nature geoscience

LETTERS

PUBLISHED ONLINE: 25 MAY 2014 | DOI: 10.1038/NGEO2170

Earth's earliest evolved crust generated in an Iceland-like setting

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It is unclear how the earliest continental crust formed on an Earth that was probably originally surfaced with oceanic crust. Continental crust may have first formed in an ocean island-like setting, where upwelling mantle generates magmas that crystallize to form new crust. Of the oceanic plateaux, Iceland is closest in character to continental crust, because its crust is anomalously thick[1] and contains a relatively high proportion of silica-rich (sialic) rocks[2]. Iceland has therefore been considered a suitable analogue for the generation of Earth's earliest continental crust[3]. However, the geochemical signature of sialic rocks from Iceland[4–7] is distinct from the typical 3.9- to 2.5-billion-year-old Archaean rocks discovered so far[8]. Here we report the discovery of an exceptionally well-preserved, 4.02-billion-year-old tonalitic gneiss rock unit within the Acasta Gneiss Complex in Canada. We use geochemical analyses to show that this rock unit is characterized by iron enrichment, negative Europium anomalies, unfractionated rare-earth-element patterns, and magmatic zircons with low oxygen isotope ratios. These geochemical characteristics are unlike typical Archaean igneous rocks, but are strikingly similar to those of the sialic rocks from Iceland and imply that this ancient rock unit was formed by shallow-level magmatic processes that include assimilation of rocks previously altered by surface waters. Our data provide direct evidence that Earth's earliest continental crust formed in a tectonic setting comparable to modern Iceland.

Our understanding of early Earth processes is limited by the paucity of rock and mineral samples with ages greater than 3.6 billion years (Gyr). The available data come from 4.0- to 4.4-Gyr-old detrital zircon grains from Western Australia[9] and small, scattered blocks of ancient crust, most being younger than 3.9-Gyr-old and nearly all of which have experienced multiple later magmatic or metamorphic events[10]. Like their younger Archaean counterparts, these ancient terranes are typically dominated by tonalite–trondhjemite–granodiorite (TTG) suite rocks, which are the main plutonic rock package of the Archaean and represent significant growth of continental crust. General geochemical characteristics of these Archaean TTGs include high Na, high Sr/Y, strong depletions in the heavy rare-earth elements (HREEs), and minor or absent Eu anomalies[11–14]. These characteristics are best explained by partial melting of hydrated basaltic rocks at depths great enough to stabilize significant quantities of residual garnet, a high-pressure phase with an affinity for HREEs (refs 14–16). The lack of a significant Eu anomaly in TTGs indicates that plagioclase, a lower pressure mineral that incorporates Eu^{2+}, had little involvement in their petrogenesis. Two main tectonic models have been proposed for the formation of Archaean TTGs and in turn early continental crust: subduction and subsequent partial melting of the down-going oceanic slab[14]; and partial melting at the base of plume-generated oceanic plateaux[17,18]. Although these models differ substantially with regard to tectonic setting, both invoke the deep-seated magmatic processes necessary to generate the geochemical features observed in TTGs. Although many detailed studies have investigated the formation of Archaean TTG suites[11–18], little is known regarding the nature and petrogenesis of Earth's earliest (aged >3.9 Gyr) sialic crust and its relationship to continental crust formed later in Earth history (for example Archaean TTGs).

