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The contribution of geochronology to understanding the Paleozoic geological history of Australia

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From the viewpoint of isotope geochronology, studies of the Paleozoic geological history of Australia can be divided into three main eras: (i) the era of stratigraphy, when the ages of igneous and metamorphic events were inferred primarily from stratigraphic relationships; (ii) the era of K–Ar and Rb–Sr, when the broad time frame of many of the main thermal events was mapped out; and (iii) the era of SHRIMP, when U–Pb microanalysis, in combination with techniques such as Ar–Ar, Sm–Nd and Lu–Hf, made it possible to study not only the most recent events in the thermal history but also cooling histories and the ages of precursors and protoliths. The work during the last era was the most ambitious and controversial. As age measurements became more precise, their accuracy and the accuracy of the calibration of the geologic time-scale were called into question. Isotopic analyses of eastern Australian granitic rocks, undertaken to help understand magma genesis and the age of the source rocks from which the magmas were derived (the basement of the Lachlan Orogen), were interpreted by different researchers in fundamentally different ways. Ages measured on detrital minerals from Paleozoic sedimentary rocks were interpreted as indicating erosion of quite different source regions. These debates did not detract from the main achievements, however. There is a large and expanding database of high-quality age measurements on thermal events throughout the Australian Paleozoic. In many cases, this provides directly determined ages for igneous, metamorphic and deformation events previously dated only approximately using stratigraphy. The distribution of coeval magmatism and the progressive migration of that activity have been mapped out. Isotopic compositions have been used to estimate the relative contributions of crust and mantle components to magmas and the ages of those components. In some cases, geochronology has changed the geological paradigm. For example, in central Australia, the Alice Springs Orogeny is now known to be a major intraplate tectonothermal event, and granulite grade metasediments in the east of the Paleoproterozoic Arunta Inlier have been shown to be deformed and metamorphosed equivalents of some of the lower units of the adjacent Centralian Superbasin, part of a previously unrecognised incipient Paleozoic transcontinental rift. In combination with field studies, dating of mineralisation has shown that ore genesis occurred not randomly, but in a series of distinct metallogenic episodes, many of the major Paleozoic mineral deposits in Australia having formed in response to far-field stresses associated with orogenic events, commonly late in a tectonic cycle. The principal episode of mineralisation (480–440 Ma) followed the end of the major tectonothermal event that coincided with the protracted collision between east and west Gondwana, the Pan-African/Ross/Delamerian Orogeny.

KEY WORDS: Australia, detrital zircon, geochronology, granite genesis, Lachlan Fold Belt, Paleozoic, sediment provenance, SHRIMP.

INTRODUCTION

To begin to appreciate the impact of geochronology on our understanding of the Paleozoic geological history of Australia, one has only to scan three of the principal publications on the subject: *The Geological Evolution of Australia and New Zealand* (Brown *et al.* 1968), *Phanerozoic Earth History of Australia* (Veevers 1984) and *Billion-year Earth History of Australia and Neighbours in Gondwanaland* (Veevers 2000). The timing of these publications, by coincidence, marks the three main eras in Australian isotope geochronology: the era of stratigraphy, the era of K–Ar and Rb–Sr, and the era of

SHRIMP, respectively. In 1968, geochronology was a relative novelty, by 1984, it had been used to outline the broad distribution and time range of the main thermal events in Australia, and by 2000, it was fundamental to understanding the tectonic evolution of the continent. Geochronology is no longer just a method for measuring the ages of igneous rocks. The combination of isotopic techniques now available makes it possible to date geological processes over the spectrum of temperatures from diagenesis to magma genesis, to track the thermal history of metamorphism, and to characterise the provenance of rock types ranging from sediments to granites.

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ERA OF STRATIGRAPHY

Brown *et al.* (1968) reviewed the geological history of Australia at a time when isotope geochronology was in its infancy. The ages of the great majority of the Paleozoic igneous and metamorphic events could only be inferred from stratigraphic relationships. In discussing the evolution of the Paleozoic, Brown and others could draw on isotopic data from only a few isolated studies: some Rb–Sr work on the ages of deposition and metamorphism of shales, including anatexis in the Cooma complex (Compston & Pidgeon 1962; Pidgeon & Compston 1965) and on late granites intruding the so-called ‘Adelaide System’ (the Burra, Umberatana and Wilpena Groups) (Compston *et al.* 1966), and some K–Ar work on igneous rocks in southeastern New South Wales (Evernden & Richards 1962), New England (Cooper *et al.* 1963), eastern Queensland (Webb *et al.* 1963; Richards *et al.* 1966a) and Tasmania (McDougall & Leggo 1965).

These studies began to provide a numerical time frame for some thermal events but inevitably left many questions unanswered. For example, despite the presence of extensive Cambrian basalts in northwestern Australia, Cambrian greenstones in central Victoria and Cambrian mafic and felsic volcanic rocks in western Tasmania, there was no evidence of Cambrian felsic plutonic rocks. The belt of serpentinites, gabbros and amphibolites near Coolac in southern New South Wales marked a major shift in crustal structural trends, but its age was unknown. The age of the extensive Late Paleozoic igneous province of north Queensland could only be approximated as Permian. Similarly, the age of the thick pile of presumably Late Paleozoic volcanic rocks near the base of the Bowen Basin remained unknown because they are separated from overlying fossiliferous sediments by an unconformity.

Dating the Lachlan Geosyncline (now Lachlan Fold Belt/Orogen) granites posed a particular problem. For example, initially it was thought that the Late Ordovician Benambran Orogeny was accompanied by the emplacement of banded and gneissic two-mica granites (Joplin 1962). However, K–Ar dating of such rocks (Evernden & Richards 1962) gave Silurian to Middle Devonian ages. Even at this early stage of geochronological work, the recurrent questions of correlating plutonic lithologies, the accuracy of the isotopic age measurements and the link between radiometric ages and the stratigraphic time-scale started to be raised. While the nature and extent of Ordovician plutonism remained in doubt, it was evident that the period from the Late Silurian to Early Devonian was one of very active magmatism in the Tasmanides. However, it was not known whether these plutonic and volcanic rocks represented separate events or different phases of the same protracted igneous episode. Much of the igneous activity in Victoria, including the large cauldron structures in central Victoria, was demonstrably Late Devonian or younger, but again it was not known whether it represented a late phase of a protracted period of earlier activity or a discrete igneous episode. The same was the case for the magmatism near Bathurst, New South Wales, thought to be associated with the Carboniferous Kanimblan Orogeny: was it a single

episode or a series of magmatic phases? Using isotope geochronology, most of these questions have now been answered.

ERA OF K–Ar AND Rb–Sr

By the time that Veevers produced *Phanerozoic Earth History of Australia* (Veevers 1984), geochronology had become an integral part of Australian geological studies. Noting that ‘chronology is the core of history’ (p. v) and that ‘... the proliferation of radiometric dates of igneous rocks ... means that attempts at correlating igneous and sedimentary events rest on an increasingly reliable basis.’ (p. 1), Veevers (1984) opened his book by compiling a radiometric time-scale. He did so by adopting an approach also followed by some later authors, starting with the best available international time-scale (Armstrong 1978) and modifying it based on the results of selected other studies. The resultant time-scale placed all major boundaries, except the base of the Cambrian, within about 10 million years of current best estimates (Gradstein *et al.* 2004).

Most of the ages on which the time-scale was based, and nearly all the ages obtained on Australian rocks until the early 1980s, were measured by the Rb–Sr and K–Ar techniques. When measured on minerals, these ages could be very precise (95% confidence limits about 0.3% of the age), but their accuracy was limited, first by the low closure temperatures of most mineral K–Ar and Rb–Sr systems, and second by uncertainties in the decay constants, particularly for ^{87}Rb . Complicating matters further, the ^{87}Rb decay constants used by different Australian researchers differed by nearly 6%. The accuracy of both isotopic methods and the agreement between them improved significantly following the adoption of the decay constant convention recommended by the IUGS Subcommittee on Geochronology (Steiger & Jäger 1977) after its meeting in Sydney in 1976.

As radiometric dating was applied more widely in Australia, the need to define the Phanerozoic stratigraphic time-scale more accurately became a pressing issue. More attempts were made to use Rb–Sr whole-rock analysis to measure the deposition ages of sediments directly (Bofinger *et al.* 1968, 1970), but doubt remained over exactly what process was being dated, so the method was not pursued. The preferred approach was to measure the ages of igneous rocks in well-defined stratigraphic relationships to fossiliferous sedimentary units. The ages of several points in the time-scale were estimated in this way: for example the Devonian–Carboniferous boundary using volcanic rocks from the Cerberean Cauldron (McDougall *et al.* 1966); the Permian–Triassic boundary using volcanic rocks in the Bowen Basin (Webb & McDougall 1967); the Silurian–Devonian boundary using the Gocup Granite (Richards *et al.* 1977); and the early Ludlow using the Laidlaw Volcanics (Wyborn *et al.* 1982).

At the same time that the stratigraphic time-scale was being refined, the paleomagnetic method was being developed for determining shifts in the apparent position of the paleomagnetic pole (Irving 1964; Collinson *et al.* 1967; McElhinny 1973). Paleozoic Australia was no

longer considered to be a static isolated continent, but rather part of a drifting supercontinent (Gondwana) with which its geological evolution was inextricably entwined. With the mapping of Australia's apparent polar wander path (APWP) by researchers such as Goleby (1980), McWilliams & McElhinny (1980), Embleton (1981) and Schmidt (1982), dramatic changes in the environments of Paleozoic sediment deposition, which had previously been so difficult to explain, for example the presence of extensive glacial deposits in the Permian, were seen to be natural consequences of the drift of Australia between low and high latitudes.

The main aim, and achievement, of the Rb–Sr and K–Ar geochronology was to determine the broad history of igneous activity in eastern Australia, both within the Paleozoic Tasman and New England Orogens and at the margin of the Precambrian craton to the west. Most of the work was carried out at the Australian National University, the Australian Mineral Development Laboratories (AMDEL) and the University of Queensland, either as academic research projects or in support of the work of the Bureau of Mineral Resources, the Geological Survey of New South Wales, the South Australian Department of Mines and the Victorian Mines Department. The projects were focused in five main areas: the Adelaide Geosyncline (Delamerian Orogen), Tasmania, New England, eastern Queensland and the Lachlan Fold Belt, the last two receiving by far the most attention.

Delamerian Orogen

Very little evidence could be found of Cambrian igneous activity in the Paleozoic terrains east of the Precambrian craton. Near the craton margin, however, granites and felsic volcanic rocks yielding Cambrian ages were identified in Tasmania (McDougall & Leggo 1965), South Australia (Webb 1976; Milnes *et al.* 1977) and Queensland (Green & Webb 1974). The granites in South Australia were of particular interest because they provided constraints on the age of the Cambrian Delamerian Orogeny (Webb 1976; Milnes *et al.* 1977). Early Cambrian shales from the Adelaide Geosyncline yielded Rb–Sr whole-rock ages of 690–530 Ma that were interpreted as approximately the ages of deposition (Compston *et al.* 1966). On the craton, mica Rb–Sr and K–Ar ages measured on igneous and metamorphic rocks from the Broken Hill area provided evidence for Cambrian magmatism and metamorphism (Richards & Pidgeon 1963; Pidgeon 1967).

Evidence of Cambrian thermal events was also found outside the Adelaide Geosyncline, for example in the basement rocks of the Thomson Orogen in central Queensland (Harding 1969). The extensive flood basalts of the Antrim Plateau Volcanics in northern Australia, which stratigraphically are of Early to Middle Cambrian age, proved particularly hard to date, yielding K–Ar ages ranging from Early Cambrian to Early Devonian (Bultitude 1972, 1976).

Tasmania

The principal interest in Tasmania was the dating of the Paleozoic granites, both in northeastern Tasmania,

where they intruded the Early Paleozoic Mathinna beds, and in western Tasmania, where they intruded the Proterozoic Tyennan Block. Rb–Sr ages measured on the granites and associated volcanic rocks in the west were Early Carboniferous (Brooks 1966), distinctly younger than the Middle to Late Devonian ages measured on the granites in the east (Cocker 1982). An important distinction between the granites in the two areas was their initial Sr isotopic composition, those in the east having a range of initial $^{87}\text{Sr}/^{86}\text{Sr}$ ($^{87}\text{Sr}/^{86}\text{Sr}_i$) values similar to that in the granites of the Lachlan Fold Belt on the mainland, while those in the west had much higher values, reflecting the involvement of Precambrian sediments in the magma genesis (Cocker 1982). Contrary to expectations, the granite ages and compositions could not be used to correlate igneous provinces between Tasmania and Victoria. However, it was possible to demonstrate that some of the mineralisation in western Tasmania (e.g. at Bischoff) was directly related to granite magmatism (Brooks 1966).

New England

Early K–Ar work on the igneous rocks of the New England region confirmed the Permian age of granites at the southern end of the New England batholith and that some granites mapped as 'pre-Permian' were certainly Early Permian or older (Cooper *et al.* 1963). Following the recognition that there were two main granite suites, early S-type granites and later I-type granites (Chappell & White 1974), two major periods of igneous activity were identified, the first in the Late Carboniferous and the second in the Late Permian to Triassic (Flood & Shaw 1977; Shaw & Flood 1981). From differences in $^{87}\text{Sr}/^{86}\text{Sr}_i$, $\delta^{18}\text{O}$ and $\delta^{34}\text{S}$, it was concluded that the two suites had different source materials, the S-type granites being derived from the partial melting of trench-complex sedimentary rocks and the I-types from the partial melting of gabbroic and shoshonitic source regions (Shaw & Flood 1981).

Eastern Queensland

Geochronological studies in eastern Queensland were launched by a major regional K–Ar reconnaissance in the Cairns hinterland involving granites, volcanic rocks and metasediments collected across the boundary between the Precambrian Georgetown Inlier and the adjacent Paleozoic Tasman Fold Belt (Richards *et al.* 1966b). Unexpectedly, several granites and one volcanic unit proved to be of Middle Paleozoic age, and some Precambrian granites and metasediments showed evidence of a strong Middle Paleozoic overprint. Other igneous rocks had Late Paleozoic (Carboniferous) ages consistent with the stratigraphy. Units further north, including the voluminous Featherbed Volcanics, were younger (Early Permian) and anatectic granites in the Cooktown region were younger again (Late Permian). A protracted period of Carboniferous magmatism had been followed by two short periods of Permian magmatism, activity progressing episodically from the southwest to northeast. Permian–Carboniferous granites

were soon traced as far north as the Torres Strait (Richards & Willmott 1970).

