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of the Forsayth Supersuite. No chemical data are available for the Lyndbrook Complex, but two samples have U–Pb zircon (SHRIMP) ages of ~1560 Ma (M Fanning unpublished report to GSQ) and inherited zircon, suggesting previous metamorphic events at ~1595 Ma and 1620 Ma.

Unnamed granites of probable Proterozoic age are widespread through the Einasleigh Metamorphics and include leucogranite and pegmatite. These contain common screens of metamorphic rocks and grade into dyke swarms and stockworks. They were folded with the metamorphic rocks and are probably mostly syn-D_2, although SHRIMP dating indicates that some deformed granites in the Einasleigh Metamorphics are ~1690–1680 Ma and predate D_1 (Black et al. 1998; Neumann & Kositcin 2011).

2.4 Subsurface elements (PA Jell)

Several deep seismic reflection lines (Figure 2.81), collectively the Isa–Georgetown – Charters Towers seismic survey by GA and the GSQ in 2007, reveal a number of discrete geological provinces. Several of these provinces that are not evident at the surface are termed seismic provinces (Figure 2.80). Seismic line 07GA–IG1 (Henson et al. 2009; Korsch et al. 2009b) allows interpretation of several discrete provinces (Figure 2.81). The Mount Isa and Etheridge provinces, at the southwestern and northeastern ends respectively, are described above from their surface exposures. The Keer Weer Province is interpreted as the northern extension of the Mount Isa Province in the subsurface below the eastern Gulf of Carpentaria (Wellman 1992a, 1992b). The seismic data show at the northeastern end the Etheridge Province rocks extending west beneath the Croydon Province, which, on a larger crustal scale, is a relatively thin surface assemblage of volcanic units. The sedimentary Millungera Basin, just beneath the thin Mesozoic Carpentaria Basin, without any surface exposure, is described below among the sedimentary basins. The Kowanyama, Numil, Abingdon and Agwamin seismic provinces that were identified as part of this and earlier seismic surveys are not exposed at the surface and so only their geophysical characteristics are diagnostic.

Kowanyama Province: This province (Figure 2.80) contains the upper crust basement to the Carpentaria and Millungera basins in the area between the Mount Isa and Etheridge provinces, extending along the western side of Cape York to north of 12° S, and is of generally low magnetisation. The Claraville Province of Wellman (1997) is included here and is represented by the largely granitic uppermost layers as shown on the seismic profile (Korsch et al. 2009b, 2011). Dating of basement cores from this granite indicates that they are Middle Devonian (Carson et al. 2011). Some variation in the gravity and magnetic features of the province has allowed recognition of five distinctive areas that have been interpreted as representing different rock assemblages (Wellman 1997). Several drill holes penetrating the Mesozoic cover reveal that rock types in the Kowanyama Province include granites, metamorphics, and Carboniferous–Permian volcanics and granites. Based on the geophysical data and limited geochronology, this province is interpreted

Figure 2.80 Location map of northern Queensland showing Proterozoic subsurface structural Keer Weer and Kowanyama provinces.

as having been cratonised during the Barramundi Orogeny, but the Middle Devonian granite that has a thrust western margin (Korsch et al. 2009b) indicates reactivation in the Phanerozoic.

Numil Seismic Province: This province is the lower crust underlying the Kowanyama and Etheridge provinces in deep seismic profile 07GA–IG1 (Henson et al. 2009; Korsch et al. 2009b). This province is highly reflective in contrast with the less reflective Kowanyama and Etheridge provinces above. A series of low-angle structures with an apparent dip of ~20° to the southwest are interpreted as a series of linked faults extending from the surface to the Moho. The upper fault of this series leaves the surface at the western edge of the Etheridge Province and extends as a remarkably planar structure to the Moho. The upper boundary is truncated by shallow (5–20°) northeast dipping faults generally showing thrust offsets, but with an occasional extensional offset and soling onto the upper southwest dipping fault.

