# The Geodynamic Significance of the DUPAL Anomaly in Asia

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**Cenozoic intraplate volcanism in Asia constitutes the largest expression of the DUPAL anomaly in the northern hemisphere. By analogy with other regions of the world, 16 hotspots should be placed under Asia to account for this volcanism. Yet to place 16 plumes under Asia upsets the correlation between hotspot location and the geoid that is used in support of the plume hypothesis. The presence of seismically fast mantle at any potential plume source depth further negates application of the plume model to this region and implies that the sources of the volcanism reside at shallow levels in the mantle. A detailed evaluation of the structure and history of the China plate indicates that the DUPAL signature and location of volcanism are the result of the plate tectonic events which led to the amalgamation of Asia. The isotopic components EM1 and EM2 are equated with cratonic continental mantle and phlogopite peridotite in remnant arc sources, respectively. The latter likely formed during the subduction events which brought the continental blocks of Asia together. The cause of intraplate volcanism was interactions between the China, Pacific and Indian plates. Subduction of the Pacific and Indian plates along the continental margin of Asia since at least the late Cretaceous led to isolation of an asthenosphere domain beneath the China plate. Abuttal of asthenospheric flow against the Pacific plate caused steepening and trench roll-back culminating in extension in eastern China in the Eocene-Oligocene and the opening of the Sea of Japan in the Eocene-Miocene. Intraplate volcanism in the back-arc region along the eastern continental margin followed pre-existing lines of weakness above regions of lithosphere thinned during rifting of continental blocks from Gondwana in the Paleozoic. Miocene-Recent volcanism in central and southeast Asia is attributed to progressive fracturing of the China plate caused by the impact of India into the southern margin of the continent, superimposed on developing hotcell conditions caused by the insulating effect of the overlying lithosphere. The volcanism in Asia demonstrates that DUPAL signatures can be generated in the continental mantle and that intraplate volcanism can be generated in the absence of plumes.**

## INTRODUCTION

The acronym DUPAL was coined by *Hart* [1984] for the discoverers of an isotopic signature characterised by high $^{207}Pb/^{204}Pb$, $^{208}Pb/^{204}Pb$ and $^{87}Sr/^{86}Sr$ ratios in Indian Ocean MORB [*Dupre and Allegre*, 1983]. *Hart* [1984] suggested the signature to result from plumes arising from a single global belt lying between $0^0$ and $50^0$S which constituted the largest isotopic feature of the mantle (Figure 1). While acknowledging that the signature could result from crustal recycling, the extent of the anomaly was interpreted to indicate a very ancient feature relating to the evolution of the early Earth. DUPAL mantle was thus interpreted as regions which had suffered less crustal extraction than the depleted mantle (DM) reservoir. The alternative crustal recycling plume model suggests different types of subducted sediment evolve to EM1 and EM2 compositions [e.g. *Weaver*, 1986] such that the DUPAL anomaly represents regions where subduction has been focussed through time [*Staudigel et al.*, 1991]. The extent of the DUPAL belt was subsequently re-interpreted by *Castillo* [1988] who proposed the anomaly is comprised of two or three subdomains representing regions where the lower

