GEOCHRONOLOGY OF THE AUSTRALIAN REGOLITH

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ABSTRACT

The application of numerical dating methods to Australian regolith is reviewed. Pre-Tertiary ages from oxygen isotopes, paleomagnetism and stratigraphic dating confirm the great antiquity of regolith in a number of regions. However, while long-term erosion and rock weathering rates in many parts of Australia are low by world standards, they are not low enough to allow pre-Tertiary regolith and landforms to survive without burial and exhumation.

INTRODUCTION

Geological evidence suggests that many parts of the Australian continent have experienced subaerial exposure over hundreds of millions of years (e.g. BMR, 1990) – see Figure 1. Consequently, there has been a long and complex history of weathering and landscape development, some of which occurred under climates quite different from the present. However, reliable numerical estimates of regolith age, using isotopic dating techniques, have been difficult to obtain. Typical problems include the lack of suitable minerals and uncertainties regarding closed system assumptions. Furthermore, the generally unfossiliferous nature of much of the Australian regolith has meant that traditional methods of biostratigraphic dating cannot always be employed.

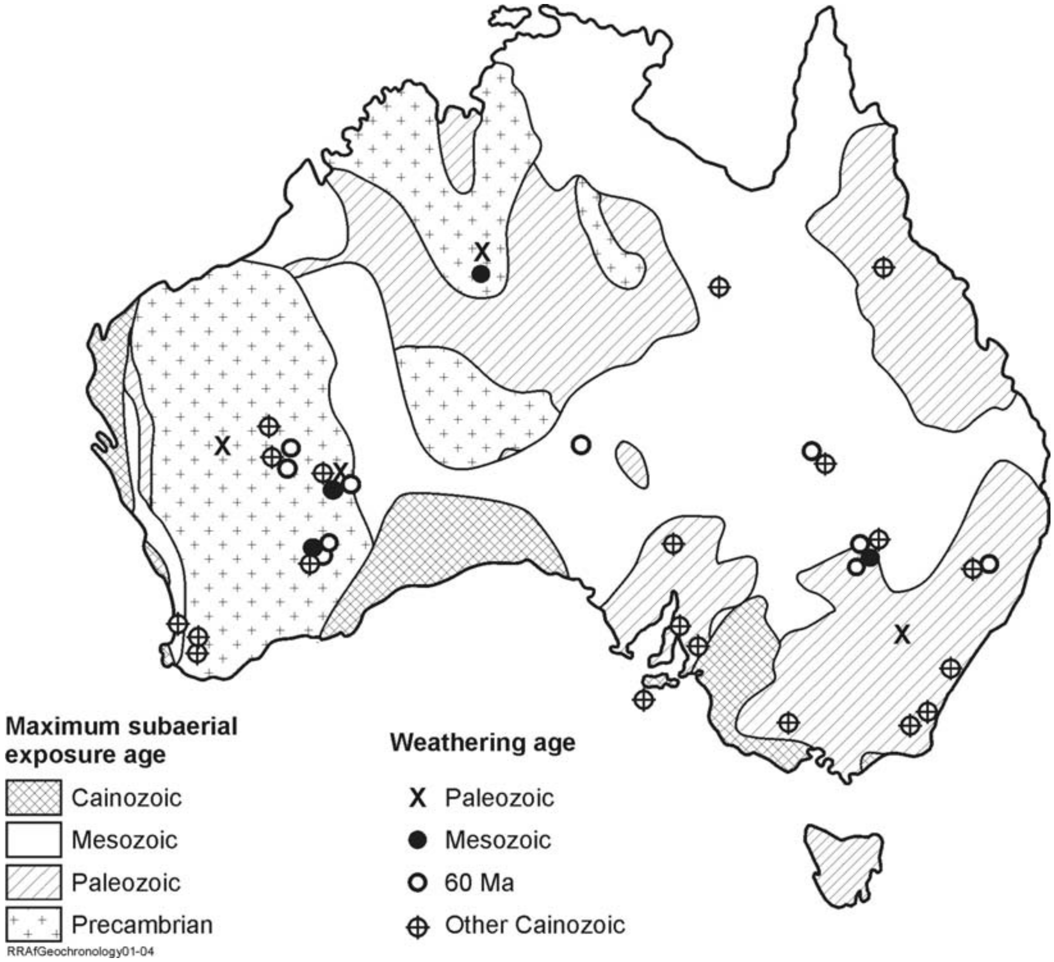

Figure 1. Maximum duration of subaerial exposure (data from BMR Palaeogeographic Group, 1990) and paleomagnetic ages determined on regolith.

Despite the above problems, a number of dating methods have been successfully applied to the Australian regolith (Pillans, 1998). On timescales of less than 10^5 years, radiocarbon and thermoluminescence have been extensively used to provide a robust chronology for late Pleistocene regolith. On timescales beyond 10^5 years, paleomagnetism, oxygen isotopes, K/Ar (including $^{40}Ar/^{39}Ar$) and stratigraphic dating have been employed. The age ranges over which various regolith dating techniques can be applied, are summarised in Figure 2.

