




Geology of Queensland

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Chapter 1 Introduction

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Queensland encompasses more than 1 730 000 km^2, a very large area to be systematically explored and geologically appreciated by any reckoning. The geology of the state involves the diversity expected for a substantial segment of Australia, and represents many of the large-scale geological elements of the crustal plate that is the continent of Australia. Geological exploration of Queensland over nearly 200 years has been largely driven by the search for economic minerals by governments and private companies, assisted by university research, although the majority of the knowledge expressed in this volume is the result of systematic surveys carried out cooperatively by the Geological Survey of Queensland (GSQ) and Geoscience Australia (GA), formerly the Australian Geological Survey Organisation (AGSO) and prior to that the Bureau of Mineral Resources (BMR). Although geological maps of the entire surface of the state have been compiled, implying that all the rocks exposed on the ground have been investigated and classified, no well-informed geologist could conclude that the geology of Queensland is fully known or entirely understood. Many of the unknowns, particularly in the subsurface and submarine, and debates about rock relationships, are highlighted in the chapters that follow.

Earth resources in the form of mineral and energy commodities and water have been vital to development of the state since its inception, and will remain so for the foreseeable future. In addition to the scope for developing known resources, there is potential for future significant mineral discoveries across a range of deposit styles, particularly from exploration under shallow sedimentary and regolith cover adjacent to proven and prospective mineralised areas. New technologies, particularly in the energy sector, will advance the inventory of state resources and management for sustainability will influence the use of water.

1.1 Development of geological knowledge

Well before Europeans arrived in the continent, geological understanding of the country by Indigenous Australians was acute. This is shown, for example, by elaborate trade arrangements for stone implements from specific quarry sites (e.g. Mount Isa) across long distances (McCarthy 1939a, 1939b; McBryde 1997; Tibbett, 2002). Indigenous communities identified and valued locations where chert or fine-grained volcanic rocks suitable for flaking to make cutting tools and spear tips could be found; they also knew areas that provided softer sedimentary stone, which they used to fashion implements for grinding grass seeds into flour. They were not noted collectors of fossils (Whitehouse 1948), but distinctive rock formations and water sources commonly embody deep spiritual meaning of the land, to which Indigenous people remain tightly bound.

The earliest Europeans to take note of Queensland geology were naturalists accompanying the very earliest exploring expeditions by sea and by land. They recorded their observations—including those related to geology—of the country they crossed and made collections of the rocks they discovered. Most notable was Ludwig Leichhardt, a well-trained and able geologist and botanist, whose expedition of 1844–45 (Leichhardt 1847) from the Darling Downs to Port Essington (Darwin) brought him worldwide acclaim and provided the first geological observations of large tracts of Queensland. He had earlier made shorter exploratory trips in southern Queensland and from all his travels he maintained detailed field notes (Leichhardt 1855, English translation Ulrich 1867–68) and collected rock specimens that he catalogued and arranged in Sydney. These collections, no doubt, inspired and guided geologists who followed him.

Prior to Queensland's separation from New South Wales in 1859, the geology of the two states was investigated collectively. In the 1850s, the Reverend William Branwhite Clarke of Sydney made a geological reconnaissance into the Moreton Bay district, including the Ipswich Coal Measures and the Darling Downs, recording his observations in a letter to the Colonial Secretary of New South Wales (Legislative Assembly Papers 1853). Samuel Stutchbury, who was appointed Government Geologist for New South Wales in 1850, mapped as far north as Keppel Bay from October 1853 to the end of 1855. He conveyed his findings in a series of reports that were published in the New South Wales Legislative Assembly Papers of 1853–55, displaying his keen powers of observation, including the discovery of gold near Port Curtis. Sir Augustus Charles Gregory's Northern Australian Expedition in 1855–56, a highly successful but rarely mentioned traverse across the whole of northern Australia, made numerous geological observations, most notably in Queensland in what is now the Georgetown inlier (Gregory 1857; Gregory & Gregory 1884).

Leichhardt, Clarke and Stutchbury had all described the Ipswich Coal Measures without recognising their age distinction from the Permian Hunter Valley coals. Coal seams outcropping in the Brisbane and Bremer rivers were mined from 1843, but the country was soon gripped by gold fever following substantial discoveries in New South Wales and Victoria in 1851. Richard Daintree, who left the Geological Survey of Victoria at the end of 1864, took up a cattle property in northern Queensland and discovered the Cape River goldfield in 1865. In 1867, James Nash made the highly publicised discovery of gold at Gympie that started the major Queensland gold rush and promoted enormous interest in the geology of northeastern Australia, particularly among prospectors and fossickers, whose numbers increased dramatically. The more significant discovery of the Charters Towers goldfield was made in 1872.

These discoveries had a major effect on the development of Queensland and the state parliament was soon debating the need to hire a government geologist. Daintree wrote to the Colonial Secretary in December 1867 strongly advocating establishment of a geological survey for the colony with a decentralised approach, recognising northern and southern divisions and outlining an approximate budget. This plan was adopted in 1868 when Christopher D'Oyly Aplin and Daintree were appointed geologists for southern and northern Queensland, respectively. Although their tenures were short-lived (Aplin to the end of 1869 and Daintree to 1870), these appointments marked the inception of the GSQ and the beginning of investigations in the fledgling colony for water, minerals and energy resources. However, it would be another 80 years before a systematic survey leading to comprehensive geological maps, such as Alfred Selwyn had initiated in Victoria in 1856, was begun.

Daintree (1872) presented the first outline of Queensland geology, with a geological sketch map of the state, to the Geological Society of London. Gregory followed Aplin in 1875 and Robert Logan Jack, who had 10 years experience with the Geological Survey of Scotland, succeeded Daintree in the north in 1877. The emphasis remained firmly on exploitation of economic resources with very detailed surveys carried out on known deposits or fields of economic significance. The first high point of geological study in Queensland came in 1892 with publication of the comprehensive *Geology and palaeontology of Queensland and New Guinea* (Jack & Etheridge 1892) accompanied by a new geological map of Queensland in six sheets at a scale of 16 miles to an inch. In his preface to that edition, Jack stated his intention to include a catalogue of the state's mines and mineral occurrences, but explained that he was dissuaded from this by the magnitude of such a catalogue. However, his intention was realised in 1913 when the then

Chief Government Geologist of the GSQ, Benjamin Dunstan, published the *Queensland mineral index*—a work of 18 000 entries (probably built on Jack's initiative) including mineral references, coal analyses, water-bore data, geological maps and other relevant material. Dunstan (1902c) published a new geological map of the state (at a scale of 1 inch to 40 miles), which he revised in 1906 and again in 1908.

The GSQ's activities peaked immediately before World War I, when coal resources, oil, natural gas and base metals were investigated, detailed mapping of the major gold fields was completed and palaeontological studies were under way. The onset of the war dramatically lessened the GSQ's progress. Following the war and during the Great Depression, the emphasis was closely attuned to the needs of prospectors, and investigations into numerous mostly small mines and prospects became the main activity. Nevertheless, some regional investigations were undertaken, including that on the Bowen Basin by Reid (1929), and the GSQ contributed to the Geological Map of the Commonwealth of Australia (David 1932).

In 1923 Dunstan initiated the use of aerial photography for geological mapping in the newly discovered Mount Isa mineral field. He also pioneered geophysical prospecting in Queensland in the Roma district in the late 1920s.

The first federal regional geological agency, the Aerial Geological and Geophysical Survey of Northern Australia (AGGSNA), was formed in 1934 by the Australian Government in cooperation with Queensland and Western Australia. It focused on areas north of 20° S and, although work was concentrated around known mineral fields, an important aspect of the work was the convincing demonstration that aerial photography was an exceptionally powerful tool in rapid geological mapping. This formed the basic framework for the monumental regional geological mapping undertaken later by the federal and state governments.

Soon after World War II the Australian Government established the BMR. It incorporated the AGGSNA and expanded its view to include the entire country, largely through development of cooperative arrangements with some state geological surveys, notably Queensland and Western Australia. The BMR and the GSQ cooperated in a regional mapping program over the entire state with the exception of the southeastern corner. The joint surveys began mapping the Mount Isa inlier and parts of the Georgina Basin in 1950 and these were completed in 1954 (an amazing effort considering the geological complexity). Work in the Cairns–Townsville hinterland started in 1956 and continued through to the mid-1960s. Meanwhile, other parties continued work in the Georgina and Eromanga basins in southwestern Queensland and the Bowen and Drummond basins in central Queensland. By 1975, all of Queensland had been covered by 1 : 250 000 scale geological mapping, and a new 1 : 2 500 000 scale Queensland geology map was compiled and published by the GSQ.

This systematic mapping has been the most important factor in the state's postwar development of its resources. Completion of the 1 : 250 000 mapping provided the essential database as resource exploration swung towards uranium, petroleum, coal, nickel, phosphate, bauxite and later oil shale, while the search for base metals and gold continued.

In the late 1960s, the BMR commenced a program of remapping important mineralised regions in Queensland and the Northern Territory at 1 : 100 000 scale. Joint BMR–GSQ work in northwestern Queensland ran from 1969 to 1979. Three teams operated in the Proterozoic rocks, with a fourth in the Georgina Basin. A separate project ran at Georgetown from 1972 to 1981. This new phase of mapping used coloured aerial photographs and included a wide range of specialised studies in addition to field mapping.

In 1982, as a result of the Australian Science and Technology Council Review, the BMR withdrew from systematic geological mapping to put a greater emphasis on research and the GSQ obtained additional funding to take over the role (although the BMR participated in projects that fitted with its research emphasis). The GSQ's focus was initially in northern Queensland, carrying on from the previous joint mapping, but it gradually extended into mapping central and southern Queensland. Through the 1990s, the work was supported by airborne geophysical surveys. In 1990, the Woods Review saw the AGSO (which had replaced the BMR) return to regional studies as part of the National Geoscience Mapping Accord. The need to provide geological data for land-use investigations of Cape York (CYPLUS) led to the joint AGSO–GSQ North Queensland Project.

Since 2000, the GSQ has revised the geology of the more complex and/or prospective areas of the state using a range of remote sensing datasets, most recently in northwestern Queensland (GSQ 2011). These have resulted in seamless geological datasets and the GSQ is working towards such coverage for the whole state at a variety of scales.

In 1911, The University of Queensland established its Geology Department, headed by Henry Caselli Richards. It developed a very strong research emphasis (Thomis 1985) through staff such as Walter Heywood Bryan, Frederick William Whitehouse and later Dorothy Hill, and it trained most of the staff for the GSQ. Close cooperation between these two organisations was most evident in 1953, when the Geological Map of Queensland, at a scale of 1 inch to 40 miles, was produced by officers of the GSQ coordinated by Hill. This was a landmark publication, as it depicted the available knowledge prior to the commencement of systematic mapping.

The organisations collaborated again in 1960 when Hill and the Chief Government Geologist, Alan Knox Denmead, jointly edited the first comprehensive volume on the geology of Queensland compiled since 1892. The 1960 edition included contributions from 62 authors from the GSQ, the BMR, The University of Queensland and industry. Although it included preliminary results from the systematic mapping program, accurate age assignments were largely restricted to sedimentary rocks and based on their fossil contents.

The 1960 edition of *The geology of Queensland* was updated in 1983 by the GSQ (Day et al. 1983). It included considerably improved interpretative discussions in the light of great advances worldwide in understanding tectonic settings of rock assemblages, completion of the 1 : 250 000 scale geological mapping program and the developing techniques for isotopic dating of igneous and metamorphic rocks.

The inception of the Department of Geology in the Townsville University College (now James Cook University) in 1962 under the guidance initially of Jon Stephenson, followed by Bill Lacy, provided another rich avenue for more detailed geological knowledge and mineral resource development of northern Queensland. This was highlighted by two superb volumes on the region (Henderson & Stephenson 1980; Bain & Draper 1997), the latter drawing together the results of the joint BMR (AGSO) – GSQ research over two decades.

Since the 1970s, in addition to the work of the abovementioned organisation, staff and students from a wide range of Australian and overseas universities have carried out a body of research too large to list here. Other organisations, including various cooperative research centres (CRCs), the Commonwealth Scientific and Industrial Research Organisation (CSIRO) and the Australian Mineral Industry Research Association (AMIRA), have also contributed to research.

Mineral and energy exploration companies have, through their discoveries, contributed greatly to the Queensland economy and to geological knowledge of the state. The results of most of this exploration are preserved in reports submitted to the Queensland Government and are available online through the Queensland Digital Exploration Reports System (QDEX), maintained by the GSQ.

Advances in geochronology (deLaeter 2008) in the last 30 years have significantly improved understanding of the geological history of the state. In particular, since 1983, new isotopic techniques (principally SHRIMP) have improved dating of igneous rocks, and allowed dating of detrital zircons from sedimentary rocks, providing constraints on provenance and ages of deposition and deformation (Section 1.4.2).

