The Kalkarindji continental flood basalt province: A new Cambrian large igneous province in Australia with possible links to faunal extinctions

Linda M Glass*
David Phillips*
Research School of Earth Sciences, Australian National University, Canberra, ACT 0200, Australia

ABSTRACT

Extensive basaltic volcanism (>10⁶ km²) occurred across northern and western-central Australia during Cambrian time. The basalts are geochemically distinctive, having unusually uniform elevated incompatible element signatures (high Th/U, La/Sm, Rb/Ba) that are atypical of most other continental flood basalt provinces. Individual volcanic and intrusive suites previously assigned to local stratigraphic units are shown to share a common parental magma. This vast Cambrian igneous province is here named the Kalkarindji continental flood basalt province, Australia's oldest and largest Phanerozoic large igneous province. High-precision $^{40}Ar/^{39}Ar$ analyses of plagioclase feldspar separates from basalt flows yield ages of 508 ± 2 Ma and 505 ± 2 Ma (2σ), indistinguishable from previous U-Pb zircon ages for related dolerites. These ages indicate that basaltic volcanism coincided with the Early-Middle Cambrian boundary and suggest a temporal link between eruption of the Kalkarindji basalts and the end-Early Cambrian (early Toyonian) faunal mass extinction event.

Keywords: flood basalt, mass extinctions, Ar dating, Australia, Cambrian, plagioclase.

INTRODUCTION

Continental flood basalt provinces (CFBPs) are characterized by voluminous outpourings (as much as 3×10^6 km³) of dominantly tholeiitic basalts, which erupt over very short geological time intervals of only 1–2 m.y. (e.g., Renne and Basu, 1991; Renne et al., 1995; Courtillot, 1999). CFBPs are generally considered to result from extensive decompressive melting in response to ascending mantle plumes and lithospheric extension (e.g., Morgan, 1972; Richards et al., 1989; White and McKenzie, 1989; Campbell and Griffiths, 1990). However, individual units within these provinces often show evidence of crustal contamination (e.g., the Bushe Formation in the Deccan Traps; Peng et al., 1994). The massive eruption rates (>1 km³/yr) associated with large igneous provinces (LIPs) have led to suggestions that CFBPs are somehow responsible for global paleoclimate changes and mass extinction events (e.g., Vogt, 1972; Officer and Drake, 1983; McLean, 1985; Phipps Morgan et al., 2004). Wignall (2001) concluded that 6 of the 15 major Phanerozoic extinction events appear to correlate with LIPs, but noted that no CFB provinces have, as yet, been located in the Cambrian to mid-Permian time interval.

In this paper we present new geochemical and $^{40}Ar/^{39}Ar$ geochronological data for a newly identified Cambrian LIP in northern and central-western Australia, which we here name the Kalkarindji continental flood basalt province. Possible links between the Kalkarindji LIP and early Toyonian mass extinction are also explored.

GEOLOGY AND PREVIOUS GEOCHRONOLOGY

The Kalkarindji CFBP is the suggested new name for a number of scattered basalt suites that occur across northern and central Australia, including the subaerial Antrim Plateau Volcanics (minimum volume of 0.15×10^6 km³) and intrusive Milliwindi dolerite dike in the north, and the stratigraphically correlated Nutwood Downs, Helen Springs, Peaker Piker, and Colless Volcanics in the east (Dunn, 1963; Bultitude, 1976; Hanley and Wingate, 2000). Recent aerial magnetic imagery across northern Australia (Clifton, 2003) reveals the presence of extensive basalt subcrops under Paleozoic and Mesozoic cover; flows as long as 200 km fill paleovalleys and stratigraphic lows. The province extends across a vast area (>10⁶ km²) (Fig. 1), and is thickest in the northwestern part of the province within the Antrim Plateau Volcanics (~1500 m; Mory and Beere, 1988). The original pre-erosion volume of the province is difficult to estimate, although it is likely to have exceeded 5×10^5 km³ (based on an areal extent of $>1 \times 10^6$ km² and an average thickness of ~0.5 km).

The Antrim Plateau basalts typically comprise ~20–60-m-thick (up to 200-m-thick) lava flows composed of mostly aphanitic massive basalt with vesicular or brecciated flow tops, and less common plagioclase-phyric porphyritic basalt. Glomeroporphyritic, often columnar-jointed, and hydrothermally altered basalts occur locally in the west. Individual basalt flows may be intercalated with thin beds of eolian sandstone, conglomerate, siltstone, and stromatolitic chert (Randal and Brown, 1967); however, age-diagnostic fossils have not been found within these units (Bultitude, 1976).