The Acasta Gneiss Complex (AGC), in northwestern Canada, contains the oldest known terrestrial rocks directly dated by zircon U–Pb isotope methods. The AGC comprises poly-deformed granitic to tonalitic and amphibolitic gneisses with igneous crystallization ages ranging from 4.03 to 3.40 Gyr (refs 19–22). Some units contain still older xenocrystic zircon cores up to 4.2 Gyr (refs 21,23). The various components of the AGC, like those of most ancient gneiss terranes, are typically interlayered at the decimetre to centimetre scale, making sampling of individual components difficult. Owing in part to their inherent complexity, very little whole-rock, major- and trace-element data has previously been reported for rocks of the AGC and, therefore, basic petrogenetic information is missing. Furthermore, rocks with crystallization ages >4.0 Gyr are rare and many of the exposed rock units have significantly younger crystallization ages (~3.8–3.6 Gyr; ref. 22). However, as part of a detailed mapping campaign we have identified, from a low strain zone of the AGC, a relatively homogeneous and mappable tonalitic gneiss unit yielding abundant well-preserved igneous zircons with a U–Pb crystallization age of 4.02 Gyr (see Supplementary Methods for a discussion of the zircon U–Pb systematics). We refer to this unit as the Idiwhaa ('ancient times' in the local aboriginal language) tonalitic gneiss (ITG). This unit affords a rare opportunity to investigate directly the processes responsible for forming pre-4.0 Gyr sialic crust. To elucidate the petrogenetic history of this earliest known sample of evolved crust, we conducted whole-rock major- and trace-element analyses of the unit as well as detailed zircon U–Pb geochronology, oxygen isotope and trace-element analyses by secondary ion mass spectrometry (SIMS).

The ITG is a relatively homogeneous mafic tonalite with small, cross-cutting leucocratic veins (Supplementary Fig. 3). The ITG consists primarily of plagioclase, quartz, hornblende, biotite and minor garnet. Whole-rock major-element compositions are characterized by intermediate levels of SiO_2 (57.9–66.9 wt.%), relatively low Al_2O_3 (13.8–14.1 wt.%), high total iron (8.6–15.3 wt.% $FeO_{(total)}$) and correspondingly low Mg-numbers ($100 \times MgO/(MgO + FeO) = 13–18$). The latter two characteristics are distinct from average Archaean TTGs (refs 12,13; 2.7 wt.% and 43, respectively)

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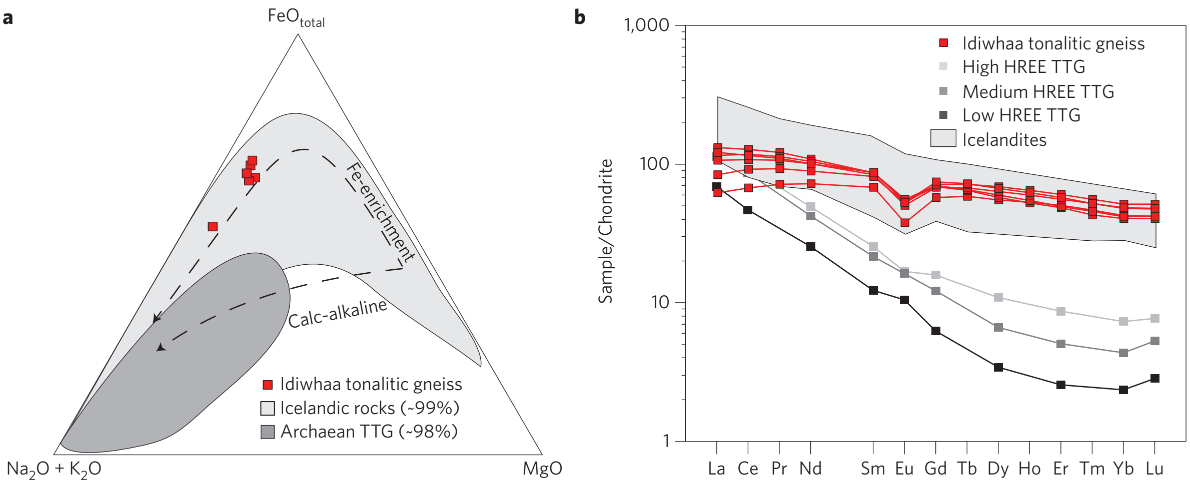

