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Chapter 29: Irindina Province

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Chapter 29: IRINDINA PROVINCE

IR Scrimgeour

INTRODUCTION

The Irindina Province (Scrimgeour 2003, **Figure 29.1**) forms part of the Arunta Region (Mawson and Madigan 1930, Shaw *et al* 1984a, Collins and Shaw 1995), and is a highly metamorphosed Neoproterozoic to Cambrian basin that includes correlatives of the Centralian Superbasin. The province includes a thick metasedimentary succession (Harts Range Metamorphic Complex) with subordinate igneous units, including metabasalts, mafic to ultramafic intrusions, granites and pegmatites. The province outcrops extensively in the Harts Range and is also exposed as scattered low outcrops that extend to the east and southeast into the Simpson Desert, and north of the Harts Range near Mallee Bore (**Figure 29.2**). The Irindina Province has a faulted contact with the surrounding Aileron Province, and is unconformably overlain by the northern extent of the Eromanga Basin.

Until the late 1990s, rocks of the Irindina Province were thought to be Palaeoproterozoic in age (Ding and James 1985, Collins and Shaw 1995). However, detrital zircon geochronology of the Harts Range Metamorphic Complex has confirmed that the protoliths of these high-grade metasedimentary rocks were deposited in the Neoproterozoic and Cambrian rather than the Palaeoproterozoic (Buick *et al* 2005, Maidment 2005). The metasedimentary rocks contain remnant detrital grains with major populations at ca 0.5–0.7, 1.0–1.2 and 1.72–1.85 Ga, and minor populations at ca 1.35, 1.58 and 2.5 Ga, consistent with the ages of detrital zircons in similarly aged sedimentary rocks of the adjacent Amadeus and Georgina basins (Buick *et al* 2005, Maidment 2005, **Figure 29.3**). The close similarity between the detrital zircon signatures of the Harts Range Metamorphic Complex and the Amadeus and Georgina basins through time suggests that the Harts Range Metamorphic Complex includes the high-grade metamorphic equivalent of the unmetamorphosed basin successions (Buick *et al* 2005, Maidment 2005). Granulite-

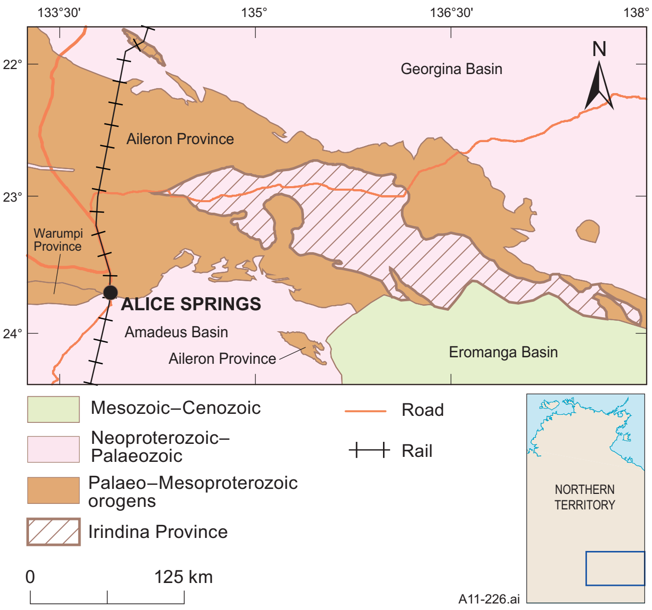

Figure 29.1. Location and geological setting of Irindina Province.

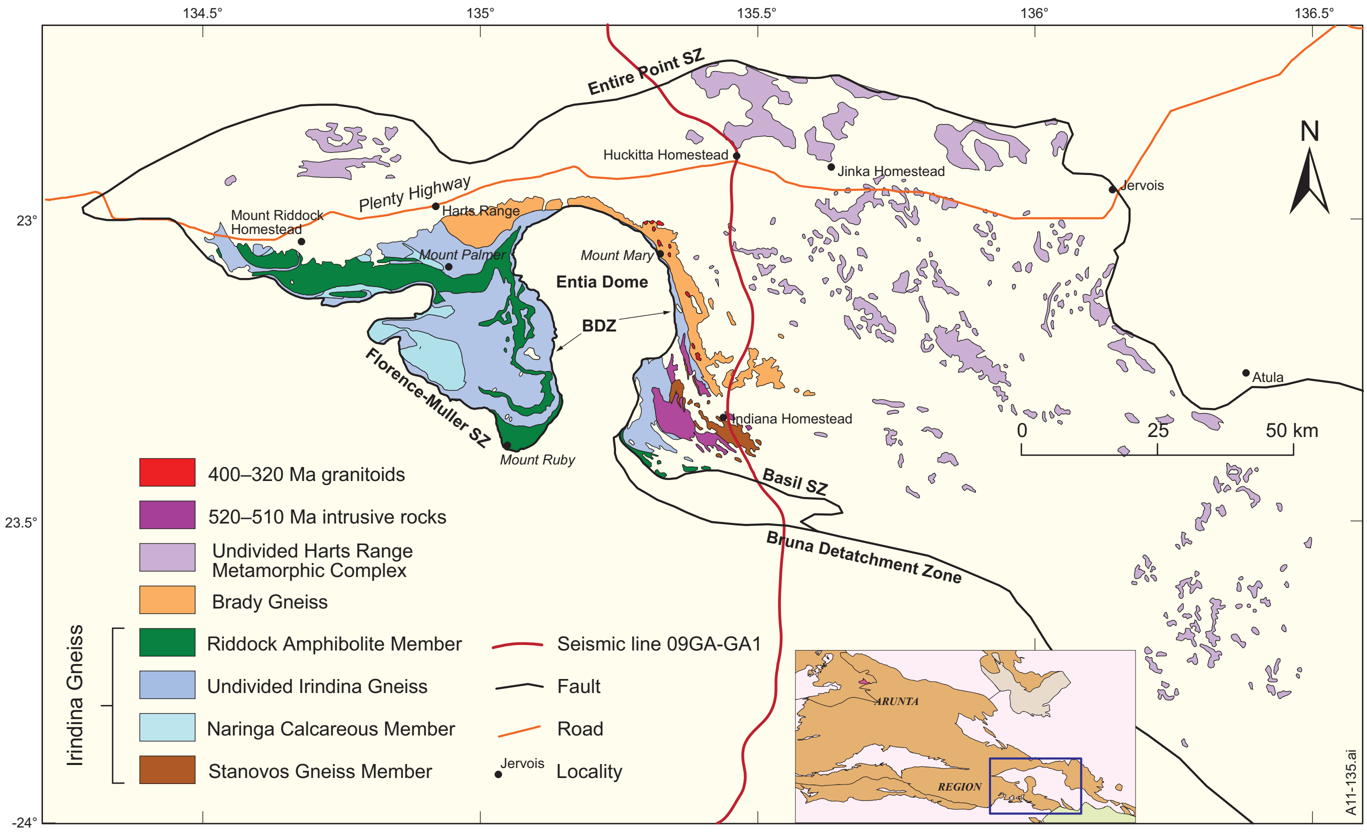

Figure 29.2. Generalised outcrop geology of Irindina Province. BDZ = Bruna Detachment Zone; SZ = Shear Zone.

to amphibolite-facies metamorphism of the Irindina Province occurred during the Ordovician Larapinta Event, and the province was exhumed during the 450–300 Ma Alice Springs Orogeny (Mawby *et al* 1999, Hand *et al* 1999a, Maidment 2005). The sedimentary precursors to the Irindina Province have been interpreted to have been deposited in an east- to southeast-trending Cambrian fault-bounded extensional basin, with metamorphism occurring as a consequence of sediment deposition at the base of an extremely deep sub-basin (Buick *et al* 2005).

