2006

4.2 Ga zircon xenocryst in an Acasta gneiss from northwestern Canada: Evidence for early continental crust

Tsuyoshi Iizuka* Department of Earth and Planetary Sciences, Tokyo Institute of Technology, Ookayama Meguro-ku, Tokyo 152-8551, Japan
Kenji Horie Department of Earth and Planetary Systems Science, Hiroshima University, Higashi-Hiroshima 739-8526, Japan
Tsuyoshi Komiya, Shigenori Maruyama, Takafumi Hirata — Department of Earth and Planetary Sciences, Tokyo Institute of Technology, Ookayama Meguro-ku, Tokyo 152-8551, Japan
Hiroshi Hidaka Department of Earth and Planetary Systems Science, Hiroshima University, Higashi-Hiroshima 739-8526, Japan
Brian F. Windley Department of Geology, University of Leicester, Leicester LE1 7RH, UK

ABSTRACT

Evidence for the existence of continental crust older than 4.06 Ga has so far been obtained only from zircons in the Yilgarn Craton of Western Australia. In this paper we report the first occurrence of a very old zircon with a U-Pb age of 4.2 Ga in the Acasta Gneiss Complex of northwestern Canada, based on a laser ablation-inductively coupled plasma–mass spectrometry and sensitive high-resolution ion microprobe study. The U-Pb data reveal that the 4.2 Ga zircon occurs as a xenocryst in a 3.9 Ga granitic rock. Trace element compositions of the xenocryst suggest that it crystallized from a granitic magma. Our results, suggesting the existence of granitic rocks outside the Yilgarn Craton at 4.2 Ga, imply that granitic continental crust was more widespread than previously thought, and that it was reworked into Early Archean continental crust.

Keywords: Acasta Gneiss Complex, Hadean, ancient zircon, crustal reworking, laser ablation-inductively coupled plasma-mass spectrometry, sensitive high-resolution ion microprobe, U-Pb dating.

INTRODUCTION

Knowledge of early crustal growth history is central to understanding the evolution of the early Earth. The oldest known rocks are 3.94–4.03 Ga rocks in the Acasta Gneiss Complex of northwestern Canada (Bowring et al., 1989b; Bowring and Housh, 1995; Stern and Bleeker, 1998; Bowring and Williams, 1999); no crustal rocks have been found from the first 500 m.y. of Earth's history (Nutman et al., 2001). Radiogenic isotopes provide a means of unraveling early crustal evolution. Studies using ^{147}Sm-^{143}Nd and ^{176}Lu-^{176}Hf isotope systematics of Early Archean rocks (e.g., Blichert-Toft et al., 1999) have suggested that the silicate Earth had geochemically differentiated into an enriched reservoir and a depleted mantle in the Hadean (we have defined Hadean as older than 4.03 Ga herein). However, it is still controversial as to whether the isotopic signatures resulted from fractionation during solidification of a magma ocean or extraction of crust from the mantle (Albarède et al., 2000), because the isotopic data do not rigidly constrain either the nature of the enriched reservoir or the timing of its formation. One way to help resolve this problem is to discover and study additional very old terrestrial materials that provide further direct evidence of early crustal evolution.

The oldest identified terrestrial materials (older than 4.06 Ga) are zircons from the Yilgarn Craton in Western Australia that occur as detrital grains in ca. 3.0 Ga metasediments (e.g., Froude et al., 1983; Compston and Pidgeon, 1986; Wilde et al., 2001; Wyche et al., 2004) or as xenocrystic grains in ca. 2.6 Ga granitoids (Nelson et al., 2000). Mineralogical and geochemical studies suggest that granitic crust was in existence only a few hundred million years after the Earth's formation (Maas et al., 1992; Mojzsis et al., 2001; Peck et al., 2001; Cavosie et al., 2005; Crowley et al., 2005; Watson and Harrison, 2005). However, its volume and geochemical influence on subsequent crustal evolution are still unresolved. To better constrain this problem, further data are required, preferably from other regions.

Here we report the first occurrence of a 4.2 Ga zircon in the Acasta Gneiss Complex. U-Pb data, acquired with a laser ablation-inductively coupled plasma–mass spectrometer (LA-ICP-MS) and a sensitive high-resolution ion microprobe (SHRIMP), reveal that the 4.2 Ga zircon is a xenocryst within 3.9 Ga granitic rock. The isotopic, geochemical, and mineralogical characteristics of this xenocryst have important implications for early crustal evolution.