Webb & McDougall (1968), in a combined K–Ar and Rb–Sr study of granites and volcanic rocks between Bowen and Brisbane in southeastern Queensland, identified two main pulses of magmatism, the first a protracted episode from the Devonian to the Triassic and the second a short pulse in the Cretaceous. They also found that the activity had moved generally from west to east. The Carboniferous granites were coeval with the Kanimblan movement and the Late Permian granites with the Hunter–Bowen Orogeny, but the Late Devonian granites, which were emplaced during a period of basin formation, appeared to be unrelated to the Tabberabberan Orogeny to the south. The youngest granites were post-tectonic. Some granites were coeval with associated volcanic rocks. All granites and volcanic rocks had low $^{87}\text{Sr}/^{86}\text{Sr}_i$ consistent with Precambrian crust playing no role in the magma genesis.

The question of the relationship between the Featherbed Volcanics and associated granites was revisited by Black & Richards (1972) using Rb–Sr. Initial Sr isotopic compositions in the volcanic rocks and nearby granites showed that all were derived from similar sources, but the ages measured on the granites were nearly 30 million years higher than those of the volcanic rocks, reversing previous interpretations that the volcanic rocks were the older. Black & Richards (1972) attempted to determine which igneous events might relate to Sn–(W–Mo) and Cu–Ag–Pb mineralisation, respectively, but they were thwarted by uncertainties in the Rb and K decay constants.

Reviewing the geochronology of the northern Tasman Orogen, Green & Webb (1974) discussed the numerous difficulties being encountered. The time-scale and the comparison between Rb–Sr and K–Ar ages were both in doubt because of large uncertainties in the K and Rb decay constants. Because of Ar loss, it was hard to resolve Precambrian from younger rocks where only K–Ar dates were available. Even in the younger rocks, the ages measured by K–Ar were more scattered and lower than those measured by Rb–Sr. South of the Broken River embayment, northeast Queensland, the succession of igneous events started with extrusion of Cambrian volcanic rocks, followed by magmatism in the Middle Ordovician, Late Silurian and Middle to Late Carboniferous. North of Broken River, the ages of the extensive Carboniferous granites and volcanic rocks were considered to be poorly determined. There were sufficient contradictions between the dating and field evidence that even the relative age of the two was in doubt. K–Ar ages measured on some Late Carboniferous granites were affected by intrusion of Permian granites nearby and Late Carboniferous ages measured on high-pressure metamorphic rocks were also considered to be unreliable due to Ar loss. Extensive mineralisation in the volcanic rocks appeared to be significantly younger than any of the associated granites.

Similar problems were encountered during K–Ar and Rb–Sr work on the igneous and metamorphic rocks of Cape York (Cooper *et al.* 1975). Four distinct periods of igneous activity spanning the period from Middle Silurian to Late Permian were identified, with the

youngest rocks in the northeast, but uncertainties in decay constants and the time-scale made correlations with stratigraphy ambiguous. The Precambrian host-rocks showed evidence for widespread Sr redistribution in the Silurian, and the high $^{87}\text{Sr}/^{86}\text{Sr}_i$ in the granites indicated the involvement of Precambrian crust in magma genesis. The scale of Silurian–Devonian Sr isotopic homogenisation in the Precambrian rocks was further documented and related more closely to the multi-episodic deformation history by Black *et al.* (1979), in one of the first successful attempts to unravel polymetamorphism.

In 1980, all available geochronology on the granites and volcanic rocks of northeastern Australia was collated (Oversby *et al.* 1980; Richards 1980), and the pattern of magmatism was becoming clear. Ordovician to Devonian granites were restricted to the Precambrian basement areas, whereas Permian to Carboniferous granites intruded both the Precambrian and the flanking Paleozoic sediments to the east. The Devonian age measurements were suspect, however, because in all such cases, the rocks were deformed, and in some the Rb–Sr and K–Ar ages did not agree. Some ‘Devonian’ granites were possibly Precambrian. The eastward migration of magmatism was well established, particularly in the north, although there were exceptions, possibly due to resetting of some K–Ar ages in the Permian. Volcanism peaked in the Late Paleozoic with major eruptions in the Late Carboniferous to Early Permian. Some conflicts with stratigraphic evidence remained, there being no isotopic evidence for either the three episodes of volcanism (Middle Carboniferous, Late Carboniferous and Permian) proposed by Branch (1966) or Late Permian eruptions. However, episodicity in the extensive Permian–Carboniferous Featherbed Volcanics was identified, consistent with the evidence from stratigraphy.

Lachlan Fold Belt

Isotopic studies in the Lachlan Fold Belt tackled a wider range of issues, but were mostly carried out on granites and on a smaller scale than those in Queensland. Exceptions were the reconnaissance K–Ar age measurements on igneous rocks in southeastern New South Wales by Evernden & Richards (1962) and the follow-up reconnaissance traverse of K–Ar and Rb–Sr ages of igneous rocks across Victoria (Richards & Singleton 1981). Regional reconnaissance K–Ar and Rb–Sr dating was also carried out across New South Wales by AMDEL, on behalf of the Geological Survey of New South Wales (Pogson & Hilyard 1981). Together these regional studies provided an overview of igneous activity in the southern Lachlan Fold Belt and still remain the principal geochronology database in some areas. The pattern of ages was complex, and the researchers emphasised that K–Ar ages are not necessarily intrusion ages, particularly in regions subject to slow cooling or protracted magmatism.

The oldest rocks dated were Ordovician granites intruding the Glenelg River Metamorphic Complex in far western Victoria close to the easternmost exposures of the Precambrian craton. Relatively early magmatism

was also identified in the eastern highlands of Victoria and New South Wales, where some granites were considered to be of Late Ordovician or Early Silurian age. Thereafter the magmatism became more widespread—extensive Late Silurian to Early Devonian rocks were found in western Victoria and to the east and west of the highlands. Even younger rocks (Late Devonian) were found in central Victoria and on the east coast, consistent with a migration of the locus of magmatism both towards the centre of the fold belt and towards the eastern margin of the continent. Igneous activity terminated, and this pattern was disrupted, with the formation of major Late Devonian volcanic cauldrons in central Victoria (McDougall *et al.* 1966) and Carboniferous magmatism west of Sydney.

Most other studies in the Lachlan Fold Belt were based on Rb–Sr analyses. These had two main advantages over the K–Ar technique. First, the Rb–Sr whole-rock isotopic system was less susceptible to isotopic resetting than K–Ar. Second, the $^{87}\text{Sr}/^{86}\text{Sr}_i$ provided an indication of the age of the rocks from which the magmas were derived. Unlike north Queensland and Tasmania, where the boundary of the Precambrian basement is relatively well defined in outcrop, the nature of the basement beneath the Lachlan Fold Belt in southeastern Australia was (and remains) a point of contention. Most evidence for the nature of the lower crust was indirect, coming from the chemical and isotopic composition of igneous rocks presumed to be derived from, or contaminated by, lower crustal rocks. However, at Delegate, xenoliths of lower crustal granulite and eclogite have been brought to the surface by two Jurassic basaltic diatremes (Pittman 1909). Rb–Sr analyses of four xenoliths by Compston & Lovering (1969) showed that, although isotopically disturbed at the time of emplacement, all were probably incorporated by the basalt magma as it passed through the lower crust. The unequilibrated Sr in one two-pyroxene granulite was interpreted as partly preserving an age of the order 1 Ga.

Several other studies also provided evidence that some of the Lachlan Fold Belt Silurian–Devonian magmas were derived from isotopically evolved crust. For example, in a Rb–Sr whole-rock and mineral study of granites near Corryong, at the southern end of the Wagga Metamorphic Belt, Brooks & Leggo (1972) showed that the so-called regional aureole granites (those surrounded by high-grade schists and gneisses, e.g. the Corryong, Koetong and Granya Granites) were both the oldest in the area (Early Silurian) and, like the granite at Cooma (Pidgeon & Compston 1965), had a high $^{87}\text{Sr}/^{86}\text{Sr}_i$ consistent with their being the product of partial or complete anatexis of sediments like their Ordovician host-rocks. A nearby high-level granite at Mt Mittamatite, in contrast, had a low $^{87}\text{Sr}/^{86}\text{Sr}_i$ consistent with derivation from a crustal source below the sediments. Considering all the available Rb–Sr and K–Ar mica data from the granites of Victoria and southern New South Wales, Brooks & Leggo (1972) noted the much tighter clustering, and bias towards higher values, of the Rb–Sr ages (*ca* 420–400 Ma). They suggested that the dispersed lower K–Ar ages might reflect Ar loss and that the migration of the locus of magmatism proposed by Evernden & Richards (1962)

possibly took place over a much shorter period of time than previously thought. They also pointed out that the susceptibility of mica ages (especially K–Ar biotite ages) to thermal overprinting is such that it is quite possible that the Evernden & Richards K–Ar reconnaissance was unable to resolve fine age differences or to detect the presence of the older granites in the Lachlan Fold Belt.

Two Rb–Sr studies in the Murrumbidgee Batholith by Roddick & Compston (1976, 1977) found further evidence for high $^{87}\text{Sr}/^{86}\text{Sr}_i$ in Lachlan Fold Belt S-type granites (those with chemical features consistent with derivation from weathered sedimentary source materials: Chappell & White 1974). However, they were faced with a paradox: several of the granites yielded Rb–Sr whole-rock ages significantly higher than the inferred age of their Ordovician host-rocks. This was attributed to the original Sr isotopic heterogeneity in the sedimentary source of the granites being partially preserved in the magmas because their Sr isotopic compositions did not equilibrate during magma genesis. A similar effect was found by Williams *et al.* (1983) in granites from the Berridale Batholith, casting further doubt on the validity of Rb–Sr whole-rock ages as a measure of granite emplacement ages in cases where the magma contained a high proportion of unmelted residual source material—restite (Chappell *et al.* 1987).

A very different method of estimating the age of the source of the Silurian–Devonian granites was explored by Compston & Chappell (1979). Assuming that the variation in granite chemical compositions, as reflected in linear correlations between the abundances of most elements, was produced by the variable separation of melt and restite, estimates of the source rock SiO_2 content and Rb and Sr distribution coefficients for the restite minerals were used to calculate the source Rb/Sr for a range of plutons. Combining this with the $^{87}\text{Sr}/^{86}\text{Sr}_i$ determined for each pluton from Rb–Sr whole-rock analyses, ‘source rock isochrons’ were constructed for two suites of restite-rich I-type plutons, one from the Moruya Batholith, and the other from the Berridale and Kosciuszko Batholiths. The latter isochron was the best defined, and the slope of the isochron suggested derivation of the granite suite from a source with a mantle extraction age of about 1.1 Ga. It was thereby inferred that the basement to the eastern Lachlan Fold Belt was not solely Paleozoic oceanic crust, but included continental blocks containing Middle to Late Precambrian igneous rocks and presumably also contemporaneous metasediments. A similar estimated source rock age (≤ 1.1 Ga) was obtained from Rb–Sr analyses of the subsurface Silurian I-type Wild Wave Granodiorite intersected by drilling near Cobar, central western New South Wales, providing further evidence for derivation of I-type granites from a Proterozoic source (Glen *et al.* 1983).

More support for the contention that the sources of eastern Australian granites were of Precambrian age was provided by a study of the Nd isotopic composition of the granites (McCulloch & Chappell 1982). Initial Sr and Nd isotopic compositions from a range of S- and I-type granites in the Berridale and Kosciuszko Batholiths formed a strongly covariant array that was consistent with derivation of the S-type granites from

a metasedimentary source and the I-type granites from a mixed source containing both mantle-like and crustal components. In both cases, the isotopic compositions were consistent with source rock ages in excess of 1 Ga. Evidence for the presence of older source material in the granite magmas was also provided by the first zircon U–Pb analyses (Williams 1978; Williams *et al.* 1983). Analyses of zircon fractions from S- and I-type granites of the Berridale and Kosciuszko Batholiths showed that much of the zircon, particularly in the S-type granites, was much older than the granite emplacement (Silurian). In most cases, the isotopic compositions did not define simple linear arrays, indicating that the inherited zircon had a range of ages. These could not be resolved by multi-grain isotope dilution analysis, but the more extreme compositions showed some inherited components to be Neoproterozoic or older.

The results of this first U–Pb work increased concerns about the accuracy of the granite ages as measured by other isotopic techniques. A study of clustered granites from the Berridale Batholith had shown that the various Rb–Sr mica ages were consistent with the mapped intrusive sequence (Williams *et al.* 1976). Further, when using the newly recommended decay constants (Steiger & Jäger 1977), there was very close agreement between granite Rb–Sr and K–Ar mineral ages (Williams *et al.* 1982). It had therefore been assumed that, in most cases, these ages were a close approximation to the granite emplacement ages, particularly for the youngest granites in an area where the local thermal overprints of later intrusions on earlier ones were still preserved. However, in one such case, the U–Pb age of monazite was more than 10 million years higher than the ages measured by Rb–Sr or K–Ar (Williams *et al.* 1983). While monazite crystallisation before granite emplacement was a possibility, lowering of the Rb–Sr and K–Ar ages by Sr and Ar loss was the most likely explanation. Adding to the uncertainty, some stratigraphically early S-type granites had monazite U–Pb ages as much as 20 million years higher than their K–Ar and Rb–Sr mica ages (Williams 1977). This problem could not be resolved by analysing zircon because the zircon precipitated from the melt phase of the magma could not be dated independently from the older zircon inheritance.