A deep seismic reflection traverse (09GA-GA1) crosses the Irindina Province east of the Entia Dome, and provides information on the architecture of the province (**Figure 29.4**, Korsch *et al* 2011). It shows that in the area of the seismic traverse, the province is around 10 km thick, and occurs above a mid-crustal detachment that separates it from the structurally underlying Aileron Province. The detachment is interpreted to sole onto the Moho, and is expressed at the surface as the Bruna Detachment Zone and Basil Shear Zone, which form the southern margin of the province. Seismic data also suggest that the crust under the Irindina Province is anomalously thick (up to 60 km; Korsch *et al* 2011).

NEOPROTEROZOIC–?LATE CAMBRIAN

Harts Range Metamorphic Complex

The Harts Range Metamorphic Complex (formerly Harts Range Group; Joklik 1955a, Shaw *et al* 1982) is a supracrustal succession consisting of pelitic and psammo-pelitic metasedimentary rocks, metabasite and calc-silicate rock, with subordinate amounts of marble, quartzite and felsic gneiss. The originally defined Harts Range Group also included the Entia Gneiss and Bruna Granitic Gneiss (Joklik 1955a, Shaw *et al* 1982). However, mapping by the University of Adelaide in the 1980s recognised that the Entia Gneiss and Bruna Granitic Gneiss form 'basement', over which the remainder of the Harts Range Group (previously the 'Irindina Supracrustal Assemblage') was structurally juxtaposed (Ding and James 1985, James and Ding 1988). The Harts Range Metamorphic Complex is now considered to consist of the Irindina Gneiss (which includes the Naringa Calcareous Member, the Stanovos Gneiss Member and the Riddock Amphibolite Member) and the stratigraphically overlying Brady Gneiss (Maidment 2005). Although

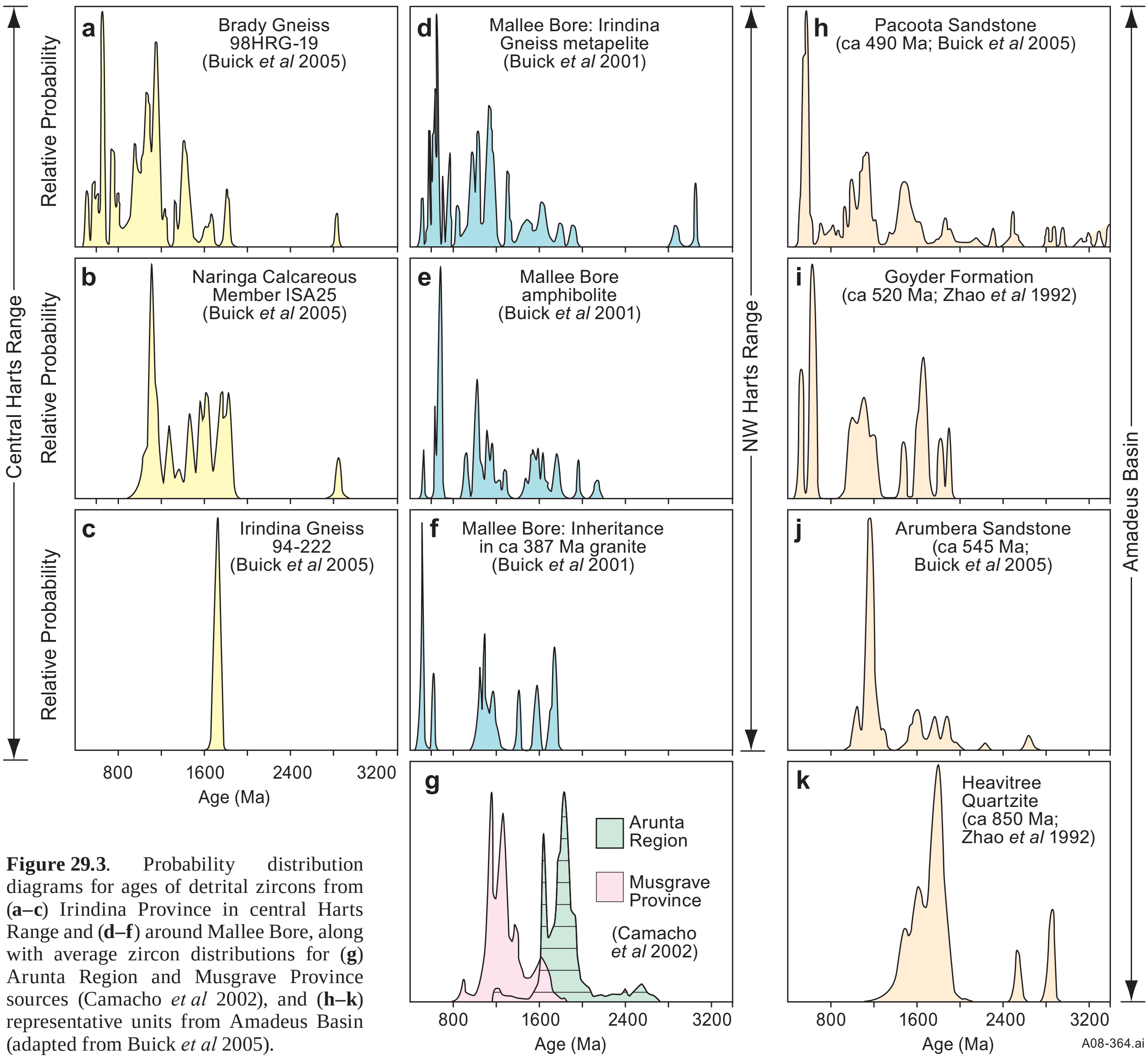

Figure 29.3. Probability distribution diagrams for ages of detrital zircons from (**a–c**) Irindina Province in central Harts Range and (**d–f**) around Mallee Bore, along with average zircon distributions for (**g**) Arunta Region and Musgrave Province sources (Camacho *et al* 2002), and (**h–k**) representative units from Amadeus Basin (adapted from Buick *et al* 2005).

the succession has undergone intense deformation, it is regionally flat-lying and Hand *et al* (1999b) interpreted that it has largely retained its initial stratigraphic order. Original stratigraphic thicknesses are difficult to determine due to multiple phases of attenuation and thickening; however, the current structural thickness of the exposed succession in the Harts Range is estimated to be up to 5–6 km (Mawby 2000). Rocks of the Harts Range Metamorphic Complex range in metamorphic grade from mid-amphibolite to granulite facies and contain a pervasive, layer-parallel amphibolite-facies foliation, interpreted to have formed during the Early Ordovician Larapinta Event (Mawby *et al* 1999).

Irindina Gneiss

The Irindina Gneiss (Shaw *et al* 1982) is dominated by a thick package of garnet- and biotite-rich psammo-pelitic schist, with localised layers of marble, calc-silicate rock and quartzite. Most of the unit remains undivided, although it also includes three named members: the Naringa Calcareous Member, the Stanovos Gneiss Member and the Riddock Amphibolite, described below.

The *undivided Irindina Gneiss* comprises a thick succession of garnet-biotite-quartz-plagioclase ± sillimanite schist, with locally interlayered marble, calc-silicate and quartzite. In areas where peak metamorphic mineral assemblages are preserved, the Irindina Gneiss is typically migmatitic, and contains coarse garnet porphyroblasts associated with felsic segregations. More commonly, the Irindina Gneiss has been strongly reworked in a planar, upper amphibolite-facies fabric that transposes and disaggregates the leucosomes, so as to form a biotite gneiss with porphyroclasts of garnet and K-feldspar (**Figure 29.5a**, **b**). Current evidence suggests that most of the Irindina Gneiss was deposited in the latest Neoproterozoic to Cambrian (Buick *et al* 2005, Maidment 2005). Detrital zircons from the basal parts of the succession are dominated by a zircon population at ca 1750 Ma, consistent with it being eroded from the 1747 ± 3 Ma Bruna Granitic Gneiss (Buick *et al* 2005, Maidment 2005). The upper parts of the succession contain detrital zircons with a wide range of ages, suggesting a more distal provenance, with a maximum depositional age of approximately 530 Ma (Buick *et al* 2005, Maidment 2005).