ACASTA GNEISS COMPLEX

The Acasta Gneiss Complex, exposed along the western margin of the Slave Craton, comprises a heterogeneous assemblage of foliated to gneissic tonalites, granodiorites, and granites, together with minor quartz-diorites, diorites, gabbros, and ultramafic rocks (Bowring et al., 1990). The occurrence of extremely old rocks in the Acasta Gneiss Complex was first demonstrated by Bowring et al. (1989a) based on a thermal ionization MS study of the U-Pb isotopic character of zircon and feldspar, and whole-rock Sm-Nd isotope systematics. The rocks have Nd_{CHUR} model ages as old as 4.1 Ga and contain zircons with a minimum age of 3.84 Ga. Subsequent ion microprobe zircon dating revealed the presence of 3.94–4.03 Ga rocks (Bowring et al., 1989b; Bowring and Housh, 1995; Stern and Bleeker, 1998; Bowring and Williams, 1999; Sano et al., 1999) and the occurrence of zircon xenocrysts as old as 4.06 Ga (Bowring and Williams, 1999). The oldest rocks underwent metamorphism ca. 3.4–3.6 Ga, coincident with intrusion of younger granites (Bleeker and Stern 1997), and Sm-Nd whole-rock data on some of them yield a regression age of 3.4 Ga corresponding to the metamorphic event (Moorbath et al., 1997). Accordingly, Moorbath et al. (1997) argued that the age of the Acasta gneisses must be regarded as 3.4 Ga. We have carried out zircon U-Pb dating on 25 Acasta gneisses from 18 localities (Fig. DR1[1]).

SAMPLES AND ANALYTICAL METHODS

Zircon samples discussed in this paper were separated from Acasta tonalitic gneiss AC012 (collected at 65°09′N, 115°33′W; Fig. DR1; see footnote 1), which mainly consists of plagioclase, quartz, biotite, and hornblende. The separated zircons are typically 100–200 μm long, and are euhedral to subhedral. We

*E-mail: tiiduka@geo.titech.ac.jp.

[1]GSA Data Repository item 2006056, Table DR1, Pb isotopic data for zircons; Figure DR1, geological map of the Acasta Gneiss Complex showing the location of AC012; Figure DR2, cathodoluminescence images of zircons; Figure DR3, Raman spectra for an apatite inclusion and the enclosing zircon AC012/07; and Appendix DR1, analytical procedures, 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.

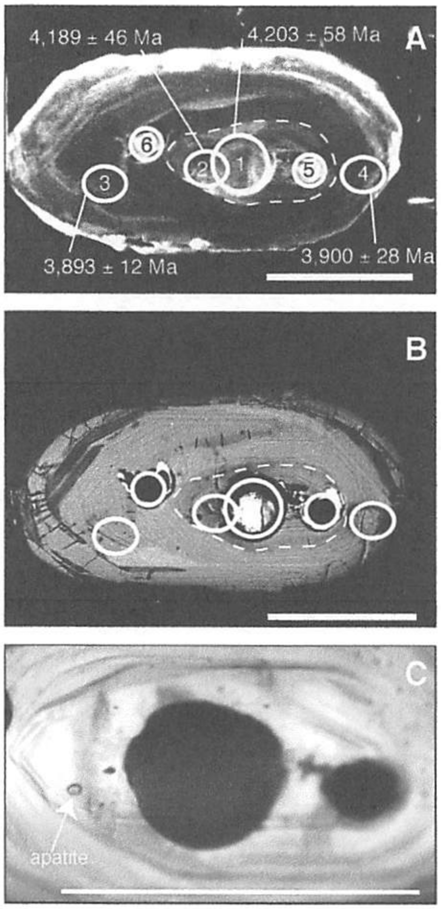

Figure 1. A: Cathodoluminescence image of zircon AC012/07. B: Backscattered electron image of zircon AC012/07. In A and B, broken line marks limits of xenocrystic core. Circles with solid lines represent analytical spots. Spot numbers correspond to those in Table 1. Values record $^{207}Pb/^{206}Pb$ age (2σ) of each spot. C: Transmitted light image of xenocryst, showing location of apatite inclusion. Scale bars are 50 µm.

checked the internal structure of ~450 zircon grains with cathodoluminescence (CL) images prior to analysis.

