rocks are ca 1860 Ma. Initial \( \epsilon_{\text{Nd}} \) values for ten mafic samples show a range from +2.9 to -3.0. LTD and LTG have the highest 143Sm/144Sm ratios (0.512462 – 0.512953), with initial \( \epsilon_{\text{Nd}} \) values of +2.9 and +2.4 for LTD and +2.2 and +1.8 for LTG. HAG and MCC have slightly enriched isotopic signatures with \( \epsilon_{\text{Nd}} \) ranging from -0.1 (close to Bulk Earth) to -2.6 (more isotopically evolved).

**DISCUSSION**

The above results indicate that the majority of Litchfield Province mafic rocks (formerly referred to as Wangi Basics) are lithologically and geochemically diverse. Some units have clearly undergone regional metamorphism, eg garnet amphibolite of the Keri Metamorphics still retains its plagioclase-accumulative geochemical signature. CJ Carson (pers comm 2006) quoted a P-T estimate of 690°C and 4.7 – 5.1 kb for a mafic (HAG) sample from WINGATE MOUNTAINS. This is in accordance with other lithological units in the Litchfield Province, where Carson et al (2008) reported peak P-T estimates for the Hermit Creek Metamorphics yielding a weighted mean P-T result of 727 ± 50°C at 5.5 ± 0.6 kb (2σ).

**WOOLIANGA GABBRO**

HAG cumulate rocks could have been derived by a combination of olivine and pyroxene fractionation/ accumulation and plagioclase accumulation from a hydrous magma within a subvolcanic magma chamber. The presence of water serves to inhibit the crystallisation of plagioclase, such that olivine and pyroxene are the only cumulate phases, alumina is enriched in the melt, and compositions derived from such melts have elevated Al2O3/TiO2 with high-alumina basalt, which is derived from primitive arc magmas by crystal fractionation under hydrous conditions (Crawford et al 1987) and are characteristic of oceanic and continental arc environments around the world. HAG, therefore, is here interpreted to represent the base of a subvolcanic magma chamber feeding island arc tholeiites, which was subsequently buried and metamorphosed to amphibolite facies conditions, presumably in a collisional event prior to exhumation. The centimetre-scale mafic (pyroxene) and felsic (plagioclase) layering shown in Figure 8 most likely represents relict igneous cumulate banding (crystal settling) from the original magma chamber.

Although a number of HAG rocks have positive Eu anomalies (indicating that they are plagioclase accumulative) or negative Eu anomalies (plagioclase fractionation), other HAG samples lack an Eu anomaly. This absence, either positive or negative (ie flat pattern between the REE Sm
and Gd, Eu/Eu* ca 1 and Mg# ca 67), indicates that these compositions are consistent with being parental liquids to the magmatic rocks. When normalised to NMORB, HAG shows marked depletions in MREE and HREE. Very low HREE is a characteristic feature of low- to medium-K arc tholeiitic rocks. Some of these liquid compositions also have strong positive Sr peaks which, when combined with low relative Nb-Ta, are a characteristic island arc signature.

Figure 39. Tectonomagmatic affinity discrimination diagrams with fields defined for MORB and BABB; Archaean spinifex-textured peridotitic komatiite (STPK) and Mg-basalt; Mariana island arc (M); Papua island arc (P); Betts Cove ophiolite (B); pyrolite (P); and Barberton komatiite. Modified after Sun and Nesbitt (1978). Data and references as for Figure 35.  