PALEOMAGNETISM

The formation of secondary iron-oxides by chemical weathering processes allows paleomagnetism to be used to date regolith materials. A Chemical Remanent Magnetisation (CRM) may be acquired by mineral grains either during nucleation and growth through a critical blocking diameter (single phase CRM), or during alteration of an existing mineral (two phase, or parent-daughter CRM). Hematite (αFe_2O_3), a commonly formed mineral in oxidising conditions, is a stable magnetic remanence carrier; goethite ($\alpha FeOOH$) is not. Thermal Remanent Magnetisation (TRM) is acquired on cooling by igneous and metamorphic rocks, and Detrital Remanent Magnetisation (DRM) acquired by particles settling out of air or water during formation of sedimentary rocks. In general, the TRM and DRM in rocks is progressively destroyed and replaced by a CRM with increasing weathering. Therefore, the magnetic remanence in weathered regolith relates to the time(s) of weathering, not to the formation of the parent rock.

An important characteristic of most CRM's is that they are acquired over long enough times (thousands of years) to average out secular variation. Thus paleomagnetic poles can be calculated from the remanence directions, which in turn are used to derive weathering ages by comparison with the trajectory of paleomagnetic poles of known age (usually referred to as an apparent polar wander path). This approach is particularly useful for sites that have substantially changed their latitudinal position as a result of plate motion (e.g. India and Australia during the Tertiary). One of the first studies to use this principle was by Schmidt & Embleton (1976), who reported paleomagnetic results from Late Paleozoic and Mesozoic rocks in the Perth Basin and adjacent areas of Western Australia. They identified a stable high temperature magnetisation, which was similar in direction for all rocks, regardless of age, and which they interpreted as a "blanket" remagnetisation resulting from a period of regional lateritisation. The age of the weathering-induced remagnetisation was estimated to be Late Oligocene to Early Miocene by comparison with the Australian Apparent Polar Wander Path (AAPWP), but more recent revisions of the AAPWP (Idnurm, 1985, 1994) indicate a Late Miocene or Pliocene age (4±2 Ma). Similarly, Schmidt *et al.* (1983) estimated Late Cretaceous and Tertiary paleomagnetic ages for Indian laterites.

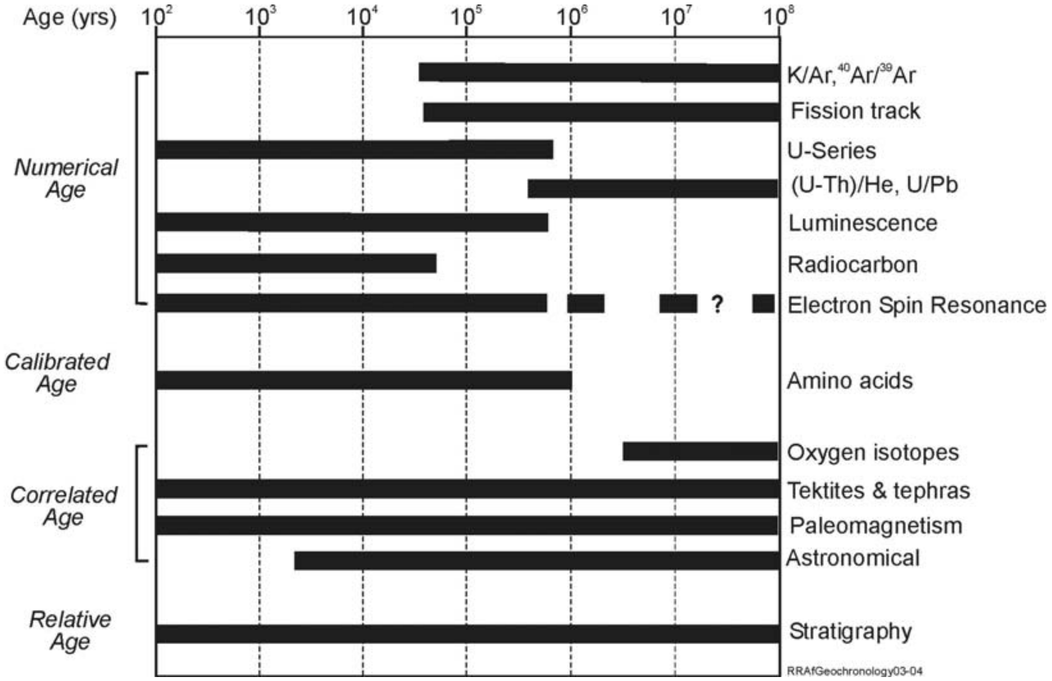

Figure 2. Age ranges of regolith dating methods (Pillans, 1998).

