LETTERS

Origin of a 'Southern Hemisphere' geochemical signature in the Arctic upper mantle

Steven L. Goldstein[1,2], Gad Soffer[1,2]†, Charles H. Langmuir[3], Kerstin A. Lehnert[1], David W. Graham[4] & Peter J. Michael[5]

The Gakkel ridge, which extends under the Arctic ice cap for ~1,800 km, is the slowest spreading ocean ridge on Earth. Its spreading created the Eurasian basin, which is isolated from the rest of the oceanic mantle by North America, Eurasia and the Lomonosov ridge. The Gakkel ridge thus provides unique opportunities to investigate the composition of the sub-Arctic mantle and mantle heterogeneity and melting at the lower limits of sea-floor spreading. The first results of the 2001 Arctic Mid-Ocean Ridge Expedition (ref. 1) divided the Gakkel ridge into three tectonic segments, composed of robust western and eastern volcanic zones separated by a 'sparsely magmatic zone'. On the basis of Sr–Nd–Pb isotope ratios and trace elements in basalts from the spreading axis, we show that the sparsely magmatic zone contains an abrupt mantle compositional boundary. Basalts to the west of the boundary display affinities to the Southern Hemisphere 'Dupal' isotopic province[2], whereas those to the east—closest to the Eurasian continent and where the spreading rate is slowest—display affinities to 'Northern Hemisphere' ridges. The western zone is the only known spreading ridge outside the Southern Hemisphere that samples a significant upper-mantle region with Dupal-like characteristics. Although the cause of Dupal mantle has been long debated, we show that the source of this signature beneath the western Gakkel ridge was subcontinental lithospheric mantle that delaminated and became integrated into the convecting Arctic asthenosphere. This occurred as North Atlantic mantle propagated north into the Arctic during the separation of Svalbard and Greenland.

The Gakkel ridge is the global ultraslow endmember among ocean ridges, with spreading rates decreasing from ~15 mm yr^{-1} (full rate) at the Lena trough near Greenland to ~6 mm yr^{-1} at the Siberian margin. It contains no significant transform offsets, which on other ridges often form mantle flow and mantle compositional boundaries. It thus provides a natural laboratory in which to study source heterogeneity and melting dynamics at ultraslow spreading rates, and where potential complications from tectonic offsets are absent. Here we report isotope and trace element data on basaltic glasses that document the Arctic mantle composition and processes contributing to its enrichment.

Prior to the 2001 Arctic Mid-Ocean Ridge Expedition, data on Gakkel lavas were restricted to three samples of basaltic cobbles and glass shards recovered on two cruises[3]. The Arctic Mid-Ocean Ridge Expedition collected samples from the western ~850 km of the ridge between longitudes 7° W and 86° E at over 200 stations. Michael et al.[1] divided the studied segments into three 'magmato-tectonic zones': the ~200-km-long, shallow, magmatically robust western volcanic zone (WVZ), characterized by normal ocean-ridge-rift

magmatism; the ~300-km-long, deep, magma-starved sparsely magmatic zone (SMZ) with peridotite outcropping along the ridge axis; and the ~400-km-long, magmatically robust eastern volcanic zone (EVZ), where axial magmatism is mainly associated with central volcanoes. On the basis of cruise chemical data, Michael et al.[1] inferred compositionally distinct mantle beneath the WVZ and the EVZ, with marked barium enrichments in WVZ lavas. Dick et al.[4] compared the broad-scale tectonic features of the Gakkel and southwest Indian ridges and posited the existence of a new class of ultraslow-spreading ocean ridge, where 'amagmatic' segments like the SMZ are a consequence of spreading rates less than ~12 mm yr^{-1}, and are thus independent of mantle composition.

Our data confirm fundamental differences in the upper-mantle sources of WVZ and EMZ lavas (locations and data tables can be found in the Supplementary Information). The fields formed by Nd–Sr isotopes of EVZ and WVZ lavas show no overlap (Fig. 1a), and samples from the western and eastern parts of the SMZ show affinities to the adjacent EVZ and WVZ. EVZ lavas have higher ^{143}Nd/^{144}Nd values than do WVZ lavas and lower ^{87}Sr/^{86}Sr values than does any mid-ocean-ridge basalt (MORB) north of Iceland.

The contrasting WVZ and EVZ mantle compositions are shown in Fig. 1b in terms of Δ8/4 (ref. 2), which reflects deviations from typical compositions of Pacific and Atlantic MORB on ^{208}Pb/^{204}Pb–^{206}Pb/^{204}Pb diagrams. The disparities also show in along-axis plots of the other radiogenic isotopes (see, for example, Supplementary Fig. 1a). West of the boundary virtually all Gakkel lavas have Δ8/4 > 30; this was shown by Hart[2] to be a primary feature of the Southern Hemisphere 'Dupal isotope anomaly' in Indian and some South Atlantic MORB. The Dupal-like character of the WVZ is further illustrated by comparison with global MORB: ^{208}Pb/^{204}Pb–^{206}Pb/^{204}Pb data for WVZ basalts lie in the field of Indian MORB (Fig 2a; Supplementary Fig. 2a). WVZ lavas also show a near-vertical trend in a ^{87}Sr/^{86}Sr–^{206}Pb/^{204}Pb diagram, reflecting a large range of ^{87}Sr/^{86}Sr values, typical of Indian MORB, whereas EVZ lavas show a shallow trend similar to that of Atlantic–Pacific basalts (Fig. 2b). Additional evidence of the WVZ's Dupal-like character is given in Supplementary Information (Supplementary Fig. 3).