(a) Ti (ppm) versus CaO/TiO₂ diagram showing data for high-Ca boninite of Troodos ophiolite and Tasmanian high-Ti rift tholeiite.  
(b) Ti (ppm) versus Al₂O₃/TiO₂ showing data for high-Ca boninite of Troodos ophiolite and Tasmanian high-Ti rift tholeiite.  
(c) Ti (ppm) versus CaO/TiO₂ showing data for global primitive arc tholeiite.  
(d) Ti (ppm) versus Al₂O₃/TiO₂ showing data for global primitive arc tholeiite. Ellipsoid in (c–d) highlights dominant spread of data for primitive arc tholeiite.  
(e) Ti (ppm) versus CaO/TiO₂ showing data for Mariana Trench and Lau BABB.  
(f) Ti (ppm) versus Al₂O₃/TiO₂ showing data for Mariana Trench and Lau BABB.
LTG has characteristic negatively sloping REE patterns (Figure 16a). A search of worldwide geochemical databases shows that they are most similar to high-Ca boninite of the Troodos ophiolite complex in Cyprus (grey boxed area in Figure 16), believed to be a section of obducted back-arc oceanic crust (Portnyagin et al. 1997). Similarly, island arc tholeiite/BABB associations show the same depleted geochemical signature (Pearce et al. 1995b).

Negatively sloping REE patterns imply derivation from a depleted upper mantle source (ie remelting depleted mantle equivalents (lavas) have yet been identified. Overall chemical signatures are consistent with back-arc spreading in proximity to a volcanic arc, where slab-derived fluid is able to enter a region of decompression melting beneath the spreading centre (S Eggins pers comm 2006). MORB-normalised geochemical signatures for inferred liquid compositions (Figure 16b) are distinctive in that they show strong positive Sr peaks coupled with low Ta-Nb, which is strongly characteristic of an island arc environment (Tatsumi and Eggins 1995).

Geochemically, LTD-south is characterised by flat REE patterns and positive Sr peaks, and has trace element abundance patterns resembling those of primitive arc tholeiitic rocks known worldwide from oceanic and continental arc settings. LTD-north has slightly steeper LREE positive slopes and lacks the positive Sr peak characteristic of LTD-south, but is nevertheless chemically consistent with island arc tholeiite compositions. LTD-south represents relatively primitive arc tholeiite, that are most likely feeder dykes to lavas that have subsequently been eroded. These may have been part of an island arc originally located outboard of the back-arc, but have since been tectonically juxtaposed.

MCC rocks with ‘crust-like’ geochemical signatures are located directly at the contact with the Ti-Tree Granophyre, hence these signatures may reflect crustal contamination with the latter. This is supported by Edgoose et al. (1989b), who documented thin veins of granophyre within the gabbro in this region.

Positive initial εNd values isotopic values for LTD and LTG are consistent with geochemical results discussed earlier, and indicate derivation from a depleted mantle source. Moreover, the data are consistent with published Sm-Nd isotopic data for island arc and back-arc terrains (eg Pearce et al. 1995a, Tatsumi and Eggins 1995, Ewart et al. 1998). MCC has more evolved (enriched) Nd signatures (εNd ranging from -2.4 to -3.0) consistent with their crust-like geochemical signature, which is indicative of crustal assimilation. HAG has slightly enriched isotopic signatures with εNd ranging from -0.1 (close to Bulk Earth) to -2.6 (a more evolved composition). This may reflect minor crustal involvement during magma chamber processes.

**Benning Gabbro**

The HTT category (the only Litchfield Province mafic rocks with high-Ti signatures) plots within the field for known high-Ti rift tholeiite worldwide (Figures 36, 40). They typically show elevated LREE and positively sloping REE patterns (Figure 27). Sample PK05CJC018 is slightly more enriched in LREE than the other HTT samples. Relative to NMORB, they have similar HREE abundances, significant Nb-Ta depletions and elevated incompatible element enrichment. Three samples have compositions that may represent primary lavas (Eu/Eu* ca 1, average Mg# ~ 43). Chemically, they are similar to high-Ti rift-related tholeiite, which typically occur in attenuated active margins.
Table 1. Sm and Nd (ppm), 143Nd/144Nd and εNd data for Litchfield mafic rocks. Nd isotope ratios are relative to La Jolla = 0.511860. Internal precision (2σe) for 143Nd/144Nd ≤ ±0.000010, external precision (2sd) ± 0.000020 or 0.004%; for 143Sm/144Nd (2sd) ± 0.2%. Modern CHUR precision (2se) for 143Nd/144Nd ≤ ±0.000010, external precision (2sd) ± 0.000020 or 0.004%; for 147Sm/144Nd (2sd) ± 0.2%. Modern CHUR is 0.1967, 0.512638; TDM model based on modern depleted mantle with 0.2136; 0.513114 and linear evolution since 4.55 Ga (εNd=0) to present (εNdnow = +10). All analyses were conducted by Dr Roland Maas at the School of Earth Sciences, University of Melbourne, Victoria, Australia.