1.2 Geological framework

The geological architecture of Queensland (Figure 1.1) is made up of five broad elements reflecting a sequential history of crustal development, differing tectonic associations and contrasting crustal levels at which their rock systems developed.

The first element includes Paleoproterozoic and Mesoproterozoic assemblages that represent the eastern part of the North Australian Craton and are exposed in the northwest and northeast of the state. Geophysical profiling indicates that these exposures are continuous beneath the Mesozoic Great Australian Superbasin.

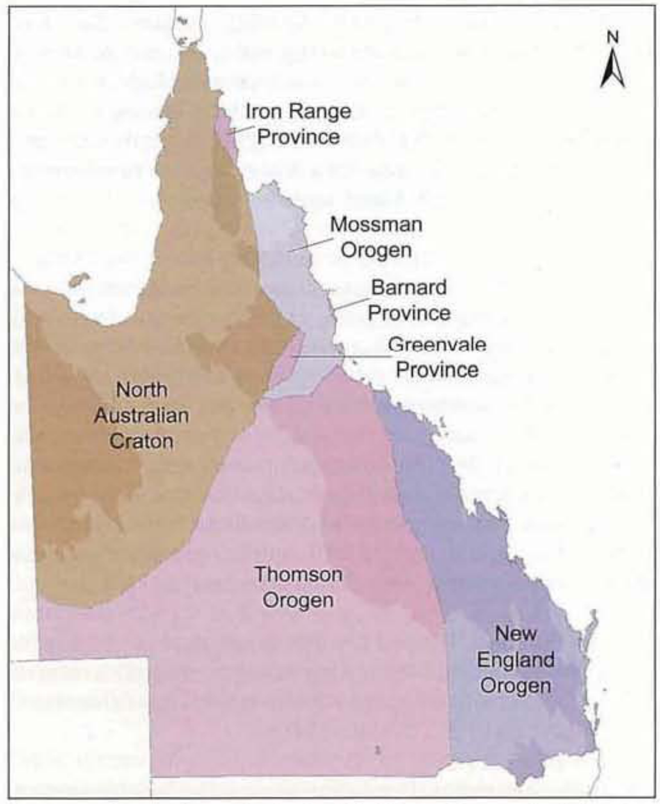

Figure 1.1 First-order geological subdivisions of Queensland showing the craton, the orogenic belts of the Tasmanides and the extent of the overlying Great Australian Superbasin (paler area).

The Neoproterozoic – early Mesozoic Tasmanides (Tasman Orogenic Zone) of eastern Australia are faulted against, or overlap, the cratonic margin to the west. Three orogenic belts of the Tasmanides are developed within Queensland and are the next three elements:

- the Neoproterozoic–Ordovician Thomson Orogen
- the Silurian–Devonian Mossman Orogen
- the New England Orogen, which is largely Carboniferous–Permian but includes some middle Paleozoic and Triassic rocks.

The fifth element includes post-tectonic basinal deposits, volcanic assemblages and widespread regolith, dominated by the Mesozoic Great Australian Superbasin, which developed on basement of deformed older rocks.

Although separation of these five elements is conceptually clear cut, their geographic distributions are overlapping and the attributes of their outlying parts may differ from those that generally apply. In particular, sedimentary basins that are coeval with, and that have their fill derived at least in part from, the Tasmanides spread extensively west of the orogenic zone *sensu stricto*. They may be little affected by deformation and in that sense may be considered post-orogenic (Figure 1.2). Similarly, rocks of the three orogenic belts do not have clear boundaries in some of the more geologically complex areas of the state.

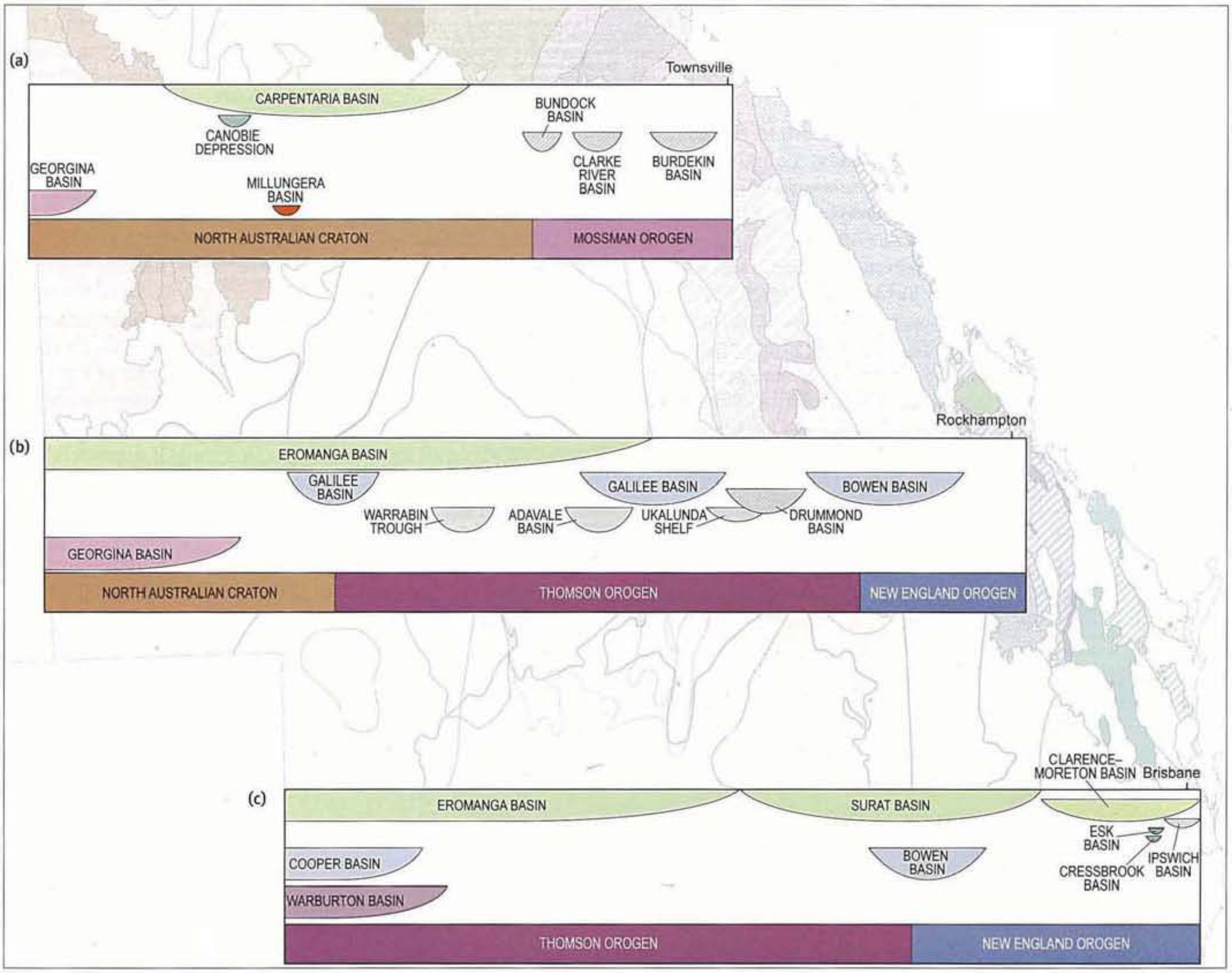

Figure 1.2 Latitudinal cross-sections of Queensland at about **(a)** Townsville, **(b)** Rockhampton and **(c)** Brisbane showing the types of basement and their relationships with overlying basins of different ages.

The five broad elements comprise the framework for this volume, but geographic context is also addressed. To facilitate regional coverage, the geographic limits of the five elements are respected here so that rock assemblages located in one broad element but associated elsewhere are considered within the element where they are situated. So, for example, Paleozoic basins above the Proterozoic craton are described within the Proterozoic section. Similarly, inliers of older orogens located within younger orogenic belts are described within sections devoted to the younger orogens, and outliers of younger orogens resting unconformably on older orogenic belts are described in the sections devoted to the older orogens.

All of the structural provinces and subprovinces outlined here and the numerous sedimentary basins (exposed and subsurface) resting on the tectonically distorted orogenic zones are assembled to define the state's structural framework (Figure 1.3).

1.2.1 North Australian Craton: Paleoproterozoic and Mesoproterozoic (Chapter 2)

Paleoproterozoic–Mesoproterozoic rocks are exposed in the northern half of Queensland as the Mount Isa Province to the west, and the Etheridge, Croydon, Savannah and Iron Range provinces in the Georgetown, Dargalong, Yambo and Coen inliers further east (Figure 2.1). They form the eastern part of the more extensive North Australian Craton (Myers et al. 1996), a discrete crustal block that was amalgamated with other microcontinents in the Paleoproterozoic to form continental Australia (Betts & Giles 2006; Cawood & Korsch 2008). The oldest dated Queensland rocks are the Kalkadoon and Ewen batholiths and coeval volcanics at ~1875–1850 Ma (Wyborn & Page 1983). Archean ages have been obtained from zircon grains in modern stream sediments from the Mount Isa (Griffin et al. 2006) and Etheridge (Murgulov et al. 2007) provinces. Archean zircon cores in meta-igneous rocks (McDonald et al. 1997) and detrital zircon grains in metasedimentary rocks as old as 3600 Ma (Bierlein et al. 2008; Neumann & Kositcin

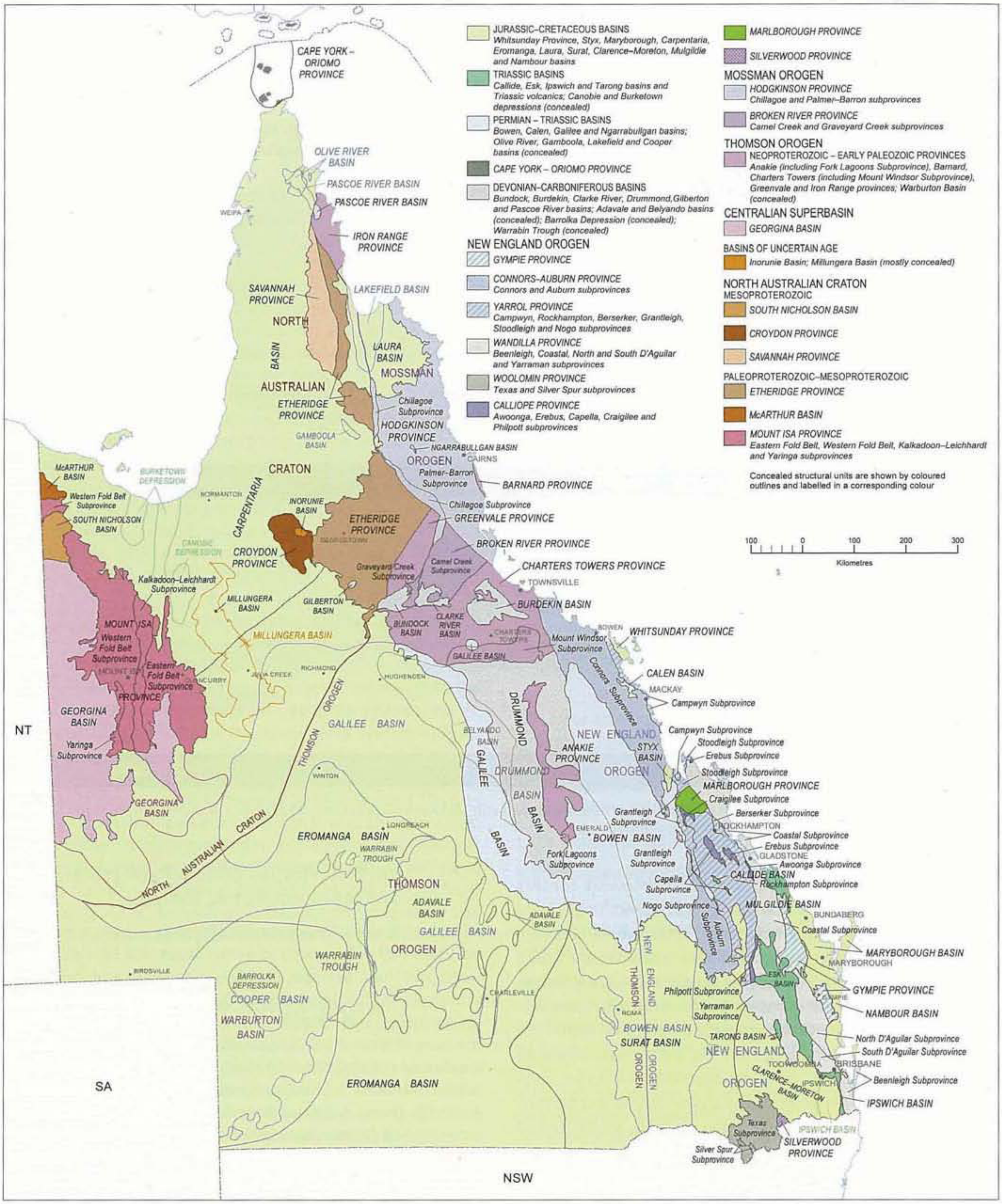

Figure 1.3 Structural framework map of Queensland showing the provinces and basins described in the text.