Data from the overlying stratigraphy suggest that the Kalkarindji volcanics are at least Middle Cambrian (Kruse et al., 1994; Bowring and Erwin, 1998), consistent with the oldest previous K-Ar ages for Antrim Plateau and Helen Springs basalt samples of ca. 510 Ma (Bultitude, 1976) and with a recent sensitive high-resolution ion microprobe (SHRIMP) U-Pb zircon age of 513 ± 12 Ma for the related Milliwindi dolerite (Hanley and Wingate, 2000). In western-central Australia, the Boondawari dolerite, within the large Neoproterozoic to Paleozoic Officer Basin (Fig. 1), has been dated as 508 ± 10 Ma (2σ), using the U-Pb zircon method (Macdonald et al., 2005). Age constraints for the Table Hill Volcanics in the south (Fig. 1) include an Rb-Sr result of 575 ± 40 Ma (Compston, 1974) and K-Ar whole-rock ages of 500 ± 14 Ma (2σ; Veevers, 2000) and 484 ± 8 Ma (2σ; Stevens

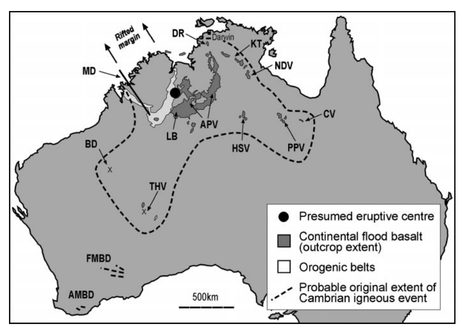

Figure 1. Outcrop areas of Antrim Plateau Volcanics and stratigraphic equivalents. APV—Antrim Plateau Volcanics; HSV—Helen Springs Volcanics and sample HS002; PPV—Peaker Piker Volcanics; CV—Colless Volcanics; NDV—Nutwood Downs Volcanics; MD—Milliwindi dolerite; BD—Boondawari dolerite; THV—Table Hill Volcanics; LB—sample LB011; DR—sample DR021; KT—sample KT001; FMBD—Fraser Mobile Belt dolerite; AMBD—Albany Mobile Belt dolerite.

*Present addresses: Glass: Pterodia Pty Ltd, P.O. Box 196, Maylands, Perth, WA 6931, Australia; Phillips: School of Earth Sciences, The University of Melbourne, Parkville, VIC 3010, Australia

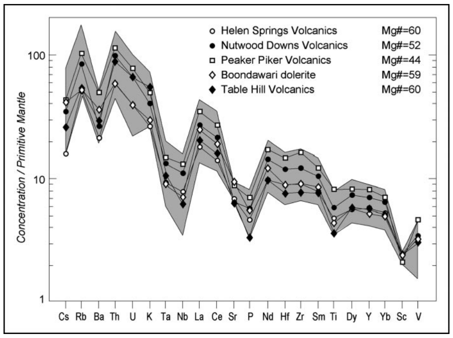

Figure 2. Primitive-mantle normalized element abundance diagram for Antrim Plateau Volcanics (shaded area) and stratigraphic equivalents. Helen Springs Volcanics—HS002; Nutwood Downs Volcanics—ND002; Peaker Piker Volcanics—PP004; Boondawari sill—BD001; Table Hill Volcanics—TH002. (Normalizing values are from McDonough and Sun, 1995.) [Mg# = 100*molar MgO/(MgO + FeO), for Fe_2O_3/FeO = 0.15]. Modified from Glass (2002).

and Apak, 1999). Harris and Li (1995) also documented ca. 500 Ma Cambrian dolerite dikes in the mobile belts of southwestern Australia (Fig. 1) and in the previously contiguous region of the East Antarctic shield, suggesting that the Kalkarindji province may be even more extensive than indicated in Figure 1.

During the Cambrian, Australia formed part of the Gondwana supercontinent (Powell et al., 1993), and was bounded to the south by Antarctica and to the west by greater India. Metcalfe (1996) suggested that several Asian microcontinental blocks were located to the north of Australia at this time. Li et al. (1996) speculated that the Antrim Plateau basalts might be related to rifting between the Kimberley block in Australia and the Tarim block of western China. Paleomagnetic studies indicate that the proto-Australian continent underwent an unprecedented ~90° counterclockwise rotation from 544 to 490 Ma (Veevers, 2001). In central and northern Australia, this rotation was associated with major changes in crustal stress regimes that led to widespread lithospheric stretching, continental extension, and basin development (Shaw, 1991) immediately following extrusion of the Cambrian basalts.