Figure 1 | Comparison of the whole-rock chemical compositions of the Idiwhaa tonalitic gneiss with Icelandic igneous rocks and Archaean TTGs. TTG data are from ref. 2, and Icelandic data are from the GEOROC database (http://georoc.mpch-mainz.gwdg.de/georoc/). **a**, Major-element compositions plotted on a standard alkali–iron–magnesium diagram. The fields shown for Icelandic rocks and Archaean TTGs include 99 and 98% of the 3,763 and 1,673 total analyses, respectively. **b**, Chondrite-normalized rare-earth element (REE) plot comparing Idiwhaa tonalite data to Archaean TTGs and icelandites. The field for icelandites was extracted from the larger Icelandic database (3,763 analyses) using: SiO_2 (55–65 wt.%), Al_2O_3 (<15 wt.%) and total FeO (>8 wt.%). This left a total of 90 ‘icelandite’ analyses, 37 containing rare-earth-element data plotted here.

and indicate magma evolution along an iron-enrichment trend (Fig. 1a). These geochemical characteristics can be produced by shallow-level fractional crystallization of a relatively reduced, low-H_2O basaltic magma in which the low-pressure mineral plagioclase is a major constituent of the fractionating assemblage (along with clinopyroxene and olivine) and Fe–Ti oxide crystallization is suppressed until late in the differentiation process[6,24].

The whole-rock trace-element systematics of the ITG are also markedly different from average Archaean TTGs (Fig. 1b and Supplementary Fig. 4). Unlike TTGs, the REE patterns of the ITG show little fractionation of light from heavy REEs and pronounced negative Eu anomalies. These features indicate, respectively, that garnet was not involved in magma genesis or evolution, but that plagioclase fractionation played a significant role. The high-field-strength elements Zr and Hf are also elevated in the ITG relative to Archaean TTGs (ref. 12; Supplementary Fig. 3).

Given the protracted post-magmatic history of rocks of the AGC (refs 20,22), it is important to evaluate whether the whole-rock trace-element composition of this unit faithfully reflects that of its igneous precursor. The refractory mineral zircon is useful in this regard because it is strongly resistant to compositional overprinting during post-magmatic processes[25]. Zircons extracted from one sample of the ITG, sample TC-3, are particularly well preserved and consist mainly of magmatic zircon with metamorphic overgrowths. There are two phases of magmatic zircon in the ITG that have identical U–Pb dates; unzoned cores (Phase I) and oscillatory-zoned mantles (Phase II). There are also two later phases involving either recrystallization of pre-existing zircon or new growth during metamorphism (Phases III and IV; Fig. 2a,b).

Phase I and II magmatic zircon, both of which record U–Pb ages of ~4.02 Gyr, have typical igneous zircon REE profiles that follow those predicted by equilibrium lattice strain models (Supplementary Fig. 10). Importantly, whole-rock REE profiles derived from the zircon REE data using published zircon-melt or zircon-whole-rock partition coefficients share all the key features of the measured ITG whole-rock profiles described above (Supplementary Fig. 11). This analysis confirms that igneous zircons present in the ITG were in magmatic equilibrium with a melt equivalent to the whole rock, and therefore provide a good estimate of the igneous crystallization age of the rock. It also confirms the validity of petrogenetic inferences drawn from the whole-rock trace-element data, namely shallow- rather than deep-level processes controlled the magmatic evolution of this unit.