From the mid 1970's onwards, paleomagnetic ages have been determined by comparison with the AAPWP, although some segments of the path have been substantially revised, while others remain contentious. The AAPWP of Schmidt & Clark (2000) is used here (Figure 3). Results from a series of studies (eg Schmidt & Embleton, 1976; Schmidt *et al.,* 1976; Idnurm & Senior, 1978; Schmidt & Ollier, 1988; Nott *et al.,* 1991; Acton & Kettles, 1996) have yielded ages ranging from latest Cretaceous through to late Tertiary at various sites across the continent, while Pillans *et al.* (1999) reported a Carboniferous age for weathered regolith at Northparkes Cu-Au mine in New South Wales. Subsequently, Late Paleozoic and Mesozoic-age weathering imprints in regolith have been paleomagnetically dated in eastern areas of the Archean Yilgarn Craton (e.g. at Mt Percy and Lancefield), Dead Bullock Soak and New Cobar Mines (Table 1, Figure 2). Deep weathering profiles at Bronzewing, Lawlers, Kanowna Belle and Mt Percy in the eastern Yilgarn also yield both early and late Tertiary paleomagnetic ages (Table 16 in Anand & Paine, 2002). The early Tertiary paleomagnetic poles are statistically identical to that for the 60 Ma Morney Profile developed on Cretaceous sedimentary rocks in southwest Queensland (Idnurm & Senior, 1978), a paleomagnetic pole from weathered volcanics near Armidale in northern New South Wales (Schmidt & Ollier, 1988), and poles from oxidised saprolite at McKinnons and Elura mines near Cobar, NSW (McQueen *et al.,* 2002). These results suggest that deep oxidation and iron mobilisation at 60 Ma may have been part of a continent-wide weathering event. In contrast, profiles at Jarrahdale and Boddington on the western margin of the Yilgarn Craton yield only late Tertiary paleomagnetic ages, similar to those reported by (Schmidt & Embleton, 1976) from the nearby Perth Basin. The absence of older weathering imprints in the western Yilgarn may well be a consequence of kilometre-scale denudation during and since the Mesozoic, as evidenced by apatite fission track data (Kohn *et al*., 2000).

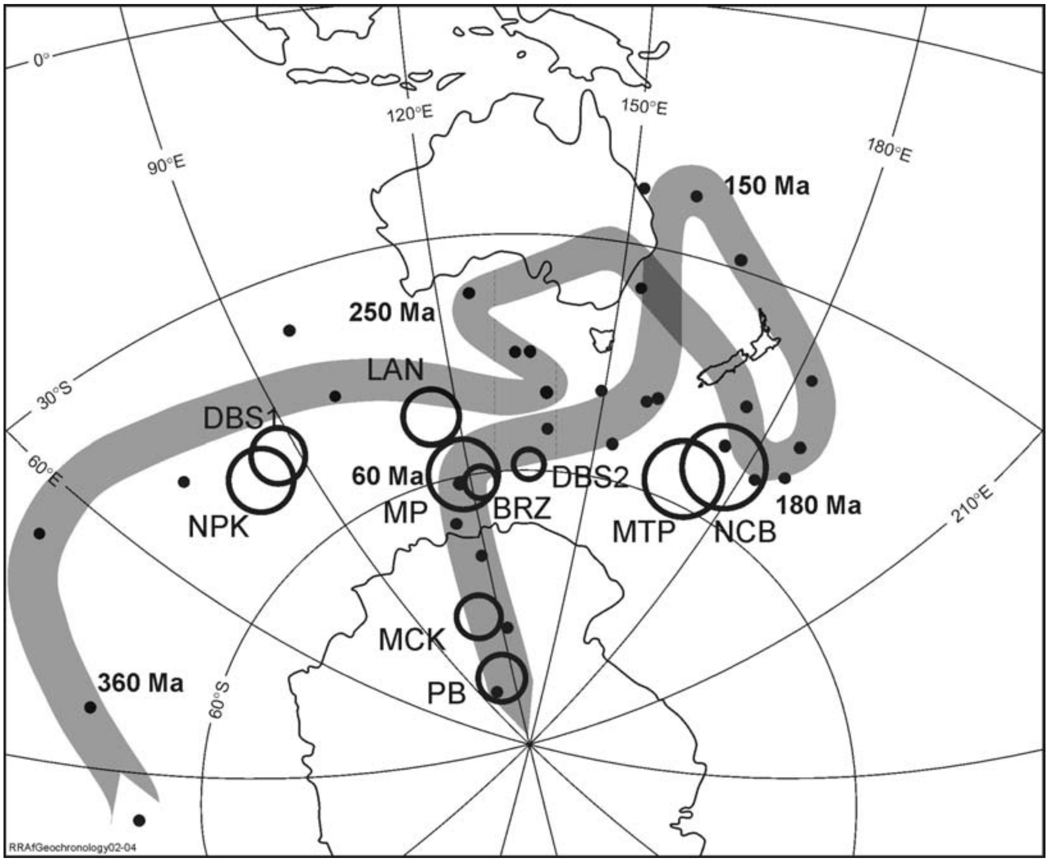

Figure 3. Australian Apparent Polar Wander Path from 360 Ma to present (Schmidt & Clark, 2000), with some representative paleomagnetic poles (95% confidence circles) from weathered regolith (PB = Perth Basin, MCK = McKinnons, MP = Morney Profile, BRZ = Bronzewing, DBS = Dead Bullock Soak, MTP = Mt Percy, NCB = New Cobar, LAN = Lancefield, NPK = Northparkes – see Table 1 for references).