Gakkel WVZ lavas, however, differ from Southern Hemisphere Dupal basalts, in that they have low Δ7/4 values[2]; their data lie near Atlantic–Pacific basalts on this diagram (Supplementary Fig. 2b). The ^{207}Pb/^{204}Pb–^{206}Pb/^{204}Pb relationships are temporal rather than a result of the formation process, because they depend primarily on the timing of major U–Pb fractionation, whereas Δ8/4 reflects the chemical composition (Th/U) and the formation age. Oceanic basalts with enriched isotopic signatures (high Sr and low Nd and Hf isotope ratios, and high Δ8/4 values) are associated with both high and low

[1]Lamont-Doherty Earth Observatory of Columbia University, [2]Department of Earth and Environmental Sciences, Columbia University, 61 Route 9W, Palisades, New York 10964, USA. [3]Department of Earth and Planetary Sciences, Harvard University, 20 Oxford Street, Cambridge, Massachusetts 02138, USA. [4]College of Ocean and Atmospheric Sciences, Oregon State University, Corvallis, Oregon 97331, USA. [5]Department of Geosciences, University of Tulsa, 600 South College Avenue Tulsa, Oklahoma 74104, USA. †Present address: Harvard Business School, Soldiers Field, Boston, Massachusetts 02163, USA.

Δ7/4 values (ref. 5), reflecting old and young formation ages, respectively. The Gakkel data thus indicate that the formation of the Arctic Dupal-like source was more recent than that of the Southern Hemisphere Dupal basalts. Although the formation ages differ, chemical characteristics are similar: like Indian MORB, the high Δ8/4 and $^{87}Sr/^{86}Sr$ values reflect high time-integrated Th/U and Rb/Sr values for the Pb and Sr in the lavas, indicating the distinctive chemical compositions of reservoirs responsible for Dupal features.

A striking feature of the Gakkel ridge is the abruptness of the isotopic boundary and its location in the middle of the SMZ (Fig. 1b; Supplementary Fig. 1a). The discontinuity is reminiscent of the Australian–Antarctic discordance of the southeast Indian ridge, which demarcates the boundary between the Indian Dupal and Pacific mantle provinces[5]. Common features include great
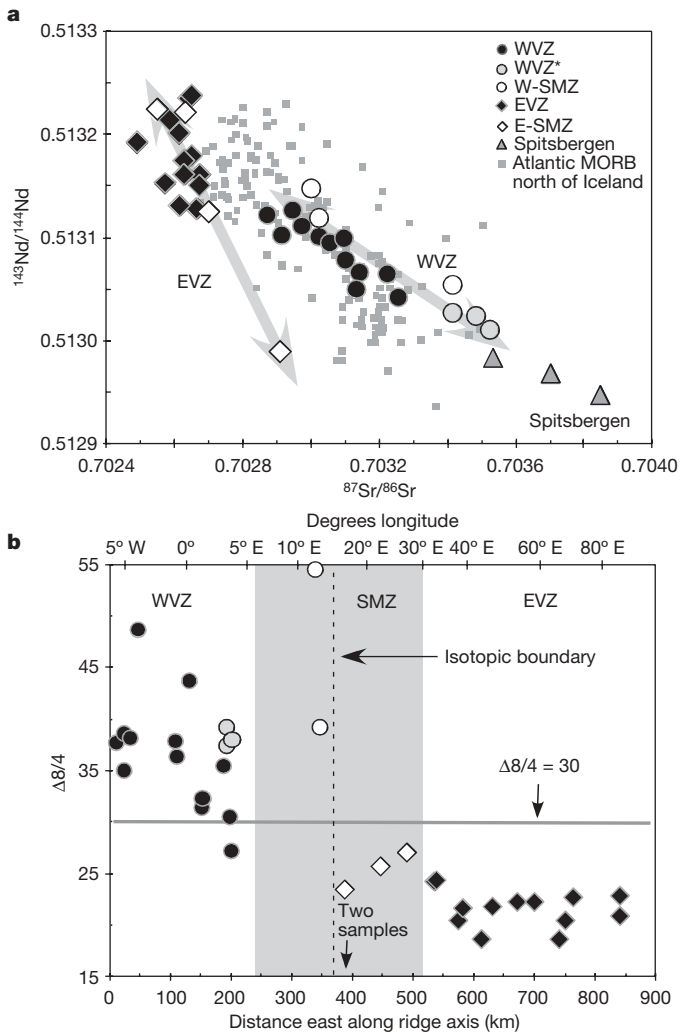
bathymetric depths and low magma production, as reflected by the basaltic crust being thin in comparison with that of adjoining segments. These indicate close relationships between seafloor structure, bathymetry and mantle convective processes. However, the Gakkel SMZ, unlike the Australian–Antarctic discordance, is not associated with any significant ridge offset. Along a continuously spreading ridge, lavas with isotopic affinities to the WVZ or EVZ were collected within 40 km of each other at longitudes 12.7° E and 16.0° E. The Gakkel SMZ data thus indicate a sharp geochemical boundary in the absence of any tectonic boundary. The Knipovich ridge to the southwest of the Gakkel ridge is also isotopically distinct from the WVZ (see, for example, Supplementary Figs 1b, 2a and 3a), but these ridges are separated by a 600 km offset. The marked change in the magmato-tectonic character at the Gakkel SMZ is therefore not simply a tectonic reflection of ultraslow seafloor spreading, as proposed by Dick et al.[4], but reflects a mantle compositional and convective boundary.

