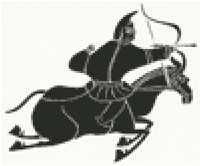

Diffuse, long-lived Cenozoic volcanism in Mongolia; thermally anomalous upper mantle?

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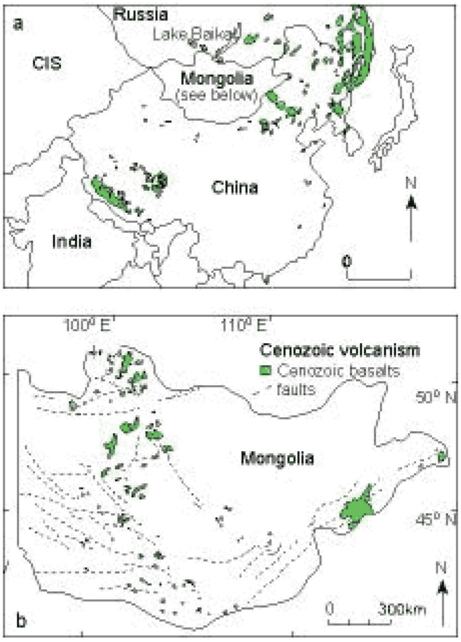

Figure 1. (a) Regional distribution of Cenozoic volcanism throughout Russia and China (based on data from Whitford-Stark, 1987, Fan & Hooper, 1989 and Lysak, 1995). (b) Distribution of Cenozoic volcanism throughout Mongolia (from Barry et al., 2003).

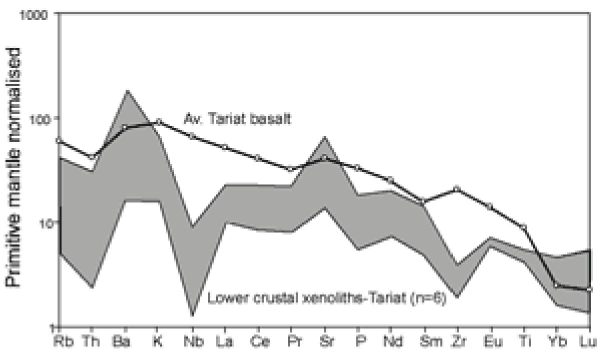

Figure 2 (Previous Page). Primitive mantle-normalized trace-element distribution pattern for an average basalt composition from central Mongolia (Tariat volcanic province), and the compositional range of crustal xenoliths from the same location. Note the large difference between the basalt and xenolith compositions for Nb, La, P, Zr and Ti.

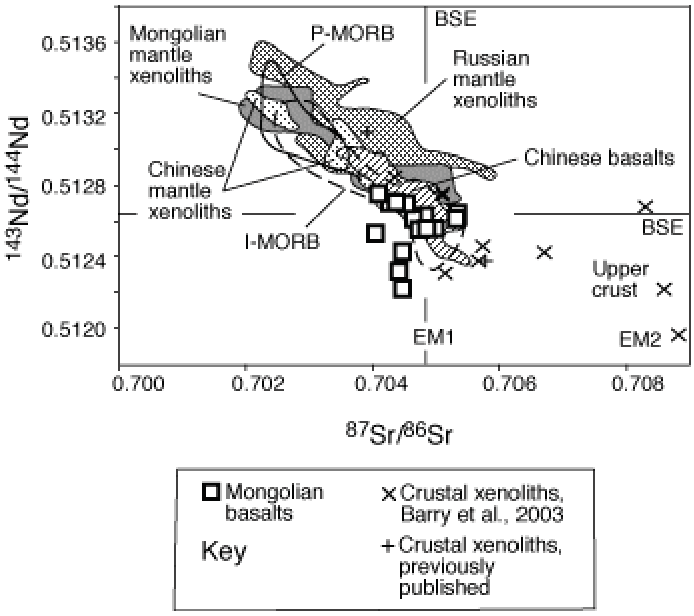

Figure 3. Plot of $^{143}Nd/^{144}Nd$ versus $^{87}Sr/^{86}Sr$ for Mongolian, Chinese and Siberian basalst and xenoliths (from Barry et al., 2003; data sources within).

Diffuse, small-volume basaltic volcanism has occurred intermittently throughout central Mongolia for the past 30 My. The causes of long-lived intraplate volcanism can be difficult to understand not least because of factors such as timing of regional and/or localised extension, timing of uplift, presence of possible crustal weaknesses and the timing of the magmatism itself. The problem is most acute in central and east Asia, one of the largest and least known areas of intraplate igneous activity (*Barry & Kent*, 1998; *Barry et al.*, 2003). In this region, Cenozoic basalt fields are scattered across an area approximately 2000 km from east to west, and 1500 km from north to south (*Whitford-Stark*, 1987) covering southern Siberia, central Mongolia and NE China (Figure 1).