Oxygen isotope data also provide important insights to the petrogenesis of the ITG, in particular the role of exogenic processes in magma evolution. Here, again, zircon has the capacity to provide the most robust indication of the primary oxygen isotope composition of the magma[25,26]. Phase I and II zircon growth zones are indistinguishable in terms of their U–Pb age but show a 0.8‰ difference in $\delta^{18}O_{VSMOW}$ values: Phase I zircon (CL-unzoned cores) has a weighted average $= +5.6 \pm 0.7$‰ (2 s.d.; $n = 62$), whereas Phase II (zoned mantles) $= +4.7 \pm 0.6$‰ (2 s.d.; $n = 66$) (Fig. 2c). The average $\delta^{18}O$ values of Phase I zircon are within the $+5.3 \pm 0.6$‰ range of zircon crystallized directly from a primary mantle melt[26]. In contrast, Phase II zircon has $\delta^{18}O$ values below +5‰, which requires that the parental magma either directly assimilated, or mixed with, partial melts of low-$\delta^{18}O$ rocks that had previously undergone relatively high-temperature hydrothermal alteration by surface waters[5,7,27,28]. Later metamorphic zircon overgrowths in the ITG (Phases III–IV) have $\delta^{18}O$ values above +6‰, indicating equilibration with metamorphic fluids enriched in ^{18}O (Fig. 2c). Although it appears some Phase I zircons have $\delta^{18}O$ values above the mantle zircon field (Fig. 2c), we attribute this to preferential alteration and partial resetting of the oxygen isotope systematics of a small subset of Phase I zircon by a later metamorphic fluid (see Supplementary Information for further discussion). The full oxygen isotope dataset for Phase I zircon has only a small portion of analyses outside of uncertainty of the mantle zircon field (Supplementary Fig. 12).

A petrogenetic model involving assimilation of low-$\delta^{18}O$ crust is consistent with the REE systematics of Phase I and II zircon growth zones in that the low-$\delta^{18}O$ Phase II igneous mantles have larger positive Ce anomalies than the unzoned cores (Supplementary Figs 8 and 9), suggesting the mantles crystallized under more oxidizing conditions than the cores[29]. Such a result would be expected if the assimilant comprised rocks that had interacted with surface waters.

The Jack Hills detrital zircons from Australia with U–Pb ages up to ~4.4 Gyr have $\delta^{18}O$ values higher than those of pristine mantle zircon[9], implying low-temperature interaction with surface waters in the Hadean. Although the ITG zircons indicate high-temperature, as opposed to low-temperature water-rock interactions, both

