Widespread Archean basement beneath the Yangtze craton

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ABSTRACT

The age distribution of the crust is a fundamental parameter in modeling continental evolution and the rate of crustal accretion through Earth's history, but this is usually estimated from surface exposures. The exposed Yangtze craton in eastern China consists mainly of Proterozoic rocks with rare Archean outcrops. However, the U-Pb ages and Hf isotope systematics of xenocrystic zircons brought to the surface in lamproite diatremes from three Proterozoic outcrop areas of the craton suggest the widespread presence of unexposed Archean basement, with zircon age populations of 2900–2800 Ma and 2600–2500 Ma and Hf model ages of 2.6 to ca. 3.5 Ga or older. The zircons also record thermal events reworked on the craton ca. 2020 Ma (remelting of older crust) and 1000–850 Ma (addition of juvenile mantle material). The observation of deep crust significantly older than the upper crust will require revision of models for the rates of crustal generation through time.

Keywords: crustal evolution, Hf isotopes, zircon geochronology, deep-crustal xenocryst, Archean basement, Yangtze craton, east China.

INTRODUCTION

The Yangtze and North China cratons are the two largest Precambrian blocks in eastern China. Archean rocks are widespread in the North China craton (Jahn et al., 1987; Liu et al., 1992), whereas the Yangtze craton consists mainly of Proterozoic rocks (Chen and Jahn, 1998) with only sparse outcrops of Archean rocks. The rocks of the ca. 2.9 Ga Kongling complex (Gao et al., 1999; Qiu et al., 2000) are considered to be the oldest in the Yangtze craton and occur along its northern margin (Fig. 1, area I). Widespread areas with outcrops of Mesoproterozoic–Neoproterozoic rocks (Fig. 1, areas II and III) that are covered by Phanerozoic strata represent Mesoproterozoic–Neoproterozoic zones of activity (Chi and Lu, 1996), and are designated the Sibao orogen (Li et al., 2002). Recent studies of zircons in deep-crustal xenoliths have shown that the deep crust in parts of the North China craton is significantly older than the exposed upper crust (Zheng et al., 2004), and the same may be true of other cratons. Lamproites, representing mantle-derived magmas, can be used as "drill holes" to sample the deep crust; they contain xenocrysts (e.g., zircon) derived from entrained crustal rocks and these xenocrysts may record the history of the unexposed crust.

GEOLOGIC SETTING AND SAMPLING

The South China block was formed by the Grenvillian-age continental collision (Li et al., 2002) between the Yangtze craton and the Cathaysia block (Fig. 1). The oldest rocks in the South China block are found in an ~360 km^2 dome in the northern Yangtze craton (110°53′–111°17′E and 30°45′–31°20′N) dominated by the poorly exposed, upper amphibolite to granulite facies Kongling Complex. This complex consists of tonalitic-trondhjemitic-granitic gneisses with Mesoarchean ages of 2.90–2.95 Ga, and metasedimentary rocks with 2.87–3.21 Ga detrital zircons (Qiu et al., 2000); amphibolite and locally preserved mafic granulite occur as lenses and layers in the gneisses (Gao et al., 1999). They are intruded by the ca 1.8–1.9 Ga Quanqitang granite.

Volcaniclastic lamproite diatremes are widely distributed in the Ningxiang (Hunan Province), Jingshan (Hubei Province), and Zhenyuan (Guizhou Province) areas within the Yangtze craton: their immediate wall rocks are Cambrian–Ordovician, Devonian, and Middle Ordovician, respectively. The Ningxiang lamproites yield whole-rock isochron ages of ca. 345 Ma (Rb-Sr) and 328 Ma (Sm-Nd); 439 Ma and 411–448 Ma K-Ar ages were obtained from phlogopite megacrysts in the Jingshan and Zhenyuan lamproites, respectively (Liu et al., 1993). Samples (~200 kg) were collected from pipes no. 3 in Ningxiang (sample Nx32), no. 7 in Jingshan (Pjb71), and no. 4 in Zhenyuan (Zy-4), and ~3 kg samples were taken from the trondhjemitic (htlltp1) and tonalitic gneisses (htlltp2) from near Longtouping village in the Kongling complex. Zircons were extracted by standard methods using a Wilfley table and electromagnetic separation, followed by heavy-liquid separation and handpicking. We recovered 312 zircon grains, including 79 from Nx32, 36 from Pjb71, 90 from Zy4, 43 from htlltp1, and 64 from htlltp2.