ERA OF SHRIMP

With the development of the SHRIMP (Sensitive High Resolution Ion MicroProbe), which enabled mineral U–Pb ages to be measured *in situ* within individual zoned crystals (Compston *et al.* 1982b; Clement & Compston 1990), geochronology in Australia entered a new era. Zircon and monazite U–Pb, with their high closure temperatures, became the favoured technique for dating felsic to intermediate igneous rocks and high-grade metamorphism. In addition, new fields of research opened up. It became possible to date the older zircon grains in igneous and metamorphic rocks that were inherited from their protoliths, and became practical to date enough detrital mineral grains from sedimentary rocks to undertake meaningful studies of their

provenance. At the same time, the use of K–Ar was widened to include studies of sediment provenance and the thermal history of metamorphic terranes, and Rb–Sr was combined with Sm–Nd to further investigate magma genesis. In some cases, the new geochronology confirmed, perhaps with greater accuracy, the geological history already mapped out. In others, it created controversy as discrepancies between previous interpretations and the dating emerged. The accuracy of SHRIMP age determinations and their relevance to the geological time-scale was particularly contentious. Sometimes the geochronology answered longstanding questions; sometimes it turned up the unexpected.

Accuracy of SHRIMP Pb/U age measurements: standards and calibration

Ion microprobes operate on the principle that high-energy ions bombarding the surface of a solid target sputter (eject) secondary ions from the target material that are then mass-analysed to determine the target's elemental and isotopic composition. The composition of the secondary-ion beam is not the composition of the target, however. Isotope ratios are fractionated, and different elements ionise with different efficiencies, so to determine absolute isotopic and elemental compositions, it is necessary to calibrate analyses against standards. The corrections for instrumentally induced isotopic fractionation are broadly mass-dependent and, for heavy elements, are sufficiently small ($\sim 2.5\%$ AMU for Pb) that they are commonly ignored (Compston *et al.* 1986). However, the differences in ionisation efficiency between elements can be very large (about a factor of three for $^{206}\text{Pb}/^{238}\text{U}$), so accurate calibration against high-quality reference materials is essential.

Several standards and calibration procedures were used as SHRIMP U–Pb analysis techniques were refined (Compston *et al.* 1984; Williams & Claesson 1987; Clauoué-Long *et al.* 1995; Williams 1998). Because secondary-ion emission is matrix-sensitive, standards must be the same mineral as that to be dated, but finding natural minerals with uniform Pb/U and U contents has proved difficult. The first zircon standard, Sri Lankan megacryst SL3 (~ 3540 ppm U), gave inconsistent results (Williams *et al.* 1988b) and so was replaced by megacryst SL13, in which U was lower (~ 238 ppm). The inconsistencies were later explained as the effects of metamictisation (McLaren *et al.* 1994) and systematic bias in SHRIMP Pb/U ages measured on zircon with U contents above ~ 2500 ppm (Williams & Hergt 2000). SL13 also proved unsatisfactory, however. Although Pb/U was very uniform on a microgram scale, on the nanogram scale of SHRIMP analyses it varied by several percent, and in rare cases by more than an order of magnitude, due to the presence of unsupported radiogenic Pb (Compston 1999). The ages measured against SL13 could change by a per cent or more, depending on how the Pb/U variation was modelled (Compston 2000a, b). SL13 was also abandoned (except as a U concentration standard) but not before it had been used to measure some key points in the stratigraphic time-scale (Clauoué-Long *et al.* 1991, 1992; Compston & Williams 1992; Compston *et al.* 1992; Roberts *et al.* 1996).

Consideration was given to using the reference zircon megacryst 91500 distributed through Geostandards (Wiedenbeck *et al.* 1995), but its composition was not ideal, and, being a single crystal, the supply was limited. It was decided instead to switch to multi-grain zircon samples that, although heterogeneous in U content, had very uniform Pb/U. Analysts at the Australian National University chose zircon from the 1.1 Ga Duluth Complex in Minnesota, from which Paces & Miller (1993) had obtained extremely concordant ID-TIMS (isotope dilution thermal ionisation mass spectrometry) analyses. The first site selected (AS3) contained zircon of variable quality and so was soon replaced by another from the same complex (FC1). Geoscience Australia chose zircon from a 1.85 Ga gabbro (QGNG) from the Cape Donnington Suite, South Australia. This was good for monitoring Pb isotopic fractionation, but both ID-TIMS and SHRIMP analyses showed it to be heterogeneous in Pb/U and slightly discordant. The standard now used by both Geoscience Australia and the Australian National University for most Phanerozoic zircon analyses is TEMORA, zircon from the 417 Ma Middledale Gabbroic Diorite in central New South Wales (Black *et al.* 2003a, b).

The use of multiple standards raised the question of bias between the ages measured against them. Black *et al.* (1997), assessing ages measured against SL13 and QGNG, applied an upward correction of 1.3% to all Pb/U ages measured relative to the former. Jagodzinski & Black (1999) noted a similar bias, but advised against a general correction because individual estimates of the correction ranged from 0 to 3%. Compston (2001) criticised the data assessment in both these studies, pointing out that the analytical uncertainties had been overestimated, so large and variable amounts of Pb loss, particularly from QGNG, had been overlooked. He argued that, if Pb loss was taken into account, the Pb/U age of QGNG measured relative to SL13 agreed with its ID-TIMS concordia intersection age within 0.4%. A more comprehensive assessment of possible bias, including new ID-TIMS analyses of QGNG and SHRIMP analyses of TEMORA and AS3, soon followed (Black *et al.* 2003b). Consistent with previous findings, the ages measured on SL13 were scattered. The implication of the measurements was that, relative to ages measured against TEMORA, ages measured against QGNG were 0.5% high unless it was assumed to be slightly discordant, ages measured against AS3 were about 1% high, and ages measured against SL13 were about 1% low. Further comparisons, between QGNG, another sample from the Middledale Gabbroic Diorite (TEMORA 2) and a new zircon standard (R33) from a 419 Ma monzodiorite in the Braintree Complex, Vermont, were reported by Black *et al.* (2004). R33 and the two TEMORA samples were found to agree within error, although a slight difference between the two TEMORA samples was suspected. All agreed with QGNG, only if it was assumed to be discordant.

The final conclusion from these studies is that there are matrix and technical effects in SHRIMP Pb/U calibrations that can introduce random differences between replicate mean $^{206}\text{Pb}/^{238}\text{U}$ age measurements of up to 2%. Based on averages of large numbers of analyses, there is also a bias between the ages measured

against different standards. Relative to ages measured against TEMORA or R33, ages measured against AS3 (FC1 has not been rigorously tested) are about 1% high, those measured against QGNG are about 0.5% high (unless it is assumed to be discordant: $^{206}\text{Pb}/^{238}\text{U}$ age = 1842 Ma; cf. $^{207}\text{Pb}/^{206}\text{Pb}$ age = 1852 Ma), and those measured against SL13 are very approximately 1% low. Most analyses from which these biases were estimated scatter beyond analytical error, however, and particularly in the case of SL13, the size of the bias depends upon how the scatter is modelled (Compston 1999). Age determinations against SL13 are the least likely to be accurate, systematic errors of up to 3%, although rare, being possible. Only a small component of the bias is likely to be due to errors in the accepted values of the U decay constants and small discrepancies between ID-TIMS spike calibrations in different laboratories (Schoene *et al.* 2006). Currently, therefore, the absolute accuracy of a modern SHRIMP Pb/U age determination referenced to QGNG, TEMORA, AS3, FC1 or R33 (namely most Phanerozoic age determinations in the last 10 years), unless it is replicated or measured against more than one standard, is limited by calibration uncertainties to about $\pm 1\%$ (95% confidence limit).

Geologic time-scale

Australian geochronology has played a longstanding role in calibration of the Phanerozoic geologic time-scale. The time-scale compiled by Kulp (1961), for example, used the K–Ar age of the Late Devonian Cerberean Volcanics in Victoria (Evernden *et al.* 1961) to place the Devonian–Carboniferous boundary at 345 Ma. The history of the numerical time-scale has been one of constant controversy and revision, some disputes continuing to the present day. Over time, however, there has been a general convergence in opinion, and the time differences under discussion have, on the whole, become progressively smaller.

PRE-SHRIMP

Prior to the early 1980s, time-scale age measurements, particularly in Australia, depended primarily on the K–Ar and Rb–Sr systems. Partial Ar and Sr losses were constant concerns, so wherever possible the results obtained by the two techniques were compared. Prior to 1976, however, even that process was subject to ambiguity because of uncertainties in the decay constants, particularly for ^{87}Rb . For example, remeasuring the age of the Cerberean Volcanics, McDougall *et al.* (1966) could achieve agreement between K–Ar and Rb–Sr biotite ages only if the ^{87}Rb decay constant was 2.7% lower than the value accepted at the time. Complicating the issue further, it was discovered that incorrect assumptions had been made about the ^{40}K decay process (Beckinsale & Gale 1969), and the assumed abundance of ^{40}K was incorrect (Garner *et al.* 1975). These issues were largely resolved by the 1976 convention in the use of decay constants (Steiger & Jäger 1977), but there is growing evidence that still further refinement is required (Renne *et al.* 1998; Min *et al.* 2000; Begemann *et al.* 2001; Schoene *et al.* 2006).

Most ages used for time-scale calibration were based on the analysis of mineral separates and/or igneous whole rocks. Two attempts to date sediment deposition directly by Rb–Sr analysis of shales (Bofinger *et al.* 1968, 1970) produced ages consistent with the expected values within the relatively large analytical uncertainties, but because it could not be proved that the process being dated was deposition, the method was abandoned.

Early studies in eastern Australia focused on the Early Paleozoic. Richards *et al.* (1977) used K–Ar and Rb–Sr ages measured on the Gocup Granite to estimate the Early Devonian to be 409 ± 3 Ma, a result consistent with the preferred time-scale at the time (Armstrong 1978). Although the original fossil evidence was subsequently shown to be erroneous (Pickett & Jenkins 1981), the measured age was supported by later zircon U–Pb dating, which gave 411 ± 5 Ma (Stuart-Smith *et al.* 1992). Wyborn *et al.* (1982), in a K–Ar and Rb–Sr study of several samples of the Laidlaw Volcanics, Australian Capital Territory, obtained a well-defined age estimate of 420.7 ± 2.2 Ma for the early Ludlow, in conflict with a very similar age previously measured on the Late Ordovician Stockdale Rhyolite in England (Gale *et al.* 1979). Wyborn *et al.* (1982) concluded correctly that the Stockdale result was in error, later reinterpreting the Stockdale analyses as indicating an age of ‘at least 430 m.y.’ (Compston *et al.* 1982a p. 297). Having confirmed the close agreement between K–Ar and Rb–Sr mica ages measured using the recommended decay constants, Williams *et al.* (1982) remeasured the age of the Cerberean Volcanics as 367 ± 2 Ma, within error of the best estimate by McDougall *et al.* (1966). They also redated micas from a Middle Ordovician bentonite from Kinnekulle, Sweden (Byström-Asklund *et al.* 1961), obtaining a minimum age of 446 ± 3 Ma for the early Caradoc.

EARLY SHRIMP CONTRIBUTIONS

Subsequent to these studies, the SHRIMP was commissioned, and there was a surge of interest in more accurate calibration of the geologic time-scale using zircon U–Pb. For example, the age of the Permian–Triassic boundary was measured as 251.2 ± 3.4 Ma using bentonite zircon from the stratotype at Meishan, China (Claoué-Long *et al.* 1991), the age of the Devonian–Carboniferous boundary was measured as 353.2 ± 4.0 Ma using bentonite zircon from the stratotype at Hasselbachtal, Germany, and tuff zircon from the Kingsfield Formation, New South Wales (Claoué-Long *et al.* 1992), a series of five zircon samples from tuffites and ashes in the British Ordovician and Silurian stratotypes yielded ages ranging from 438.7 ± 2.0 Ma for the early Llandovery to 465.7 ± 2.1 Ma for the early Llanvirn (Compston & Williams 1992), and the Late Middle Cambrian was dated at 505–502 Ma using the Mt Read Volcanics, Tasmania (Perkins & Walshe 1993; Black *et al.* 1997). The age of the Early Cambrian was measured using zircon from a tuff at Sellicks Hill, near the top of the Heatherdale Shale, South Australia, 526 ± 4 Ma (Cooper *et al.* 1992), and from the Lie de Vin Formation, Morocco (521 ± 7 Ma) and the Meishucun section, China, 525 ± 7 Ma (Compston *et al.* 1992). The last two determinations were

particularly important because they showed that the Precambrian–Cambrian boundary was much younger than the *ca* 570 Ma proposed in the favoured time-scale of the day (Harland *et al.* 1990). A series of ages was measured on the Carboniferous to Permian volcanic rocks of northeastern New South Wales, providing age estimates through from the middle Viséan to late Artinskian: 332.3 ± 2.2 to 274.1 ± 3.4 Ma (Claoué-Long *et al.* 1995; Roberts *et al.* 1995).

Except for the base of the Cambrian, these ages were in broad agreement with ages previously measured, a testament to the accuracy of the newly developed SHRIMP dating technique. In detail, however, there was a persistent discrepancy—the ages measured on the zircon from the British stratotypes (Compston & Williams 1992) were mostly about 1% lower than those measured on the same zircon samples by ID-TIMS (Tucker *et al.* 1990). The SHRIMP ages for the Cambrian also appeared to be relatively low (Tucker & McKerrow 1995). The SHRIMP analysts argued that the multi-grain samples analysed by ID-TIMS contained unidentified xenocrysts (Compston & Williams 1992); the ID-TIMS analysts argued that either the SHRIMP data were biased or included discordant analyses that could not be detected because of SHRIMP’s poor analytical precision (Tucker & McKerrow 1995). It is the ID-TIMS data that have formed the basis for the currently accepted numerical time-scale (Gradstein *et al.* 2004).

Expanding the dataset on Permian tuffs and volcanic rocks from the Sydney and Bowen Basins and New England Orogen, and using a new power-law for SHRIMP Pb/U calibration (Claoué-Long *et al.* 1995), Roberts *et al.* (1996) established the first direct correlation between the eastern Australian Early Permian succession and the type sections in Russia. Although again some SHRIMP ages were slightly lower than the ID-TIMS zircon ages measured on comparable rocks (Gulson *et al.* 1990), the study showed that volcanism in the Sydney Basin and southern New England Orogen started earlier than previously thought, that the Greta Coal Measures were diachronous and that Late Permian volcanism in the Warwick region was contemporaneous with the oldest plutonism in the New England Batholith. The accuracy of some of the SHRIMP ages was challenged by Draper & Fielding (1997) but defended by Roberts *et al.* (1997), who pointed out that the SHRIMP ages for both the Carboniferous (Claoué-Long *et al.* 1995) and the Permian–Triassic boundary (Claoué-Long *et al.* 1991) had been substantiated by measurements by other techniques (Renne *et al.* 1995). It was also pointed out that zircon ages measured on tuffs must be considered maximum estimates because of the possibility of reworking. In another major study in the New England region focused on dating the base of the Late Carboniferous to Middle Permian Kiaman magnetic reversal, Opdyke *et al.* (2000) obtained a series of closely spaced zircon ages consistent with the stratigraphic sequence and again strongly defended the accuracy of ages measured against SL13.

