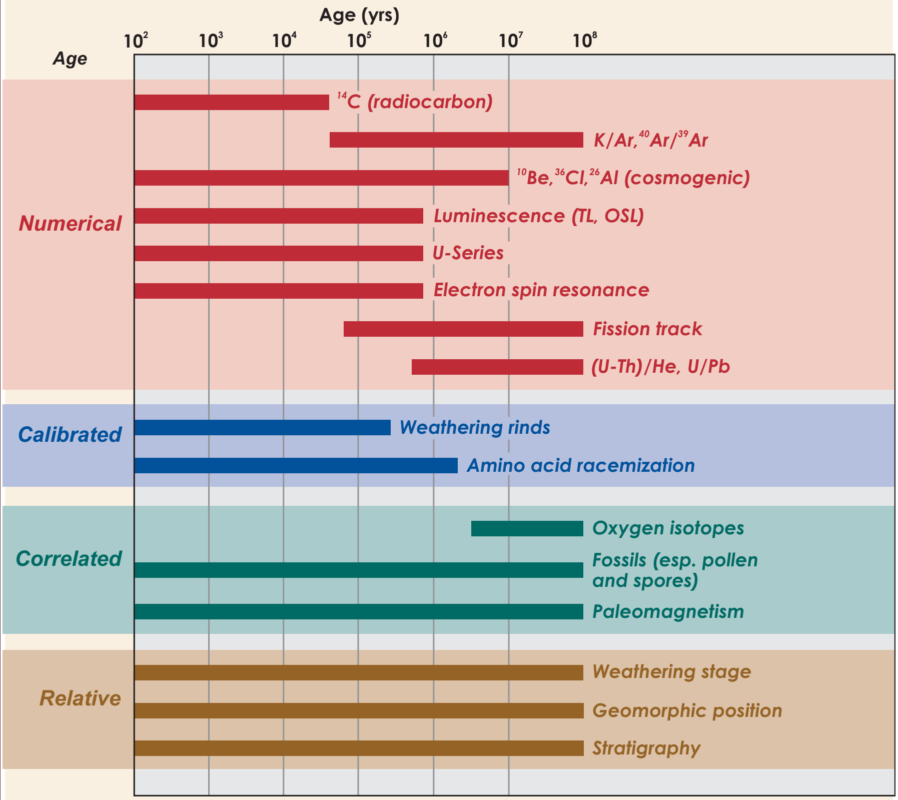
Cooperative Research Centre for Landscape Environments and Mineral Exploration

Regolith dating methods: A guide to numerical dating techniques in Australia

Brad Pillans



REGOLITH DATING METHODS: A GUIDE TO NUMERICAL DATING TECHNIQUES IN AUSTRALIA

Brad Pillans

Reference:

Pillans B, 2008

Regolith Dating Methods: A Guide to Numerical Dating Techniques in Australia

1. Regolith. 2. Geochronology. 3. Dating methods. 4. Australia

ISBN 1 921039 98 1

Publisher: CRC LEME c/o CSIRO Exploration and Mining, P.O. Box 1130, Bentley WA 6102

Editors: David Garnett, Gerry Govett and Lisa Worrall

Copy editor: Peter Storer, Peter Storer Editorial Services

Cover, graphic design and illustrations: Angelo Vartesi and Travis Naughton, CSIRO Visual Resources Unit, Perth.

Printer: Printezy.com, 128 Canning Highway South Perth WA 6151

Electronic copies of this publication in PDF format can be downloaded from the CRC LEME website http://crcleme.org.au

Disclaimer

The user accepts all risks and responsibility for losses, damages, costs and other consequences resulting directly or indirectly from using any information or material contained in this report. To the maximum permitted by law, CRC LEME excludes all liability to any person arising directly or indirectly from using any information or material contained in this report.

Address and affiliation of the author

B Pillans
CRC LEME
Research School of Earth Sciences
The Australian National University
Canberra ACT 0200
Australia
brad.pillans@.anu.edu.au

CONTENTS

PREFACE TO THE SECOND EDITION

The decade since the publication of the first edition of this guide (Pillans 1998) has seen a marked upsurge in the application of geological dating methods to Australian regolith. A significant driver of this upsurge has been the research programs of CRC LEME (see Pillans 2005, 2006).

The format and content of the first edition was well received, so changes to this edition largely reflect updates to the reference lists and laboratory contact details. However, some techniques that were only briefly mentioned in the first edition, such as (U-Th)/He and SHRIMP U/Pb dating, are now fully described.

INTRODUCTION

Before the twentieth century, notions of geological age and time were founded on the principles of geological correlation and superposition. In other words, geologists erected a relative time scale, which was expressed in the broadest sense by the now standard geological time scale of eras (e.g. Mesozoic), periods (e.g. Cretaceous), stages (e.g. Albian), and so on. However, since 1905, when Ernest Rutherford first proposed that radioactive decay could form the basis of dating minerals, a wide variety of geological dating techniques have been discovered and refined. Consequently, geologists increasingly are able to assign numerical ages (and age uncertainties) to particular strata and events.

The purpose of this guide is to provide information on existing dating techniques that may be useful in determining numerical ages of Australian regolith materials. It does not contain detailed information on how each method works, but rather is intended as a guide to selecting appropriate methods for particular dating problems. In almost every case close consultation with dating practitioners regarding sampling strategies and general methodologies, is recommended.

For each dating method, the following headings are used:

METHOD:	Name of technique, e.g. fission-track.
TYPE:	Classified according to type of result: e.g. calibrated age or type of method; e.g. isotopic (Colman *et al.* 1987). See *Table 1*.
AGE RANGE:	Age range over which the method may be applied (*Figure 1*).
PRECISION:	Uncertainty of age determination.
MATERIALS:	Types of minerals, rocks, etc which can be dated.
DESCRIPTION:	Summary of how the method works.
APPLICATIONS:	General summary of applications in regolith studies.
PROBLEMS:	Complications, tricks, assumptions etc in applying the method.

FIELD SAMPLING: Sampling equipment, sample size etc.

LABS: Names of laboratories where the measurements are carried out.

COSTS: Indicative costs for age determinations.

REFERENCES: Key papers illustrating methodology, applications, etc.

SIDEREAL[1]	ISOTOPIC	RADIOGENIC	CHEMICAL/ BIOLOGICAL	GEOMORPHIC	CORRELATION
Historical records	**Radiocarbon**	**Fission-track**	**Racemization**	**Weathering rinds**	**Paleomagnetism**
Dendro-chronology	**K/Ar and Ar/Ar**	**Luminescence**	Obsidian hydration	Soil development	**Stable isotopes**
Varve chronology	**Cosmogenic isotopes**	**ESR**	Lichenometry	Geomorphic position	**Spores & pollen**
	(U+Th)/He		Soil chemistry	Rate of deposition	Other fossils
	U/Pb			Rate of deformation	Orbital variations
					Lithostratigraphy
					Tektites
[1]SIDEREAL: based on solar time.					Tephrochronology
					Rock varnish

Table 1: Classification of dating methods according to type method employed (modified from Colman et al. 1987).

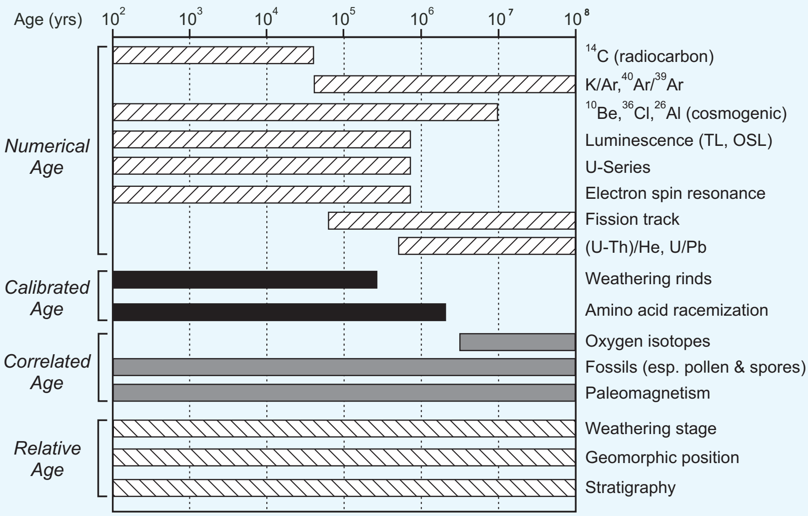


Figure 1: Age ranges over which regolith dating methods can be applied. Methods are grouped according to type of age result produced (see Colman et al. 1987).

TERMINOLOGY

Wherever appropriate, the recommendations of Colman *et al.* (1987) are followed:

"A date is a specific point in time, whereas an age is an interval of time measured back from the present. The use of 'date' as a verb to describe the process of producing age estimates is generally accepted. However, in geologic applications, 'date', when used as a noun, carries a connotation of calendar years and a degree of accuracy that is seldom appropriate. Most 'dates' are better described as 'age estimates' or simply 'ages'. Exceptions include dates derived from historical records, and some ages derived from tree rings or varves. In spite of its connotations, we recognize that the use of 'date' is firmly entrenched, that alternatives are sometimes awkward, and that the verb or its derivatives are acceptable. For these reasons we use the phrase 'dating methods' and we do not expect phrases such as 'radiocarbon dating' to be abandoned."