GEOCHEMISTRY

In an effort to verify the stratigraphic correlations between the different basaltic outcrops in northern and central Australia, we present new comparative laser-ablation inductively coupled plasma–mass spectroscopy geochemical data for the main igneous suites. The full geochemical data set is listed in Data Repository Table DR1[1] and details of the analytical techniques were given in Glass (2002).

The geochemical analyses demonstrate that the basalts are all low-Ti tholeiites. In Figure 2, results from 80 Antrim Plateau samples, spanning an Mg# range of 34–72, are compared with data for representative samples from the northern and western-central Australian stratigraphic equivalents. The stratigraphic correlatives are geochemically indistinguishable from the Antrim Plateau Volcanics, with nearly constant trace element ratios (e.g., Ba/Th, Nb/La, and P/Nd), indicating a common parentage. However, abundances of the highly incompatible elements Rb and Cs in the Table Hill Volcanics are likely affected by alteration.

Relative to mid-oceanic-ridge basalts, the Kalkarindji province is characterized by low FeO_{total} and TiO_2 contents at fixed Mg# (e.g., at $Mg\#_{65}$, FeO_{total} ~8.4 wt% and TiO_2 ~0.8 wt%). The Kalkarindji basalts are distinguished by low high field strength element abundances (Ti, P, Nb) relative to the incompatible elements and extreme enrichment in the most incompatible elements, such as Th, U, and light rare earth elements (Glass, 2002). The distinctive low-Ti and incompatible element-enriched geochemical signature is far removed from typical tholeiitic basalts and implies crustal involvement in the genesis of the Kalkarindji basalts. Compared to most other continental flood basalts worldwide, where crustal contamination signatures are restricted to particular eruptive units, the Kalkarindji basalts are characterized by a relatively homogeneous continental crustal signature across the province (Glass, 2002).

[1]GSA Data Repository item 2006090, Table DR1, geochemical data; and Table DR2, Ar/Ar data, is available online at www.geosociety.org/pubs/ft2006.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

TABLE 1. SUMMARY OF $^{40}Ar/^{39}Ar$ RESULTS FOR THE ANTRIM PLATEAU AND HELEN SPRINGS VOLCANICS

Sample Number	Total-gas Age (Ma) (±2σ)	Plateau Age (Ma) (±2σ)	MSWD	Total External Error (Ma) (±2σ)#	Isochron Age (Ma) (±2σ)*	MSWD	$^{40}Ar/^{36}Ar$ (±2σ)*
Helen Springs Volcanics							
HS002(1)	507.6 ± 3.3	507.5 ± 1.6	0.89	9.2	507.9 ± 1.8	1.41	290.5 ± 9.8
HS002(2)	513.2 ± 4.5	506.0 ± 2.0	1.30	9.4	512.7 ± 9.0	34.30	299.4 ± 28.4
Antrim Plateau Volcanics							
LB011	503.3 ± 5.1	504.7 ± 2.2	1.89	9.2	506.2 ± 4.6	3.1	285.6 ± 12.2
DR021	500.5 ± 5.7	N.A.	N.A.	10.8	497.9 ± 4.0	6.25	307.2 ± 12.4
KT001	492.3 ± 3.9	N.A.	N.A.	9.6	494.3 ± 7.4	24.15	283.2 ± 29.0

#Total external errors include uncertainties in $^{40}Ar^{*}/^{39}Ar$ ratio, irradiation parameter (J), K-Ar age of the fluence monitor (GA1550) and decay constants of Steiger and Jager (1977).
*Error weighted by √MSWD (MSWD = mean squared of weighted deviates).