The impact of SHRIMP geochronology on calibration of the numerical time-scale is reflected in the Australian Phanerozoic time-scale compiled by the Australian Geological Survey Organisation (Young & Laurie 1996).

SHRIMP data played a key role in defining the Atdabanian–Botoman, the Middle–Late Cambrian, the Arenig–Llanvirn, the Early–Late Ordovician, the Ordovician–Silurian, the Devonian–Carboniferous, the Tournasian–Visean, the Visean–Namurian and the Permian–Triassic boundaries. This was a conscious decision by Young & Laurie (1996), who accepted the argument by Compston & Williams (1992) that the slightly higher zircon ages for most boundaries measured by ID-TIMS (Tucker *et al.* 1990) were probably in error because of the presence of inherited grains. The argument was not accepted by Gradstein *et al.* (2004).

THE TIME-SCALE DEBATE

Frustration with uncertainty in the geologic time-scale became evident in a series of letters to *The Australian Geologist* in 1999. VandenBerg (1999a), from the Geological Survey of Victoria, noted the absence of a definitive time-scale, particularly for the Early Paleozoic, and conflicts between existing time-scales and the ages of some Victorian rocks of known biostratigraphic age. He proposed creating a composite time-scale based on the time-scales of Harland *et al.* (1990), Tucker & McKerrow (1995), Young & Laurie (1996) and Tucker *et al.* (1998). Packham (1999b) criticised this approach, suggesting instead that each point in the time-scale should be assessed on the basis of all the available data. However, he noted the possibility of bias between SHRIMP ages measured relative to different standards. Fordham (1999) supported the amalgam concept, proposing his own version of the time-scale as used by the Geological Survey of Queensland and questioning the stratigraphic control on one of the Victorian data points. Black *et al.* (1999), on behalf of the Australian Geological Survey Organisation and the Australian National University, argued that defining the time-scale was a major undertaking involving many specialist disciplines, and it should not be modified *ad hoc* for regional convenience. They also pointed out that the discrepancies between ages measured against preferred SHRIMP standards were less than 1%. In the Early Paleozoic, this is significant, however, ~4 million years being longer than the duration of many graptolite and conodont zones. In a more detailed response, Young *et al.* (1999) also played down the possible bias between SHRIMP standards, noting several examples where SHRIMP ages agreed well with determinations by other techniques. However, they cautioned against using ages related to QGNG until its composition was published. They were most concerned about moves by Jagodzinski & Black (1999) to use ID-TIMS zircon ages as a 'benchmark' for the Australian Devonian, emphasising that those ages (Tucker *et al.* 1998) were based on $^{207}\text{Pb}/^{206}\text{Pb}$, which was susceptible to the presence of inheritance and error in corrections for common Pb. They warned that the precision of an age measurement should not be mistaken for accuracy, and urged a cautious, evolutionary approach to refining the time-scale, noting that discrepancies were mostly at the sub-1% level.

The decision by Compston (1999) that the SL13 crystal was heterogeneous and should be modelled (Sambridge & Compston 1994) as a mixture of zircon of two different

ages (580 and 565 Ma) necessitated a review of much of the SHRIMP geochronology and a reassessment of the question of bias between SHRIMP and ID-TIMS (Compston 2000a, b). Recalculation of SHRIMP analyses used to define the Late Cambrian to Devonian time-scale yielded mixed results. The age of the Arenig Llyfnant Flags became ambiguous because it depended on how the dispersed zircon ages were modelled, but that of the Llanvirn Serw Formation moved to within error of the ID-TIMS result (Tucker *et al.* 1990). The age of bentonite from the Llandovery Birkhill Shale was also ambiguous because of possible inheritance, but that of the Caradoc Pont-y-ceunant Ash agreed well with the ID-TIMS age once analyses of inherited grains were omitted. The unexpectedly high revised SHRIMP age for the Early Caradoc Kinnekulle Bentonite (*ca* 463 Ma) was explained by the presence of inheritance that could not be detected because of large analytical uncertainties. The age of the Ludlow Laidlaw Volcanics was ambiguous because the igneous zircon overgrowths appeared to have a range of ages from *ca* 476 to *ca* 417 Ma, only the youngest of which was consistent with Rb–Sr and K–Ar age measurements. It was shown that apparently discrepant ID-TIMS ages on the Tremadoc (Landing *et al.* 1997), Dolgellian (Davidek *et al.* 1998), Frasnian and Lochkovian (Tucker *et al.* 1998) could be made consistent with SHRIMP measurements by appropriate choice of the common Pb composition. Compston (2000b) concluded that, following the recalculations, there was no bias between SHRIMP and ID-TIMS results, and that the suggestion by Compston & Williams (1992) that the multi-grain analyses of Tucker *et al.* (1990) were high because of inheritance could not be proven.

Dating Early Devonian volcanogenic rocks from the Hill End Trough, Jagodzinski & Black (1999) noted that the ages measured against SL13 were slightly low relative to those measured against QGNG, but both were higher than expected given the age assigned to the Silurian–Devonian boundary by Young & Laurie (1996), consistent with the revision of the time-scale proposed by Tucker *et al.* (1998). Compston (2001) disagreed that there was a bias between SHRIMP standards and, omitting analyses possibly affected by Pb loss, calculated the ages of the Hill End rocks to be slightly higher still. This created a conflict with the sedimentological evidence, prompting Packham (2003) to question the value of all the ages recalculated by Compston (2000a, b, 2001) in defining the numerical time-scale. Black & Jagodzinski (2003) disagreed with the recalculated results, pointing out that the errors in SHRIMP analyses are not only due to counting statistics, in which case mixture modelling of both SL13 and sample analyses was invalid. Taking as many errors as possible into account and rejecting analyses referenced to SL13, they agreed with Packham's argument that, contrary to previous conclusions, the whole of the Merriens Formation was deposited very rapidly at *ca* 412.5 Ma, consistent with its Pragian stratigraphic age.

Noting the discrepancy between the age of 367 Ma measured on the Cerberean Volcanics by Rb–Sr and K–Ar (Williams *et al.* 1982) and the zircon age of 381 Ma measured by Tucker *et al.* (1998) on the Frasnian Little War Gap Bentonite, Compston (2004) redated the

volcanics by SHRIMP U–Pb using the AS3 and TEMORA standards and UO_2^{+} rather than U^{+} as the reference U species. Despite concerns about heterogeneous Pb/U in AS3, he determined that volcanic units above and below the Givetian Taggerty Formation (Young & Turner 2000) had indistinguishable ages of 374 ± 1.4 Ma, consistent with the proposal that the Little War Gap Bentonite is actually Eifelian (Streel 2000). Nevertheless, the Frasnian age assignment based on conodonts (Tucker *et al.* 1998) is by far the more reliable (G. Packham pers. comm. 2006).

All this work to define the geologic time-scale is part of an evolving story in which the revised time-scale recently adopted by the International Commission on Stratigraphy (Gradstein *et al.* 2004) is simply the next chapter.

Evolution of the Tasman Fold Belt system

MAGMATISM, METAMORPHISM AND OROGENESIS

The tectonothermal history of the Tasman Fold Belt system, namely the orogenic belts east of the Precambrian craton, spans the whole of the Paleozoic and beyond. Detailed discussions of that history as presently understood, with references to much of the growing geochronology dataset on which it is based (see also the Geoscience Australia geochronology database OZ-CHRON at <<http://www.ga.gov.au/oracle/ozchron/>>) can be found in the compilations by Bain & Draper (1997), Douglas & Ferguson (1988), Scheibner & Basden (1998), VandenBerg *et al.* (2000), Veevers (2000), Birch (2003) and Glen (2005). The review of the whole Tasmanides by Glen (2005) provides the most recent comprehensive assessment, using geochronology to integrate the major thermal events throughout eastern Australia into a geologic history described in terms of a series of tectonic cycles at a convergent plate margin involving no continent–continent collision, and overlapping in space and time. The sequence of phases in a complete idealised cycle, best exemplified in the Delamerian Orogen, is envisaged to be rift, drift, convergence and collision, but not all phases are necessarily present in every cycle. Based on the Glen (2005) interpretation, the evolution of the Tasmanides can be summarised as follows.

The prelude to the formation of the Tasmanides was the breakup of a Mesoproterozoic supercontinent and the separation of an eastern continental block (probably Laurentia), leaving a passive eastern margin on Gondwana (Moores 1991; Burrett & Berry 2000). The exact timing of the breakup has been difficult to determine, and it is likely that it was a protracted process. The 827 Ma Gairdner dyke swarm in South Australia has been interpreted as being rift-related (Wingate *et al.* 1998), there is evidence for rift-related magmatism in Tasmania at ≥ 777 Ma (Holm *et al.* 2003), and there are extensive 600–580 Ma rift-related volcanic rocks in Tasmania and western New South Wales (Crawford & Berry 1992; Crawford *et al.* 1997). Two main cycles of rifting have been identified (Haines & Flöttmann 1998; Glen 2005), the first represented by the growth of the Adelaide Rift Complex and the second by formation of

the Kanmantoo Trough and its equivalents during the closure of the Mozambique Ocean, amalgamating east and west Gondwana (Dalziel 1997). Evidence for a plate-margin setting and orogenesis at this time is also preserved further east in the form of ca 560 Ma ophiolite near Rockhampton (Bruce *et al.* 2000) and 583–500 Ma high-grade metamorphism in the Anakie Inlier (Fergusson *et al.* 1998).

Post-rifting convergence was marked by the development of Cambrian mafic to ultramafic complexes, most of which are under cover and detectable only by geophysics, and by a ca 510 Ma overprint on the Ar–Ar ages of some Adelaidean metasediments (Offler *et al.* 1998). MORB-like mafic magmas intruded both the Adelaidean and Kanmantoo Trough from 526 to 510 Ma (Chen & Liu 1996). Mafic to felsic volcanic and intrusive rocks exposed or accessed by drilling on the eastern margin of the Curnamona Craton have ages of 520–480 Ma (Fanning 1996; Maher *et al.* 1997). Similar rocks, with ages ≥ 500 Ma, are exposed in the Wellington and Heathcote belts, central Victoria, and as small bodies in the Melbourne and Bendigo Zones (Spaggiari *et al.* 2003). A possibly related, but as yet undated, concealed belt of volcanic rocks extends along the southern margin of the Thomson Orogen. Eclogite blocks, plagiogranites and metadiorites in serpentinite with ages of ca 530 Ma (Aitchison *et al.* 1992; Fanning *et al.* 2002; Sano *et al.* 2004) exposed along the Peel–Manning Fault System in the southern New England Orogen are probably also part of this episode. The tectonic relationship between this igneous activity off the continental margin and the coeval (513 Ma) Antrim Plateau Volcanics (Hanley & Wingate 2000), a vast outpouring of flood basalts across the Precambrian craton in northern Australia, remains unclear.

Collision following convergence produced metamorphism and eclogite (502 Ma) in Tasmania (Turner *et al.* 1998), a major episode of metamorphism and igneous activity along the craton margin in South Australia and western Victoria (Haines & Flöttmann 1998) and deformation in central Queensland (Withnall *et al.* 1996)—the Delamerian Orogeny. Deformation in the Kanmantoo Trough started at 514 Ma (Foden *et al.* 1999) and lasted until 490 Ma. It was accompanied and followed by the intrusion of 497–481 Ma gabbros and high-level granites (Foden *et al.* 2002). Outboard, in western Victoria, the tectonothermal history was very similar. Peak deformation at about 516 Ma (Turner *et al.* 1993b) was followed by 500 Ma extensional volcanism (Crawford *et al.* 1996), then granite magmatism and regional cooling until about 480 Ma (Turner *et al.* 1993b). At the same time (505–495 Ma) there was also voluminous extensional volcanism in western Tasmania followed by late granites (Perkins & Walshe 1993).

The Delamerian Orogeny was followed by a succession of three orogenic cycles that affected the eastern Tasmanides from Tasmania to north Queensland over the period ca 490–320 Ma, the Lachlan supercycle (Glen 2005). The first cycle, the Benambran, was initiated by the widespread deposition of Early to Middle Ordovician turbidites and the offshore formation of the intra-oceanic Macquarie Arc which developed in three pulses; 490–475, 466–455 and 452–438 Ma (Butera *et al.* 2001; Glen

et al. 2003; Simpson *et al.* 2005; Percival & Glen 2007), the last of which produced shoshonites coeval with zoned igneous complexes to the west (Elliott & Martin 1991). Benambran components have also been identified in the accretionary complex at the southern margin of the New England Orogen—480 Ma gabbros and blueschists with mica K–Ar ages of 482–444 Ma (Fukui *et al.* 1995; Fanning *et al.* 2002). The early Benambran cycle in north Queensland produced Late Cambrian to Late Ordovician magmatism that records a progression from intraplate bimodal volcanism to subduction-related calc-alkaline magmatism, reflecting rifting of the continental margin and the development of a continental arc (Henderson 1986; Berry *et al.* 1992; Hutton *et al.* 1994). High-grade metamorphism of Late Neoproterozoic to Early Paleozoic rift sediments in central Australia at 470–460 Ma (Buick *et al.* 2005; Maidment *et al.* 2004) reflected far-field effects of the orogeny within the craton. Deformation, in some cases terminating the cycle, is recorded in Ar–Ar mica ages ranging from *ca* 455 Ma in western Victoria to *ca* 430 Ma in the east (Foster *et al.* 1999), and in Ar–Ar ages of *ca* 435 Ma from low-grade metasediments in central New South Wales (Ferguson *et al.* 2005). Post-deformation granites in eastern Victoria with ages up to 430 Ma (Maas *et al.* 1998) provide a time constraint on the end of the event (VandenBerg 1999b).