In terms of abbreviations used to express ages, Colman *et al.* (1987) followed the North American Commission on Stratigraphic Nomenclature in distinguishing between ages determined by geochronologic methods and other intervals of time. They recommend "the use of the SI-derived abbreviations ka and Ma (thousand and million years, respectively, measured from the present) for ages, and informal abbreviations such as yr, k.y. and m.y. for time intervals. Time measured from the present is implicit in ka and Ma; neither 'before present' nor 'ago' should be added to these abbreviations. Radiocarbon dating has established the use of the phrase 'yr B.P.' to indicate ^{14}C ages measured from 1950 A.D. To avoid confusion, the use of yr B.P. should be restricted to radiocarbon ages."

Colman *et al.* (1987, p. 315) strenuously object to the use of the word absolute to describe any dating method. As they say: "this term is more appropriate for despots and deities than for dating methods." Absolute is commonly used to describe the results of isotopic dating methods; however, analytical uncertainties, undetected contamination, and geological uncertainties—such as the temporal relationship between a geological event and time zero of a dating method—all mean that isotopic ages are less than absolute. It is recommended that the term absolute should be replaced with the term numerical, for ages.

GENERAL REFERENCES ON DATING METHODS

A number of books, book chapters and journal articles deal with a range of dating methods, rather than a single method. For a general, non-specialist introduction to dating methods, these sources are often the best way to become familiar with applications and methodologies of dating methods. These publications are included in the reference list below.

REFERENCES:

Colman SM, Pierce KL and Birkeland PW, 1987. Suggested terminology for Quaternary dating methods. *Quaternary Research* 28, 314–319.

Dalrymple GB, 1991. Modern radiometric methods: How they work: in Dalrymple GB *The Age of the Earth.* Stanford University Press, Stanford.

Dickin AP, 1995. *Radiogenic isotope geology.* Cambridge University Press, Cambridge, UK.

Duller GAT, 2000. Dating methods: geochronology and landscape evolution. *Progress in Physical Geography* 24, 111–116.

Easterbrook DJ, (editor.), 1988. *Dating Quaternary sediments.* Geological Society of America Special Paper 227.

Faure G, 1986. *Principles of isotope geology.* John Wiley & Sons, New York.

Geyh MA and Schleicher H, 1990. *Absolute age determination: physical and chemical methods and their application.* Springer-Verlag, Berlin.

Noller JS, Sowers JM and Lettis WR (editors), 2000. *'Quaternary geochronology. Methods and applications.' AGU Reference Shelf 4.* American Geophysical Union, Washington DC.

Pillans B, 1998. *Regolith dating methods. A guide to numerical dating techniques.* CRC LEME, Perth.

Pillans, B., 2005. Geochronology of the Australian regolith. In: R.R. Anand and P. de Broekert (Editors), *Regolith-Landscape Evolution Across Australia.* CRC LEME, Perth, pp. 41-61.

Pillans B (editor), 2006. Regolith Geochronology and Landscape Evolution. *CRC LEME Open File Report* 189.

Rutter NW and Cato ER (editors), 1995. *'Dating methods for Quaternary deposits.' Geotext 2.* Geological Association of Canada, St Johns.

Vasconcelos PM, Knesel KM, Cohen, BE and Heim JA, 2008. Geochronology of the Australian Cenozoic: a history of tectonic and igneous activity, weathering, erosion, and sedimentation. *Australian Journal of Earth Sciences* 55, 865-914.

Wagner GA, 1998. *Age determination of young rocks and artifacts.* Springer-Verlag, Berlin.

Walker, M., 2005. *Quaternary dating methods.* John Wiley & Sons, Chichester, UK.

Watchman AL and Twidale CR, 2002. Relative and 'absolute' dating of land surfaces. *Earth-Science Reviews* 58, 1–49.

Williams, MAJ, Dunkerley DL, De Deckker P, Kershaw AP and Chappell J, 1998. *Quaternary environments, Appendix: Dating methods in Quaternary research.* Edward Arnold, London, 269–284.

METHODS

Radiocarbon

TYPE:	Numerical age; isotopic.
AGE RANGE:	0–50 ka.
PRECISION:	Better than ± 1% for samples 2–20 ka; lower precision in younger and older samples.
MATERIALS:	Organic materials including shell, charcoal, wood, peat, carbonates, etc.
DESCRIPTION:	Radioactive decay of ^{14}C with half life 5730 years. By convention, ages are reported as years B.P. (before present, i.e. 1950 AD) using the 'Libby' half-life of 5568 years. Because the amount of ^{14}C in the atmosphere is not constant, conversion of radiocarbon age to calendar age uses calibration curves from dated tree rings.
APPLICATIONS:	Numerous applications in 'young' sedimentary sequences.
PROBLEMS:	Age limited; contamination; organics uncommon in some sedimentary environments; radiocarbon ages need calibration before comparison with results from other techniques.
FIELD SAMPLING:	Sample size depends on material: a few grams of charcoal is recommended for a conventional age determination, whereas more than 1 kg may be required to date soil materials with low (< 1%) carbon contents. Milligram- to microgram-size samples may be dated by accelerator mass spectrometry (AMS).
LABS:	Australian National University (Dr S Fallon). Australian Nuclear Science and Technology Organisation, Lucas Heights (Dr D Fink). Waikato University, New Zealand (Dr A Hogg).

COSTS: Typically around $400–450 for conventional ages; $700–900 for AMS ages.

REFERENCES:

Bird MI, Ayliffe LK, Fifield LK, Turney CSM, Cresswell RG, Barrows TT and David B, 1999. Radiocarbon dating of 'old' charcoal using a wet oxidation-stepped combustion procedure. *Radiocarbon* 41, 127–140.

Bird MI, Turney CSM, Fifield LK, Smith MA, Miller GH, Roberts RG and Magee JW, 2003. Radiocarbon dating of organic- and carbonate-carbon in *Genyornis* and *Dromaius* eggshell using stepped combustion and stepped acidification. *Quaternary Science Reviews 22*, 1805–1812.

Callen RA, Wasson RJ and Gillespie R, 1983. Reliability of radiocarbon dating of pedogenic carbonate in the Australian arid zone. *Sedimentary Geology* 35, 1–14.

Chappell J, Head J and Magee J, 1996. Beyond the radiocarbon limit in Australian archaeology and Quaternary research. *Antiquity* 70, 543–552.

Gillespie R, Magee JW, Luly JG, Dlugokencky RJ, Sparks RJ and Wallace G, 1991. AMS radiocarbon dating in the study of arid environments: examples from Lake Eyre, South Australia. *Palaeogeography, Palaeoclimatology, Palaeoecology* 84, 333–338.

Reimer PJ, Baillie MGL and Bard E, 2004. IntCal04 terrestrial radiocarbon age calibration/comparison, 26-0 ka B.P. *Radiocarbon* 46, 1029-1058.

Stuiver M, Reimer PJ, Bard E, Beck JW, Burr GS, Hughen KA, Kromer B, McCormac FG, van der Plicht J and Spurk M, 1998. INTERCAL98 radiocarbon age calibration 24,000-0 cal BP. *Radiocarbon* 40, 1041–1083.

Potassium–argon and argon–argon

TYPE: Numerical age; isotopic.

AGE RANGE: Typically 100 ka+; occasionally as young as 20 ka or younger in favourable circumstances (e.g. high K-bearing minerals).

PRECISION: Typically 1% for K/Ar and better than 1% for Ar/Ar in cases where proportion of radiogenic argon > 10%.

MATERIALS: Potassium-bearing minerals in igneous and metamorphic rocks; well crystallised whole rock samples, especially volcanic rocks; secondary alunite and K-Mn oxides; glauconite.

DESCRIPTION: Based on radioactive decay of ^{40}K to ^{40}Ar. In the conventional K–Ar dating method, total K is measured on an aliquot of the sample, and the amount of ^{40}K determined from the essentially constant $^{40}K/K$ ratio in terrestrial materials; the amount of ^{40}Ar is determined on a separate aliquot by isotope dilution. In the $^{40}Ar/^{39}Ar$ method, the argon and potassium are determined on a single aliquot of the sample by isotope analysis in a mass spectrometer, after irradiation in a nuclear reactor to convert a proportion of the ^{39}K atoms to ^{39}Ar atoms. Because the $^{40}K/^{39}Ar$ ratio is essentially constant in nature, the $^{40}Ar/^{40}Ar$ ratio, and hence the age, can then be calculated. Although it is more time consuming and more expensive, the $^{40}Ar/^{39}Ar$ method has advantages over the conventional K–Ar method, such as smaller sample size and greater precision; also, stepwise heating release of Ar from a sample yields a spectrum of apparent ages, which provides better understanding of the thermal history of a sample.

APPLICATIONS: Wide applications in dating igneous rocks and secondary minerals.

PROBLEMS: Argon loss, excess and inherited argon.

FIELD SAMPLING: Rock samples must be fresh and unaltered; alteration of rock samples and purity of secondary mineral phases should be verified in the laboratory. Sample size varies with age, material and K content.

LABS: Australian National University (Dr M Forster).

Melbourne University (Dr D Foster).

University of Queensland (Dr P Vasconcelos).

COSTS: For collaborative studies, typically $650 for K/Ar and $1000 for $^{40}Ar/^{39}Ar$; commercial rates available on request.