METHODS

Zircon Internal Structure

Backscattered electron–cathodoluminescence (BSE-CL) images were taken from 82 zircon grains using a Cameca SX-50 electron

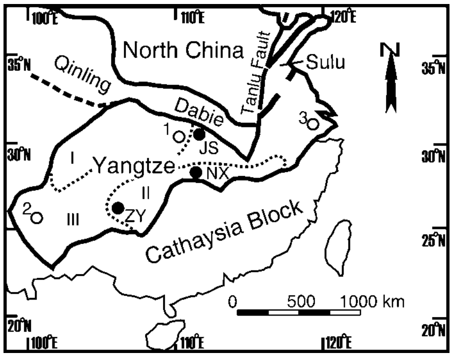

Figure 1. Major tectonic units in southeastern China. I, Archean–Paleoproterozoic nucleus; II, proposed Mesoproterozoic–Neoproterozoic activity zone with outcrops of older rocks; III, Mesoproterozoic–Neoproterozoic activity zone without outcrop of pre-Mesoproterozoic rocks (Chi and Lu, 1996), named Sibao orogen (Li et al., 2002). Localities: NX, Ningxiang; JS, Jingshan; ZY, Zhenyuan; 1, Kongling; 2, Kangdian; 3, Nanjing.

microprobe operating at 15 kV and 20 nA, in the Geochemical Evolution and Metallogeny of Continents (GEMOC) Australian Research Council (ARC) National Key Centre at Macquarie University. These images were used to define the shape and internal structures of the grains (GSA Data Repository Table DR1[1]) and to select the positions for laser ablation microprobe–inductively coupled plasma mass spectrometry (LAM-ICP-MS) and LAM-multicollector (MC)-ICP-MS analyses. Each grain was also analyzed for Hf and Y contents (Table DR2). Common-Pb corrections were carried out using the method described by Andersen (2002); none of the grains reported here required significant correction.

U-Pb Dating

In situ U-Pb dating of zircons by LAM-ICP-MS was carried out at the GEMOC ARC National Key Centre, Macquarie University, using methods described by Jackson et al. (2004). The precision and accuracy obtained with this technique are illustrated by comparison with thermal ionization mass spectrometry data for some well-characterized zircons.

Hf Isotopes

In situ Hf isotope analyses were carried out with a New Wave LUV213 nm LAM, attached to a Nu plasma MC-ICP-MS in the GEMOC ARC National Key Centre, using techniques described by Griffin et al. (2000). Typical precision on $^{176}Hf/^{177}Hf$ is ±0.00003 (2σ), or $\sim\pm1$ ε_{Hf}. The calculation of model ages is based on the depleted-mantle (DM) source using 1.865×10^{-11} for the ^{176}Lu decay constant. The U-Pb and Lu-Hf data are given in Tables DR1 and DR2 (see footnote 1). Table DR2 reports both T_{DM} model ages, calculated using the measured Lu/Hf of zircon, and T_{crust} model ages, which assume that the protolith from which the host magma of a given zircon was derived from the depleted mantle source, and has the composition of the average continental crust ($^{176}Lu/^{177}Hf = 0.015$; Griffin et al., 2000).

RESULTS

U-Pb Ages

Zircons from sample NX32 (Ningxiang) are light purple to transparent, and subhedral to rounded. The grains are 85–260 μm long with length/width values of 1.0–3.0. The oldest zircon (Nx32–50) has oscillatory zoning and gives a concordant $^{207}Pb/^{206}Pb$ age of 2980 Ma (Fig. 2A). All others are structureless except for six grains (Nx32–38, Nx32–41, Nx32–42, Nx32–43, Nx32–46, and Nx32–47) that have euhedral to irregular relict cores. In one grain (nx32–43), the rim is 325 m.y. younger than the core (2525 Ma); in two others there is no significant age difference from core to rim. Most of the zircons are concordant or near concordant, and $^{207}Pb/^{206}Pb$ ages range from 2835 Ma (nx32–37) to ca. 530 Ma. A cluster of three grains is near 2800 Ma; another cluster of four grains gives a mean age of 2497 ± 15 Ma, and a trail of discordant grains suggests nonzero lead loss from this group (Fig. 2A, inset). There are several concordant Paleoproterozoic to Mesoproterozoic grains (2100–1400 Ma) and other clusters of near-concordant grains near 800 Ma and 500–600 Ma.