TABLE 1: Summary of paleomagnetic ages (Ma) from weathered regolith

LOCATION	0-20	20-50	50-65	65-250	>250	Reference
Perth Basin, WA	X					Schmidt & Embleton, 1976
Jarrahdale bauxite mine, WA	X					Anand & Paine, 2002
Boddington Au mine, WA	X					Anand & Paine, 2002
St Barbara's Au mine, WA	X				X	Pillans, unpublished
Wiluna, WA	X	X				Pillans, unpublished Schmidt & Williams, 2002
Lawlers Au mine, WA	X		X		X?	Anand & Paine, 2002
Bronzewing Au mine, WA	X		X			Anand & Paine, 2002
Murrin Murrin Ni mine, WA				X		Anand & Paine, 2002
Mt Percy Au mine, WA	X		X	X		Pillans & Bateman, 2000
Kanowna Belle Au mine, WA			X			Anand & Paine, 2002
Lancefield Au mine, WA	X	X	X		X	Pillans, unpublished
Marla bore, SA			X			Pillans, unpublished
Springfield Basin, SA	X					Schmidt *et al.*, 1976
Moonta mine, SA	X					Pillans, unpublished
Kangaroo Is., SA	X					Schmidt *et al.*, 1976
Mt Lofty Range, SA	X					Pillans, unpublished
McKinnons Au mine, NSW	X		X			McQueen *et al.*, 2002
Elura Cu mine, NSW	X		X			McQueen *et al.*, 2002
New Cobar Cu mine, NSW				X		McQueen *et al.*, 2002
Lapstone Monocline, NSW	X					Bishop *et al.*, 1982
Lucas Heights, NSW	X					Pillans, unpublished
Bunyan/Bredbo, NSW	X					Schmidt *et al.*, 1982
New England, NSW	X		X			Schmidt & Ollier, 1988 Acton & Kettles, 1996
Merimbula, NSW	X					Nott *et al.*, 1991
Northparkes Cu/Au mine, NSW					X	Pillans *et al.*, 1999
Dundas Tableland, Vic	X	X				Pillans, unpublished
Southwest Qld	X	X				Idnurm & Senior, 1978
Pajingo Au mine, Qld	X					Pillans, unpublished
Mt Isa, Qld		X				Pillans, unpublished
Dead Bullock Soak mine, NT				X	X	Pillans & Idnurm, unpublished

Paleomagnetism has also been applied to weathering profiles using the known history of reversals of the Earth's magnetic field (magnetostratigraphy) – e.g. to determine the downwards rate of movement of the weathering front in saprolite in French Guiana (Theveniaut & Freyssinet, 1999). In a similar study in north Queensland, Australia, Pillans (1997) reported paleomagnetic results from a chronosequence of soils formed on basalt flows up to 6 Ma in age. However, in contrast to the results from French Guiana, the lower parts of the soil profiles in Queensland, closest to the weathering front, showed reverse polarity magnetic directions. Pillans (1997) interpreted the reverse polarities as being relict from a time, prior to the B/M transition, when both the amount, and depth of infiltration, of rainfall was significantly higher than present. Thus, a simple model of progressive downwards movement of the weathering front is only likely to be applicable under constant climatic boundary conditions. Pillans & Bourman (1996) reviewed the use of the Brunhes/Matuyama polarity transition at 0.78 Ma in Australian regolith studies, and Pillans & Bourman (2001) showed that it preceded a major arid shift in climate across southern Australia (see also Zheng *et al*,, 1998).

OXYGEN ISOTOPES

Mean annual air temperature is one of the major factors controlling the isotopic composition of meteoric waters, and hence the regolith minerals formed in equilibrium with them. Since the Australian continent has been drifting north across a marked latitudinal temperature gradient as a consequence of the continental breakup of Gondwanaland, the isotopic composition of regolith minerals would have become increasingly enriched in ^{18}O (Bird & Chivas 1988, 1989). By analysing samples from profiles independently dated by other techniques, Bird & Chivas (1988, 1989) were able to calibrate the change in isotopic composition over time, and distinguish four broad age groups of residual kaolinitic clays:

1. Post mid-Tertiary clays, with δ^{18}O values of +17.3% to +22.0%.
2. Pre mid-Tertiary clays (late Cretaceous to early Tertiary), with δ^{18}O values between +15 and +17.5%
3. Late Paleozoic to pre-late Mesozoic clays, with δ^{18}O values between +10 and +15%.
4. Early Permian clays, with δ^{18}O values less than +10%.