$^{40}Ar/^{39}Ar$ GEOCHRONOLOGY

In order to obtain more precise age constraints for the Kalkarindji igneous province, four basalt samples from across the province were selected for $^{40}Ar/^{39}Ar$ age dating. Sample selection was limited by the altered nature of many basalts and was thus restricted to material containing relatively coarse, unaltered plagioclase crystals. Three samples from the Antrim Plateau Volcanics and one sample from the Helen Springs Volcanics (Fig. 1) were ultimately selected on the basis of stringent petrographic criteria. Plagioclase separates were prepared using standard crushing, desliming and heavy liquid methods, and were then carefully hand-picked based on optical clarity. The plagioclase samples, together with interspersed aliquots of the flux monitor GA1550 biotite (98.8 ± 0.5 Ma; Renne et al., 1998), were irradiated in position X33 or X34 of the High Flux Australian Reactor (HIFAR) nuclear reactor, Lucas Heights, NSW, Australia. Analytical protocols follow those described by Fergusson and Phillips (2001). The definition of a plateau age follows that given by McDougall and Harrison (1999). The full $^{40}Ar/^{39}Ar$ data set is available in Table DR2 (see footnote 1).

The $^{40}Ar/^{39}Ar$ step-heating results for one Helen Springs (HS002, $An_{62.9}Or_{1.6}$) and three Antrim Plateau samples (LB011, $An_{66.3}Or_{1.6}$; KT001, $An_{61.7}Or_{1.8}$; DR021, $An_{64.1}Or_{1.5}$) are summarized in Table 1 and Figure 3. The $^{40}Ar/^{39}Ar$ analyses of two aliquots from sample HS002 (Helen Springs Volcanics) produced indistinguishable age plateau segments with weighted mean ages of 507.5 ± 1.6 Ma (2σ; mean square of weighted deviates, MSWD = 0.9) and 506.0 ± 2.0 Ma (2σ; MWSD = 1.3), respectively (Figs. 3A, 3B). Sample HS002(2) is characterized by anomalously old low-temperature ages, possibly due to excess argon contamination related to melt and/or fluid inclusions (Fig. 3B). Only one sample from the Antrim Plateau Volcanics (LB011) yielded an age plateau, with a weighted mean age of 504.7 ± 2.2 Ma (2σ; MSWD = 1.9) (Fig. 3C). The remaining Antrim Plateau samples (DR021 and KT001; Figs. 3D, 3E) exhibit somewhat saddle-shaped apparent age spectra, suggestive of excess argon contamination and/or alteration of the plagioclase feldspar. Sample DR021 is characterized by apparent ages ranging from 493 to 512 Ma, for a total-gas age of 500.5 ± 5.7 Ma (2σ) (Fig. 3D), whereas more discordant re-

