Geology of the Gascoyne Province

by

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Introduction

The Gascoyne Province lies at the western end of the Capricorn Orogen, and includes a range of Neoarchean to Paleoproterozoic gneisses, granites, and metasedimentary basins that record the amalgamation of the Archean Pilbara and Yilgarn Cratons to form the West Australian Craton, and over one billion years of subsequent intracontinental crustal reworking. During these multiple reworking events, different parts of the Gascoyne Province have responded differently to deformation, metamorphism, and magmatism. This has led to the subdivision of the province into several fault or shear zone bounded, easterly–southeasterly trending structural and metamorphic zones (Frontispiece 1–3; Fig. 1; Sheppard et al., 2010b).

The oldest crust in the Gascoyne Province is the Glenburgh Terrane, which is exposed only within the southern part of the province (Frontispiece 1–3; Plate 1). The southern boundary is marked by the Errabiddy Shear Zone, a high-strain zone up to 25 km wide that contains imbricated slices of reworked Yilgarn Craton. The northern margin of the Glenburgh Terrane is not exposed, but is interpreted from various geophysical data to coincide roughly with the Talga Fault (Frontispiece 2; Selway, 2008; Selway et al., 2009), implying that the terrane also forms basement to the northern part of the province. During subsequent crustal reworking, the Glenburgh Terrane was intruded by various generations of granitic magmas and overlain by numerous metasedimentary basins, some of which have been deformed at low- to medium-metamorphic grades. During these multiple tectonomagmatic reworking events, deformation, metamorphism, and magmatism were focused into discrete easterly–southeasterly trending tectonic corridors (structural and metamorphic zones), each of which is bounded by a major fault or shear zone (Frontispiece 1; Fig. 1; Sheppard et al., 2010b). Variable uplift on major faults across the province has then juxtaposed blocks of contrasting crustal depth.

The Glenburgh Terrane and assembly of the West Australian Craton

The Glenburgh Terrane comprises: (i) a basement of heterogeneous granitic gneisses (the Halfway Gneiss) with ages between c. 2555 and c. 2430 Ma; (ii) an overlying package of continent-derived siliciclastic metasedimentary rocks (the 2240–2125 Ma Moogie Metamorphics); (iii) a c. 2000 Ma belt of metagranitic rocks (the Dalgaringa Supersuite), which are interpreted to have formed in a continental-margin volcanic arc; and (iv) arc-related metasedimentary rocks (the 2000–1955 Ma Camel Hills Metamorphics) that are in tectonic contact with both the arc rocks and the deformed northern margin of the Yilgarn Craton. The oldest tectonic unit, the Halfway Gneiss, consists of heterogeneous, variably pegmatite-banded, granitic gneisses. The protoliths have crystallization ages between c. 2555 and c. 2430 Ma, but also contain abundant older inherited zircons, some of which are as old as c. 3447 Ma (Johnson et al., 2011c). Although no older crust (>2555 Ma) is exposed, the Lu–Hf compositions and crustal model ages of both magmatic and inherited zircons indicate a long crustal history ranging back to c. 3700 Ma (Johnson et al., 2011c). These isotopic data also demonstrate that large parts of the terrane, presumably representing the mid and lower crust (none of these rocks are currently exposed), formed via juvenile crustal growth processes between c. 2730 and c. 2600 Ma (Johnson et al., 2011c). Formation of the 2555–2430 Ma gneisses occurred mainly by the in situ reworking of these older crustal components (Johnson et al., 2011c). A comparison of the U–Pb zircon ages and zircon-Hf isotopic compositions of the Halfway Gneiss with those of the bounding Pilbara and Yilgarn Cratons indicates that the Halfway Gneiss (and thus the Glenburgh Terrane) is exotic to, and evolved independently from, these cratons (Johnson et al., 2011c). The Glenburgh Terrane is interpreted to have collided and accreted with the Pilbara Craton during the 2215–2145 Ma Ophthalmian Orogeny (Occhipinti et al., 2004; Johnson et al., 2010, 2011a,c).

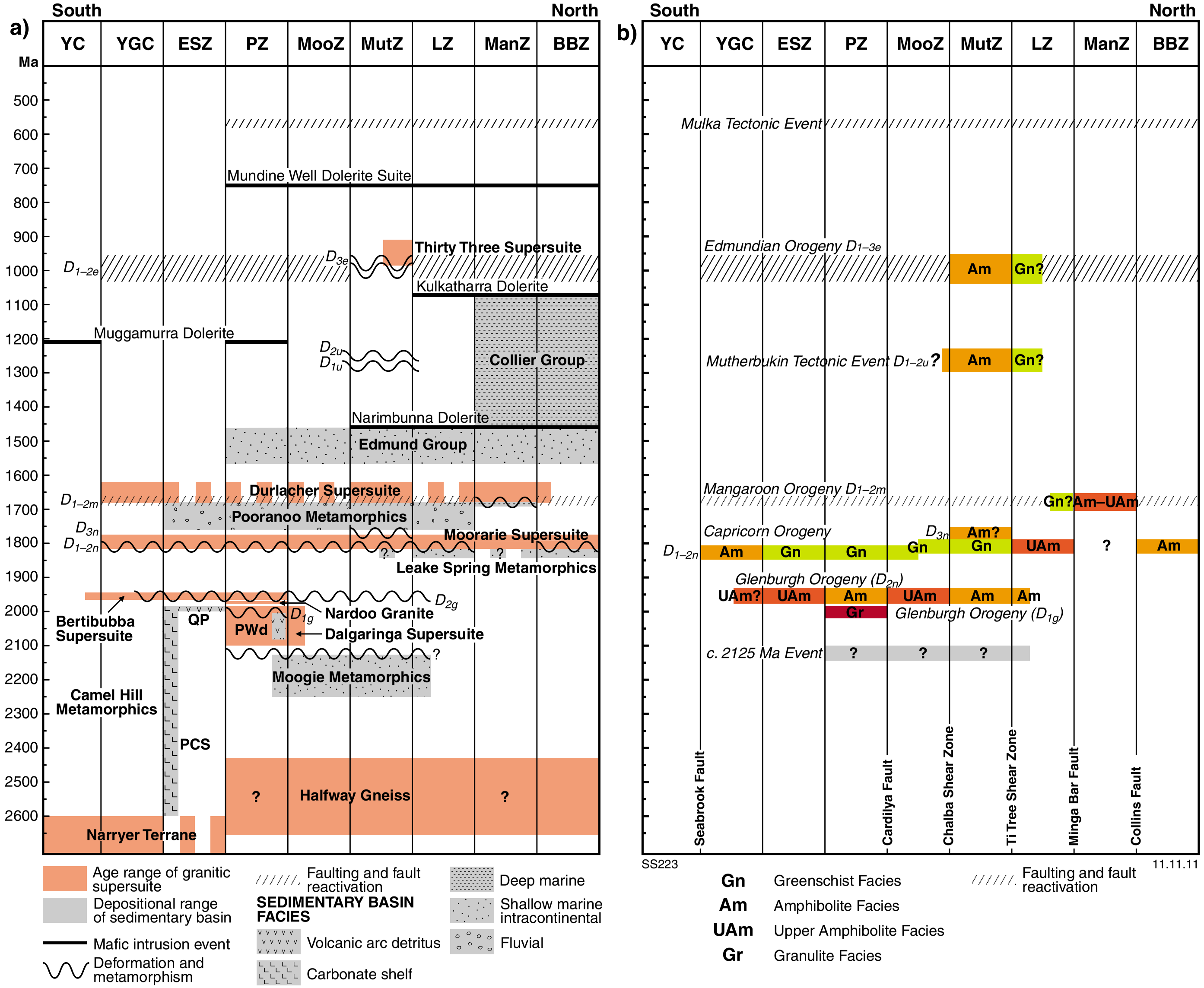

Figure 1. Time–space plot for the Gascoyne Province. Zone boundary abbreviations: BBZ — Boora Boora Zone; ESZ — Errabiddy Shear Zone; LZ — Limejuice Zone; ManZ — Mangaroon Zone; MooZ — Mooloo Zone; MutZ — Mutherbukin Zone; PZ — Paradise Zone; YC — Yilgarn Craton; YGC — Yarlarweelor Gneiss Complex. Abbreviations in time–space plot: PCS — Petter Calc-silicate; QP — Quartpot Pelite; PWd — Paradise Well diatexite.