Their study demonstrated that regolith profiles containing clays with low δ^{18}O values (< +15%) are widespread in Australia, and they concluded that a much greater part of the modern landscape than previously recognised may have developed in the early and mid Mesozoic. Furthermore, their results suggested that much of the Australian regolith formed in comparatively cold conditions, in contrast to some traditional interpretations that lateritisation and deep weathering largely occurred in tropical and sub-tropical climates.

POTASSIUM-ARGON AND ARGON-ARGON

In eastern Australia K/Ar dating of Cainozoic basaltic lavas (e.g. Wellman & McDougall, 1974) permits ages of associated regolith materials to be inferred (e.g. Exon *et al.*, 1970). However, Cainozoic basalts are absent from large areas of the continent and many regolith materials cannot be dated in this way.

The application of K/Ar and ^{40}Ar/^{39}Ar dating methods to weathered materials has been thoroughly reviewed by Vasconcelos (1999a). Two main groups of potassium-bearing secondary minerals have been successfully dated: Alunite-group sulphates (alunite and jarosite) and hollandite-group manganese oxides. A common problem in dating both groups of minerals is admixture of K-bearing mica inherited from the bedrock, which if uncorrected for will produce anomalously old ages. Dammer *et al.* (1996, 1999) used a two-stage K/Ar method to correct for inherited mica by measuring radiogenic argon and potassium in the total sample, and making a proportional correction for the radiogenic argon and potassium measured in the silicate residue. To avoid possible contamination from inherited micas in samples dated by the ^{40}Ar/^{39}Ar method, Dammer *et al.* (1999) dated only void-filling Mn-oxides that were not formed by replacing a pre-existing rock substrate. Exhaustive examination of void-filling samples, by optical and electron microscopy, electron microprobe and selective dissolution, verified that they were generally free from inherited micas.

A probability plot of all published K/Ar and ^{40}Ar/^{39}Ar ages from weathering profiles around the world (Vasconcelos, 1999b) shows that the majority of alunite-jarosite ages are younger than 20 Ma, whereas the Mn-oxide ages have a broader distribution extending back into the late Mesozoic. Formation of alunite group minerals is generally favoured by conditions of weak leaching and strong evaporation found in arid and semi-arid environments (Bird *et al*., 1990), whereas formation of Mn-oxides is favoured by intense leaching in humid environments (Dammer *et al.,* 1999). Thus, the differing age distributions for the two mineral groups might reflect a global shift to greater aridity in the last 20 Ma. While such an arid shift may be true for Australia (see later discussion), it is unclear whether this was a global event. Rather, the age distribution may simply reflect the fact that alunite-group minerals are unstable in a humid climatic regime, while Mn-oxides, once formed, are stable in both humid and arid climates. Long-term regional fluctuations between humid and arid climatic regimes would therefore favour longer preservation of Mn-oxides compared to alunite-group minerals.

Reconnaissance K/Ar dating of alunite in Australian regolith (Bird *et al.,* 1990) yielded 25 ages between 0 and 62 Ma. At one site (Mt Leyshon in north Queensland), subsequent ^{40}Ar/^{39}Ar dating (Vasconcelos, 1999) confirmed the K/Ar ages. Two samples of alunite from a pre-Jurassic regolith profile on Kangaroo Island yielded ages of 6.2 and 12.0 Ma, indicating that the alunite is not always genetically related to the weathering profile in which it is found. In general, Bird *et al.* (1990) concluded that alunite is a late-stage weathering product in Australian regolith profiles, associated with a continent-wide arid shift during the Tertiary.

From the evidence of a number of studies (e.g. Dammer *et al.*, 1996, 1999; Feng, 2001; Li & Vasconcelos, 2002), the formation of Mn-oxides in Australian weathering profiles is episodic. Furthermore, at two sites in western Australia, K/Ar ages of Mn-oxides increase with depth (Dammer, 1999), suggesting that the formation of these weathering profiles did not occur during a single episode of a downwards-moving weathering front. (Li, 2002) established the duration of weathering in a single 8 cm wide specimen from Mt Tabor in central Queensland – the inner band yielded well-defined ^{40}Ar/^{39}Ar ages of 24.7-26.0 Ma, while the outer bands gave ages as young as 14.9 Ma. This indicates that precipitation of the Mn-oxide spanned a period of about 11 Ma, at an average rate of 0.007 mm/ka.