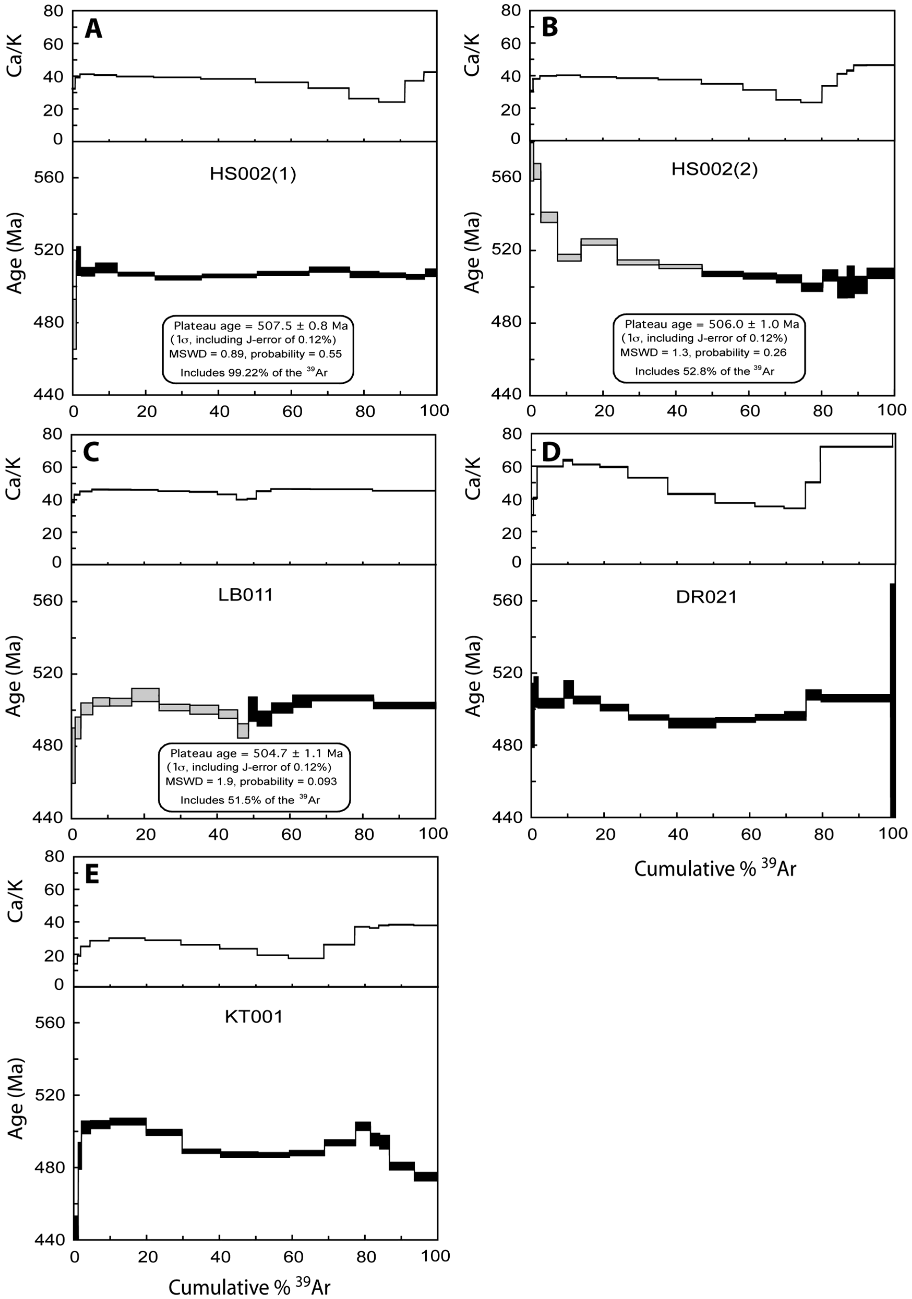

Figure 3. Apparent $^{40}Ar/^{39}Ar$ age spectra for Helen Springs and Antrim Plateau Volcanics. Uncertainties are ±1σ and include errors associated with J value. Ca/K plots above age spectra are expressed as molar ratios. Individual steps that are included in age plateaus are shown in black. MSWD—mean square of weighted deviates.

sults of 442–506 Ma (total-gas age = 492.3 ± 3.9 Ma) were obtained from sample KT001 (Fig. 3E). If the latter two samples contain excess ^{40}Ar, then the youngest apparent ages represent maximum estimates of the time of volcanism (i.e., younger than ca. 490 Ma). However, this interpretation is at odds with biostratigraphic constraints, suggesting that the discordance is due to alteration and partial argon loss, resulting in erroneously young apparent ages. Inverse isochron plots for the four samples are consistent with the above plateau age results and also indicate atmospheric initial $^{40}Ar/^{36}Ar$ ratios (Table 1).

DISCUSSION AND CONCLUSIONS

The new $^{40}Ar/^{39}Ar$ ages obtained for the Helens Springs Volcanics (508 ± 2 Ma; 2σ) and Antrim Plateau Volcanics (505 ± 2 Ma; 2σ) are indistinguishable from recent SHRIMP U-Pb zircon ages obtained from Kalkarindji Province dolerites (513 ± 12 Ma; Hanley and Wingate, 2000; 508 ± 10 Ma; Macdonald et al., 2005) and a recent K-Ar age for the Table Hill Volcanics (500 ± 14 Ma; Veevers, 2000). Although there is clearly a need for additional high-precision geochronological analyses, the existing age and geochemical evidence points to a single magmatic event involving Cambrian tholeiitic volcanism across northern and western-central Australia. To avoid confusion with the well-known Antrim basalts of the British Tertiary Igneous Province and to provide a definitive link between correlative igneous suites, we suggest that the Australian Cambrian igneous event be termed the Kalkarindji continental flood basalt province (after a Northern Territory Aboriginal locality). The eruptive volume of the Kalkarindji province likely exceeded 5×10^5 km^3 and constitutes Australia's largest and oldest Phanerozoic igneous province. The province is also characterized by unique incompatible element abundance patterns, distinguishing it from most other LIPs. It is probable that the province is related to the dominant extensional and rotational tectonic regimes active during the Cambrian.

On the basis of a 2004 geologic time scale (see Shergold and Cooper, 2004) the preceding age data suggest that the Kalkarindji CFBP erupted during the early Middle Cambrian Period. The Berkeley group (e.g., Min et al., 2000) highlighted the uncertainties (±1%–3%) in the K-Ar decay constants and suggested that $^{40}Ar/^{39}Ar$ ages may underestimate U-Pb ages by ~0.5%–1%. If correct, this would place the new $^{40}Ar/^{39}Ar$ ages closer to the Early-Middle Cambrian boundary of Shergold and Cooper (2004; 513 ± 2 Ma).