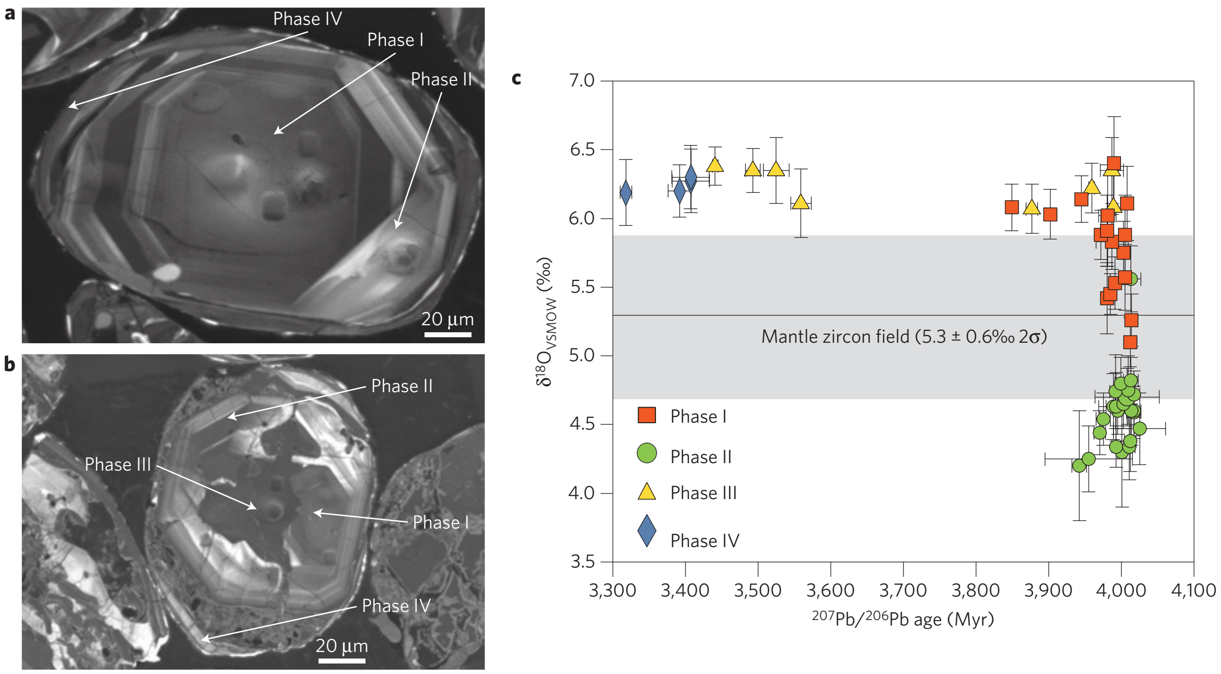

Figure 2 | Zircon phase relations and correlated zircon U–Pb and oxygen isotopic data from an Idiwhaa sample. a,**b**, Cathodoluminescence images of representative zircons in Idiwhaa tonalite sample TC-3, which show the zoning characteristics used to distinguish different phases of zircon growth. Phase I growth zones represent unzoned igneous cores. Phase II comprises fine-scale oscillatory-zoned igneous zircon, which commonly conformably overgrows Phase I zircon. Phase III growth dominantly occurs as dark metamorphic incursions grown into all earlier phases. Phase IV growth consists of metamorphic rims overgrowing all phases. **c**, Plot of $\delta^{18}O$ values (reported relative to Vienna-Standard Mean Ocean Water, VSMOW) versus $^{207}Pb/^{206}Pb$ for various zircon growth phases. The field for mantle zircon is from ref. 26. Uncertainties on all data points are shown at the 95% confidence level.

indicate the existence of a pre-4.0 Gyr hydrosphere on Earth. Cerium anomalies in the Australian detrital zircons[29] and ITG zircons also indicate similar magmatic oxidation states.

Although distinct from later-formed Archaean TTGs as well as igneous rocks from many modern-day tectonic settings, the geochemical features of the ITG are nearly identical to those of some intermediate rocks from Iceland (Fig. 1). In particular, a suite of rocks commonly referred to as icelandites are characterized by ~60 wt.% SiO_2, low Al_2O_3, high FeO, and low Mg-numbers[4,6]. These rocks also share many of the trace-element features of the ITG, including negative Eu anomalies, little fractionation of LREE from HREE (Fig. 1b), and elevated concentrations of high-field-strength elements (Supplementary Fig. 4).

Icelandites are thought to result from some combination of low-pressure fractional crystallization of basaltic magma, hybridization of mafic and silicic magmas, and assimilation of hydrothermally altered, low-^{18}O crust[4–7]. The latter process lowers the primary $\delta^{18}O$ values of some icelandite magmas to below pristine mantle values (+5.5 ± 0.5‰; ref. 26). In this regard, low-^{18}O magmatic rocks are relatively rare worldwide and have most commonly been documented in rift- or plume-related settings (for example, Iceland, Yellowstone, Hawaii, Skye) in which the shallow-level intrusion of hot, dry magma has produced high geothermal gradients and in turn driven hydrothermal circulation cells above the magma chambers[5,27,28,30].

