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Helium isotopes provide no evidence for deep mantle involvement in widespread Cenozoic volcanism across Central Asia

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Abstract

Small-volume alkali basaltic volcanism has occurred intermittently for the past +30 My across a vast area of thick continental crust from southern Siberia, through Mongolia to northeast China. With a lack of evidence for Basin-and-Range-type crustal extension or rifting, models to explain the widely dispersed, yet long-lived, volcanism tend to favour involvement of one or more mantle plume(s). We examine the range of $^3He/^4He$ isotope values in olivine phenocrysts from basalts, and their entrained mantle xenoliths, from Hamar Daban in southern Siberia, and Hangai in central Mongolia, in order to examine whether upwelling lower mantle appears to be present beneath central Asia and thus test the validity of the plume model for this region. Our results show that the maximum $^3He/^4He$ value for the Siberian basalts is $8.12 \pm 0.2 R_a$, and the maximum value for Mongolian basalts is $9.5 \pm 0.5 R_a$. These values suggest that there is no significant contribution from a high $^3He/^4He$ primordial component that would strongly argue a lower mantle source. Overlap with commonly reported values for MORB leads us to propose that the source of the magmatism derives from the shallow asthenosphere. Alternative models to a deeply sourced mantle plume that may be able to explain the magmatism include: a shallow thermal anomaly confined to the upper mantle but either fed laterally or caused by thermal blanketing of the large Asian landmass; replacement or delamination of the lowermost lithosphere in response to tectonic stresses; or large-scale mantle disturbance or overturn caused by a protracted history of subduction beneath central Asia that ended regionally with the Jurassic closure of the Mongol-Okhotsk Ocean, but continues further afield with the present Indo-Asia collision.

Keywords: Central Asia; Helium isotopes; Continental volcanism; Mantle dynamics; Mantle plumes

1. Introduction

There have been a number of recent, high profile debates, with associated abstract volumes, about the applicability of the mantle plume hypothesis to explain intraplate volcanism (e.g. Penrose conference: Plume IV — "beyond the plume hypothesis"; and AGU Chapman

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Conference on "the Great Plume debate: the origin and impact of LIPs and hotspots"). Relevant to this debate is the example of central Asian intraplate volcanism, a vast region spanning southern Siberia, northeast China and Mongolia (approximately 3,000,000 km^2; Fig. 1a) consisting of small-volume (commonly < 30 km^3) basaltic volcanic provinces that have erupted throughout the Cenozoic. This volcanism is inadequately explained by both traditional models of mantle plumes (e.g. Courtillot et al., 2003) and alternative models, such as edge convection (King and Anderson, 1998). The traditional 'start-up' plume model, used to describe lower mantle material that wells up from a mantle boundary layer, e.g. the core–mantle boundary or 670 km discontinuity, does not readily explain the long-lived, small-volume volcanism over such a vast area. An alternative to the plume model, the edge convection model, predicts that decompressive melting of the asthenosphere occurs at juxtaposed margins of thick-to-thin lithosphere, where rapid shallowing of the asthenospheric mantle enables melting. However, this model fails to explain the observed distribution of basaltic provinces across central Asia, because the volcanism is not restricted to known terrane boundaries (e.g. Badarch et al., 2002). Furthermore, volcanism is not presently observed to occur where an edge convection model would most predict it, i.e. within the thinnest basins of the Baikal Rift Zone (BRZ) which delimits a sharp lithospheric boundary between thick Siberian cratonic lithosphere to the northwest and thinner Palaeozoic accreted terranes to the southeast (although volcanic rocks crop out on the flanks of the rift and elsewhere within the broader margins of the rift zone, and crustal thickness and structure is variable within the rift zone; Suvorov et al., 2002; Fig. 1a). Thus, the somewhat enigmatic origin of the Asian intraplate magmatism has been variously explained by active