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<th>Sample</th>
<th>Lithostratigraphic unit</th>
<th>Sm (ppm)</th>
<th>Nd (ppm)</th>
<th>143Sm/144Nd</th>
<th>143Nd/144Nd</th>
<th>εNd(measured)</th>
<th>TDM (Ga)</th>
<th>Assumed age (Ga)</th>
<th>εNd(t)</th>
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<td>5.54</td>
<td>0.1724</td>
<td>0.512462</td>
<td>-3.43</td>
<td>1.86</td>
<td>2.4</td>
<td></td>
</tr>
<tr>
<td>PC05CJC028</td>
<td>Woolianna Gabbro - LTG</td>
<td>1.14</td>
<td>3.59</td>
<td>0.1920</td>
<td>0.512674</td>
<td>0.70</td>
<td>1.86</td>
<td>1.8</td>
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<tr>
<td>PC05CJC029</td>
<td>Woolianna Gabbro - LTG</td>
<td>0.72</td>
<td>2.05</td>
<td>0.2132</td>
<td>0.512953</td>
<td>6.15</td>
<td>1.86</td>
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<tr>
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<td>Woolianna Gabbro - LTDsouth</td>
<td>1.30</td>
<td>4.62</td>
<td>0.1698</td>
<td>0.512457</td>
<td>-3.53</td>
<td>1.86</td>
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<td>PK05CJC018</td>
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<td>6.04</td>
<td>25.28</td>
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<td>0.511951</td>
<td>-13.40</td>
<td>1.86</td>
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Table 1: Sm and Nd (ppm), 143Nd/144Nd and εNd data for Litchfield mafic rocks. Nd isotope ratios are relative to La Jolla = 0.511860. Internal precision (2σe) for 143Nd/144Nd ≤ ±0.000010, external precision (2sd) ± 0.000020 or 0.004%; for 143Sm/144Nd (2sd) ± 0.2%. Modern CHUR is 0.1967, 0.512638; TDM model based on modern depleted mantle with 0.2136; 0.513114 and linear evolution since 4.55 Ga (εNd=0) to present (εNdnow = +10). All analyses were conducted by Dr Roland Maas at the School of Earth Sciences, University of Melbourne, Victoria, Australia.

Keri Metamorphics

Metamorphosed noritic cumulate rocks (MNC) of the Keri Metamorphics are difficult to place within a tectonic framework. Spatially associated MFG (ferrogabbro now garnet-bearing amphibolite) lacks the characteristic negative Nb-Ta anomaly evident in the other arc-related rocks. Its relationship to other mafic rocks in the area is unclear as it has most likely metamorphosed at deeper crustal levels. Its proximity to the other former Wangi Basics rocks may be the result of tectonic juxtaposition. MFG was most likely plagioclase cumulate prior to its conversion to garnet amphibolite.

Lilybarra Mafics

The two isolated LSS samples from central Wingate Mountains plot in the absarokite field of the TAS diagram as defined by Rock (1991; Figure 7b). Sample FE04JHL002 is a feldspar cumulate (positive Eu anomaly) and FE04NJD005 is a possible lamprophyre. Evaluation of thin sections discloses some degree of alteration and overprinting, so it is unclear to what extent a primary alkaline signature is preserved. Nevertheless, the combined geochemical features of these rocks are consistent with a shoshonitic affinity and the age of ca 1830 Ma obtained for sample FE04JHL002 is typical of alkaline rocks of the PCO. Clearly, more work on these rocks is warranted.