2011) are also known. The significance of these old mineral ages is unclear, but they may reflect deep crustal inheritance or far field provenance.

Deep seismic traversing and associated magnetotelluric data have clarified the nature of the crust across the Mount Isa and Georgetown inliers and the intervening country (Korsch et al. 2012). A crustal scale discontinuity dipping moderately to the west and located close to the eastern boundary of the Mount Isa inlier separates crust of contrasting seismic character (Figure 2.81). It is coincident with a striking magnetotelluric anomaly and also registered in magnetic and gravity spectra. It marks a suture within the fabric of the North Australian Craton. Crust to the east of this suture beneath the Great Australian Superbasin and across the Etheridge Province shows a reflective lower crustal domain as separate from a non-reflective upper crustal domain (Figure 2.81). The Etheridge Province includes mostly late Paleoproterozoic rocks at the surface, so the whole upper crustal domain is inferred to be of this age.

The lower crustal reflective domain also contains a westward dipping discontinuity, marked at the Moho by a narrow zone of crust projecting into the lithospheric upper mantle (Figure 2.81). Such structures mark crustal delamination associated with orogenic accretion during continental assembly (Hammer et al. 2010). Accordingly, these two lower crustal sectors, the Numil and Abingdon seismic provinces (Korsch et al. 2012), represent microcontinents that accreted to the eastern fringe of the North Australian Craton prior to the late Paleoproterozoic. They are likely to include the Archean crust that is the source for the mineral grains of this age known from the Mount Isa and Georgetown inliers.

Reflective lower crust extends east of the Etheridge Province, beneath the Tasmanides (Korsch et al. 2012), indicating that for northern Queensland, Precambrian crust lies beneath almost all of the surface geology.

Northwestern Queensland: Rocks of the Mount Isa Province can be divided into three subprovinces of differing character and history. Early Paleoproterozoic basement forms the Kalkadoon–Leichhardt Domain, a meridional belt dividing the younger domains that comprise the Eastern and Western fold belts (GSQ 2011) basically equated with subprovinces as used elsewhere in this volume. The precise age and context of the Kalkadoon–Leichhardt Domain remains unresolved. Its rock assemblages registered deformation and metamorphism, generally to amphibolite grade, during the Barramundi Orogeny, which was widespread in the North Australian Craton at 1900–1870 Ma (Etheridge, Rutland & Wyborn 1987; Betts et al. 2006). For the Mount Isa inlier, this episode of orogenesis reflects east–west contraction (Blake & Stewart 1992).

Protoliths of late Paleoproterozoic metasedimentary rocks of the Eastern and Western fold belts were generally marine sediments deposited during three discrete episodes of basin formation (Jackson, Scott & Rawlings 2000; Southgate et al. 2000; Betts et al. 2006). The Leichhardt Superbasin (1790–1730 Ma) is best represented in the Western Fold Belt, along the north–south Leichhardt Rift (Derrick 1982; O'Dea et al. 1997b) at the western margin of the Kalkadoon–Leichhardt Domain. Its basin fill includes the products of bimodal volcanism.

Successions of the Calvert Superbasin (1720–1670 Ma) were deposited in half-grabens formed by northwest–southeast extension. They consist largely of marine siliciclastics locally intercalated with rift-related volcanics. Successions of the Isa Superbasin (1670–1590 Ma), best represented in the Western Fold Belt, are predominantly marine siliciclastics with geometries that relate to extensional faulting. Inversion history for the Leichhardt and Calvert superbasins remains unclear but involved significant granitic plutonism. The Isan Orogeny, terminal to the basinal development, involved components of both north–south and east–west shortening strain and extensive plutonism. Although these generalisations apply to the inlier as a whole, different areas within its compass show considerable diversity, as recognised in the most recent assessment (GSQ 2011), in which 15 domains are recognised.

Rocks of the Mount Isa Province have been overprinted by regional metasomatism to an extraordinary degree. The inlier is host to globally significant base metal deposits (GSQ 2011), with some 11% of the world's Pb and Zn resources (Wallis 1998b). Stratiform Pb–Zn–Ag ore bodies are considered to be syngenetic/diagenetic in origin (McGoldrick & Large 1998; Large et al. 2005; Chapman 2004), whereas the origin of stratabound Cu and iron oxide Cu–Au deposits are thought to involve deep crustal fluids (Perkins 1984), in some cases linked to plutonism (Wang & Williams 2001).

The assembly of Proterozoic geology of northwestern Queensland includes small parts of the Paleoproterozoic McArthur Basin (Sweet et al. 1981), which is broadly correlative with the superbasin successions of the Mount Isa Province, the early Paleoproterozoic Murphy inlier (Ahmad & Wygralak 1990) and the Mesoproterozoic South Nicholson Basin (Jackson et al. 1999) extending across the Northern Territory border between Lawn Hill and the Gulf of Carpentaria. The relationship of the Mount Isa Province to other Proterozoic provinces of the North Australian Craton to the west, such as the Tennant Creek, Arunta and Tanami provinces, is impeded by expanses of Phanerozoic sedimentary cover and remains contentious (Greene 2010). However, the interpretation of late Paleoproterozoic superbasinal successions of the Mount Isa Province as backarc to a plate boundary to the east (Cawood & Korsch 2008) or south (Betts et al. 2006) is widely held.

Northeastern Queensland: Proterozoic rocks of the Georgetown, Yambo and Coen inliers have been subdivided into the Etheridge (Forsayth and Yambo subprovinces), Croydon, Savannah and Iron Range provinces (Bain & Draper 1997).

The Etheridge Province is the most extensive, comprising most of the Georgetown inlier, extending across the Yambo inlier and forming the eastern part of the Coen inlier (Bain & Draper 1997; Withnall et al. 2009b). Its southern Forsayth Subprovince is a late Paleoproterozoic (>1700–1630 Ma) marine metasedimentary succession with associated metabasalt and metadolerite. Rocks of this subprovince were multiply deformed and metamorphosed, undergoing a significant orogenic episode at 1620–1590 Ma. The deformation and metamorphism were more intense in the east where granulites developed locally. Substantial S-type granitoid plutonism occurred at 1550–1560 Ma accompanied by deformation and low pressure – high temperature metamorphism. The late Paleoproterozoic – early Mesoproterozoic Yambo Subprovince consists of multiply deformed metasedimentary and meta-igneous rocks formed after 1640 Ma that underwent high-grade, locally granulite grade metamorphism closely associated with I-type and S-type granitoid plutonism at 1560–1590 Ma.

The Croydon Province includes mainly early Mesoproterozoic silicic volcanics and related granites in the western Georgetown inlier and was little affected by deformation and metamorphism. The Savannah Province, in the western Coen inlier, includes greenschist to upper amphibolite metasediments, derived from shallow-marine protoliths and intruded by metadolerite and amphibolite. Age control for deposition in the province is poor, but is constrained by geochronology to 1560–1410 Ma.

The Iron Range Province, in the northern Coen inlier, has had only reconnaissance study. It contains a range of metasediments and metadolerite generally of greenschist grade. It is assigned as no older than Neoproterozoic based on detrital zircons dated at 1130 Ma. It is grouped here as part of the North Australian Craton because of its spatial association, but it may well represent an outlier of the Thomson Orogen, with which it appears to be broadly correlative.

The relationships and tectonic setting of Precambrian assemblages in northern Queensland remain open to debate. The broad overlap in age and similarities in sedimentary protoliths of the metasedimentary successions of the Forsayth Subprovince and the Calvert and Isa superbasins of the Mount Isa Province suggest a spatial linkage at their formation. Comparable age and style for the Isan Orogeny and the terminal orogenic episodes in the Etheridge Province (1620–1550 Ma) strengthen the view that the crustal sectors of northwestern and northern Queensland were conjoint in the late Paleoproterozoic (Cawood & Korsch 2008). However, the reverse has also been argued (Boger & Hansen 2004). The metasedimentary successions of the Etheridge Province represent one of several intracratonic volcano-sedimentary basins developed across the North Australian Craton (Betts & Giles 2006). Baker, Crawford and Withnall (2010) considered that mafic rocks of the Forsayth Subprovince have geochemical signatures typical of rift tholeiites and interpreted the metasedimentary succession with which they are associated as a passive margin assemblage. Seismic profiling (Figure 2.81) suggests that crustal accretion in northern Queensland prior to the late Paleoproterozoic involved the aggregation of three microcontinents, two of which are represented in the lower crust of the Georgetown inlier (Korsch et al. 2012).

Long after stabilisation of the Queensland sector of the North Australian Craton by Mesoproterozoic orogenesis, scattered Paleozoic intracontinental basins accumulated thin cover sequences, coeval with tectonic activity in the Tasmanides to the east. The middle Cambrian – Late Ordovician Georgina Basin that laps onto the Mount Isa Province is an extensive, little-disturbed, sedimentary basin along the Northern Territory border. Locally, Neoproterozoic strata are developed in the floor of the Georgina Basin, but their context is uncertain. The subsurface Millungera Basin to the east of the Mount Isa Province (Korsch et al. 2011) is known mostly from seismic profiling and aeromagnetic mapping and its age is unknown as initial drilling failed to recover fossils. Recent evidence suggests that it may be Mesoproterozoic. Smaller Phanerozoic basins resting on the craton include the Canobie and Burketown depressions in the Carpentaria lowlands, the offshore Bamaga Basin, the Olive River and Pascoe River basins in the Shelburne Bay hinterland on the eastern margin of the Coen inlier and the Gamboola and Gilberton basins resting on the Georgetown inlier.

1.2.2 Tasmanides: Neoproterozoic–Triassic

The Tasman Line (Hill 1951) marks the eastern outcrop limit of Proterozoic cratonic rocks (Figure 2.1) and has historically been taken as an important boundary in the crustal evolution of the Australian continent. However, its precise significance and exact position, other than in northern Queensland where it can be accurately mapped from surface outcrop, remains open to question (Direen & Crawford 2003b). Even so, the Tasman Line segregates the eastern third of Australia as the Tasmanides (Figure 2.1), part of the linear Terra Australis Orogenic System (Cawood 2005), which extends along the eastern margin of Gondwana through eastern Australia, central Antarctica (Ross Orogen), the southern tip of South Africa (Cape Fold Belt) and western South America (Andean Orogen).

The Tasmanides include several orogenic belts developed sequentially in eastern Australia between the Neoproterozoic and the Triassic in response to plate convergence that became widespread in eastern Gondwana at the margin of the Pacific Ocean at ~520 Ma. Each orogenic belt is represented by voluminous sedimentary and igneous rock assemblages, developed during changing stress regimes of extension and contraction at the eastern Gondwana continental margin. Exotic crustal elements of oceanic origin, brought in by plate convergence, form a minor part of the orogenic zone. Each orogenic belt underwent terminal contraction that separated its history from that of its successor.

The oldest orogenic belt of the Tasmanides, the Delamerian Orogen, is represented in western Tasmania, in eastern South Australia (by the Kanmantoo Trough and Adelaide Fold Belt), in the Stavely Zone of western Victoria and in the Koonenberry Belt of western New South Wales. It includes an older passive margin assemblage along the eastern Gondwana margin in response to the breakup of Rodinia ~850 Ma, and a younger assemblage related to convergence of mainly arc-related volcanics and granitoids (Glen 2005). Its terminal deformation was middle–late Cambrian, 514–490 Ma (Foden et al. 2006). Although southward continuation of the Delamerian Orogen as the Ross Orogen of East Antarctica is well established, its continuation north into Queensland is obscure. Poorly known Neoproterozoic sedimentary rocks unconformable beneath middle Cambrian strata of the Georgina Basin in western Queensland may relate to this orogenic belt. Delamerian orogenesis is recorded in the structural histories of some older assemblages in the Tasmanides of northern Queensland.

The Lachlan Orogen developed in southeastern Australia, east of the Delamerian Orogen, under the ongoing influence of plate convergence. Its complex history involved multiple episodes of contraction and extension (Foster & Gray 2000; Glen 2005). Although the detail of its development remains contentious, much of its rock volume is related to the Ordovician–Devonian infill of backarc basins on oceanic crust and to Silurian–Devonian granitic magmatism. It includes the oceanic Ordovician – early Silurian Macquarie arc (Crawford et al. 2007) and inliers of Cambrian oceanic crust.