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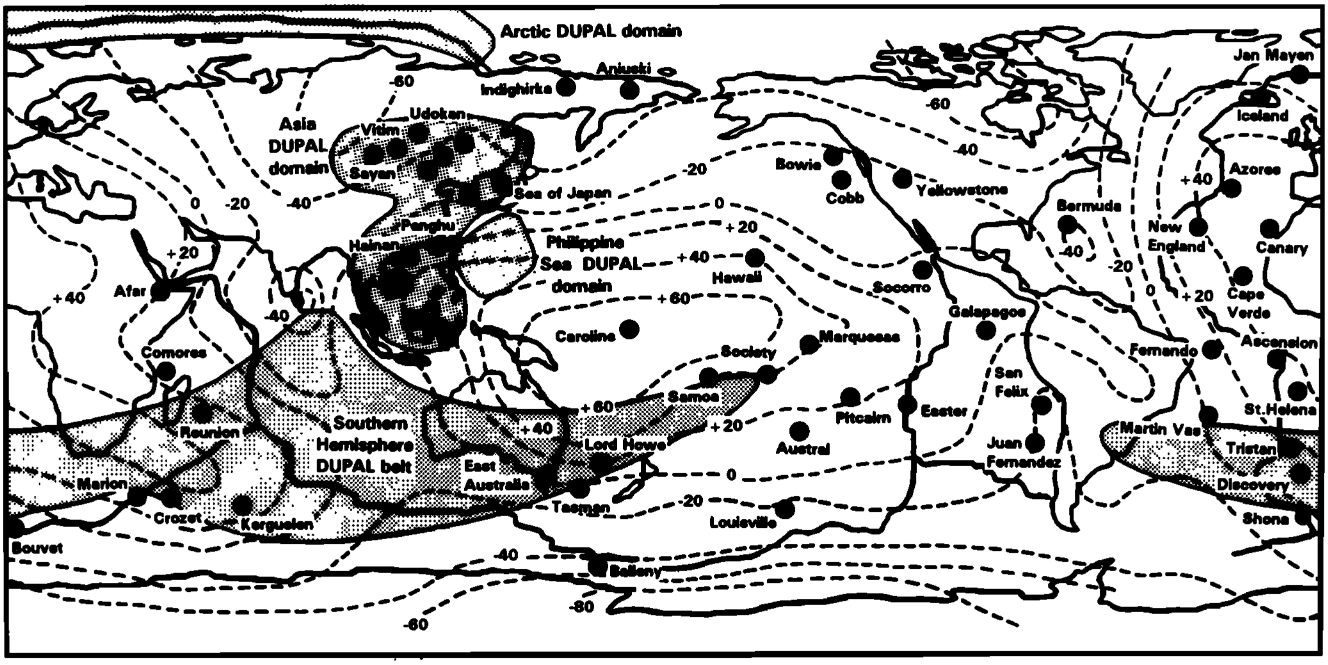


Fig. 1. Location of DUPAL domains (shaded) relative to the Earth's residual geoid anomalies (contours in metres after *Crough and Jurdy* [1980]) and supposed hotspots (from *Duncan and Richards* [1991]). Approximately 16 hotspots (positions from *Stefanick and Jurdy* [1984], *Nakamura et al.* [1989]) are required to account for the intraplate volcanism in Asia; however the majority of these would be associated with regions of negative geoid anomalies. The extent of the southern hemisphere DUPAL domain, shown according to the definition of $\Delta 8/4 > +60$, is depicted from the data distribution in *Hart* [1984]. Following the model in Figure 9, the extent of the DUPAL anomaly in Asia is suggested to correspond to the outline of the asthenospheric hotcells shown in Figure 6. An Arctic DUPAL domain is known only from MORB on the Nansen-Gakkel ridge [*Mühe et al.*, 1993], but may be continuous with the DUPAL domain in Asia from the intersection of the ridge system with northern Siberia. Likewise, from the mantle flow directions in Figure 6, the Philippine Sea DUPAL domain [*Hickey-Vargas et al.*, 1995] may be an extension of that in Asia.

mantle upwells as a consequence of being displaced by young subducting oceanic lithosphere. These various scenarios were complicated by the discovery of the DUPAL signature in the northern hemisphere. DUPAL basalts from the Arctic Ocean are problematic for the concept of equatorial mantle upwelling-polar mantle downwelling which arose from early plume models [*Mühe et al.*, 1993]. But perhaps the most severe test comes from the widespread occurrence of DUPAL signatures in Cenozoic intraplate and marginal basin basalts in Asia [*Peng et al.*, 1986; *Basu et al.*, 1991; *Tatsumoto and Nakamura*, 1991; *Chung and Sun*, 1992; *Tu et al.*, 1992; *Liu et al.*, 1994; *Chung et al.*, 1994, 1995a; *Hoang et al.*, 1996]. This volcanism defines the largest DUPAL domain yet discovered in the northern hemisphere, covering an area equal to about 5% of the Earth's surface (Figure 2).