Ages of Mn-oxides from Groote Eylandt, one of the worlds largest supergene manganese oxide deposits, appear to indicate three major episodes of weathering: a pre-late Eocene episode (prior to 43.7±1.2 Ma), an Oligocene episode (around 30 Ma), and a Miocene episode (6-18 Ma), interpreted as representing three episodes of intense chemical weathering under humid climatic conditions, during which times the original sedimentary manganese minerals (of Cretaceous age) were replaced with tetravalent Mn-oxides (Dammer *et al.,* 1996). Results from a wider study of supergene Mn deposits in Australia (Dammer *et al.,* 1999) appear to support the model of episodic accumulation associated with Tertiary climatic fluctuations. The prevalence of older ages for Mn-oxides (36-20 Ma) in the central part of the Yilgarn Craton, compared with those from coastal areas in the region (as young as 1.4 Ma), may be indicative of the time when climate became too dry for Mn-oxides to form in the regolith of the inland areas.

Results from five regions in Queensland suggest that warm and wet conditions may have prevailed for a large part of the Tertiary. A systematic decrease in ages from Mt Isa (70 to 0.6 Ma), to Mt Tabor (27.2 to 6.8 Ma), to Charters Towers (17-0.6 Ma), and two coastal regions (15 to 0.2 Ma) is interpreted by Li & Vasconcelos (2002) to reflect generally increasing erosion rates from west to east.

TEKTITES

Physical markers such as tektites and tephras can be very powerful dating media in regolith profiles. Firstly, they both contain minerals that can be directly dated by methods, such as fission-track, K/Ar and ^{40}Ar/^{39}Ar, and secondly, they can be correlated over large distances, including both marine and terrestrial deposits. Tektites have a widespread, if somewhat sporadic distribution in Australian regolith.

About 790 ka (Schneider *et al.,* 1992), an asteroid or comet impacted somewhere in southeast Asia, producing tektites, microtektites and impact debris which are found over more than 10% of the Earth's surface (Schnetzler & McHone, 1996), including much of Australia and surrounding oceans. Although there has been considerable debate concerning the age of the Australasian tektites, their age is now firmly established through magnetostratigraphy of deep sea cores in which microtektites occur just prior to the Brunhes/Matuyama polarity transition (Schneider *et al.,* 1992), as well as direct laser fusion ^{40}Ar/^{39}Ar dating of tektite glass (Izett 1992). Previously, a number of field studies supported a late Pleistocene age in the range 5 to 25 ka (Gill 1970; Lovering *et al.,* 1972), but these occurrences are now considered to represent reworking into younger sediments (e.g. Fudali, 1993; Shoemaker & Uhlherr, 1999). Even in regolith deposits where reworking is suspected, the presence of tektites provides a maximum age of 790 ka for the enclosing sediment. For example, waterworn tektites have been found in diamond-bearing alluvial gravel terraces some 25 km downstream of the Argyle diamond mine in northwestern Australia (Fudali *et al.,* 1991; Fudali 1993), indicating a maximum age of 790 ka for the terraces. Australasian microtektites are also present in Chinese loess sequences, where their presence as a discrete layer has been used to correct the misleading position of the Brunhes/Matuyama polarity transition (Zhou & Shackleton, 1999). Australasian tektites associated with Acheulean-like stone tools in South China yield an ^{40}Ar/^{39}Ar age of 803±3 ka, thus making them the oldest known large cutting tools in East Asia (Hou *et al.,* 2000).

STRATIGRAPHIC DATING

Standard principles of geological stratigraphy and dating apply to regolith materials, including superposition, cross-cutting relationships, fossil content and landscape position etc. Excellent examples include studies in South Australia by Alley (1998) and Alley *et al.* (1999).

Pre-Tertiary ages for landforms in Australia have been postulated on geological evidence. Examples include Cambrian river terraces in the Davenport Range (Stewart *et al.,* 1986, pre-Cretaceous plateaux in Arnhem Land (Nott 1995), Triassic surfaces in South Australia (Twidale, 2000) and a Precambrian age for the Kimberley High Plateau (Ollier *et al.,* 1988). The survival of such ancient landforms and weathering profiles in Australia is usually rationalised as being a consequence of prolonged tectonic stability and postulated low rates of weathering and erosion (e.g. Gale, 1992).

URANIUM SERIES

This group of methods is based on decay or accumulation of various parent/daughter isotopes in the U-series decay chains, especially ^{234}U/^{238}U and ^{230}Th/^{234}U. Commonly used for dating cave speleothems (e.g. Ayliffe & Veeh, 1988; Ayliffe *et al.,* 1998) and fossil corals in shoreline deposits (e.g. Stirling *et al.*, 1995). However, other suitable materials may include U-bearing oxides (Short *et al.,* 1989), peat (Longmore & Heijnis, 1999), silica (Ludwig & Paces, 2002), carbonates (Herczeg & Chapman, 1991) and egg shell (Miller *et al.,* 1999).

URANIUM-LEAD

The Sensititive High Resolution Ion Micro-Probe (SHRIMP) allows U/Pb dating of single mineral grains, such as zircon. Although normally applied to rocks of great antiquity (e.g. Froude *et al.,* 1983), this method has several potential applications to dating regolith materials.