Abingdon Seismic Province: This province is the highly reflective lower crust underlying the Etheridge Province at the northeast end of deep seismic profile 07GA–IG1, where it is separated from the overlying Numil Seismic Province by a shallow southwest dipping structure extending into the Moho and interpreted as a fossil subduction zone (Henson et al. 2009; Korsch et al. 2009b). This province extends beneath the Etheridge Province through

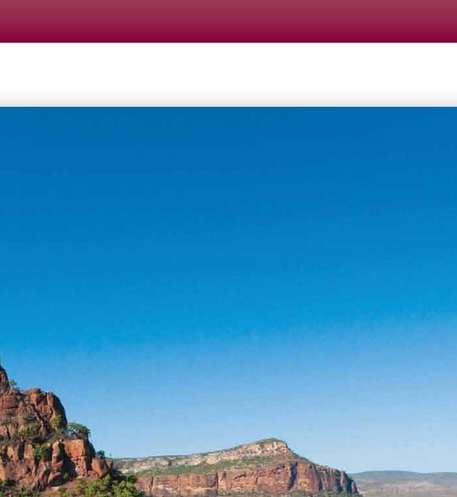


Figure 2.81 Seismic profile 07GA–IG1 showing subsurface seismic provinces. Figure 2.92 locates seismic line.

most of profile 07GA–IG2 (Hutton et al. 2009b; Korsch et al. in press) and beneath the Etheridge Province and Agwamin Seismic Province (which underlies the Greenvale Province) on profile 07GA–GC1 (Withnall et al. 2009b; Korsch et al. in press). No major structures are evident within the province and its base has strong reflectivity that terminates at the Moho. Its upper boundary (~16–21 km deep) is virtually horizontal in the north but dips to wedge out against the Moho in profile 07GA–GC1.

Agwamin Seismic Province: This province is highly reflective lower crust in the southeastern part of deep seismic profile 07GA–GC1 (Withnall et al. 2009b; Korsch et al. in press) extending beneath upper crust Greenvale Province and its extension beneath the Camel Creek Subprovince and the Charters Towers Province. There is little internal structure in the province except for some broad antiforms as part of a thrust duplex or antiformal stack and further southeast a series of deep penetrating southeast dipping faults, some of which transect the entire crust and apparently control the location of Paleozoic basins. This province may represent the Mesoproterozoic orogen inferred in this approximate position by Fergusson et al. (2007b). This province is also identified in deep seismic profile 07GA–A1 (Henderson et al. 2009; Korsch et al. in press) northeast of Georgetown.

Keer Weer Province: Along the eastern margin of the Gulf of Carpentaria is a 650 – 200 km area of strong gravity and magnetic anomalies (the Keer Weer Geophysical Domain of Wellman 1992a, 1992b). The main features are a broad gravity low and an almost coincident broad magnetic high along its length.

Wellman (1997) divided the province into five discontinuous north–south bands 20–50 km wide that are alternately gravity highs and gravity lows. Most of the magnetic anomalies are due to magnetisation in the direction of Earth's field. A few scattered near-circular anomalies 2–5 km in diameter are due to reverse magnetisation; these bodies may be Carboniferous–Permian.

The southern part of the eastern margin, with unusually low magnetisation of the rocks, exceptionally strong gravity gradients (400–600 mm s^{-1}) and strong magnetic and gravity anomalies adjacent to the west, may have been thrust eastwards. The high gravity gradient is most likely due to the western dip of the boundary of the province at depth, the low magnetisation in the east due to thermal effects of overthrusting and the high magnetisation due to higher deformation and metamorphism.

There is no direct evidence for the rock types and for an area of this size a range of possibilities is likely. The relatively high density and magnetisation may indicate metamorphic rock, mafic igneous rock, or carbonates in the east of the band, but the elongate and circular shape of anomalies is most consistent with mafic igneous rocks. There is no direct information on the age of the Keer Weer Province. Wellman (1997b) suggested possibly a similar age to the Mount Isa Province, based on apparent continuity and similar normal magnetic anomalies.

2.5 Platform cover (PA Jell)

Several sedimentary basins rest nonconformably on the North Australian Craton in Queensland. The Neoproterozoic–Ordovician Georgina Basin (Section 2.6) is the largest along the Northern Territory border, with most of the basin in the Northern Territory. This productive basin harbours major exploitable phosphate, limestone, rare earth element and potentially petroleum reserves. The other basins in this group

3.7 Subsurface elements of the Thomson Orogen (CL Fergusson)

The Thomson Orogen is widely developed below several sedimentary basins in central and southern Queensland (Figure 3.3). Numerous basement cores have been taken during petroleum exploration (Figure 3.77). These cores are the main source of information for the subsurface Thomson Orogen and have been described in detail in Murray (1994a), which forms the basis for this account (see also Murray 1997a). New U–Pb zircon (SHRIMP) ages presented by Draper (2006a) have resulted in a revised interpretation of the significance of basement rocks, especially in central Queensland. Basement cores of the Thomson Orogen are divided into three main categories: metasedimentary rocks, volcanics and granites (Murray 1994a).

