Warakurna large igneous province: A new Mesoproterozoic large igneous province in west-central Australia

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ABSTRACT

Coeval mafic igneous rocks emplaced rapidly over ~1.5 × 10^6 km^2 in western and central Australia represent the erosional remnants of a late Mesoproterozoic large igneous province, named here the Warakurna large igneous province. SHRIMP U-Pb dating of rocks separated by as much as 1500 km indicates that the main episode of magmatism occurred between 1078 and ca. 1070 Ma. The Warakurna large igneous province includes layered mafic-ultramafic intrusions and mafic to felsic volcanic rocks and dikes in central Australia, a 1000-km-long mafic sill province in Western Australia, and several swarms of mafic dikes. The large areal extent and short duration imply emplacement above a mantle-plume head. Despite their wide separation, the mafic rocks have similar mid-oceanic-ridge basalt–normalized trace element patterns and rare earth element characteristics. West-directed paleocurrents, westward-radiating dike swarms, and the occurrence of high-Mg rocks indicate that the center of the plume head was located beneath central Australia. Other late Mesoproterozoic large igneous provinces, in the Laurentia and Kalahari cratons, appear to be significantly older than the Warakurna large igneous province in Australia and thus are unlikely to be related to the same mantle-plume head.

Keywords: Australia, large igneous province, geochronology, geochemistry, mantle plume, Mesoproterozoic, paleomagnetism.

INTRODUCTION

Large igneous provinces consist of mainly mafic igneous rocks emplaced over large areas (>10^5 km^2), typically within a few million years (Coffin and Eldholm, 1994; Ernst and Buchan, 2001). Owing to erosion and tectonism, pre-Mesozoic large igneous provinces have lost many of their volcanic components, leaving mainly dikes, sills, and layered mafic-ultramafic intrusions. Most large igneous provinces have been linked to mantle plumes (Ernst and Buchan, 2001, 2003), several host world-class Ni-Cu and platinum-group element (PGE) deposits (Naldrett and Lightfoot, 1993), and some are associated with continental breakup and mass-extinction events (Coffin and Eldholm, 1994). In this paper we synthesize the results of field, petrographic, geochronological, geochemical, and paleomagnetic studies of mafic igneous rocks in central and western Australia (Fig. 1), and we argue that these rocks, collectively, represent a large igneous province emplaced above a mantle plume ca. 1075 Ma. We adopt the name Warakurna large igneous province after the community of that name located near the inferred plume center.

AGE AND EXTENT OF THE WARAKURNA LARGE IGNEOUS PROVINCE

Coeval mafic igneous rocks occur from the western margin of Australia to the center of the continent (Fig. 1; Table DR1[1]). The Bangemall Supergroup, deposited on deformed rocks of the Paleoproterozoic Capricorn orogen between the Archean Pilbara and Yilgarn cratons, is a 4–10-km-thick succession of siliciclastic and carbonate sedimentary rocks, consisting of the Edmund and overlying Collier Groups (Martin and Thorne, 2004). These rocks are intruded by two suites of mainly bedding-concordant quartz dolerite sills, with mean sensitive high-resolution ion microprobe (SHRIMP) U-Pb ages of 1465 ± 3 Ma and 1070 ± 6 Ma (Wingate et al., 2002). The older sills occur only within the Edmund Group, whereas 1070 Ma sills intruded both the Edmund and Collier Groups.

North of the Bangemall Supergroup, a north-northeast–trending dolerite dike intruded into 2.45 Ga Woongarra Rhyolite possesses a primary magnetization identical in direction to that of the Bangemall Supergroup sills (Wingate et al., 2002), implying that 1070 Ma magmatism extended into the southern Pilbara craton. An east-northeast–trending dike swarm within Archean granitoids of the northwest Yilgarn craton (Fig. 1) has a SHRIMP U-Pb age of 1075 ± 10 Ma (Wingate, 2003).