Zircons from sample Pjb71 (Jingshan) are light yellow to transparent, and euhedral (e.g., Pjb71–54, Pjb71–65) to irregular. The grains are 100–280 μm long with length/width values of 1.1–4.4: 40% have relict cores with oscillatory or lamellar internal structure. Others are uniformly structureless. There are 8 concordant Neoarchean to Paleoproterozoic zircons, with $^{207}Pb/^{206}Pb$ ages ranging from 2751 Ma (Pjb71–60) to 2020 ± 12 Ma (Pjb71–54, Pjbj71–55c, Pjb71–68, Pjb71–70) (Fig. 2B). One grain with an Archean core (2708 Ma) has a Paleoproterozoic rim (2035 Ma). Grain pjb71–65, a euhedral zircon with lamellar internal structure, gives weakly discordant $^{206}Pb/^{238}U$ ages of 457 ± 5 Ma (core) and 367 ± 4 Ma (rim). All 13 Proterozoic and Paleozoic zircons yield an upper intercept age of 2040 ± 23 Ma and a lower intercept age of 304 ± 89 Ma (Fig. 2B, inset), within error of the rim age for grain Pjb71–65.

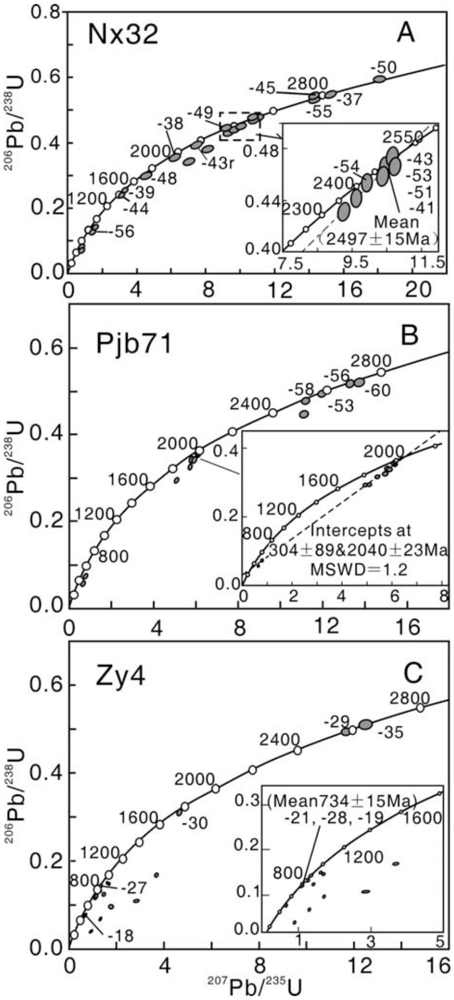

Figure 2. Concordia plots showing results of U-Pb dating for zircons from lamproites on Yangtze craton. MSWD—mean square of weighted deviates.

Zircons from sample Zy4 are light purple to transparent and forms range from euhedral to rounded. The grains are 75–150 μm long with length/width values of 1.2–3.8. Three grains (Zy4–19, Zy4–25, Zy4–26) show oscillatory zoning, and the others have no internal structure. Seven zircons are concordant (Fig. 2C), with $^{207}Pb/^{206}Pb$ ages ranging from Neoarchean (2632 Ma; Zy4–35), to Mesoproterozoic (1786 Ma; Zy4–30) and Neoproterozoic (855 Ma [Zy4–27] and 734 Ma [Zy4–21, Zy4–8, Zy4–19]). Grain zy4–18 gives a weakly discordant Paleozoic $^{206}Pb/^{238}U$ age of 486 ± 6 Ma. Several high-U grains are strongly discordant with Paleozoic $^{206}Pb/^{238}U$ ages and appear to represent recent Pb loss from older populations.

Zircons from htlltp1 and htlltp2 are light purple to light brown; forms range from euhedral, through mainly subhedral and irregular; a few are rounded. They are 85–185 μm

[1]GSA Data Repository item 2006082, U-Pb dating and Hf-isotope analyses of zircons, 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.