The Moogie Metamorphics are dominated by psammitic schists, the protoliths to which were deposited across the Glenburgh Terrane sometime between c. 2240 and c. 2125 Ma. The timing of deposition is essentially coincident with the 2215–2145 Ma Ophthalmian Orogeny, and these protoliths are interpreted to represent a pro-foreland basin deposited in response to uplift of the southern Pilbara Craton margin during the collision and accretion of the Glenburgh Terrane with the Pilbara Craton (Fig. 2; Occhipinti et al., 2004; Johnson et al., 2010, 2011a). The Moogie Metamorphics are probably roughly time-equivalent to the Beasley River Quartzite of the lower Wyloo Group, which was deposited in a retro-foreland basin during the Ophthalmian Orogeny (Fig. 2; Martin and Morris, 2010).

Following this collision on the northern margin of the Glenburgh Terrane, continental-margin arc-magmatic activity was initiated along the southern margin at c. 2080 Ma (Fig. 2; Johnson et al., 2010, 2011a). Although magmatic rocks with ages between c. 2080 and c. 2005 Ma are not exposed within the province, detrital and inherited zircons of this age, with slightly evolved Lu–Hf compositions, are abundant within the volcanoclastic metasediments of the 2000–1955 Ma Camel Hills Metamorphics (Johnson et al., 2010, 2011a), and within the granitic gneisses of the 2005–1985 Ma Dalgaringa Supersuite.

The Dalgaringa Supersuite is exposed in the southern part of the province, within the Paradise Zone (Frontispiece 1–3; Plate 1), and comprises massive, foliated, and gneissic granitic rocks that have major-, trace-, and rare earth element (REE) concentrations consistent with formation in a supra-subduction zone setting (Sheppard et al., 2004). Their whole-rock Sm–Nd, and magmatic zircon Lu–Hf, isotopic signatures indicate the incorporation of Neoarchean granitic gneisses with isotopic compositions similar to those of the Halfway Gneiss (Sheppard et al., 2004; Johnson et al., 2011a), suggesting that magmatism occurred in a continental-margin arc, termed the Dalgaringa Arc, which formed along the southern margin of the Glenburgh Terrane (Fig. 2). This magmatic event records the progressive closure and northward subduction of an oceanic tract under the combined Pilbara Craton – Glenburgh Terrane. The older parts of the Dalgaringa Supersuite (2005–1985 Ma), including lenses of pelitic diatexite and mafic granulite, were deformed and metamorphosed at high temperatures and pressures during the D_{1g} event (2005–1985 Ma) of the 2005–1950 Ma Glenburgh Orogeny. This event is interpreted to reflect the construction of the arc in the middle crust (Johnson et al., 2010, 2011a).

Terminal ocean closure, the collision between the Pilbara Craton – Glenburgh Terrane and the Yilgarn Craton, and the formation of the West Australian Craton, all took place during the 1965–1950 Ma D_{2g} event of the Glenburgh Orogeny (Johnson et al., 2010, 2011a). The collision resulted in the imbrication of the northern Yilgarn Craton margin with Glenburgh Terrane lithologies along the Errabiddy Shear Zone (Frontispiece 1–3; Fig. 2; Plate 1), and the high-grade tectonometamorphism of metasedimentary and meta-igneous rocks along the southern margin of the Glenburgh Terrane. The D_{2g} event was accompanied by the intrusion of granitic stocks and dykes of the 1965–1945 Ma Bertibubba Supersuite. These granitic rocks are the first common magmatic element of the northern margin of the Yilgarn Craton, the Yarlarweelor Gneiss Complex, the Errabiddy Shear Zone, and the Paradise Zone of the Glenburgh Terrane. Therefore, suturing of the combined Pilbara Craton – Glenburgh Terrane with the Yilgarn Craton, and thus the assembly of the West Australian Craton, was complete by this time (Fig. 2).

Intracontinental magmatism and repeated crustal reworking

Subsequent to the assembly of the West Australian Craton during the Glenburgh Orogeny, the history of the Capricorn Orogen is dominated by more than one billion years of episodic intracontinental reworking and reactivation. These multiple crustal events took place during the 1820–1770 Ma Capricorn Orogeny, the 1680–1620 Ma Mangaroon Orogeny, the 1385–1200 Ma Mutherbukin Tectonic Event, the 1030–955 Ma Edmundian Orogeny, and the c. 570 Ma Mulka Tectonic Event.

The 1820–1770 Ma Capricorn Orogeny

Although the Capricorn Orogeny had been widely interpreted to be the result of oblique collision between the Yilgarn and Pilbara Cratons (Myers, 1990; Tyler and Thorne, 1990; Krapež, 1999; Evans et al., 2003), most of these models were based largely on interpretations of poorly dated metasedimentary successions in the northern part of the orogen, or else did not take into account the ages, spatial distribution, and composition of granitic magmatism in the Gascoyne Province. The recognition of pre-1950 Ma tectonometamorphic events associated with the assembly of the West Australian Craton also negate a Capricorn Orogeny aged collision. Structures and metamorphic mineral assemblages related to the Capricorn Orogeny, and granites of the accompanying Moorarie Supersuite, are recognized across the province and in adjacent tectonic units such as the Ashburton Basin to the north, the Yarlarweelor Gneiss Complex and Errabiddy Shear Zone to the south, and the Padbury, Bryah, and Yerrida Basins to the east (Thorne and Seymour, 1991; Occhipinti et al., 1998; Sheppard and Swager, 1999; Occhipinti and Myers, 1999; Krapež and McNaughton, 1999; Pirajno et al., 2000; Sheppard et al., 2003; Martin et al., 2005; Sheppard et al., 2011). The orogeny is characterized by extensive deformation at low- to medium-metamorphic grades, and was accompanied by the intrusion of voluminous, felsic magmatic stocks and plutons, including the Minnie Creek batholith in the central part of the province (Fig. 3).

Three main tectonothermal events are recognized in the Gascoyne Province (D_{1n}, D_{2n}, and D_{3n}). The oldest event (D_{1n}) is recorded in the Yarlarweelor Gneiss Complex, Errabiddy Shear Zone, and southern part of the Mooloo Zone, occurring between c. 1820 and c. 1810 Ma. This event is dominated by intense upright to isoclinal folds,