Quartz dolerite sills of the Glenayle Dolerite, with SHRIMP U-Pb baddeleyite ages of 1068 ± 20 Ma and 1063 ± 21 Ma (Fig. 1), were intruded into subhorizontal siliciclastic rocks of the Salvation Group (Pirajno and Hocking, 2002; Wingate, 2003). Regional gravity data suggest that sills in the northwest part of the Glenayle area are underlain by a laccolith-shaped mafic body, 36 km in diameter by 3 km thick (Morris et al., 2003), which may be part of a local feeder system. Fine-grained, plagioclase-phyric sills of the Prenti Dolerite (Fig. 1), dated as ca. 1050 Ma by Rb-Sr and K-Ar techniques, intruded the Glenayle Dolerite as well as Paleoproterozoic sedimentary rocks of the Earaheedy Basin (Pirajno and Hocking, 2002). Farther east, beneath Neoproterozoic rocks of the Officer Basin, fine-grained mafic rocks at 1600 m depth in the Empress 1A drill hole yielded a K-Ar whole-rock age of 1058 ± 13 Ma (Stevens and Apak, 1999).

In central Australia, emplaced within Mesoproterozoic granulites of the western Musgrave block, the Giles Complex (Fig. 1) consists of a series of partly deformed and recrystallized layered mafic-ultramafic intrusions, mafic and felsic dikes, and remnants of bimodal volcanic rocks (Glikson et al., 1996). Doleritic and gabbroic dikes, probably feeders to the layered intrusions or volcanic rocks, provided SHRIMP U-Pb zircon ages of 1078 ± 3 Ma and 1073 ± 5 Ma (Sun et al., 1996). The volcanic rocks (Tollu Group) include a 240-m-thick succession of amygdaloidal basalt and rhyolite with a SHRIMP U-Pb zircon age of 1078 ± 5 Ma (Sheraton and Sun, 1997). The Giles Complex was variably uplifted, sheared, and recrystallized at high pressures during the 550–530 Ma Petermann Ranges orogeny (Glikson et al., 1996; White et al., 1999).

Mesoproterozoic gneisses in the eastern Musgrave block were intruded by south- to southeast-dipping sills of the Alcurra (Kulgera) suite, one of which provided Sm-Nd and Rb-Sr mineral isochron ages of 1090 ± 32 Ma and 1054 ± 14 Ma, respectively (Camacho et al., 1991; Zhao and McCulloch, 1993a). Along the southern Arunta block, mainly north-trending dolerite dikes of the Stuart Pass Dolerite (Fig. 1) yielded a similar Sm-Nd isochron age of 1076 ± 33 Ma (Zhao and McCulloch, 1993a). Subaerial amygdaloidal basalt of the Beda Vol-

[1]GSA Data Repository item 2004016, Tables DR1–3 and Figure DR1, isotopic ages, whole-rock chemistry, and paleomagnetic poles, is available online at www.geosociety.org/pubs/ft2004.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