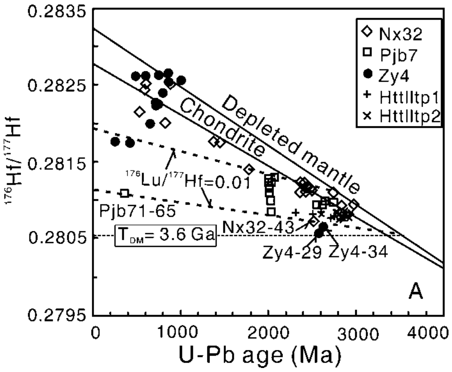

Figure 3. U-Pb age vs. ^{176}Hf/^{177}Hf for zircons from Yangtze craton. MSWD—mean square of weighted deviates.

TABLE 1. THERMAL EVENTS FOR THE YANGTZE CRATON SUMMARIZED FROM TABLES DR1-DR2 (see footnote 1)

Occurence Location Sample	Method	Xenocryst			Outcrop
		Ningxiang NX32	Jingshan PJB71	Zhenyuan ZY4	Kongling
Eoarchean	$T_{(DM)}$			3.63 Ga	
Paleoarchean	U-Pb age				3.2 Ga*
	T (crust)	3.4–3.2 Ga	3.5–3.2 Ga		
	$T_{(DM)}$	3.4 Ga	3.3 Ga		3.4–3.2 Ga
Mesoarchean	U-Pb age	3.0–2.8 Ga			2.9–2.8 Ga
	T(crust)	3.1–3.0 Ga	3.2 Ga	3.2–3.1 Ga	
	$T_{(DM)}$	3.2–2.9 Ga	3.2–29 Ga		
Neoarchean	U-Pb age	2745, 2525 Ma	2708, 2614, 2559 Ma	2632, 2576 Ma	2524 Ma
Paleoproterozoic	U-Pb age	2488, 2441 Ma			
	U-Pb age	2364, 2200 Ma			
	U-Pb age	2005 Ma	2020 Ma		1933 Ma*
	U-Pb age	1777 Ma		1786 Ma	
Mesoproterozoic	U-Pb age	1458, 1383 Ma			
Neoproterozoic	U-Pb age	820, 600 Ma		734 Ma	800–1000 Ma
Paleozoic	U-Pb age	533–525 Ma	457–367 Ma	486 Ma	

Note: $T_{(DM)}$, depleted mantle Hf model age; $T_{(crust)}$, average crustal Hf model age (^{176}Lu/^{177}Hf = 0.015)
*after Qiu et al. (2000).

long in htlltp1, and 70–125 μm long in htllp2, with similar length/width values (mean 1.6). Most grains in both samples have euhedral to irregular cores defined by different BSE-CL brightness and oscillatory or lamellar internal structure. Cores and rims were analyzed in 10 grains (Table DR1; see footnote 1). Four of them show rims 140–170 m.y. younger than the cores (e.g., 2822 Ma in htlltp1–31c, 2900 Ma in htlltp2–3c). Concordant grains in htlltp1 give Archean ^{207}Pb/^{206}Pb ages of 2880 ± 5 Ma (htlltp1–19, htlltp1–20, htlltp1–27, and htlltp1–30), 2857 ± 3 Ma (htlltp1–25, htlltp1–28) and 2822 Ma (htlltp1–31). All zircon analyses from htlltp1 yield an upper intercept age of 2858 ± 25 Ma and a lower intercept age of 923 ± 150 Ma (Fig. DR1; see footnote 1). Concordant grains in htlltp2 give Archean ^{207}Pb/^{206}Pb ages from 2921 ± 20 Ma to 2816 ± 8 Ma. A regression through all zircon analyses from htlltp2 yields an upper intercept concordia age of 2893 ± 29 Ma and a lower intercept age of 1027 ± 230 Ma (Fig. DR1; see footnote 1). The two samples therefore have both upper and lower intercept ages that are within error of one another, recording Archean crustal formation and Neoproterozoic metamorphism.