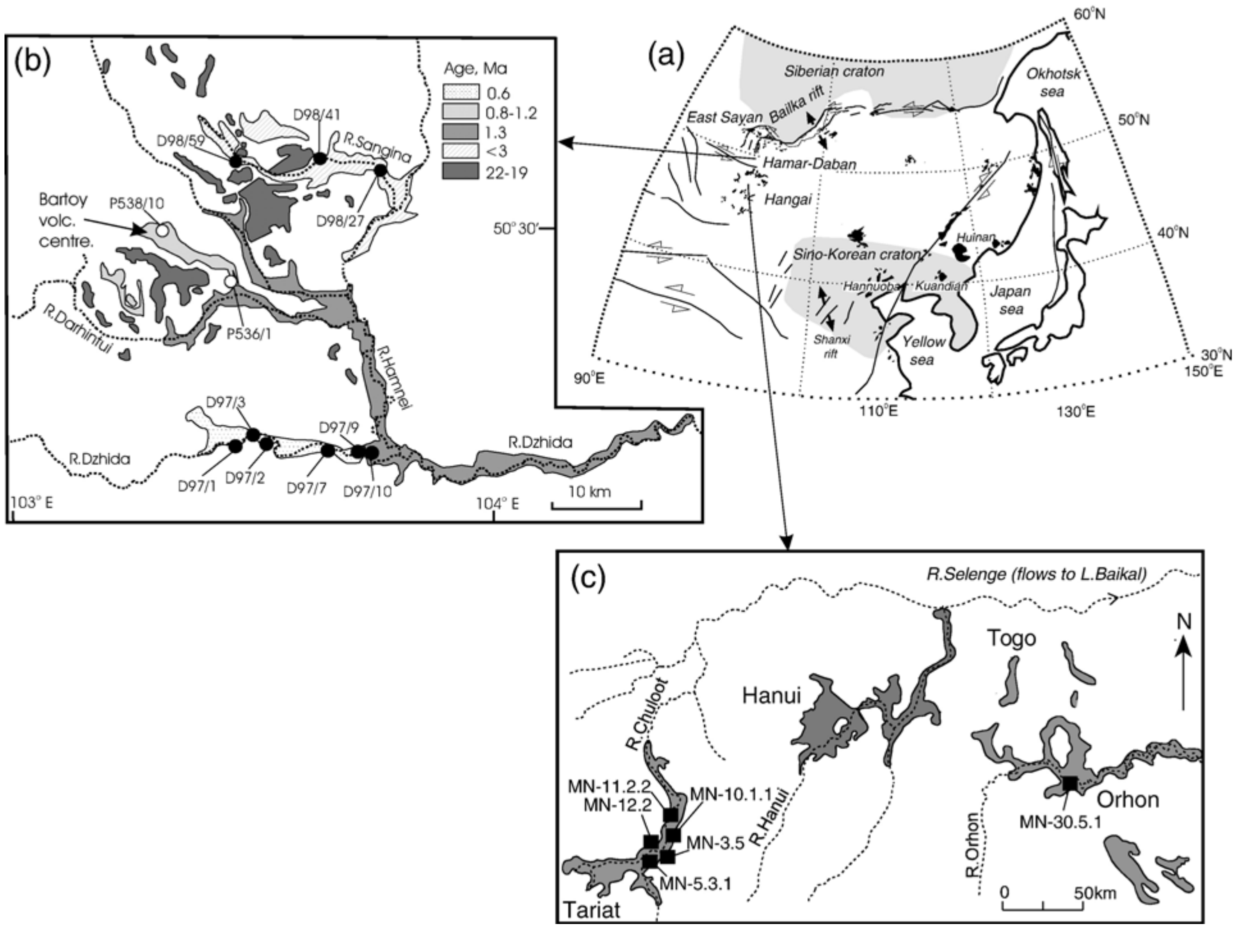

Fig. 1. (a) Geographic location of Cenozoic volcanism (shaded black) within east and central Asia relative to Archaean cratons (light grey) and major faults. (b) Map of sample localities within the Hamar-Daban volcanic province. (c) Map of Cenozoic volcanism around Hangai region of Mongolia (grey shaded). Sample localities within Tariat and Orhon volcanic provinces.

mantle processes (e.g. Windley and Allen, 1993) and/or passive far-field responses to plate collision (e.g. Molnar and Tapponnier, 1975).

In order to test the relevance of the mantle plume hypothesis in explaining Asian volcanism, we look at the $^3He/^4He$ signature of basalts from southern Siberia and Mongolia (Fig. 1), selected on the basis of their temporal and spatial distribution as well as their content of abundant fresh phenocrysts. It has long been thought that a high $^3He/^4He$ signature in basalts is indicative of undegassed primordial mantle, i.e. mantle that has a lower time integrated $^3He/(Th+U)$ signature than convecting mantle. Therefore, it is assumed that basalts with high $^3He/^4He$ signatures (e.g. $<42R_a$ and $<51R_a$ in Iceland and Baffin Island, respectively; Hilton et al., 2000; Breddam and Kurz, 2001; Stuart et al., 2003; [R_a refers to normalization to the atmospheric $^3He/^4He$ ratio of 1.39×10^{-6}]) have a contribution from a low time integrated $^3He/(Th+U)$ reservoir that must have remained isolated for a long enough time period for it to develop these distinct isotopic characteristics. Because of its isolation, this reservoir has been most commonly thought to reside within the lower mantle (e.g. Graham, 2002; Day et al., 2005), although incomplete degassing of the mantle during crustal formation can also explain the range of helium isotope ratios in ocean island basalts (Class and Goldstein, 2005). Whilst it is widely regarded that a high $^3He/^4He$ ratio is positive evidence for undegassed primordial (lower) mantle material, some ocean island basalts and their inferred mantle plumes (e.g. Tristan da Cunha-Gough; Kurz et al., 1982) have helium isotope ratios similar and lower than mid-ocean ridge basalts (MORB) which derive from relatively degassed and incompatible element-depleted convecting asthenosphere ($^3He/^4He=8.75R_a\pm2.14$, $n=658$; Graham, 2002). On the basis of radiogenic isotopes, low $^3He/^4He$ mantle plumes ('low $^3He/^4He$'$=<7R_a$ and 'MORB-like $^3He/^4He$'$=8R_a\pm1$, Class and Goldstein, 2005 and references therein) are thought to reflect involvement of recycled ancient ocean crust and sediment, and thus carry a degassed, high ^4He signature that derives from crustal formation and Th–U radioactive decay (e.g. Hanyu and Kaneoka, 1997).