3.7.1 Nebine Ridge

Basement cores taken from along the subsurface Nebine Ridge contain metasedimentary rocks ranging from phyllite to garnet schist. Bedding is typically developed and is overprinted by up to three generations of structures. Small-scale folds are preserved in bedding and cleavage. Cleavage dips at steep to moderate angles. Metamorphism ranges from lower greenschist grade with chlorite and muscovite to probable amphibolite rocks with biotite. A K–Ar age of 416 ± 2 Ma from biotite in AOP Alba 1 (Murray 1986) indicates metamorphic cooling at the Silurian–Devonian boundary, although this age may not indicate timing of the main metamorphism, as post-Ordovician K–Ar ages have also been determined from the Anakie Metamorphic Group. It is possible that these basement rocks are a southern continuation along the Nebine Ridge from the Anakie Metamorphic Group, exposed 150–400 km to the north.

3.7.2 Southwestern and northern Thomson Orogen

Murray (1994a) emphasised the remarkably uniform character of the deep basement cores west of the Nebine Ridge, which are mainly low-grade metasedimentary rocks with well-preserved clastic textures in sandstones. The metasedimentary rocks are dominantly quartzose siliciclastic sandstone and mudstone. In southwestern Queensland adjacent to the South Australian border, calcareous rocks are widespread, with sandstone and mudstone containing large proportions of carbonate; interbedded limestone is present in some cores. These rocks are included in the Warburton Basin (Figure 3.77). Bedding is typically moderately to steeply dipping and is folded in places. Variably developed cleavage/foliation is either subparallel to bedding or more steeply dipping. Most cores have lower greenschist metamorphism; upper greenschist rocks containing biotite are only found in a few widely distributed boreholes. Murray (1994a) suggested that most metasedimentary rocks of the southwestern Thomson Orogen were a probable eastward extension of the Dullingari Group, which is now considered of middle Cambrian to Middle Ordovician age (PIRSA 2007). He noted that bedrock from three holes adjacent to the Warburton Basin in South Australia had similarities to redbeds of the Early Ordovician Innamincka Formation, and they are included with this unit in Figure 3.77.

Granites are widely scattered in the basement cores and are exposed along the Eulo Ridge to the north of the New South Wales border (Figure 3.77). They include muscovite–biotite and biotite-bearing granites. U–Pb zircon ages of 428 ± 5 Ma and 469 ± 7 Ma were determined from granite in DIO Ella 1 in the southwestern Thomson Orogen and in AMX Toobrac 1 in the northern subsurface Thomson Orogen respectively (Draper 2006a).

Basement cores in the northern subsurface Thomson Orogen include silicic volcanics that were considered by Murray (1986, 1994a) to be a widespread western subsurface extension of cycle 1 volcanics of the Drummond Basin. A U–Pb zircon age of 385 ± 5 Ma was determined for rhyolitic ignimbrite from AAE Towerhill 1 but was somewhat older than the 344 Ma age of the Silver Hills Volcanics in the southern Drummond Basin adjacent to the Anakie Province (Henderson, Davis & Fanning 1998; Draper 2006a). Volcanics in the Gumbardo Formation at the base of the Adavale Basin have U–Pb zircon ages of 402 ± 2 Ma and 408 ± 4 Ma (McKillop et al. 2007). In PPC Carlow 1, the Gumbardo Formation unconformably overlies volcanics with a U–Pb zircon age of 484 ± 6 Ma. Other U–Pb zircon ages on volcanics and granite from three widely spaced wells north of the Adavale Basin have ages in the range 469–478 Ma (Draper 2006a). Thus these widely scattered age determinations are suggestive of a subsurface Early Ordovician magmatic province in central Queensland.