The northern extent of the Lachlan Orogen is obscured by Mesozoic cover of the Great Australian Basin and has been placed at the Olepoloko Fault, a curved, east–west structure close to the New South Wales – Queensland border (southern margin of the Benambran reworked zone on Figure 3.118), recognised from aeromagnetic imaging of basement rocks (Glen 2005). North of this structure, pre-Late Devonian rocks are referred to the Thomson Orogen, known from basement cores obtained by drilling through late Paleozoic and Mesozoic cover in southwestern Queensland and from outcrop of the Anakie, Charters Towers and Greenvale provinces in central and northern Queensland. However, seismic profiling shows the Olepoloko Fault to be a relatively young structure that displaces Late Devonian strata. Recent geophysical data and geochronology of rocks to the north suggest that the Lachlan Orogen continues into Queensland (Burton 2010) and the boundary between these two orogens remains poorly defined (Chapter 3). Surface exposures in northern Queensland show the content and history of the Thomson Orogen to be different from that of the Lachlan Orogen. In particular, the Thomson Orogen contains Neoproterozoic sedimentary rocks interpreted as a passive margin assemblage best known from the Delamerian Orogen, and Ordovician silicic volcanics and granitoids, which are not found in the Lachlan Orogen. The latter are represented beneath Mesozoic cover in southern Queensland, but in that area, contents of the Thomson Orogen are very poorly established. The terminal tectonic event of the Thomson Orogen occurred in the Telychian (late early Silurian), broadly correlative with the Benambran Orogeny recognised in the Lachlan Orogen, and this term is applied in its description.

A discrete orogenic belt of the Tasmanides, for which the name Mossman Orogen is introduced here, is recognised east of the Thomson Orogen in northern Queensland. It is characterised by extensively deformed late Silurian–Devonian continental margin marine strata developed to the east and north of a chain of granitoids of similar age, emplaced into the fringe of the North Australian Craton and adjoining rocks of the Thomson Orogen. Its terminal tectonic event commenced in the Late Devonian, and is here equated with the Tabberabberan Orogeny, extending usage of this term from the Lachlan Orogen, where it is applied to a late Middle Devonian orogenic episode (Glen 2005).

The New England Orogen, the youngest and most easterly orogenic belt of the Tasmanides, extends along the eastern Australian coast from central New South Wales to northern Queensland and is divided into northern and southern tracts by Mesozoic cover of the Clarence–Moreton Basin near the New South Wales – Queensland border. The northern New England Orogen extends from the state border to near Townsville, including coastal islands, but its limits to the north and east are undefined. Basement core from the Queensland Plateau suggests that it continues northwards offshore from Townsville (Mortimer, Hauff & Calvert 2008), perhaps as far as to include Permian–Triassic igneous rocks in Papua New Guinea (Pigram & Panggabean 1984). The southern New England Orogen extends just north of the state border, mainly as the Texas Subprovince.

This largely late Paleozoic orogen also has small older components. Like the Mossman Orogen, it is characterised by extensively deformed continental margin sedimentary assemblages. Its sedimentary successions and its Thomson and Mossman borderlands to the west and north host voluminous granitoids distributed as many separate plutons. Crustal contraction during the Hunter–Bowen Orogeny, which terminated the New England Orogen, was initiated in the early Permian, but its effects migrated westwards and extended into the Triassic.

1.2.3 Thomson Orogen: Neoproterozoic–Ordovician (Chapter 3)

Exposures in the Anakie and Charters Towers provinces include upper greenschist to amphibolite grade metasedimentary rocks with siliciclastic protoliths interpreted to have been marine sediments. These Neoproterozoic–Cambrian rocks, dated using age profiles of detrital zircon and monazite grains, are interpreted as remnants of the east Gondwana passive margin. Early Paleozoic plate convergence is represented by the late Cambrian – Early Ordovician volcano-sedimentary Mount Windsor Subprovince in the Charters Towers Province and the metamorphosed remnants of coeval basins in the Greenvale Province. Early Paleozoic rocks of the Greenvale Province forming basement to the western Broken River Province include ocean floor rocks, a deepwater, marine, turbidite package and an exotic, oceanic, volcano-sedimentary tract. The Barnard Province at the eastern margin of the Hodgkinson Province includes early Paleozoic metasedimentary siliciclastic rocks. Sedimentary rocks at the western perimeter of the Hodgkinson Province and deep seismic profiles suggest that a crustal layer of the Thomson Orogen may form basement to the Mossman Orogen (Korsch et al. 2012).

Granitoid plutons that are widespread in exposed parts of the Thomson Orogen, most abundantly in the Charters Towers Province, are grouped as the Macrossan Igneous Association (505–460 Ma; Bain & Draper 1997). Most are I-type, but S-types are represented. Early Paleozoic granitoids and silicic volcanic rocks intersected in basement cores beneath late Paleozoic and Mesozoic basins in central Queensland, at least as far south as Adavale, are part of the association.

A widespread early Silurian crustal contraction is deduced from dating metamorphism in the Charters Towers and Greenvale provinces. It is also reflected in basement cover relationships and ages in the Broken River Province, and is consistent with basement cover relationships known or inferred for the Anakie Province, the subsurface Adavale Basin and the Hodgkinson Province, for which age control is less precise. This general contraction across the Thomson Orogen was responsible for inversion of its basinal systems and is equated with the broadly coeval Benambran Orogeny of the Lachlan Orogen (Foster & Gray 2000).

Subsequent to this Benambran orogenesis, scattered, intracontinental, middle–late Paleozoic basins, some of substantial extent and containing thick successions, developed on the Thomson Orogen. Large basins include the Early Devonian – Mississippian Adavale Basin, the Late Devonian – mid-Carboniferous Drummond Basin and the Permian – Middle Triassic Galilee and Cooper basins. Smaller, poorly exposed elements to the east of these basins include the poorly known Timbury Hills, Belyando and Ukalanda basins, the Burdekin Basin and remnant late Paleozoic outliers in the Greenvale Province.

The more easterly Drummond and Burdekin basins were inverted in a poorly dated, middle–late Carboniferous crustal contraction equated with the Kanimblan Orogeny, evidence of which is widespread in rocks of this age in the Lachlan Orogen (Gray & Foster 1997).

1.2.4 Mossman Orogen: Silurian–Devonian (Chapter 4)

This orogenic belt in northern Queensland comprises the Hodgkinson and Broken River provinces and passes offshore to the north and east so that its full extent remains undefined. Its other boundaries are major faults against the Charters Towers Province to the south, the Barnard Province in the southeast and the Greenvale Province and Yambo and Coen inliers to the west. It is dominated by multiply deformed, poorly dated, deep-marine turbidites with subordinate mafic volcanics and chert, which have generally experienced low greenschist grade metamorphism. Along the western margin is a discontinuous belt of generally less deformed, late Silurian – early Late Devonian, shallow-marine sedimentary rocks dominated by limestone. In the north, this assemblage is locally interlayered with voluminous, coeval, deeper marine mafic volcanics. In the south, scattered Devonian sedimentary cover on the older assemblages indicates that the shallow-marine succession of the Mossman Orogen was originally much more widespread.

Inliers of Thomson Orogen rocks in the southwestern Mossman Orogen with unconformable contacts suggest an overlapping relationship between the orogens. Deep seismic profiles of the western and central Hodgkinson Province and western Broken River Province show a similar relationship, but with overlap that may have been induced by overthusting of Mossman rocks across those of the Thomson Orogen (Korsch et al. 2012).

Thomson Orogen and North Australian Craton rocks abutting the Mossman Orogen are intruded by late Silurian – Early Devonian (380–425 Ma) granitoid plutons grouped as the Pama Igneous Association (Bain & Draper 1997). I-type granitoids are characteristic, but S-types are dominant in the Coen inlier.

The Mossman Orogen was terminated near the end of the Devonian by crustal contraction that resulted in inversion of sedimentary assemblages and the syn-tectonic emplacement of small granitoids. The age of deformation is constrained in the Hodgkinson Province by a syn-tectonic granitoid dated at 357 ± 6 Ma. In the Broken River Province, termination is constrained by the Famennian–Tournaisian base to cover sequences and minor syn-tectonic granite dated at 357 Ma. Strain induced by this crustal contraction was essentially confined to the Mossman Orogen, as shown by little-disturbed Devonian cover successions on the Greenvale and Charters Towers provinces. However, a Frasnian and slightly older contractional episode in the New England Orogen in central Queensland correlates with the Givetian Tabberabberan Orogeny of the Lachlan Orogen (Gray & Foster 1997). This name is applied here despite its expression in the Frasnian compared to its Givetian occurrence in the Lachlan Orogen.

Pennsylvanian – Early Triassic variably deformed cover successions, remnants of post-Tabberabberan basins, are represented in the Hodgkinson Province. The more extensive, better preserved, latest Devonian to early Carboniferous Bundock and Clarke River basins in the southwestern Broken River Province were inverted by open folding in the middle or late Carboniferous Kanimblan Orogeny. Little-disturbed Permian elements, the Wade Basin and the Sybil Graben, are developed at the southern margin of the Broken River Province.

1.2.5 New England Orogen: Silurian–Triassic (Chapter 5)

The New England Orogen is conveniently divided into northern and southern parts by Mesozoic cover of the Clarence–Moreton Basin in southeastern Queensland. The southern New England Orogen is in New South Wales, except for the Texas Subprovince and Silverwood Province that extend into Queensland southwest of Warwick.

This youngest and most completely preserved orogenic belt is the most complex, with north-northwest structural grain of the orogen evident in the distribution of structural provinces and their subdivisions. The outboard Wandilla Province in the east is a distinctive assemblage of multiply deformed, deep-marine siliciclastic sediments, in part volcaniclastic and in part quartzose associated with chert and mafic volcanics, and generally preserves the effects of greenschist grade metamorphism. It is divided into the Coastal, Yarraman, North D'Aguilar, South D'Aguilar and Beenleigh subprovinces, which are separated by either younger structural elements or major faults. The province represents a subduction complex or accretionary wedge (Fergusson, Henderson & Leitch 1990a, 1990b). Blueschist metamorphic rocks and large bodies of ultramafic rocks occur in the North D'Aguilar Subprovince and were exhumed during a late Pennsylvanian extensional event that formed a metamorphic core complex (Little, Holcombe & Sliwa 1993). The western boundary of the province is the major Yarrol Fault System. The assemblage is Late Devonian – Carboniferous, constrained by a combination of biostratigraphy, a provenance linkage (involving oolites reworked from adjacent shallow-marine successions of known age), and the age spectra of detrital zircon. Metamorphic mineral growth indicates deformation in the late Permian. It hosts scattered Permian – early Triassic plutons.

East of the subduction complex, the discrete, younger (Permian–Triassic) Gympie Province contains mafic to intermediate volcanics succeeded by shallow-marine siliciclastics and minor limestone. Its context is contentious, having been interpreted as an active continental margin element, an exotic oceanic terrane emplaced by plate convergence, or a sequential history involving both settings.

West of the subduction complex in central Queensland lies a heterogeneous assemblage divided into two sequential parts by a regional Frasnian unconformity. The older part, the Calliope Province, is dominantly volcaniclastic to siliceous siliciclastics with associated subordinate mafic to silicic volcanics and sporadic Early–Middle Devonian limestone lenses (Murray et al. 2012). The province includes fossiliferous late Silurian and rare Ordovician strata. Its rocks are variably deformed and locally cleaved. Geochemistry of the mafic volcanics indicates an oceanic island arc provenance and the province hosts the Mount Morgan Trondhjemite, also considered to have island arc geochemical affinities. Rocks of this province represent, at least in part, an exotic island arc assemblage developed outboard of the continental margin with their accretion marked by the regional Frasnian unconformity.

The assemblage above the unconformity, assigned to the Yarrol Province, generally has an ordered, well-dated stratigraphy displayed across fault blocks and broad, open folds. It consists of a Late Devonian – Mississippian volcaniclastic succession with subordinate mafic to felsic volcanics and intervals of oolitic limestone in its upper part. A thick, distinctive Pennsylvanian succession characterised by non-marine sandstone and conglomerate is sporadically developed. Permian rocks are also sporadically represented and are largely mafic to felsic volcanics with some marine and terrestrial siliciclastic sediments. The Mississippian, and at least part of the Pennsylvanian part of this province, overlaps in age with the inferred subduction complex to the east. It has generally been interpreted as an arc flank and forearc basinal assemblage, with a contrary opinion that it has a backarc setting (Murray et al. 2003; Bryan, Holcombe & Fielding 2001). Basinal developments associated with its late Carboniferous and Permian history have been attributed to an extensional regime (Holcombe et al. 1997a, 1997b).

To the south, the Calliope and Yarrol provinces pass beneath the Great Australian Superbasin, which separates them from the Silverwood Province in the southern New England Orogen. The Silverwood Province is considered equivalent to the Calliope Province because it includes a similar rock assemblage of similar age. The Texas Subprovince (part of the Woolomin Province of the southern New England Orogen) contains a turbidite succession and is equivalent to the Wandilla Province. It forms one hinge of a major oroclinal structure, the formation of which is still the subject of debate (Rosenbaum, Li & Rubatto 2012).