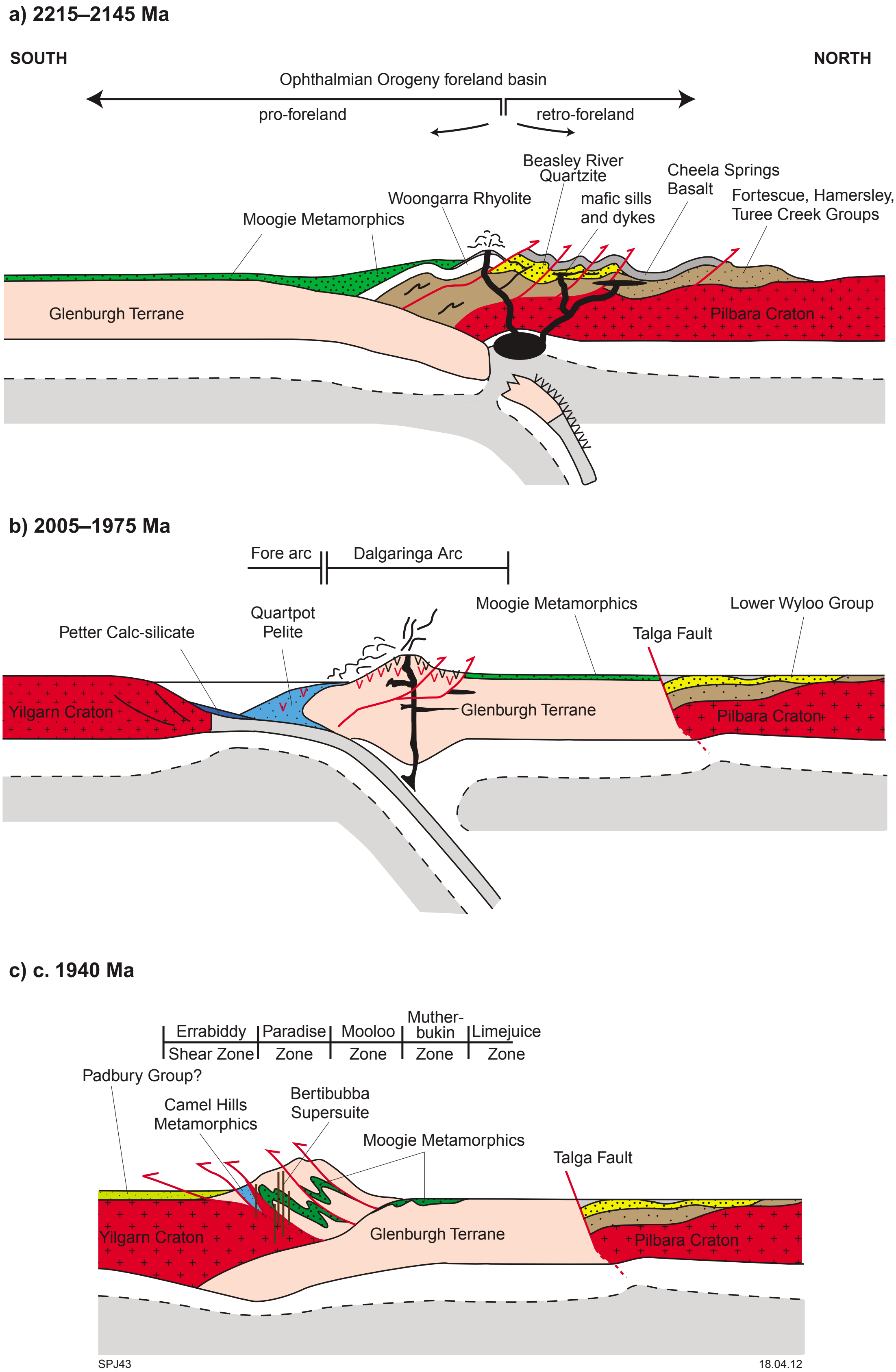

Figure 2. **Schematic cross sections showing possible tectonic settings for the deposition of: a) the Moogie Metamorphics during the 2215–2145 Ma Ophthalmian Orogeny, modified from Martin and Morris (2010); b) the Camel Hills Metamorphics during the 2005–1975 Ma period of the Glenburgh Orogeny; and c) the post-collisional architecture at c. 1940 Ma, modified from Cawood and Tyler (2004). Note that cross sections are not intended to infer orthogonal collision or plate motions between the tectonic blocks or cratons.**

with the production of an intense foliation or gneissic fabric. Apart from the Yarlarweelor Gneiss Complex, where metamorphism peaked in the upper amphibolite facies (Sheppard and Swager, 1999), metamorphism during this event was generally of greenschist-facies grade, and was responsible for the wholescale retrogression of high-grade metamorphic minerals formed during the Glenburgh Orogeny. Tectonometamorphism was accompanied by the intrusion of extensive sheets and stocks of granodiorite and monzogranite.

In the central part of the province, the main tectonic event is represented by D_{2n}, which is dated to between c. 1808 and c. 1786 Ma, and was synchronous with the intrusion of the Minnie Creek batholith. Due to subsequent structural and metamorphic overprinting, the structures and mineral assemblages associated with D_{2n} are commonly difficult to identify, especially in the Mutherbukin Zone; however, in the Limejuice Zone, inclusions and rafts of pelitic and semipelitic material (belonging to the 1840–1810 Ma Leake Spring Metamorphics) found within granites of the Minnie Creek batholith commonly contain a strong gneissic fabric or schistosity. Although the peak mineral assemblages have been wholly retrogressed, they probably contained andalusite as a porphyroblastic phase. In the southeastern portion of the Minnie Creek batholith, the appearance of cordierite indicates metamorphism at higher temperatures. Gneissic fabrics are also developed in granites of the Minnie Creek batholith, such as the Middle Spring Granite. Based on the age of undeformed granites that crosscut the strongly deformed Middle Spring Granite, the D_{2n} event in the batholith as a whole appears to have been a very short lived event, occurring between c. 1788 and c. 1786 Ma (Sheppard et al., 2010b; Geological Survey of Western Australia, 2011).

Throughout the province, granites of the Moorarie Supersuite mostly range from about 61 wt% SiO_2 to 77 wt% SiO_2, although the Minnie Creek batholith also includes some mafic–ultramafic intrusions and mafic inclusions. The granites show a wide range in initial εNd values, extending from -1.7 to -14.3, although most have initial εNd values between -1.7 and -8.1. The most evolved compositions, between -11.6 and -14.3, belong to very silicic, leucocratic, pegmatitic granites in the Yarlarweelor Gneiss Complex that were derived from the melting of Archean crust (Sheppard et al., 2003). Granites from individual regions show a more restricted range of values (Fig. 3a). Minnie Creek batholith granites have initial εNd values of -1.7 to -5.5, which are less negative than coeval granites to the north and south (-4.0 to -8.1; Fig. 3), and on the whole have younger T_{DM} model ages (between 2570 and 2250 Ma) than contemporaneous granites elsewhere in the province. These data imply a more juvenile source for the Minnie Creek batholith. The presence of gabbros and widespread mafic inclusions in this batholith's granites suggests that this juvenile component was probably derived directly from the mantle. However, all of the granites, including those of the Minnie Creek batholith, have much lower εNd values than depleted mantle at this time (~+6, using the depleted mantle model of Goldstein et al. (1984)), implying that the granites themselves were derived largely by melting older crust, which must have included components older than c. 2570 Ma; i.e. the Yarlarweelor Gneiss Complex of the Yilgarn Craton, and the Halfway Gneiss of the Glenburgh Terrane.

The third tectonic event, D_{3n}, is only recognized in the Limejuice Zone, where D_{2n} gneissic fabrics and foliations in the Minnie Creek batholith and associated pelitic inclusions are folded about upright, local- to regional-scale, close to tight folds. A well-developed crenulation cleavage is developed parallel to these macroscopic F_{3n} fold traces, and is defined by a lower-greenschist facies mineral assemblage. Low Th/U metamorphic or hydrothermal zircon rims, obtained from quartzites in the Mutherbukin Zone, have been dated at c. 1772 Ma (Johnson et al., 2010, 2011a). Although zircon-rim growth cannot be directly related to any tectonic fabric, it is possible that they record hydrothermal fluid flow during the D_{3n} event.

On a regional scale, deformation and metamorphism associated with the main D_{2n} event in the central part of the Gascoyne Province was synchronous with deformation and metamorphism in the Ashburton Fold Belt and Boora Boora Zone to the north. In the Boora Boora Zone, metasedimentary rocks of the Leake Spring Metamorphics are interpreted to grade northwards into lower-grade metasedimentary rocks of the upper Wyloo Group, particularly the Ashburton Formation (Williams, 1986; Myers, 1990). In the Ashburton Fold Belt, D_{1ash} is dated to between c. 1806 and c. 1786 Ma, which occurred before the deposition of the Capricorn Group. D_{2ash} occurred between c. 1786 and c. 1738 Ma, after deposition of the Capricorn Group. Both events occurred at low- to medium-metamorphic grade, peaking during M_{1a} with the production of garnet, cordierite, and andalusite in pelitic schists. Both events are also associated with the generation of local- to regional-scale tight to isoclinal folds and associated strike-slip faults.

The spatial and temporal patterns of deformation, metamorphism, magmatism, and sedimentation, along with the geochemical and isotopic composition of the granites in the Gascoyne Province, are best explained by intracontinental reworking during the Capricorn Orogeny (Sheppard et al., 2010a,b), rather than by continental collision during the assembly of the West Australian Craton. Although the tectonic driver of the Capricorn Orogeny is unknown, it is possible that tectonism was in response to plate-margin stresses associated with the collision of the West Australian and North Australian Cratons during the 1795–1760 Ma Yapungku Orogeny.