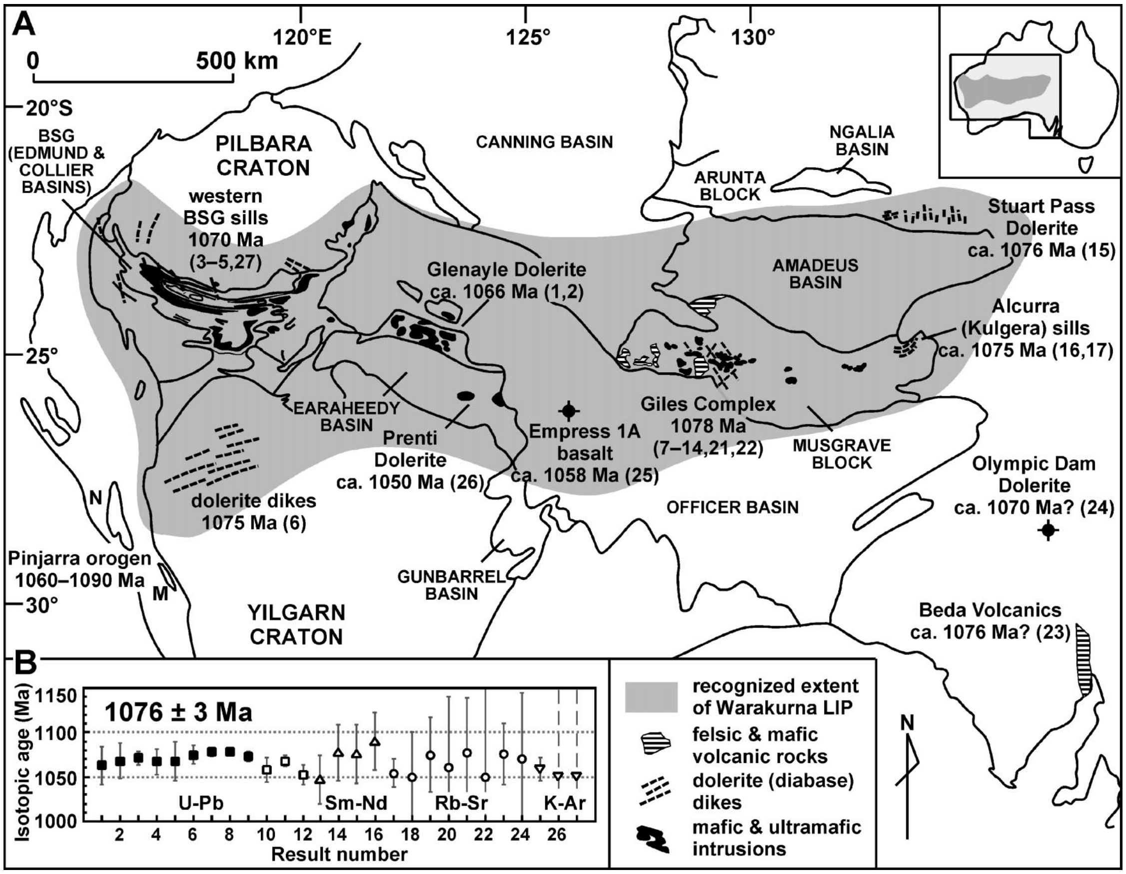

Figure 1. A: Simplified geology of southwest Australia, showing distribution of ca. 1075 Ma igneous rocks of Warakurna large igneous province (LIP). Numbers after rock ages refer to plot B and Table DR1 (see footnote 1). BSG—Bangemall Supergroup; N—Northampton inlier; M—Mullingarra inlier. B: Isotopic age determinations for rocks of Warakurna LIP, grouped according to isotopic system (cf. Table DR1; see footnote 1). Error bars are ±2σ or 95%; no precision was reported for results 26 and 27. Age of 1076 ± 3 Ma is weighted mean of U-Pb ages 1–9 (solid symbols) and is interpreted as best estimate of age of main phase of magmatism associated with Warakurna LIP.

canics (Fig. 1) furnished an Rb-Sr whole-rock age of 1076 ± 34 Ma (Webb and Coats, 1980), and an Rb-Sr isochron age of 1070 ± 74 Ma was reported for dolerite at Olympic Dam (R.A. Creaser, 1990, in Drexel et al., 1993). Accuracy of the latter two results is difficult to assess, however, because these rocks have yielded younger Rb-Sr and K-Ar ages and may be related to the 825 Ma Gairdner dike swarm (Wingate et al., 1998).

There are 27 age determinations, employing 4 isotopic systems, on rocks of the Warakurna large igneous province (Fig. 1B; Table DR1 [see footnote 1]). Of 12 U-Pb ages, 9 agree to within analytical uncertainty and have a weighted mean of 1076 ± 3 Ma (1–9 in Fig. 1; mean square of weighted deviates, MSWD = 1.2). These nine results are for samples separated by as much as 1500 km, i.e., the Bangemall Supergroup sills, the northwest Yilgarn craton dikes, the Glenayle Dolerite, and the Giles Complex (Fig. 1). Three U-Pb ages, for a gabbronorite dike and two granitic dikes of the Giles Complex (10–12 in Fig. 1), are significantly younger and imply that mafic magmatism and crustal anatexis in this area continued after the main magmatic event. The bulk of the magmatic products was emplaced between 1078 and ca. 1070 Ma, along an east-west swath ~800 km wide and 2400 km long, and cover an area of ~1.5×10^6 km^2 in western and central Australia (shaded area in Fig. 1).