North of Rockhampton and extending to Marlborough, the Yarrol Fault Zone is associated with serpentinised ultramafic rocks. Small lenses of serpentinite also occur along this structure further to the south. Near Marlborough, more extensive, flat-lying thrust sheets of serpentinised ultramafics locally interleaved with metasedimentary belts are distributed west of the Yarrol Fault. Isotopic dating indicates that the ultramafics are latest Neoproterozoic, suggesting they represent much older crust than that represented by the assemblages with which they are now associated. However, they were probably reworked in the middle Paleozoic in a supra-subduction setting, prior to emplacement as an out-of-sequence thrust nappe in the Permian (Murray 2007a).

West of the Yarrol Province, the Connors–Auburn Province is a linear belt of predominantly subaerial, terrestrial felsic volcanics and granitoids of the Auburn Subprovince in the south and the Connors Subprovince in the north (Withnall et al. 2009a). The northern part of the Connors Subprovince is dominated by plutonic rocks, which are also abundant in the southern part of the Auburn Subprovince. The two subprovinces form broad arches flanked by Permian sediments of the Bowen Basin and are separated by deformed equivalents of those sediments in the Gogango Thrust Zone. Most of the magmatic belt is late Carboniferous – early Permian, but some volcanics and granitoids are early Carboniferous and considered to represent an Andean-style, continental volcanic arc associated with the Yarrol Province forearc assemblage and the accretionary wedge of the Wandilla Province. Towards the top of the volcanic succession in the latest Carboniferous – early Permian, a transition to a more bimodal association (along with geochemical patterns) suggests development of an extensional setting with thinning crust that heralded the onset of deposition in the Bowen Basin (to which the volcanic rocks are basement). Bimodal dyke swarms in the northern Connors Subprovince may be related to this extension.

The Bowen Basin is a major element of Queensland geology, characterised by a thick Permian–Triassic succession of marine siliciclastics succeeded by coal measures, which continues south beneath the Great Australian Basin into New South Wales as the Gunnedah and Sydney basins (Korsch & Totterdell 2009a, 2009b).

Permian sediments immediately east of the arches formed by the Auburn Subprovince and southern part of the Connors Subprovince are part of the Bowen Basin, but along with the underlying volcanic rocks have been strongly deformed by thrusting in the Gogango Thrust Zone. There is no evidence that the Connors–Auburn Province was a positive feature during deposition in the Bowen Basin and it is therefore thought that the arching results from later tectonism. The boundary between the Gogango Thrust Zone and the less deformed Yarrol Province is a line of major east dipping roof thrusts, but it is likely that the Bowen Basin originally extended eastwards because there is no obvious basin marginal facies. Partly fault-bounded packages of Permian marine sediments overlying the Wandilla Province, such as in the Cressbrook Basin and the Gympie Province, may originally have been continuous with the Bowen Basin, as were the Calen Coal Measures to the east of the Connors Subprovince near Mackay.

In the later part of its development the Bowen Basin is regarded as a foreland basin (Korsch & Totterdell 2009a, 2009b) inextricably linked to thrust uplifts to the east. It was inverted with major thrusting and local folding by the Hunter–Bowen Orogeny, which likewise deformed assemblages to the east. The approach taken here is to consider the Bowen Basin as an inboard element of the northern New England Orogen developed above, and lapping onto, rocks of the Thomson Orogen. During an Early–Middle Triassic foreland loading phase, the Esk Basin and Arbroath Trough received sediments. The last compressional phase of the Hunter–Bowen Orogeny ended sedimentation in these basins before the Late Triassic. Soon after, roll-back of the subducting slab led to Late Triassic extension during which the Ipswich, Tarong, Callide and Horrane basins received sediments. These Late Triassic basins and contemporaneous magmatism are here described as part of the New England Orogen, but they may equally be argued to be post-orogenic.

Hunter–Bowen orogenesis was terminal to development of the northern New England Orogen. Its metamorphic expression in the outboard assemblage regarded as a subduction complex (Wandilla Province) is as old as early Permian, whereas Early Triassic strata were folded and thrust during inversion of the Bowen Basin. Hunter–Bowen deformation is considered to have progressively moved inboard with time, and its expression is heterogeneous across rock assemblages in the northern New England Orogen. Thrust transport has disrupted rock relationships and strike-slip displacements may also have contributed to complexity. A large-scale, oroclinal fold attributed to dextral shear is recognised for assemblages of the southern New England Orogen in the Texas region of southern Queensland. Its relationship to the Hunter–Bowen Orogeny remains unresolved.

Discontinuous, Permian–Triassic granitoid plutons and associated Early Triassic silicic volcanics are distributed across all parts of the northern New England Orogen east of the Bowen Basin. Emplacement ages overlap with the Hunter–Bowen Orogeny.

1.2.6 Kennedy Igneous Association (Chapter 6)

The Kennedy Igneous Association (Bain & Draper 1997) continues northward from the New England Orogen as a large silicic igneous province—an expansive, discontinuous, belt of Carboniferous–Permian granitoid plutons, hypabyssal porphyry systems and dyke swarms and felsic volcanic fields emplaced into, or unconformable on, rocks of the Proterozoic Etheridge Province and the Paleozoic Charters Towers, Greenvale, Broken River and Hodgkinson provinces of the Thomson and Mossman orogens. Geophysical data (and limited geochronology) show that Carboniferous–Permian granites also form a west-northwest trending belt, the Townsville – Mornington Island Belt, which extends under cover from north of Mount Surprise and at least as far as Mornington Island in the Gulf of Carpentaria, transecting regional trends. The geodynamic environment of the Kennedy Igneous Association magmatism is not well understood, but the widespread volcanic cauldron complexes were undoubtedly initiated by, and formed in response to, regional extensional events.

Discrimination of magmatic rocks of the Kennedy Igneous Association and those of the coeval Connors–Auburn Province, traditionally assigned to the northern New England Orogen and considered to have formed as a subduction-related, continental magmatic arc, is open to debate. Whether the arc extended further north, and if so how far, is uncertain.

1.2.7 Post-tectonic geological elements: Jurassic–Pleistocene (Chapters 7–9)

Hunter–Bowen tectonism marks the last episode of crustal shortening that generated fold and thrust belts, and pervasively metamorphosed rock assemblages in Queensland. Although largely restricted to the New England Orogen, it was followed by a change in crustal regime for eastern Australia in general, with active margin tectonics either lacking or a far-field influence. Post-Triassic stress fields in some crustal sectors of Queensland induced block faulting, variously expressed by normal and reverse geometries, and associated local tilting and open folding of stratiform rocks (Elliot 1993). However, crustal strain has been mild since the Jurassic. Epicontinental sedimentary basins, and surficial sediment assemblages and igneous associations are characteristic of this interval. The contemporary landscape, including regolith mantles (which influence its character and the physiography and sediment repositories of the submerged continental margin), were generated during the Cretaceous and Cenozoic.

More than 60% of Queensland is covered by a relatively thin (rarely >3 km thick), subhorizontal blanket of Jurassic–Cretaceous sediments often referred to as the Great Artesian Basin. However, that name has a very distinct hydrogeological concept that includes aquifers of the Bowen and Galilee basins. Although the Great Australian Basin was coined to replace it as a geological concept, the constituent Carpentaria, Eromanga and Surat basins have long been recognised as different basins separated by distinct subsurface basement ridges. Therefore, the Great Australian Basin remains as an informal but convenient term for the aggregate of these three basins. Similar basement ridges separate these three basins from several other continuous and contemporary basins including the Laura, Peninsula, Papuan and Money Shoals in the north and the Clarence–Moreton and Nambour in the southeast, so the concept of the Great Australian Superbasin is introduced here to recognise this wider continuity of those basins. In spite of the basement structures, the stratigraphic succession within the superbasin is remarkably consistent. Fluviatile Jurassic strata with thick quartzose sandstones are succeeded by Early Cretaceous, predominantly marine mudstone, of volcanic provenance. This Aptian marine inundation was generally coeval with worldwide continental inundation, suggesting a global rise in sea level. However, maximum marine flooding of the Great Australian Superbasin occurred in the middle Albian, followed by general regression in the late Albian, a pattern that is not synchronous with the inferred Cenomanian global sea level maximum. Remains of marine reptiles and dinosaurs associated with the Cretaceous section are some of the signature fossils for which the state is known.

The largely Jurassic Nambour and Clarence–Moreton basins extend from the Surat Basin across the New England Orogen in southeastern Queensland and northern New South Wales. Thin, ephemeral Mesozoic successions are sporadically developed on basement rocks of the orogen along much of its length.

Early Cretaceous volcanics on the Whitsunday Islands and adjoining coast of central Queensland, along with some plutonic rocks, overlap in age with and supply enormous volumes of sediment to the Cretaceous succession of the Great Australian Basin. They range widely in composition, but are predominantly felsic. Geochemistry of mafic and intermediate lavas, including niobium depletion, suggest a relationship to a subduction zone, but the assemblage has also been interpreted as related to continental rifting, independent of subduction (Bryan et al. 2012).

A series of narrow Paleocene grabens, several with kilometres of infill, are developed in eastern coastal Queensland, mainly between Gladstone and Proserpine. Intervals of oil shale are characteristic. More expansive but thin Cenozoic sedimentary assemblages, generally of continental character, are represented in northern Queensland. They include the Neogene Karumba Basin, with some marine facies, which is widely developed in western Cape York Peninsula, and the Kalpowar Basin, north of Laura. Sheets of Cenozoic sedimentary cover, some of which are areally extensive, are widespread in the northern, central and southwestern parts of the state. They are poorly dated but mostly attributed to the Paleogene, where they are associated with duricrust. Subsequent erosion has resulted in topographic inversion such that duricrust commonly stands as plateau and mesa landforms. A thin (<150 m) Pliocene sediment sheet is extensively developed in the Charters Towers region.

Widespread intraplate basaltic volcanism in eastern Queensland is the northern part of a general pattern for eastern Australia in the Cenozoic, mainly as surface lava fields but also as volcanic centres with topographic expression and as plugs. Mount Barney and Mount Warning in the Gold Coast hinterland and the Glasshouse Mountains near the Sunshine Coast are striking volcanogenic landforms. The Lamington shield volcano centred on Mount Warning in New South Wales provides some of the most striking landforms in the southern border area. In places, topographic inversion has produced prominent plateau landforms capped with flow basalt. In northern Queensland, plugs, scoria cones, maars and extensive lava fields with some extraordinarily long flows are also prominent in the landscape. Volcanism throughout eastern Queensland was episodic from the Paleocene with the youngest flow dated at 13 000 ka near Charters Towers. The distribution of basalt in Queensland, and eastern Australia in general, is spatially related to the Great Dividing Range, which separates eastern and western drainage. This upland reflects Cenozoic within-plate tectonism. However, fission track records suggest that eastern Queensland had been an extensive upland before being extensively stripped by erosion in the Late Cretaceous.

The submerged continental borderland to Queensland has a complex physiography of submarine plateaus and troughs thought to have been generated by ocean spreading associated with formation of the Coral Sea and the Tasman Sea. The Marion and Queensland plateaus have thick Miocene carbonate cappings, representing a precursor reef system to the Great Barrier Reef of the contemporary outer shelf. The Townsville and Queensland troughs are contemporary basinal systems with an infill history spanning most of the Cenozoic. Quartzose sand delivered to the coast of southern Queensland during the Quaternary has been reworked by northward transport to form the large sand bodies of Moreton, Stradbroke and Fraser islands, which are striking coastal features.

1.3 Mineral and energy resources (Chapter 10)

The timely discovery of gold at Gympie in 1867 saved Queensland from the worst effects of the 1866 economic depression, and goldmining provided an important boost to the state's economy up until World War I, with important discoveries at Charters Towers, the Palmer River, Etheridge and Croydon.

Although gold is no longer pre-eminent, the other Queensland minerals that have surpassed gold in economic and exploration importance have placed the state as one of the world's outstanding mineral and energy producing regions. The best known resource regions are the:

- Surat and Bowen basins—coal and coal seam gas
- western Cape York Peninsula (including Weipa)—bauxite
- North West Queensland Mineral Province—base metals, phosphate and gold
- Charters Towers region (northern Queensland)—gold
- Cooper and Eromanga basins—oil and gas.

In 2010–11, mining (including coal and petroleum) provided more than 70% of Queensland's total exports according to the Australian Bureau of Statistics. At the same time the industry employed ~55 000 people directly and a further 165 000 indirectly in regional and outback Queensland.

1.3.1 Coal

Most of Queensland's coal is produced from the Bowen Basin, where it is found at accessible depths for open-cut mining within a triangular area of central Queensland that extends from Collinsville in the north to Theodore in the south and west to Springsure. Both metallurgical coal and thermal coal are produced. Thermal coal is also produced from the Callide, Tarong, Surat and Clarence–Moreton basins in southeastern Queensland, where much of it is used in nearby power stations. The Galilee Basin in central Queensland is emerging as a significant source of thermal coal for export.