The 1680–1620 Ma Mangaroon Orogeny

The Mangaroon Orogeny encompasses complex and progressive deformation, metamorphism, sedimentation, and granite magmatism. Structures and metamorphic assemblages related to the orogeny appear to be restricted entirely to the Mangaroon Zone in the northern part of the Gascoyne Province, although granite magmatism (the Durlacher Supersuite) and sedimentation (the Pooranoo Metamorphics) took place across the entire province.

The Pooranoo Metamorphics contain a well-defined stratigraphy consisting of a lower succession of fluvial

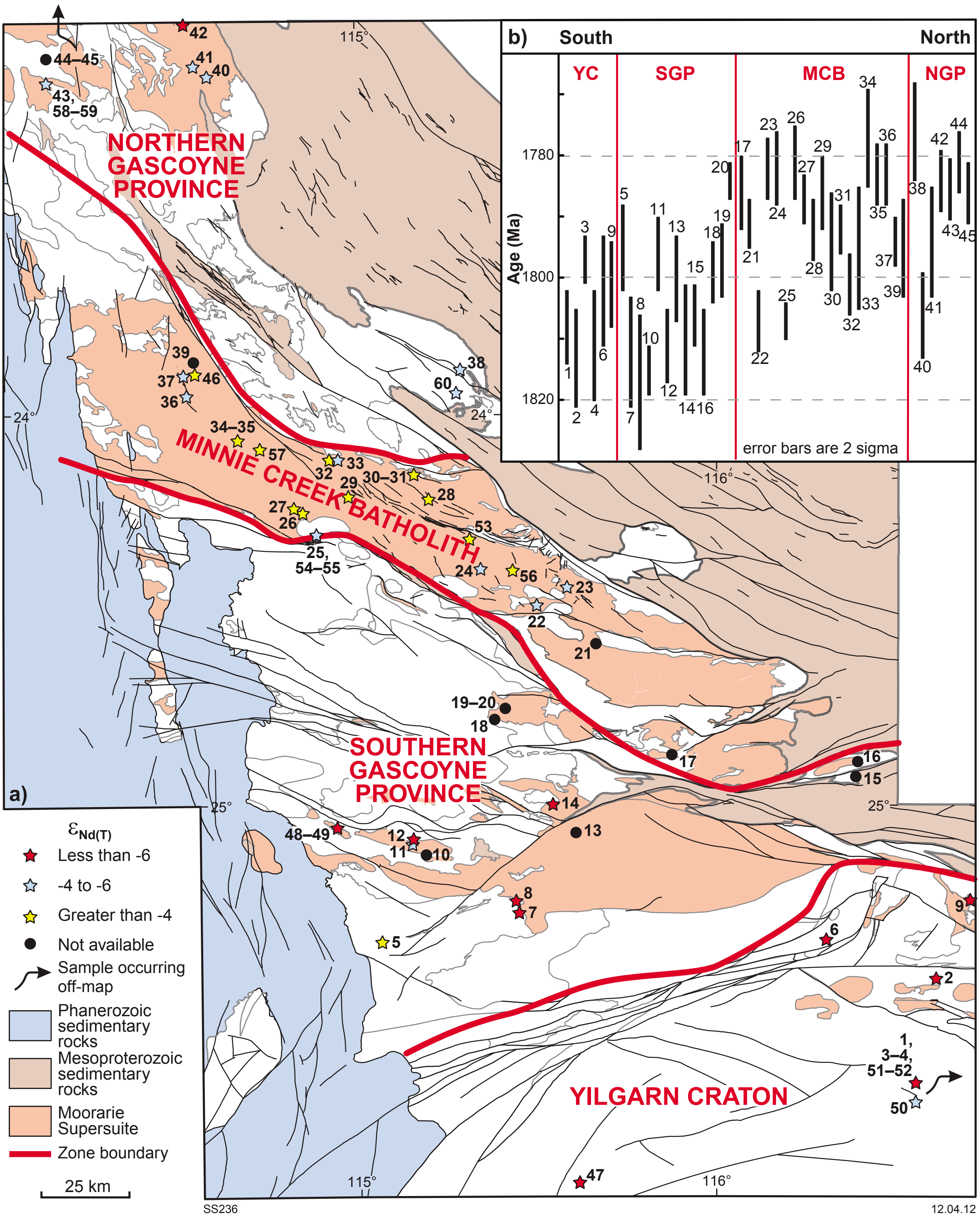

Figure 3. Summary of: (a) whole-rock Nd isotope compositions; and (b) SHRIMP U–Pb zircon ages for granites of the Moorarie Supersuite from south to north. Age data from Perring et al. (1996), Krapež and McNaughton (1999), Evans et al. (2003), and Geological Survey of Western Australia (2011). Numbers on part (a) refer to sample numbers in part (b). Key to abbreviations: YC — reworked Yilgarn Craton; SGP — southern Gascoyne Province; MCB — Minnie Creek batholith; NGP — northern Gascoyne Province.

conglomerates and sandstones up to 700 m thick, overlain by shallow-marine sandstones. This basal package is known as the Mount James Subgroup, and is present from the Errabiddy Shear Zone through to the Limejuice Zone (Frontispiece 1–3; Plate 1). In the northern part of the Limejuice Zone and throughout the Mangaroon Zone, these rocks grade upwards into turbiditic sandstones, siltstones, and shales that appear to mark a deepening of the basin to the north. SHRIMP U–Pb geochronology of detrital zircons from the Mount James Subgroup indicate that these sediments were deposited after c. 1760 Ma, but prior to deformation and the intrusion of Durlacher Supersuite granites at c. 1670 Ma. The depositional age of the turbiditic rocks in the Mangaroon Zone is well constrained by the youngest detrital zircon population at 1680 ± 13 Ma, and by granite plutons that intruded the metasedimentary rocks at 1677 ± 5 Ma (Sheppard et al., 2005), indicating a very short time-span between sedimentation, high-grade metamorphism, and granite magmatism.

In the Mangaroon Zone, deformation and metamorphism has been divided into two events (D_{1m} and D_{2m}), which were probably broadly associated with the intrusion of voluminous granite plutons of the Durlacher Supersuite. During D_{1m}, between c. 1680 and c. 1677 Ma, the Pooranoo Metamorphics were metamorphosed in the upper amphibolite facies, and characterized by the production of gneissic fabrics and extensive melting of pelitic and semipelitic rocks, although the grade of metamorphism appears to be lower in the northern half of the Mangaroon Zone where migmatites are less common. The D_{2m} event appears to have immediately followed the D_{1m} event, and was responsible for the production of a pervasive schistosity, metre- to kilometre-scale upright folds, and the retrogression of D_{1m} metamorphic minerals to greenschist-facies assemblages. Many granites of the Durlacher Supersuite with igneous crystallization ages of c. 1675 Ma or older were deformed during D_{2m}. The lack of megascopic compressional structures during the low-pressure, high-temperature metamorphism of D_{1m}, and the near-synchronous timing of basin deposition and granite intrusion, both suggest that the Mangaroon Zone was under extensional crustal regimes during this event.

After the termination of D_{1m} and D_{2m} deformation and metamorphism, granitic magmatism ceased in the Mangaroon Zone and stepped across into the other parts of the Gascoyne Province, especially the Mutherbukin Zone. Large volumes of megacrystic K-feldspar-phyric monzogranite and leucocratic tourmaline-bearing monzogranite were emplaced between c. 1670 and c. 1650 Ma, although the Discretion Granite, a pluton of granite in the Yarlarweelor Gneiss Complex, has been dated at c. 1620 Ma. Deformational structures and metamorphic assemblages associated with this younger period (1670–1620 Ma) of magmatism have yet to be identified in the Gascoyne Province. However, $^{40}Ar/^{39}Ar$ age determinations of c. 1950 Ma have been obtained on sericite from strongly cleaved metamudstones from the Earaheedy Basin in the southern part of the orogen (Pirajno et al., 2009b), and on muscovite from regional-scale extensional faults within the Sylvania Inlier along the northern margin of the orogen (Sheppard et al., 2006).

Similar to the Capricorn Orogeny, the nature, style, and timing of deformation, metamorphism, sedimentation, and granite magmatism suggest that the Mangaroon Orogeny was an intraplate event, the driver of which is currently unknown.