CONCLUSIONS

Mafic/ultramafic rocks of the Litchfield Province clearly demonstrate geochemical and Nd isotopic diversity. Most rock types have been metamorphosed at mid-crustal levels (~12–15 km depth) yet retain evidence that they originated by shallow-level magmatic processes. This indicates that the now-exposed rocks have undergone collisional orogeny and burial before exhumation to surface levels.

Relative to NMORB, HAG (Woolianna Gabbro) has very low HREE abundances, which is characteristic of primitive low- to medium-K arc tholeiite. Samples lacking a Eu anomaly (ie flat pattern between Sm and Gd when normalised to carbonaceous chondrite) and with Eu/Eu* ~ 1 and Mg# ~67 may have been parental liquid compositions to HAG. These samples have strong positive Sr peaks combined with low relative Nb-Ta, which is a characteristic arc signature. HAG therefore most likely represents the base of a subvolcanic magma chamber feeding island arc tholeiites, which was subsequently buried and metamorphosed to amphibolite facies prior to exhumation. In summary, the Woolianna Gabbro is interpreted to represent part of a now dismembered Palaeoproterozoic island arc tholeiite/BABB association. However, only subvolcanic levels are exposed; high-level equivalents (lava) are rare, although metadacite of the Warrs Volcanic Member (Dundas et al 1987a) is exposed in DALY RIVER.

LTG (Woolianna Gabbro) has characteristic negatively sloping REE patterns similar to those of island arc tholeiite/BABB and fractionated Troodos high-Ca boninitic lavas. Negatively sloping REE patterns imply derivation from a depleted upper mantle source (ie remelting depleted mantle which has already experienced a previous episode of melt extraction). Nd isotope data (positive εNd values) confirm...
derivation from a depleted juvenile mantle source. By analogy with Troodos lavas, LTG probably represents a mid-level portion of back-arc oceanic crust. Distinctive, strongly positive Sr peaks coupled with low Ta-Nb are particularly characteristic of island arc environments. Overall, the chemical signatures are consistent with back-arc spreading in proximity to a volcanic arc where the slab fluid signature was able to enter a region of decompression melting beneath the spreading centre. LTG is most likely a boninite-related low-Ti tholeiite and similarities to Troodos high-Ca boninite highlight the possibility of these rocks being associated with Cu mineralisation. The Troodos complex in Cyprus is host to historical Cu-rich volcanic-hosted massive sulfide ( VHMS) deposits (Galley and Koski 1999). The majority of mineralisation is hosted within pillow lavas, but some mineralisation is found in the sheeted dyke complex stratigraphically below these lavas. In DALY RIVER, a belt of copper anomalies, hosted within the 1862 ± 3 Ma felsic Warrs Volcanic Member (Ferenczi 1990), lies immediately east of LTG (Figure 6). One copper occurrence in DALY RIVER has been documented within former Wangi Basics (LTG) metaquartz dolerite (Ferenczi 1990), but further work is required to determine the nature of this occurrence. Given the geochemical similarities with the Troodos complex in Cyprus, LTG has economic potential for hosting copper deposits.

LTD-south (Woolianna Gabbro) represents a category of relatively primitive arc tholeiite that most likely represents feeder dykes to lavas that have subsequently been eroded. These may have been part of an island arc originally located outboard of the back-arc, but subsequently tectonically juxtaposed with the back-arc. Positive εNd isotopic values for these rocks are consistent with published Sm-Nd isotopic data for worldwide island arc and back-arc terranes (eg Pearce et al 1995a, Ewart et al 1998). LTD-north (Woolianna Gabbro) has slightly steeper LREE positive slopes and lacks the positive Sr peak characteristic of LTD-south, but is nevertheless chemically consistent with island arc tholeiite compositions. MCC most likely represent HAG samples that have been crustally contaminated by adjacent felsic crustal rocks.