Zhuravlev and Wood (1996) documented two major global extinction events corresponding to the Botomian and the Toyonian stages of the Early–Middle Cambrian. These mass extinctions followed the rapid appearance of many marine invertebrates in Early Cambrian time, the so-called Cambrian explosion (Brasier et al., 1994). Mass extinction of archaeocyathan reef biota, and other reef-associated fauna, including trilobites, coincided with sharp changes in $\delta^{13}C$ values of Cambrian carbonate sequences (Brasier et al., 1994; Zhuravlev and Wood, 1996; Saltzman et al., 2000). The Toyonian stage coincides with the Early-Middle Cambrian boundary, and the mass extinction during this stage appears to have been pronounced in the Australia region (Zhuravlev and Wood, 1996). This event is correlated with the Hawke Bay sea-level regression episode, which may be related to lithospheric updoming associated with mantle plume ascent and CFB volcanism (e.g., Williams and Gostin, 2000). Although association between large igneous provinces and mass extinctions remains enigmatic (see Wignall, 2001), our age constraints suggest that volcanism associated with the Kalkarindji

CFBP could be linked to the Early–Middle Cambrian mass extinction, although definitive proof must await more accurate age determinations of both the timing of the Kalkarindji CFBP and the Cambrian time scale. No other sizable LIPs are known from this time period, and the Kalkarindji is the most significant CFBP recognized from the Cambrian Period.

ACKNOWLEDGMENTS

Glass gratefully acknowledges funding for her Ph.D. research through an Australian Postgraduate Research Award. Sample irradiations at Lucas Heights were supported by an Australian Institute of Nuclear Science and Engineering grant. We thank Xiadong Zhang and Robyn Maier for technical assistance in acquiring the $^{40}Ar/^{39}Ar$ results, the Northern Territory Geological Society and Geological Society of Western Australia for access to drill cores, and Michael Wingate for providing the sample for the Boondawari dolerite. We have benefited from discussions with W.R. Taylor, V.C. Bennett, J.M. Miller, and G. Shields, and formal reviews by R. Burgess, J. Phipps Morgan, and an anonymous reviewer.

REFERENCES CITED

Bowring, S.A., and Erwin, D.H., 1998, A new look at evolutionary rates in deep time; uniting paleontology and high-precision geochronology: GSA Today, v. 8, no. 9, p. 1–8.

Brasier, M.D., Corfield, R.M., Derry, L.A., Rozanov, A.Y., and Zhuravlev, A.Y., 1994, Multiple $\delta^{13}C$ excursions spanning the Cambrian explosion to the Botomian crisis in Siberia: Geology, v. 22, p. 455–458, doi: 10.1130/0091-7613(1994)022<0455:MCESTC>2.3.CO;2.

Bultitude, R.J., 1976, Flood basalts of probable Early Cambrian age in northern Australia, *in* Johnson, R.W., ed., Volcanism in Australia: New York, Elsevier Science, p. 1–20.

Campbell, I.H., and Griffiths, R.W., 1990, Implications of mantle plume structure for the evolution of flood basalts: Earth and Planetary Science Letters, v. 99, p. 79–93, doi: 10.1016/0012-821X(90)90072-6.

Clifton, R., 2003, Magnetic map of the Northern Territory: Northern Territory Geological Survey, scale 1:2,500,000.

Compston, W., 1974, The Table Hill Volcanics of the Officer Basin—Precambrian or Palaeozoic?: Geological Society of Australia Journal, v. 21, p. 403–411.

Courtillot, V., 1999, Evolutionary catastrophes: The science of mass extinction: Cambridge, Cambridge United Press, 237 p.

Dunn, P.R., 1963, Hodgson Downs, Northern Territory, *in* Geological series sheet SD/53–14: Canberra, Australian Bureau of Mineral Resources, scale 1: 250,000.

Fergusson, C.L., and Phillips, D., 2001, $^{40}Ar/^{39}Ar$ and K-Ar age constraints on the timing of regional deformation, south coast of New South Wales, Lachlan Fold Belt: Problems and implications: Australian Journal of Earth Sciences, v. 48, p. 395–408, doi: 10.1046/j.1440-0952.2001.00866.x.