We present new helium isotope data for mantle xenoliths and their host basalts from southern Siberia, adjacent to the Baikal Rift Zone (BRZ), and from the Hangai area of central Mongolia. Earlier studies on helium isotopes from southern Siberia and Mongolia present unreliable and contradictory data (Drubetskoi and Grachev, 1987; Grachev, 1998; Grachev et al., 2003); therefore, we focus on comparisons with helium isotope data from NE China (Xu et al., 1998). In light of our examination of helium isotopes from the region, we assess the relative contribution to central and eastern Asian basalts from undegassed primordial (lower) mantle material and review current models that may be able to explain the intraplate volcanism.

2. Sample localities

2.1. Southern Siberia; Hamar-Daban

Samples were collected from the Dzhida volcanic province on the southern slope of the Hamar-Daban range (Fig. 1a and b). Olivine and clinopyroxene mineral separates were handpicked from ten basalt samples from Pliocene(?)–Quaternary lavas (3–0.6 Ma; Fig. 1b) from the Sangina River unit (~3 Ma or less), the lower Dzhida River unit (~1.3 Ma) and the upper Dzhida River unit (0.6 Ma; Rasskazov et al., 1996). We also separated olivine crystals from an amphibole-bearing spinel lherzolite xenolith (p538/10) and a spinel lherzolite xenolith (p536/1) hosted within glassy, highly alkaline basalts from the Bartoy unit (Fig. 1b). Miocene volcanic rocks within the area did not contain fresh olivine phenocrysts nor mantle xenoliths and thus could not be included in our study.

2.2. Central Mongolia; Hangai

Two volcanic provinces within the central Mongolian region of Hangai were selected for this study: Tariat and Orhon (Fig. 1c). Tariat, in western Hangai, lies within an east–west trending river valley with basalt lava covering ~600 km^2. Olivine phenocrysts were handpicked from basalt lavas from the ~6 My Morün Formation (MN-11.2.2), the 0.6 My Chuluut Formation (MN-3.5, -10.1.1), and the ~0.005 My Sumyn Formation (MN-5.3.1, -12.2; Barry et al., 2003; Fig. 1a and c). Also, olivine and pyroxene separates were picked from a single 10-cm-sized mantle xenolith hosted within the Sumyn Formation basalt MN-5.3.1. In addition to the temporal constraints offered by looking at samples spanning a 6 My history from Tariat, we also tested the spatial variability across the Hangai area by separating olivine phenocrysts from a basalt (MN-30.5.1) from the Quaternary Orhon volcanic province, located approximately 200 km to the east of Tariat. Fresh samples were collected away from old exposed surfaces to minimize effects of cosmic rays, and olivine phenocrysts were selectively handpicked for their lack of alteration and presence of inclusions.

3. Geochemical rationale for helium isotope study

Primitive mantle-normalized element distribution diagrams for basalts from southern Siberia (Table 1) and central Mongolia (Barry et al., 2003) are shown in Fig. 2. Although basalts from central Mongolia reveal some distinct chemical variations from southern Siberian basalts, i.e. a negative Ti anomaly in Mongolian basalts from Tariat, it is their overall similarity that is most striking. This similarity is the more remarkable given the 500 km distance between the two regions (Fig. 1) and the complex nature of the underlying accreted crust (e.g. Logatchev and Zorin, 1992; Badarch et al., 2002).

Published Sr–Nd–Pb isotope data for the southern Siberian and central Mongolian regions show broad overlap in basalt composition (Fig. 3; Pb not shown). Sr–Nd isotopes of the central Mongolian basalts plot within the upper range of $^{87}Sr/^{86}Sr$ values for the southern Siberian rocks and slightly towards lower εNd values. Sr–Nd (–Pb) isotopic compositions of the basalts have previously been inferred to reflect mixing between three mantle components (e.g. Barry et al., 2003); two end-members – referred to here as ‘B’ and ‘C’ – are locally variable, whereas a third component – referred to as ‘A’ – is considered ‘common’ to all. End-members ‘B’ and ‘C’ trend towards EMI and EMII, respectively (Fig. 3), and vary in percentage of total contribution between individual lavas. On the basis of abundant fresh mantle xenoliths present in Mongolian and Siberian basalts and REE and isotope modeling, components ‘B’ and ‘C’ are interpreted as mantle-derived rather than crustal (Barry et al., 2003).

The source of the three end-members required to explain the full chemical diversity of the central Asian basalts is unclear and opinions differ. Because it is common to all samples over such a wide area, component ‘A’ is inferred to have originated in the asthenosphere (Rasskazov et al., 2002; Barry et al., 2003). In 22–12 My basalts from the southwestern BRZ component ‘A’ is characterized by isotopic values of $^{87}Sr/^{86}Sr$

Table 1
Major and trace element analyses for the basalts from Hamar-Daban, Dzhida volcanic provinces used in the helium isotope study