SHRIMP dating of detrital zircons is a very powerful tool in provenance studies. For example, Pell *et al.* (1997, 2001) and Gatehouse *et al.* (2001) identified possible source areas of aeolian sand and dust deposits in southeastern Australia. In the latter study, the distinction between allochthonous and autochthonous grains supported the evidence from mineralogy, geochemistry and particle size analyses, of an aeolian component in soil profiles. The distinction between transported and *in situ* regolith is an important one, and fingerprinting of zircon populations by SHRIMP U/Pb dating is a potential way of doing so.

Studies by (Sircombe & Freeman, 1999) and (Cawood & Nemchin, 2000) have highlighted the paucity of Archean-age zircon grains derived from the Yilgarn Craton in modern beach deposits and sediments of the Perth Basin respectively. Either the Yilgarn Craton was not a significant source area, or it was covered by younger sediments (now removed), or denudation rates on the craton have been exceptionally low.

Fletcher *et al.* (2000) have dated authigenic xenotime in sedimentary basins. In regolith materials, other secondary minerals such as anatase may also be amenable to U/Pb dating

(URANIUM-THORIUM)/HELIUM

Although the (U-Th)/He method was one of the first isotopic dating methods to be investigated early this century, helium loss by diffusion resulted in lower than expected ages. However, recent studies have shown that certain minerals (e.g. zircon, apatite, magnetite, pyrite and hematite) quantitatively retain radiogenic ^{4}He (e.g. Bahr *et al.,* 1994; Farley, 2000). Lippolt *et al.* (1995) reported concordant (U-Th)/He and K/Ar ages for co-occurring Pliocene specular hematite and adularia. Farley *et al.* (2002) dated zircon and apatite from the Pleistocene Rangitawa Tephra in New Zealand, and calculated an eruption age (after correction for secular disequilibrium) in excellent agreement with previously published ages determined by other techniques. It seems likely that the method will be suitable for dating similar minerals produced by low temperature weathering processes in regolith.

In southeastern Australia (U-Th)/He dating of apatite has been successfully used as a thermochronometer. Persano *et al.* (2002) have used it to demonstrate that some 3-4 km of erosion occurred along the south coast of NSW within a maximum of 28 Ma of continental breakup at 85-100 Ma. Inland of the escarpment, apatite ages indicate that the plateau remained stable throughout continental breakup, with average erosion rates of less than 10 m/Ma since the late Paleozoic/early Mesozoic.

FISSION-TRACK

The major application of fission-track dating in Australian regolith studies has been as a thermochronometer to determine long-term denudation rates. Numerous studies (Moore *et al.,* 1986; Dumitru *et al.,* 1991; Gallagher *et al.,* 1994; O'Sullivan *et al.,* 1995, 1996, 1998, 1999, 2000; Kohn *et al.,* 1999, 2002; Mitchell *et al.,* 2002) using apatite fission track ages (AFTA) demonstrate kilometre-scale denudation over much of the Australian continent in the last 250 Ma. The AFTA data have seemed difficult to reconcile with the widespread preservation of Tertiary landforms and regolith, which imply landscape stability and low rates of denudation. However, it should be noted that the AFTA-derived rates are average rates, over time intervals of 10's to 100's of millions of years, within which there may be long periods of landscape stability (see Persano *et al.,* 2002, for example).

Fission track dating of gypsum has been reported (Li, 1991), but requires further investigation. Jackson *et al.* (1977) reported fission track ages on pedogenic micas from Antarctica.

LUMINESCENCE

Luminescence methods, including thermoluminescence (TL), infra-red stimulated luminescence (IRSL) and optically stimulated luminescence (OSL) have wide application in dating Quaternary regolith materials, particularly aeolian deposits (Readhead, 1988; Chen *et al.,* 1990, 2002; Lees *et al.,* 1995; Zheng *et al.,* 2002). Materials up to several hundred thousand years have been dated (Huntley *et al.,* 1993, 1994; Huntley & Prescott, 2001).

Examples of applications include dating human colonisation of Australia (Thorne *et al.,* 1999; Roberts *et al.,*. 2001), extinction of the Pleistocene megafauna (Roberts, 2001) fluvial deposits (Page *et al.,* 1991) and soil dynamics (Heimsath *et al.,* 2002).

COSMOGENIC ISOTOPES

Cosmic ray interactions produce ^{10}Be, ^{36}Cl, ^{26}Al and ^{21}Ne in the atmosphere and lithosphere. Accumulation reflects the duration of cosmic ray exposure within the upper 1-2 m of the Earth's surface, modulated by surface erosion rates.

Barrows *et al.* (2001, 2002) used cosmogenic ^{10}Be and ^{36}Cl in surface boulders to determine ages of late Pleistocene glacial moraines in Tasmania and the Mt Kosciuszko area of NSW.