REFERENCES:

Bird MI, Chivas AR and McDougall I, 1990. A reconnaissance isotopic study of surficial alunite in Australia. 2. Potassium-argon geochronology. *Chemical Geology (Isotope Geoscience Section)* 80, 133–145.

Coventry RJ, Stephenson PJ and Webb AW, 1985. Chronology of landscape evolution and soil development in the upper Flinders River area, Queensland, based on isotopic dating of Cainozoic basalts. *Australian Journal of Earth Sciences* 32, 314–319.

Dammer D 1995. *Geochronology of chemical weathering processes in the northern and western Australian regolith.* PhD thesis, Australian National University, Canberra.

Dammer D, Chivas AR and McDougall I, 1996. Isotopic dating of supergene manganese oxides from the Groote Eylandt deposit, Northern Territory, Australia. *Economic Geology* 91, 386–401.

Dammer D, McDougall I and Chivas AR, 1999. Timing of weathering-induced alteration of manganese deposits in Western Australia: Evidence from K/Ar and $^{40}Ar/^{39}Ar$ dating. *Economic Geology* 94, 87–108.

Feng Y and Vasconcelos P, 2001. Quaternary continental weathering geochronology by laser-heating $^{40}Ar/^{39}Ar$ analysis of supergene cryptomelane. *Geology* 29, 635–638.

Gibson DL, 2007. Potassium-argon ages of Late Mesozoic and Cainozoic igneous rocks of eastern Australia. *CRC LEME Open File Report* 193.

Li J-W and Vasconcelos P, 2002. Cenozoic continental weathering and its implications for the palaeoclimate: evidence from $^{40}Ar/^{39}Ar$ geochronology of supergene K-Mn oxides in Mt Tabor, central Queensland, Australia. *Earth and Planetary Science Letters* 200, 223–239.

McDougall I, 1996. Potassium-argon dating in the Pleistocene: in: Rutter NW and Cato ER (Editors) '*Dating methods for Quaternary deposits*.' *Geotext 2*. Geological Association of Canada, St Johns, 1–14.

McDougall I and Harrison TM, 1988. *Geochronology and thermochronology by the $^{40}Ar/^{39}Ar$ method*. Oxford University Press, New York.

Vasconcelos PM, 1999. K-Ar and $^{40}Ar/^{39}Ar$ geochronology of weathering processes. *Annual Reviews of Earth and Planetary Sciences* 27, 183–229.

Vasconcelos PM, 1999. $^{40}Ar/^{39}Ar$ geochronology of supergene processes in ore systems. *Reviews in Economic Geology* 12, 73–113.

Vasconcelos PM, 2002. Geochronology of weathering in the Mt Isa and Charters Towers regions, northern Queensland. *CRC LEME Open File Report* 139.

Vasconcelos PM and Conroy M, 2003. Geochronology of weathering and landscape evolution, Dugald River valley, NW Queensland, Australia. *Geochimica et Cosmochimica Acta* 67, 2913–2930.

Wellman P and McDougall I, 1974. Potassium-argon ages on the Cainozoic volcanic rocks of New South Wales. *Journal of the Geological Society of Australia* 21, 247–272.

Cosmogenic isotopes (e.g. ^{3}He, ^{10}Be, ^{26}Al, ^{21}Ne, ^{36}Cl)

TYPE:	Numerical age; isotopic.
AGE RANGE:	0–5 Ma.
PRECISION:	3–10%, depending on age, sample type and measured isotope.
MATERIALS:	Quartz; carbonates; Ca-, K-, Cl-bearing whole rocks; soils.
DESCRIPTION:	Cosmic ray interactions produce ^{3}He, ^{10}Be, ^{21}Ne, ^{26}Al and ^{36}Cl, in the atmosphere and lithosphere. Accumulation reflects the duration of cosmic ray exposure within the upper 1–2 metres of the Earth's surface.
APPLICATIONS:	Rock surface exposure ages and erosion rates.
PROBLEMS:	Uncertainties in isotope production rates and altitude/latitude corrections. Ability to determine surface age often compromised by erosion: resulting in a minimum age estimate.
FIELD SAMPLING:	Stable rock surfaces, which must have been created by the event to be dated. Collect surface sample up to ~5 cm thick. Near-horizontal surfaces most appropriate; otherwise corrections for cosmic-ray obstruction are required. Sample altitude and latitude are required for age calculation.
LABS:	Research Schools of Earth Sciences and Physical Sciences and Engineering, Australian National University (Prof. K Fifield). Australian Nuclear Science and Technology Organisation, Lucas Heights (Dr D Fink).
COSTS:	$600–1800 per isotopic determination, depending on preparation costs.

REFERENCES:

Barrows TT, Stone JO, Fifield LK and Cresswell RG, 2001. Late Pleistocene glaciation of the Kosciuszko Massif, Snowy Mountains, Australia. *Quaternary Research* 55, 179–189.

Barrows TT, Stone JO, Fifield LK and Cresswell RG, 2002. The timing of the Last Glacial Maximum in Australia. *Quaternary Science Reviews* 21, 159–173.

Barrows TT, Stone JO and Fifield LK, 2004. Exposure ages for Pleistocene periglacial deposits in Australia. *Quaternary Science Reviews* 23, 697–708.

Bierman P, 1994. Using in situ cosmogenic isotopes to estimate rates of landscape evolution: A review from the geomorphic perspective. *Journal of Geophysical Research* 99, 13,885–13,896.

Bierman PR and Caffee M, 2002. Cosmogenic exposure and erosion history of Australian bedrock landforms. *Geological Society of America Bulletin* 114, 787–803.

Bierman P and Turner J, 1995. ^{10}Be and ^{26}Al evidence for exceptionally low rates of Australian bedrock erosion and the likely existence of pre-Pleistocene landscapes. *Quaternary Research* 44, 378–382.

Cerling TE and Craig H, 1994. Geomorphology and in-situ cosmogenic isotopes. *Annual Reviews of Earth and Planetary Sciences* 22, 273–317.

Chappell J, 2006. Australian landscape processes measured with cosmogenic nuclides: in Pillans B (editor) *Regolith geochronology and landscape evolution*. CRC LEME, Perth, 19–26.

Fifield LK, 1999. Accelerator mass spectrometry and its applications. *Reports on Progress in Physics* 62, 1223–1274.

Fujioka T, Chappell J, Honda M, Yatsevich I, Fifield K and Fabel D, 2005. Global cooling initiated stony deserts in central Australia 2-4 Ma, dated by cosmogenic 21Ne-10Be. *Geology* 33, 993–996.

Heimsath AM, Chappell J, Dietrich WE, Nishiizumi K and Finkel RC, 2000. Soil production on a retreating escarpment in southeastern Australia. *Geology* 28, 787–790.

Heimsath AM, Chappell J, Dietrich WE, Nishiizumi K and Finkel RC, 2001. Late Quaternary erosion in southeastern Australia: a field example using cosmogenic isotopes. *Quaternary International* 83-85, 169–185.

Mackintosh AN, Barrows TT, Colhoun EA and Fifield LK, 2006. Exposure dating and glacial reconstruction at Mt Field, Tasmania, Australia, identifies MIS3 and MIS 2 glacial advances and climatic variability. *Journal of Quaternary Science* 21, 363–376.

Quigley M, Sandiford M, Fifield K and Alimanovic A, 2007. Bedrock erosion and relief production in northern Flinders Ranges, Australia. *Earth Surface Processes and Landforms* 32, 929-944.

Wilkinson MT, Chappell J, Humphreys GS, Fifield K, Smith B and Hesse P, 2005. Soil production in heath and forest, Blue Mountains, Australia: influence of lithology and palaeoclimate. *Earth Surface Processes and Landforms* 30, 923–934.

(U/Th)/He

TYPE: Numerical age, isotopic.

AGE RANGE: 1 Ma+.

PRECISION: Typically ± 5% or better

MATERIALS: Iron oxides, apatite.

DESCRIPTION: Radioactive decay of U and Th produces ^4He which is trapped in crystal lattices. Ages for Fe oxides are minimum ages unless corrected for He diffusion.

APPLICATIONS: Potential wide applications in weathered regolith materials containing Fe oxides.

PROBLEMS: He diffusion.

FIELD SAMPLING: Contact lab for details.

LABS: University of Melbourne (Dr B Kohn)

The Australian National University (Dr M Honda)

California Institute of Technology (Prof. K Farley)

COSTS: Negotiable.

REFERENCES:

Bahr HJ, Lippolt HJ and Wernicke RS, 1994. Temperature-induced ^4He degassing of specularite and botryoidal hematite: A ^4He retentivity study. *Journal of Geophysical Research* 99, 17, 695-707.

Flowers RM, Bowring SA and Reiners PW, 2006. Low long-term erosion rates and extreme continental stability documented by ancient (U-Th)/He dates. *Geology* 34, 925–928.

Heim JA, Vasconcelos PM, Shuster DL, Farley KA and Broadbent G, 2006. Dating paleochannel iron ore by (U-Th)/He analysis of supergene goethite, Hamersley province, Australia. *Geology* 34, 173–176.

Lippolt HJ, Wernicke RS and Bahr R, 1995. Paragenetic specularite and adularia (Elba, Italy): Concordant (U+Th)-He and K-Ar ages. *Earth and Planetary Science Letters* 132, 43–51.