	D-98-27	D-98-41	D-98-59	D-97-2-6	D-97-8-1	BHVO-1
Rb	18	23	18	21	20	9.2 (6.4)
Ba	341	416	359	372	362	133 (3.7)
Th	2.7	2.7	2.4	2.6	2.7	1.4 (7.1)
K	n.d.	16437	16271	n.d.	n.d.	n.d.
Nb	45.8	49.4	49.0	50.2	50.7	19.0 (2.7)
La	26.5	28.0	29.5	30.0	28.4	16 (6.3)
Ce	55.5	58.5	61.5	62.6	60.6	39.4 (2.3)
Pr	7.1	7.3	7.7	7.3	7.1	5.4 (2.4)
Sr	703	856	850	732	811	378 (4.6)
P	n.d.	3054	3490	n.d.	n.d.	n.d.
Nd	31.2	32.4	32.3	30.9	32.2	24.5 (1.6)
Sm	6.81	7.32	7.46	6.94	7.03	6.03 (1.4)
Zr	237	198	194	192	196	164 (4.8)
Eu	2.42	2.51	2.43	2.23	2.27	2.02 (2.4)
Ti	n.d.	16007	16247	n.d.	n.d.	n.d.
Gd	6.5	6.3	6.8	6.3	6.3	6.1 (3.2)
Tb	1.05	0.99	1.00	0.92	0.93	0.965 (3.6)
Dy	5.1	5.0	4.8	4.5	4.8	5.2 (3.1)
Y	23	23	24	23	23	27 (5.9)
Ho	0.90	0.94	0.89	0.80	0.82	1.02 (2.3)
Er	2.14	2.19	2.24	1.97	2.07	2.54 (3.7)
Tm	0.29	0.29	0.32	0.25	0.26	0.345 (7.1)
Yb	1.65	1.68	1.52	1.40	1.37	1.98 (2.9)
Lu	0.23	0.24	0.22	0.20	0.20	0.28 (5.5)

Data determined by ICP-MS at PlasmaQuad 2+ Joint Analytical Facility of Irkutsk Scientific Centre, following the procedures of Ivanov et al., 2000.
Data for K, P and Ti have been calculated from wet chemistry analyses (n.d. — not determined). Values for BHVO-1 SRM are an average of 10 measurements conducted together with the sample analyses. Figures in parentheses refer to one standard deviation.

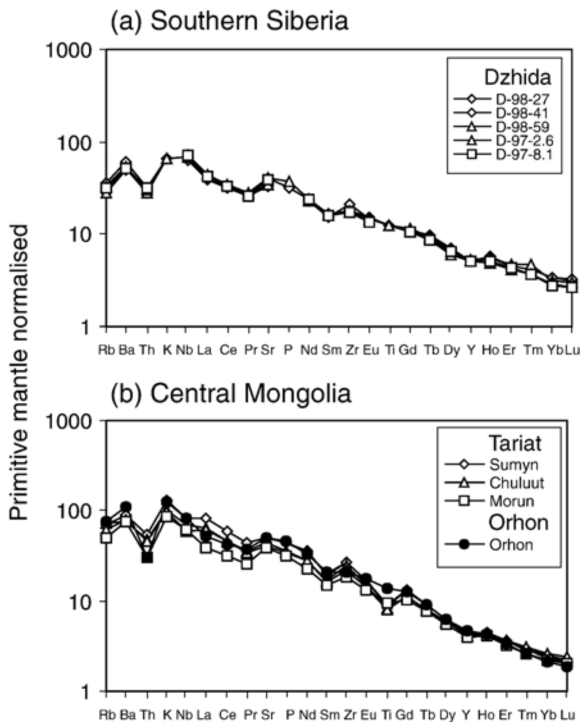

Fig. 2. Primitive mantle normalized trace element variation diagrams for (a) basalts from Dzhida volcanic province, Siberia (Table 1) and (b) basalts from Tariat and Orhon volcanic provinces, Mongolia (Barry et al., 2003). Normalization values from Sun and McDonough (1989). All samples exhibit similar positive anomalies of Ba, K, Sr, P, Zr and negative anomalies of Rb and Th.

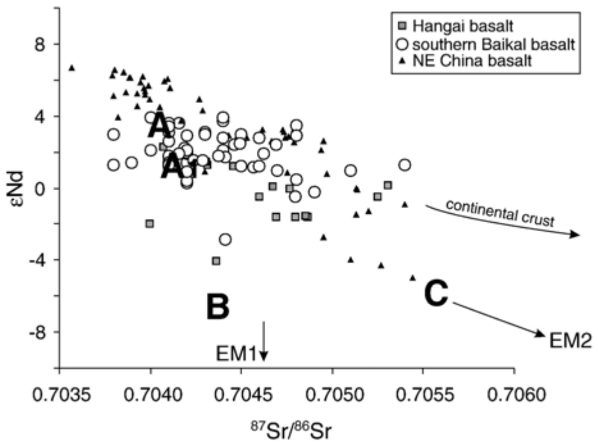

Fig. 3. εNd versus $^{87}Sr/^{86}Sr$ for Cenozoic alkali basalts in Asia. Data sources: Hangai basalts — Barry et al. (2003), Yarmolyuk et al. (2003); Southern Baikal basalts — Ionov et al. (1992), Yarmolyuk et al. (2003), Rasskazov et al. (2002), Chinese basalts — Basu et al. (1991), Song et al. (1990), Zhi et al. (1990). EM1 and EM2 values from Zindler and Hart (1986).