Queensland produced about 206 Mt of saleable coal during 2009–10 and 183 Mt were exported to >30 countries (mainly for steel manufacture), maintaining the state's position as a world leader in the coal export trade.

1.3.2 Oil and gas

Queensland has had modest discoveries of oil and gas, but has significant future potential based on relatively under-explored basins, extensive source rocks and developing infrastructure.

Before the 1970s, limited exploration was undertaken in high-risk areas, which included most of Queensland. The discovery of oil in southwestern Queensland in the early 1980s changed the industry's perspective and renewed interest in oil and gas exploration in the state. Areas producing conventional petroleum and/or gas include the:

- St George – Roma and Moonie regions of the Surat and Bowen basins
- Injune–Emerald regions of the Denison Trough (western Bowen Basin)
- Cooper and Eromanga basins in southwestern Queensland.

Queensland also has large resources of coal seam gas, which is mainly methane. The Surat and Bowen basins have the greatest potential for coal seam gas, with significant proven reserves in both regions. Commercial production of coal seam gas commenced in the Bowen Basin in 1996 and in the Surat Basin in 2006. The main producing areas are the:

- Moranbah and Moura regions (northern Bowen Basin)
- Injune area (western Bowen Basin)
- Wandoan area (eastern Bowen Basin)
- Dalby–Roma region (Surat Basin).

The potential for other unconventional gas sources (shale gas and tight gas) has yet to be assessed.

Queensland contains most of the known oil shale resources in Australia, with a total of 30 billion barrels of shale oil identified in numerous deposits. The major deposits are Condor near Proserpine and Stuart and Rundle northwest of Gladstone.

1.3.3 Metalliferous minerals

Queensland is widely recognised for its world-class endowment of base metals. In 2010 it was the world's second largest producer of lead (10.4% of global production), the third largest zinc producer (6.9%) and the fifth largest silver producer (7.6%) and accounted for 1.3% of global copper production (BREE 2011). Queensland leads Australia in copper, lead, silver and zinc production, as well as being Australia's second largest bauxite producer and the third largest gold producer. It is expected to become an important producer of molybdenum and rhenium in the future.

Most of the base metal and gold production is now from the North West Queensland Mineral Province, which is one of the world's leading base metal provinces. Numerous base metal deposits have also been worked throughout eastern Queensland, although most were relatively small. An exception was the Mount Morgan mine, which although primarily a world-class gold mine, was also an important copper producer.

1.3.4 Gemstones

Queensland's renowned gem deposits are quite diversified. Sapphires have been mined commercially for more than 100 years on the Anakie field west of Emerald, while opal and chrysoprase are also mined for international markets. The state's opal fields lie in a belt 300 km wide extending from the New South Wales border, west of Cunnamulla, and north through Quilpie, Longreach and Winton to Kynuna. Most of the opal mined in Queensland is boulder opal, a form of precious opal unique to the state.

1.3.5 Water (Chapter 13)

Queensland is well endowed with groundwater resources, not only along the eastern coastal strip (where it is used extensively for human consumption, agriculture and stock) but also in the Great Artesian Basin in the interior, beneath more than half the state. The Great Artesian Basin, at 1 700 000 km^2, is one of the largest artesian groundwater basins in the world. It extends from Cape York to Dubbo and from the Darling Downs to west of Lake Eyre. It stores an estimated 47 027 million ML (Chapter 13). This groundwater has made possible human settlement in this vast arid area, supported the extensive pastoral industry for more than a century and is now extensively used in the mining industry.

1.4 Geological time

Calibration of Queensland geology against the global geological time scale prior to the 1960s relied largely on the available fossil contents (Hill & Denmead 1960). Large areas of unfossiliferous rocks in Queensland remained undated at that time, seriously hampering their interpretation or in some cases attracting incorrect inferences of age that led to erroneous interpretations.

During the latter part of the twentieth century, various absolute dating techniques were developed and are more accessible (deLaeter 2008). This evolution of dating techniques on a global scale has promoted much international effort and cooperation to relate the traditional comparative scale, with eras, periods and series, to the absolute scale, dealing only in millions of years before the present (Ma). The peak earth science body, the International Union of Geological Sciences, established the International Commission on Stratigraphy to coordinate global efforts and to set standards. Further effort on many aspects of the time scale will allow continuing improvement to, and upgrading of, the standard time scale.

In this volume we acknowledge, and as far as possible follow, the commission's International Chronostratigraphic Chart (Figure 1.4). Periodic publications explaining the updating work are listed on the upgraded chart (Gradstein et al. 2004; Ogg et al. 2008) and these are integral commentaries on the improved charts. The chart retains several informal time divisions within the Cambrian Period that are to be formalised with future work by the Subcommission on Cambrian Stratigraphy. Where traditional divisions of long-established periods widely used in the literature on Queensland have been replaced (e.g. Early and Late Carboniferous replaced by Mississippian and Pennsylvanian), those traditional terms are used in lower case (e.g. early Carboniferous) if the translation to the International Chronostratigraphic Chart scale cannot be achieved simply. We acknowledge that early absolute dates achieved with radioisotopic techniques may need reassessment due to a better understanding of standards and physical constants that were used in the past. However, the dates presented here are the most up to date and as far as possible the sources and techniques for all absolute dates are provided.

1.4.1 Palynostratigraphy

The considerable exploration effort in Queensland for oil, gas and coal has relied heavily on palynostratigraphy for correlation between drill holes and validation of geophysical survey results. Whereas marine conodonts and protozoans have been readily related to international biostratigraphic schemes, non-marine palynomorphs that are the main biological age indicators in the extensive subsurface late Paleozoic and Mesozoic basins of Queensland are not so easily related to well-studied successions in the northern hemisphere, because they represent mainly endemic, or at least markedly different, floras. Various zonation schemes for these floras have developed in different parts of Australia and efforts have been made to create a continent-wide scheme (Dettmann & Playford 1969; Helby, Morgan & Partridge 1987; Monteil 2006).

As the zonation in Queensland became more and more finely divided, Price et al. (1985) established an intuitive zonation scheme with the initial P for palynomorphs or D for dinoflagellates followed by C, D, P, T, J or K for the periods from Carboniferous to Cretaceous, followed by a numbered zonation (1 at the base) of the period and decimals to indicate successive subdivisions of zones (e.g. PJ2 with its first-order subdivisions of PJ2.1 and PJ2.2). This allows finer and finer subdivisions without altering any of the higher level zonal scheme and allows immediate recognition of superpositional relationships. Price (1997) removed the decimal point, used whole numbers that were not intuitive and added the prefix A to denote the Australian region. Although this zonation does not strictly follow the generally agreed provisions of biostratigraphy to use names of key faunal or floral elements to designate zones, it has been extensively used in Queensland geology and has entered mainstream literature (Turner et al. 2009). Some efforts to correlate Australian palynostratigraphic schemes to the international standard have ignored the alphanumeric scheme (Monteil 2006). However, the alphanumeric scheme is included here with the original decimal notation and has been related to the international scheme where applicable (Figures 5.70, 7.2).

1.4.2 Geochronology

Since the publication of the volume by Hill and Denmead (1960), apart from the regional mapping programs, the application of geochronological techniques (deLaeter 2008) has probably been the most significant factor in the much improved understanding of geological history of Queensland. Because most chapters of this volume refer to dates by a variety of methods, an overview of the main isotopic, chemical and physical techniques that have been applied in Queensland is given here. For a more comprehensive explanation of isotopic methods, see Faure and Mensing (2004).

Until the 1980s, **K–Ar dating** was the most widely used technique in Queensland and most mapping projects included a dating program. K–Ar dating is based on the branched radioactive decay (by K-capture) of the minor isotope ^{40}K to ^{40}Ar. The 1.250×10^9 year half-life of ^{40}K, coupled with geochemical differences between it and its smaller, monatomic, gaseous daughter isotope (with a low terrestrial abundance), make the technique useful for dating many rocks. Analyses were done at a variety of laboratories, chiefly the Australian National University through the 1960s, mainly by Jack Evernden, John Richards, Alan Webb and Ian McDougall. In the 1970s, a laboratory was established at The University of Queensland (Green 1975; Golding 2008), and it provided support to GSQ mapping programs. The GSQ also had some analyses done at the Australian Mineral Development Laboratories (AMDEL) in Adelaide. In Queensland, the method was applied particularly to dating micas and amphiboles in Paleozoic and Mesozoic plutonic rocks (Webb & McDougall 1968; Whitaker, Murphy & Rollason 1974) and also to many of the extensive Cenozoic basalts by whole-rock dating (Wellman 1978; Griffin & McDougall 1975). By the mid-1970s, in conjunction with biostratigraphic studies, the work had helped to establish a comprehensive temporal framework for much of Queensland geology.

However, the K–Ar isotopic system is prone to resetting by subsequent events, so more robust techniques were needed to refine this framework, particularly for the non-fossiliferous and multiply deformed Proterozoic and early Paleozoic rocks.

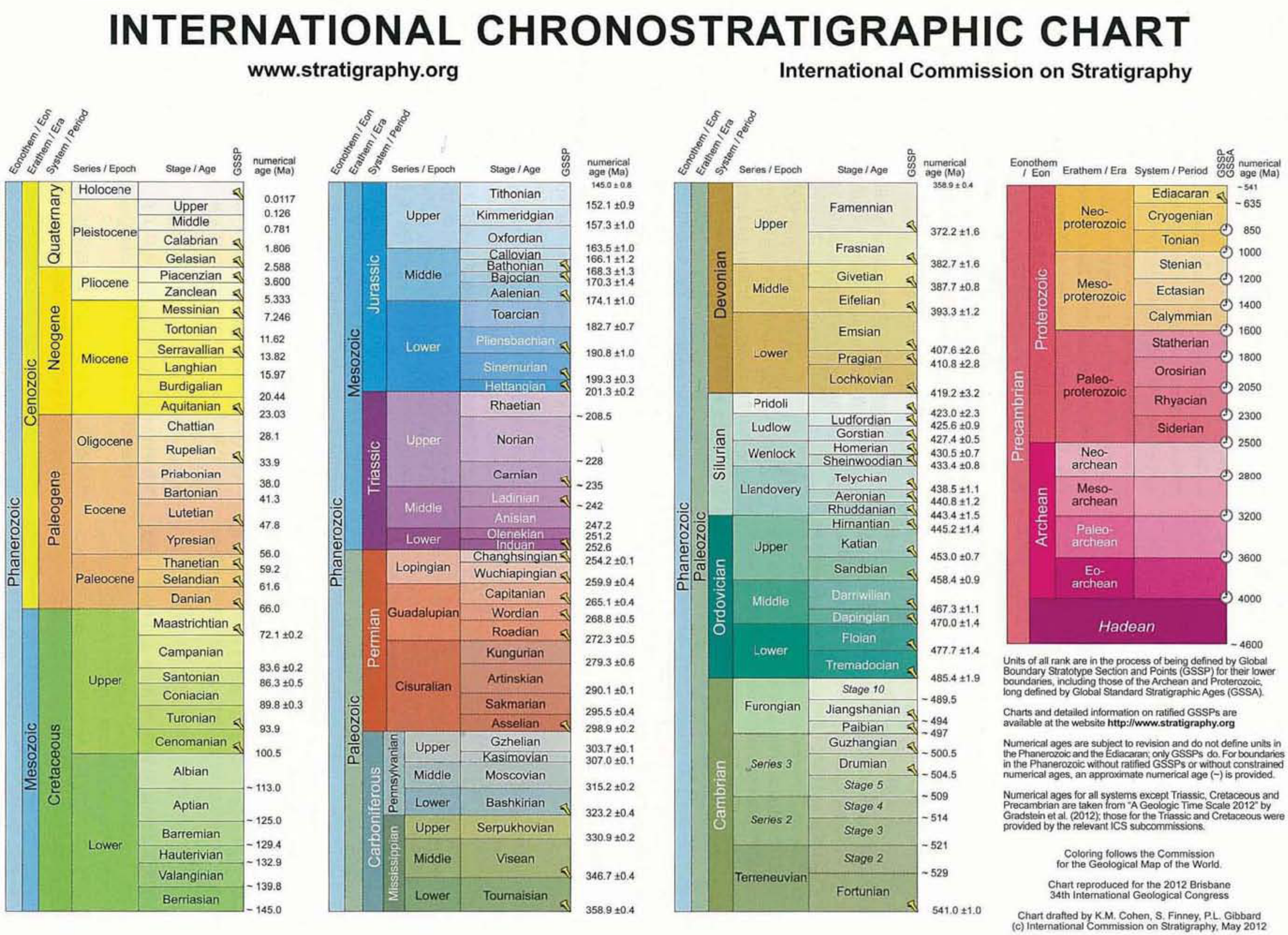

Figure 1.4 The International Chronostratigraphic Chart as at May 2012 (adopted here as the primary source of stratigraphic nomenclature) and its relationship to numerical ages. Global Boundary Stratotype Section and Points (GSSPs) to formalise the bases of stages and series that have been agreed internationally for the Phanerozoic and Ediacaran are indicated, as are the ages of boundaries in the Precambrian.