Hf Isotopes

In sample Nx32 (Ningxiang), the Hf model ages indicate the generation of juvenile crust between 3.0 and 2.7 Ga, but one grain in this age group has a minimum model age (T_{DM}) of 3.0 Ga; even assuming a relatively felsic composition (^{176}Lu/^{177}Hf = 0.01), the crustal protolith of the original host rock is older than 3.1 Ga (Fig. 3). The cluster of zircon grains with ages of 2.5–2.3 Ga is well below the depleted mantle line, implying the derivation of the host magmas of those zircon grains through reworking of older crust, which could be represented by the juvenile 2.7 Ga rocks (assuming their ^{176}Lu/^{177}Hf = 0.01). However, one Neoarchean grain has a T_{DM} of 3.2 Ga and a probable protolith age older than 3.4 Ga. Most of the scattered Mesoproterozoic to Paleozoic grains also have $\varepsilon_{Hf} < 0$, implying that their original host magmas were generated by melting of old crustal material, but high ε_{Hf} in some Neoproterozoic grains suggests the generation of juvenile crust at that time.

In sample Pjb71 (Jingshan), five zircons with Neoarchean ages (2751–2559 Ma) have essentially identical ^{176}Hf/^{177}Hf, suggesting Pb loss from a single population ca. 2750 Ma; this population has a T_{DM} model age of 3.0 Ga, and a probable crustal protolith age older than 3.1 Ga. The zircons with Paleoproterozoic ages (2008–2069 Ma) show a wide range of ^{176}Hf/^{177}Hf (0.280851–0.281292); this range may reflect either mixing between an old crustal component and a more juvenile one, or the resetting of U-Pb ages in zircons from a heterogeneous older crust. The zircon with the least radiogenic Hf suggests the presence of a crustal component older than 3.5 Ga (assuming ^{176}Lu/^{177}Hf = 0.01). The single Paleozoic zircon (457 Ma) may also reflect this component (Fig. 3).

In sample Zy4 (Zhenyuan), two Neoarchean zircons (Zy4–29, Zy4–34) have the lowest ^{176}Hf/^{177}Hf observed in this study; their minimum (T_{DM}) model ages are 3.4–3.5 Ga, and a probable crustal protolith (assuming ^{176}Lu/^{177}Hf = 0.01) would be older than 3.6 Ga. There are 10 zircons with Neoproterozoic ages (600–1003 Ma) that have a very wide range of ^{176}Hf/^{177}Hf (ε_{Hf} of −13.1 to ∼+15.0) (Fig. 3), suggesting mixing between juvenile material and a crustal component at least 2 b.y. old. Two Paleozoic zircons have ε_{Hf} of −30.0, implying the reworking of crust at least 2.5 b.y. old.

In samples htlltp1 and htlltp2, all zircons have negative ε_{Hf} (−16.5 to −2.2) and have essentially uniform ^{176}Hf/^{177}Hf, regardless of their U-Pb ages (Fig. 3). This pattern is typical of zircons that have undergone thermal resetting without disturbance of their Hf isotope composition (Amelin et al., 2000; Zheng et al., 2004). The low ε_{Hf} values suggest a crustal protolith ≥3.4 b.y. old.

DISCUSSION

Widespread Archean Basement

Most of the zircons in the lamproites from all three locations are older than the eruption ages of their host rocks (Table 1), indicating that they are xenocrysts. U-Pb ages ca. 2500 Ma or older are common among the zircons from the lamproites (Fig. 2), indicating the presence of unexposed Archean rocks beneath the Ningxiang, Jingshan, and Zhenyuan areas, which have been regarded as zones of activity (Sibao orogen; Li et al., 2002), where basement outcrops consist of rocks with Mesoproterozoic–Neoproterozoic ages (Chi and Lu, 1996). The Ningxiang lamproite contains zircons as old as 3.0 Ga with juvenile Hf isotope compositions, and other Archean zircons with Hf isotope compositions suggest protolith ages older than 3.5 Ga. These observations suggest the existence of Mesoarchean rocks containing older crustal components beneath the southern margin of the craton (Fig. 1). The oldest U-Pb ages in the Jingshan and Zhenyuan areas are Neoarchean (2708 Ma and 2632 Ma, respectively). However, all Jingshan zircons have negative ε_{Hf}, and the model ages of some Mesoproterozoic zircons imply the presence of protoliths older than 3.5 Ga. In the Zhenyuan sample, two Neoarchean grains (Zy4–29, Zy4–35) have ca 3.6 Ga T_{DM} model ages and probably require protoliths ca. 3.6 Ga or older. These data strongly suggest the existence of Neoarchean rocks containing Paleoarchean to Eoarchean components beneath both the northern margin (e.g., Jingshan) and the south-central part (e.g., Zhenyuan) of the Yangtze craton (Fig. 1).