Mesoproterozoic sedimentation and tectonism

Following the Mangaroon Orogeny, mostly fine-grained siliciclastic sediments and carbonates were deposited, firstly in the Edmund Basin and then within the Collier Basin, both of which unconformably overlie the Gascoyne Province (Frontispiece 1; Plate 1). A detailed description of the stratigraphy and tectonic history of these basins is provided by Cutten et al. (2011).

Both the Edmund and Collier Basins were deposited as a response to the intracratonic reactivation of the Capricorn Orogen, and the sedimentation, at least in the lower part of the Edmund Group, appears to have been controlled principally by the Talga Fault (Martin and Thorne, 2004; Martin et al., 2008). However, structures or metamorphic assemblages associated with this intracratonic reactivation have yet to be identified within the Gascoyne Province. The upper part of the Edmund Basin, specifically the Ullawarra Formation, contains thin felsic tuffs dated at c. 1460 Ma (Cutten et al., 2011; Geological Survey of Western Australia, 2011), the ages of which are within uncertainty of the abundant c. 1465 Ma dolerite sills that intrude the upper parts of the basin (Wingate, 2002; Cutten et al., 2011). These dates provide a younger age limit for sedimentation, the older limit being provided by the age of Gascoyne Province basement (c. 1620 Ma), upon which the basin was unconformably deposited. The Collier Basin was deposited unconformably on both the Gascoyne Province basement and the Edmund Basin (Frontispiece 1; Plate 1), and was not affected by the 1385–1200 Ma Mutherbukin Tectonic Event, indicating deposition after c. 1200 Ma. As both the Edmund and Collier Basins were intruded by c. 1070 Ma dolerite sills of the Warakurna Large Igneous Province (Morris and Pirajno, 2002; Wingate et al., 2004), this set of sills provides a younger age limit for deposition of the Collier Basin.

The 1385–1200 Ma Mutherbukin Tectonic Event

The Mutherbukin Tectonic Event is a poorly defined tectonothermal event, known primarily from the Mutherbukin Zone in the central part of the Gascoyne Province (Johnson et al., 2011b). However, hydrothermal alteration and faulting also affected rocks of the Edmund Basin.

In the Gascoyne Province, mineral assemblages and tectonic fabrics related to the Mutherbukin Tectonic Event occur within a 50 km wide corridor, bounded by the Ti Tree and Chalba Shear Zones, lying directly south of the Minnie Creek batholith (Frontispiece 1–3; Fig. 4; Plate 1). However, discrete narrow shear zones of this age are also present within, and to the north of, the Minnie Creek batholith. The primary expression of this event is

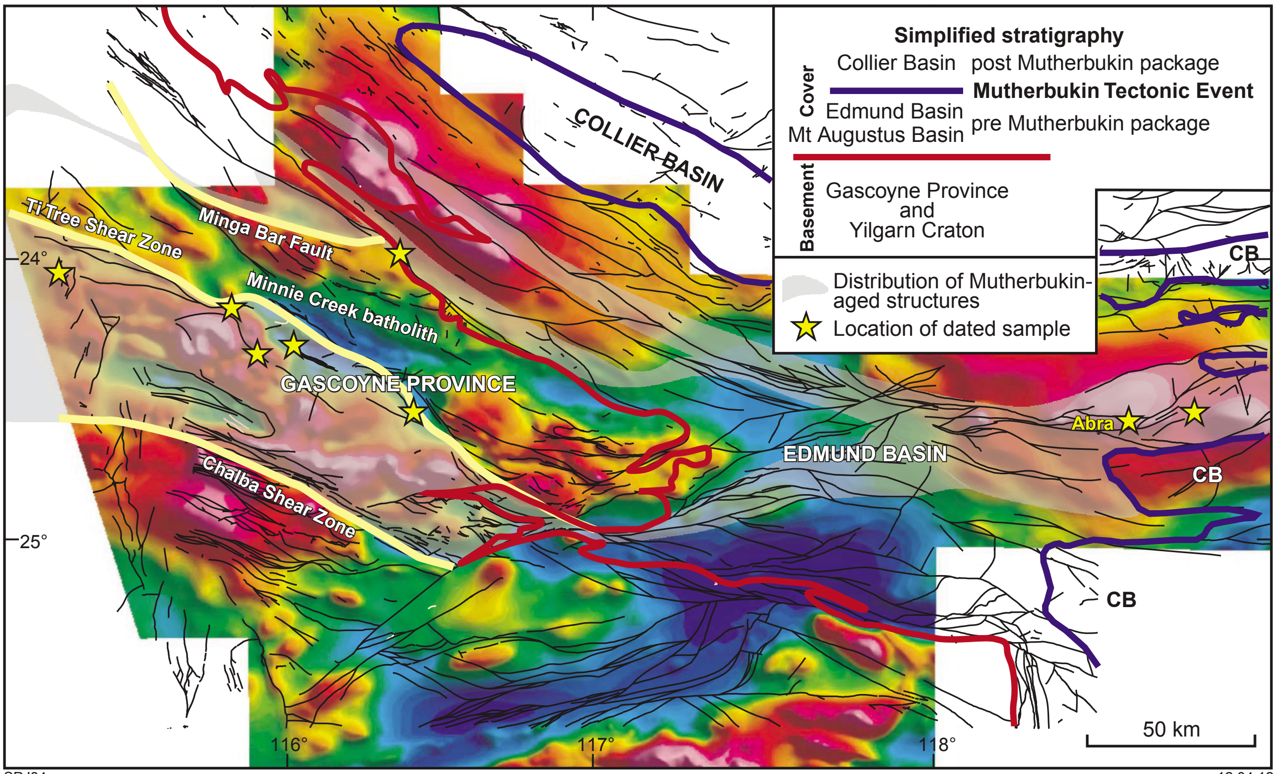

Figure 4. **Regional distribution of Mutherbukin-aged structures. The mapped 1:100 000 scale surface structures are overlain on a 2000 m upward-continuation model of 400 m line-spaced reduced-to-pole aeromagnetic data. The stratigraphy of the region has been divided into three main packages: Gascoyne Province basement, and overlying sedimentary cover rocks, with the cover rocks divided into pre-Mutherbukin (Mount Augustus and Edmund Basins) and post-Mutherbukin (Collier Basin) packages.**

a strong schistosity in the metasedimentary rocks, and a widely developed foliation or gneissic banding within metamorphosed granites. Garnet and staurolite-bearing semipelitic schists on the south side of the Minnie Creek batholith pass into upper-amphibolite facies granitic gneisses of the 1680–1620 Ma Durlacher Supersuite that are interpreted to have been emplaced in the mid crust. These gneisses locally preserve evidence for in situ melting. Both the metasedimentary rocks and gneissic granites contain a strong, shallow, east-plunging mineral lineation parallel to the hinges of decametre- to kilometre-scale, shear-related folds. Abundant shear sense indicators in both the schists and granitic gneisses reveal sinistral transtensional shear regimes. Dating of metamorphic monazite, mainly from garnet–staurolite schists, from widely spaced localities provides a range of ages between c. 1280 and c. 1200 Ma, interpreted as the age of deformation and metamorphism (Johnson et al., 2011b).

Field evidence for Mutherbukin-age deformation in the sedimentary rocks of the Edmund Group and the underlying Mount Augustus Sandstone is more cryptic, due to its very low metamorphic grade and restriction to narrow shear zones and faults that were reactivated during the 1030–955 Ma Edmundian Orogeny and c. 570 Ma Mulka Tectonic Event. However, Mutherbukin-aged hydrothermal monazite and xenotime within these sedimentary rocks indicates that they were subject to low-grade metamorphism and hydrothermal alteration during this event (Rasmussen et al., 2010; Johnson et al., 2011c). Furthermore, many faults within the Edmund Group rocks have large, sinistral, strike-slip offsets, although only small offsets are seen in rocks of the overlying Collier Group, suggesting that the main faulting event was of Mutherbukin age. This has been confirmed by the dating of authogenic illite from a fault gouge, yielding a $^{40}K/^{40}Ar$ date of 1171 ± 25 Ma (GSWA, unpublished data).