The CL images (Fig. DR2) show that oscillatory (OSC) zoning structures, which are very common in magmatic zircons (Corfu et al., 2003), are preserved in only ~5% of the zircons. Most zircons are mottled or dark in the images, suggesting that magmatic zircons were altered (metamictization or recrystallization and/or homogenization), or that metamorphic zircons were formed during later metamorphism (Corfu et al., 2003). The growth of metamorphic zircons is also predicted by the common occurrence of thin (~20 µm) and dark overgrowths on the OSC zircons. These observations suggest that the protolith of tonalitic gneiss AC012 underwent a metamorphic event. In addition, the CL image (Fig. 1A) and the backscattered electron image (Fig. 1B) show that grain AC012/07

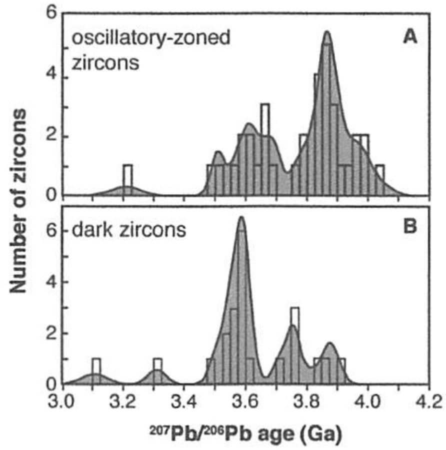

Figure 2. $^{207}Pb/^{206}Pb$ age histograms for oscillatory zoned and dark zircons from AC012, respectively. Shaded areas represent cumulative Gaussian distribution.

consists of three generations of zircon: a light (in the CL image) and homogeneous core, a partly OSC zoned mantle, and a homogeneous rim that cut the OSC zoning. This indicates that a magmatic zircon, containing the xenocrystic zircon, was overgrown by a metamorphic zircon.

We dated 55 zircon grains using LA-ICP-MS at the Tokyo Institute of Technology (Iizuka and Hirata, 2004). The xenocrystic zircon (AC012/07) was also analyzed with a SHRIMP II at Hiroshima University (Hidaka et al., 2002). To constrain the provenance of this xenocryst, the abundances of Sc, Y, rare earth elements (REE), and Hf were measured with the LA-ICP-MS at the Tokyo Institute of Technology. The detailed procedures of the U-Pb isotope and trace element analyses are described in Appendix DR1 (see footnote 1). We also identified a mineral inclusion in this zircon using JASCO NRS-2000 laser Raman spectroscopy at the Tokyo Institute of Technology.

RESULTS: U-Pb GEOCHRONOLOGY

The U-Pb data are summarized in Table DR1 (see footnote 1) and Figures 2 and 3. The analyses of OSC zoned zircons range from 3.4 to 4.0 Ga ($^{207}Pb/^{206}Pb$), and show a peak ca. 3.9 Ga in the histogram of $^{207}Pb/^{206}Pb$ ages (Fig. 2A), suggesting that crystallization of magmatic zircons took place ca. 3.9 Ga. In contrast, the histogram of $^{207}Pb/^{206}Pb$ ages for the dark zircons shows a distribution between 3.1 and 3.9 Ga, and a peak ca. 3.6 Ga (Fig. 2B), suggesting metamorphic zircon growth and/or Pb loss event ca. 3.6 Ga. This is consistent with previous studies that indicated the presence of a metamorphic event at 3.6 Ga (e.g., Bleeker and Stern, 1997). Hence, these data are interpreted to indicate that the protolith of tonalitic gneiss AC012 was emplaced ca. 3.9 Ga, and underwent a metamorphic event, probably at 3.6 Ga. We estimated the precise emplacement age of the protolith of tonalitic gneiss AC012 from the oldest $^{207}Pb/^{206}Pb$ ages of the OSC zoned zircons on the assumption that the variation of their $^{207}Pb/^{206}Pb$ ages was caused by Pb loss events from one generation of zircons, rather than by mixing of multiple generations of xenocrysts, whereas the emplacement age may be meaningless for a whole-rock geochemical study (e.g., Moorbath et al., 1997). The 10 highest $^{207}Pb/^{206}Pb$ measurements on 9 OSC zoned grains are similar within analytical uncertainty, and yield a mean $^{207}Pb/^{206}Pb$ age of 3942 ± 32 Ma (2 s.e.).