~0.7041, $^{143}Nd/^{144}Nd$ ~0.5128, and $^{206}Pb/^{204}Pb$ ~18.1 (Rasskazov et al., 2002; Fig. 3). The 'common' component appears to have a slightly different isotopic composition in <12 My old basalts from southern Siberia (Rasskazov et al., 2002), which has been attributed to ponding and subsequent modification at the base of the lithosphere. This shift from composition 'A' to 'A1' is characterized by an 'A1' isotopic composition of $^{87}Sr/^{86}Sr$ ~0.7042, $^{143}Nd/^{144}Nd$ ~0.5127, $^{206}Pb/^{204}Pb$ ~17.9 (Rasskazov et al., 2002; Fig. 3). Supporting the idea of melt ponding near or within the lowermost lithosphere is the presence of a low velocity seismic anomaly between 100 and 200 km depth (Villaseñor et al., 2001). Furthermore, gravity data suggests an anomalous low-density gravity body within the lithospheric mantle, possibly reflecting a maximum 10 km thickness of magmatic underplating (Petit et al., 2002). Components 'B' and 'C' with their EM1- and EM2-like characteristics, similarly observed in Siberian and Mongolian basalts, can be attributed to the presently attached lithospheric mantle at the base of the crust (Barry et al., 2003). On the basis of Pb isotopes (Barry et al., 2003), there is no argument for a recycled ancient crust or sediment, or high-μ, component synonymous with low $^3He/^4He$ mantle plumes.

Alternatively, components 'A1', 'B' and 'C' can be interpreted as originating within the lower mantle, lower-upper mantle transitional zone and 'D' layer, respectively (e.g. Yarmolyuk et al., 2003). The EM1- ('B') and EM2-like ('A') components may thus represent recycled lithosphere that has resided in the deep mantle for a long period of time (Yarmolyuk et al., 2003), and along with lower mantle material has been transported to the surface by a mantle plume.

4. Helium isotope analysis

Helium isotopes for the southern Siberian and central Mongolian samples were analysed at the University of Manchester and Vrije Universiteit Amsterdam, respectively, but followed similar analytical procedures. Unaltered olivine and clinopyroxene phenocrysts (2 to 5 mm in size) were selected from the basalt and xenolith samples and repeatedly ultrasonically cleaned in deionised water and then acetone. Separates were then handpicked under a binocular microscope and loaded into a crusher extraction system. The crusher and neighbouring stainless steel housing were baked at <150 °C under vacuum for 12 h to liberate any adsorbed atmospheric gases. Gases were extracted from the mineral separates by crushing, and then cleaned by exposure to a SAES Zr–Al getter operating at 250 °C to remove any active gases such as N_2, O_2 and CO_2. After purification, gases were condensed on a charcoal finger held at −196 °C with liquid nitrogen. Non-condensable gases, including He, Ne and H_2 were then exposed to a second SAES Zr–Al getter operating at room temperature. A second charcoal finger, also held at −196 °C, adjacent to the source inlet, was used to minimize and stabilize background levels of any residual Ar, CO_2, and H_2O during the helium analysis. Further details are presented in Harrison et al. (2004).

Analyses at the University of Manchester were determined using a MAP 215 noble gas mass spectrometer and a VG 5400 mass spectrometer at Vrije Universiteit Amsterdam, and both gave negligible blank effect. Analytical blanks for the analyses at University of Manchester were: ^3He undetectable; ^4He between 2.6×10^{-12} and 1.8×10^{-11} ml STP; ^{20}Ne blanks between 1.2 and 2.7×10^{-11} ml STP; and ^{40}Ar blanks between 1.8×10^{-10} and 1.9×10^{-9} ml STP. Analytical blanks at Vrije Universiteit Amsterdam were: ^3He undetectable; $^4He < 0.1\times10^{-9}$ ml STP; $^{20}Ne<2.9\times10^{-12}$ ml STP; and $^{36}Ar<6.5\times10^{-12}$ ml STP.

Post-eruptive radiogenic ^4He ingrowth and/or the effects of cosmogenic exposure to ^3He production was minimized during analyses by using the crushing extraction procedure. We do not have strong controls on the U and Th concentrations within the rocks, which would have affected ^4He production, nor good constraints on the exposure history of all the samples. However both these processes would most strongly affect nuclides sited within the crystal matrix. Therefore, by performing a pressure fracturing crush procedure to release volatiles from fluid inclusions, and not matrix-sited volatiles, we are unlikely to release any significant amount of matrix-sited gas (Scarsi, 2000). Furthermore, only one single crush step was performed on each sample and therefore the amount of sample actually crushed is approximately 10% (Harrison et al., 2004).

5. Helium isotope results

All $^3He/^4He$ ratios are recalculated for normalization to the value for air (quoted as R_a). The Siberian basalt-hosted clinopyroxenes have lower $^3He/^4He$ ratios (0.87 to 4.47R_a) than the olivines from the same samples (7.18 to 8.12R_a; Table 2). $^{40}Ar/^{36}Ar$ ratios recorded for the clinopyroxenes were indistinguishable from air indicating that crystallisation occurred in equilibrium with the atmosphere (Harrison et al., 2004). Previously, crustal storage and/or crustal contamination have been invoked to explain such low values. However, the Siberian and Mongolian basalts suggest very little interaction with continental crust, as discussed in the 'Geochemical Rationale'. Instead, the lower $^3He/^4He$ ratios for the clinopyroxene separates has been attributed to small amounts of isotopic fractionation of ^3He from ^4He during magma degassing, as a result of the relatively large mass difference between the two isotopes (Harrison et al., 2004).