HTT (Benning Gabbro), the only category with high-Ti signatures, is geochemically similar to known high-Ti rift tholeiite worldwide. HTT has clearly retained the arc signature which, combined with the alkaline nature of these rocks, suggests that they are most likely part of a post-collisional remnant-arc regime. LSS alkaline rocks (Lilyarya Mafics) in central WINGATE MOUNTAINS most likely have lamprophyric/shoshonitic affinities indicative of post-collisional tectonics.

Given the considerable chemical and Nd isotopic heterogeneity of the above Litchfield Province mafic/ultramafic rocks, it is clear that not all units are related to the same igneous tectonic regime and that they do not share a common parental magma. HAG, LTG, LTD-south and LTD-north (Woolianna Gabbro) are associated with an island arc/BABB tectonic regime. HTT (Benning Gabbro) with a high-Ti signature (yet also shares island arc-like geochemical features) and the shoshonitic rocks (Lilyarya Mafics) dated at ca 1830 Ma were both most likely emplaced in a post-collisional regime. In contrast, MNC and MFG (Keri Metamorphics) appear to be genetically unrelated. The term ‘Wangi Basics’ is therefore discontinued and new stratigraphic names (Appendix II) are adopted herein.

Elements of modern day island-arc systems ie lithologies of back-arc-basin and primitive-arc basaltic affinity appear to be preserved, however, the tectonic configuration of the various components is unclear due to subsequent tectonic activity. The Woolianna Gabbro represents a dismembered island arc system with various arc-related rocks exposed at different stratigraphic levels which have subsequently been tectonically juxtaposed.

The identification of an island arc/BABB association in the Litchfield Province is significant, as this is the first recognition of such rock types in this region of the Northern Territory. The new data are in agreement with Sheppard et al (1999), who documented depleted Palaeoproterozoic metabasalt (low- to high-grade Tickalara Metamorphics in the central zone of the HCO) as being representative of an oceanic island arc/back-arc basin tectonic setting [see also Tyler et al (1995) and Griffin et al (2000)]. The age of the Tickalara Metamorphics metabasalt is thought to be ca 1865 Ma (Sheppard et al 1999). Results of the present geochemical investigation support this tectonic concept, though not the intraplate hypothesis for the origin of the NAC proposed by earlier workers. Coeval tectonometamorphic events at 1855–1853 Ma have been documented for both the Litchfield Province (Litchfield Event) and the Western and Central Zones of the HCO (Carson et al 2008), however the Central Zone of the HCO also underwent a subsequent 1845–1835 Ma tectonometamorphic event which to date has not been identified in the Litchfield Province. While the new findings lend support to the concept of the Litchfield Province being a structural and tectonic continuum with the HCO, there are still significant differences between the two orogenic domains that require further research. The new data highlight the Cu-Zn mineral potential associated with arc-related volcanism, with existing VHMS Cu-Zn mineralisation hosted by the dacitic Warrs Volcanic Member (mostly drillhole intersections) in DALY RIVER (Ferenczi 1990) (Figure 6). Given the paucity of outcrop in this region, the potential for significant mineralisation remains. This potential is further enhanced by the discovery of copper sulfide and gold mineralisation within the arc-related Narracoota Volcanics at the Doolgunna Cu-Au project on the northern margin of the Yilgarn Block, Western Australia. The Narracoota Volcanics have geochemical similarities to boninites (Hynes and Gee 1986), and this discovery highlights the potential for mineralisation within the Woolianna Gabbro. The tectonic environment for the Narracoota Volcanics is analogous to that of the Woolianna Gabbro, even though this latter unit does not have high-level mafic rocks preserved.

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REFERENCES


Flower MFJ and Levine HM, 1987. Petrogenesis of a tholeite-boninite sequence from Ayios Mamas, Troodos


Morgan CM, Sweet IP, Mendum JR and Pontifex IR, 1970. The geology of the Cape Scott, Port Keats, Fergusson River and Delamarle 1:250,000 sheet areas, Northern Territory. *Bureau of Mineral Resources, Geology and Geophysics, Australia, Record 3*.