Comparison with global MORB (Fig. 2) shows that the Pb–Sr–Nd isotope variations in this small Arctic region mimic the global upper-mantle variability. The Gakkel ridge is far from the Indian Ocean. Although enriched MORBs are found along North Atlantic ridges
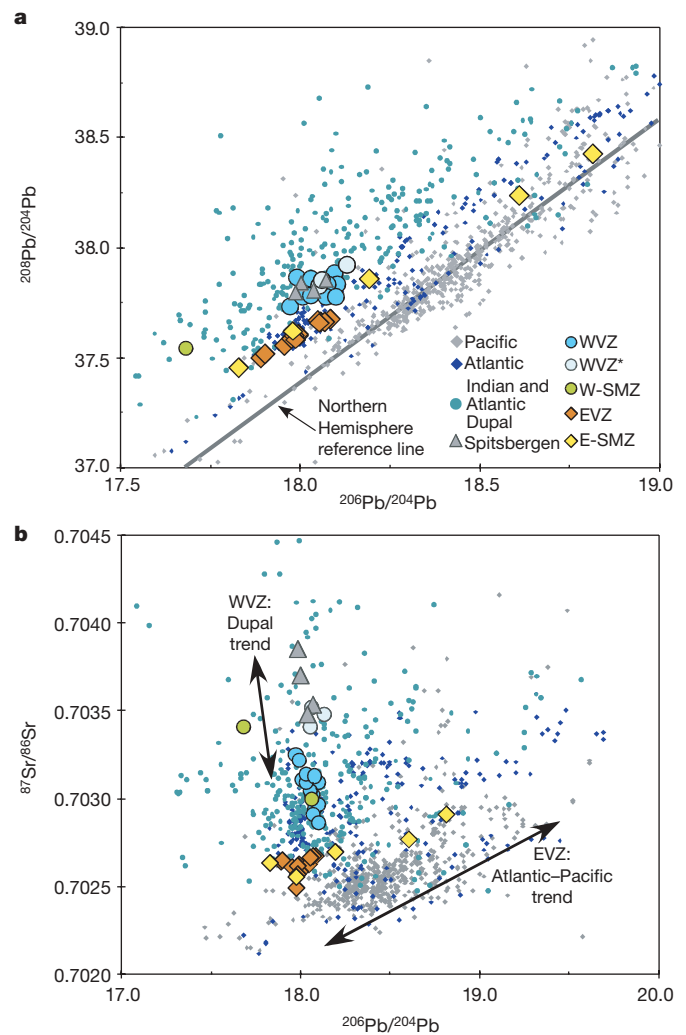

Figure 1 | Distinct western and eastern geochemical provinces in Gakkel ridge basalts. a, $^{143}Nd/^{144}Nd$ versus $^{87}Sr/^{86}Sr$. Data fields for EVZ and WVZ lavas do not overlap. WVZ lava data points overlap with those for Atlantic MORBs north of Iceland and display a trend towards those for Spitsbergen Quaternary-period alkaline basalts. SMZ lavas show affinities to those in the adjacent WVZ and EVZ. W-SMZ and E-SMZ refer to lavas in the SMZ having isotopic affinities to the WVZ and EVZ, respectively. **b**, Δ8/4 (representing deviations from the Northern Hemisphere reference line[2]) versus distance from the western end of the Gakkel ridge near Greenland. (The key is the same as that in **a**.) This shows the distinct WVZ and EVZ compositions and the position and abruptness of the isotopic boundary. Three samples, labelled WVZ*, from near the WVZ–SMZ boundary have unusual chemistry (low SiO_2 and incompatible element abundances, and positive Eu and Sr anomalies on trace element diagrams) and follow the WVZ isotope trend (**a**) but not the WVZ chemical trends (Fig. 3).