Persano C, Stuart FM, Bishop P and Barfod DN, 2002. Apatite (U-Th)/He age constraints on the development of the Great Escarpment on the southeastern Australian passive margin. *Earth and Planetary Science Letters* 200, 79–90.

Pidgeon RT, Brander T and Lippolt HJ, 2004. Late Miocene (U+Th)-^{4}He ages of ferruginous nodules from lateritic duricrust, Darling Range, Western Australia. *Australian Journal of Earth Sciences* 51, 901–909.

Shuster DL, Farley KA, Sisterson JM and Burnett DS, 2004. Quantifying the diffusion kinetics and spatial distributions of radiogenic ^{4}He in minerals containing proton-induced ^{3}He. *Earth and Planetary Science Letters* 217, 19–32.

Shuster DL, Vasconcelos PM, Heim JA and Farley KA, 2005. Weathering geochronology by (U-Th)/He dating of goethite. *Geochimica et Cosmochimica Acta* 69, 659–673.

Stock GM, Ehlers TA and Farley KA, 2006. Where does sediment come from? Quantifying catchment erosion with detrital apatite (U-Th)/He thermochronometry. *Geology* 34, 725–728.

Uranium–lead

TYPE:	Numerical age; isotopic.
AGE RANGE:	100 yrs–4.5 Ga+.
PRECISION:	Varies with age and material—typically 0.1–1% in zircon; around 2% in speleothems reported by Woodhead *et al.* (2006).
MATERIALS:	Zircon is most common mineral dated, but monazite, titanite, xenotime and baddeleyite are also suitable; carbonates (e.g. speleothems) can also be dated.
DESCRIPTION:	Based on radioactive decay of ^{238}U to ^{206}Pb (half life ~4.5 Ga) and ^{235}U to ^{207}Pb (half life ~700 Ma).
APPLICATIONS:	The sensitive high-resolution ion micro-probe (SHRIMP) designed and operated in the Research School of Earth Sciences, ANU, allows U/Pb dating of single zircons. Although normally applied to rocks of great antiquity (e.g. Froude *et al.* 1983), this method is widely used for provenance studies of detrital zircon.
PROBLEMS:	Non-radiogenic Pb in carbonates; Pb loss in zircon
FIELD SAMPLING:	Sample size varies with lithology
LABS:	Australian National University (Dr IS Williams)
	Melbourne University (Dr J Woodhead)
	Curtin University (Dr M McWilliams)
COSTS:	Available on request.

REFERENCES:

Cawood PA and Nemchin AA, 2000. Provenance record of a rift basin: U/Pb ages of detrital zircons from the Perth Basin, Western Australia. *Sedimentary Geology* 134, 209–234.

de Broekert PP, Wilde SA and Kennedy AK, 2004. Variety, age and origin of zircons in the mid-Cenozoic Westonia Formation, southwestern Yilgarn Craton, Western Australia. *Australian Journal of Earth Sciences* 51, 157-171.

Fletcher, I.R., Rasmussen B and McNaughton NJ, 2000. SHRIMP U-Pb geochronology of authigenic xenotime and its potential for dating sedimentary basins. *Australian Journal of Earth Sciences* 47(5), 845–859.

Froude DO, Ireland T., Kinny PD, Williams IS, Compston W, Williams IR and Myers JS, 1983. Ion microprobe identification of 4100–4200 M yr-old terrestrial zircons. *Nature* 304, 616-618.

Gatehouse RD, Williams IS and Pillans BJ, 2001. Fingerprinting windblown dust in south-eastern Australian soils by uranium-lead dating of detrital zircon. *Australian Journal of Soil Research* 39, 7–12.

Pell SD, Chivas AR and Williams IS, 2001. The Mallee Dunefield: development and sand provenance. *Journal of Arid Environments* 48, 149–170.

Pell SD, Williams IS and Chivas AR, 1997. The use of zircon-age fingerprints in determining the protosource areas for some Australian dune sands. *Sedimentary Geology* 109, 233–260.

Reid AJ and Hou B, 2006. Source of heavy minerals in the Eucla Basin palaeobeach placer province, South Australia: age data from detrital zircons. *MESA Journal* 42, 10–14.

Sircombe KN, 1999. Tracing provenance through the isotope ages of littoral and sedimentary detrital zircon, eastern Australia. *Sedimentary Geology* 124, 47–67.

Sircombe KN and Freeman MJ, 1999. Provenance of detrital zircons on the Western Australia coastline—Implications for the geological history of the Perth Basin and denudation of the Yilgarn Craton. *Geology* 27(10), 879–882.

Veevers JJ, Saeed A, Belousova EA and Griffin WL, 2005. U-Pb ages and source composition by Hf-isotope and trace-element analysis of detrital zircons in Permian sandstone and modern sand from southwestern Australia and a review of the paleogeographical and denudational history of the Yilgarn Craton. *Earth-Science Reviews* 68, 245–279.

Woodhead J. Hellstrom J, Maas R, Drysdale R, Zanchetta G, Devine P and Taylor E, 2006. U-Pb geochronology of speleothems by MC-ICPMS. *Quaternary Geochronology* 1, 208–221.

Luminescence (including TL and OSL)

TYPE:	Numerical age; radiogenic.
AGE RANGE:	10 yrs–1 Ma.
PRECISION:	± 5–15% (OSL), ± 10–20% (TL).
MATERIALS:	Quartz, feldspars and gypsum in aeolian sediments.
DESCRIPTION:	Natural radiation (α, β, γ and cosmic) produces electron and hole pairs, which can be trapped at defects in a crystal lattice. Luminescence is emitted when electrons liberated from the traps by heating (thermoluminescence or TL) or exposure to visible - wavelength light (optically stimulated luminescence or OSL) or infra-red light (infra-red stimulated luminescence or IRSL) recombine with trapped holes. The greater the radiation dose accrued, the greater the resulting luminescence. Age is found by calibrating the luminescence with known radiation doses, in combination with measurements of the environmental dose rate.
APPLICATIONS:	Wide application in Australian landscapes, especially aeolian deposits.
PROBLEMS:	Incomplete bleaching during sediment transport
FIELD SAMPLING:	Samples cannot be exposed to light. Usually, steel tubes are hammered into the outcrop, sealed in black polythene and only subsequently opened under darkroom conditions in the luminescence lab. Extra samples are taken for radioisotope assays and water content determinations. Sediment should ideally be of uniform composition within a 30 cm radius of the sample (the limit of the γ radiation dose).
LABS:	Australian National University (Dr K Fitzsimmons). University of Wollongong (Prof. RG Roberts). University of Adelaide (Prof. J Prescott). University of Melbourne (Dr M Cupper) CSIRO (Dr Jon Olley)

COSTS: $700–2000 depending on nature of sample.

REFERENCES:

Aitken MJ, 1985. *Thermoluminescence dating.* Academic Press, London.

Aitken MJ, 1994. Optical dating: a non-specialist review. *Quaternary Science Reviews (Quaternary Geochronology)* 15, 503–508.

Chen XY, Prescott JR and Hutton JT, 1990. Thermoluminescence dating of gypseous dunes of Lake Amadeus, central Australia. *Australian Journal of Earth Sciences* 37, 93–101.

Chen XY, Spooner NA, Olley JM and Questiaux DG, 2002. Addition of aeolian dusts to soils in southeastern Australia: red silty clay trapped in dunes bordering Murrumbidgee River in the Wagga Wagga region. *Catena* 47, 1–27.

Fitzsimmons KE, Bowler JM, Rhodes EJ and Magee JM, 2007. Relationships between desert dunes during the late Quaternary in the Lake Frome region, Strzelecki Desert, Australia. *Journal of Quaternary Science* 22, 549–558.

Fitzsimmons KE, Rhodes EJ, Magee JW and Barrows TT, 2007. The timing of linear dune activity in the Strzelecki and Tirari Deserts, Australia. *Quaternary Science Reviews* 26, 2598–2616.

Heimsath AM, Chappell J, Spooner NA and Questiaux DG, 2002. Creeping soil. *Geology* 30, 111–114.

Huntley DJ, Hutton JT and Prescott JR, 1993. The stranded beach-dune sequence of south-east South Australia: a test of thermoluminescence dating, 0-800 ka. *Quaternary Science Reviews* 12, 1–20.

Huntley DJ, Hutton JT and Prescott JR, 1994. Further luminescence dates from the dune sequence in the southeast of South Australia. *Quaternary Science Reviews* 13, 201–207.

Lees BG, Stanner J, Price DM and Lu Y, 1995. Thermoluminescence dating of dune podzols at Cape Arnhem, northern Australia. *Marine Geology* 129, 63–75.

Nott J and Roberts RG, 1996. Time and process rates over the past 100 m.y.: a case for dramatically increased landscape denudation rates during the late Quaternary in northern Australia. *Geology* 24, 883–887.

Nott J, Young R, Bryant E and Price D, 1994. Stratigraphy vs. pedogenesis; problems of their correlation within coastal sedimentary facies. *Catena* 23, 199–212.

Page KJ, Nanson GC and Price DM, 1991. Thermoluminescence chronology of late Quaternary deposition on the Riverine Plain of south-eastern Australia. *Australian Geographer* 22, 14–23.