The *Naringa Calcareous Member* outcrops in the western Harts Range, where it structurally underlies metapelitic rocks of the Irindina Gneiss. Shaw *et al* (1979, 1984b) considered that the member occurs at a low stratigraphic level within the Irindina Gneiss, although the typically sheared contacts of this unit make its relationships uncertain. It consists of calc-silicate rock, calcareous quartzofeldspathic gneiss, marble, biotite gneiss and quartzite.

The *Stanovos Gneiss Member* outcrops in the area of Stanovos Creek, southeast of the Entia Dome, and has structural contacts with the Brady Gneiss and undivided Irindina Gneiss. The Stanovos Gneiss Member consists of two main lithological associations: (1) a calcareous lower unit consisting of quartzite, marble, calc-silicate rock and biotite gneiss, and (2) a dominantly pelitic upper unit consisting of garnet-poor biotite schist, amphibolite and quartzofeldspathic gneiss with minor psammitic rock. SHRIMP U-Pb dating of the lower unit of the Stanovos Gneiss Member by Maidment (2005) suggested that it contains no zircons younger than 1.04 Ga, with similar populations to the Heavitree Quartzite (basal Amadeus Basin) and Naringa Calcareous Member. In comparison, the upper unit has numerous Neoproterozoic zircons with a youngest age of 630 Ma (Maidment 2005). This led Maidment to suggest that the two may be separate units, and that the lower Stanovos Gneiss may be a correlative of the Naringa Calcareous Member, near the base of the Harts Range Metamorphic Complex.

Large volumes of mafic amphibolite, including the *Riddock Amphibolite Member* (Joklik 1955a, Shaw *et al* 1982) are intercalated with the Irindina Gneiss, and were included within the 'Harts Range Meta-Igneous Complex' of Ding and James (1985), Storkey *et al* (2005) and Buick *et al* (2005). It consists of variably deformed metagabbro or metadolerite, interlayered with layered, quartz-rich amphibolite, metapsammopelitic rock, and minor marble,

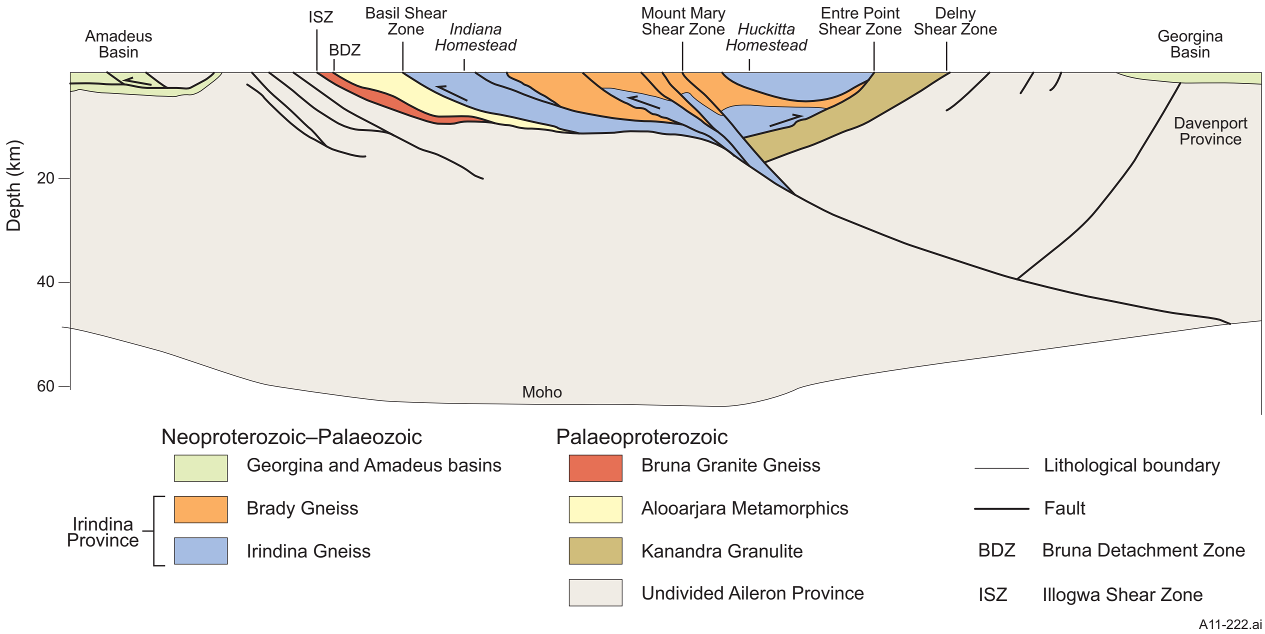

Figure 29.4. Portion of interpreted migrated seismic section for Georgina–Arunta seismic line (09GA-GA1) showing interpretation of architecture of Irindina Province (adapted from Korsch *et al* 2011). Location of seismic line is given in **Figure 29.2**.

calc-silicate rock, and quartzo-feldspathic gneiss. Peak metamorphic mineral assemblages are preserved in the large metabasite bodies of the northern Harts Range and in the southwestern Harts Range near Mount Ruby. In these areas, metabasites contain a weakly defined layer parallel fabric with coarse-grained (up to 15 cm) garnet ± clinopyroxene-bearing migmatitic segregations, interpreted to have formed by fluid-absent partial melting (Mawby *et al* 1999, Hand *et al* 1999b, Storkey *et al* 2005, **Figure 29.5c**). Whelan *et al* (2010) identified two geochemically distinct groups in the Riddock Amphibolite Member. Dominant tholeiitic metagabbroic compositions (plagioclase + clinopyroxene + amphibole + opaque oxides) are light rare-earth element (LREE) depleted and have REE patterns characteristic of normal mid-ocean ridge basalts (NMORB). In contrast, layered quartz-rich amphibolites (quartz + amphibole + minor feldspar + opaque oxides) are LREE enriched, with pronounced negative Eu anomalies, and have REE pattern characteristic of Average North Australian Felsic Crust. Juvenile isotopic signatures for both groups [ϵNd values of +6.4 to +6.9 (LREE-depleted) and +5.0 (LREE-enriched)], coupled with the geochemistry, are consistent with the Riddock Amphibolite Member being emplaced in a rift setting with very little crustal contamination (Sivell 1988, Whelan *et al* 2010). The isotopic signature of the LREE-enriched group invokes an igneous, rather than a sedimentary protolith.

SHRIMP and LA-ICPMS U-Pb dating of samples of amphibolite from the Riddock Amphibolite Member have yielded detrital zircons with maximum deposition ages of 734 ± 44 Ma (SHRIMP, Mount Riddock; Claoué-Long and Hoatson 2005), 679 ± 8 Ma (SHRIMP, Mallee Bore; Buick *et al* 2001), 599 ± 12 Ma (LA-ICPMS, LREE-enriched group; Whelan *et al* 2010) and ca 560 Ma (SHRIMP, Mount Ruby; Maidment 2005). In contrast, a sample of the LREE-depleted group yielded zircons with a LA-ICPMS U-Pb age of 447 ± 2 Ma, interpreted to be entirely metamorphic in origin (Mount Ruby; Whelan *et al* 2010). The presence of detrital zircon in amphibolites, the locally well developed compositional layering (**Figure 29.5d**) and the intimate interlayering of metasedimentary rock and metabasite has led some workers to interpret that the amphibolites were originally lava flows (Sivell and Foden 1985, Hoatson and Stewart 2001).

Brady Gneiss

The Brady Gneiss is structurally the highest member of the Harts Range Metamorphic Complex and outcrops in a belt north and east of the Entia Dome. Maidment (2005) separated the gneiss into a lower metapelitic and an upper calcareous unit. The lower unit is predominantly comprised of garnet-muscovite-biotite schist, with minor amphibolite and metapsammitic rock, and typically has a much greater density of late-stage pegmatites than the rest of the succession. The upper unit is dominated by quartz-clinozoisite-hornblende-clinopyroxene-scapolite calc-silicate rock with minor metapelitic schist. The uppermost section of the upper Brady Gneiss is a garnet-poor, migmatitic biotite-muscovite-bearing schist.

[1] Names of 1:250 000 mapsheets are shown in large capital letters eg ILLOGWA CREEK.