The second cycle, the Tabberabberan, was the period of the most voluminous and widespread magmatism in eastern Australia. In north Queensland, granites were emplaced into both the North Queensland Orogen and the Precambrian basement to the west (Bultitude *et al.* 1993). The large Cape York Peninsula Batholith consists of mainly Devonian granite of both S- and I-type with Paleoproterozoic model ages, consistent with derivation from older continental crust (Cooper *et al.* 1975; Bain & Draper 1997). Granites of the Ravenswood Batholith intruded the North Queensland Orogen in four episodes: 435–424 Ma regional aureole I- and S-types; 425–410 Ma oxidised I-types; 410–400 Ma regional aureole granites; and 400–380 Ma high-level granites (Hutton *et al.* 1994; Bain & Draper 1997). Silurian to Devonian granites in the Lachlan Orogen constitute about 35% of the exposure. The earliest are extensive large 435–425 Ma S-type plutons, many within regional metamorphic aureoles, in the Wagga Metamorphic Belt and the highlands of southern New South Wales and northern Victoria (Brooks & Leggo 1972; Williams 2001; OZ-CHRON). These were followed by large contact-aureole I-type plutons east of the highlands (Williams 1992), then smaller I-type bodies over a wide area (420–410 Ma). Rb–Sr and K–Ar ages of the granites decrease east and west of the highlands (Evernden & Richards 1962; Richards & Singleton 1981), but the ages are regional (Ramsay & VandenBerg 1986) so this could well be in part a cooling phenomenon. Cooling to the Ar and Sr closure temperature of biotite ($\sim 350^{\circ}\text{C}$) following high-grade metamorphism and anatexis in the Cooma region took ~ 40 million years (Williams 2001). The youngest granites of the generation (400–385 Ma) are A-types and isotopically primitive I-types along the coast of southern New South Wales and northern Victoria.

The collision phase of the Tabberabberan cycle involved widespread basin inversion and deformation

in the Lachlan Orogen, recorded by K–Ar cooling ages of *ca* 395–370 Ma in central and eastern New South Wales (Vernon & Flood 1979; Glen *et al.* 1992, 1999) and mica Ar–Ar ages of 415–390 Ma in Cambrian duplexes of the Melbourne Zone (Foster *et al.* 1999). Some older granites in the eastern Lachlan Orogen were strongly deformed (Lennox *et al.* 1998), resetting their mica Ar–Ar ages to 390–380 Ma (Foster *et al.* 1999). Early deformation in the central Lachlan Orogen is recorded by Ar–Ar ages of 420–395 Ma (Foster *et al.* 1999) and the intrusion of *ca* 400 Ma plagiogranites, probably the differentiation products of continental rift tholeiites (Meffre & Glen 2006), in the ophiolites of the Coolac serpentinite belt (Graham *et al.* 1996). The age of deformation in eastern Tasmania is tightly constrained as 390 Ma by pre- and post-tectonic granites. K–Ar and Rb–Sr cooling ages on the same units are up to 15 million years lower (Black *et al.* 2005).

The third cycle, the Kanimblan, had widespread effects in the Lachlan and Delamerian Orogens, but only local effects in north Queensland. In the eastern and central Lachlan Orogen, the cycle started with Early to Middle Devonian rifting and local A-type magmatism (Dadd 1992). There was widespread deposition of largely fluvial sediments—the Lambie facies (Powell *et al.* 1984)—possibly resulting from major uplift in central Australia associated with the Alice Springs Orogeny. In northern New South Wales, these sediments include volcanic detritus derived from the New England Orogen to the north (Powell *et al.* 1984). The cycle in central Victoria began at *ca* 375 Ma with the widespread intrusion of high-level S- and I-type granites and the eruption of felsic volcanic rocks in cauldron complexes (VandenBerg *et al.* 2000). The cycle was terminated by regional deformation between *ca* 370 Ma (Packham 1999a) and *ca* 345 Ma (Shaw *et al.* 1982), followed by the intrusion of 340–320 Ma high level granites west of Sydney (Shaw & Flood 1993).

The Lachlan supercycle was followed by the Hunter–Bowen supercycle, a series of events related to the convergence of the New England microplate and development of the adjacent Sydney and Bowen Basins. The cycle started in the Late Devonian with the formation of an arc along the margin of the New England Orogen, a backarc basin to the west (the Drummond Basin) and a forearc basin to the east (the Yarrol Trough). The earliest bimodal volcanic rocks in the Drummond Basin are Late Devonian in the north and Carboniferous (*ca* 345 Ma) in the south (Henderson *et al.* 1998). The Yarrol Basin received only minor andesites, dacites and rhyolites (Fordham *et al.* 1998). Late Devonian (*ca* 374 Ma) ultramafic rocks in northern New England (Aitchison *et al.* 1994) are some of the few remnants of the arc itself. Felsic magmatism became more widespread in the Carboniferous. Magmatism (granites and volcanic rocks) in northern New England started at *ca* 360 Ma, peaked at 325–315 Ma and persisted until *ca* 305 Ma (Allen *et al.* 1998; Murray 2003; Bryan *et al.* 2004). In southern New England, an arc developed that produced andesitic and rhyolitic volcanism that peaked at 342–327 Ma, but continued until *ca* 303 Ma (Roberts *et al.* 2003, 2004). The volcanic rocks are similar in age and composition to the nearby 340–320 Ma post-Kanimblan granites in the Lachlan Orogen (Shaw & Flood 1993).

Riebeckite K–Ar ages of *ca* 315 Ma on high-pressure metamorphic rocks record cooling following post-subduction exhumation (Watanabe *et al.* 1988).

Cessation of subduction was followed by a major episode of granite emplacement (310–300 Ma) in both the south and north of the New England Orogen (Landenberger *et al.* 1995; Allen *et al.* 1998), accompanied by deformation and exhumation. This was followed by extension, further granite magmatism, emplacement of *ca* 280 Ma serpentinite along the Peel–Manning fault (Lanphere & Hockley 1976) and *ca* 275 Ma MORB-like bimodal volcanism in the Tamworth region (Roberts *et al.* 1996). There was also widespread felsic magmatism in north Queensland (Bain & Draper 1997). The Bowen and Sydney Basins began to develop, floored by 295–270 Ma volcanic rocks (Shaw *et al.* 1989; Allen *et al.* 1998). Following large-scale folding, convergence resumed, accompanied by extrusion of widespread ignimbrites and intrusion of the large 255–222 Ma subduction-related New England Batholith (Shaw *et al.* 1991b; Bryant *et al.* 1997). Gabbros and high-level granites in the northern New England Orogen span a wider time range, 270–205 Ma (Murray 2003). Volcanic debris from the orogen accumulated in the Bowen and Sydney Basins from *ca* 265 to *ca* 250 Ma, after which the cycle was terminated by the Hunter–Bowen Orogeny.

GRANITE GENESIS AND THE NATURE OF THE LACHLAN FOLD BELT BASEMENT

When Chappell & White (1974) first proposed that the granites of eastern Australia could be divided into S- and I- types based on their chemical compositions, which in turn reflected the nature of their source materials, they sparked a lively debate that continues today over granite genesis and the nature of the basement to the Lachlan Orogen. The contrast between the two types of granite was attributed to the source rocks for the S-types having been through a prior sedimentary cycle, while the sources for the I-types had not. This interpretation was supported by the granite Sr isotopic compositions. $^{87}\text{Sr}/^{86}\text{Sr}_i$ was much higher in the S-types (>0.708) than in the I-types (0.706–0.704). Noting that there was a sharp easterly limit to the occurrence of S-type granites (the I–S line), White *et al.* (1976) suggested that it marked the eastern boundary of thick continental crust, possibly crystalline shield, possibly of Precambrian age.

Treating the granite magmas as mixtures of melt and unmelted residue (restite), Compston & Chappell (1979) modelled the Sr isotopic evolution of the sources for I-type granites from three batholiths in southeastern New South Wales and concluded that the source material was first separated from the mantle ~ 1.1 billion years ago. Further evidence for the antiquity of the sources was provided by a Sr and Nd isotopic study of the same area by McCulloch & Chappell (1982). High $^{87}\text{Sr}/^{86}\text{Sr}_i$ (0.709–0.718) and strongly negative ϵ_{Nd} (–6.1 to –9.8) in the S-types was interpreted as indicating the presence of metasedimentary source components ~ 1.4 billion years old. The Sr and Nd in the I-types was less evolved and more variable ($^{87}\text{Sr}/^{86}\text{Sr}_i = 0.7045\text{--}0.7119$, $\epsilon_{\text{Nd}} = +0.4$ to –8.9). The possibility that this range in isotopic

compositions resulted from mixing between a depleted mantle and a crustal component was considered but dismissed because it was inconsistent with the chemical data. When the proportions of crust and mantle components inferred from the isotopic compositions were used to calculate the concentrations of elements such as K, Rb, Cr and Ni in the mantle component, the calculated concentrations were impossibly low, i.e. negative. The source material for the I-types was inferred to be derived predominantly from the mantle over a period of 1 billion years prior to granite formation. The isotopic compositions of the S- and I-type granites of the New England batholith were much less evolved, consistent with an almost complete absence of Proterozoic or older material in the granite sources (Hensel *et al.* 1985). The source of the New England S-types was inferred to be weathered sediment little older than the granites themselves. The source of the I-types was isotopically more primitive, but whether it was igneous rock or immature island-arc detritus could not be determined.

Gray (1984), on the other hand, argued that the published isotopic data for the southeastern Australian granites could be explained by mixing between two end members, a high-Si magma derived from metasediment and a low-Si magma of basaltic composition. The granites, from hornblende tonalites to cordierite granodiorites, were considered to be ‘... a single broad family, products of variable mixing between distinct batches of basaltic material and a uniform partial melt of the regional basement’ (Gray 1984 p. 47). Chappell and his coworkers argued that mixing two such magmas could not explain the isotopic and chemical data simultaneously. For example, although the $^{87}\text{Sr}/^{86}\text{Sr}_i$ of the S-type granites was similar to that of their host sedimentary rocks, with the exception of the few granites of the Cooma Suite, the granites were consistently more Na-rich than the sediments and so could not be derived directly from them (Chappell 1984). Adding a basalt component to increase the Na would also increase the Ni, yet the S-type granites contained less Ni than the sediments (White & Chappell 1988). Further, as the S-type granites became more mafic, they mostly became more peraluminous and had higher $^{87}\text{Sr}/^{86}\text{Sr}_i$, the opposite to the behaviour expected if the more mafic rocks contained a larger basaltic component, but consistent with the more mafic granites containing a higher proportion of unmelted peraluminous sedimentary source material (White & Chappell 1988).

The progressive westward change in the chemical and isotopic composition of the Bega Batholith I-type granites was interpreted to indicate a westward increase in the sediment component in the magmas. This could not be explained by two-component magma mixing, however. The chemical and isotopic regularity in the granites showed that their sources shared the same chemical and isotopic characteristics in narrow meridional strips, most less than 20 km wide, over distances of up to 300 km, so the sediment component must have been present in the source prior to partial melting (Chappell & Stephens 1988; Williams *et al.* 1988a). Support for this argument was provided by SHRIMP zircon analyses. The most easterly I-type

granites contained the smallest number of inherited zircon grains, the inherited zircon content and its average age increasing to the west (Williams *et al.* 1988a). Further, the mafic meta-igneous enclaves in the most inheritance-rich granites contained only the youngest inherited component found in the magma (0.6–0.5 Ga). Reasoning that magmas derived directly from the mantle would not contain inherited zircon, and therefore that the enclaves were residual from an igneous component in the source rocks of the granites, Chen & Williams (1990) argued that that component was of Late Neoproterozoic age.

Assessing regional differences in the chemical composition of the granites in the southern Lachlan Fold Belt, Chappell *et al.* (1988) identified nine distinct granite provinces that they interpreted as reflecting regional differences in the composition of the deep crust corresponding to discrete basement terranes. Gray (1990) showed that some of the province boundaries in Victoria corresponded to steps in the age and $^{87}\text{Sr}/^{86}\text{Sr}_i$ of the granites, but argued again that the granite compositions could be explained by mixing between melts derived from the local basement and basaltic material. The inferred basement in Gray's eastern and western zones was similar in composition to the surface Paleozoic sedimentary rocks, but that in the central zone (encompassing the Melbourne Basement Terrane of Chappell *et al.*) was inferred to be isotopically more juvenile than the exposed Ordovician turbidites. Gray (1990) explained the decreasing peraluminosity of the S-type granites with increasing silica content as the result of fractionation, but Chappell (1994) pointed out that this implied a source for the component of sediment-derived magma so peraluminous that it would be extremely refractory.

With additional SHRIMP dating of I-type zircon inheritance and work on some of the S-type granites, it became evident that the inheritance patterns in both were very similar (Williams 1992). The difference between the two granite types was that inherited zircon was rare in the I-types, but most zircon grains in the S-types contained an inherited core. Backscattered electron imaging showed most cores to be rounded fragments of formerly larger grains, consistent with the cores originally having been detrital grains (Paterson *et al.* 1992). Dating of detrital zircon in the host Ordovician turbidites strongly supported this conclusion—the ages and relative abundances of detrital zircon in the sediments matched those of the inherited zircon in the granites (Williams 1995). Consistent with the tectonic argument that in some places thrusting thickened the Ordovician turbidites sufficiently for them to start melting (Glen 1992), it was possible isotopically that the source of the S-type granites was part of the Ordovician sedimentary pile, and, given that the youngest inherited and detrital zircons were of Early Ordovician age, there was no compelling evidence that the source of the granites was Precambrian (Williams 1995). The same was found in Victoria in comparisons of the inheritance and detrital zircon ages in S-type granites, their deep-sourced enclaves and their host sediments (Anderson *et al.* 1996; Keay *et al.* 1999).