32


Appendix I: Major and trace element results for Litchfield mafic rocks (Excel chart)

Appendix II: Definitions of new stratigraphic units

Woolianna Gabbro

Proposer: LM Glass

Derivation of name: After Woolianna homestead, Woolianna Road and Woolianna school 5 km north of Daly River township, Northern Territory; (PINE CREEK, DALY RIVER), Litchfield Province, Pine Creek Orogen, NT.

Synonymy: Previously known as Wangi Basics (Needham and Stuart-Smith 1984, Dundas et al 1987 a, b). This name is abandoned, as it is now known to comprise distinct geochemical groups which are genetically unrelated.

Constituent units: Has five distinct geochemical categories which are linked to a common tectonic paragenesis.

Type locality: Large outcrop on MOYLE and WINGATE MOUNTAINS about 40 km southwest of Daly River township (663172mE 8442583mN; GDA94 Zone 52L; 14°4°59’S 130°30’41”E).

Description at type locality: Large area of good exposure comprising metamorphosed medium-to-coarse-grained, variably altered, equigranular rocks that include gabbro, hypersthene gabbro and microgabbro to coarse-grained dolerite. In DALY RIVER, it comprises metaperidotite, metapyroxenite, metaharzburgite, amphibolite, metadolerite and metabasalt.

Area: Area for large stock in WINGLET MOUNTAINS is about 28 km² (Edgoose et al 1989b).

Relationships and boundary criteria: Contact relationships between the large stock and surrounding rock units are not known. Edgoose et al (1989b) inferred that the stock mostly intrudes nearby Hermit Creek Metamorphics, Burrell Creek Formation and Berinka Volcanics. Mafic xenoliths in adjacent Murra-Kamangee Granodiorite are thought to be of Woolianna Gabbro (former Wangi Basics; Edgoose et al 1989b).

Distinguishing or identifying features: Woolianna Gabbro is metamorphosed to amphibolite facies with overprinting greenschist-facies retrogression. It is characterised by a distinctive island arc (back-arc basin) chemical signature which is most apparent in DALY RIVER (Glass 2007).

Age and evidence: Not adequately constrained, but believed to be in the range 1860–1855 Ma (Glass 2010) based on stratigraphic constraints.

Correlation with other units: Possible correlative of Tickalara Metamorphics in Central Zone of Halls Creek Orogen, Western Australia (Sheppard et al 1999).

Regional aspects: Beyond MOYLE-WINGLET MOUNTAINS, unit also occurs as scattered exposures in REYNOLDS RIVER, GREENWOOD and DALY RIVER. Unifying characteristic is distinctive back-arc basin geochemical signature.

Alteration and mineralisation: Localised chlorite and sericite alteration. A minor occurrence of shear-zone-hosted polymeric Cu-Pb-Zn-Ag veins occurs at 862030mE 8492161mN (13°38’1”S 130°40’58”E) in DALY RIVER (Ferenzi 1990; NTGS MODAT database).

Geophysical expression: Large stock on WINGLET MOUNTAINS has strong magnetic response.

Geochemistry: Woolianna Gabbro rocks are characterised by a distinctive island arc (back-arc basin) chemical signature (Glass 2007) which is further reinforced by positive εNd isotopic signatures.

Genesis: Intrusive rocks related to island-arc/back-arc basin setting.

Lilyarba Mafics

Proposer: LM Glass

Derivation of name: After Lilyarba Waterhole 706200mE 8410100mN; 14°22’25”S 130°54’44”E) and Lilyarba Tinfield (703900mE 8410830mN; GDA 94 Zone 52L; 14°22’2”S 130°53’27”E), FERGUSSON RIVER, WINGLET MOUNTAINS, Litchfield Province, Pine Creek Orogen, NT.

Synonymy: Previously known as Wangi Basics (Needham and Stuart-Smith 1984, Dundas et al 1987 a, b). This name is now abandoned, as it is now known to comprise distinct geochemical categories which are genetically unrelated.

Constituent units: Nil

Type locality: Large exposure in FERGUSSON RIVER and central WINGLET MOUNTAINS, 60 km south of Daly River township (693500mE 8417500mN, GDA 94, Zone 52L; 14°18’28”S 130°47’38”N).