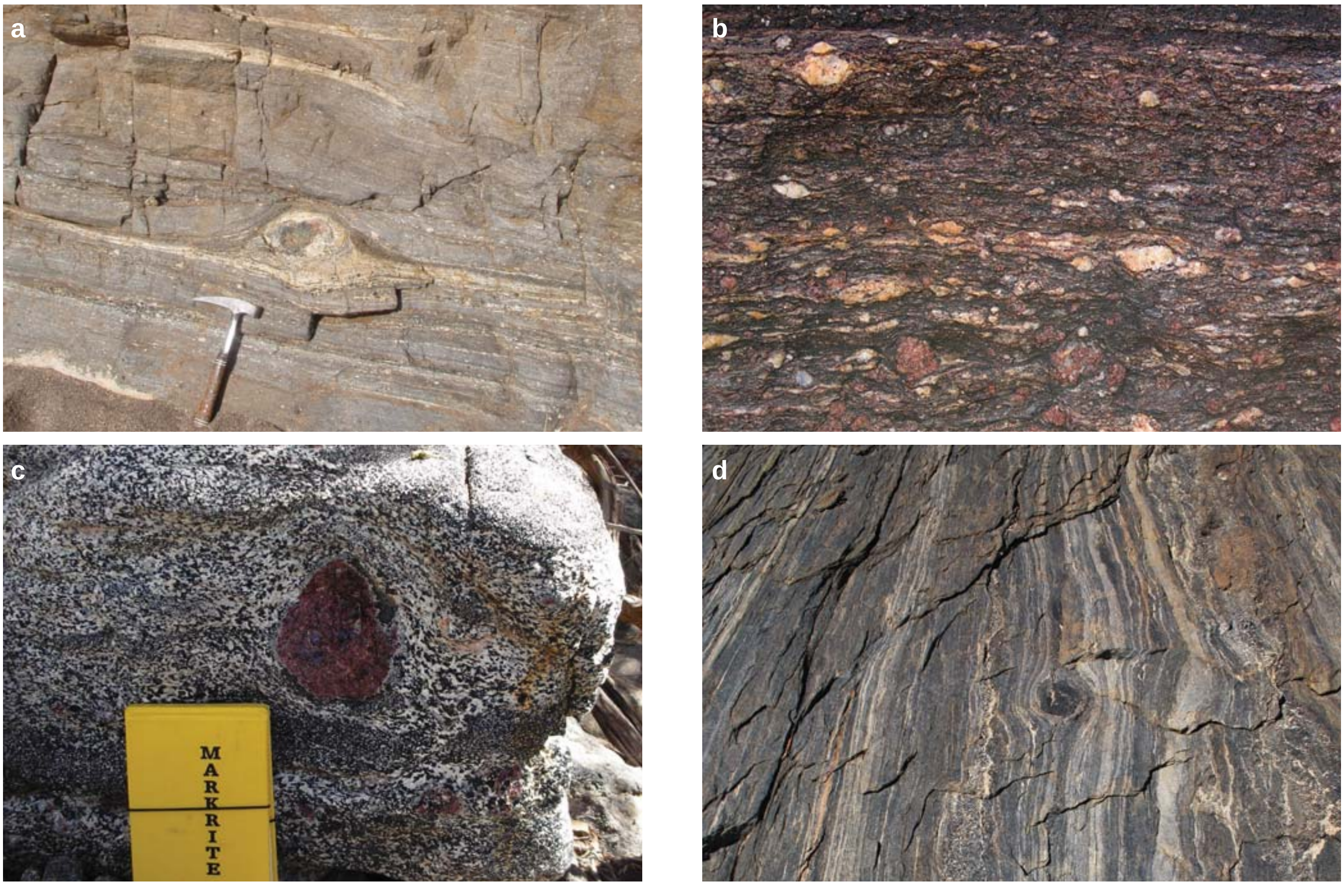

Figure 29.5. Irindina Gneiss. (**a**) Typical highly strained Irindina Gneiss with porphyroclastic K-feldspar. ILLOGWA CREEK[1], 53K 503965mE 7443703mN (**b**) Psammo-pelitic Irindina Gneiss with porphyroclastic garnet and K-feldspar. ILLOGWA CREEK, 53K 502579mE 7450100mN. (**c**) Coarse grained garnet within Riddock Amphibolite Member. ILLOGWA CREEK, location unknown. (**d**) Layered quartz-rich amphibolite, Riddock Amphibolite Member. ALICE SPRINGS, location unknown.

The metamorphic grade of the Brady Gneiss is significantly lower than that of the underlying succession, implying that there is a major structural break at its base (Hand *et al* 1999b). The top of the Brady Gneiss is not exposed. SHRIMP U-Pb dating of detrital zircons from two samples of the Brady Gneiss yielded maximum deposition ages of 509 ± 8 Ma and 499 ± 6 Ma, based on the single youngest grain (Buick *et al* 2005 and Maidment 2005, respectively), suggesting deposition in the late Cambrian.

Metasedimentary rocks east of the Harts Range

Scattered outcrops of metasedimentary rock occur over a wide area east of the Harts Range towards the Simpson Desert. These were interpreted to be part of the Harts Range Metamorphic Complex by Shaw *et al* (1982), although they did not attempt to assign them to individual lithostratigraphic units. Many of the outcrops have not been studied in detail, but are dominated by quartzite, calc-silicate rock, metapelitic rock, and relatively minor metabasite. Outcrops north and northeast of Huckitta homestead consist of migmatitic, mostly metasedimentary gneisses, dominated by biotite ± garnet-bearing gneiss, with less abundant metabasite, garnet-hornblende-biotite gneiss, garnet-biotite-sillimanite metapelitic gneiss and calc-silicate rock, and rare quartzite and marble (Scrimgeour and Raith 2001a). Metamorphic P-T conditions north of Huckitta homestead have been estimated at 8–10 kbar and 800°C, but the metamorphic grade appears to decrease to the southeast (Shaw and Freeman 1985). Detrital zircon geochronology on six samples from across this region by Maidment (2005) has confirmed that most, if not all outcrops in this area are likely to belong to the Harts Range Metamorphic Complex. Low ridges of quartzite and biotite-muscovite-garnet-sillimanite schist (p€q of Freeman 1986) in the vicinity of Jervois Homestead, ca 100 km east of the Harts Range, have a maximum deposition age of 1.04 Ga (Maidment 2005) and are likely to be stratigraphic correlatives of the lower Stanovos Gneiss and Heavitree Quartzite. An amphibolite-facies biotite-quartz-feldspar gneiss, intersected in drillhole BMR Hay River-4, beneath the Eromanga Basin, is from further southeast than any exposed rock in the Irindina Province. This rock contains monazite with a SHRIMP U-Pb age of 469 ± 2 Ma (Carson *et al* 2009), suggesting that it was metamorphosed during the 480–460 Ma Larapinta Event.

525–515 Ma INTRUSIVE ROCKS

A suite of mafic and felsic rocks (*Indiana Suite* of Whelan *et al* 2010; informally referred to as the 'Stanovos Igneous Suite' by Lawley 2005), with ages of around 520 Ma, occurs in the southeastern Harts Range around the Stanovos Valley and Indiana homestead (Maidment 2005, Lawley 2005, Whelan *et al* 2010). A prominent body of megacrystic gneissic granite, informally named the *'Indiana Walls granite'* by Maidment (2005), occurs as an ENE-dipping sheet-like body up to ca 60 m thick and at least 10 km long, along the eastern side of the Stanovos Valley in the southeastern Harts Range (**Figure 29.6**). It is a foliated, locally garnet-bearing, biotite granite with megacrysts of K-feldspar and numerous layer-parallel to weakly discordant, locally garnet-bearing leucocratic layers ranging from a few cm to 0.5 m in thickness (Maidment 2005). The unit also contains equigranular quartzo-feldspathic gneiss and feldspar-rich leucocratic gneiss. The granite has high K/Na, low Ca and is peraluminous, suggesting an S-type composition (Maidment 2005). SHRIMP U-Pb zircon dating of the granite has yielded an age of 523 ± 4 Ma (Maidment 2005). The lower margin of the granite is relatively sharp, overlying marble, calc-silicate rocks and quartzite of the Stanovos Gneiss. The upper margin is relatively indistinct and grades into biotite-rich metapelitic gneiss of the upper Stanovos Gneiss. The gradational character of the upper contact was interpreted by Maidment (2005) as evidence that the granite formed as a near-*in situ* accumulation of partial melt from the surrounding migmatitic metapelitic gneiss. This model requires a significant volume of partial melting, which has not been verified through systematic geochemical and isotopic analysis. On this basis, Maidment (2005) proposed that the granite was evidence of an extensional event involving partial melting in the middle to lower crust, which he named the Stanovos Event.