Figure 2 | Gakkel basalts as a microcosm of global MORBs. a, $^{208}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$. WVZ and Spitsbergen lavas show the characteristic Dupal MORB offset to high $^{208}Pb/^{204}Pb$. Global MORB data are from the Petrological Database of the Ocean Floor (www.petdb.org). **b**, $^{87}Sr/^{86}Sr$ versus $^{206}Pb/^{204}Pb$. (The key is the same as that in **a**.) EVZ lavas display a trend similar to that of Atlantic-Pacific MORBs, whereas WVZ MORBs display a near-vertical trend similar to Indian and South Atlantic MORBS showing the Dupal anomaly. The WVZ data points display a trend towards those for Spitsbergen lavas.
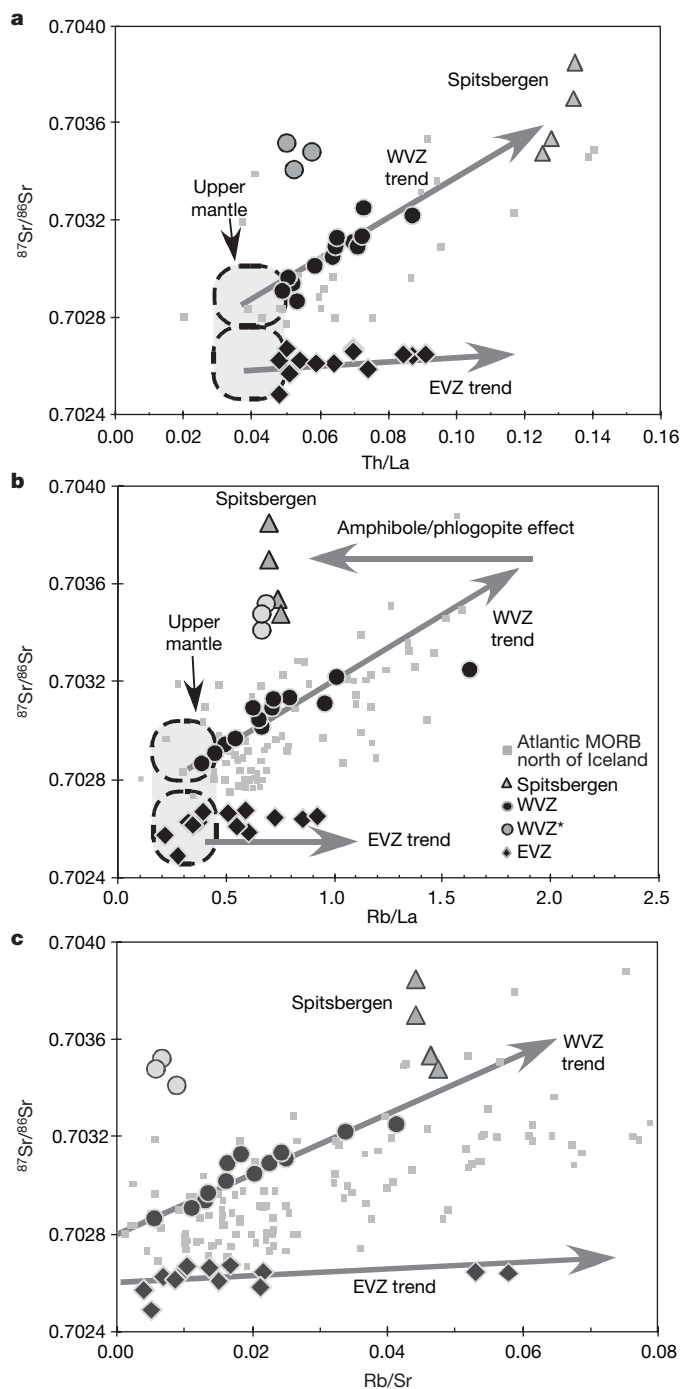
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Figure 3 | Gakkel ridge and Spitsbergen basalts. a, $^{87}Sr/^{86}Sr$ versus Th/La. (The key is the same as that in **b**.) WVZ and EVZ lavas form distinct trends. WVZ data points display a trend towards those for Spitsbergen, indicating that the Spitsbergen magma source is the enriched WVZ endmember. **b,** $^{87}Sr/^{86}Sr$ versus Rb/La. WVZ and EVZ lavas display distinct trends. Spitsbergen lava data points lie away from the WVZ trend, with low Rb/La values (and Ba/La values, not shown), which is consistent with partial melting in the presence of residual amphibole and/or phlogopite, and indicates a SCLM source. **c,** $^{87}Sr/^{86}Sr$ versus Rb/Sr. (The key is the same as that in **b**.) The Sr isotope ratios are distinct for the WVZ and EVZ even when Rb/Sr = 0. In **a** and **b**, for low Th/La and Rb/La values corresponding to depleted mantle composition estimates[32,33] (labelled 'upper mantle'), the WVZ and EVZ Sr isotope ratios also are different. In all three panels, 'depleted' WVZ compositions are consistent with Atlantic MORBs from north of Iceland, but EVZ compositions are distinct. MORB data are taken from the Petrological Database of the Ocean Floor.

even far from hotspots[6,7], the WVZ is unique among North Atlantic MORB, with Dupal characteristics dominating along ~350 km of the spreading axis. Their occurrence in Arctic MORB shows that Dupal characteristics are not simply an attribute of the Indian–South Atlantic oceanic mantle, but reflect processes that are more general.

The small geographical scale and well-understood tectonic history of the Eurasian basin affords opportunities to explore how the Dupal signature is created. Quaternary alkaline basalts ranging from hawaiites to nephelinitic basanites in northwestern Spitsbergen have been attributed to low-degree melting of subcontinental lithospheric mantle (SCLM)[8–10], and form an enriched endmember for WVZ lavas in isotope plots (Figs 1a and 2). This relationship also holds for trace elements that are highly incompatible for melting of both anhydrous and metasomatized mantle mineral assemblages, where abundance ratios in lavas are almost the same as in the mantle source (shown for $^{87}Sr/^{86}Sr$ versus Th/La and U/La in Fig. 3a and Supplementary Fig. 4a, respectively). The trace elements and isotopes together strongly indicate that the component causing the Dupal-like characteristics is also the source of Spitsbergen alkaline basalts.