The xenocrystic core of zircon grain AC012/07 exhibits a $^{207}Pb/^{206}Pb$ age of 4203 ± 58 Ma (2σ) (Table 1; Fig. 1A), ~140 m.y. older than the oldest zircon identified in the Acasta Gneiss Complex (Bowring and Williams, 1999). The core has a $^{207}Pb/^{206}Pb$ SHRIMP age of 4189 ± 46 Ma (2σ) (Table 1; Figs. 1A and 3), which corresponds to the LA-ICP-MS result within analytical uncertainty. The overgrowth area yielded $^{207}Pb/^{206}Pb$ SHRIMP ages of 3900 ± 28 and 3893 ± 12 Ma (2σ) (Table 1; Figs. 1A and 3) that are similar to the emplacement age of the protolith of tonalitic gneiss AC012. These results indicate that a magma containing the 4.2 Ga zircon xenocryst was emplaced at 3.9 Ga, and subsequently underwent metamorphism.

DISCUSSION: PROVENANCE OF THE 4.2 Ga ZIRCON XENOCRYST

In order to understand the nature of very early crust in the Acasta Gneiss Complex, it is important to determine the provenance of the xenocryst. Because zircon is ubiquitous as an accessory mineral in granitic rocks, it is reasonable to suspect that they are the source of the xenocryst. However, zircon occurs in other igneous rocks such as syenites, carbonatites, kimberlites, and mafic rocks, and it can also form during metamorphism. We used trace element compositions of the zircon and its mineral inclusion to constrain its provenance.

The trace element abundances of grain AC012/07 are summarized in Table 1. The 4.2 Ga xenocryst has a Th/U ratio of 0.52, suggesting a magmatic rather than a metamorphic origin (Th/U < 0.1; Hoskin and Schaltegger, 2003). Relatively high contents of incompatible elements such as Y, Nb, Hf, Th, and U suggest that it crystallized from an evolved magma (Belousova et al., 2002; Crowley et al., 2005). Figure 4 shows the REE pattern of the core compared with that of zircons from the Blind Gabbro of Australia (Hoskin and Ireland, 2000). The REE data, especially for light (L)REE, must be regarded with caution, because LREE overabundances resulting from secondary alteration are often observed in an-

TABLE 1. U-Pb-Th AND TRACE ELEMENT DATA FOR AC012/07

U-Pb-Th data Spot	Method	U (ppm)	Th (ppm)	Th/U	$^{204}Pb/^{206}Pb$	$^{206}Pb^{*}/^{238}U$	$^{207}Pb^{*}/^{206}Pb^{*}$	Age (Ma) $^{206}Pb/^{238}U$	Age (Ma) $^{207}Pb/^{206}Pb$	Disc (%)
1	LA-ICP-MS	N.D.†	N.D.†	N.D.†	0.0002	N.D.†	0.4874 ± 191	N.D.†	4203 ± 58	N.D.†
2	SHRIMP	699	347	0.496	0.0006	0.8611 ± 316	0.4827 ± 150	4004 ± 110	4189 ± 46	4
3	SHRIMP	621	115	0.185	0.0005	0.6900 ± 224	0.3957 ± 32	3383 ± 86	3893 ± 12	13
4	SHRIMP	649	48	0.075	0.0002	0.7567 ± 320	0.3976 ± 76	3632 ± 118	3900 ± 28	7

Trace element data (ppm)

Spot	Sc	Y	Nb	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Hf
5	396	1196	624	0.1	15	0.2	1.5	9.1	1.3	22	8.0	89	36	155	36	400	54	13621
6	336	547	663	N.D.†	2	0.1	0.5	2.5	0.2	6.5	2.0	37	16	94	28	295	53	16047

Note: Spot numbers correspond to those in Figure 2. Pb* corrected for common Pb using ^{204}Pb. All errors are quoted at 2σ.
†N.D. = not determined.