Glass, L.M., 2002, Petrogenesis and geochronology of the North Australian Kalkarinji low-Ti continental flood basalt province [Ph.D. thesis]: Canberra, Research School of Earth Sciences, Australian National University, 325 p.

Hanley, L.M., and Wingate, M.T.D., 2000, SHRIMP zircon age for an Early Cambrian dolerite dyke: An intrusive phase of the Antrim Plateau Volcanics of northern Australia: Australian Journal of Earth Sciences, v. 47, p. 1029–1040, doi: 10.1046/j.1440-0952.2000.00829.x.

Harris, L.B., and Li, Z.-X., 1995, Palaeomagnetic dating and tectonic significance of dolerite intrusions in the Albany Mobile, Western Australia: Earth and Planetary Science Letters, v. 131, p. 143–164, doi: 10.1016/0012-821X(95)00013-3.

Kruse, P.D., Sweet, I.P., Stuart-Smith, P.G., Wygralak, A.S., Pieters, P.E., and Crick, I.H., 1994, Katherine SD53–9, *in* Geological map series, explanatory notes: Northern Territory Geological Survey Department of Mines and Energy, scale 1: 250,000.

Li, Z.X., Zhang, L., and Powell, C.M., 1996, Positions of the East Asian cratons in the Neoproterozoic supercontinent Rodinia: Australian Journal of Earth Sciences, v. 43, p. 593–604.

Macdonald, F.A., Wingate, M.T.D., and Mitchell, K., 2005, Geology and age of the Glikson impact structure, Western Australia: Australian Journal of Earth Sciences, v. 52, p. 641–651.

McDonough, W.F., and Sun, S.-s., 1995, The composition of the Earth: Chemical Geology, v. 120, p. 223–253, doi: 10.1016/0009-2541(94)00140-4.

McDougall, I., and Harrison, T.M., 1999, Geochronology and thermochronology by the $^{40}Ar/^{39}Ar$ method: New York, Oxford University Press, 269 p.

McLean, D.M., 1985, Mantle degassing unification of the trans-K-T geobiological record: Evolutionary Biology, v. 19, p. 287–313.

Metcalfe, I., 1996, Gondwanaland dispersion, Asian accretion and evolution of eastern Tethys: Australian Journal of Earth Sciences, v. 43, p. 605–623.

Min, K., Mundil, R., Renne, P.R., and Ludwig, K.R., 2000, A test for systematic errors in the $^{40}Ar/^{39}Ar$ geochronology through comparison with U/Pb analysis of a 1.1-Ga rhyolite: Geochimica et Cosmochimica Acta, v. 64, p. 73–98, doi: 10.1016/S0016-7037(99)00204-5.

Morgan, W.J., 1972, Deep mantle convection plumes and plate motion: American Association of Petroleum Geologists Bulletin, v. 56, p. 203–213.

Mory, A.J., and Beere, G.M., 1988, Geology of the onshore Bonaparte and Ord Basins in Western Australia: Bulletin—Geological Survey of Western Australia, Report 134, 183 p.

Officer, C.B., and Drake, C.L., 1983, The Cretaceous-Tertiary transition: Science, v. 219, p. 1383–1390.

Peng, Z.X., Mahoney, J., Hooper, P., Harris, C., and Beane, J., 1994, A role for lower continental crust in flood basalt genesis? Isotopic and incompatible element study of the lower six formations of the western Deccan Traps: Geochimica et Cosmochimica Acta, v. 58, p. 267–288, doi: 10.1016/0016-7037(94)90464-2.

Phipps Morgan, J., Reston, T.J., and Ranero, C.R., 2004, Contemporaneous mass extinctions, continental flood basalts, and 'impact signals': Are mantle plume-induced lithospheric gas explosions the causal link?: Earth and Planetary Science Letters, v. 217, p. 263–284, doi: 10.1016/S0012-821X(03)00602-2.

Powell, C.M., McElhinny, M.W., Meert, J.G., and Park, J.K., 1993, Paleomagnetic constraints on timing of the Neoproterozoic breakup of Rodinia and the Cambrian formation of Gondwana: Geology, v. 21, p. 889–892, doi: 10.1130/0091-7613(1993)021<0889:PCOTOT>2.3.CO;2.

Randal, M.A., and Brown, M.C., 1967, The geology of the northern part of the Wiso Basin, N.T.: Australian Bureau of Mineral Resources, Geology and Geophysics, Record 1967/110, 125 p.