A variation of the K–Ar technique is **Ar–Ar ($^{40}Ar/^{39}Ar$) dating** (McDougall & Harrison 1999). Whereas the former method requires analysis of separate sample aliquots for K and ^{40}Ar, the Ar–Ar method requires only one, because it converts a stable form of K (^{39}K) into ^{39}Ar by irradiation with fast neutrons in a nuclear reactor. It can apply to both separated minerals and whole-rock samples. Because the K signature of a sample is converted *in situ* to an Ar signature, it is possible to liberate Ar in stages from different domains of the sample by 'step heating' and to recover full age information from each step. The great advantage of the step heating technique over the conventional 'total fusion' technique is that progressive outgassing allows the possibility that anomalous subsystems within a sample, such as those that have undergone Ar loss, can be identified, and, ideally, excluded from an analysis. In a plot of results from successive steps, the undisturbed age of the sample is shown as a 'plateau age'. Using the better precision and accuracy of this technique on Oligocene volcanic rocks in southeastern Queensland, Cohen, Vasconcelos and Knesel (2007) were able to demonstrate an age progression with latitude, consistent with plate motion over a hotspot. This was not evident for samples previously dated by K–Ar from the same localities. Although the technique is most commonly used to resolve the ages of samples with Ar loss, it may also help identify inherited or so-called 'excess Ar'. Most modern studies applying the K–Ar isotopic system to dating use the Ar–Ar technique (Feature 3.3 and Chapter 8). A further refinement is laser-heating $^{40}Ar/^{39}Ar$ dating of single crystals or clusters of crystals within a sample. This technique has been applied to studying weathering profiles in Queensland by dating alunite, jarosite and K–Mn oxides (Vasconcelos et al. 2008). The single crystal or single grain approach allows the study of weathering profiles where K-bearing supergene minerals occur as minor phases.

Rb–Sr dating is based on the beta-decay of ^{87}Rb to ^{87}Sr. Although both elements occur only in trace concentrations, they are found in most rocks. Their contrasting geochemical characteristics (Rb tends to be enriched in more felsic rocks, and Sr in more mafic varieties) make them highly suitable for dating (and as isotopic tracers), as does the 4.88×10^{10} year half-life of ^{87}Rb. In common with K–Ar studies, both whole-rock and mineral systems can be used for dating.

The most important feature of the Rb–Sr method was the development of the isochron concept, which was subsequently applied to other isotopic systems. On an $^{87}Rb/^{86}Sr$ – $^{87}Sr/^{87}Sr$ plot, isotopically undisturbed whole-rock samples that are genetically and temporally related define a straight line (known as an isochron), the slope of which is proportional to age. In some instances it is possible to obtain both an original crystallisation age (from whole-rock samples) and that of a subsequent event (from minerals) from a small outcrop. The method was applied to dating granitic rocks using both whole-rock and mineral systems in studies of the Mount Isa and Cairns–Townsville hinterland areas by the BMR in the 1960s and 1970s (Johnston & Black 1986). It was also used by Black et al. (1979) to date metamorphic events using whole-rock isochrons, although the significance of these ages is now in doubt.

As for K–Ar, the Rb–Sr isotopic system, particularly for mineral ages, is prone to resetting by subsequent events due to the mobility of Rb and Sr. Furthermore, sets of granitic samples can give false isochrons, if not genetically related or if produced by mixing of magmas from different sources. Therefore Rb–Sr is not often used for dating now. Recent work has also shown that the decay constant is 2% lower than the previously recommended value, suggesting that previously determined ages are also 2% too young (Nebel, Scherer & Mexger 2011). However, one strength of the method that is still applicable is its ability to determine initial $^{87}Sr/^{87}Sr$ ratios (from the intersection of the isochron with the ordinate), which can yield useful information on the origin of the rock or its precursor and limit possible ranges of source rocks (Black & Richards 1972a; Black & McCulloch 1990).

Sm–Nd dating is based on the decay, by alpha-particle emission, of ^{147}Sm to ^{143}Nd. The long half-life of the decay process (1.06×10^{11} years) and similar geochemical properties of these trace elements produce only small variations in isotopic composition over geological time, and this necessitates particularly precise isotopic measurement. Because parent and daughter isotopes are relatively inert (both are lanthanides), the Sm–Nd system is less prone to disturbance than the Rb–Sr system.

In Queensland, the method has not often been used for direct dating, but has been extensively used as an isotopic tracer, primarily to obtain comparative genetic information on different rock suites. Through the analysis of isotopic compositions of Nd, DePaolo and Wasserburg (1976) discovered that terrestrial igneous rocks closely followed the chondritic uniform reservoir (CHUR) evolution line. Chondritic meteorites are thought to represent the earliest material that formed in the solar system before planets formed and their isotopic evolution can model the evolution of the 'Bulk Earth'. Since $^{143}Nd/^{144}Nd$ departures from the CHUR evolution line are very small, DePaolo and Wasserburg (1976) realised that it would be useful to create a notation that described $^{143}Nd/^{144}Nd$ in terms of their deviations from the CHUR or Bulk Earth evolution line. This is the epsilon notation in which one $\varepsilon_{Nd}(T)$ unit represents a one part per ten thousand deviation from the CHUR composition at time T.

In addition, since CHUR defines initial ratios of continental rocks through time, it was deduced that measurements of $^{143}Nd/^{144}Nd$ and $^{147}Sm/^{144}Nd$, with the use of CHUR, could produce model ages for the segregation from the mantle of the melt that formed any crustal rock. These are termed T_{CHUR} (McCulloch & Wasserburg 1978). However, since the mantle has been continuously fractioned to produce crust, it has been progressively depleted in Nd with time, so it is more usual to calculate model ages with reference to a 'depleted mantle' composition, and these are referred to as T_{DM}. The latter is currently widely used, given the evidence for the presence of depleted mantle back to the Archean. A depleted mantle model age (T_{DM}) provides an estimate of the time a rock unit (e.g. a granite or the crust it was derived from) has been separated from its depleted mantle source, and in many cases can be taken to be a good estimate of the age of crust formation. In all calculations the reference reservoir (CHUR or depleted mantle) must be specified, and in the case of depleted mantle model ages the depleted mantle model evolution curve must also be specified.

Single-stage model ages, such as T_{CHUR} and T_{DM}, are calculated using the measured (present-day) $^{144}Nd/^{143}Nd$ and $^{147}Sm/^{143}Nd$ values of the sample to find the intersection of the sample and the modelled source growth curves, that is the point at which the $^{144}Nd/^{143}Nd$ values of both are identical (Figure 1.5). The time, T, at which this occurred is the model age. Assumptions involved in model age calculations include:

- The modelled growth curve is realistic.
- There is no significant change in parent/daughter (Sm/Nd) isotopic ratios after extraction from the mantle source.
- The crustal reservoir had a simple evolutionary history; that is, it only represents one crustal growth event.

It is generally accepted that the depleted mantle growth curve is an appropriate concept. However, several depleted mantle growth curves have been used, based on linear v. non-linear growth models of the depleted mantle reservoir as well as the timing of initial depletion.

The second assumption is also not universally true. Partial melting, fractional crystallisation, alteration, weathering and so on can modify Sm/Nd and hence affect $^{147}Sm/^{143}Nd$ values. In model age studies of granites and related rocks, two-stage depleted mantle model ages (T_{2DM}) have been increasingly used to help overcome post-mantle-extraction changes in the Sm/Nd ratio. As the name suggests, the calculated isotopic evolution curve of the sample follows a two-stage trend with differing $^{147}Sm/^{143}Nd$ ratios for different parts of the curve. The measured (present-day) $^{147}Sm/^{143}Nd$ ratio is used to calculate back to the crystallisation age of the rock, and an average crustal value (commonly 0.11) is used for $^{147}Sm/^{143}Nd$ from the

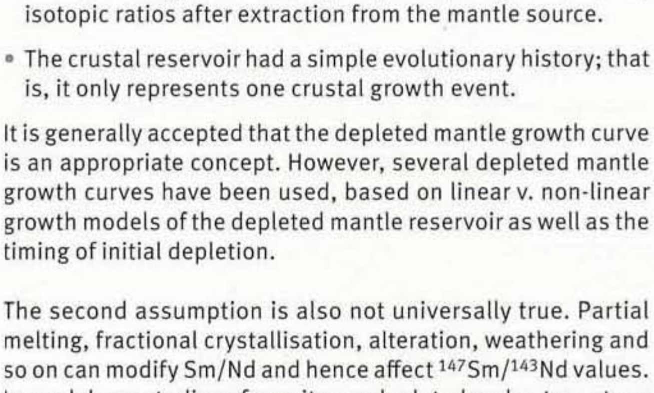

Figure 1.5 Plot of ε_{Nd} v. time illustrating single-stage (T_{DM}) and two-stage (T_{2DM}) Nd depleted mantle model ages. For T_{DM}, the measured $^{147}Sm/^{143}Nd$ ratio is used for the isotope evolution curve; for the two-stage calculation, an assumed $^{147}Sm/^{143}Nd$ ratio is used when extrapolating back in time beyond the age (T) of the sample in question. This typically results in a different evolution curve (in green) and hence a different model age from the single-stage model (in red). ε_{Nd} is the deviation (in parts per ten thousand) of the measured $^{144}Nd/^{143}Nd$ from CHUR.

crystallisation age to the intersection with the depleted mantle evolution curve. Calculated T_{2DM} ages, although commonly similar to single-stage T_{DM} model ages, can be significantly different. Unlike single growth-curve models, T_{2DM} requires knowledge of when the sample crystallised.

The last of the assumptions is clearly not always, and perhaps not often, true. Both granites and their sources, for example, can have several components with complex histories, making interpretation of the model age more problematic. For units with multiple crustal components, such as sediments and some granites, calculated model ages are best thought of as average ages. For rocks with a mixture of crustal and mantle-derived components, such as suggested for many granites, calculated model ages may have less meaning, though the greater abundance of Sm and Nd in crustal rocks (relative to mantle rocks) means granite model ages are largely indicative of their crustal components. Despite these shortcomings, model ages at a regional scale commonly prove very useful, the relative differences in ages being more important than the absolute values.

For summaries of the application of Nd isotopes to the study of magmatic rocks in Queensland, see Chapters 3, 4, 5 and 6.

U–Th–Pb dating is based on three complex radioactive decay schemes involving the emission of both alpha and beta particles, and the production of 41 nuclides of 10 elements. The three stable nuclides (^{206}Pb, from ^{238}U; ^{207}Pb, from ^{235}U; and ^{208}Pb, from ^{232}Th) form the end products of their respective decay schemes. **U–Pb dating** has been exceptionally useful. Much of its advantage arises from having two linked decay schemes with chemically identical, but isotopically distinct, end products. This provides an extra way of resolving complex isotopic behaviour, particularly in terms of quantifying the relatively common phenomenon of Pb loss, by plotting the isotopic ratios of the two schemes on a concordia plot. It also creates an additional means of dating, namely the $^{207}Pb/^{206}Pb$ method.

Zircon is the mineral most commonly dated by the U–Pb method. Uranium easily substitutes for zirconium, while lead is strongly excluded. Zircon is widespread as a primary mineral in igneous rocks, particularly the more felsic ones, and is also common in sandy sedimentary rocks and their metamorphic equivalents. It is very inert chemically and resistant to mechanical weathering, and has a high trapping temperature of 900 °C. Therefore, its 'clock' is not easily disturbed by geologic events, such as weathering, erosion and incorporation into sedimentary rocks, or by metamorphism and melting to form igneous rocks from which new zircon will crystallise. Zircon crystals with prolonged and complex histories can thus contain zones of dramatically different ages (usually with the oldest and youngest zones forming the core and rim, respectively, of the crystal), and are said to demonstrate inherited characteristics. Other minerals sometimes used for U–Pb dating are monazite, titanite, xenotime and two other zirconium-bearing minerals, baddeleyite and zirconolite.

Although U–Pb dating of zircon was first done in the 1950s, the method originally relied on dating samples of multiple grains, often referred to as **conventional U–Pb dating**. Therefore, unless the zircons were structurally simple without inherited cores, the method was likely to give inaccurate ages. Nevertheless, it was applied successfully in establishing the age of such rocks as the 'tuff marker beds' in the Mount Isa ore body (Page 1981) and the Croydon Volcanic Group in the Georgetown inlier (Black & McCulloch 1990). An improvement in the method was the introduction of **isotope dilution thermal ionisation mass spectrometry (ID–TIMS** or simply **TIMS)**, where single crystals can be dated to high precision (Parrish & Noble 2008). However, the problem of inheritance is still a serious issue. The inheritance problem was solved by the development of ion microprobes, which allow an ion beam to eject secondary ions from a small spot within a grain. These are collected and analysed in a mass spectrometer. The most successful of these instruments is the **sensitive high resolution ion microprobe (SHRIMP)** developed at the Australian National University in the late 1970s (McDougall 2008), although it did not become readily available for routine use until the 1990s as more machines were built. SHRIMP laboratories are now also installed at Curtin University in Perth and GA in Canberra, and have revolutionised the dating of geological events. Combined with the techniques of cathode luminescence, which images the detailed zonation within a zircon grain, SHRIMP can accurately date rims and cores of grains and determine crystallisation ages as well as provide information on inherited ages.