cient zircons (Whitehouse and Kamber, 2002; Hoskin, 2005). Several important points emerge from our Figure 4. (1) A prominent positive Ce anomaly, a feature typical of terrestrial zircons, suggests that AC012/07 crystallized under oxidizing conditions (Hoskin and Schaltegger, 2003). (2) A pronounced enrichment of heavy REEs relative to light REEs with prominent negative Eu anomalies suggests that the source magma of AC012/07 coexisted with feldspar and not garnet. This is consistent with its crustal rather than mantle origin (e.g., from kimberlites and carbonatites) (Hoskin and Schaltegger, 2003). In addition, because a prominent negative Eu anomaly is not observed in zircons from alkalic felsic rocks such as syenites (Hoskin and Schaltegger, 2003), possibly due to the high [Na_2O + K_2O/Al_2O_3] of their source magma that significantly decreases the distribution of Eu in alkali feldspars (White, 2003), it is unlikely that alkalic felsic rocks are the source of the xenocryst. (3) Zircons from the Blind Gabbro have a concave-down curvature in the middle-heavy REE patterns ($[2Ho/(Gd + Yb)]_N$ = 0.84–1.01), but the xenocryst shows no such curvature ($[2Ho/(Gd + Yb)]_N$ = 0.50); this pattern, which is typical of zircons from mafic rocks, could be due to heavy REE depletion of melt caused by crystallization of clinopyroxene and/or orthopyroxene (Hoskin and Ireland, 2000). This suggests that the xenocryst formed in a granitic magma, rather than in a differentiated melt from a mafic parental magma. In addition, we have determined with laser Raman spectroscopy that the xenocryst contains an apatite inclusion (Figs. 1C and DR3; see footnote 1); this does not contradict its growth from a granitic magma. These geochemical and mineralogical characteristics suggest that the 4.2 Ga zircon xenocryst was derived from a granitic source, providing new evidence for the existence of granitic continental crust outside the Yilgarn Craton at that time.

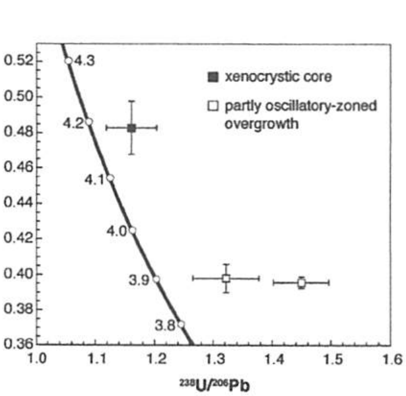

Figure 3. Tera-Wasserburg plot showing sensitive high-resolution ion microprobe U-Pb data for zircon AC012/07. Errors bars on individual spots are at 2σ level.

IMPLICATIONS

Evidence for the existence of continental crust older than 4.06 Ga is restricted to three parts of the Yilgarn Craton: the Narryer, Murchison, and Southern Cross terranes. The recognition of another area of very old continental crust has several implications for the early evolution of the silicate Earth, because the Slave and Yilgarn Cratons seem to be historically unrelated (Bleeker, 2003). The ^{147}Sm-^{143}Nd and ^{176}Lu-^{176}Hf isotope compositions of Early Archean rocks [$\varepsilon^{143}_{Nd(3.85\ Ga)} = 2 \pm 2$ and $\varepsilon^{176}_{Hf(3.85\ Ga)} = 4 \pm 2$; Blichert-Toft et al., 1999] indicate that some of them are derived from highly depleted mantle. This suggests a differentiation event before ca. 4.0 Ga. The application of coupled ^{147}Sm-^{143}Nd and short-lived ^{146}Sm-^{142}Nd isotope systematics could constrain the timing and the degree of the early differentiation. Boyet and Carlson (2005) indicated that $^{142}Nd/^{144}Nd$ ratios of most terrestrial rocks are 20 ppm higher than those of chondrites. These $^{142}Nd/^{144}Nd$ ratios, with $^{143}Nd/^{144}Nd$ ratios of mid-ocean ridge basalt, suggest that the silicate Earth had differentiated geochemically into an early enriched reservoir and an early depleted reservoir by 4.53 Ga, possibly during solidification of a magma ocean. This primary differentiation would have produced an Early Archean depleted mantle with an $\varepsilon^{143}_{Nd(3.85\ Ga)} = \sim+2$, consistent with that of the Early Archean rocks. However, the subchondritic ε^{143}_{Nd} with a superchondritic ε^{142}_{Nd} of some Early Archean rocks (e.g., Regelous and Collerson, 1996; Boyet et al., 2003) cannot be explained only by the primary differentiation event; it requires within the early depleted reservoir either early crustal formation after 4.3 Ga or redistribution of Sm-Nd isotope systems of the rocks during later metamorphic events (as was pointed out for other Early Archean rocks; Vervoort et al., 1996; Moorbath et al., 1997). In the former case, some (e.g., Collerson et al., 1991) have envisaged that most of the early crust was mafic or ultramafic, mainly because of the extreme rarity of evidence for the existence of continental crust older than 3.9–4.0 Ga. However, our data, suggesting the existence of granitic crust older than 4.0 Ga in two independent cratons, increase the probability that granitic continental crust made up a significant part of the early crust.