The volcanism in Asia was originally interpreted in terms of hotspots [*Burke and Wilson*,1976; *Stefanick and Jurdy*, 1984; *Zhou and Armstrong*, 1982; *Whitford-Stark*, 1983] and consideration of plume models has persisted as a cause of large-scale rifting events in eastern China and the Sea of Japan [*Liu*, 1987; *Nakamura et al.*, 1989]. However, the low volumes of volcanism, lack of discernable age progressions, and correlations with lithospheric structure have led most workers to favour continental mantle and enriched asthenospheric sources [*Zhou et al.*, 1988; *Basu et al.*, 1991; *Zartman et al.*, 1991; *Tu et al.*, 1991, 1992; *Chung et al.*, 1994, 1995a]. The validity of assigning intraplate volcanism in Asia to non-plume processes while the same petrological products elsewhere are interpreted in terms of plumes should however be questioned. Not only must there then be two mechanisms for the generation of intraplate volcanism, identical geochemical signatures must also exist at two levels in the mantle. The multiplicity of models has generally been ignored because the assumption has always

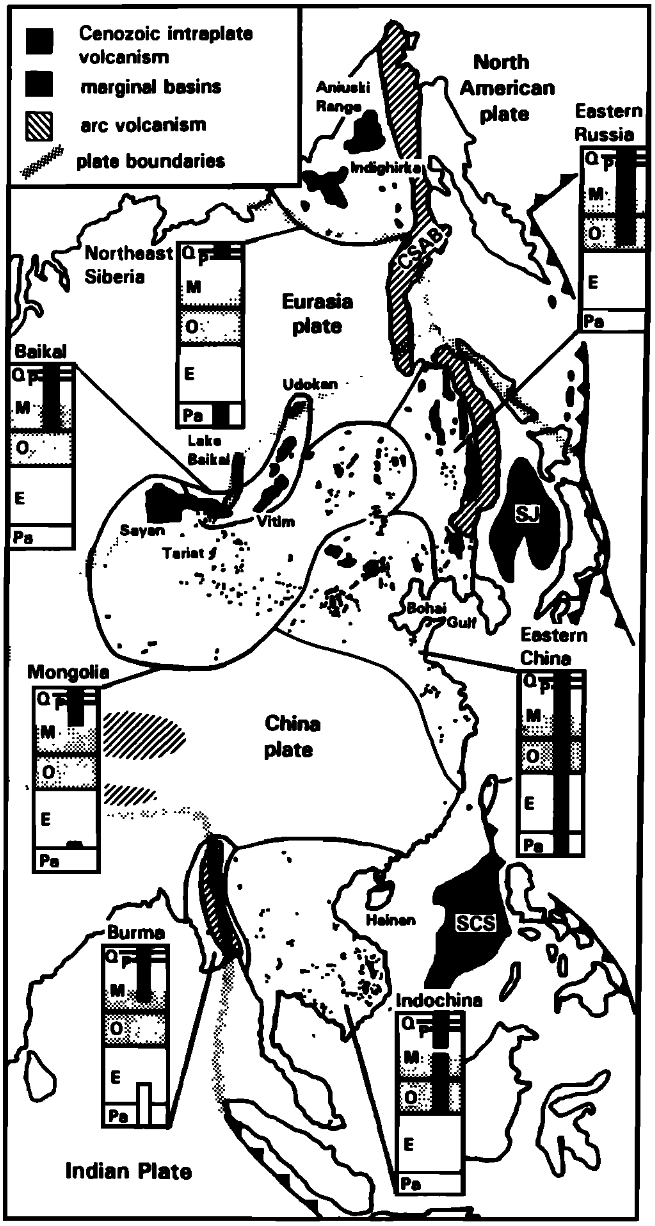


Fig. 2. Distribution of Cenozoic intraplate, arc (CSAB: Chukotki-Sikhote-Alin belt), and marginal basin (SCS: South China Sea, SJ: Sea of Japan) volcanism in Asia. The intraplate volcanism has been grouped into seven domains: northeast Siberia, eastern Russia, Baikal, eastern China, Mongolia, Indochina, and Burma (after *Whitford-Stark* [1987]). The timing of volcanism (Pa: Paleocene, E: Eocene, O: Oligocene, M: Miocene; Pliocene, Q: Quaternary) is depicted relative to the duration of extrusion tectonics (shaded, after *Molnar and Tapponnier* [1975]) caused by the impact of India into south Asia.