Prescott JR and Habermehl MA, 2008. Luminescence dating of spring mound deposits in the southwestern Great Artesian Basin, northern South Australia. *Australian Journal of Earth Sciences* 55, 167–181.

Prescott JR and Robertson GB, 2008. Luminescence dating: an Australian perspective. *Australian Journal of Earth Sciences* 55, 997-1007.

Readhead ML, 1988. Thermoluminescence dating study of quartz in aeolian sediments from southeastern Australia. *Quaternary Science Reviews* 7, 257–264.

Roberts RG, Jones R, Spooner NA, Head MJ, Murray AS and Smith MA, 1994. The human colonisation of Australia: optical dates of 53,000 and 60,000 years bracket human arrival at Deaf Adder Gorge, Northern Territory. *Quaternary Science Reviews (Quaternary Geochronology)* 13, 575–583.

Yoshida H, Roberts RG and Olley JM, 2003. Progress towards single-grain optical dating of fossil mud-wasp nests and associated rock art in northern Australia. *Quaternary Science Reviews* 22, 1273–1278.

Uranium series

TYPE:	Numerical age; isotopic.
AGE RANGE:	0–1 Ma.
PRECISION:	Better than 0.5% using mass spectrometry.
MATERIALS:	Carbonates (speleothems, corals), U-bearing oxides, bone, volcanic rocks; opal; peat is sometimes suitable.
DESCRIPTION:	Based on decay or accumulation of various parent/daughter isotopes in the U-series decay chains, especially $^{234}U/^{238}U$ and $^{230}Th/^{234}U$.
APPLICATIONS:	Commonly used for dating cave speleothems, and fossil corals in shoreline deposits.
PROBLEMS:	Uranium mobility; detrital Th contamination. For example, dating pedogenic calcrete is generally unreliable because of detrital Th contamination.
FIELD SAMPLING:	Check corals for recrystallisation from aragonite to calcite.
LABS:	Australian National University (Prof M McCulloch). Melbourne University (Dr J Woodhead, Dr J Hellstrom). ANSTO (Dr T Esat). University of Queensland (Prof. K Collerson).
COSTS:	Negotiable.

REFERENCES:

Ayliffe LK, Marianelli PC, Moriarty KC, Wells RT, McCulloch MT, Mortimer GE and Hellstrom JC, 1998. 500 ka precipitation record from southeastern Australia: Evidence for interglacial relative aridity. Geology 26, 147–150.

Ayliffe LK and Veeh HH, 1988. Uranium-series dating of speleothems and bones from Victoria Cave, Naracoorte, South Australia. *Chemical*

Geology (Isotope Geoscience Section) 72, 211–234.

Bernal JP, Eggins SM, McCulloch MT, Grun R and Eggleton, RA, 2006. Dating of chemical weathering processes by in situ measurement of U-series disequilibria in supergene Fe-oxy/hydroxides using LA-MC-ICPMS. *Chemical Geology* 235, 76–94.

Eggins SM, Grun R, McCulloch MT, Pike AWG. Chappell J, Kinsley L, Mortimer G, Shelley M, Murray-Wallace CV, Spotl C and Spotl LT, 2005. In situ U-series dating by laser-ablation multi-collector ICPMS: new prospects for Quaternary geochronology. *Quaternary Science Reviews* 24, 2523–2538.

Herczeg AL and Chapman A, 1991. Uranium-series dating of lake and dune deposits in southeastern Australia: a reconnaissance. *Palaeogeography, Palaeoclimatology, Palaeoecology* 84, 285–298.

Ku T-L, 1976. The uranium-series methods of age determination. *Annual Reviews of Earth and Planetary Sciences* 4, 347–380.

Ludwig KR and Paces JB, 2002. Uranium-series dating of pedogenic silica and carbonate, Crater Flat, Nevada. *Geochimica et Cosmochimica Acta* 66, 487–506.

Short SA, Lowson RT, Ellis J and Price DM, 1989. Thorium-uranium disequilibrium dating of Late Quaternary ferruginous concretions and rinds. *Geochimica et Cosmochimica Acta* 53, 1379–1389.

Simons SL and Nemchin AA, 2006. Application of SHRIMP for U-Pb and U-series dating of opal: in Pillans B (editor) Regolith geochronology and landscape evolution. *CRC LEME Open File Report* 189, 42–46.

Stirling CH, Esat TM, McCulloch MT and Lambeck K, 1995. High-precision U-series dating of corals from Western Australia and implications for the timing and duration of the Last Interglacial. *Earth and Planetary Science Letters* 135, 115–130.

Stirling CH, Esat TM, Lambeck K and McCulloch MT, 1998. Timing and duration of the Last Interglacial: evidence for a restricted interval of widespread coral reef growth. *Earth and Planetary Science Letters* 160, 745–762.

Xia Q, Zhao J and Collerson KD, 2001. Early-Mid Holocene climatic variations in Tasmania, Australia: multi-proxy records in a stalagmite from Lynds Cave. *Earth and Planetary Science Letters* 194, 177–187.

Electron spin resonance

TYPE:	Numerical age; radiogenic.
AGE RANGE:	2 ka–1 Ma+.
PRECISION:	Best values around 5–7%.
MATERIALS:	Carbonates (shell, coral), teeth, quartz, gypsum, silcrete.
DESCRIPTION:	Radiation produces unpaired electrons in crystal lattices. The concentration of unpaired electrons increases with time and radiation dose.
APPLICATIONS:	Widely used overseas for dating vertebrate fossils, including human fossils. Has been used to date silcrete in Queensland.
PROBLEMS:	Dose response curves not well defined; U migration in teeth.
FIELD SAMPLING:	Contact lab for details.
LABS:	Quaternary Dating Research Centre, ANU (Dr R Grün).
COSTS:	Only available for collaborative research projects. Costs will be detailed for specific projects.

REFERENCES:

Chen Y, Arakel AV and Lu J, 1989. Investigation of sensitive signals due to gamma-ray irradiation of chemical precipitates. A feasibility study for ESR dating of gypsum, phosphate and calcrete deposits. *Applied Radiation and Isotopes* 40, 1012.

Chen Y, Lu J, Head J, Arakel AV and Jacobson G, 1988. ^{14}C and ESR dating of calcrete and gypcrete cores from the Amadeus Basin, Northern Territory, Australia. *Quaternary Science Reviews* 7, 447–453.

Grün R, 1989. Electron spin resonance (ESR) dating. *Quaternary International* 1, 65–109.

Grün R, 2007. Electron spin resonance dating: in: Elias SA(Editor) *Encyclopedia of Quaternary Science*. Elsevier, Amsterdam, 1505–1516.

Grün R, Wells R, Eggins S, Spooner N, Aubert M, Brown L and Rhodes E, 2008. Electron spin resonance dating of South Australian megafauna sites. *Australian Journal of Earth Sciences* 55, 917-935.

Ikeya M, 1993. *New applications of electron spin resonance dating—dating, dosimetry and microscopy.* World Scientific, Singapore.

Jacobson G, Arakel AV and Chen Y, 1988. The central Australian groundwater discharge zone: Evolution of associated calcrete and gypcrete deposits. *Australian Journal of Earth Sciences* 35, 549–565.

Radke U and Bruckner H, 1991. Investigation on age and genesis of silcretes in Queensland (Australia)—preliminary results. *Earth Surface Processes and Landforms* 16, 547–554.

Thorne A, Grün R, Mortimer G, Spooner NA, Simpson JJ, McCulloch M, Taylor L and Curnoe D, 1999. Australia's oldest human remains: age of the Lake Mungo 3 skeleton. *Journal of Human Evolution* 36, 591-612.

Fission track

TYPE:	Numerical age
AGE RANGE:	150 ka+.
PRECISION:	Typically better than 5–10%.
MATERIALS:	Uranium-bearing minerals such as zircon, sphene, apatite, volcanic glass; possibly gypsum.
DESCRIPTION:	Spontaneous fission of ^{238}U produces two fragments that disrupt the crystal lattice to create damage tracks. The number of tracks is proportional to the age of the U content and thermal history. Dates the time of cooling below a mineral-dependent track annealing temperature.
APPLICATIONS:	Widely used overseas for dating tephras. Major application in Australia to thermochronology of landscape evolution. If gypsum proves to be a suitable mineral (c.f. Li 1991), then many new applications will become possible in Australia.
PROBLEMS:	Interpretation of fission-track data in terms of denudation history is complex.
FIELD SAMPLING:	Sample size depends on mineral content. Contact lab for details.
LABS:	Melbourne University (Prof A Gleadow; Assoc Prof B Kohn).
COSTS:	$400 per mineral sample for collaborative studies; commercial rates available on request.

REFERENCES:

Brown RW, Summerfield MA and Gleadow AJW, 1994. Apatite fission track analysis: Its potential for the estimation of denudation rates and implications for models of long term landscape development: in Kirkby MJ (editor) *Process models and theoretical geomorphology*, John Wiley & Sons, Chichester, 23–53.

Dumitru TA, Hill KC, Coyle DA, Duddy IR, Foster DA, Gleadow AJW, Green PF, Kohn BP, Laslett GM and O'Sullivan AJ, 1991. Fission track thermochronology: application to continental rifting of south-eastern Australia. *APEA Journal* 31, 131–142.