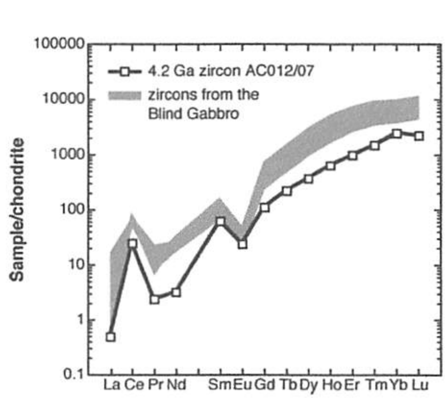

Figure 4. Chondrite-normalized (Anders and Grevesse, 2004) rare earth element plot for xenocrystic core within AC012/07. Also plotted are data for zircons from Blind Gabbro (Hoskin and Ireland, 2000).

Importantly, the fact that the 4.2 Ga zircon in the Acasta Gneiss Complex occurs as a xenocryst within a 3.9 Ga granitic rock suggests that granitic magma was derived from 4.2 Ga Hadean continental crust and entrained the 4.2 Ga zircon during its passage through the continental crust, to be finally emplaced in the Acasta Gneiss Complex at 3.9 Ga. From

Lu-Hf isotopic studies of zircons from the Yilgarn Craton and Acasta Gneiss Complex, Amelin et al. (1999) demonstrated that some Early Archean continental crust formed by remelting of significantly older enriched material. Our results provide direct evidence for the formation of Early Archean continental crust by remelting of ca. 4.2 Ga crust. This is consistent with previous zircon Lu-Hf isotopic studies and suggests that crustal reworking was already an important process by the Early Archean, in a manner similar to that from the Late Archean to present (Iizuka et al., 2005). Although the poorly constrained processes of crustal recycling into the mantle and/or destruction of early crust by meteorite heavy bombardment may have been causative factors in the removal of some early crustal material, we argue that crustal reworking was a viable and important cause of the lack of preserved crust older than 4.0 Ga.

ACKNOWLEDGMENTS

We thank M. Senkiw, W. Humphries, D. Baldwin, K. Gochnauer, A. Motoki, Y. Ueno, I. Katayama, S. Rino, and Y. Uehara for assistance with field work, and N. Sakamoto for analytical support. Comments by S. Johnson, J. Valley, P.A. Mueller, S. Wilde, and an anonymous reviewer improved the paper.

REFERENCES CITED

Albarède, F., Blichert-Toft, J., Vervoort, J.D., Gleason, J.D., and Rosing, M., 2000, Hf-Nd isotope evidence for transient dynamic regime in the early terrestrial mantle: Nature, v. 404, p. 488–490.

Amelin, Y., Lee, D.-C., Halliday, A.N., and Pidgeon, R.T., 1999, Nature of the Earth's earliest crust from hafnium isotopes in single detrital zircons: Nature, v. 399, p. 252–255.

Anders, W., and Grevesse, N., 1989, Abundances of the elements: Meteoritic and solar: Geochimica et Cosmochimica Acta, v. 53, p. 197–214.

Belousova, E.A., Griffin, W.L., O'Reilly, S.Y., and Fisher, N.I., 2002, Igneous zircon: Trace element composition as an indicator of source rock type: Contributions to Mineralogy and Petrology, v. 143, p. 602–622.

Bleeker, W., 2003, The late Archean record: A puzzle in ca. 35 pieces: Lithos, v. 71, p. 99–134.

Bleeker, W., and Stern, R., 1997, The Acasta gneisses: An imperfect sample of Earth's oldest crust, *in* Cook, F., and Erdmer, P., eds., Slave–Northern Cordillera lithospheric evolution (SNORCLE) transect and cordilleran tectonics workshop meeting: Lithosphere Report, v. 56, p. 32–35.

Blichert-Toft, J., Albarède, F., Rosing, M., Frei, R., and Bridgwater, D., 1999, The Nd and Hf isotopic evolution of the mantle through the Archean. Result from the Isua supracrustals, West Greenland, and from the Birimian terranes of West Africa: Geochimica et Cosmochimica Acta, v. 63, p. 3901–3914.