Table 2
Helium isotope results for southern Siberian (Hamar-Daban: Dzhida volcanic province) and central Mongolian (Hangai: Tariat and Orhon volcanic provinces) alkali basalts and their mantle xenoliths

Sample no.	Mineral	$^3He/^4He$ (R_a)	^4He ml STP g^{-1}
Dzhida, Hamar-Daban, Siberia			
D-97/1	ol	8.03±0.2	1.67×10^{-8}
D-97/1	cpx	3.11±0.3	6.51×10^{-10}
D-97/2-2	ol	7.99±0.2	1.34×10^{-8}
D-97/2-2	cpx	3.30±0.4	3.55×10^{-10}
D-97 2-4	ol	8.00±0.3	1.03×10^{-8}
D-97/3	ol	7.96±0.3	1.22×10^{-8}
D-97/7-2	cpx	4.47±0.3	2.90×10^{-10}
D-97/9	cpx	1.20±0.3	3.09×10^{-10}
D-97/10-1	ol	8.12±0.2	1.20×10^{-7}
D-98/27	ol	7.80±0.3	1.65×10^{-10}
D-98/27	cpx	0.87±0.4	3.16×10^{-9}
D-98-41	ol	7.18±0.2	4.58×10^{-8}
D-98/59	cpx	1.68±0.9	1.60×10^{-10}
P-536/1	xeno-ol	4.73±0.3	1.24×10^{-9}
P-538/10	xeno-ol	8.28±0.3	2.45×10^{-9}
Tariat and Orhon, Hangai, Mongolia			
MN-5.3.1	ol	10.20±3.1	8.00×10^{-10}
MN-5.3.1	xeno-ol	8.78±0.9	5.30×10^{-10}
MN-5.3.1	xeno-cpx	8.26±2.0	3.92×10^{-10}
MN-12.2	ol	10.80±3.3	9.40×10^{-10}
MN-3.5	ol	6.90±0.5	1.37×10^{-9}
MN-10.1.1	ol	6.75±0.3	2.28×10^{-9}
MN-11.2.2	ol	9.50±0.5	4.97×10^{-9}
MN-30.5.1	ol	8.80±2.2	1.11×10^{-9}

The Siberian samples were analysed at the University of Manchester and the Mongolian samples were analysed at Vrije Universiteit Amsterdam.
ol — olivine, cpx — clinopyroxene, *prefix* xeno — mineral from basalt-hosted mantle xenolith.

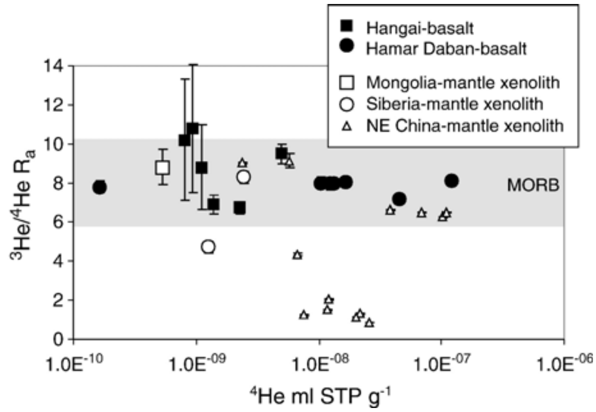

Fig. 4. New Siberian and Mongolian $^3He/^4He$ R_a data for olivine separates only, plotted against ^4He ml STP g^{-1}. Note: data for clinopyroxenes not shown. Also plotted are published data for Chinese basalt-hosted mantle xenoliths (Xu et al., 1998). Analytical error bars shown, though these are smaller than the symbol size for the Chinese data. Grey-shaded area = mean MORB value of 8.75±2.14R_a (Graham, 2002).

The average $^3He/^4He$ ratio for olivine phenocrysts within the southern Siberian basalts is 7.87±0.32R_a (1 S.D.) with a maximum value of 8.12±0.2R_a. From the central Mongolian basalts, two olivine-separate samples gave low total He gas yields and hence high error (<3.3R_a; Table 2). These data are omitted from further discussion. The maximum He isotope value of 9.5±0.5R_a, for olivine phenocrysts selected from the Mongolian basalts, is from the Morün Formation (Tariat). Almost all the olivine-separates have $^3He/^4He$ R_a values that are within error of values measured for mid-ocean ridge basalts (8.75R_a±2.14, n=658, Graham, 2002; Fig. 4), representative of shallow asthenospheric mantle. Even this value of 9.5±0.5R_a (discounting samples MN-5.3.1 and MN-12.2 on the basis of high error) does not imply a significant contribution from a high $^3He/^4He$ R_a primordial source component.

6. Discussion and conclusions

Due to similarities in the geochemical nature of basalts across central and eastern Asia and the need to explain the volcanism under a unified model, we compare our helium isotope results with those determined on mantle xenoliths erupted within Miocene to Holocene lavas from NE China (Xu et al., 1998). Three basaltic volcanic provinces within NE China – Kuandian, Huinan and Hannuoba (Fig. 1) – lie within the Archaean Sino-Korean block and contain mantle xenoliths with $^3He/^4He$ R_a values of 9.0 to 11.35R_a from Kuandian, 4.35 to 6.60R_a from Huinan and 0.88 to 2.05R_a from Hannuoba (Xu et al., 1998). The lower-than-MORB values for Huinan and Hannuoba have been attributed to the nature of the sub-continental mantle and radiogenic He ingrowth, respectively (Xu et al., 1998). No explanation is offered for the higher-than-MORB values found within Kuandian province, although Xu et al. (1998) rule out input from a mantle plume on the basis that mantle beneath eastern China is characterized by cold subducted material. Using a combination of isotope and trace element data, Xu et al. (1998) conclude that the source regions for basalts erupted within the Kuandian, Huinan and Hannuoba volcanic provinces are, respectively, depleted upper mantle (i.e. MORB-source mantle), slightly enriched lithospheric mantle and possibly metasomatised lithospheric mantle.