Mongolia provides an excellent opportunity to study intraplate continental volcanism that is far removed from subduction zones and continental rifts. The crust within central Mongolia is estimated to be 45 km thick on the basis of P-T studies of crustal xenoliths (*Stosch et al.,* 1995). Despite having erupted through 45-km-thick crust, the basalts appear to show little crustal contamination (Figure 2; *Barry et al.,* 2003).

Mongolian volcanic provinces provide an important link between Cenozoic basalt volcanics to the north around the Baikal rift zone, in Russia (see also One rift, two models), and similar aged basalt volcanic provinces to the east in NE China spatially associated with extensional grabens. Volcanism and rifting in the Baikal region have been explained by several suggested processes including (1) partial melting of upper mantle due to either small asthenospheric diapirs (*Ionov et al.,* 1998) or a large mantle plume (e.g., *Logatchev* , 1984; *Windley & Allen*, 1993), (2) a crustal weakness (*Yarmolyuk et al.,* 1991), and (3) the combined effects of the India-Asia collision with secondary input from a mantle plume (*Khain*, 1990). Within NE China, Cenozoic volcanism has been attributed to passive upwelling of ocean island basalt (OIB) and/or mid-ocean ridge basalt (MORB) type mantle, with subsequent modification of magmas by assimilation of continental lithospheric mantle or crust (e.g., *Song et al.,* 1990; *Tatsumoto et al.,* 1992).

A close spatial relationship between older Paleogene Chinese basalts and sedimentary basins suggests that, initially at least, Cenozoic magmatism was associated with extension and thinning of the lithosphere along the eastern margin of the Eurasian plate (*Northrup et al.,* 1995). This in turn was related to the rate of convergence between the Pacific plate and Eurasia, with the Indo-Eurasian collision only a “far-field” influence (*cf* . *Northrup et al.,* 1995). Younger Neogene basalts, however, are not confined to basins.

Despite the contrasting explanations for the volcanism in Russia and China, the chemical composition of lavas in Baikal, Mongolia, and NE China are remarkably similar, especially given the large variation in underlying crustal and lithospheric mantle compositions and the wide range in eruption ages, *i.e.,* sporadically throughout the past 30 Myr (Figures 3 & 4; *Barry & Kent*, 1998). And yet Mongolia shows neither rifting-dominated processes such as are evident along the Baikal rift zone, extension-related processes nor changes in subduction convergence such as in the NE China basins. The independence of the basalt volcanism from crustal composition and structure suggests that the mantle source region beneath this vast area has played a significant role in contributing to magma genesis. Therefore, when considering a model to explain Mongolian volcanism, it seems reasonable to seek a single general model that can explain the volcanism throughout all these regions.