Abra is a major polymetallic lead–silver–copper–gold deposit within the lower part of the Edmund Basin, which has been interpreted as part of a hydrothermal breccia-pipe system (Pirajno et al., 2009a). The geochronology of the deposit and surrounding sedimentary host rocks is complex; however, primary mineralization, or secondary upgrading of the polymetallic ore, appears to have occurred during the Mutherbukin Tectonic Event (Rasmussen et al., 2010; Cutten et al., 2011). Irrespective of these geochronological complexities, the ages obtained from phosphate dating demonstrate that this part of the Edmund Basin underwent a prolonged period of low-grade metamorphism, hydrothermal activity, and faulting at a time when low- to medium-grade metamorphism and deformation was also affecting the underlying Gascoyne Province basement.

The Mutherbukin Tectonic Event may have been a relatively protracted intracontinental oblique strike-slip event, or series of events (1385–1200 Ma), the driver of which is currently unknown. During the event, near-continuous shearing and faulting were accompanied by regional-scale hydrothermal fluid flow. The geological, geochronological, and geophysical data demonstrate that the major Mutherbukin-aged structures in the Gascoyne Province basement extend into the overlying Edmund Basin, albeit at a much lower metamorphic and structural grade (Fig. 4). Regional-scale faulting and the transport of hydrothermal fluids from the mid to upper crust, appear to have played a critical role in the formation or upgrading of the Abra polymetallic deposit.

The 1030–955 Ma Edmundian Orogeny

The latest Mesoproterozoic to earliest Neoproterozoic Edmundian Orogeny is best known for widespread folding and low-grade metamorphism in the Edmund and Collier Basins (Martin and Thorne, 2004), although the orogeny was also responsible for reworking a southeast-striking corridor between the Chalba and Ti Tree Shear Zones in the Gascoyne Province (Frontispiece 1–3; Plate 1). Within this zone, garnet–staurolite or garnet–andalusite porphyroblasts were developed in the pelitic and semipelitic rocks of the Leake Spring Metamorphics, Pooranoo Metamorphics, and Ullawarra Formation of the Edmund Group (Frontispiece 1). In rocks of the Gascoyne Province, three events (D_{1e}, D_{2e}, and D_{3e}) have been attributed to the Edmundian Orogeny, although it is not clear how these relate to the three Edmundian Orogeny events (D_{1e}, D_{2e}, and D_{3e}) identified in the Edmund and Collier Basins (Martin and Thorne, 2004). These events were accompanied and post-dated by leucocratic granite stocks and sheets, and REE-bearing pegmatites, of the 1030–925 Ma Thirty Three Supersuite.

The first of these events in the Gascoyne Province (D_{1e}) is preserved only as inclusion trails within syn-D_{2e} metamorphic porphyroblasts. Kilometre-scale upright folds, and a crenulation schistosity that folds the earlier D_{2e} fabrics, characterize the D_{3e} event. Monazite and xenotime, which grew during amphibolite-facies metamorphism along the northern margin of the Mutherbukin Zone, have been dated at 1030–995 Ma (Sheppard et al., 2007). The older age of c. 1030 Ma is interpreted to date the timing of D_{1e}, whereas the bulk of the phosphate ages, which lie between c. 1005 and c. 995 Ma, are interpreted to date peak amphibolite-facies metamorphism during D_{2e}. Sheppard et al. (2007) estimated pressure–temperature conditions of 3–5 kbar and 500–550°C for the garnet–staurolite-bearing schists. Further south, in the central part of the Mutherbukin Zone, melt-filled pockets that developed within a c. 1665 Ma metamonzogranite cut the main gneissic fabrics associated with the Mutherbukin Tectonic Event. Metamorphic zircons (as rims around older igneous cores) extracted from these melt pockets are contemporaneous with the D_{2e} monazite and xenotime ages of c. 1000 Ma. Upright folding and a schistosity that formed during D_{3e} are only loosely constrained to between 995 and 955 Ma (Sheppard et al., 2007), the younger limit defined by an undeformed REE-bearing pegmatite that cuts the crenulation schistosity.

Porphyritic metamonzogranites, REE-bearing pegmatites, and leucocratic tourmaline-bearing granites of the 1030–925 Ma Thirty Three Supersuite were intruded during and after the Edmundian Orogeny, and are currently only known from the northern part of the Mutherbukin Zone (Frontispiece 1–3; Plate 1). The granites are typically leucocratic and locally tourmaline-rich, ranging in composition from granodiorite to monzogranite. Most of the pegmatites are composed of quartz, feldspar, and tourmaline, although some REE-rich, bismuth-bearing pegmatites are locally common. All phases of the Thirty Three Supersuite are generally zircon poor, but dating of magmatic monazite and xenotime from both the granites and pegmatites provide a wide range of ages between c. 1030 and c. 925 Ma. However, due to limited data, it is not clear whether this age range represents a single period of protracted magmatism or several discrete intrusion pulses.

The interval between 1050 and 1000 Ma is commonly thought to mark the assembly of the Rodinia supercontinent (e.g. Li et al., 2008, and references therein), of which the Australian continent may have been an integral part. Collision between the eastern margin of Australia and a partly assembled Rodinia is estimated at c. 1000 Ma (Li et al., 2008), the timing of which coincides with the growth of peak metamorphic phases during the Edmundian Orogeny. However, in all reconstructions of Rodinia (e.g. Pisarevsky et al., 2003; Li et al., 2008), the western margin of the West Australian Craton is shown to face an open ocean. If so, then the deformation and metamorphism associated with the Edmundian Orogeny may have been a response to plate reorganization and collisions elsewhere in Rodinia, since no other impinging crustal block was present to the west.

The c. 570 Ma Mulka Tectonic Event

The Mulka Tectonic Event is responsible for a series of anastomosing shear zones or faults that cut rocks of the Gascoyne Province and Edmund and Collier Groups across the southwestern part of the Capricorn Orogen (Frontispiece 1; Plate 1). This tectonic event is characterized by fault reactivation, rather than reworking. Mulka-aged faults are generally concentrated within discrete corridors such as the Chalba and Ti Tree Shear Zones (Frontispiece 1–3; Fig. 5a,b), the largest of these being the Chalba Shear Zone – Clere Fault (Frontispiece 1; Plate 1). The shear zones and faults display consistent dextral strike-slip kinematics. Most faults and shear zones range from a few centimetres to several tens of metres wide, and have dextral offsets generally in the order of 10–100 m, commonly displacing c. 755 Ma dykes of the Mundine Well Dolerite Suite (Fig. 5a). An estimate of fault offsets across the region (Fig. 5c) shows both that displacements across individual faults in these zones be as large as 1–4 km, but also that smaller-scale movements, in the order of 100–500 m, across a greater density of faults can lead to significant cumulative regional-scale displacements; e.g. up to 35 km dextral displacement across the 5–10 km wide Chalba Shear Zone (Fig. 5a,c).