Renne, P.R., and Basu, A.R., 1991, Rapid eruption of the Siberian Traps flood basalts at the Permo-Triassic boundary: Science, v. 253, p. 176–179.

Renne, P.R., Zichao, Z., Richards, M.A., Black, M.T., and Basu, A.R., 1995, Synchrony and causal relations between the Permian-Triassic boundary crises and Siberian Flood Volcanism: Science, v. 269, p. 1413–1416.

Renne, P.R., Swisher, C.C., Deino, A.L., Karner, D.B., Owens, T.L., and DePaolo, D.J., 1998, Intercalibration of standards, absolute ages and uncertainties in $^{40}Ar/^{39}Ar$ dating: Chemical Geology, v. 145, p. 117–152, doi: 10.1016/S0009-2541(97)00159-9.

Richards, M.A., Duncan, R.A., and Courtillot, V.E., 1989, Flood basalts and hotspot tracks: Plume heads and tails: Science, v. 246, p. 103–108.

Saltzman, M.R., Ripperdan, R.L., Brasier, M.D., Lohmann, K.C., Robison, R.A., Chang, W.T., Peng, S., Ergaliev, E.K., and Runnegar, B., 2000, A global carbon isotope excursion (SPICE) during the Late Cambrian: Relation to trilobite extinctions, organic-matter burial and sea level: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 162, p. 211–223, doi: 10.1016/S0031-0182(00)00128-0.

Shaw, R.D., 1991, The tectonic development of the Amadeus Basin, central Australia, *in* Korsch, R.J., and Kennard, J.M., eds., Geological and geophysical studies in the Amadeus Basin, central Australia: Canberra, Australian Government Publishing Service, p. 429–461.

Shergold, J.H., and Cooper, R.A., 2004, The Cambrian Period, *in* Gradstein, F.M., et al., eds., A geologic time scale 2004: Cambridge, Cambridge University Press, p. 147–164.

Steiger, R.H., and Jäger, E., 1977, Subcommission on geochronology: Convention on the use of decay constants in geo- and cosmochronology: Earth and Planetary Science Letters, v. 36, p. 359–362, doi: 10.1016/0012-821X(77)90060-7.

Stevens, M.K., and Apak, S.N., 1999, GSWA Empress 1 and 1A well completion report, Yowalga Subbasin, Officer Basin, Western Australia: Geological Survey of Western Australia, Record 4, 110 p.

Veevers, J.J., 2000, Neoproterozoic Australia, *in* Veevers, J.J., ed., Billion-year old earth history of Australia and neighbours in Gondwanaland: Sydney, GEMOC Press, 388 p.

Veevers, J.J., 2001, Atlas of billion-year earth history of Australia and neighbours in Gondwanaland: Sydney, GEMOC Press, 76 p.

Vogt, P.R., 1972, Evidence for global synchronism in mantle plume convection and possible significance for geology: Nature, v. 240, p. 338–342, doi: 10.1038/240338a0.

White, R.S., and McKenzie, D.R., 1989, Magmatism at rift zones: The generation of volcanic continental margins and flood basalts: Journal of Geophysical Research, v. 94, p. 7685–7729.

Wignall, P., 2001, Large igneous provinces and mass extinctions: Earth-Science Reviews, v. 53, p. 1–33, doi: 10.1016/S0012-8252(00)00037-4.

Williams, G.E., and Gostin, V.A., 2000, Mantle plume uplift in the sedimentary record: Origin of kilometre-deep canyons within late Neoproterozoic successions, South Australia: Geological Society [London] Journal, v. 157, p. 759–768.

Zhuravlev, A.Y., and Wood, R.A., 1996, Anoxia as the cause of the mid-Early Cambrian (Botomian) extinction event: Geology, v. 24, p. 311–314, doi: 10.1130/0091-7613(1996)024<0311:AATCOT>2.3.CO;2.

Manuscript received 14 August 2005
Revised manuscript received 24 January 2006
Manuscript accepted 3 February 2006

Printed in USA

Geology

The Kalkarindji continental flood basalt province: A new Cambrian large igneous province in Australia with possible links to faunal extinctions

Linda M Glass and David Phillips

Geology 2006;34;461-464
doi: 10.1130/G22122.1

Notes

The Geological Society of America, Inc.

THE GEOLOGICAL SOCIETY OF AMERICA