GEOCHEMISTRY

Tholeiitic 1070 Ma sills in the western Bangemall Supergroup have similar SiO_2 contents (48.3–54.6; average 51.0), and most have Mg# < 50 (Mg# = Mg/[Mg + Fe] where all Fe is FeO), and mid-oceanic-ridge basalt (MORB)–normalized spider diagrams (Fig. 2A; Table DR2 [see footnote 1]) show enrichment in large ion lithophile elements (LILEs) relative to high field strength elements (HFSEs) and positive Pb anomalies and negative P anomalies. Although most sills show some sign of alteration (pyroxene locally altered to amphibole, sericitization of feldspar), the coherent behavior of labile elements indicates limited mobility. $(La/Yb)_{CN}$ is close to 5.3, and $(Gd/Yb)_{CN}$ is near 1.9 (CN is chondrite normalized). Empress 1A basalt and most Glenayle sills have similar trace element and REE (rare earth element) patterns. Some Glenayle sills are more LILE and light REE (LREE) enriched, which can be modeled by addition of 4%–10% Archean Yilgarn craton granitoid.

MORB-normalized patterns for two Musgrave block dikes are similar (Fig. 2B), although element concentrations are lower, possibly reflecting their relatively unfractionated nature. The Stuart Pass (Fig. 1 of Zhao and McCulloch, 1993b) and Alcurra dikes are olivine-normative high-Mg tholeiites depleted in HFSEs and enriched in LILEs relative to MORB, which Zhao and McCulloch (1993b) attributed to melting of subduction-modified lithospheric mantle. They argued that the high MgO and heavy REE contents, and low HFSE contents, indicate melting above the garnet stability field, induced by a rising mantle plume. Glikson et al. (1996) also suggested melting of a subduction-modified lithospheric mantle to explain the elevated LILE/Zr and LREE/Zr, but primordial HFSE/Zr, of Giles Complex mafic rocks, and invoked a major thermal event to account for the scale of melting. The Beda Volcanics (Fig. 2B) show MORB-normalized patterns similar to those of Bangemall Supergroup dolerites, although LILE concentrations in the Beda rocks are more variable owing to postmagmatic alteration.

PALEOMAGNETISM

Paleomagnetic results for Bangemall Supergroup sills, the Glenayle Dolerite, the Prenti Dolerite, and dikes of the northwest Yilgarn and southwest Pilbara cratons are in good agreement (Fig. DR1; see footnote 1), indicating that the western Warakurna large igneous prov-