A number of plausible tectonic scenarios have been suggested for forming sialic crust on the early Earth. We have documented the need for shallow-level fractionation of basaltic magma and assimilation of hydrothermally altered crust to generate the observed geochemical characteristics of the ~4.02 Gyr-old ITG. On the modern Earth, zones of mantle upwelling, such as plumes, rifts and ocean ridges, create the necessary conditions for generation of evolved rocks similar to the ITG. Rift- and ridge-related settings, however, produce only a very small proportion of such rocks. In contrast, the combined thermal effects of the mid-Atlantic Ridge and a mantle plume, as well as a high degree of hydrothermal activity, has produced in Iceland a crustal thickness approaching that of typical continental crust[1], as well as a larger proportion of intermediate and felsic composition rocks (~25%; ref. 2) than in ocean ridges and other oceanic plateaux. The greater thickness and buoyancy of Icelandic-type crust makes it less susceptible to recycling back into the mantle, either in subduction zones or some other form of mantle downwelling. Therefore, we suggest that a setting similar to modern Iceland, where mantle upwelling creates a thickened plateau with a relatively high proportion of evolved rocks, would be most likely to form and preserve the ITG unit (Fig. 3).

Although the formation of Earth's earliest continental crust in an Iceland-like setting has been suggested on theoretical grounds[3], no direct geological evidence supporting this hypothesis has previously been available[8]. The data presented here indicate that the oldest known sialic rock unit bears the geochemical fingerprints of shallow-level magmatic and hydrothermal processes involved in the formation of evolved Icelandic rocks. Thus, we propose that such a setting on the early Earth may have generated an analogous proto-continental crust that was sufficiently thick and buoyant to avoid later recycling into the mantle. Notably, owing to Earth's higher heat production at 4 Gyr, the confluence of a mantle plume and an ocean ridge, such as is present in modern Iceland, may not have been necessary to generate Iceland-like crust. Rather, any long-lived mantle upwelling in a planet with an operating hydrosphere may have been capable of producing the requisite conditions for formation of this type of crust. Once formed, these small continental nuclei may have served as the substrate for later, deeper-seated TTG magmatism.

Data reported here are presented in Supplementary Tables 1–8.