Insight into the mineral assemblage of the Spitsbergen magma source can be gleaned from the comparison of elements more compatible in amphibole or phlogopite (such as Rb, Ba and K) with other elements unaffected by amphibole or phlogopite (such as Th, U and La). In plots of $^{87}Sr/^{86}Sr$ versus Rb/La (Fig. 3b) and Ba/Th (Supplementary Fig. 4b), Spitsbergen lavas deviate from the WVZ trend at low values of Rb/La and Ba/Th , respectively; however, they are not offset in plots involving Th, U and La. Such chemical behaviour indicates the presence of amphibole or phlogopite among the residual minerals[11,12]. Spitsbergen lavas include olivine, titanaugite and plagioclase, but no amphibole or phlogopite[8]. Because these phases are unstable at asthenospheric temperatures[12,13], the data require an SCLM source for Spitsbergen lavas. Subsequent asthenospheric melting beneath the Gakkel ridge would then release the Rb and Ba, leading to the relative enrichments of these elements in the lavas of the WVZ.

The data offer insight into the long-term history of the Gakkel asthenosphere. A Rb–Sr 'pseudo-isochron' plot (Fig. 3c) shows that the WVZ mantle least contaminated by SCLM is distinct from the EVZ mantle, because their respective $^{87}Sr/^{86}Sr$ values differ when Rb/Sr = 0. This WVZ–EVZ offset is further confirmed by comparing isotopes and trace elements (Fig. 3a, b and Supplementary Fig. 4). The 'least contaminated' WVZ lavas are similar to Atlantic MORB north of Iceland, in terms of Nd–Sr isotopes and combined isotopes and trace elements (Figs 1 and 3 and Supplementary Fig. 4), whereas the EVZ basalts are distinct from both groups. These observations suggest that WVZ isotopic relationships can be explained by the addition of Spitsbergen SCLM to the North Atlantic asthenosphere, and that the WVZ and EVZ are distinct mantle provinces. The Gakkel SMZ thus bounds distinct upper-mantle regions that have experienced long-term convective isolation.

The introduction of the Svalbard SCLM to the WVZ asthenosphere, the leakage of North Atlantic mantle into the Arctic, and the formation of the boundary can be understood in the context of Arctic tectonic history (Fig. 4). The Eurasian and Atlantic oceans were separated by continent when seafloor spreading began in the Arctic and North Atlantic 55–60 million years (Myr) ago[14]. During the early Oligocene epoch ~34 Myr ago, Greenland and Norway–Svalbard began to separate, accompanied by northwards propagation of North Atlantic ridges, with linkage of the Arctic and North Atlantic occurring ~10 Myr ago. Our data suggest that North Atlantic mantle flowed into the Arctic, accompanied by delamination and dispersal of the Svalbard SCLM. Whether this was simply a consequence of rifting or was facilitated by thermal erosion caused by an Arctic hotspot is beyond the scope of this work (a hotspot has been postulated to be responsible for the Yermak plateau (Fig. 4c), but its existence is disputed[15]). In any case, the Gakkel SMZ appears to be the surface
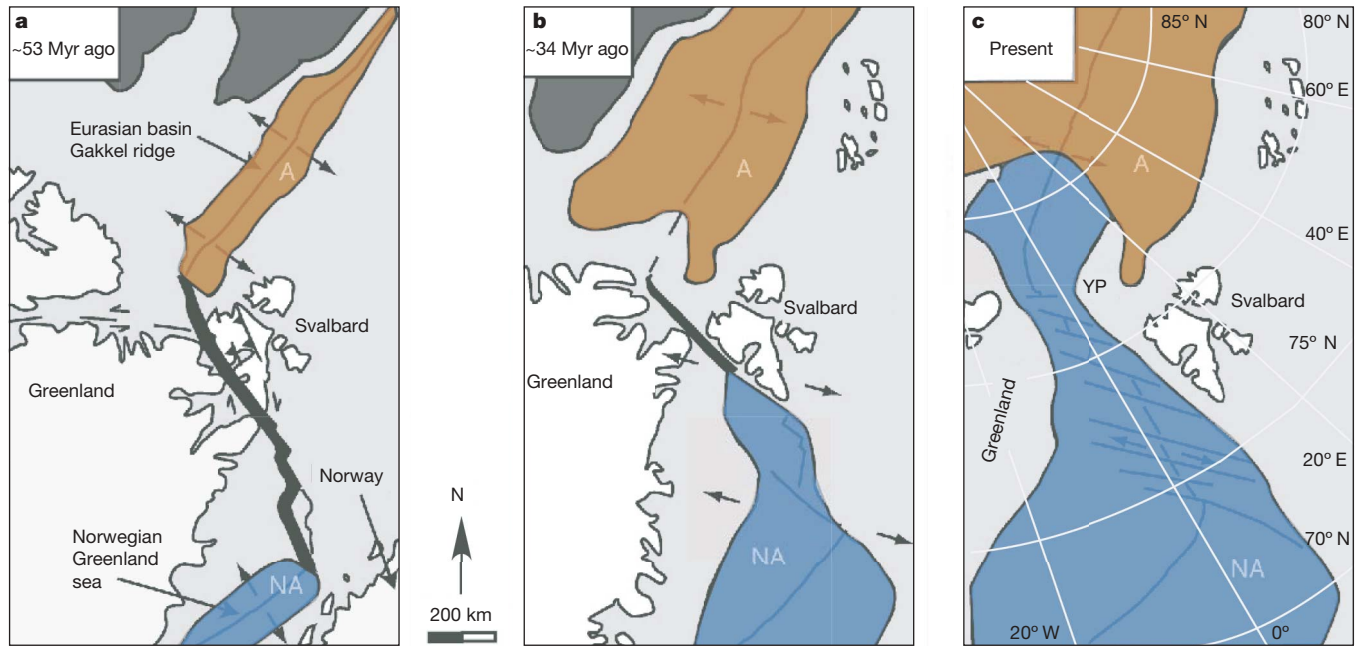
Figure 4 | Cenozoic-era evolution of the Arctic upper mantle.
a, Approximately 53 Myr ago, the nascent Eurasian basin, underlain by
'Arctic' upper mantle (labelled 'A') as sampled today in the EVZ, was
separated from the North Atlantic ridges (labelled 'NA') by a continent.
b, During the Cenozoic, the Eurasian basin continued to widen, and the
North Atlantic ridges propagated north, with Greenland and Svalbard
separating ~10 Myr ago. **c**, Present-day situation based on the Gakkel data,
with the boundary between the North Atlantic and Arctic upper-mantle
provinces well within the Eurasian basin, in the middle of the SMZ. 'YP'
labels the Yermak plateau, near the WVZ. Images modified from Blythe and
Kleinspehn[14].