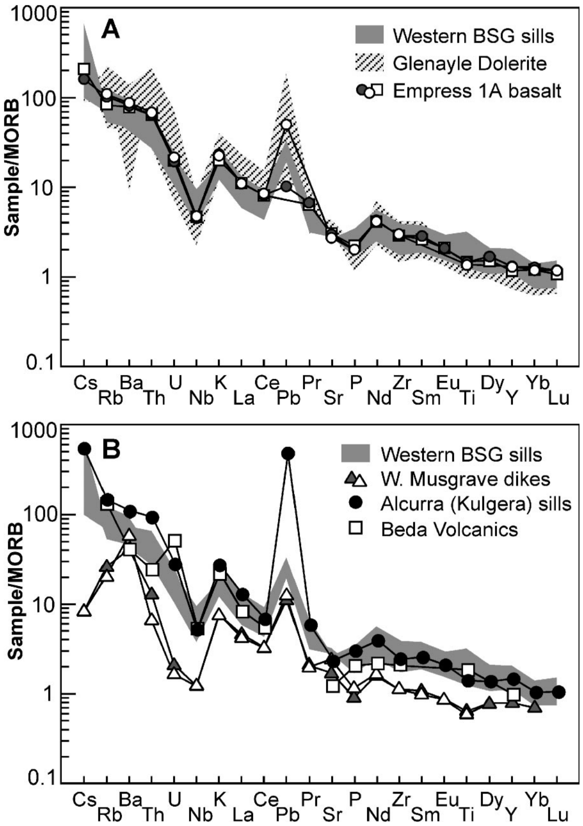

Figure 2. Normal mid-oceanic-ridge basalt (N-MORB) normalized spider diagrams for Warakurna large igneous province samples; data are listed in Table DR2 (see footnote 1). A and B: Gray field—western Bangemall Supergroup (BSG) 1070 Ma sills (*n* = 25). A: Striped field—Glenayle Dolerite (*n* = 27); individual symbols—ca. 1058 Ma mafic igneous rocks from Empress 1A drill hole (Stevens and Apak, 1999). B: Squares—average Beda Volcanics (*n* = 40; Cowley, 1991); circles—average Alcurra dikes (*n* = 5; C.J. Edgoose, 2001, personal commun.); triangles—western Musgrave block dikes 91988021 and 91988086 (Glikson et al., 1996; reanalyzed in this study). Beda Volcanics average includes N-MORB–normalized Cs abundance of 2857 (not shown).

ince has undergone no significant internal vertical-axis rotation since ca. 1070 Ma (Wingate et al., 2002; Wingate, 2003). Paleopoles from mafic rocks in central Australia, however, do not agree with each other, or with those from the west. Reliable constraints on the paleohorizontal plane are not available for the Giles Complex, Stuart Pass, or Alcurra intrusions, and all three suites are located in fault-bounded blocks that were deformed and probably reoriented during the Petermann Ranges and/or Alice Springs orogenies. Significant discrepancies between the ca. 1075 Ma poles probably reflect relative movements of crustal blocks in central Australia during these younger orogenic events.

DISCUSSION

The voluminous, largely unfractionated, layered mafic-ultramafic intrusions, bimodal volcanic rocks, and feeder dikes that make up the Giles Complex have been interpreted as the result of either rift-related lithospheric thinning or mantle-plume activity (Glikson et al., 1996). The presence of coeval dikes and sills elsewhere in Australia (shaded area, Fig. 1) indicates that the Giles Complex is part of a large igneous province. The main magmatic phase, which occurred between 1078 and ca. 1070 Ma, resulted in emplacement of mafic magma over at least ~1.5 $\times$ 10^6 km^2 and to 1500 km from the Giles Complex. The large areal extent and short duration indicate emplacement above a mantle-plume head (Ernst and Buchan, 2001, 2003). The Warakurna large igneous province is similar in scale to the Kalkarinji province (which includes the Antrim Plateau Volcanics) of northern Australia (Glass, 2002), the Midcontinent rift system (Okajangas et al., 2001), and the Siberian Traps (Reichow et al., 2002). The Warakurna large igneous province may originally have covered a much larger area, but has been diminished in extent by erosion and is partly concealed beneath younger strata.

Several observations indicate that the center of the Warakurna plume was located in central Australia: (1) West-directed paleocurrents in sedimentary rocks of the Collier and Salvation Groups (Muhling and Brakel, 1985; Martin and Thorne, 2004), which were deposited immediately before sill intrusion (as indicated by peperitic contacts), indicate an uplifted source region to the east. (2) The apparent absence of exposed feeder systems for sills in the Collier and Salvation Groups suggests that dikes exist at depth. Sills may have formed as actively propagating dikes intersected levels of neutral density within basin depocenters, or they may have been emplaced by lateral flow from a central plume feeder. Together with west-southwest–trending dikes in the northwest Yilgarn craton (Fig. 1), the west-northwest–trending sill province may represent a sector of a westward-radiating dike swarm, with a focal point in central Australia. (3) High-Mg parental melts (~12% MgO, Glikson et al., 1996) of some Giles Complex intrusions may imply proximity to the hot center of a plume head (Campbell, 2001).