Three other ca 520 Ma granites were identified by Maidment (2005). A small body of porphyritic garnet-biotite granite, informally called the '*Dinki Di granite'* by Maidment (2005), occurs within a low-strain boudin in migmatitic biotite gneiss and amphibolite of the upper Stanovos Gneiss Member, 4 km east-southeast of Indiana Homestead. This has a SHRIMP U-Pb age of 520 ± 4 Ma, which is identical to the age of a 20 m x 50 m body of leucocratic quartzofeldspathic gneiss 2 km northeast of Rockhole Bore. An anastomosing network of granite veins intruding metabasite south of Indiana Homestead has a SHRIMP U-Pb age of 521 ± 4 Ma, providing both an age for felsic magmatism and a minimum age for the metabasite (Maidment 2005). Mafic rocks of the Indiana Suite are tholeiitic gabbros that are variably intermingled with coarse-grained, porphyritic garnet-biotite granitoids and migmatite (Lawley 2005). The gabbros are locally plagioclase-phyric and, in places, preserve primary igneous textures. Coeval mafic/felsic magmatism in the area around Mount Karinga occurred at 524 ± 8 Ma (Lawley 2005). The more mafic compositions share geochemical similarities with the ca 508 Ma Kalkarindji Suite of northern Australia

Figure 29.6. Outcrop of 525–515 Ma granite, forming 'Indiana Walls' along eastern side of Stanovos Valley, southeastern Harts Range. ILLOGWA CREEK, 53K 539510mE 7424980mN.

(Glass 2002, Lawley 2005), although ϵNd values (+0.7 to -0.7) values indicate that the Indiana Suite is more isotopically juvenile (Whelan *et al* 2010). Whelan *et al* interpreted that mafic rocks of the Indiana Suite intruded the lower levels of the basin in an extensional setting, with some crustal contamination during emplacement.

LARAPINTA EVENT (480–460 Ma)

The Ordovician Larapinta Event was the dominant metamorphic event in the Irindina Province, resulting in upper amphibolite- to granulite-facies metamorphism of the Harts Range Metamorphic Complex. The timing of this event was first defined through Sm-Nd dating by Mawby *et al* (1999) and has been confirmed through a large number of U-Pb zircon and monazite studies (Hand *et al* 1999a, Buick *et al* 2001, 2005, Maidment 2005, Carson *et al* 2009). Metamorphism and deformation coincided with deposition of the Larapinta Group in the adjacent Amadeus Basin, and for this reason, the tectonism was termed the Larapinta Event (Hand *et al* 1999a, b). The Larapinta Event can be divided into an early peak metamorphic event at 475 Ma, and a subsequent event at 460 Ma that was associated with the formation of a near-pervasive flat-lying fabric.

P-T conditions for peak metamorphism during the Larapinta Event have been estimated at 800°C and 10.5 kbar (Harts Range; Mawby *et al* 1999), >800°C and 8–12 kbar (Mallee Bore; Miller *et al* 1997, Buick *et al* 2001), 800°C and 8–10 kbar (Huckitta station; Scrimgeour and Raith 2001a) and 770°C and 10 kbar (southern Harts Range; Goscombe 2007). Metabasite that preserves peak metamorphic mineral assemblages at Mallee Bore has yielded metamorphic zircon ages of 478 ± 4 and 471 ± 7 Ma (Buick *et al* 2001); these are indistinguishable from Sm-Nd ages of 475 ± 40 and 485 ± 18 Ma for garnet-bearing peak metamorphic assemblages in the Harts Range (Mawby *et al* 1999), and for the earliest generations of zircon growth in peak metamorphic tonalitic melt from Mount Ruby (483 ± 6 Ma; Maidment 2005) and calc-silicate rock from the Brady Gneiss (479 ± 7 Ma; Maidment 2005).

Mawby *et al* (1999) proposed that the Larapinta Event was extensional, on the basis of deepening isopachs towards the eastern Arunta Region in Cambrian sedimentary rocks in surrounding basins, extensional kinematic indicators in the Harts Range Metamorphic Complex and tholeiitic mafic dykes synchronous with metamorphism. Peak metamorphic pressures during the Larapinta Event imply burial depths of 30–35 km (Mawby *et al* 1999). The mechanism for burial of these sediments to depths of >30 km has been attributed to ongoing sedimentary burial in an extremely deep, possibly transtensional sub-basin, rather than compressional tectonism (Buick *et al* 2005).

Metamorphic zircon and monazite ages of ca 460 Ma are ubiquitous within rocks containing the near-pervasive layer-parallel fabric (Hand *et al* 1999a, Buick *et al* 2001, Maidment 2005), and are interpreted as dating retrograde metamorphism during near-isothermal decompression of around 4 kbar, following peak metamorphism (Mawby *et al* 1999). This retrograde flat-lying fabric accompanied decompression in the middle to lower crust and has been interpreted to reflect extensional exhumation (Hand *et al* 1999a, Mawby *et al* 1999). However, Maidment (2005) has suggested that the 460 Ma fabric development may alternatively reflect the initiation of convergent deformation and inversion of the basin.

Although the Larapinta Event resulted in high-grade metamorphism throughout the Irindina Province, it appears to have had little or no effect in surrounding Palaeoproterozoic rocks, such as the Strangways Metamorphic Complex. This is consistent with the model of burial metamorphism in an extremely thick rift-basin, which would not have caused significant metamorphism of the rift margins (Maidment 2005).

460–400 Ma MAFIC INTRUSIVE ROCKS

The *Lloyd gabbro* (Whelan *et al* 2010) comprises a number of olivine-bearing gabbro and gabbronorite bodies that intrude the Irindina Gneiss and lower Brady Gneiss; these intrusions host the Blackadder and Baldrick Ni-Cu prospects. They are extension-related tholeiitic magmas that have high MgO contents (17 to 24 wt%) suggesting that they may represent an olivine cumulative phase, consistent with elevated Ni, Cu, Cr and Co (Whelan *et al* 2009). SHRIMP U-Pb zircon dating of the Lloyd gabbro from the Baldrick Ni-Cu prospect has yielded an emplacement age of 409 ± 9 Ma (Whelan *et al* 2010). The rocks have slightly elevated light rare earth element contents and are isotopically evolved (εNd = +0.7), consistent with crustal contamination from underlying Palaeoproterozoic crust following the juxtaposition of the Irindina and Aileron Provinces (Whelan *et al* 2010).

Meta-anorthositic gneiss (*Entire Anorthosite* of Katz 1981, Ding *et al* 1983) outcrops in the Harts Range Metamorphic Complex on the western side of the Entia Dome in the vicinity of Spriggs Creek. Geochemical data suggest that the meta-anorthosite may have been derived from a similar source to the Lloyd gabbro. It is intimately associated with anorthositic metagabbro, meta-ultramafic rock and amphibolite of the Riddock Amphibolite Member (Sivell *et al* 1985) and is semi-continuous along strike for about 20 km, reaching thicknesses of up to 50 m. Geochemical and isotopic signatures are consistent with the anorthositic gneiss having evolved from a mafic source through assimilation and fractional crystallisation (AFC) processes in an extensional setting.