Lithology: Possible altered lamprophyre; mineralogy dominated by sericitised plagioclase (labrodorite, andesine) and hornblende, and minor biotite and opaque minerals (Edgoose et al 1989 b).

Distinguishing or identifying features: Comprises fine-grained, altered low-grade metamorphic rocks with distinctive strong alkaline geochemical signatures. Age of 1830 Ma distinguishes these rocks from other former Wangi Basics constituents, which must be in range 1860–1855 Ma based on stratigraphic relationships.

Age and evidence: Worden et al (2008 a) reported a 207Pb/206Pb SHRIMP zircon age of 1829 ± 4 Ma.

Correlation with other units: Possible correlative of olivine-mica-K-feldspar lamprophyre dykes at Mt Bundey, Central Domain, Pine Creek Orogen, NT (Sheppard and Taylor 1992).

Regional aspects: Slightly altered, lower amphibolite-facies probable lamprophyre; includes minor shoshonitic cumulate. Rocks are characteristically low-SiO₂ with no free quartz.


Structure and metamorphism: Lower amphibolite-facies metamorphism. Structural relationships unknown.

Alteration and mineralisation: Sericitic alteration of plagioclase feldspar; some alteration of hornblende to actinolite and tremolite; partial chloritisation of biotite. No known mineralisation. Geophysical expression: Positive magnetic response.

Geochemistry: Mafic rocks with distinctive potassic signatures; silica values typically low (<50 wt% SiO₂), alumina high (20 wt% Al₂O₃).

Genesis: Intrusive.

Comments: Rocks from this locality, described by Edgoose et al (1989 b) as ‘quartz-bearing diorite, gabbro and some dolerite’ are not included in this unit. Although Lilyarba Mafics is defined by only a small number of historical samples collected in 2004 from a region with restricted access, the distinctive geochemistry and younger age of these rocks distinguish them from other former Wangi Basics constituents.

**Benning Gabbro**

**Proposer:** LM Glass

**Derivation of name:** After Benning (695700mE 8409400mN; 14°22′51″S 130°48′54″E) on FERGUSON RIVER and PORT KEATS, MOYLE and WINGATE MOUNTAINS, Litchfield Province, Pine Creek Orogen, NT.

**Synonymy:** Previously known as Wangi Basics (Needham and Stuart-Smith 1984, Dundas et al 1987 a, b). This name is abandoned, as it is now known to comprise distinct geochemical groups of rocks which are genetically unrelated.

**Type locality:** Prominent sill (0.6 km length) within Chilling Sandstone, WINGATE MOUNTAINS, FERGUSON RIVER (668414mE 8434455mN, GDA 94, Zone 52L; 14°9′22″S 130°33′43″E).

**Description at type locality:** Occurs as gabbro forming a prominent linear sill in Wingate Mountains 1:100 000 mapsheet, length ca 0.6 km within the Chilling Sandstone.

**Lithology:** Metamorphosed high-Ti tholeitic gabbro mostly occurring as northeast-trending linear sills over an area 6 km long and 200 m wide within Burrell Creek Formation and Chilling Sandstone (Edgoose et al 1989 a, b). Mostly quartz-hypersthene normative; comprises metamorphosed equigranular assemblages of (rare) quartz, plagioclase with highly saussuritised/sericitised cores and unaltered rims, clinopyroxene, pale brown to green pleochroic hornblende; fibrous actinolite/tremolite and uralitised hornblende common.

**Relationships and boundary criteria:** Intrudes 1860 Ma Burrell Creek Formation and Chilling Sandstone in WINGATE MOUNTAINS and MOYLE.

**Distinguishing or identifying features:** Typically high-Ti tholeitic gabbro with characteristic alkaline enrichment (Glass 2007).

**Age and evidence:** Not adequately constrained but 1860 Ma or younger based on field relationships with metasedimentary Burrell Creek Formation and Chilling Sandstone.