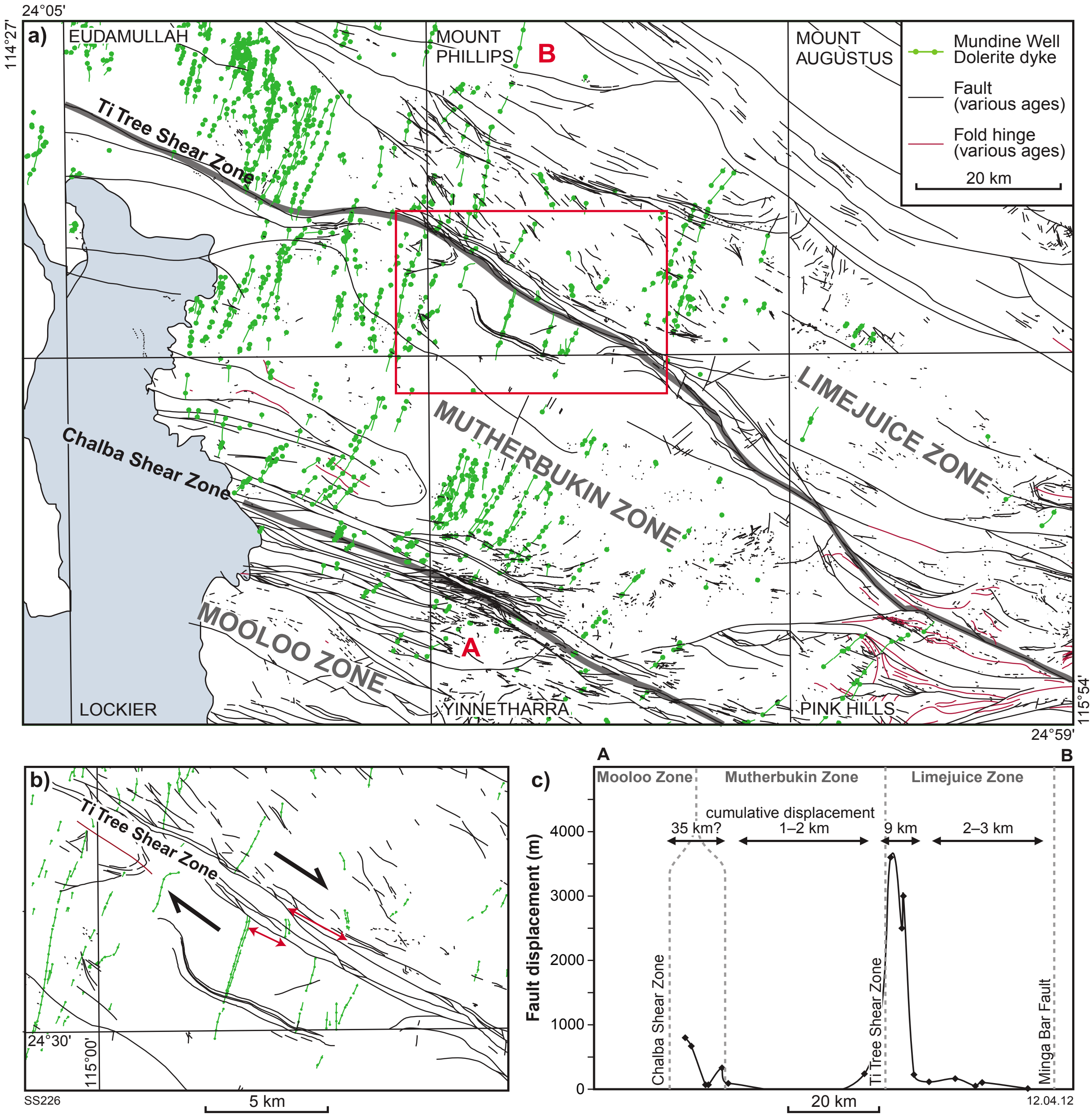

Figure 5. **a) Map of the central part of the Gascoyne Province showing Mulka-aged (c. 570 Ma) fault displacements on c. 755 Ma Mundine Well Dolerite Suite dykes. Location of enlarged map (b) is shown by the highlighted box. The location of the calculated fault offsets along A and B, as shown in graph (c), is also marked on the main map.**

White mica in the S-planes of an S–C fabric in the Chalba Shear Zone has been dated in situ using the $^{40}Ar/^{39}Ar$ method, yielding a single age of 570 ± 10 Ma (Bodorkos and Wingate, 2007). In the southern part of the province, faults belonging to the Mulka Tectonic Event appear to have been sinistrally offset by 15–20 km across a single discrete fault known as the Deadman Fault (Frontispiece 1–3; Plate 1). The age of this fault is not precisely known, but it may relate either to the late stages of the Mulka Tectonic Event, or to Phanerozoic extensional processes that accommodated the deposition of the Southern Carnarvon Basin to the west. The Mulka Tectonic Event is coeval with the Petermann, Paterson, and King Leopold Orogenies, and reflects an episode of 'pan-Gondwana' intracontinental reactivation.

Crustal architecture and fault reactivation

The different fault and shear zone bounded structural/metamorphic zones of the Gascoyne Province juxtapose rocks from various crustal levels (Fig. 6). An isostatic analysis of the regional gravity field suggests that the Gascoyne Province topography is significantly overcompensated, presumably due to intense erosion during the Mesozoic and Cenozoic (Hackney, 2004). However, various lines of geological evidence indicates that the current crustal architecture of the province is a much older, Proterozoic feature.

The Errabiddy Shear Zone and Cardilya Fault

The Errabiddy Shear Zone (Frontispiece 1–3; Plate 1) is the suture zone between the Glenburgh Terrane and the Yilgarn Craton, specifically the Narryer Terrane. Rocks in this zone were deformed and metamorphosed in the upper-amphibolite facies during the 2005–1950 Ma Glenburgh Orogeny (Occhipinti et al., 2004; Johnson et al., 2010, 2011a,d), whereas those of the Narryer Terrane were metamorphosed up to the granulite facies during the Archean. However, some of the Archean gneisses show evidence for high-grade metamorphism during the Glenburgh Orogeny (Muhling, 1986, 1988; Muhling et al., 2008). The precise dating of metamorphic monazite from high-grade rocks in the Errabiddy Shear Zone indicate that juxtaposition occurred during the collisional phase (D_{2g} at 1965–1950 Ma) of the Glenburgh Orogeny (Johnson et al., 2010, 2011a). Subsequent reworking and uplift across the Errabiddy Shear Zone is recorded by several $^{40}Ar/^{39}Ar$ mica dates between 960–820 Ma (Occhipinti, 2007).

The Cardilya Fault separates the Paradise and Mooloo Zones. The Paradise Zone contains upper amphibolite to granulite-facies gneisses of the Dalgaringa Supersuite, and the Mooloo Zone contains mid- to upper-amphibolite facies rocks of the Halfway Gneiss and Moogie Metamorphics (Frontispiece 1–3; Fig. 6; Plate 1; Johnson et al., 2010, 2011a). Rocks within the Mooloo Zone were significantly retrogressed in the greenschist facies during the 1820–1770 Ma Capricorn Orogeny, but those within the Paradise Zone were essentially unaffected (Occhipinti et al., 2004; Johnson et al., 2010; Sheppard et al., 2010b; Johnson et al., 2011a). Furthermore, during the Capricorn Orogeny, the Cardilya Fault appears to have been a conduit for the intrusion of voluminous Moorarie Supersuite granitic magmas, essentially sealing any large-scale movements on the fault. Although this fault is a principal crustal structure related to the assembly of the West Australian Craton, reactivation and uplift of upper-mid crustal rocks in the Mooloo Zone must have taken place during the Capricorn Orogeny. The truncation of c. 755 Ma aged dolerite dykes of the Mundine Well Dolerite Suite at the eastern end of the Cardilya Fault, close to where the fault is truncated by the Clere Fault (Frontispiece 1–3; Plate 1), suggests that this fault may have been partly reactivated during the c. 570 Ma Mulka Tectonic Event.

The Limejuice Zone, Ti Tree Shear Zone, and Lyons River Fault

The mapped surface geology of the Minnie Creek batholith in the Limejuice Zone indicates the presence of abundant, lower-greenschist facies grade inclusions of the 1840–1810 Ma Leake Spring Metamorphics (Frontispiece 1; Plate 1). The low to very low metamorphic grade of these inclusions demonstrates not only that the batholith was emplaced at upper crustal levels, but also that it has remained a highstand within the Gascoyne Province basement since its intrusion at c. 1800 Ma. During the 1680–1620 Ma Mangaroon Orogeny, the Lyons River, Minnie Creek, and Minga Bar Faults (Frontispiece 1–3; Plate 1) must have been active, in order to partition sedimentation, deformation, and granite magmatism to the north and into the Mangaroon Zone. Equally, the Lyons River Fault, Godfrey Fault, and Ti Tree Shear Zone must have been active during the 1385–1200 Ma Mutherbukin Tectonic Event in order to partition deformation to the north and south of the Limejuice Zone.

Since both the low-grade upper-crustal rocks of the Limejuice Zone, and the high-grade rocks of the Mangaroon Zone, are unconformably overlain by sediments of the Edmund Basin (Frontispiece 1; Plate 1), juxtaposition and exhumation must have occurred after high-grade D_{1m} metamorphism of the Mangaroon Orogeny (1680–1675 Ma), but before the deposition of the Edmund Basin at ≤1620Ma. This uplift event is recorded by the intense retrograde replacement of high-grade metamorphic minerals in diatexites of the Pooranoo Metamorphics during the 1675–1650 Ma D_{2m} event of the Mangaroon Orogeny (Sheppard et al., 2005).