The Warakurna large igneous province extends to the western margin of Australia (Fig. 1), where deformation, magmatism, and metamorphism ca. 1080 Ma are documented in the Northampton and Mullingarra inliers of the Pinjarra orogen (Bruguier et al., 1999; Cobb et al., 2001). The inliers, however, may be allochthonous terranes transported northward during late Neoproterozoic tectonism (Fitzsimons, 2000) and therefore unrelated to the Warakurna large igneous province. Nevertheless, the similarity in age suggests that the Warakurna event was linked in some fashion to plate-boundary forces along the combined Australia-Antarctic margin. Deformation and metamorphism in the Pinjarra orogen could also be related to compression at the western edge of the uplifted region (peripheral contractional belt), in the manner suggested by Mège and Ernst (2001). The eastern extent of the large igneous province, and its relationship to the eastern margin of Proterozoic Australia, is unknown, owing to a thick cover of younger strata.

Emplacement of large volumes of mafic magma in southern Africa and North America was broadly coeval with the Warakurna event. Powell and Pisarevsky (2001) suggested that the Kalahari craton may have been joined to the western margin of Australia until ca. 750 Ma, inviting comparison between the Warakurna and Umkondo large igneous provinces. The Umkondo province, dated by U-Pb zircon and baddeleyite at 1105 $\pm$ 5 Ma (Hanson et al., 1998; Wingate, 2001), covers an area of ~2 $\times$ 10^6 km^2 and contains sill-like layered intrusions, dolerite and gabbro sills and dikes, and bimodal volcanic rocks. The 3.6 $\times$ 10^5 km^2 southwestern U.S. diabase province (Ernst and Buchan, 2001, and references therein) includes dolerite dikes and sills, with precise U-Pb zircon and baddeleyite ages between 1100 and 1069 Ma. The Keweenawan event involved emplacement of layered mafic intrusions, sills, dikes, and flood basalts of the Midcontinent rift system between 1109 and 1087 Ma (Okajangas et al., 2001).

The onset of magmatism in these three provinces appears to be significantly older than in the Warakurna large igneous province, and thus they are unlikely to be related to the same plume-head event. However, the progression in age, from the Midcontinent rift system, to the southwestern U.S. diabase province, to the Warakurna large igneous province could conceivably result from motion of a combined Australia-Laurentia continent over a single plume tail (i.e., hotspot), or from separate plume heads within a superplume (Condie, 2001). Paleomagnetic data for the western Warakurna large igneous province, however, permit only a tenuous connection between northeast Australia and southwest Laurentia ca. 1070 Ma (Wingate et al., 2002). Moreover, at 1.2 Ga, Australia occupied high latitudes, whereas Laurentia was at low latitudes, precluding any connection at that time (Pisarevsky et al., 2003).

Recognition of a Mesoproterozoic large igneous province in Australia has important implications for mineral potential, including Noril'sk type Ni-Cu sulfides and PGEs (Naldrett and Lightfoot, 1993). Ni-Cu-PGE sulfide mineralization in the western Giles Complex is currently being evaluated. Emplacement of large igneous provinces can also be linked to giant hydrothermal systems, activated by heat advection and high geothermal gradients induced by intrusion of large melt volumes (Pirajno, 2000; Ernst and Buchan, 2003). Hydrothermal base- and precious-metal mineralization is common in the Bangemall Supergroup region and has been linked to the 1075 Ma magmatic event (Pirajno, 2004). A reassessment and better understanding of the primary cause for this mineralization could have far-reaching implications in terms of economically viable mineral deposits.

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REFERENCES CITED

Bruguier, O., Bosch, D., Pidgeon, R.T., Byrne, D.I., and Harris, L.B., 1999, U-Pb geochronology of the Northampton Complex, Western Australia—Evidence for Grenvillian sedimentation, metamorphism and deformation and geodynamic implications: Contributions to Mineralogy and Petrology, v. 136, p. 258–272.

Camacho, A., Simons, B., and Schmidt, P.W., 1991, Geological and paleomagnetic significance of the Kulgera dyke swarm, N.T., Australia: Geophysical Journal International, v. 107, p. 37–45.