manifestation of a physical boundary within the mantle where the
linkage occurred.

The origin of the Southern Hemisphere Dupal signature is an
ongoing debate in mantle dynamics, and a recent summary high-
lights inadequacies of postulated models[16]. Explanations[16–28] include
upwelling of a thermal anomaly from the core–mantle boundary;
contamination of sub-Indian mantle by the Kerguelen plume;
mantle modification by subduction surrounding Gondwana; ancient
subduction of altered oceanic crust and sediment; recycled lower-
continental or arc crust; and detachment of SCLM during contin-
ental break-up. Hybrid scenarios invoke both subduction and
lithosphere delamination[29–31]. It has been suggested that SCLM dela-
mination would impart 'too low' an osmium isotope signature to
MORB[26,27], but this depends on the age of the recycled SCLM. The
combined Gakkel and Spitsbergen data and the well-constrained
Arctic tectonic history provide relationships where the geochemistry
and tectonics are in remarkable accord.

In summary, the Gakkel ridge is an ultraslow-spreading ridge sur-
rounded by continental lithosphere, with clear evidence of regional
SCLM contributing a Dupal geochemical signature to the astheno-
spheric mantle. Unlike in other regions on Earth, we have the strong
evidence of Spitsbergen volcanics, with the requisite isotopic com-
positions to be the Gakkel endmember, and a source mineralogy
definitively indicating SCLM melting. The process documented
in the Arctic is chemically and geologically feasible and probably
plays an important role in generating chemical heterogeneity along
the mid-ocean ridge system. Dupal signatures globally may have
multiple sources; nevertheless, the migrating continents that have
traversed the Indian Ocean basin, where Dupal characteristics occur
on a large scale, would generate substantial opportunities for analog-
ous SCLM contributions to the sub-Indian Ocean mantle.

METHODS SUMMARY

All analyses were made on hand-picked basaltic glasses. Major elements were
measured on a Cameca electron microprobe at the American Museum of Natural
History, operated as a joint facility with the Lamont-Doherty Earth Observatory

of Columbia University (LDEO). Trace elements were measured using a Plasma
Quad 2 inductively coupled plasma mass spectrometer at LDEO or a Thermo
Electron X-series inductively coupled plasma mass spectrometer at Harvard. Pb,
Nd and Sr isotope ratios were measured using a VG Sector 54 multicollector
thermal ionization mass spectrometer at LDEO.

Full Methods and any associated references are available in the online version of
the paper at www.nature.com/nature.