Numerous references to dates obtained by U–Pb zircon (SHRIMP) dating occur throughout this volume, but examples of studies in which the technique has played a pivotal role include joint GA/AGSO–GSQ work in the Georgetown and Coen inliers (Black et al. 1998, 2005; Blewett & Black 1998; Blewett et al. 1998; Neumann & Kositcin 2011), GSQ mapping of the Connors–Auburn Province (Withnall et al. 2009a) and various studies in the Mount Isa inlier (Southgate et al. 2000; Neumann, Southgate & Gibson 2009; Neumann, Gibson & Southgate 2009; Carson et al. 2008, 2011). The studies in the Mount Isa and Georgetown inliers not only dated plutonic and volcanic rocks, but also applied the method to sedimentary rocks to characterise the provenance of the sediments and constrain the maximum depositional ages. Combined with sequence stratigraphic studies, this approach has resulted in a very robust temporal framework for these geologically complex areas (Sections 2.2, 2.3).

A more recent development in U–Pb dating has been the application of **laser ablation inductively coupled plasma mass spectrometry (LA–ICP–MS)**. It is similar in principle to the SHRIMP technique, except that a laser is used rather than an ion beam. The main drawback of the method is that the laser burns a much larger spot in the grain and is less able to resolve fine zones within the grains. However, a LA–ICP–MS facility is less expensive to establish than a SHRIMP laboratory and can produce large amounts of data very rapidly. The technique can also be applied to other isotopic systems in zircons, such as Lu–Hf, which is very useful in petrogenetic studies (Belousova et al. 2002). A novel technique applied by geochronologists at Macquarie University to characterise the crustal evolution in the Mount Isa and Georgetown regions was to analyse zircons from modern drainage catchments by LA–ICP–MS to obtain both their U–Pb ages and Hf-isotope compositions (Griffin et al. 2006; Murgulov et al. 2007). A variation on the instrumentation is referred to as **laser ablation microprobe multi collector inductively coupled plasma mass spectrometry (LAM–MC–ICP–MS)**.

Another recent innovation has been the development of the zircon **U–Pb chemical abrasion (CA–TIMS) method**, which can result in very high precision dating of simple zircons by chemically removing zircon domains that have lost Pb, and analysing residual, perfectly closed-system zircon (Mattison 2005). This has been applied in Queensland to dating some of the tuff beds in the Bowen Basin (Metcalfe et al. 2011).

For a combination of reasons, including the fact that it is commonly the easiest of the three systems to be disturbed by secondary processes, Th–Pb dating was not as widely used as the two U–Pb systems until the advent of the **chemical Th–U–total Pb isochron (CHIME)** dating method, also referred to as **electron probe micro-analyser (EPMA)** dating. This is now used extensively to date monazite grains *in situ* using an electron microprobe as an alternative to more expensive and less accessible isotopic dating techniques (Montel et al. 1996; Cocherie & Albarede 2001). The age is determined from the U, Th and Pb concentrations of the monazite by iteratively solving the age equation of Montel et al. (1996) assuming negligible common Pb and that the isotopes of U are present in their crustal abundances. The method is commonly used to date *in situ* monazite grains in metamorphic rocks that record a multi-phase tectono-thermal history evidenced by porphyroblasts of different generations. Dating monazite inclusions in each porphyroblast generation should provide constraints on the ages of these events. The method has been applied to metamorphic rocks in the Mount Isa and Georgetown inliers in Queensland (Rubenach et al. 2008; Cihan et al. 2006; Ali 2010), although some of the results are difficult to rationalise with dates obtained by U–Pb zircon (SHRIMP) dating and regional considerations (Sections 2.2.11, 2.3.2).

The study of **common Pb** isotopes can also be directed at petrogenetic and metallogenetic problems (Black & Richards 1972b, 1972c) and can provide model ages for mineral deposits. Due to continuing radioactive decay of U and Th, the total reservoir of common Pb in the earth has become progressively more radiogenic with time. The simplest systems to interpret are usually those with high concentrations of Pb and much of the theory was derived from mineral deposits, particularly stratabound bodies of volcanogenic massive sulphides. The Pb in these approximates an evolutionary curve from which model ages of reasonable merit could be determined. Various growth curves have been proposed, but those by Stacey and Kramers (1975) and by Cumming and Richards (1975) have met with broad acceptance. For the Mount Isa Province, a refined model was proposed by Sun et al. (1994). This used the U–Pb zircon age (1653 ± 7 Ma) of the Mount Isa Group as a temporal calibration point on the Cumming and Richards (1975) growth curve for the isotopic composition of the spatially associated, and probably genetically related, Mount Isa Pb–Zn deposit. Using this model or modifications of it, it is possible to deduce ages for other stratabound deposits in the region, such as at

Century, Cannington and Dugald River (Carr et al. 1996, 2001; Large et al. 2005) and also for more distant deposits such as those near Einasleigh in the Georgetown inlier (Black, Carr & Sun 1997, p. 442).

Fission track dating is a relatively simple but robust radiometric dating technique based on analyses of the damage trails or tracks left by fission fragments in uranium-bearing minerals such as zircon, titanite and apatite and glasses (Wagner & Van den Haute 1992). Fission tracks are preserved in a crystal when the ambient temperature of the rock falls below the annealing temperature, which varies from mineral to mineral (~110 ± 10 °C for F-apatite, 125–150 °C for Cl-apatite and ~240 °C for zircon). Rocks cool as they are exhumed by erosion, and given certain assumptions such as geothermal gradient, the technique can be used to determine the rate of uplift and erosion of regions, by recording when rocks at a location reached the annealing temperature for a particular mineral. In Queensland, the technique has been applied to determine the thermal history of the Mount Isa and Georgetown inliers since the Neoproterozoic (Spikings et al. 2001a, 2001b).

The **(U–Th)/He** technique can also reveal a sample's thermal history, and is particularly effective on apatite, although it can be used for zircon and titanite. Helium is generated by radioactive decay of U and Th to Pb and, to a lesser extent, by Sm to Nd. (U–Th)/He dating effectively records the time a sample passed through the temperature range of ~40–80 °C. Lippolt et al. (1998) also applied (U–Th)/He dating to supergene iron hydroxides by demonstrating that goethite contains significant concentrations of U, Th and He, and that the calculated results qualitatively suggest He retention. Such dating of iron oxides in weathering profiles in Australia, including Queensland, was reviewed by Vasconcelos et al. (2008).

Most of the above techniques, with the exception of the last two, are applicable only to relatively old rocks because of the long half-lives of the parent isotopes. Studies of Pliocene and Quaternary deposits must rely on other techniques, which have been reviewed in detail by Vasconcelos et al. (2008) and for which numerous examples of their application in Queensland are given in Chapter 9.

The most well known of these techniques is **radiocarbon dating**. It uses the naturally occurring radioisotope carbon-14 (^{14}C), which is produced by cosmic ray interactions with the atmosphere, to estimate the ages of carbon-bearing materials up to ~62 000 years (Sheridan 1990). When plants fix atmospheric carbon dioxide into organic material during photosynthesis, they incorporate a quantity of ^{14}C that approximately matches its atmospheric level of this isotope. After plants die or are consumed by other organisms, the ^{14}C fraction of this organic material declines at a fixed rate due to radioactive decay. Comparing the remaining ^{14}C fraction of a sample to that expected from atmospheric ^{14}C allows the age of the sample to be estimated. The raw radiocarbon dates are calibrated to give calendar dates. Calibration is needed because the ^{14}C content of the atmosphere has varied through time because of variations in the flux of cosmic rays and the strength of Earth's magnetic field, and because of changes in the carbon distribution among terrestrial reservoirs (biosphere, atmosphere and ocean). Standard calibration curves are based on comparison of radiocarbon dates of samples that can be dated independently by other methods, such as examination of tree growth rings (dendrochronology), deep ocean sediment cores, lake sediment varves, coral samples and speleothems. Shells that obtain carbonate from sea water can also be dated, but require special calibration curves because of the slow uptake of atmospheric carbon into the oceans.

The intermediate nuclides in the **U–Pb** and **Th–Pb decay series** have very short half-lives in comparison with their parents, which make these nuclides useful for dating Pleistocene geological events that are too old to be resolved by the radiocarbon method and too young to be resolved by decay schemes with long half-lives. Among materials suitable for U–Th-series dating, corals and speleothems are the two most important types, as they bear important climatic information. The University of Queensland's Radiogenic Isotope Facility was among the first in Australia to establish U–Th-series dating techniques and has applied these to date speleothems from Queensland, New Zealand and China, and corals from the South China Sea, the Great Barrier Reef, Moreton Bay, Western Australia and Pacific islands for a range of research projects (Zhao 2006).

Radiation exposure dating includes fission track dating but also includes several techniques that are applicable to young deposits. They are thermoluminescence (TL), optically stimulated luminescence (OSL) and electron spin resonance (ESR) dating. These work on the same principle: natural radiation from U, Th and K from the surrounding environment causes electrons to become trapped in structural defects in a mineral, and the longer the exposure to radiation, the more electrons are trapped. However, the three methods differ in the approach employed for measuring the amount of trapped electrons. TL uses heat and OSL uses light to release and detect the electrons, but ESR uses a magnetic field to excite and detect them (Geyh & Schleicher 1990). The luminescent clock is set to zero by exposure to sunlight or heat. Thus minerals formed or heated (e.g. phenocrysts and xenocrysts) during eruption of a volcanic rock can be dated, as can materials exposed to sunlight before burial.

Cosmogenic isotopes provide another potentially fruitful avenue for dating young volcanism that could be applied to some of the young basalts in northern Queensland. Lavas extruded at Earth's surface ascend from depths beyond the penetration length of most cosmic rays (520 m for muons, and mostly <2 m for neutrons and protons). Once exposed at or near the surface, these lavas will accumulate cosmogenic isotopes (^{3}He, ^{10}Be, ^{14}C, ^{21}Ne, ^{26}Al, ^{36}Cl, etc.), whose abundances can be used to date the exposure (extrusion).

Amino acid racemisation dating is used to estimate the age of a specimen by measuring changes in amino acid molecules with respect to the time elapsed since they were formed. Most amino acids are optically active, having an asymmetric carbon atom and one of two different configurations, D (dextrorotary) or L (laevorotary), which are mirror images of each other.

Most living organisms keep all their amino acids in the L configuration. When an organism dies, control over the configuration of the amino acids ceases, and the ratio of D to L moves from a value near 0 towards an equilibrium value near 1, a process called racemisation. Thus, measuring the ratio of D to L in a sample gives an estimate of time elapsed since the specimen died.

1.4.3 Geochronology databases

A database of radiogenic-isotope geochronology spanning Precambrian and Phanerozoic terranes across Australia and its territories is managed and maintained by GA, in collaboration with the GSQ and the Northern Territory Geological Survey, under the National Geoscience Agreement. The database comprises isotopic analytical data and the associated interpreted radiometric dates, compiled from a range of published and unpublished sources. All new analyses acquired by GA geochronologists are entered into the database. Previously data was held in the superseded OZCHRON database.

Public access to the contents of the database is via GA's **Geochron Delivery** system, a web-based geographical information system interface, which allows external users to query, view and download analytical and interpreted-age data according to spatial, geological and geochronological criteria. At 1 June 2012, Geochron Delivery contained only some U–Pb zircon (SHRIMP) data. Migration of legacy data from the superseded OZCHRON database (which also encompassed Ar–Ar, K–Ar, Rb–Sr and Sm–Nd isotopic analyses) by GA is ongoing. It is anticipated that all isotopic dates referred to OZCHRON through this volume will be available through Geochron Delivery in due course.

In addition, the GSQ manages a database of isotopic dates for Queensland as part of its Geoscience and Resources Database. Most of the dates have been extracted from literature, although some are unpublished. The majority are by the K–Ar method, although U–Pb zircon (SHRIMP) dates obtained during GSQ projects are also included. The database contains mainly the ages, along with location, rock unit information, lithology and bibliographic source, although analytical data are included for some K–Ar samples. This dataset is released annually by the GSQ on the Mineral Occurrence and Geological Observation Data DVD. Databases of dates for Cenozoic volcanic rocks have been compiled by Gibson (2007) and Vasconcelos et al. (2008). Isotopic dates in theses from The University of Queensland have also been compiled by Mostert (2012) under the sponsorship of the GSQ and are available online through The University of Queensland's institutional digital repository.