In a study of the Cooma metamorphic complex, Williams (2001) demonstrated that the U–Pb ages of

detrital zircon in metasediment were preserved without detectable modification when that sediment was partially melted to produce an S-type granite magma and the detrital zircon was incorporated as inheritance. This provided a firmer basis on which to argue that the inheritance patterns in the S-types were an unbiased record of the ages of zircon in their source rocks, reinforcing earlier conclusions that the source rocks for the granites were Ordovician sediments. However, there remained arguments that, other than for the granites of the Cooma Suite, the source sediments must differ from those exposed at the surface (Chappell 1984, 1998). First, the batholithic S-type granites and their deeply sourced enclaves were substantially richer in Ca, Na and Sr than the exposed sediments, and second, back-calculated to the time of granite emplacement, the $^{87}\text{Sr}/^{86}\text{Sr}_i$ of the exposed sediments was distinctly higher than that of the granites. Both features were consistent with the sedimentary source of the granites being less mature and more feldspathic than the surface turbidites. The turbidites at the base of the Ordovician sequence in the Lachlan Fold Belt are much less mature than those at the top (Glen 1992; VandenBerg & Stewart 1992; Fergusson & Tye 1999). Immature metasediments with the appropriate detrital zircon age patterns are also exposed in South Australia (Ireland *et al.* 1998) and southern New Zealand (Gibson & Ireland 1996). It is therefore very likely that such sediments underlie at least those areas of the Lachlan Orogen where S-type magmas were generated.

To overcome the inconsistencies in the two-component mixing model, a three-component model was proposed (Collins 1996; Keay *et al.* 1997). The chemical and isotopic variation in the isotopically primitive Moruya Batholith was explained by the mixing between mantle-derived magma and two contrasting crustal components, one similar to Cambrian greenstones found elsewhere in the Lachlan Orogen and the other the Ordovician turbidites (Keay *et al.* 1997). Similarly, chemical and isotopic features of S- and I-type granites in the Kosciuszko Batholith were explained by mixing between Ordovician sediment remobilised at high temperature and an isotopically primitive end member consisting of mantle-derived basaltic magma mixed with material from a Neoproterozoic–Cambrian arc or backarc (Collins 1996). The implication of this model for the range of granite compositions was that the different granite types were not derived from contrasting source materials and therefore could not be used to infer source rock compositions. There was no Precambrian basement beneath the Lachlan Orogen and the granites formed in an environment related to subduction where arc magmatism promoted crustal fusion and crust–mantle mixing (Keay *et al.* 1997).

Responding to the model, Chappell (1996) pointed out its inconsistencies, emphasising that the amount of sediment required in the mixtures to account for the granite isotopic compositions was commonly not consistent with the chemical composition of the rock. For example, to account for the isotopic composition of the I-type Jindabyne Tonalite by magma mixing required the magma to contain ~60% sediment, but its K, Rb and Cr contents were too low for that to be possible. Also, the

Glenbog Suite contained the most isotopically evolved granites in the Bega Batholith and therefore the largest sediment component, but there was no correlation between the isotopic and chemical composition of the granites over a wide range of SiO_2 . The source, including sediment, must have been isotopically homogenised during magma genesis, so the sediment component could not have been introduced by late assimilation. Isotopic homogenisation of the sources immediately prior to granite genesis was also suggested by McCulloch & Woodhead (1993) on the basis of Pb isotopes. Arguing that sediment assimilation could be detected in those rare cases where it had occurred, Chappell (1996) cited the example of the Boggy Plain pluton, formed from one of the hottest magmas in the Lachlan Orogen, in which assimilation of sedimentary country rock had raised the $^{87}\text{Sr}/^{86}\text{Sr}_i$ from 0.7044 in the most mafic rocks to 0.7055 in the most felsic.

Some researchers used microgranitoid enclaves to argue for coexisting magmas having mingled but not mixed. Mafic enclaves in the S-type Wilsons Promontory Batholith, for example, had less evolved Sr and Nd isotopic compositions (Elburg & Nicholls 1995) and contained less inherited zircon (Elburg 1996) than the host granite. Others argued that enclave compositions were consistent with magma mixing. Vernon *et al.* (1983) documented evidence for coexisting magmas of contrasting compositions in the Tuross Head Tonalite. Maas *et al.* (1997), working on the S-type Deddick Granodiorite, also found that the Sr and Nd isotopes in the enclaves had not equilibrated with the host granite. The isotopic compositions were more evolved in metasedimentary enclaves and less evolved in microgranular enclaves, from which they concluded that the latter were remnants of a hybrid mafic magma, possibly basaltic to andesitic, that had played a role in granite petrogenesis. Subsequent zircon U–Pb analyses (Maas *et al.* 1998) showed that the inherited zircon ages in the metasedimentary enclaves and host granite were similar, and that the youngest zircon in both was of Cambrian–Ordovician age, precluding the derivation of both from Proterozoic continental basement. Responding to Maas *et al.* (1997), White *et al.* (1999) pointed out that the microgranular enclaves in the Deddick Granodiorite had compositions unlike any igneous rock, but might represent metamorphosed calcareous sediment (the migmatites of the Cooma Complex contain enclaves of calc silicate). Differences in the isotopic compositions of the enclaves and granodiorite were explained by incomplete equilibration of isotopic heterogeneities in the source rocks, as reflected to a lesser extent in the isotopic heterogeneity of the granodiorite itself.

The magma mixing debate peaked when Collins (1998) evaluated the tectonic implications of the different petrogenetic models, concluding that neither the restite model nor the two-component mixing model could explain the chemical and isotopic features of the Lachlan Fold Belt granites. Arguing again for three-component mixing, he reiterated that granite compositions do not image those of their source rocks, and that there was no compelling evidence for Proterozoic basement or basement terranes beneath southeastern Australia. Chappell *et al.* (1999) countered, pointing out

several flaws in the magma mixing model, including its failure to explain the decrease in $^{87}\text{Sr}/^{86}\text{Sr}_i$ with rising SiO_2 in S-type granite suites or the considerable isotopic heterogeneity within individual S-type plutons. They also reiterated that the Proterozoic Nd model ages of the granites should be interpreted as the average mantle extraction ages for the components in their sources, not necessarily the ages of their source rocks *per se*. Additional isotopic evidence against large-scale magma mixing was put forward by Chappell *et al.* (2000). They argued, for example, that as the I-type granite suites of the Bega Batholith became more isotopically evolved, they also became more Ca-rich, which was inconsistent with the evolved component being magma derived from the partial melting of sediments. Further, that sediment-derived magma would have had a low oxygen fugacity, but the isotopically evolved I-type granites were not consistently the less oxidised. Reviewing the situation after more than 20 years of debate, Chappell *et al.* (2000) concluded that, although the isotopic evidence ruled out the presence of Precambrian crystalline shield beneath the eastern Lachlan Orogen, the evidence from granite compositions for the presence of thick continental (metasedimentary) crust beneath much of the orogen at the time of magmatism was conclusive. The eastern edge of that thickened crust probably coincides with the eastern limit of the S-type granites, the I–S line (White *et al.* 1976; White & Chappell 1983).

Later developments in micro-analytical techniques made it possible to approach the problem of granite petrogenesis from another direction: interrogation of the record of magma evolution preserved in the growth zones of individual melt-precipitated zircon grains. After analysing zircon from the I-type Kosciusko tonalite (Jindabyne Tonalite) from the Kosciuszko Batholith, the S-type Berridale adamellite (Numbla Vale Adamellite) from the Berridale Batholith, and the I-type Dundee rhyodacite from the New England Orogen for trace elements and Hf isotopes, Belousova *et al.* (2006) concluded that there was evidence for magma mixing, mingling and progressive crystallisation. The zoning in the zircon from each rock recorded changes in crystal morphology and composition consistent with changes in the magma composition. Zircon from the tonalite recorded a simple evolution of the magma by fractional crystallisation, with no chemical or isotopic evidence for magma mixing. The uniform Hf_{DM} model age of ca 1.13 Ga was interpreted as a minimum age for the source materials. The magmatic history of the adamellite was more complex. Chemical trends in the early crystallised zircon recorded crystallisation of plagioclase and mafic minerals from a crustally derived magma (Hf_{DM} model age ca 1.94 Ga). The dominant late-crystallised zircon was precipitated from hotter, more juvenile magma (Hf_{DM} model age ca 1.3 Ga), consistent with magma mixing. Zircon from the rhyodacite had much more radiogenic Hf, consistent with younger source rocks (Hf_{DM} model age 700–530 Ma). Changes in the chemical and Hf isotopic compositions were considered to reflect crustal contamination of a mantle-derived magma.

Combining zircon Hf and O isotopic analyses, Hawkesworth & Kemp (2006) studied granites from two I-type suites, one the same as that studied by Belousova

et al. (2006) from the Kosciuszko Batholith and the other from the Bega Batholith. The zircon from the relatively primitive Bega samples had a relatively high ϵ_{Hf} and a range of low $\delta^{18}\text{O}$ that they interpreted as indicating the assimilation of anatectic melts from metasedimentary host-rocks by a mantle-derived magma or its differentiate. The zircon from the more evolved Kosciuszko samples had a larger range of lower ϵ_{Hf} and higher $\delta^{18}\text{O}$ values, interpreted as indicating extensive mixing of crustal (probably metasedimentary) material with a differentiated, isotopically enriched, mantle-derived magma similar to that which formed a nearby gabbro. Comparing the Hf model ages and U–Pb ages of detrital zircon from the Ordovician sediments with those of inherited zircon from the granites, Hawkesworth & Kemp (2006) concluded that the zircon with mantle-like $\delta^{18}\text{O}$ values had ϵ_{Hf} values reflecting crustal growth at 1.9–1.7 and 3.1–2.9 Ga, while that with $\delta^{18}\text{O}$ values indicating sedimentary input to the magma had ϵ_{Hf} values reflecting the same average crustal residence age (2.0–1.8 Ga) as the provenance of the sediments and many S-type granites. They concluded that there was scant evidence for a mafic precursor to the I-type granites being extracted from the mantle at 1.2–1.0 Ga as suggested from previous isotopic studies, and that if the I-type granites came from 600–450 Ma source rocks, then they contained a significant metasedimentary component.

Until the apparently contradictory evidence pointing to magma mixing on the one hand, and restite unmixing on the other is reconciled, the processes of granite genesis in the Lachlan Orogen and the extent to which granite chemical and isotopic compositions can be used to infer the age and composition of the lower crust will remain a subject of heated debate. In the end, it might all come down to a matter of location, mixing of partial melts from various sources being significant in determining the composition of magmas in a lower crustal zone of magma accumulation, and restite unmixing (sometimes followed by crystal fractionation) determining the compositions of the various magmas extracted from that zone.

PROVENANCE OF THE LOWER PALEOZOIC TURBIDITES

A major feature of the Lachlan Orogen is the huge expanse of Lower to mid-Paleozoic turbidites. Estimates of the original size of the deposition area vary depending upon the amount of shortening attributed to post-deposition deformation and whether the sequence is thought to have been doubled by strike-slip faulting (VandenBerg & Stewart 1992; Glen 2005). However, it is widely agreed that the scale of the deposits was similar to that presently found in the Bengal and Amazon fans (Cas 1983; Coney 1992; Fergusson & Coney 1992; VandenBerg & Stewart 1992; Gray & Foster 1997; Fergusson & Tye 1999). Considering the exposed Lachlan Orogen alone, the fan was possibly as much as 1700 km wide and 1000 km long (Fergusson & Coney 1992). It was relatively thin, however, probably less than 4 km over most of its extent (VandenBerg & Stewart 1992). The most recent assessment of the dimensions of the original sedimentary fan in the western Lachlan

Orogen (Gray *et al.* 2006) estimated the width to be between 800 and 1150 km, and thickness between 6 and 12 km. The thickness of any underplate of igneous material was estimated to be less than ~2 km.

The turbidites are overwhelmingly quartz-rich and in bulk remarkably uniform in composition and lithotectonic assemblage, prompting Coney *et al.* (1990) to coin the phrase Lachlan ‘mud pile.’ In detail, there are changes in the sedimentology both on a regional and local scale. The turbidites represent a complex of evolving facies with an overall increase in sediment maturity up-section (Glen 1992; VandenBerg & Stewart 1992). The basal units (earliest Ordovician) are the least mature, with the highest content of feldspar and lithic fragments (Fergusson & Tye 1999). The great bulk of the sediment (Middle Ordovician) is much more quartz-rich, with feldspar a very minor component. By the Late Ordovician, except in the far west, sediment supply had slowed, and black shale became common. Sedimentary structures indicate deposition below storm wave-base, probably in water hundreds to thousands of metres deep (VandenBerg & Stewart 1992). There is a broad consensus that this pattern reflects deposition at a continental margin, the sediment originating from the progressive erosion of a rapidly uplifted mountain chain (Cas 1983; Coney *et al.* 1990; VandenBerg & Stewart 1992; Gray and Foster 1997; Fergusson & Tye 1999; Glen 2005), but the original location of those mountains has been a subject of much speculation. The Kanmantoo Group, an older (Early Cambrian), thicker (~8 km), much more localised turbidite sequence that overlies the Proterozoic continental margin in South Australia, possibly reflects the initiation of that uplift (Flöttmann *et al.* 1998).

There is a long-held belief, based principally on paleocurrent directions and the location of the turbidite fan system at the proto-Pacific margin of Gondwana, that the sediments were derived from Delamerian mountains that formed along the eastern margin of Gondwana in the latest Neoproterozoic to Early Cambrian. Some researchers have suggested that the most likely source is the Australian craton (Cas 1983; Veevers 1984; Cas & VandenBerg 1988; Turner *et al.* 1993a; Gray & Webb 1995; Gray 1997; Scheibner & Basden 1998), but more commonly the source proposed has been the more extensive Delamerian–Ross Orogen, extending from South Australia into Antarctica (Coney *et al.* 1990; VandenBerg & Stewart 1992; Gray & Foster 1997; Ireland *et al.* 1998; Fergusson & Tye 1999; Fergusson & Fanning 2002). A factor rarely considered in the early studies is that the Lachlan Orogen is just part of a much larger system that once extended along the whole proto-Pacific margin of Gondwana at least from what is now South America, through South Africa and Antarctica to northern Australia (Coney 1992).