Gallagher K, Dumitru TA and Gleadow AJW, 1994. Constraints on the vertical motion of eastern Australia during the Mesozoic. *Basin Research* 6, 77–94.

Kohn BP, Gleadow AJW and Cox SJD, 1999. Denudation history of the Snowy Mountains: constraints from apatite fission track thermochronology. *Australian Journal of Earth Sciences* 46, 181–198.

Kohn BP, Gleadow AJW, Brown RW, Gallagher K, O'Sullivan PB and Foster DA, 2002. Shaping the Australian crust over the last 300 million years: insights from fission track thermotectonic imaging and denudation studies of key terranes. *Australian Journal of Earth Sciences* 49, 697–717.

Li J, 1991. The environmental effects of the uplift of the Qinghai-Zizang Plateau. *Quaternary Science Reviews* 10, 479–483.

Mitchell MM, Kohn BP, O'Sullivan PB, Hartley MJ and Foster DA, 2002. Low-temperature thermochronology of the Mt Painter Province, South Australia. *Australian Journal of Earth Sciences* 49, 551–563.

Moore ME, Gleadow AJW and Lovering JF, 1986. Thermal evolution of rifted continental margins: new evidence from fission tracks in basement apatites from southeastern Australia. *Earth and Planetary Science Letters* 78, 255–270.

O'Sullivan PB, Foster DA, Kohn BP and Gleadow AJW, 1996. Multiple postorogenic denudation events: an example from the eastern Lachlan Fold Belt. *Geology* 24, 563–566.

O'Sullivan PB, Kohn BP, Foster DA and Gleadow AJW, 1995. Fission track data from the Bathurst Batholith: evidence for rapid mid-Cretaceous uplift and erosion within the eastern Highlands of Australia. *Australian Journal of Earth Sciences* 42, 597–608.

O'Sullivan PB, Gibson DL, Kohn BP, Pillans B and Pain CF, 2000. Long-term landscape evolution of the Northparkes region of the Lachlan Fold Belt, Australia: Constraints from fission track and paleomagnetic data. *Journal of Geology* 108, 1–16.

O'Sullivan PB, Pillans B, Gibson DL, Kohn BP and Pain CF, 2000. Long-term landscape evolution of the Northparkes region of the Lachlan Fold Belt, Australia: constraints from fission-track and paleomagnetic data: a reply. *Journal of Geology* 108, 750–752.

Spikings RA, Foster DA and Kohn BP, 2006. Low-temperature (< 110º C) thermal history of the Mt Isa and Murphy Inliers, northeast Australia: evidence from apatite fission track thermochronology. *Australian Journal of Earth Sciences* 53, 151–165.

Weber UD, Kohn BP, Gleadow AJW and Nelson DR, 2005. Low temperature Phanerozoic history of the Northern Yilgarn Craton, Western Australia. *Tectonophysics* 400, 127–151

Amino acid racemisation

TYPE: Calibrated age.

AGE RANGE: 100 yrs –1 Ma+, depending on temperature and nature of material.

PRECISION: Better than ± 10% in favourable circumstances.

MATERIALS: Organic materials containing fossil proteins including marine shell, wood, eggshell, speleothems, teeth, bone, snail shell.

DESCRIPTION: Living organisms contain dominantly L-amino acids. After death, the amino acids undergo diagenetic changes, including racemisation, which converts L-amino acids into D-amino acids. The D/L ratio increases over time at a rate that is dependent on temperature.

APPLICATIONS: Widely used for correlation and dating of coastal deposits containing molluscan shells. Can be used to calculate palaeotemperatures when age is independently known.

PROBLEMS: Temperature dependence of racemisation; requires calibration using other numerical dating methods; contamination and degradation of proteins.

FIELD SAMPLING: Avoid excessive handling of samples; seal in plastic bags. Samples from depths of less than 1 m may be adversely affected by ground-temperature fluctuations.

LABS: University of Wollongong (Dr C Murray-Wallace).

CSIRO, Adelaide (Dr R Kimber).

COSTS: Contribution to costs depending on nature of collaboration.

REFERENCES:

Bowen DQ, Pillans B, Sykes GA, Beu AG, Edwards AR, Kamp PJJ and Hull AG, 1998. Amino acid geochronology of Pleistocene marine sediments in the Wanganui Basin: a New Zealand framework for correlation and dating. *Journal of the Geological Society, London* 155, 439–446.

Hare PE, Hoering TC and King K Jr, 1980. *Biogeochemistry of amino acids.* John Wiley & Sons, New York.

Kimber RWL and Griffin, CV, 1988. Amino acid racemization dating of soils and sediments: in Prescott, J. (editor) *Archaeometry: Australasian Studies 1988.* University of Adelaide, Adelaide, 22–29.

Lauritzen S-E, Haugen JE, Løvlie R and Gilje-Nielsen H, 1994. Geochronological potential of isoleucine epimerization in calcite speleothems. *Quaternary Research* 41, 52–58.

Miller GH, Magee JW, Johnson BJ, Fogel ML, Spooner NA, McCulloch MT and Ayliffe LK, 1999. Pleistocene extinction of *Genyornis newtoni*: Human impact on Australian megafauna. *Science* 283, 205–208.

Miller GH, Magee JW and Jull AJT, 1997. Low latitude cooling in the Southern Hemisphere from amino acid racemization in emu eggshells. *Nature* 385, 241–244.

Murray-Wallace CV, 1995. Aminostratigraphy of Quaternary coastal sequences in southern Australia—an overview. *Quaternary International* 26, 69–86.

Weathering rinds

TYPE: Calibrated age.

AGE RANGE: 100 yrs–1 Ma.

PRECISION: Better than ± 10% in favourable circumstances.

MATERIALS: Rocks of relatively uniform composition and grain size; may be exposed rock surfaces or pebbles and boulders that are buried below the ground surface.

DESCRIPTION: The depth of chemical weathering on the surfaces of rocks progressively increases over time, to produce a weathering skin or rind.

APPLICATIONS: Used overseas for dating and correlation of glacial moraines.

PROBLEMS: Requires calibration.

FIELD SAMPLING: Samples are obtained by fracturing weathered clasts with a heavy hammer so as to obtain small rock chips with complete sections through the rinds. At least 50 rind chips are recommended for each dated site.

LABS: No specialised lab facilities required. See McSaveney (1992) for details of measurement techniques, etc.

COSTS: Nil.

REFERENCES:

Chinn TJH, 1981. Use of rock weathering-rind thickness for Holocene absolute age-dating in New Zealand. *Arctic and Alpine Research* 13, 33–45.

Colman SM and Pierce KL, 1981. Weathering rinds on andesitic and basaltic stones as a Quaternary age indicator, Western United States. *US Geological Survey Professional Paper* 1210.

Gordon SJ and Dorn RI, 2005. In situ weathering rind erosion. *Geomorphology* 67, 97–113.

Kiernan K, 1990. Weathering as an indicator of age of Quaternary glacial deposits in Tasmania. *Australian Geographer* 21, 1–17.

Knuepfer PLK, 1988. Estimating ages of late Quaternary stream terraces from analysis of weathering rinds and soils. *Geological Society of America Bulletin* 100, 1224–1236.

McSaveney MJ, 1992. A manual for weathering-rind dating of grey sandstones of the Torlesse Supergroup, New Zealand. *Institute of Geological and Nuclear Sciences Science Report* 92/4.

Mills HH, 2005. Relative-age dating of transported regolith and application to study of landform evolution in the Appalachians. *Geomorphology* 67, 63–96.

Sak PB, Fisher DM, Gardner TW, Murphy K and Brantley SL, 2004. Rates of weathering rind formation on Costa Rican basalt. *Geochimica et Cosmochimica Acta* 68, 1453–1472.

Palaeomagnetism

TYPE: Correlated age.

AGE RANGE: 100 yrs–100 Ma+.

PRECISION: Varies with age. Typically ± 10 Ma for Cenozoic age estimates determined using the Australian Apparent Polar Wander Path (AAPWP).

MATERIALS: Most igneous, metamorphic and sedimentary rocks, palaeosols, oxidised regolith materials.

DESCRIPTION: Palaeomagnetism uses past changes in the Earth's magnetic field on three broad time scales:

1. Secular variation, on time scales of 10 yrs–10 ka.
2. Reversal stratigraphy, on time scales of 10 ka–100 Ma+.
3. Apparent polar wander, on time scales of 5–100 Ma+.

APPLICATIONS: Wide application in regolith studies, including sedimentary sequences and weathered regolith materials.

PROBLEMS: There is some uncertainty regarding the Cenozoic apparent polar wander path for Australia. Reversal stratigraphy must be tied to independent ages.

FIELD SAMPLING: Rocks are sampled using a portable rock drill; unconsolidated samples are obtained using 6 cm3 plastic boxes. Samples must be oriented using a magnetic compass (corrected for local field variation) or sun compass.

LABS: Australian National University (Prof. B Pillans)

CSIRO, North Ryde (Dr P Schmidt)

University of Western Australia

COSTS: Available on request.

REFERENCES:

Acton G. and Kettles WA, 1996. Geologic and palaeomagnetic constraints on the formation of weathered profiles near Inverell, Eastern Australia. *Palaeogeography, Palaeoclimatology, Palaeoeclogy* 126, 211–225.