ALICE SPRINGS OROGENY (450–300 Ma)

The Alice Springs Orogeny was a long-lived intraplate event that affected large regions of central Australia, particularly the Arunta Region and adjacent basins, at 450–300 Ma (Collins and Teyssier 1989, Haines *et al* 2001). The orogeny is described in more detail in **Aileron Province**, and a comprehensive summary of the relationship between the Alice Springs Orogeny and synorogenic sedimentation in central Australian basins is given by Haines *et al* (2001). The Alice Springs Orogeny includes the 450–440 Ma Rodingan Event, the Devonian Pertnjara-Brewer events, and the Carboniferous Eclipse Event. Unlike the Entia Dome, which underwent near-pervasive high-temperature deformation during the Carboniferous, deformation in the

Irindina Province during the Devonian and Carboniferous was typically restricted to discrete shear zones at lower amphibolite- or greenschist-facies conditions.

Late Ordovician (Rodingan Event)

During the Rodingan Event at 450–440 Ma, regional-scale reverse and transpressional shear zones juxtaposed the Irindina Province with the Palaeoproterozoic Aileron Province. Deformation was partitioned into south-directed thrusting in the south (Florence-Mueller Shear Zone and Bruna Detachment Zone; Mawby *et al* 1999) and sinistral strike-slip movement in the north (Entire Point Shear Zone; Scrimgeour and Raith 2001a, b).

In the Harts Range, the Irindina Province was transported southwards over the Entia Dome along the Bruna Detachment Zone (Mawby *et al* 1999; equivalent to the Harts Range Detachment Zone of James and Ding 1988). The Bruna Detachment Zone forms near flat-lying, mid- to upper amphibolite-facies, south-directed high-strain zones along the contact of the Irindina Province with the Palaeoproterozoic Bruna Granitic Gneiss, at metamorphic conditions estimated at 600–650°C and 5–6 kbar (Mawby *et al* 1999). A Sm-Nd isochron on a garnet-hornblende migmatite from the Bruna Detachment Zone has yielded an age of 449 ± 10 Ma (Mawby *et al* 1999). To the west, the Florence-Mueller Shear Zone juxtaposed the Irindina Province against the Strangways Metamorphic Complex and Bungatina Metamorphics, at similar metamorphic grades to the Bruna Detachment Zone (Hand *et al* 1999b). Immediately north of the Irindina Province, Scrimgeour and Raith (2001b) documented Late Ordovician reworking of the Kanandra Granulite within the Entire Point Shear Zone. This reworking was associated with sinistral, south-side-up transpression along steeply dipping mylonites, at conditions of 670–730°C and 6.4–7.6 kbar, associated with juxtaposition of the two provinces. SHRIMP U-Pb dating of monazite from the Entire Point Shear Zone yielded an age of 445 ± 5 Ma (Scrimgeour and Raith 2001b). This timing corresponds to the Rodingan Event, which is the first Palaeozoic compressional event identified in the Amadeus Basin (Shaw *et al* 1991).

Devonian–Carboniferous (Pertnjara-Brewer and Eclipse events)

Throughout the Devonian, the Irindina Province was within the core of an east-trending bivergent intraplate orogen, with exhumation being accommodated along major structures, including the Illogwa Shear Zone to the south and Delny Shear Zone to the north. Carboniferous tectonism in the adjacent Arunta Region during the Alice Springs Orogeny had a distinctly different structural and metamorphic style to Devonian tectonism, with a change to more northwest-trending regional structures, and the development of pervasive amphibolite-facies deformation in the Entia Dome, which structurally underlies the Irindina Province. The effects of Devonian and Carboniferous deformation within the Irindina Province (D_4 of Mawby 2000) is not well documented, and relatively few direct constraints exist on structures of this age in the province. However, in a SHRIMP U-Pb zircon and monazite study of numerous deformed and undeformed pegmatites at Brett Creek in the northern Harts Range near Atijere community, Buick *et al* (2008) determined that the youngest deformed leucogneiss has an age of 364 ± 8 Ma, whereas the oldest discordant planar pegmatite has an age of 348 ± 10 Ma. This implies that the last main phase of ductile deformation in the northern Harts Range, comprising south-directed deformation along muscovite-bearing fabrics that dip at 60–80° to the north-northeast, was at about 360 Ma. Maidment (2005) considered that west-trending ductile shear zones in the Harts Range Metamorphic Complex are overprinted by northwest-trending structures related to the development of a southwest-directed fold and thrust belt. A pegmatite that was intruded into an east-trending, steeply north-dipping shear zone in Eblana Creek, 10 km southwest of Atijere in the northern Harts Range, has a SHRIMP U-Pb zircon age of 373 ± 3 Ma (Maidment 2005), similar to the age of east–west-trending shear zones in the Strangways Range. A folded pegmatite in Huckitta Gorge, southeast of the Entia Dome, interpreted to have intruded in the late stages of southwest-directed deformation, has an age of 357 ± 4 Ma (Maidment 2005; **Figure 29.7**).

Constraints on the timing of uplift and exhumation of the Irindina Province during the Alice Springs Orogeny are provided by $^{40}Ar/^{39}Ar$ dating. $^{40}Ar/^{39}Ar$ cooling ages on hornblende from the Irindina Province suggests that large areas of the province (eg north of the Plenty Highway, and around Mount Ruby) cooled through 500°C at between 420–370 Ma (Dunlap and Teyssier 1995, Mawby 2000, Scrimgeour and Raith 2001a). $^{40}Ar/^{39}Ar$ muscovite ages of 349 ± 2 Ma in the northern Irindina Province, south of the ca 360 Ma Delny Shear Zone, suggest that the northern Irindina Province cooled through 350°C by about 350 Ma (Scrimgeour and Raith 2001a). In contrast, $^{40}Ar/^{39}Ar$ cooling ages from muscovite from the Harts Range area west of the Entia Dome suggest that exhumation and cooling through ca 350°C occurred at about 330 Ma (Mawby 2000), synchronous with high-grade metamorphism in the Entia Dome and the development of the Arltunga Nappe Complex (Dunlap and Teyssier 1995, Hand *et al* 1999a). The preservation of high-grade metamorphism of this age in the Entia Dome, suggests that uplift of the dome was one

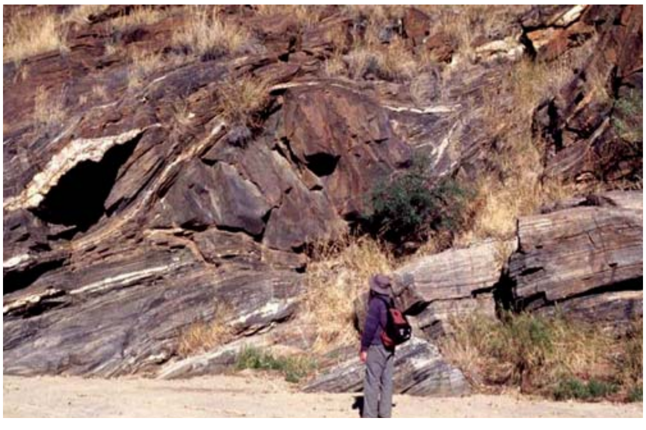

Figure 29.7. Boudinaged mafic rock within high-strain zone with southwest-directed sense of reverse movement, interpreted to have developed at or before pegmatite intrusion at ca 360 Ma. (ILLOGWA CREEK, Huckitta Gorge, 53K 536985mE 7434607mN, from Maidment 2005).

of the last events to take place in the Alice Springs Orogeny, possibly associated with extensional collapse of the orogen (Maidment 2005). Evidence exists for rapid cooling of the southeastern Arunta Region, including the Irindina Province, in the period 320–290 Ma, with temperatures decreasing to <250°C (Dunlap *et al* 1995, Mawby *et al* 1998).