Some isotopic studies of the Lachlan turbidites have lent strong support to the concept that the sediments originated from the local Delamerian Orogen. Turner *et al.* (1993b) showed that the initial Nd isotopic compositions of the turbidites were very similar to those of the Neoproterozoic and Cambrian sedimentary sequences in South Australia, but different from those of the Archean to Mesoproterozoic basement rocks of the Gawler Craton. Although noting evidence for a shift in

provenance between the Adelaidean and Kanmantoo sediments, Turner *et al.* (1993b) concluded that the Lachlan turbidites were produced by erosion and recycling of the sediments of the Adelaide Fold Belt with some minor additions from Cambrian–Ordovician igneous rocks from the Delamerian Orogen.

Assuming that the Sr isotopic composition of sediment is not modified by interaction with sea water, Gray & Webb (1995) compared the $^{87}\text{Sr}/^{86}\text{Sr}_i$ of Lachlan turbidites with that of possible source rocks from South Australia and western Tasmania. Their reasoning was that, whereas the ages of detrital minerals would reflect only the ages of the primary source rocks, individual source terranes should have distinctive whole-rock Sr isotopic compositions. Supplementing literature data with their own analyses, Gray & Webb (1995) showed that the $^{87}\text{Sr}/^{86}\text{Sr}$ of the Lachlan turbidites at the time of deposition (0.712–0.720) was much lower than that of all potential Australian Precambrian source terranes (0.729–0.810). However, it was close to the initial Sr isotopic compositions of Early Paleozoic rocks, including Delamerian igneous rocks and the sediments of the Kanmantoo Group. They concluded that the Lachlan turbidites did not originate from the continental interior, but originated from the Delamerian mountains, the regional uniformity of the turbidite Sr isotopic composition suggesting that all the turbidites were part of a single system with no major contribution from island arc volcanism.

Turner *et al.* (1996) compared the ^{40}Ar – ^{39}Ar ages of detrital muscovite grains from two Early Ordovician turbidites from the Lachlan Orogen in Victoria with biotite and hornblende ^{40}Ar – ^{39}Ar ages of igneous and metamorphic rocks from the Delamerian Orogen in South Australia. The muscovite ages (507–480 Ma) matched the range of Delamerian igneous and cooling ages very closely (525–480 Ma), from which it was concluded that the Delamerian Orogen was the source of the sediments. Further, the similarity in age between the youngest detrital muscovite and sediment deposition was interpreted as indicating that the Delamerian mountains were exhumed and eroded very rapidly (5–15 mm/y). Detrital micas with a very similar ^{40}Ar – ^{39}Ar age range (515–490 Ma) were subsequently found in the Ordovician Greenland Group turbiditic metasediments in New Zealand (Adams & Kelley 1998), reinforcing the conclusion that the Early Paleozoic sediments were derived from an Early Cambrian orogen, either the Delamerian Orogen in Australia or the Ross Orogen in Antarctica.

The most direct information on the likely provenance of the Lachlan turbidites, and an indication of the truly enormous scale of the original sediment system, has been provided by U–Pb age measurements on detrital zircon. When Williams *et al.* (1990) showed that the detrital zircon in turbidites from southeastern New South Wales fell mostly into two main age groups, 650–450 and 1075–800 Ma, with a continuum of ages up to 3.35 Ga, it was evident that derivation of the Ordovician sediments from the Australian craton was most unlikely. The sediment appeared to have been transported over a much longer distance and from an extensive and uniform terrane (Williams *et al.* 1994). As more zircon was analysed, very similar detrital age patterns were

found in Ordovician sediments the length and breadth of the Lachlan Fold Belt and in central Australia (Williams *et al.* 1994; Buick *et al.* 2005; Williams 1995; Fergusson *et al.* 2007), in Early Paleozoic paragneisses in New Zealand (Ireland 1992; Gibson & Ireland 1996), in Paleozoic sediments of North Victoria Land and Marie Byrd Land, Antarctica, and on Campbell Island south of New Zealand (Ireland *et al.* 1994), in the Kanmantoo Group in South Australia (Ireland *et al.* 1998), in the Malmesbury Group, South Africa (Armstrong *et al.* 1998) and in Early Paleozoic sediments along the Transantarctic Mountains (Goodge *et al.* 2002, 2004; Williams *et al.* 2002). All these locations are adjacent to the former proto-Pacific margin of Gondwana, so the distinctive detrital zircon age pattern has become recognised as the signature of the eastern Gondwanan Early Paleozoic (Williams 1995).

A critical feature of the eastern Gondwanan age signature is that it arrived at the various localities with the turbidites and contrasts dramatically with the zircon age pattern in the wide range of underlying rocks (Williams & Chappell 1998). For example, detrital zircon ages from the Neoproterozoic Adelaidean sediments in South Australia are dominantly 2.0–1.5 and 1.2–1.0 Ga, consistent with derivation from the Proterozoic rocks of the Australian craton. With the arrival of the Early Cambrian Kanmantoo turbidites, however, there was a sudden appearance of 0.6–0.5 and 1.2–1.0 Ga zircon in approximately equal abundance, plus Paleoproterozoic to Archean components and a virtual disappearance of the 2.0–1.5 Ga population (Ireland *et al.* 1998). Similarly, in the Transantarctic Mountains, the arrival of the Early Cambrian turbidites with their characteristic age signature supplanted the deposition of older sediments in which the predominant detrital zircon ages varied with location from 3.0–2.5 plus 2.0–1.5 Ga, to simply 2.0–1.5 Ga, to 2.0–1.5 plus 1.3–1.0 Ga (Goodge *et al.* 2004). In central Australia, the units underlying the Ordovician sediments contain detrital zircon of 1.9–1.5 and 1.2–0.9 Ga (Buick *et al.* 2005). Many of these zircon data and others were collated by Veevers (2000).

Noting the contrast between the Gondwana zircon age pattern and the ages of the zircon derived from the local adjacent craton, Williams & Chappell (1998) proposed that the Lachlan turbidites had a remote protosource, possibly the Mozambique Belt. This idea was developed by Williams *et al.* (2002) and Squire *et al.* (2006). The Mozambique Belt, the youngest and largest of the Pan-African (Late Neoproterozoic to Early Cambrian) orogenic belts, formed during the protracted (*ca* 650–500 Ma), massive collision between eastern and western Gondwana (Dalziel 1997; Piper 2000; Trompette 2000). The belt extends along the entire east coast of Africa and west coast of India. At its southern end, it follows the line of a major Grenville orogen in Antarctica. The combination of zircon produced during the orogeny (partly coeval with the Ross–Delamerian Orogeny) and from those basement terranes accounts for the major zircon populations in the eastern Gondwanan sediments. The orogeny was so large that it flooded not only the Gondwana margin with sediment but also the North African craton. In fact, a detrital zircon age pattern remarkably similar to that of the turbidites of

the Lachlan Fold Belt has been found in Cambrian sediments from southern Israel (Avigad *et al.* 2003).

Central Australia

HARTS RANGE METAMORPHIC COMPLEX

The Arunta Inlier in central Australia is a predominantly Paleoproterozoic high-grade metamorphic terrane with a very complex thermal history (Collins & Shaw 1995). It is overlain by remnants of the formerly extensive Neoproterozoic to mid-Paleozoic Centralian Superbasin (Shaw *et al.* 1991a). The two were exhumed and interleaved during the protracted mid-Paleozoic (440–300 Ma) Alice Springs Orogeny (Haines *et al.* 2001).

Until relatively recently, even after extensive geological and geochronological studies in the region, it was generally accepted that all the high-grade rocks in the Arunta Inlier had Paleoproterozoic to Mesoproterozoic protoliths, that all the high-grade metamorphic events were also of that age, and that metamorphism of the superbasin sediments reached at most greenschist grade (Shaw *et al.* 1984, 1991a; Collins & Shaw 1995). These assumptions, which underpinned tectonic models for the area and the broader central Australian craton (Shaw *et al.* 1984; James & Ding 1988), had to be radically revised once the high-grade metamorphic rocks in the eastern Arunta were dated by Sm–Nd and U–Pb.

Dating basement gneisses in the Harts Range, Cooper *et al.* (1988) obtained zircon ages of 1.77–1.73 Ga, consistent with expectations based on the results of geochronology elsewhere in the inlier. From one gneiss, however, they obtained a monazite U–Pb age of 360 ± 5 Ma that was so unexpected that it was attributed to Paleozoic Pb loss. Several years later, working in the same area, Foden *et al.* (1995) obtained Sm–Nd mineral isochron ages of *ca* 460 and 475 ± 5 Ma from basement gneiss and overlying high-grade metasediments, respectively, prompting a closer investigation. A detailed Sm–Nd study of the high-grade metasediments and some basement gneisses, supported by U–Pb analysis of metamorphic monazite (Mawby *et al.* 1998; Hand *et al.* 1999), found consistent evidence that the high-grade metamorphism, termed the Larapinta Event (Miller *et al.* 1999), was not Proterozoic but Early Paleozoic (*ca* 485–460 Ma). Dating of metamorphic monazite and pegmatite zircon recorded a second period of Paleozoic high-temperature metamorphism and partial melting at 345–330 Ma (Hand *et al.* 1999) coeval with the Alice Springs Orogeny, which elsewhere was a very low-temperature event (Collins & Shaw 1995).

U–Pb analyses of metamorphic zircon and monazite from a sequence of granulite grade metapelites and metabasites a short distance to the north of the Harts Range (Miller *et al.* 1998) yielded a similar result (480–460 Ma) and also showed, through the ages of surviving detrital zircon cores, that the protolith metasediments were not Paleoproterozoic, but of Late Neoproterozoic or possibly Cambrian age. Titanite U–Pb ages of *ca* 415 Ma reflected slow cooling until the Devonian. Further, inherited zircon in a small intrusion of Devonian (387 Ma) granite had the same age range as the metasediment zircon cores, showing that the Neoproterozoic/

Cambrian metasediment was not a shallow surface layer but extended to the depths of partial melting (Buick *et al.* 2001). Comparison of the protolith zircon ages from the granulites with those from detrital zircon in the low-grade sediments of the adjacent remnant basins showed that the granulites were in fact high-grade equivalents of some of the lower sediments in the basin sequence (Maidment *et al.* 2004; Buick *et al.* 2005). The tectonic interpretation was that the volcano-sedimentary sequence represented by the granulites was deposited in a Cambrian rift, in places possibly 30 km deep, that once extended half-way across the continent from central Australia to the northwest coast of Western Australia (Maidment *et al.* 2004). Cambrian mafic volcanic rocks in the rift sequence, and nearby newly discovered Delamarian (520 Ma) granites, were interpreted as being coeval with the flood basalts of the Antrim Plateau Volcanics— 513 ± 12 Ma (Hanley & Wingate 2000) to the north.

THERMAL HISTORY OF THE ALICE SPRINGS OROGENY

The Alice Springs Orogeny is now recognised as the biggest Paleozoic intracratonic folding and thrusting event to have affected the Australian craton, but the scale of the event has only become apparent relatively recently, largely as a result of geochronological studies. Evidence of the event was first found during reconnaissance mapping of the Amadeus Basin when it was noted that some of the Neoproterozoic sedimentary units along the upturned northern edge of the basin southwest of Alice Springs were structurally repeated. The structure was initially interpreted as a 20 km-scale isoclinal fold, but subsequent detailed mapping showed that it was in fact a large nappe (the Blatherskite Nappe) thrust over the basin from the north (Stewart 1967). Subsequent mapping of the basin margin east of Alice Springs identified a series of nappes (the Arltunga Nappe Complex) consisting of several thrust nappes overlain by a large fold nappe with a core of crystalline basement rocks (Forman *et al.* 1967). The deformation event responsible was named the Alice Springs Orogeny.

K–Ar dating of the largest Arltunga nappe (Stewart 1971) showed that, although the basement rocks in front of the nappe preserved Mesoproterozoic ages (1.66–1.37 Ga), those at the rear had been overprinted in the Paleozoic (431–345 Ma). The ages measured on the metasediments in the nappe were even lower (358–322 Ma), proving conclusively that the Alice Springs Orogeny was a Late Paleozoic event.

Reviewing the tectonic history of the Arunta Inlier, Shaw *et al.* (1984) viewed the Alice Springs Orogeny as an event characterised by thrusting, greenschist facies metamorphism and local pegmatite formation. Deformation was considered to be focused in the south of the inlier, the main effect to the north being widespread heating and retrogression as indicated by Paleozoic resetting of K–Ar mineral ages. The only evidence of related igneous activity was Paleozoic pegmatite in the Harts Range (Black 1975). Collins and Teyssier (1989) argued that the orogeny was actually a much larger-scale event that was responsible for much of the major faulting and uplift of the Arunta basement. One of their

main lines of evidence was the prevalence of 370–310 Ma K–Ar and Rb–Sr ages measured on large Arunta basement shear zones (Allen & Stubbs 1982; Shaw *et al.* 1984). Their argument was supported by subsequent Rb–Sr work on one of the largest crust-penetrating basement faults, the Redbank Thrust Zone, that demonstrated that it was a Mesoproterozoic (1.5–1.4 Ga) structure that had been reactivated in the Early Paleozoic (400–300 Ma; Shaw & Black 1991).

The question of scale was resolved by a K–Ar and Ar–Ar study of the uplift and exhumation history of the Arltunga Nappe Complex (Dunlap *et al.* 1995). Three tectonic units were identified, each with a different Paleozoic dynamothermal history. These had been imbricated over a period exceeding 100 million years. The hottest rocks, the structurally highest unit, were uplifted and cooled at 430–400 Ma. Continued piggyback imbrication and exhumation resulted in duplexing of the crust until 325–300 Ma. The final phase of uplift culminated at *ca* 310 Ma, but slow cooling of the assembled stack lasted until *ca* 225 Ma. The contrasting thermal histories of the three units indicated juxtaposition of once widely separated crustal segments, consistent with a proposed crustal shortening of over 85 km (Teyssier 1985), implying very large amounts of strain on the basement shear zones. Far-field deformation over the same time period (430–400 Ma and *ca* 330 Ma) was later documented in the Proterozoic rocks of the northern Flinders Ranges (McLaren *et al.* 2002), proving the Alice Springs Orogeny to be a major intraplate tectonothermal event.