As all the $^3He/^4He$ results available thus far plot dominantly within the MORB-field, we concur with Xu et al. (1998) that the simplest explanation is that the asthenospheric upper mantle is the source of the basaltic magmatism, rather than primordial (lower) mantle material. Of course, this view could change in time, given the current paucity of analysed samples; even Iceland, a classic mantle plume example, records dominantly MORB-like $^3He/^4He$ ratios and only a few samples reveal a high $^3He/^4He$ signature (Stuart et al., 2003; MacPherson et al., 2005). The depleted upper mantle contribution to NE China magmatism, described as isotopically MORB-like, may differ from the upper mantle contribution to Siberian and Mongolian magmatism, because of variations in the extent of previous melt extraction and/or degassing history. Within NE China, evidence for multiple magmatic events related to mantle overturn has been suggested on the basis of compositional zoning in zircons within Cenozoic basalt-hosted lower crustal xenoliths from NE China (Hannuoba volcanic province; Wilde et al., 2003). The U–Pb ages of the growth zones suggest that the mantle overturn event occurred during the Mesozoic, despite being recorded within Cenozoic-hosted basalts (Wilde et al., 2003). The cause of such dramatic mantle dynamics has been attributed to subduction of oceanic lithosphere and its sinking into the lower mantle, accompanied by rapid plate dispersal associated with the break-up of Gondwana (Wilde et al., 2003).

So, how can the widespread magmatism across central and eastern Asia be explained, if not by the presence of an underlying mantle plume? A number of observations are pertinent to this question. (1) Volcanism is not related to the thinnest parts of the crust. For example, there are no volcanic rocks observed within the largest BRZ basin, the South Baikal basin, which is locally characterized by thin crust (<34 km thick), and juxtaposed against the thick Siberian craton. Although Cenozoic volcanism has occurred elsewhere within the rift zone, the largest volcanic provinces lie outside the rift on crust that is approximately 55 km thick e.g. at Vitim (Johnson et al., 2005), Udokan and Hamar Daban (Zorin et al., 2003, references therein). (2) Throughout Mongolia volcanism is not associated with rifts, and generally occurs on crust that is <45 km thick. (3) There is no evidence of a flood basalt province within central and eastern Asia, traditionally associated with 'arrival' of a plume beneath the lithosphere. Possibly the largest volcanic province within central and eastern Asia is Dariganga which straddles the SE Mongolia–NE China border. It approximates 20,000 km^2 and is described as a Quaternary cinder cone field. Few age data are available to constrain the longevity or frequency of the volcanism (Whitford-Stark, 1987). (4) Seismic tomographic studies suggest that central and eastern Asia is underlain by high velocity, cold mantle indicative of subducted material rather than low velocity mantle characteristic of an upwelling mantle plume (Richards and Engebretson, 1992). For example, Jurassic-aged slabs have been imaged down to at least 2500 km depth beneath Siberia, as a result of the Mongol-Okhotsk Ocean closure (Maruyama, 1994; Van der Voo et al., 1999). (5) Volcanism across Mongolia, NE China and Siberia is sparsely distributed (Fig. 1) yet has been intermittently active for at least 30 My (Barry et al., 2003). Therefore, whatever process controls the production of basaltic melt, it must be long-lived, very extensive, yet of low heat flux.

At this time, we cannot completely rule out the possibility that a 'MORB-like $^3He/^4He$' mantle plume is involved in the central and eastern Asian magmatism. However, such a model would seem unlikely given the lack of evidence for a high $^{208}Pb/^{204}Pb$ signature seen in other global examples e.g. Heard and Pitcairn (Class and Goldstein, 2005, and references therein). A modification of the large plume-head model is the idea of numerous narrow plumes, or 'plumelets', as invoked for volcanism within central Europe (Hoernle et al., 1995; Granet et al., 1995). This is not a new model for this region (Barry and Kent, 1998) and is supported by tomographic evidence from around Lake Baikal of a narrow negative anomaly along the southern and eastern margin of the

Siberian craton that extends down to at least 400 km depth (Petit et al., 1998). Disconnected shallow anomalies are observed elsewhere, e.g. beneath the northern end of Lake Baikal, but do not appear to extend into the deeper mantle (Petit et al., 1998). Although, narrow 'fingers' of hot material have been imaged beneath Baikal, at present there is insufficient evidence to suggest that this process can explain all the volcanism throughout the whole of the region. Such a model would require numerous hot 'fingers', all of which would presumably root to a low-velocity anomaly, at depth. However, such an anomaly, or sheet, has yet to be imaged.

Disturbance in the mantle of Cenozoic Asia could be a lingering effect of a mantle overturn event or arrival of a large mantle plume during the Mesozoic, though at present there is no evidence for Mesozoic plume-related flood basalts. Alternatively, a Mesozoic mantle disturbance might have resulted from large volumes of descending subducted slab material as suggested by Wilde et al. (2003). Subduction beneath central Asia ended regionally with the Jurassic closure of the Mongol-Okhotsk Ocean, but continues further away, presently, with ocean-closure and suturing related to the Indo-Asia collision, and along the western margin of the Pacific. The Cenozoic magmatism in central Asia could therefore be a legacy of lingering upper mantle mobilisation and the far-field product of ongoing plate re-organisation (e.g. Zorin et al., 2006).