Campbell, I.H., 2001, Identification of ancient mantle plumes, *in* Ernst, R.E., and Buchan, K.L., eds., Mantle plumes: Their identification through time: Geological Society of America Special Paper 352, p. 5–21.

Cobb, M.M., Cawood, P.A., Kinny, P.D., and Fitzsimons, I.C.W., 2001, SHRIMP U-Pb zircon ages for the Mullingarra Complex, Western Australia: Isotopic evidence for allochthonous blocks in the Pinjarra orogen and implications for East Gondwana assembly: Geological Society of Australia Abstracts, v. 64, p. 21–22.

Coffin, M.F., and Eldholm, O., 1994, Large igneous provinces: Crustal structure, dimensions, and external consequences: Reviews of Geophysics, v. 32, p. 1–36.

Condie, K.C., 2001, Mantle plumes and their record in Earth history: Oxford, Cambridge University Press, 306 p.

Cowley, W.M., 1991, Beda Volcanics and Backy Point Formation of the eastern Gawler craton: South Australia Department of Mines and Energy Report Book 90/16, 45 p.

Drexel, J.F., Preiss, W.V., and Parker, A. J., eds., 1993, The geology of South Australia, Volume 1, The Precambrian: South Australian Geological Survey Bulletin 54, 242 p.

Ernst, R.E., and Buchan, K.L., 2001, Large mafic magmatic events through time and links to mantle-plume heads, *in* Ernst, R.E., and Buchan, K.L., eds., Mantle plumes: Their identification through time: Geological Society of America Special Paper 352, p. 483–575.

Ernst, R.E., and Buchan, K.L., 2003, Recognizing mantle plumes in the geological record: Annual Review of Earth and Planetary Sciences, v. 31, p. 469–523.

Fitzsimons, I.C.W., 2000, Grenville-age basement provinces in East Antarctica: Evidence for three separate collisional orogens: Geology, v. 28, p. 879–882.

Glass, L.M., 2002, Petrogenesis and geochronology of the low-Ti Kalkarinji continental flood basalt province [Ph.D. thesis]: Canberra, Australian National University, 326 p.

Glikson, A.Y., Stewart, A.J., Ballhaus, C.G., Clarke, G.L., Feeken, E.H.J., Leven, J.H., Sheraton, J.W., and Sun, S.-S., 1996, Geology of the western Musgrave block, central Australia, with particular reference to the mafic-ultramafic Giles Complex: Australian Geological Survey Organization Bulletin 239, 206 p.

Hanson, R.E., Martin, M.W., Bowring, S.A., and Munyanyiwa, H., 1998, U-Pb zircon age for the Umkondo dolerites, eastern Zimbabwe: 1.1 Ga large igneous province in southern Africa–East Antarctica and possible Rodinia correlations: Geology, v. 26, p. 1143–1146.

Martin, D.M., and Thorne, A.M., 2004, Tectonic setting and basin evolution of the Bangemall Supergroup in the northwestern Capricorn orogen: Precambrian Research (in press).

Mège, D., and Ernst, R.E., 2001, Contractional effects of mantle plumes on Earth, Mars and Venus, *in* Ernst, R.E., and Buchan, K.K., eds., Mantle plumes: Their identification through time: Geological Society of America Special Paper 352, p. 103–140.

Morris, P.A., Pirajno, F., and Shevchenko, S., 2003, Proterozoic mineralization identified by integrated regional regolith geochemistry, geophysics and bedrock mapping in Western Australia: Geochemistry: Exploration, Environment, Analysis, v. 3, p. 13–28.

Muhling, P.C., and Brakel, A.T., 1985, Geology of the Bangemall Group: Western Australian Geological Survey Bulletin 128, 264 p.

Naldrett, A.J., and Lightfoot, P.C., 1993, Ni-Cu-PGE ores of the Noril'sk region, Siberia: A model for giant magmatic sulfide deposits associated with flood basalts, *in* Whiting, B.W., et al., eds., Giant ore deposits: Society of Economic Geologists Special Publication 2, p. 81–124.