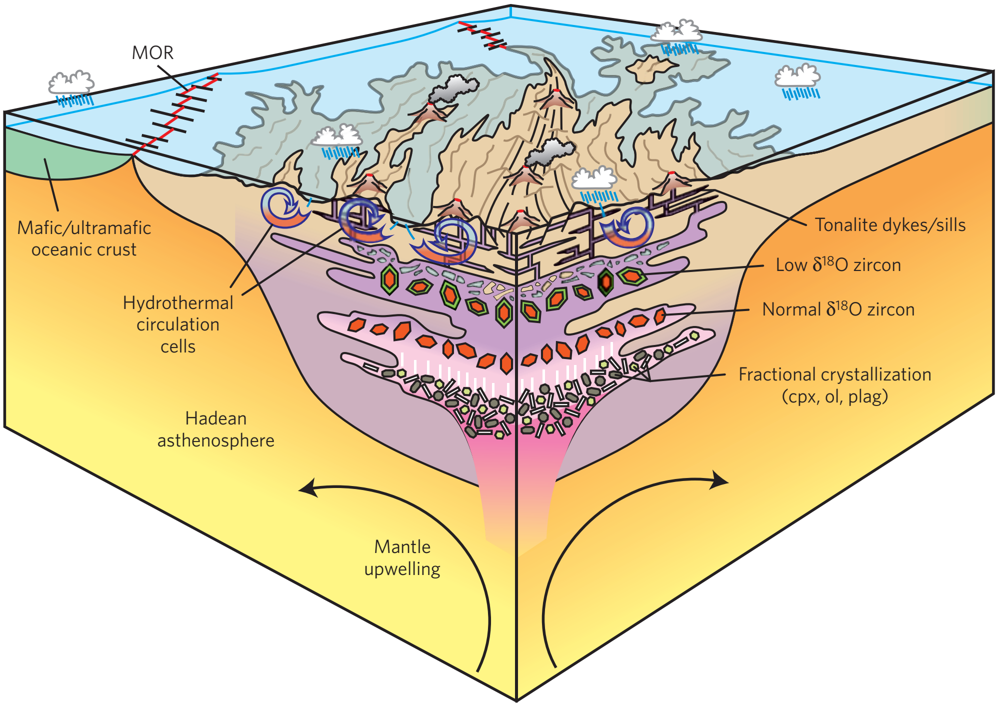

Figure 3 | Schematic diagram illustrating the major processes responsible for the formation of the Idiwhaa tonalitic gneiss. Basaltic melts are fractionated at shallow crustal levels to produce Fe-enriched intermediate magmas. These magmas initially crystallize zircon with mantle-like δ^{18}O values. Assimilation of overlying rocks that have been hydrothermally altered by surface waters lowers the δ^{18}O values of later-stage magmas and in turn produces magmatic zircon rims that have δ^{18}O values lower than those of the mantle (+5‰). All the aforementioned processes have been documented in modern-day Iceland, suggesting that Earth's earliest known sialic crust may have formed in an Iceland-like tectonic setting. MOR, mid-ocean ridge; cpx, clinopyroxene; ol, olivine; plag, plagioclase.

Received 24 September 2013; accepted 16 April 2014; published online 25 May 2014

References

1. Allen, R. M. *et al.* Plume-driven plumbing and crustal formation in Iceland. *J. Geophys. Res.* **107,** 1–19 (2002).
2. Jakobsson, S. P., Jonasson, K. & Sigurdsson, I. A. The three igneous rocks series of Iceland. *Jokull* **58,** 117–138 (2008).
3. Kroner, A. Evolution of the Archean continental crust. *Ann. Rev. Earth Planet. Sci.* **13,** 49–74 (1982).
4. Carmichael, I. S. E. The petrology of Thingmuli, a tertiary volcano in eastern Iceland. *J. Petrol* **5,** 435–460 (1964).
5. Muehlenbachs, K., Anderson, A. T. & Sigvaldason, G. E. Low-O^{18} basalts from Iceland. *Geochim. Cosmochim. Acta* **38,** 577–588 (1974).
6. Nicholson, H. *et al.* Geochemical and isotopic evidence for crustal assimilation beneath Krafla, Iceland. *J. Petrol.* **32,** 1005–1020 (1991).
7. Bindeman, I. N. *et al.* Silicic magma petrogenesis in Iceland by remelting of hydrothermally altered crust based on oxygen isotope diversity and disequilibria between zircon and magma with implications for MORB. *Terra Nova* **24,** 227–232 (2012).
8. Martin, E., Martin, H. & Sigmarsson, O. Could Iceland be a modern analogue for the Earth's early continental crust? *Terra Nova* **20,** 463–468 (2008).
9. Harrison, T. M. The Hadean crust: Evidence from >4 Ga zircons. *Annu. Rev. Earth Planet. Sci.* **37,** 479–505 (2009).
10. Condie, K. in *Earth's Oldest Rocks* Vol. 15 (eds Van Kranendonk, R., Smithies, H. & Bennett, V. C.) 9–18 (Developments in Precambrian Geology, 2007).
11. Barker, F. & Arth, J. G. Generation of trondhjemitic-tonalitic liquids and Archean bimodal trondhjemite-basalt suites. *Geology* **4,** 596–600 (1976).
12. Moyen, J. F. The composite Archaean grey gneisses: Petrological significance, and evidence for a non-unique tectonic setting for Archaean crustal growth. *Lithos* **123,** 21–36 (2011).
13. Moyen, J. F. & Martin, H. Forty years of TTG research. *Lithos* **148,** 312–336 (2012).
14. Martin, H. Effect of steeper Archean geothermal gradient on geochemistry of subduction-zone magmas. *Geology* **14,** 753–756 (1986).
15. Rapp, R. P., Watson, E. B. & Miller, C. F. Partial melting of amphibolite/eclogite and the origin of Archean trondhjemites and tonalities. *Precambr. Res.* **51,** 1–25 (1991).
16. Nair, R. & Chacko, T. Role of oceanic plateaus in initiation of subduction and origin of continental crust. *Geology* **36,** 583–586 (2008).
17. Smithies, R. H., Champion, D. C. & Van Kranendonk, M. J. Formation of Paleoarchean continental crust through infracrustal melting of enriched basalt. *Earth Plant. Sci. Lett.* **281,** 298–306 (2009).
18. Zegers, T. E. & van Keken, P. E. Middle Archean continent formation by crustal delamination. *Geology* **29,** 1083–1086 (2001).
19. Bowring, S. A., Williams, I. S. & Compston, W. 3.96 Ga gneisses from the Slave province, Northwest Territories, Canada. *Geology* **17,** 971–975 (1989).
20. Stern, R. A. & Bleeker, W. Age of the world's oldest rocks refined using Canada's SHRIMP: The Acasta Gneiss Complex, Northwest Territories, Canada. *Geosci. Can.* **25,** 27–31 (1998).
21. Bowring, S. A. & Williams, I. S. Priscoan (4.00–4.03 Ga) orthogneisses from northwestern Canada. *Contrib. Min. Petrol.* **134,** 3–16 (1999).
22. Iizuka, T. *et al.* Geology and zircon geochronology of the Acasta Gneiss Complex, northwestern Canada: New constraints on its tectonothermal history. *Precambr. Res.* **153,** 179–208 (2007).
23. Iizuka, T. *et al.* 42 Ga zircon xenocryst in an Acasta gneiss from northwestern Canada: Evidence for early continental crust. *Geology* **34,** 245–248 (2006).
24. Grove, T. L. & Kinzler, R. J. Petrogenesis of Andesites. *Ann. Rev. Earth Planet. Sci. Lett.* **14,** 417–454 (1986).
25. Page, F. Z. *et al.* High-precision oxygen isotope analysis of picogram samples reveals 2 μm gradients and slow diffusion in zircon. *Am. Mineral.* **92,** 1772–1775 (2007).
26. Valley, J. W. *et al.* Zircon megacrysts from kimberlite: Oxygen isotope variability among mantle melts. *Contrib. Min. Petrol.* **133,** 1–11 (1998).
27. Taylor, H. P. & Sheppard, S. M. F. Igneous Rocks: I Processes of isotopic fractionation and isotope systematics. *Rev. Min. Geochem.* **16,** 227–271 (1986).
28. Bindeman, I. N. & Valley, J. W. Low-δ^{18}O Rhyolites from Yellowstone: Magmatic evolution based on analyses of zircons and individual phenocrysts. *J. Petrol.* **42,** 1491–1517 (2001).