An Z, Bowler JM, Opdyke N., Macumber PG and Firman JB, 1986. Palaeomagnetic stratigraphy of Lake Bungunnia: Plio-Pleistocene precursor of aridity in the Murray Basin, southeastern Australia. *Palaeogeography, Palaeoclimatology, Paleoecology* 54, 219–239.

Augustinus PC and Idnurm M, 1993. Palaeomagnetism of ferricrete from Vale of Belvoir, Western Tasmania: Implications for Tasmanian Cenozoic glacial history. *Exploration Geophysics* 24, 301–302.

Augustinus PC, Pollington MJ and Colhoun EA, 1995. Magnetostratigraphy of the Late Cenozoic glacial sequence, Pieman River basin, western Tasmania. *Australian Journal of Earth Sciences* 42, 509–518.

Butler RF, 1992. *Paleomagnetism: magnetic domains to geologic terrains.* Blackwell, Boston.

Idnurm M, 1985. Late Mesozoic and Cenozoic palaeomagnetism of Australia - I. A redetermined apparent polar wander path. *Geophysical Journal* 83.

Idnurm M and Senior B, 1978. Palaeomagnetic ages of Late Cretaceous and Tertiary weathered profiles in the Eromanga Basin, Queensland. *Palaeogeography, Palaeoclimatology, Palaeoecology* 24, 263–277.

McQueen KG, Gonzalez OR, Roach IC, Pillans BJ, Dunlap WJ and Smith ML, 2007. Landscape and regolith features related to Miocene leucitite lava flows, El Capitan northeast of Cobar, New South Wales. *Australian Journal of Earth Sciences* 54, 1–17.

Musgrave RJ, 1989. A weighted least-squares fit of the Australian apparent polar wander path for the last 100 Myr. *Geophysical Journal* 96, 231-243.

Nott JF, Idnurm M and Young RW, 1991. Sedimentology, weathering, age and geomorphological significance of Tertiary sediments on the far south coast of New South Wales. *Australian Journal of Earth Sciences* 38, 357–373.

Pillans B, 2003. Dating ferruginous regolith to determine fault capability at Lucas Heights, Sydney: in Roach IC (editor) *Advances in Regolith. Proceedings of the CRC LEME Regional Regolith Symposia, 2003.* CRC LEME, Perth, 324–327.

Pillans B and Bourman R, 1995. The Brunhes/Matuyama polarity transition (0.78 Ma) as a chronostratigraphic marker in Australian regolith studies. *AGSO Journal of Australian Geology and Geophysics* 16, 289–294.

Pillans B and Bourman R, 2001. Mid Pleistocene arid shift in southern Australia, dated by magnetostratigraphy. *Australian Journal of Soil Research* 39, 89–98.

Schmidt PW and Clark DA, 2000. Paleomagnetism, apparent polar wander path and paleolatitude: in Veevers JJ (editor) *Billion-year earth history of Australia and neighbours in Gondwanaland.* Gemoc Press, Sydney, 12–17.

Schmidt PW and Embleton BJJ, 1976. Palaeomagnetic results from sediments of the Perth Basin, Western Australia, and their bearing on the timing of regional laterisation. *Palaeogeography, Palaeoclimatology, Palaeoecology* 19, 257–273.

Schmidt PW and Ollier CD, 1988. Palaeomagnetic dating of Late Cretaceous to Early Tertiary weathering in New England, NSW, Australia. *Earth-Science Reviews* 25, 363–371.

Stable isotopes (^{18}O, ^{13}C)

TYPE:	Correlated age.
AGE RANGE:	5 Ma+.
PRECISION:	Provides broad age estimates only, e.g. Late, Middle and Early Cenozoic.
MATERIALS:	Clay minerals, especially kaolinite; Fe oxides
DESCRIPTION:	Systematic variations in the isotopic composition of meteoric waters—and therefore of the authigenic regolith materials that formed in equilibrium with them—are the result of the drift of the Australian continent from high to low latitudes and changes in global climate.
APPLICATIONS:	Potential wide applications in weathered regolith materials containing kaolinite and/or Fe oxides.
PROBLEMS:	Lacks precision.
FIELD SAMPLING:	Contact lab for details.
LABS:	University of Wollongong (Prof. A Chivas) University of Queensland
COSTS:	Negotiable.

REFERENCES:

Atlhopheng JR, 2002. *Weathering profiles: their development and ages using oxygen isotopes*. PhD thesis, University of Wollongong, Wollongong.

Bird MI and Chivas AR, 1988. Stable-isotope evidence for low-temperature weathering and post-formational hydrogen-isotope exchange in Permian kaolinites. *Chemical Geology* 72, 249–265.

Bird MI and Chivas AR, 1988. Oxygen isotope dating of the Australian regolith. *Nature* 331, 513–516 and erratum, *Nature* 332, 568.

Bird MI and Chivas AR, 1989. Isotope dating of the Australian regolith—reply. *Nature* 337, 22–23.

Bird MI and Chivas AR, 1989. Stable isotope geochronology of the Australian regolith. *Geochimica et Cosmochimica Acta* 53, 3239–3256.

Bird MI, Chivas AR and AndrewAS, 1989. A stable-isotope study of lateritic bauxites. *Geochimica Cosmochimica et Cosmochimica Acta* 53, 1411–1420.

Bird MI, Chivas AR and AndrewAS, 1990. Reply to comment by C.-H. Chen, K.-K. Liu and Y.-N. Shieh on 'A stable-isotope study of lateritic bauxites'. *Geochimica et Cosmochimica Acta* 54, 1485–1486.

Bird MI and Chivas AR, 1993. Geomorphic and palaeoclimatic implications of an oxygen-isotope chronology for Australian deeply weathered profiles. *Australian Journal of Earth Sciences* 40, 345–358.

Smith ML, 2006. *Towards a geochronology for long-term landscape evolution, northwestern New South Wales.* PhD Thesis, Australian National University, Canberra.

Young RW, Cope S, Price DM, Chivas AR and Chenhall BE, 1996. Character and age of lateritic weathering at Jervis Bay, Southern New South Wales. *Australian Geographic Studies* 34, 237–246.

Zhou T and Dobos SK, 1994. Stable isotope geochemistry of kaolinite from the 'White Section', Black Ridge, Clermont, central Queensland: implications for the age and origin of the 'White Section'. *Clays and Clay Minerals* 42, 269–275.

Pollen spores, dinoflagellates and acritarchs

TYPE:	Correlated age
AGE RANGE:	0–400 Ma
PRECISION:	Resolution varies with age and location—from less than 1 Ma for Cenozoic sections in southeast Australia to greater than 10 Ma for Palaeozoic rocks in northwest and central Australia.
MATERIALS:	Most fine-textured sediments that have not been subjected to prolonged weathering.
DESCRIPTION:	Usually based on a combination of first and last appearances of selected fossil species (concurrent range zones); less often using relative abundance data or associations between pairs of species (Opel zones).
APPLICATIONS:	Widely used for age control, correlation and palaeoenvironmental analysis in onshore sedimentary basins and analogous depositional environments, e.g. palaeochannels incised into Archean rocks.
ADVANTAGES:	Provides a cheap, quick and reliable method for correlating within and between widely separated sedimentary basins.
PROBLEMS:	Contamination due to downhole caving (rotary chip samples); bioturbation and reworking of older sediments (all depositional environments); oxidative destruction of organic matter by weathering processes (most areas).
FIELD SAMPLING:	Preferably core or cuttings from fully flushed drill holes. Strongly weathered or jointed outcrops should be avoided.
LABS:	Geoscience Australia (Assoc. Prof. C Foster)
	Australian National University (Prof. G Hope)
	Primary Industries and Resources, Adelaide (L Stoian)

Monash University (Prof. AP Kershaw)

CoreLab (Australia) Pty Ltd, Perth

COSTS: $100–350 per sample (including processing), depending on requirements, including age determination and detailed report.

REFERENCES:

1. General

Cecil CB and Edgar NT (editors), 2003. *Climate Controls on Stratigraphy SEPM Special Publication 77*, SEPM, Tulsa.

Haq BU, Hardenbol J and Vail PR, 1987. Chronology of fluctuating sea levels since the Triassic (250 million years ago to present). *Science* 235, 1156–1167.

Hill RS (editor), 1994. *History of the Australian vegetation: Cretaceous to recent.* Cambridge University Press, Cambridge.

Laurie JR and Foster CB (editors), 2001. Studies in Australian Mesozoic palynology II. *Association of Australasian Palaeontologist Memoir* 24.

Macphail M, 2007. Australian palaeoclimates: Cretaceous to Tertiary, a review of palaeobotanical and related evidence to the year 2000, *CRC LEME Open File Report* 151.

McLaughlin S, 2001. Breakup of Gondwana and its impact on pre-Cenozoic floristic provincialism. *Australian Journal of Botany* 49, 271–300.

Traverse A, (1988). *Palaeopalynology.* Unwin and Hyman, Winchester, UK.

Wright AJ, Young GC, Talent JA and Laurie JR (editors), 2000. Palaeobiogeography of Australasian faunas and floras. *Association of Australasian Palaeontologists Memoir* 23.

2. Palaeozoic

Backhouse J, 1993. Palynology and correlation of Permian sediments in the Perth Collie, and Officer Basin, Western Australia. *Geological Survey of Western Australia Report* 34, 111–128.