SYN-ALICE SPRINGS OROGENY INTRUSIVE ROCKS

The Alice Springs Orogeny in the Irindina Province was accompanied by the emplacement of numerous pegmatites and granitoids, that are generally peraluminous (Hand *et al* 1999a, Buick *et al* 2001, 2008, Maidment 2005). These intrusions have been summarised by Buick *et al* (2008) as including larger pluton-style bodies (up to 3 x 0.5 km) and extensive planar pegmatite dyke swarms (up to 2 km long and locally 50 m wide) that are by far the most abundant granitoid type. Dating of these pegmatites and granites by numerous authors (Mortimer *et al* 1987, Cooper *et al* 1988, Hand *et al* 1999a, Buick *et al* 2001, 2008, Maidment 2005) suggest that granitoid emplacement in the Harts Range during the Alice Springs Orogeny occurred in a series of pulses. Buick *et al* (2008) has correlated these pulses with episodic metamorphic and deformational activity in the southeastern Arunta Region at ca 445 Ma, 415 Ma, 380 Ma, 360 Ma and 340–320 Ma (**Figure 29.8**). The larger pluton-style bodies include a weakly deformed, fine-grained granite that forms a plug-like intrusion (70 m long x 30 m wide) near Mallee Bore, north of the Harts Range, and a 7 m-thick body of weakly foliated, fine-grained biotite-muscovite granite that intruded the Brady Gneiss near Atijere community. These granites have SHRIMP U-Pb zircon ages of 387 ± 4 Ma (Buick *et al* 2001) and 361 ± 3 Ma (Maidment 2005), respectively.

MINERAL RESOURCES

The Irindina Province is underexplored, particularly in the poorly outcropping regions east of the Entia Dome. Most mining activity has focused on numerous small pegmatite-hosted mica deposits that were mined in the period 1926–1952, with the production of 1660 t of muscovite (Joklik 1955a, b, Shaw and Milligan 1969). Some small-scale mining of gem-quality corundum (ruby) has occurred in meta-anorthositic rocks at the *Hillrise* mine south of Mount Brady (Shaw and Freeman 1985). However, the area has significant potential for a range of commodities including mafic-hosted nickel-copper and PGE, copper and polymetallic base metals, rare-earth elements and uranium. Previous descriptions of prospects and mines in the Irindina Province were compiled by Joklik (1955a, b), Stewart and Warren (1977), Warren (1980) and Shaw and Freeman (1985). The distribution of the prospects described below is given in **Figure 29.9**.

Nickel-copper-PGE

The *Blackadder* and *Baldrick* prospects, located north of Indiana homestead, comprise nickel-copper sulfide mineralisation associated with olivine-bearing gabbro of the Lloyd gabbro that intrudes the Irindina and Brady gneisses. Initial rock chip samples at Blackadder assayed up to 3.8% Ni and 9.6% Cu, with anomalous cobalt, platinum and palladium (Mithril Resource Ltd, ASX Announcement, 15 September 2008). The prospects were drilled by Mithril Resources in 2009, with a best intersection of 9 m at 0.48% Ni and 0.3% Cu from Baldrick, including both oxide and sulfide mineralisation (Mithril Resource Ltd, ASX Announcement, 30 October 2009). Numerous mafic intrusions across the Irindina Province remain untested. The *Hammer Hill* prospect comprises an isolated hill of weathered ultramafic rock within the Harts Range Metamorphic Complex that contains anomalous nickel, chromium and cobalt, although drilling at the prospect has failed to intersect significant mineralisation.

In a study of the prospectivity of mafic rocks of the Arunta Region, Hoatson *et al* (2005) included the Riddock Amphibolite Member in their S-poor group, and considered the unit to be prospective for orthomagmatic PGE

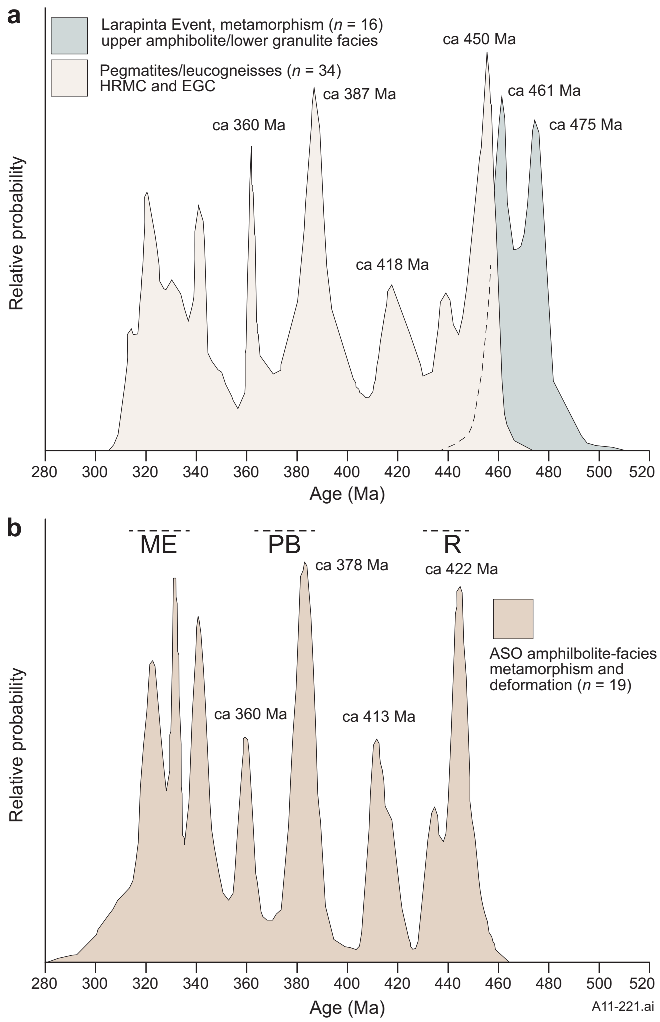

Figure 29.8. Relative probability distribution diagram for age of (**a**) emplacement of ASO-related granitic rocks and granulite-facies Larapinta Event; and (**b**) high-grade metamorphic mineral growth in eastern Arunta Region (both Irindina Province and adjacent areas of Aileron Province) during ASO, as constrained by dating of high-closure temperature minerals (U–Pb: zircon, monazite, titanite; Sm–Nd: prograde growth-zoned garnet-based isochrons). R = Rodingan Event; PB = Pertnjara-Brewer Events; ME = Eclipse Event (adapted from Buick *et al* 2008).

mineralisation, as well as stratabound and/or hydrothermal PGE mineralisation.

Copper (± cobalt, zinc)

The *Basil* copper-cobalt prospect was discovered by Mithril Resources Ltd in 2009, and comprises a 10 km-long trend of copper-bearing gossanous outcrop and hydrothermal alteration associated with a large-scale EM anomaly. Drilling of the prospect up to July 2011 yielded best intersections of 59 m at 0.63% Cu and 0.07% Co and 10.5 m at 1.02% Cu and 0.07% Co; Mithril Resources Ltd, ASX Announcements, 27 August 2010, 29 July 2011). Mineralisation is associated with massive (20–50%) and stringer sulfides comprising pyrrhotite, pyrite and chalcopyrite, within the Riddock Amphibolite Member, close to the structural contact with the Aileron Province. Additional parallel zones containing copper-bearing gossans occur at the nearly *Polly* and *Manuel* prospects.

Drilling of a number of widely spaced blind EM targets east of the Entia Dome by Mithril Resources during 2008 intersected significant sulfide mineralisation containing anomalous copper, hosted within metasedimentary rocks of the Harts Range Metamorphic Complex. Intersections from this drilling include 15 m at 0.18% Cu and 6.25 m at 0.28% Cu (Mithril Resources Ltd, ASX Announcement, 4 July 2008).

The *Selins* Cu-Zn prospect, 4.5 km south-southwest of Mount Riddock homestead, consists of atacamite, chalcanthite and malachite in anthophyllite rock, garnet-hornblende rock and calc-silicate rock. These distinctive magnesium-calcium-rich rocks occur in a unit of garnet quartzite and garnet quartzofeldspathic gneiss, hosted by the Riddock Amphibolite Member. Shaw *et al* (1984b) reported values of 0.5% Cu and 0.1% Zn from this prospect.

The *Virginia* Cu prospect, 12 km southeast of Mount Riddock homestead, consists of copper carbonate-stained garnet quartzite in association with quartzofeldspathic gneiss and migmatitic garnet-quartz-rich hornblende rock. The mineralised zone contains quartz veins and is more schistose than the surrounding Riddock Amphibolite Member (Shaw *et al* 1984b).