Another possible cause for intraplate magmatism is the over-thickening of crust following continent collision, leading to delamination of the lower lithosphere and/or crust. This process has been inferred for apparent Cenozoic-aged lithospheric removal beneath parts of NE China (Menzies et al., 1993), but it is not apparent beneath Mongolia or Siberia from available data (Petit et al., 2002).

Our results and the tomographic evidence for the presence of high-velocity subduction-dominated mantle beneath much of central and eastern Asia (Van der Voo et al., 1999) favours an anomalous upper mantle source rather than a lower-mantle derived plume. Narrow mantle upwellings, or 'fingers' of hotter-than-ambient mantle from a deep mantle boundary layer, cannot be unambiguously ruled out but would need to be compatible with evidence for a low-velocity anomaly between 100 and 200 km depth (Villaseñor et al., 2001). The model we propose (Fig. 5) satisfies the evidence presently available, although what initiated and sustains the envisaged process remains speculative. We propose that slightly hotter-than-ambient upper mantle lies close to the asthenosphere–lithosphere boundary and drives metasomatic fluids into the lowermost lithosphere, as recorded within some mantle xenoliths from the area (Ionov et al., 1994; Ionov and Hofmann, 1995) and in the petrogenesis of some Siberian and Mongolian basalts (Barry et al., 2003; Johnson et al., 2005). These asthenospheric-derived melts are likely to cool within the lithosphere and produce incompatible element-enriched veins or disseminated assemblages that are prone to melt with subsequent influx of melts and/or hot fluids (Barry et al., 2003). Melts from these enriched regions of the lithosphere, between 150 and 90 km depth, ultimately form basaltic magma that gets erupted at the

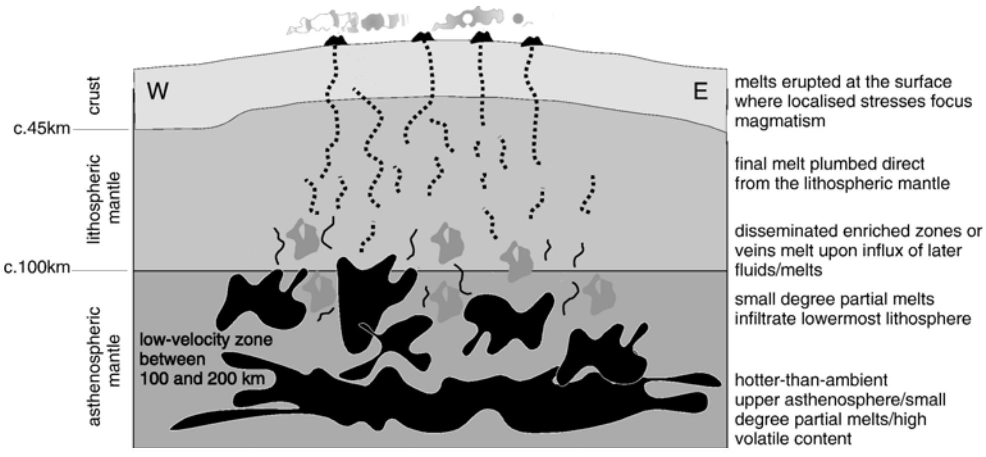

Fig. 5. A schematic representation of the proposed model for magma genesis beneath central Asia. Dark shaded areas represent melt zones. Lighter shaded areas represent disseminated crystallisation zones, and thin solid lines represent enriched metasomatic veins. Thick dotted lines represent melt pathways from the region of metasomatic enrichment in the lower lithospheric mantle, along which fractional crystallisation takes place at shallow levels.

surface, commonly containing lithospheric mantle xenoliths. The sites of individual volcanic provinces most likely reflect the position of localised crustal weaknesses, although this is speculative due to a limited understanding of the structure of the Mongolian-Siberian crust (e.g. Badarch et al., 2002), particularly at depth. Due to the lack of Basin-and-Range-type topography and/or evidence for crustal thinning, we consider that melting was initiated by mantle-driven processes rather than reflecting any particular volcano-tectonic setting such as rift-zones. However, we are unable to say whether a hotter-than-ambient-mantle anomaly beneath central and eastern Asia is an effect of deeper mantle processes, or the result of lateral mantle flow. Further evidence, particularly detailed geophysical studies, may help resolve the overall cause of this widespread, but enigmatic, intraplate volcanism. The existence of the volcanism, however, highlights how little we understand the nature of mantle dynamics beneath central and eastern Asia. If not by a large, long-lived mantle plume, then how can long-term, small-volume, diffuse basalt volcanism be sustained?

7. Note added in proof

Upper mantle anisotropy and tomography beneath Baikal has recently been inferred to indicate NW to SE horizontal flow with no evidence of a vertical component (Lebedev et al., 2006). This is consistent with the low velocity anomaly (Fig. 5) being fed laterally, although it perhaps does not completely rule out radial spreading of mantle welling up elsewhere beneath the Siberian Platform.

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