Reports of metasedimentary rocks with 3.2 Ga detrital zircons from the Kongling complex (Qiu et al., 2000) were not duplicated in this study. All zircons from the Kongling tonalitic and trondhjemitic gneisses have Mesoarchean U-Pb ages (to 2.9 Ga, also see Qiu et al., 2000) and negative ε_{Hf} (-16.6 to ~ -2.2). In these samples, the zircons with magmatic internal structure (Table DR1; see footnote 1) yield minimum T_{DM} model ages of 3.1–3.2 Ga and probable protolith ages older than 3.4 Ga (T_{crust},) indicating the presence of Paleoarchean components in the northern margin of the Yangtze craton, consistent with evidence from zircon in the lamproites. In the Kangdian area (Fig. 1), zircons from gneisses yielded a U-Pb concordia intercept age of ca 2.5 Ga and a Pb-Pb isochron age of 2957 $\pm$ 304 Ma (Yuan, 1985). Zhang et al. (2003) reported the SHRIMP zircon U-Pb ages of 2621–2403 and 3232 Ma in the volcanic rocks ~50 km south of Nanjing city (Fig. 1). The occurrences of these Archean windows, combined with the zircon data from the lamproites, indicate that Archean basement is widespread beneath the exposed Proterozoic rocks of the Yangtze craton, and this basement may contain Paleoarchean (even Eoarchean) components (Table 1).

Post-Archean Thermal Events

The zircon data from the lamproites and the Kongling gneisses also indicate several important post-Archean thermal events that may be related to the Proterozoic reworking event forming the uppermost crust of the craton. The data from Jingshan show a distinct age group, ca. 2 Ga; the Hf isotope data indicate that this event involved thermal reworking of a heterogeneous older crust. There is also evidence for this event in the Ningxiang sample, but it is not obvious in the Zhenyuan zircons. The two gneiss samples from the Kongling complex show considerable discordance with a lower concordia intercept ca. 1 Ga, implying a significant thermal event; the Hf isotope data show resetting of U-Pb ages without disturbance to the Lu-Hf system. The late Paleoproterozoic event can also be illustrated by the intrusive age of the ca 1.9 Ga Quanqitang granite in the Kongling complex (Yuan et al., 1991), and by a cluster of 1.7–2.2 Ga U-Pb zircon dates (Gan et al., 1996) and an Sm-Nd isochron of 1895 $\pm$ 72 Ma (Xing et al., 1993) in the middle to lower Yangtze region. The inferred Neoproterozoic event is consistent with the widespread occurrence of granitoids, which have been connected to the proposed ca. 820 Ma mantle plume beneath south China (Li et al., 2003). High values of ε_{Hf} (as high as $+15.1$ in Zhenyuan and $+10.3$ in Ningxiang) in 850–1000 Ma zircons are consistent with the addition of depleted mantle material (e.g., a mantle plume) beneath the Yangtze craton. A number of zircons in all three lamproite samples plot near the concordia with Paleozoic minimum ages.

CONCLUSIONS

Our data suggest that the Yangtze craton has a widespread Archean basement, overlain by shallow crust partially reworked in Proterozoic time. The major Mesoproterozoic event appears to have largely involved remelting of the Archean basement rocks; the Neoproterozoic event may have added juvenile material to the crust. Accumulating evidence suggests that in many areas, later reworking of the deep crust is more widespread than previously recognized. Such observations have important implications for models of continental formation and preservation. The formation of significantly greater volumes of crust early in Earth's history would also affect development of depleted-mantle geochemical reservoirs and imply the early formation of larger volumes of refractory subcontinental lithospheric mantle.

ACKNOWLEDGMENTS

The National Natural Science Foundation of China (40425002), the Program for Changjiang Scholars and Innovative Research Team in University (PCSIRT-IRT0441), and the Australian Research Council (ARC) Discovery Project and Linkage International grants (O'Reilly and Griffin) supported this study. This is from the ARC National Key Centre for the Geochemical Evolution and Metallogeny of Continents contribution 422 (www.es.mq.edu.au/GEMOC/). We thank K. Condie, M. Sun, A. Kroener, and H. Jenkyns for helpful reviews.

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Manuscript received 7 October 2005
Revised manuscript received 23 December 2005
Manuscript accepted 28 December 2005

Printed in USA