Bowring, S.A., and Housh, T., 1995, The Earth's early evolution: Science, v. 269, p. 1535–1540.

Bowring, S.A., and Williams, I.S., 1999, Priscoan (4.00–4.03 Ga) orthogneisses from northwestern Canada: Contributions to Mineralogy and Petrology, v. 134, p. 3–16.

Bowring, S.A., King, J.E., Housh, T.B., Isachsen, C.E., and Podosek, F.A., 1989a, Neodymium and lead isotope evidence for enriched Early Archean crust in North America: Nature, v. 340, p. 222–225.

Bowring, S.A., Williams, I.S., and Compston, W., 1989b, 3.96 Ga gneisses from the Slave province, Northwest Territories, Canada: Geology, v. 17, p. 971–975.

Bowring, S.A., Housh, T.B., and Isachsen, C.E., 1990, The Acasta gneisses: Remnant of Earth's early crust, *in* Newsom, H.E., and Jones, J.H., eds., Origin of the Earth: New York, Oxford University Press, p. 319–343.

Boyet, M., and Carlson, R.W., 2005, ^{142}Nd evidence for early (>4.53 Ga) global differentiation of the silicate Earth: Science, v. 309, p. 576–581.

Boyet, M., Blichert-Toft, J., Rosing, M., Storey, M., Télouk, P., and Albarède, F., 2003, ^{142}Nd evidence for early Earth differentiation: Earth and Planetary Science Letters, v. 214, p. 427–442.

Cavosie, A.J., Valley, J.W., Wilde, S.A., and Edinburgh Ion icroprobe Facility, 2005, Magmatic δ^{18}O in 4400–3900 Ma detrital zircons: A record of the alteration and recycling of crust in the Early Archean: Earth and Planetary Science Letters, v. 235, p. 663–681.

Collerson, K.D., Campbell, L.M., Weaver, B.L., and Palacz, Z.A., 1991, Evidence for extreme mantle fractionation in early Archaean ultramafic rocks from northern Labrador: Nature, v. 349, p. 209–214.

Compston, W., and Pidgeon, R.T., 1986, Jack Hills, evidence of more very old detrital zircons in Western Australia: Nature, v. 321, p. 766–769.

Corfu, F., Hanchar, J.M., Hoskin, P.W.O., and Kinny, P., 2003, Atlas of zircon texture, *in* Hanchar, J.M., and Hoskin, P.W.O., eds., Zircon: Mineralogical Society of America Reviews in Mineralogy and Geochemistry, v. 53, p. 469–500.

Crowley, J.L., Myers, J.S., Sylvester, P.J., and Cox, R.A., 2005, Detrital zircons from the Jack Hills and Mount Narryer, Western Australia: Evidence for diverse >4.0 Ga source rocks: Journal of Geology, v. 113, p. 239–263.

Froude, D.O., Ireland, T.R., Kinny, P.D., Williams, I.S., and Compston, W., 1983, Ion microprobe identification of 4,100–4,200 Myr-old terrestrial zircons: Nature, v. 304, p. 616–618.

Hidaka, H., Shimizu, H., and Adachi, M., 2002, U-Pb geochronology and REE geochemistry of zircons from Palaeoproterozoic paragneiss clasts in the Mesozoic Kamiaso conglomerate, central Japan: Evidence for an Archean provenance: Chemical Geology, v. 187, p. 279–293.

Hoskin, P.W.O., 2005, Trace elements composition of hydrothermal zircon and the alteration of Hadean zircons from the Jack Hills, Australia: Geochimica et Cosmochimica Acta, v. 69, p. 637–648.

Hoskin, P.W.O., and Ireland, T.R., 2000, Rare earth element chemistry of zircons and its use as a provenance indicator: Geology, v. 28, p. 627–630.

Hoskin, P.W.O., and Schaltegger, U., 2003, The composition of zircon and igneous and metamorphic petrogenesis, *in* Hanchar, J.M., and Hoskin, P.W.O., eds., Zircon: Mineralogical Society of America Reviews in Mineralogy and Geochemistry, v. 53, p. 27–62.

Iizuka, T., and Hirata, T., 2004, Simultaneous determinations of U-Pb age and REE abundances for zircons using ArF excimer laser ablation-ICPMS: Geochemical Journal, v. 38, p. 229–241.