29. Trail, D., Watson, E. B. & Tailby, N. D. The oxidation state of Hadean magmas and the implications for the early Earth's atmosphere. *Nature* **480,** 79–83 (2011).
30. Balsley, S. D. & Gregory, R. T. Low-^{18}O silicic magmas: Why are they so rare? *Earth Planet. Sci. Lett.* **162,** 123–136 (1998).

Acknowledgements

We thank R. Ickert and A. Burnham for advice on zircon strain partition modelling; J. Davies for critical discussions throughout; J. Ketchum and the Northwest Territories Geoscience Office staff for scientific and field support; and E. Thiessen for mapping assistance. We thank T. Iizuka and T. Kemp for constructive and informative reviews. This research was funded by National Science and Engineering Research Council of Canada grants to T.C. and L.M.H. as well as a Circumpolar/Boreal Alberta Research grant for fieldwork to J.R.R.

Author contributions

Mapping and sample collection was conducted by J.R.R. and T.C. Sample crushing, processing, and zircon separations were carried out by J.R.R. R.A.S. and J.R.R. carried out collection of zircon oxygen and U–Th–Pb isotopic data by SIMS. Chemical abrasion of zircon was carried out by J.R.R. and L.M.H. All authors contributed to discussion of results and their implications, as well as preparation of the manuscript.

Additional information

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Competing financial interests

The authors declare no competing financial interests.