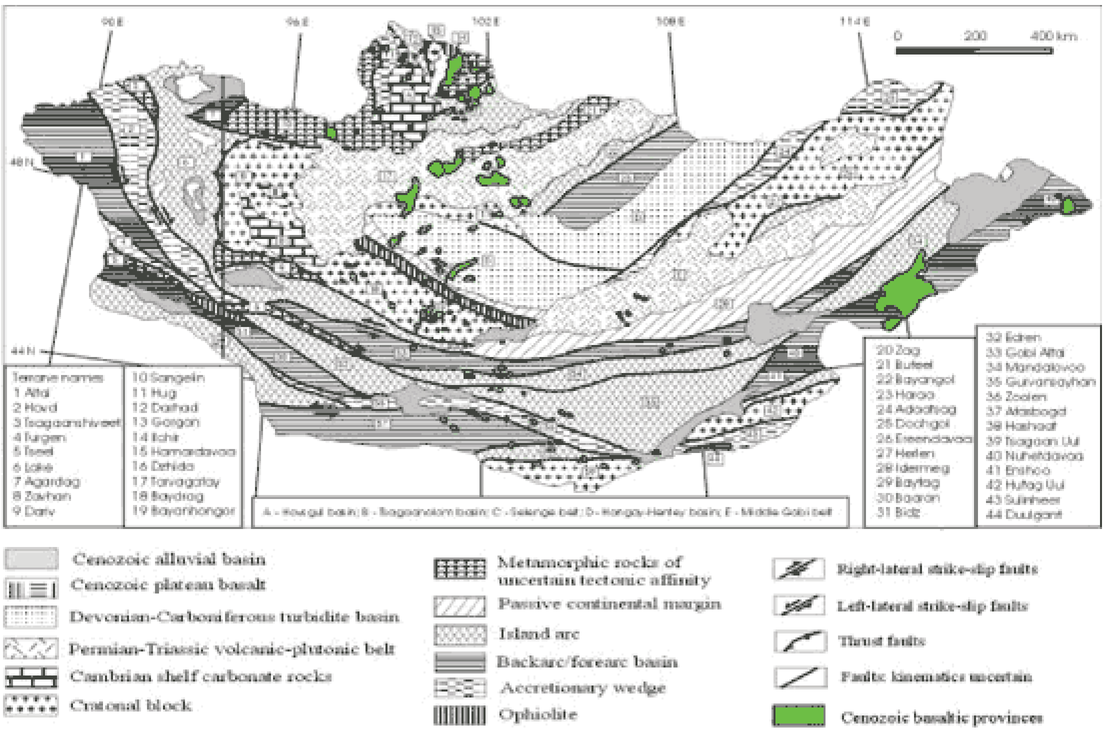

Figure 4. Terrane (compiled by Badarch et al., 2002) and volcanic provinces (compiled by Barry et al., 2003). (Modified from Whitford-Stark, 1987).

Mongolian basalts do not have the same isotopic composition as sampled mantle xenoliths, suggesting that the basalts are not derived from a source represented by the xenoliths. Trace element, REE and isotopic modeling of Mongolian basalt compositions indicate that the parental basalt melts were most likely derived from the lowermost lithospheric/ uppermost asthenospheric mantle. Large-ion lithophile elements and Nb concentrations suggest derivation from recently metasomatised lithosphere [see also Metasomatic OIB]. This is further supported by studies of mantle xenoliths erupted in the Mongolian and Russian basalts that show multi-enrichment and replacement textures (*Ionov,* 1994). **There is no evidence for high heat flow within the mantle beneath Mongolia (***Khutorskoy & Yarmolyuk***, 1989) as one might expect if a mantle plume were present. Instead, recent geophysical studies infer anomalously dense material at the base of the lithospheric mantle (***Petit et al.,*** 2001). The geochemistry of the basalts is therefore best explained by progressive enrichment of the lithospheric mantle by small degree partial melts from the asthenosphere. Even helium isotopes plot within the range of values found for sub-continental upper mantle and are not elevated towards high $^{3}He/^{4}He$ which may indicate a greater proportion of primordial ^{3}He (***Barry et al.***, in prep.) [see also** Helium: Fundamental models].

Whilst localized extensional tectonics may have facilitated transport of magma to the surface, the small amount of extension within Mongolia is insufficient to account for the generation of the basalts (*cf. McKenzie & Bickle*, 1988), thus suggesting that a mantle process must initiate melt generation. This raises the interesting question of how intraplate volcanism over such a vast area can be sustained, albeit intermittently, for tens of millions of years, if not by the presence of a large, long-lived mantle plume? Yet the area lacks evidence for a high-heat-flux mantle plume and there is no evidence for age progression of volcanic eruptions, nor for excess lithospheric temperatures from mantle xenoliths (*Ionov et al.,* 1998). Furthermore, there is no geophysical evidence for a mantle upwelling although the possibility of small diapiric upwellings, such as imaged beneath Europe (*Hoernle et al.*, 1995), and perhaps not resolvable by present tomography, cannot be ruled out.

Although the plume hypothesis may be inadequate to explain volcanism in central Asia with the data available at present, alternative models also struggle. Plate-edge convection models (*cf. King & Anderson*, 1998; see also Understanding the Edge-Driven Convection Hypothesis) fail to explain the distribution of basaltic provinces within Mongolia, which appear to be random and with no preferred occurrence along terrane boundaries (Figure 4). They also fail to explain why there is no volcanism within the Baikal rift where a plate-edge convection model would most likely predict magmatism. Furthermore, a crack propagation theory seems unlikely given the 45-km-thick crust and again, the non-aligned, broad spatial and temporal distribution of the volcanic rocks.

These types of volcanic occurrences present a problem for the geological community. Without detailed tomography, we do not know the structure of the mantle beneath Mongolia, but from the work that has been done, only the mantle above 200 km appears to have relatively low velocities (*Villaseñor et al.*, 2001). However, the geochemical evidence points towards a process involving asthenospheric fluids and/or melts infiltrating the lowermost lithosphere. These fluids/melts must be produced and driven by a process, but what, and how? A high-heat-flux mantle plume that causes melting of anhydrous asthenosphere does not appear to fit the evidence available for central Asia. However, melting of previously enriched, hydrous lower lithosphere could be triggered by a low-heat-flux thermal anomaly, either fed laterally from mantle upwelling elsewhere, or alternatively caused by thermal blanketing by the large Asian landmass. The ultimate cause of such a phenomenon remains enigmatic but, if understood, might help explain other regions of diffuse, long-lived intraplate volcanism.

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