Both the Minga Bar Fault and Lyons River Fault show evidence of younger reactivation. The southerly extension of the Minga Bar Fault cuts and offsets mafic dykes of the c. 755 Ma Mundine Well Dolerite Suite (Frontispiece 1–3; Plate 1), indicating that that this fault was reactivated during the c. 570 Ma Mulka Tectonic Event. The truncation of folded Edmund Group rocks by the Lyons River Fault demonstrates that this fault was reactivated during the 1385–1280 Ma Mutherbukin Tectonic Event and/or the 1030–955 Ma Edmundian Orogeny.

The Mutherbukin Zone and the Chalba Shear Zone

The Mutherbukin Zone exposes rocks of various crustal levels. Semipelitic schists of the 1840–1810 Ma Leake Spring Metamorphics and the 1760–1680 Ma Pooranoo Metamorphics (specifically the Mount James Subgroup) show a gradual increase in metamorphic grade southward, away from the Ti Tree Shear Zone (Fig. 6). These pass exclusively into the very strongly deformed plutonic rocks of the 1680–1620 Ma Durlacher Supersuite, which in the central part of the zone show evidence for in situ melting (Johnson et al., 2011b). The highest metamorphic grades attained are in the central part of the zone, which forms the core of a kilometre-scale mid-crustal extensional sheath fold (Fig. 6). Tectonometamorphism is related to the 1385–1200 Ma Mutherbukin Tectonic Event (Johnson et al., 2011b), although a narrow strip of staurolite-grade schists along the southern margin of the Ti Tree Shear Zone in the Nardoo Hills region also indicate metamorphism during the 1030–955 Ma Edmundian Orogeny (Sheppard et al., 2007).

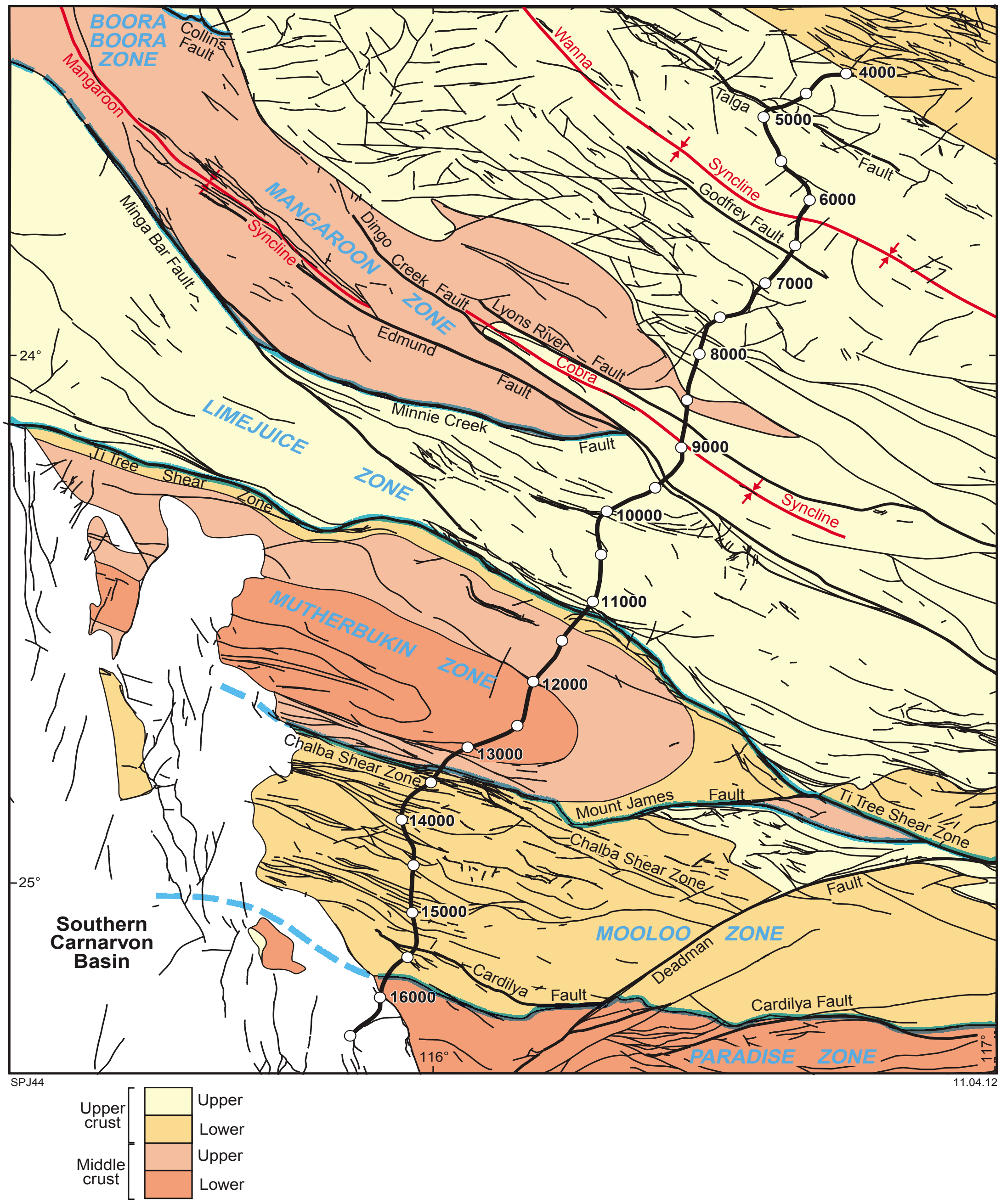

Figure 6. Schematic map of relative crustal levels across the Gascoyne Province

At depth, the Ti Tree Shear Zone has been shown to merge with the Lyons River Fault, and is interpreted to be the suture zone between the Glenburgh Terrane and Pilbara Craton (Bandee Seismic Province; Johnson et al., 2011d). This structure shows a long and punctuated history of reactivation, as shown by the tectonometamorphic history of the rocks within the Mutherbukin Zone and adjoining Limejuice Zone. The differential exhumation of these rocks presumably took place during the Mutherbukin Tectonic Event, as the structural fabrics that define the regional-scale southeast-plunging sheath fold (Fig. 6) are of this age.

The dextral offset, across the Chalba Shear Zone, of mafic dykes belonging to the c. 755 Ma Mundine Well Dolerite Suite indicates that this fault was active during the c. 570 Ma Mulka Tectonic Event. The total cumulative dextral offset across this 5–10 km wide zone is in excess of 35 km (Sheppard et al., 2010b). However, since Mutherbukin-aged tectonometamorphism has yet to be identified south of the Chalba Shear Zone, it is possible that this structure is a much older feature, reactivated during the Mulka Tectonic Event.

The Talga and Godfrey Faults

As shown by the seismic reflection data (Johnson et al., 2011d), the Talga Fault is a south-dipping structure. Its dominant listric normal character was obtained during extensional reactivation, when it formed part of a major system of half grabens facilitating the deposition of sediments into the Edmund Basin (Martin and Thorne, 2004; Martin, 2006; Cutten et al., 2011). Thus, extensional reactivation on this and other half graben-bounding faults, such as the Godfrey Fault, must have occurred shortly after uplift and juxtaposition of the rocks within the Mangaroon and Limejuice Zones; i.e. at c. 1620 Ma. Extension on these faults continued until the cessation of Edmund Basin deposition at c. 1465 Ma, implying an almost continuous period of fault activation and reactivation from the beginning of the Mangaroon Orogeny at c. 1680 Ma, through to the culmination of basin deposition at c. 1465 Ma.

Summary

The subparallel orientation, seismic character, and tectonic history of these major zone-bounding faults indicate that they are principal crustal features, such as suture zones and crustal-scale shear zones, originally related to the assembly of the West Australian Craton during the 2215–2145 Ma Ophthalmian and 2005–1950 Ma Glenburgh Orogenies. Their subsequent tectonic history is one of constant reactivation during greater than one billion years of episodic crustal reworking. These inherent crustal-scale features have facilitated the partitioning of deformation, metamorphism, magmatism, and possibly mineralization, to the point where the present-day architecture of the Gascoyne Province has ultimately been influenced by events that took place some 2200 to 1950 million years ago.

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