**Geomorphic Expression:** Blocky ridges within surrounding metasedimentary host rocks.

**Structure and metamorphism:** Amphibolite-facies metamorphism; disrupted by south-southwest-trending faults. First Edition mapping (Edgoose et al 1989 b) shows regional open folding of host successions around southwest-plunging axes.

**Alteration and mineralisation:** Saussuritisation/sericitisation of feldspars; hornblende altered to actinolite/tremolite and uralite; minor chlorite alteration.

**Geophysical expression:** Linear sills have strong positive magnetic response.

**Geochemistry:** High-Ti tholeitic gabbro (TiO₂ values in range 1.9–4.2 wt%, average 2.3 wt%) with some degree of alkaline enrichment (Glass 2007).

**Genesis:** Intrusive sills into metasedimentary Burrell Creek Formation and Chilling Sandstone.

**Keri Metamorphics**

**Proposer:** LM Glass

**Derivation of name:** After Keri homestead (669230mE 8534660mN, GDA 94, Zone 52L; 13°15′9″S 130°33′43″E) on PINE CREEK, REYNOLDS RIVER, Litchfield Province, Pine Creek Orogen, NT.

**Synonymy:** Previously known as Wangi Basics (Needham and Stuart-Smith 1984, Dundas et al 1987 a, b). This name is abandoned, as it is now known to comprise distinct geochemical groups which are genetically unrelated.

**Constituent units:** Includes metamorphosed noritic cumulate and metaferrogabbro.

**Type locality:** Low boulder-strewn hills 12 km north of Keri homestead on REYNOLDS RIVER (670455mE 8548345mN, GDA 94, Zone 52L; 13°7′35″S 130°34′21″E).

**Description at type locality:** Low boulder-strewn hills among Cenozoic cover.

**Lithology:** Metamorphosed mafic/ultramafic assemblages (metamorphosed noritic cumulate, metaproxenite and metaperidotite) and garnet-bearing mafic amphibolite (metaferrogabbro) (Glass 2007).

**Relationships and boundary criteria:** Contact relationships not observed, but possibly intrudes Welltree Metamorphics (Pietsch 1989).
Distinguishing or identifying features: Metamorphosed mafic/ultramafic assemblages are moderate to strongly foliated (typical mineral assemblages include tremolite, anthophyllite, actinolite and hornblende). Metaferrogabbro has distinctive large garnet porphyroblasts up to and greater than 10 mm in diameter, which commonly amalgamate to form linear segregations in an amphibole-rich groundmass.  

Age and evidence: Carson et al (2009) determined a weighted mean $^{207}\text{Pb}/^{206}\text{Pb}$ SHRIMP zircon date of 1860 ± 6 Ma (95% confidence level) for a garnet-bearing mafic amphibolite, which is interpreted to represent the magmatic crystallisation age for this sample.

Correlation with other units: None known.

Regional aspects: Exposures occur within an area of 16 km$^2$ in northwestern REYNOLDS RIVER; however, magnetic imagery indicates that true extent under surficial cover may be much greater.

Geomorphic expression: Boulder-strewn outcrops.

Structure and metamorphism: Amphibolite-facies metamorphism.

Alteration and mineralisation: Abundant fibrous amphibole (tremolite-actinolite) is interlaminated with chlorite and is most likely replacement product of primary orthopyroxene. Uralitic amphibole is most likely derived from granular clinopyroxene. Residual partly sericitised (± clinozoisite) platy plagioclase (up to 2 mm in size) has in part been overprinted by recrystallised amphibole. No known mineralisation.

Geophysical expression: Appears to be associated with a magnetic high in northwestern corner of REYNOLDS RIVER, which extends slightly into adjoining mapsheets. No observable radiometric or gravity response.

Geochemistry: Metamorphosed noritic cumulate is typically low Ti and highly magnesian. Metaferrogabbro is metamorphosed plagioclase-pyroxene cumulate with very high FeO (18.8–23.2 wt%).

Genesis: Intrusive.