Iizuka, T., Hirata, T., Komiya, T., Rino, S., Katayama, I., Motoki, A., and Maruyama, S., 2005, U-Pb and Lu-Hf isotope systematics of zircons from the Mississippi River sand: Implications for reworking and growth of continental crust: Geology, v. 33, p. 485–488.

Maas, R., Kinny, P.D., Williams, I.S., Froude, D.O., and Compston, W., 1992, The Earth's oldest known crust: A geochronological and geochemical study of 3900–4200 Ma old detrital zircons from Mt. Narryer and Jack Hills, Western Australia: Geochimica et Cosmochimica Acta, v. 56, p. 1281–1300.

Mojzsis, S.J., Harrison, T.M., and Pidgeon, R.T., 2001, Oxygen-isotope evidence from ancient zircons for liquid water at the Earth's surface 4,300 Myr ago: Nature, v. 409, p. 178–181.

Moorbath, S., Whitehouse, M.J., and Kamber, B.S., 1997, Extreme Nd-isotope heterogeneity in the early Archaean—Fact or fiction? Case histories from northern Canada and West Greenland: Chemical Geology, v. 135, p. 213–231.

Nelson, D.R., Robinson, B.W., and Myers, J.S., 2000, Complex geological histories extending ≥4.0 Ga deciphered from xenocryst zircon microstructures: Earth and Planetary Science Letters, v. 181, p. 89–102.

Nutman, A.P., Friend, C.R., and Bennett, V.C., 2001, Review of the oldest (4400–3600 Ma) geological and mineralogical record: Glimpses of the beginning: Episodes, v. 24, p. 93–101.

Peck, W.H., Valley, J.W., Wilde, S.A., and Graham, C.M., 2001, Oxygen isotope ratios and rare earth elements in 3.3 to 4.4 Ga zircons: Ion microprobe evidence for high δ^{18}O continental crust and oceans in the Early Archean: Geochimica et Cosmochimica Acta, v. 65, p. 4215–4229.

Regelous, M., and Collerson, K.D., 1996, ^{147}Sm-^{143}Nd, ^{146}Sm-^{142}Nd systematics of Early Archaean rocks and implications for crust-mantle evolution: Geochimica et Cosmochimica Acta, v. 60, p. 3513–3520.

Sano, Y., Terada, K., Hidaka, H., Yokoyama, K., and Nutman, A.P., 1999, Palaeoproterozoic thermal events recorded in the ~4.0 Ga Acasta gneiss, Canada: Evidence from SHRIMP U-Pb dating of apatite and zircon: Geochimica et Cosmochimica Acta, v. 63, p. 899–905.

Stern, R.A., and Bleeker, W., 1998, Age of the world's oldest rocks refined using Canada's SHRIMP: The Acasta Gneiss Complex, Northwest Territories, Canada: Geoscience Canada, v. 25, p. 27–31.

Vervoort, J.D., Patchett, P.J., Gehrels, G.E., and Nutman, A.P., 1996, Constraints on early Earth differentiation from hafnium and neodymium isotopes: Nature, v. 379, p. 624–627.

Watson, E.B., and Harrison, T.M., 2005, Zircon thermometer reveals minimum melting conditions on earliest Earth: Science, v. 308, p. 841–844.

White, J.C., 2003, Trace-element partitioning between alkali feldspar and peralkalic quartz trachyte to rhyolite magma. Part II: Empirical equations for calculating trace-element partition coefficients of large-ion lithophile, high field strength, and rare-earth elements: American Mineralogist, v. 88, p. 330–337.

Whitehouse, M.J., and Kamber, B.S., 2002, On the overabundance of light rare earth elements in terrestrial zircons and its implications for Earth's earliest magmatic differentiation: Earth and Planetary Science Letters, v. 204, p. 333–346.

Wilde, S.A., Valley, J.W., Peck, W.H., and Graham, C.M., 2001, Evidence from detrital zircons for the existence of continental crust and oceans on the Earth 4.4 Gyr ago: Nature, v. 409, p. 175–178.

Wyche, S., Nelson, D., and Riganti, A., 2004, 4350–3130 Ma detrital zircons in the Southern Cross Granite-Greenstone terrane, Western Australia: Implications for the early evolution of the Yilgarn Craton: Australian Journal of Earth Sciences, v. 51, p. 31–45.

Manuscript received 3 August 2005
Revised manuscript received 22 November 2005
Manuscript accepted 24 November 2005

Printed in USA