Backhouse J, 1998. Palynological correlation of the Western Australian Permian. *Proceedings of the Royal Society of Victoria* 110, 107–114.

Foster CB, 1979. Permian plant microfossils of the Blair Athol Coal Measures, Baralba Coal Measures, and basal Rewan Formation of Queensland. *Geological Survey of Queensland Palaeontological Paper* 45, 1–244.

Foster CB and Archbold NW, 2001. Chronologic anchor points for the Permian and Early Triassic of the eastern Australian basins: in Weiss RH (editor) *Contributions to Geology and Palaeontology of Gondwana in honour of Helmut Wopfner*, University of Cologne, Cologne, 175–197.

Grey K, 1992. Miospore assemblages from Devonian reef complexes, Canning Basin, Western Australia. *Geological Survey of Western Australia Bulletin* 140, 1–139.

Jones MJ and Truswell EM, 1992. The Late Carboniferous and Early Permian palynostratigraphy of the Joe Joe Group, southern Galilee Basin, Queensland, and their implications for Gondwanan stratigraphy. *BMR Journal of Australian Geology and Geophysics* 13, 143–185.

Kemp EM, Balme BE, Helby RJ, Kyle RA, Playford G. and Price PL, 1977. Carboniferous and Permian palynostratigraphy in Australia and Antarctica – a review. *BMR Journal of Australian Geology and Geophysics* 2, 177–208.

Mory AJ and Backhouse J, 1997. Permian stratigraphy and palynology of the Carnarvon Basin, Western Australia. *Geological Survey of Western Australia Report* 51, 1–41.

Playford G, 1976. Plant microfossils from the Upper Devonian and Lower Carboniferous of the Canning Basin, Western Australia. *Palaeontographica* 158, 1–71.

Powis G, 1983. The palynostratigraphy of the Permo-Carboniferous of the Galilee Basin, Queensland. *Proceedings of the Geological Society of Australia (Queensland Division)* 231.

Powis G, 1984. Palynostratigraphy of the Late Carboniferous sequence, Canning Basin, WA: in Purcell PG (editor) *Canning Basin, WA*, Geological Society of Australia/PESA, Perth, 429–438.

Price PL, 1983. A Permian palynostratigraphy of Queensland. *Proceedings of the Geological Society of Australia (Queensland Division)* 155–221.

3. Mesozoic

Backhouse J, 1988. Late Jurassic and Early Cretaceous palynology of the Perth Basin, Western Australia. *Geological Survey of Western Australia Bulletin* 135, 1–233.

Backhouse J, 2006. Albian (Lower Cretaceous) dinoflagellate cyst biostratigraphy of the lower Gearle Siltstone, southern Carnarvon Basin, Western Australia. *Palynology* 30, 43–68.

Burger D, 1980. Palynology of the Lower Cretaceous in the Surat Basin. *Bureau of Mineral Resources Bulletin* 189, 1–106.

Burger D, 1993. Early and Middle Cretaceous angiosperm pollen grains from Australia. *Review of Palaeobotany and Palynology* 78, 183–234.

Dolby JH and Balme BE, 1976. Triassic Palynology of the Carnarvon Basin, Western Australia. *Review of Palaeobotany and Palynology* 22, 105–168.

Dettmann ME, 1963. Upper Mesozoic palynofloras from south-eastern Australia. *Proceedings of the Royal Society of Victoria* 77, 1–148.

Filatoff J, 1975. Jurassic palynology of the Perth Basin. *Palaeontographica Abteilung* B 154, 1-120.

Helby R, Morgan R and Partridge AD, 1987. A palynological zonation of the Australian Mesozoic. *Memoirs of the Australasian Palaeontologists Association* 4, 1–134.

McKellar J, 2008. Late Early to Late Jurassic palynology and biostratigraphy of the Roma Shelf area, northwester Surat Basin, Queensland. *Association of Australasian Palaeontologists Memoir* (in press).

Morgan R, 1980. Palynostratigraphy of the Australian Early and Middle Cretaceous. *Memoirs of the Geological Survey of New South Wales (Palaeontology)* 18, 1-153.

Price PL, 1997. Permian to Jurassic palynostratigraphic nomenclature: in Green PM (Editor) *The Surat and Bowen Basins.* Queensland Department of Mines and Energy, Brisbane, 137–178.

Sajjadi F and Playford G, 2002a. Systematic and stratigraphic palynology of Late Jurassic-earliest Cretaceous strata of the Eromanga basin, Queensland, Australia. Part one. *Palaeontographica Abteilung B* 261, 1–97.

Sajjadi F and Playford G, 2002b. Systematic and stratigraphic palynology of Late Jurassic-earliest Cretaceous strata of the Eromanga Basin, Queensland, Australia. Part two. *Palaeontographica Abteilung B* 261, 99–165.

4. Cenozoic

Alley NF, Kreig GW and Callen RA, 1996. Early Tertiary Eyre Formation, lower Nelly Creek, southern Lake Eyre Basin, Australia: palynological dating of macrofloras and silcrete, and palaeoclimatic interpretations. *Australian Journal of Earth Science* 43, 71–84.

Alley NF and Lindsay JM, 1995. Tertiary. Mines and Energy of South Australia Bulletin 4, 151-217.

Dettmann ME and Clifford HT, 2003. Miocene palynofloras from subsurface sediments in the Bundaberg District. *Memoirs of the Queensland Museum* 49, 261–267.

Dodson JR and Macphail MK, 2004. Palynological evidence for aridity events and vegetation change during the Middle Pliocene, a warm period in southwestern Australia. *Global and Planetary Change* 41, 285–307.

Gallagher SJ, Greenwood DR, Taylor D, Smith AJ, Wallace MW and Holdgate GR, 2003. The Pliocene climatic and environmental evolution of southeastern Australia: evidence from the marine and terrestrial realm. *Palaeogeography, Palaeoclimatology, Palaeoecology* 193, 349–382.

Holbourn A, Kuhnt W, Simo JA and Li Q, 2004. Middle Miocene isotope stratigraphy and palaeoceanographic evolution of the northwest and southwest Australian margins (Wombat Plateau and Great Australian Bight). *Palaeogeography, Palaeoclimatology, Palaeoecology* 208, 1–22.

Macphail MK and Truswell EM, 1993. Palynostratigraphy of the Bookpurnong Beds and related Late Miocene-Early Pliocene facies in the central west Murray Basin. Part 2: spores and pollen. *AGSO Journal of Australian Geology and Geophysics* 14, 383–409.

Macphail MK, 1997. Late Neogene climates in Australia: Fossil pollen and spore-based estimates in retrospect and prospect. *Australian Journal of Botany* 45, 425–464.

Macphail MK, 1997. Palynostratigraphy of Late Cretaceous to Tertiary basins in the Alice Springs district, Northern Territory. *Australian Geological*

Survey Organisation Report 1997/31.

Macphail MK, 1999. Palynostratigraphy of the Murray Basin, inland southeastern Australia. *Palynology* 23, 199–242.

Macphail MK and Stone MS, 2004. Age and palaeoenvironmental constraints on the genesis of the Yandi channel iron deposits, Marillana Formation, Pilbara, northwestern Australia. *Australian Journal of Earth Sciences* 51, 497–520.

Martin HA, 2006. Cenozoic climatic change and the development of arid vegetation in Australia. *Journal of Arid Environments* 66, 533–563.

Sniderman JMK, Pillans B, O'Sullivan PB and KershawAP, 2007. Climate and vegetation in southeastern Australia respond to Southern Hemisphere insolation forcing in the late Pliocene-early Pleistocene. *Geology* 35, 41–44.

Stover LE and Partridge AD, 1973. Tertiary and Late Cretaceous spores and pollen from the Gippsland Basin, southeastern Australia. *Proceedings of the Royal Society of Victoria* 85, 237–286.

ACKNOWLEDGEMENTS

The Cooperative Research Centres Program is acknowledged for financial support. I thank Allan Chivas, Rainer Grun, Barry Kohn, Mike Macphail, Malcolm McCulloch, Ian McDougall, Nigel Spooner and John Stone for their comments on the manuscript.

CRC LEME FIELD GUIDES

This *CRC LEME Guide* is one of a number of Field Guides designed to complement the CRC LEME series of Guides for Mineral Exploration through the Regolith. Primarily written for use by mineral explorers, scientists and students dealing with natural resource management, it is useful aid to selecting techniques for dating regolith: that layer of weathered material between fresh rock and fresh air that blankets much of Australia.

CRC LEME Field Guides include:

Field guide for describing regolith and landforms

Regolith dating methods: a guide to numerical dating techniques in Australia

A guide to the use of biogeochemical techniques in mineral exploration in Australia

The CRC LEME Explorer's Guides include:

A guide for mineral exploration through the regolith in the Cobar region, Lachlan Orogen, New South Wales

A guide for mineral exploration through the regolith in the Curnamona Province, South Australia

A guide for mineral exploration through the regolith of the Central Gawler Craton, South Australia

A guide for mineral exploration through and within the regolith in the southwestern Thomson Orogen, New South Wales

A guide for mineral exploration through the regolith in the Yilgarn Craton, Western Australia

A guide for mineral exploration through the regolith in the Tanami Desert region, North Australia

Series Editors: D Garnett, G Govett and L Worrall.