Western Australia

Most of the Precambrian basement of Western Australia yields Precambrian isotopic ages, but not so along the southwestern margin of the Yilgarn Craton. East of the Darling Fault between Perth and the south coast, biotite Rb–Sr ages of basement granites and gneisses drop progressively westwards from the age of the local craton (2.5–1.1 Ga) to *ca* 430 Ma over a distance of about 50 km (Libby & De Laeter 1979, 1998; De Laeter & Libby 1993). The zone of near-complete resetting widens from 30 km in the north to over 100 km in the south. It is generally accepted that the mica ages record the last time that any given locality cooled below the closure temperature for Sr diffusion in biotite, $\sim 320^{\circ}\text{C}$ (Harrison & McDougall 1980), but it is not clear how or when the initial temperature gradient was imposed. De Laeter & Libby (1993) considered several possibilities: heating by intrusion of Boyagin dyke swarm; heating by unexposed granites; cooling after crystallisation at depth; and cooling by exhumation after burial. The last was considered the most likely. Another possibility was suggested by Wilde *et al.* (1996): imbrication of basement gneisses along a series of eastward-dipping boundary shear zones. Assessing all the available data, Libby and De Laeter (1998) concluded that cooling after burial and exhumation remained the most likely explanation. They suggested that thrusting of a thick sedimentary sequence over the western edge of the craton during the Pan-African Orogeny locally loaded the crust, causing burial heating. Subsequent erosion and uplift led to

progressive cooling and the gradient in closure ages now observed.

The Leeuwin Complex, in far southwestern Australia, consists of Cambrian orthogneisses, the Neoproterozoic protoliths of which were probably intruded during the breakup of the Rodinia supercontinent at *ca* 750 Ma (Collins 2003). A SHRIMP zircon U–Pb study of metamorphic zircon overgrowths from the gneisses (Collins 2003) demonstrated that previously measured ages of *ca* 520 Ma were not simply the result of isotopic disturbance (Nelson 2002), but the age of high-grade granulite to upper amphibolite facies metamorphism. Similar Ar–Ar ages (508–495 Ma) measured on dredge samples from the southern Naturaliste Plateau 500 km offshore (Beslier *et al.* 2001) raised the possibility that the Leeuwin Complex is just a small part of a much larger Pan-African orogenic terrane formed from disparate Proterozoic blocks amalgamated at *ca* 550 Ma (Janssen *et al.* 2004).

Mineralisation

Paleozoic mineralisation in Australia is concentrated in the Tasman Fold Belt system. It includes volcanic-hosted massive sulfide, porphyry- and granite-associated Cu and Au, granite-associated Sn and W, and structurally controlled Au, Cu, Pb and Zn deposits (Walshe *et al.* 1995). Initially, formation of these deposits was interpreted mainly in terms of local spatial associations, for example correlations with particular structures or igneous lithologies, but as more deposits have been dated isotopically, it has become evident that there have been a series of distinct metallogenic episodes related to particular periods of tectonism (Rutland *et al.* 1990). For example, early base- and precious-metal mineralisation in western Tasmania was associated with *ca* 500 Ma magmatism and 480–440 Ma tectonism, Cu and Au mineralisation in New South Wales was related to the end stages of 480–440 Ma magmatism, later Au and base-metal mineralisation in both Tasmania and the south-eastern mainland was associated with 420–390 Ma deformation and magmatism, and Au mineralisation in north Queensland was coeval with 350 Ma magmatism (Perkins *et al.* 1995; Large *et al.* 1996; Perkins & Kennedy 1998). The *ca* 440 Ma episode is now recognised as one of the major mineralisation events in Australia (Vos *et al.* 2004) and has been linked to asthenospheric upwelling driven by major lithospheric instabilities (Bierlein 2005). Recognition of such widespread events has assisted in targeting ground selection for mineral exploration (Crawford *et al.* 1996).

Reviewing the timing of mineralisation in Australia, Jaques *et al.* (2002) noted that many major mineral deposits appear to have formed in response to orogenic events, commonly late in a tectonic cycle, indicating that mineralisation is ultimately initiated by far-field crustal stresses. Further, mineralisation associated with igneous activity commonly occurred late in the magmatic cycle or during a break in volcanism, for example the Cambrian base-metal deposits of Tasmania, the Ordovician Cu–Au deposits of central western New South Wales and the Permian–Carboniferous Au deposits of north Queensland.

MT READ VOLCANICS

The Mt Read Volcanics in western Tasmania host some of the state's largest massive sulfide deposits and also have sufficient biostratigraphic control to provide an important Middle Cambrian reference point in the geologic time-scale (Gee *et al.* 1970). Initially, dating the volcanic rocks and associated granites proved extremely difficult. Each of the dating techniques attempted (Rb–Sr, K–Ar and U–Pb) showed evidence of radiogenic daughter loss, and zircon U–Pb was also affected by inheritance (Adams *et al.* 1985). Measured ages ranged from *ca* 523 Ma (McDougall & Leggo 1965) to *ca* 400 Ma (Adams *et al.* 1985). Even ages of *ca* 500 Ma were considered to be in error because the preferred time-scale at the time (Harland *et al.* 1982) placed the Cambrian–Ordovician boundary at 505 Ma.

SHRIMP zircon U–Pb dating resolved the issue (Perkins & Walshe 1993). Several volcanic units all yielded ages of *ca* 502 Ma, indicating rapid eruption over a short period of time. Ar–Ar dating of one andesite and an associated granite gave the same result. A slightly later volcanic episode at 494 Ma was identified. The presence of massive sulfide clasts in some of the volcanic rocks indicated that initial massive base-metal sulfide mineralisation was coeval with volcanism, so dating the volcanic rocks also placed a tight constraint on the age of ore genesis. A subsequent SHRIMP study of additional volcanic units by Black *et al.* (1997) confirmed the conclusion that the volcanic rocks were erupted over a very short period of time. The ages measured (506–503 Ma) were slightly but not significantly higher than those reported by Perkins & Walshe (1993), probably because they were referenced to a different zircon standard. Ages measured at the northern end of the volcanic belt were consistently *ca* 500 Ma, which Black *et al.* (1997) interpreted as indicating that the igneous activity migrated to the north.

The ages measured on the Mt Read Volcanics and their chemical compositions were very similar to those measured on andesites and dacites from the Mt Stavelly Volcanic Complex in western Victoria (Crawford & Berry 1992), prompting the suggestion that the largely subsurface Stavelly Greenstone Belt is highly prospective for Au-rich volcanic-hosted massive sulfide deposits similar to those in western Tasmania (Crawford *et al.* 1996).

GOONUMBLA REGION

The Cu–Au ore bodies of the Goonumbla region, near Parkes in central western New South Wales, are associated with Early Paleozoic mafic magmatism interpreted to be part of an intraoceanic island arc (Glen *et al.* 1998). Fossil evidence indicates that the igneous activity started in the Early Ordovician and extended possibly into the earliest Silurian (Krynen *et al.* 1990), but dating the magmatism directly proved difficult. Although Ar–Ar ages measured on hydrothermal sericite (439 Ma) provided a date for alteration associated with Cu–Au mineralisation, the age of 438.5 ± 3.6 Ma measured by zircon U–Pb on underlying volcanic rocks was in conflict with the biostratigraphy (Perkins *et al.* 1990). Attempts to date other volcanic

rocks in the sequence failed for lack of zircon, but the issue was resolved by zircon U–Pb dating of a series of monzodiorites intruded into the volcanic pile (Butera *et al.* 2001). These age measurements showed that the volcanic rocks were intruded over an extended period of time, from 484 Ma (481 Ma if the age of the high-U zircon is calculated from $^{207}\text{Pb}/^{206}\text{Pb}$) to 439 Ma, and thereby that the mineralisation occurred very late in the tectonic cycle (Glen *et al.* 2003). Three distinct volcanic packages have now been recognised: Early Ordovician deep-water distal deposits; Middle to Late Ordovician shallow water breccias, limestones and lavas; and Late Ordovician proximal volcanoclastics (Simpson *et al.* 2005). The hiatus between the two older packages lasted about 10 million years.

VICTORIAN GOLDFIELDS

Studies of the timing of Au mineralisation in the Victorian goldfields illustrate well how geochronology has helped to answer a difficult question about a complex process of ore genesis. Central Victoria is a major mesothermal Au province in which the mineralisation occurs mainly in quartz-vein systems controlled by the conjugation of structural and chemical traps (Cox *et al.* 1991). There has been extensive Early Paleozoic magmatism in the region, but there is no obvious genetic relationship between the Au deposits and any particular igneous rock type (Sandiford & Keays 1986; Phillips & Hughes 1996). Using Ar–Ar to date metamorphic mica growth, Foster *et al.* (1998) showed that central Victoria had been subject to Early Paleozoic deformation that progressed from Late Ordovician (453 Ma) in the west to Early Devonian (390 Ma) in the east. Dating sericites from some of the major Au deposits, they demonstrated that early mineralisation and deformation were coeval at 440 Ma. A second episode of mineralisation at 420–410 Ma in some deposits coincided with reactivated faulting, and some late mineralisation at 380–360 Ma coincided with Late Devonian magmatism. Dual periods of diachronous mineralisation, one pre-dating and one accompanying both Late Silurian and Late Devonian magmatism, were also identified by Arne *et al.* (1998). Working just in the Ballarat region, Bierlein *et al.* (1999) used Ar–Ar to document several episodes of Au mineralisation over a period of nearly 100 million years, the first pulse (440 Ma) coinciding with deformation, the second (410–380 Ma) associated with faulting and magmatism, and the third (*ca* 370 Ma) with magmatism. A later study of a wider area (Bierlein *et al.* 2001) found a similar result. This pattern of mineralisation was explained by the initial production of hydrothermal fluids by shallow devolatilisation of a thickening turbidite pile, then later production of deeply sourced metamorphic fluids and magmas as lower crustal temperatures reached the point of partial melting. The specific tectonic context of these events remains to be determined.

Apparent polar wander

The accurate mapping of an apparent polar wander path depends on accurate dating of the units on which

magnetic directions are measured. Based on a relatively sparse dataset, Embleton (1984) inferred that, in the Neoproterozoic to Cambrian, Australia rotated anticlockwise by about 90°. This was followed by a similar clockwise rotation through the Ordovician and Silurian, then a drift into south polar latitudes by the end of the Carboniferous. As more poles were measured, more detail emerged. Li *et al.* (1990) described the motion as rapid clockwise rotation during the Middle Ordovician to Early Silurian, then anticlockwise rotation from the Middle Silurian to Late Devonian, both at low to equatorial latitudes, then rapid southward drift during the Middle Carboniferous. Poles measured from the craton and the Lachlan Fold Belt indicated that the two had been amalgamated since the Middle Devonian.

Reviewing the history of the Australian apparent polar wander curve for the Early Paleozoic, Schmidt *et al.* (1993) lamented the lack of reliable poles from the Gondwana continents. While some poles suggested a small separation between Gondwana and Laurentia, others suggested the presence of a wide ocean. On the basis of a newly measured pole from the Early Ordovician (490 Ma) Black Hill Norite (Milnes *et al.* 1977), it was suggested that some Australian Cambrian poles might have been overprinted during the Delamerian Orogeny.

Several years later, there was a disagreement about the poles for the Early Ordovician (Schmidt & Clark 2000) but an acceptance that the Tasmanides were part of the Australian continent by the Silurian. Their Tasman pole path was complicated, however, showing the pole traversing Gondwana from North Africa to South America and back during the Cambrian to Silurian, from South America to central Africa during the Devonian to Carboniferous and across Antarctica to Australia during the Late Carboniferous to Early Permian. A complexity in the polar wander path was a jump of ~128° between 430 and 400 Ma, requiring either very rapid motion or a reversal in polarity and reversal in the orientation and paleolatitude of the continent. A further complexity was disagreement over the path in the Late Carboniferous to Permian, Klootwijk (1996) interpreting data from southern New England as indicating a large eastward loop in the path for Gondwana, and Schmidt *et al.* (1994) arguing for a rotation of New England alone.

Currently, the Late Paleozoic pole path for Australia remains in dispute. The path originally proposed by Schmidt *et al.* (1986) and still being refined (Anderson *et al.* 2003) is based on a selection of data which shows a relatively simple westward Devonian to Carboniferous loop. The alternative proposed by Klootwijk & Giddings (1988), which is also being refined (Klootwijk 2002) accommodates a larger dataset and features an eastward loop over the same time period. From the Late Carboniferous onward, the two models agree. The two models have very different implications for the relationship between Gondwana and Laurussia. A westward loop implies a rapid anticlockwise rotation of Gondwana during the Devonian and the opening of a wide equatorial ocean in the west. An eastward loop implies that such an ocean did not form. Resolution of the problem will depend heavily on the measurement of

poles on accurately dated Carboniferous igneous rocks in the Lachlan and New England Orogens.

Following their paleomagnetic study of Siluro-Devonian volcanic rocks from the central Lachlan Orogen, Vêrard *et al.* (2005) concluded that the data from the orogen, previously used as key poles for defining the Siluro-Devonian loop, were not representative of Gondwana because the Lachlan Orogen was subject to rotation relative to the rest of Gondwana until at least the mid-Paleozoic. This possibility remains to be tested further.

CONCLUSIONS

Isotope geochronology is now an integral part of the study of the Paleozoic geological history of Australia. Some of our understanding of that history is based entirely on isotopic age measurements. The science of geochronology has matured over the last 40 years, and the applicability of different techniques to dating different stages of a tectonothermal history, and their strengths and weaknesses, are relatively well known. The development of SHRIMP had a major impact, making it possible not only to date high-temperature events such as magmatism and high-grade metamorphism but to 'see through' those events to the U-Pb isotopic record of the ages of the protoliths. Further, SHRIMP first made it feasible to date individual detrital mineral grains fast enough to undertake meaningful studies of sediment provenance. The need now is to supplement that work with a wider application of state-of-the-art, high-precision U-Pb geochronology by ID-TIMS. SHRIMP, laser ICP-MS and ID-TIMS are complementary techniques, providing high spatial resolution and accuracy, speed and very high precision, respectively. Together with techniques such as Rb-Sr, Ar-Ar, Sm-Nd, Lu-Hf, Re-Os and U-He, they provide Australian geologists with access to a geochronological arsenal that is second to none. As always, however, the success of any geochronological study will remain totally dependent upon the participants choosing the most appropriate samples in a very well-defined geological context.

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