Okajangas, R.W., Morey, G.B., and Green, J.C., 2001, The Mesoproterozoic Midcontinent rift system, Lake Superior region, USA: Sedimentary Geology, v. 141–142, p. 421–442.

Pirajno, F., 2000, Ore deposits and mantle plumes: Dordrecht, Kluwer Academic Publishers, 556 p.

Pirajno, F., 2004, Metallogeny in the Capricorn orogen, Western Australia, the result of multiple ore-forming processes: Precambrian Research (in press).

Pirajno, F., and Hocking, R.M., 2002, Glenayle, W. A., Sheet 3347: Western Australia Geological Survey, Geological Series, scale 1:100,000.

Pisarevsky, S.A., Wingate, M.T.D., and Harris, L.B., 2003, Late Mesoproterozoic (ca. 1.2 Ga) palaeomagnetism of the Albany-Fraser orogen: No pre-Rodinia Australia–Laurentia connection: Geophysical Journal International, v. 155, p. F6–F11.

Powell, C.M., and Pisarevsky, S.A., 2001, Late Neoproterozoic assembly of East Gondwanaland: Geology, v. 30, p. 3–6.

Reichow, M.K., Saunders, A.D., White, R.V., Pringle, M.S., Al-Mukhamedov, A.I., Medvedev, A.I., and Kirda, N.P., 2002, $^{40}Ar/^{39}Ar$ dates from the West Siberian Basin: Siberian flood basalt province doubled: Science, v. 296, p. 1846–1849.

Sheraton, J.W., and Sun, S.-s., 1997, Mafic dyke swarms of the western Musgrave block, central Australia: Their geochemistry, origin, and relationships to the Giles Complex: AGSO Journal of Australian Geology and Geophysics, v. 16, p. 621–636.

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

Sun, S.-s., Sheraton, J.W., Glikson, A.Y., and Stewart, A.J., 1996, A major magmatic event during 1050–1080 Ma in central Australia, and an emplacement age for the Giles Complex: AGSO Research Newsletter, v. 24, p. 13–15.

Webb, A.W., and Coats, R.P., 1980, A reassessment of the age of the Beda Volcanics on the Stuart Shelf, South Australia: South Australia Department of Mines and Energy Report 80/6.

White, R.W., Clarke, G.L., and Nelson, D.R., 1999, SHRIMP U-Pb dating of Grenville-age events in the western part of the Musgrave block, central Australia: Journal of Metamorphic Geology, v. 17, p. 465–481.

Wingate, M.T.D., 2001, SHRIMP baddeleyite and zircon ages for an Umkondo dolerite sill, Nyanga Mountains, eastern Zimbabwe: South African Journal of Geology, v. 104, p. 13–22.

Wingate, M.T.D., 2003, Age and paleomagnetism of dolerite intrusions of the southeastern Collier basin, and the Earaheedy and Yerrida Basins, Western Australia: Western Australian Geological Survey Record, 2003/3, 35 p.

Wingate, M.T.D., Campbell, I.H., Compston, W., and Gibson, G.M., 1998, Ion microprobe U-Pb ages for Neoproterozoic basaltic magmatism in south-central Australia and implications for the breakup of Rodinia: Precambrian Research, v. 87, p. 135–159.

Wingate, M.T.D., Pisarevsky, S.A., and Evans, D.A.D., 2002, Rodinia connections between Australia and Laurentia: No SWEAT, no AUSWUS?: Terra Nova, v. 14, p. 121–128.

Zhao, J.-X., and McCulloch, M.T., 1993a, Sm-Nd mineral isochron ages of Late Proterozoic dyke swarms in Australia: Evidence for two distinct events of mafic magmatism and crustal extension: Chemical Geology, v. 109, p. 341–354.

Zhao, J.-X., and McCulloch, M.T., 1993b, Melting of a subduction-modified continental lithospheric mantle: Evidence from Late Proterozoic mafic dike swarms of central Australia: Geology, v. 21, p. 463–466.

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