There are numerous other occurrences of copper in the Irindina Province. These are often associated with quartz veins, such as at the *Bruces* Cu prospect, where east-trending quartz veins contain copper and also locally contain gold (up to 53 ppm Au; Wygralak and Mernagh 2005).

Gold-tungsten

The *Tibbs* gold-tungsten-copper prospect was discovered by Mithril Resources Ltd. in 2010. Anomalous gold, tungsten and copper mineralisation occurs along an outcropping layer of ironstone and gossan interval more than 3 km in length at the contact between felsic gneiss and marble in the Irindina Gneiss. Maximum values from initial rock chip samples from the prospect include 13.6 g/t Au and 0.1% W, and 3.6 g/t Au, 0.5% W and 0.13% Cu (Mithril Resources Ltd, ASX Announcement, 8 December 2010).

Rare earth elements (REE)

REE-bearing pegmatites in the Irindina Province were first documented by Joklik (1955a) and Daly and Dyson (1956) as part of an investigation into the *Harts Range* and *Plenty River* mica fields. Samarskite occurs at the *Painted Canyon*

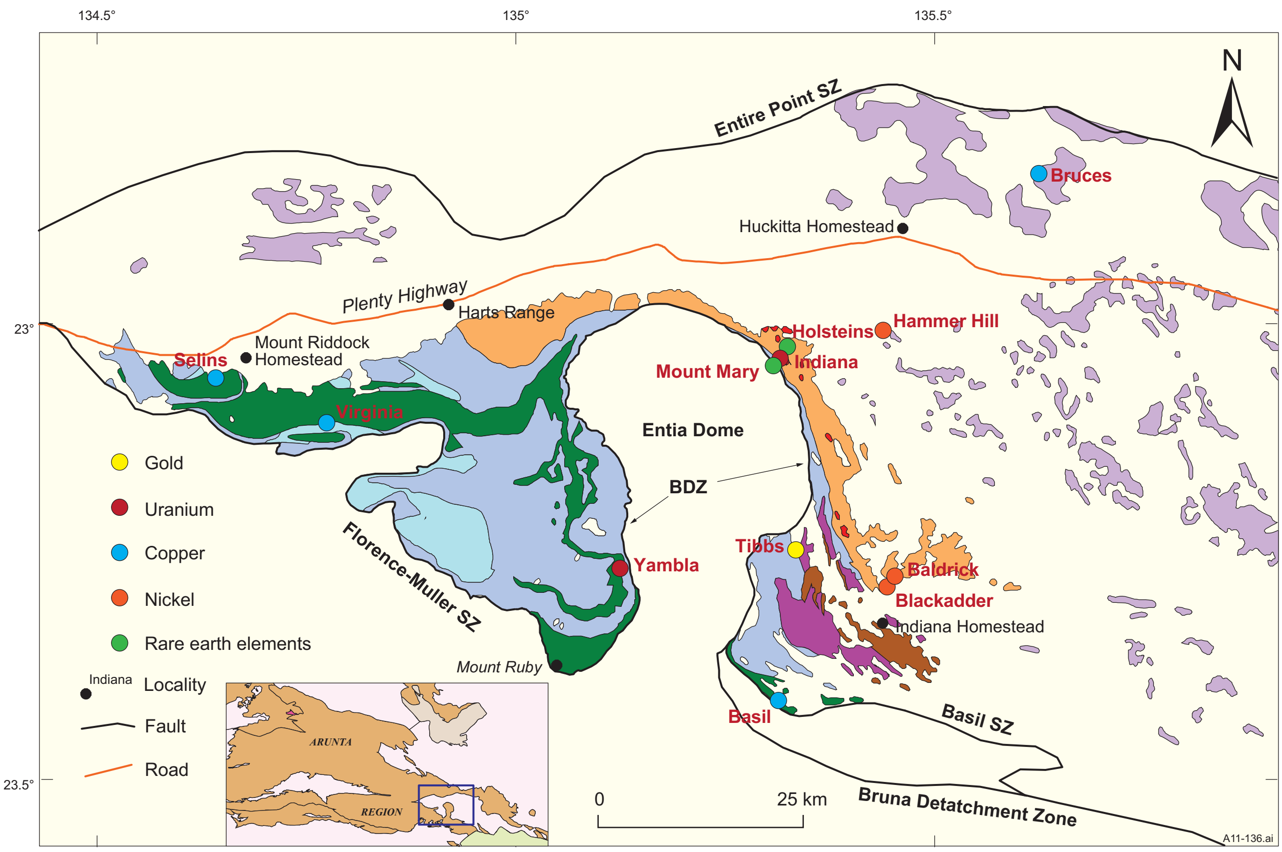

Figure 29.9. Map showing location of prospects and occurrences described in text. Abbreviations: BDZ = Bruna Detachment Zone; SZ = Shear Zone.

and *Butcher Bird* mines, and also occurs at the *Walter Smiths* mine, along with allanite. Coarse monazite crystals, some of gem quality, occur in the northern workings of the *Last Hope* mine, and at the *Marenga* and *Ciccones North* mines. These observations are consistent with work by PNC Exploration (Australia) Pty Ltd, who found these and numerous other REE phases at various prospects throughout this region (Drake-Brockman 1995, Drake-Brockman *et al* 1996a, b). Hussey (2003) considered that the presence of REE-enriched sweats and skarns surrounding all of the above REE-enriched pegmatites in the Irindina Province suggests a significant potential for REE mineralisation. The abundance of REE-rich breccia veins and calcsilicate rock units in this area suggests that there is significant potential for REE skarns or hydrothermal vein deposits. It is likely that significant REE-flushing occurred along shear zones during the Alice Springs Orogeny.

Holsteins and Mount Mary region

Drake-Brockman (1995) documented late-stage, gossanous, radioactive breccia veins cutting the Brady Gneiss, northeast of the Entia Dome. They contain chalcedony-barite-carbonate-haematite-monazite, with minor to very high REE-Th (up to 12% Ce and 7% La) residing mainly in monazite and xenotime (Drake-Brockman 1995). Matheson (1968) also reported anomalous Cd and In from this area. The fluids responsible for these occurrences appear to have been oxidised and alkaline, consistent with a fluid derived from the adjacent pegmatite swarms. Mineralisation at the Holsteins prospect is associated with elevated Ba and Fe-oxide. Given the abundant pegmatites in the area, Hussey (2003) considered it possible that a large area in the vicinity of Holsteins and Mount Mary has potential for REE.

Uranium

The Irindina Province hosts a number of uranium prospects, that are typically located close to the margins of the Entia Dome. The most significant exploration program for uranium in the Harts Range was by PNC Exploration (Australia) Pty Ltd in the 1990s (Drake-Brockman 1995, Drake-Brockman *et al* 1996b, Follington 1997). Uranium occurrences in the area occur more commonly in the Entia Dome (Aileron Province) and were divided into four types based on mineralogy: uraninite type, episodite type, retrogressed type and pegmatite type (Drake-Brockman *et al* 1996b, see **Aileron Province**). The most significant known prospect in the Irindina Province is *Yambla*, which is a uraninite-type occurrence, containing macroscopic uraninite as 1 mm- to 1 cm-sized crystals in crystalline aggregates or nodules (**Figure 29.10**), and as intergrowths with brannerite. The mineralisation is related to quartz veining within an albite-scapolite-altered fault zone in the Riddock Amphibolite Member, and has been dated at ca 350 Ma. Drilling at the prospect by PNC failed to intersect significant mineralisation (Drake-Brockman *et al* 1996b). Mineralisation at the *Indiana* prospect, immediately northeast of the Entia Dome, is associated with an outcropping pegmatite in a shear zone that extends for more than 600 m along strike, with rock chip samples up to 780 ppm U (Thor Mining, ASX Announcement, 6 March 2008).

Figure 29.10. Uranium-rich nodule, mainly composed of uraninite, from Yambla uranium prospect, Harts Range (from UXA Resources, ASX Announcement, 5 July 2010).

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