In GSQ Maneroo 1, the Early Ordovician rhyolite of the basal volcanic unit unconformably overlies low-grade sandstone and mudstone (Figure 3.77; Draper 2006a). The discovery of widespread Ordovician volcanics and granites in addition to the unconformity in GSQ Maneroo 1 implies that the metamorphic basement of the northern subsurface Thomson Orogen is earliest Ordovician, or older, and may be similar to the age of metamorphic basement in the Anakie and Charters Towers provinces. These ages also raise doubts about the significance of the metamorphic basement encountered in wells throughout the southwestern Thomson Orogen and Warburton Basin.

3.7.3 Roma Shelf

Many deep wells are in the Roma region, and Murray (1994a, 1997a) was able to construct a map of the basement geology (which is included in Figure 3.77). Three main units are developed: the Devonian Timbury Hills Formation, the latest Devonian – earliest Carboniferous Roma granites, and the late Carboniferous – earliest Permian Combarngo Volcanics.

The **Timbury Hills Formation** consists of turbiditic quartzose sandstone and mudstone deposited in a deep-marine environment. They are generally steeply dipping with usually a single slaty cleavage and regional low-grade metamorphism. Some rocks have higher metamorphic grade including garnet–mica schist, but it is not clear if these represent a different unit

Figure 3.77 Geological map of Queensland showing the distribution and main rock types of basement cores in the Thomson Orogen along with U–Pb zircon ages by Draper (2006a) from volcanics and granites. *Column* (top left) shows a stratigraphic log from the basal part of GSQ Maneroo 1.

association, is separated as the **Larramore Metabasalt Member**. It commonly shows greenschist facies metamorphism in the chlorite and biotite zones (Bultitude et al. 1993).

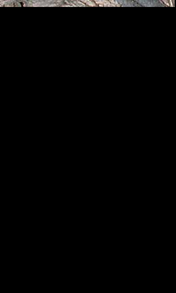
Siliciclastic rocks of the Hodgkinson Formation are universally regarded as representing turbidite facies and having been deposited in deep sea fans by gravity flow mechanisms in which turbidity flows were prominently represented. The more prominent development of amalgamated sandstone beds in the west of the Hodgkinson Province suggests that its western parts were commonly more proximal in the deep sea fan architecture and its eastern parts more distal. The representation of sedimentary clasts, including limestone, in conglomerates suggests shelf-edge collapse, or in cases where basement clasts are also represented, active erosion as coarse siliciclastics were channelled down seafloor gradients by grain flow to form a minor part of the systems. The framework grain composition of sandstones and conglomerates is consistent with a cratonic source like that of the Yambo and Coen inliers immediately west of the Hodgkinson Province.

Chert intervals represent accumulation of biogenic pelagic sediment. Limestone was mainly of shallow-marine origin and ranges from an allochthonous relationship with enclosing deep-marine siliciclastics to an autochthonous relationship with the enveloping siliciclastics (e.g. Melody Rocks, 27 km southwest of Cooktown; Donchak et al. 1992). The context of mafic rocks, apart from submarine eruption, is generally unresolved. Their typical spatial association with limestone, including local interbedding, suggests shallow-marine eruption.

Thin- to medium-bedded sandstone and mudstone in a small belt extending for ~5 km south of Mount Molloy, in the central part of the Palmer–Barron Subprovince, were assigned to the **Molloy beds** by Cranfield and Hegarty (1989), but had previously been included in the Hodgkinson Formation by deKeyser and Lucas (1968) and Gregory (1977). Deposition was interpreted by Cranfield and Hegarty (1989) to postdate the regional Late Devonian – early Carboniferous cleavage-forming event (D_2) affecting the subprovince, and on this basis the unit was inferred to be early–middle Carboniferous.

These strata are best exposed in cuttings along the main Mareeba–Cooktown road, as graded, upward fining cycles, each ~40 m thick (Cranfield 1990b). Beds are generally shallowly dipping (~15°) to subhorizontal away from the bounding faults, in contrast to subvertical strata of the remainder of the Hodgkinson Formation. In describing drill core of Molloy beds from GSQ Mossman 1, Cranfield (1990b) considered the sediments were most probably deposited in a deepwater environment by turbidity currents and that they are very similar to the finer turbidites of the Hodgkinson Formation.

Although the structural attitude and deformation history of this unit (Cranfield & Hegarty 1989; Cranfield 1990b) appear to be different to that of the adjacent Hodgkinson Formation, at


brachiopod
conodont fauna
coral fauna
plant fossil
radiolarian
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