Heimsath *et al.* (2000, 2001) determined rates of soil production in southern NSW, using cosmogenic ^{10}Be in saprolite beneath soil profiles on granite parent material. Apparent soil production rates varied according to an inverse exponential function of soil depth, with a maximum of over 100 m/Ma under zero soil depth. Average denudation rates in the late Quaternary were in the range 15-25 m/Ma, significantly higher than rates predicted over longer timescales (generally less than 10 m/Ma).

Bierman & Turner (1995) and Bierman & Cafee (2002) calculated long term erosion rates of less than 1 m/Ma from bedrock surfaces of granite domes on the Eyre Peninsula, South Australia, using ^{10}Be and ^{26}Al measurements. They concluded that at least some of the granite domes (inselbergs) are probably relict features of pre-Pleistocene landscapes. Using additional data from Northern Territory sites, Bierman & Cafee (2002) showed that bedrock erosion rates increase with higher rainfall.

Van der Wateren & Dunai (2001) measured ^{21}Ne in quartz veins and pebbles in the Namib Desert, and obtained surface exposure ages up to 5 Ma, and denudation rates as low as 0.1 m/Ma. Cosmogenic ^{21}Ne is being applied to sites in Australia where similar old exposure ages and low denudation rates have been measured by ^{10}Be (J. Chappell, pers. comm., 2002).

ELECTRON SPIN RESONANCE

The method has been widely used overseas to date vertebrate fossils, including human fossils of Pleistocene age. Examples of applications to regolith dating in Australia include studies by Chen *et al.* (1988) and Radtke & Bruckner (1991). The latter authors reported preliminary ESR ages for late Tertiary silcretes in Queensland, but verification with other dating methods is required.

AMINO ACID RACEMIZATION

Commonly used for correlation and dating of Pleistocene coastal deposits containing molluscan shells (e.g. Murray-Wallace, 1995). Using the extent of isoleucine racemization in fossil eggshell from emu and the now extinct *Genyornis newtoni*, Miller *et al.* (1999) estimated that *Genyornis* became extinct about 50,000 years ago (see also Roberts *et al.*, 2001). Since amino acid racemization is a temperature-dependent chemical reaction, paleotemperature history can be investigated, when samples are dated by another method (e.g. Miller *et al.*, 1997)

RADIOCARBON

The radiocarbon method has been successfully and widely applied to dating deposits of late Quaternary age for about 50 years. It is not possible, here, to review the vast literature pertaining to radiocarbon dating of Australian regolith. Suffice it to say, that radiocarbon dating forms the majority of numerical ages for regolith materials up to 50,000 years.

Since the amount of ^{14}C in the atmosphere is not constant, conversion of radiocarbon ages to calendar age, utilising calibration curves (e.g. Stuiver *et al.*, 1998) from dated tree ring chronologies, is necessary before radiocarbon ages can be compared with numerical ages determined by other methods.

Much current research is directed towards increasing the reliability of the technique for dating materials >40 Ka in age (e.g. Chappell *et al.*, 1996; Bird *et al.*, 1999; Santos *et al.*, 2001), and for dating small (milligram) size samples using accelerator mass spectrometry (AMS).

DISCUSSION

Given the long history of subaerial weathering in many regions of Australia, polygenetic weathering profiles are likely to be the rule rather than the exception. Consequently one should expect a range of ages from a single profile, whether determined by a single method, or by more than one method. Furthermore, different ages should be expected from different mineral phases, because each mineral can form under differing environmental conditions. For example, on Kangaroo Island, an intensely kaolinised profile is developed on Permian fluvial sands which underlie unweathered mid Jurassic (165-175 Ma) basalt. Low δ^{18}O values from the kaolinite support the pre-late Mesozoic age (Bird & Chivas, 1993), however, paleomagnetic ages of iron oxides (Schmidt *et al.*, 1976) and K-Ar ages of alunite (Bird *et al.*, 1990), from the same site, are late Tertiary.

The lack of pre-Tertiary ages from Mn-oxides in Australian regolith is somewhat surprising. According to Dammer *et al.* (1999) and Li & Vasconcelos, 2002) this may be attributable to erosion and/or dissolution of older weathering products, but the evidence from paleomagnetism and oxygen isotopes indicates that pre-Tertiary regolith has survived in many regions. However, while measured rates of long-term weathering (e.g. Pillans, 1997; Heimsath *et al.*, 2000) and bedrock erosion (e.g. Bierman & Turner, 1995; Bierman & Caffee, 2002) in Australia may indeed be low by world standards, they are not low enough to explain the continuous subaerial survival of pre-Tertiary landforms and weathering profiles. Burial and exhumation must therefore be significant contributing factors in the preservation of ancient features in the Australian landscape, as evidenced by the widespread occurrence of exhumed Permian glacial landforms (e.g. Crowell & Frakes, 1971; Eyles & de Broekert, 2001).

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