1. Michael, P. J. et al. Magmatic and amagmatic seafloor generation at the ultraslow-
    spreading Gakkel ridge, Arctic Ocean. *Nature* **423**, 956–961 (2003).
2. Hart, S. R. A large-scale isotopic anomaly in the Southern Hemisphere mantle.
    Nature **309**, 753–757 (1984).
3. Mühe, R., Bohrmann, H., Garbe-Schönberg, D. & Kassens, H. E-MORB glasses
    from the Gakkel Ridge (Arctic Ocean) at 87°N: evidence for the Earth's most
    northerly volcanic activity. *Earth Planet. Sci. Lett.* **152**, 1–9 (1997).
4. Dick, H. J. B., Lin, J. & Schouten, H. An ultraslow-spreading class of ocean ridge.
    Nature **426**, 405–412 (2003).
5. Klein, E. M., Langmuir, C. H., Zindler, A., Staudigal, H. & Hamelin, B. Isotope
    evidence of a mantle convection boundary at the Australian-Antarctic
    Discordance. *Nature* **333**, 623–629 (1988).
6. Dosso, L. et al. The age and distribution of mantle heterogeneity along the Mid-
    Atlantic Ridge (31–41°N). *Earth Planet. Sci. Lett.* **170**, 269–286 (1999).
7. Shirey, S. B., Bender, J. F. & Langmuir, C. H. Three-component isotopic
    heterogeneity near the Oceanographer transform, Mid-Atlantic Ridge. *Nature*
    325, 217–223 (1987).
8. Skjelkvale, B. L., Amundsen, H. E. F., Oreilly, S. Y., Griffin, W. L. & Gjelsvik, T. A
    primitive alkali basaltic stratovolcano and associated eruptive centers,
    Northwestern Spitsbergen: Volcanology and tectonic significance. *J. Volcanol.
    Geotherm. Res.* **37**, 1–19 (1989).
9. Ionov, D. A., Bodinier, J. L., Mukasa, S. B. & Zanetti, A. Mechanisms and sources of
    mantle metasomatism: Major and trace element compositions of peridotite
    xenoliths from Spitsbergen in the context of numerical modeling. *J. Petrol.* **43**,
    2219–2259 (2002).
10. Ionov, D. A., Mukasa, S. B. & Bodinier, J. L. Sr-Nd-Pb isotopic compositions of
    peridotite xenoliths from Spitsbergen: Numerical modelling indicates Sr-Nd
    decoupling in the mantle by melt percolation metasomatism. *J. Petrol.* **43**,
    2261–2278 (2002).
11. Clague, D. A. & Frey, F. A. Petrology and trace element chemistry of the Honolulu
    volcanics, Oahu: Implication for the oceanic mantle below Hawaii. *J. Petrol.* **23**,
    447–504 (1982).

12. Class, C. & Goldstein, S. L. Plume-lithosphere interactions in the ocean basins: constraints from the source mineralogy. *Earth Planet. Sci. Lett.* **150**, 245–260 (1997).

13. Niida, K. & Green, D. H. Stability and chemical composition of pargasitic amphibole in MORB pyrolite under upper mantle conditions. *Contrib. Mineral. Petrol.* **135**, 18–40 (1999).

14. Blythe, A. E. & Kleinspehn, K. L. Tectonically versus climatically driven exhumation of the Eurasian plate margin, Svalbard: Fission track analyses. *Tectonics* **17**, 621–639 (1998).

15. Ritzmann, O. & Jokat, W. Crustal structure of northwestern Svalbard and the adjacent Yermak Plateau: evidence for Oligocene detachment tectonics and non-volcanic breakup. *Geophys. J. Int.* **152**, 139–159 (2003).

16. Zhang, S. Q. *et al.* Evidence for a widespread Tethyan upper mantle with Indian-Ocean-type isotopic characteristics. *J. Petrol.* **46**, 829–858 (2005).

17. Dupré, B. & Allègre, C. J. Pb–Sr isotope variation in Indian Ocean basalts and mixing phenomena. *Nature* **303**, 142–146 (1983).

18. Hawkesworth, C. J., Mantovani, M. S. M., Taylor, P. N. & Palacz, Z. Evidence from the Paraña of south Brazil for a continental contribution to Dupal basalts. *Nature* **322**, 356–359 (1986).

19. Castillo, P. The Dupal anomaly as a trace of the upwelling lower mantle. *Nature* **336**, 667–670 (1988).

20. Arndt, N. T. & Goldstein, S. L. An open boundary between lower continental crust and mantle: its role in crust formation and crustal recycling. *Tectonophysics* **161**, 201–212 (1989).

21. le Roex, A. P., Dick, H. J. B. & Fisher, R. L. Petrology and geochemistry of MORB from 25°E to 46°E along the Southwest Indian Ridge: Evidence for contrasting styles of mantle enrichment. *J. Petrol.* **30**, 947–986 (1989).

22. Mahoney, J. J. *et al.* Isotopic and geochemical provinces of the Western Indian Ocean spreading centers. *J. Geophys. Res.* **94**, 4033–4052 (1989).

23. Barling, J., Goldstein, S. L. & Nicholls, I. A. Geochemistry of Heard Island (southern Indian Ocean): Characterization of an enriched mantle component and implications for the enrichment of the sub-Indian Ocean mantle. *J. Petrol.* **35**, 1017–1053 (1994).

24. Rehkamper, M. & Hofmann, A. W. Recycled ocean crust and sediment in Indian Ocean MORB. *Earth Planet. Sci. Lett.* **147**, 93–106 (1997).

25. Kempton, P. D. *et al.* Sr-Nd-Pb-Hf isotope results from ODP Leg 187: Evidence for mantle dynamics of the Australian-Antarctic Discordance and origin of the Indian MORB source. *Geochem. Geophys. Geosyst.* **3**, doi:10.1029/2002GC000320 (2002).

26. Hanan, B. B., Blichert-Toft, J., Pyle, D. G. & Christie, D. M. Contrasting origins of the upper mantle revealed by hafnium and lead isotopes from the Southeast Indian Ridge. *Nature* **432**, 91–94 (2004).

27. Escrig, S., Capmas, F., Dupré, B. & Allègre, C. J. Osmium isotopic constraints on the nature of the DUPAL anomaly from Indian mid-ocean-ridge basalts. *Nature* **431**, 59–63 (2004).

28. Meyzen, C. M. *et al.* New insights into the origin and distribution of the DUPAL isotope anomaly in the Indian Ocean mantle from MORB of the Southwest Indian Ridge. *Geochem. Geophys. Geosyst.* **6**, doi:10.1029/2005GC000979 (2005).

29. Geldmacher, J., Hoernle, K., Klugel, A., van den Bogaard, P. & Bindemann, I. Geochemistry of a new enriched mantle type locality in the northern hemisphere: Implications for the origin of the EM-I source. *Earth Planet. Sci. Lett.* **265**, 167–182 (2008).

30. le Roux, P. J. *et al.* Mantle heterogeneity beneath the southern Mid-Atlantic Ridge: trace element evidence for contamination of ambient asthenospheric mantle. *Earth Planet. Sci. Lett.* **203**, 479–498 (2002).

31. Janney, P. E., le Roex, A. P. & Carlson, R. W. Hafnium isotope and trace element constraints on the nature of mantle heterogeneity beneath the central Southwest Indian Ridge (13°E to 47°E). *J. Petrol.* **46**, 2427–2464 (2005).

32. Salters, V. J. M. & Stracke, A. Composition of the depleted mantle. *Geochem. Geophys. Geosyst.* **5**, doi:10.1029/2003GC000597 (2004).

33. Workman, R. K. & Hart, S. R. Major and trace element composition of the depleted MORB mantle (DMM). *Earth Planet. Sci. Lett.* **231**, 53–72 (2005).

METHODS

Major elements. Major elements were measured at the American Museum of Natural History on the AMNH-LDEO Cameca electron microprobe. Each analysis represents an average of five individual measurements on a single glass chip. A glass chip of the Lamont glass probe standard, JDF-D2, was repeatedly analysed in each probe session to monitor long-term drift. No long-term drift was evident in any run. The errors are based on the reproducibility of JDF analyses over multiple probe sessions and are ≤1% for SiO_2 and MgO.

Trace elements. Hand-picked glass separates with minimal surface alteration were analysed for trace element compositions and measured on the Plasma Quad 2 inductively coupled plasma mass spectrometer at LDEO or a Thermo Electron X-series inductively coupled plasma mass spectrometer at Harvard . Solutions were spiked with Ge, In, Tm and Bi to correct for in-run drift. Concentrations were determined using a calibration curve based on US Geological Survey and in-house standards measured during each run. Errors are 3–5%.

Isotope ratios. Pb, Nd and Sr isotope ratios were measured on separate glass chips from the trace element analyses. These were leached cold for 12 minutes with 8N HNO_3. Pb was separated using AG1-X8 anion resin, Sr was separated using Eichrom Sr resin and Nd was separated in a two-column procedure using Eichrom TRU-spec resin to separate the rare-earth elements, followed by α-hydroxy isobutyric acid. Sr, Nd and Pb isotopes were measured on a VG Sector 54 multicollector thermal ionization mass spectrometer at LDEO. $^{87}Sr/^{86}Sr$ ratios were normalized to $^{86}Sr/^{88}Sr = 0.1194$. Sr isotopes were measured in multidynamic mode. Instrumental reproducibility was monitored by repeated measurements of the US National Institute of Standards and Technology SRM 987 standard, which yielded $^{87}Sr/^{86}Sr = 0.710246 \pm 0.000016$ (2-s.d. external reproducibility, $n > 40$). All samples were further corrected to a value of 0.71024 for SRM 987. All Nd analyses were made in multidynamic mode as NdO^+. $^{143}Nd/^{144}Nd$ ratios were normalized to $^{146}Nd/^{144}Nd = 0.7129$. Repeated measurements of the La Jolla Nd standard yielded $^{143}Nd/^{144}Nd = 0.511838 \pm 0.000012$ (2-s.d. external reproducibility, $n > 30$). All samples were further corrected to a value of 0.511860 for the La Jolla standard. Pb isotope analyses used a $^{207}Pb-^{204}Pb$ double spike. All measurements were performed in static mode. Measurements of unspiked–double-spiked pairs of the NBS 981 standard were replicated to 183, 284 and 300 p.p.m. (2-s.d. external reproducibility, $n = 20$) for $^{206}Pb/^{204}Pb$, $^{207}Pb/^{204}Pb$ and $^{208}Pb/^{204}Pb$ ratios, respectively. These measured Pb isotope ratios were corrected to the Todt et al.[34] values of 16.9356, 15.4891, and 36.7006, respectively, for NBS 981.

34. Todt, W., Cliff, R. A., Hanser, A. & Hofmann, A. W. in *Earth Processes: Reading the Isotopic Code* Vol. 95 (eds Basu, A. & Hart, S. R.) 429–437 (American Geophysical Union, Washington DC, 1996).