been that plumes must exist, yet provides a clear demonstration that plume models can not be developed into a comprehensive geodynamic model for the origin of intraplate volcanism. The only way to avoid such duplicatiôn is to derive intraplate volcansim globally from shallow-level sources [*Smith*, 1993; *Lewis and Smith*, 1995; *Anderson*, 1994, 1996]. Rather than exploring further variations to the plume model, the intraplate volcanism in Asia can be used to illustrate the evolution of shallow-level domains and to provide clues as to how they may be tapped by non-plume processes.

## INTRAPLATE VOLCANISM IN ASIA: BACKGROUND

Syntheses of the volcanism by region throughout Asia have been given by *Whitford-Stark* [1987] and *Zhou et al.* [1988]. A simplified grouping into seven provinces (northeast Siberia, eastern Russia, Baikal, Mongolia, eastern China, Indochina, and Burma) based on these works is shown in Figure 2. Post-spreading volcanism in the Sea of Japan [*Tatsumoto and Nakamura*, 1991] and the South China Sea [*Tu et al.*, 1991] is included with the eastern Russia and Indochina provinces, respectively. Subordinate intraplate volcanism also occurred along with calc-alkaline volcanism in Tibet where it can be related to back-arc extension and/or delamination of the subducting Indian plate [*Zhou et al.*, 1988]; however the distribution of intraplate volcanism in this province is poorly known [*Whitford-Stark*, 1987] and will not be considered further.

Early Cenozoic volcanism was concentrated largely along the eastern continental margin. Paleocene to Oligocene basin-filling tholeiitic to transitional basalts occur in the Bohai Gulf region of the eastern China province [*Zhou et al.*, 1988; *Fan and Hooper*, 1991] and Paleocene potasssic basalts are found in the Aniuski range of the northeast Siberian province. However, there are small amounts of Eocene basalt in the extreme west of the Mongolian province [*Whitford-Stark*, 1987], and late Cretaceous to Paleocene basalts and pyroclastic rocks are found in the Baikal province [*Kiselev et al.*, 1978]. The most widespread phase of volcanism occurred from the Miocene to Recent. In Burma and eastern China, Miocene tholeiitic and alkaline basalts were erupted in proximity to major fault systems [*Zhou et al.*, 1988]. Likewise in the Baikal province, the Miocene marks a major pulse of activity with tholeiitic, transitional, and alkaline basalts erupted in the Sayan and Vitim areas, and a basalt-trachyte sequence on the Udokan plateau [*Kiselev et al.*, 1978; *Zonenshain and Savostin*, 1981]. Volcanism commenced in the Indochina province in the mid to late Miocene with the eruption of tholeiitic followed by alkaline basalts in Vietnam, Laos, Cambodia and Thailand [*Barr and Macdonald*, 1979, 1981; *Intasopa et al.*, 1995; *Hoang et al.*, 1996; *Mukasa et al.*, 1996]. On Hainan Island in this province, volcanism began in the Quaternary, though displaying a similar eruption sequence [*Fan and Hooper*, 1991; *Tu et al.*, 1992]. Pleistocene to Recent volcanism also occurred throughout the Mongolian province where trachybasalt associations predominate and in northeast Siberia where hawaiites are common [*Whitford-Stark*, 1987].

Several common trends may be identified between the provinces. The volcanism at any locality rarely exceeds a volume of 1000 km$^3$, although basalts around the Bohai Gulf have been considered to represent a flood basalt province [*Zhou et al.*, 1988]. At most localities the progression is from tholeiitic or transitional basalts to increasingly alkaline varieties over time. This progression occurs irrespective of the size of the province; similar eruption sequences are noted for the relatively large volume eruptions in eastern China or on Hainan Island and for the Denchai basalt of Thailand where the total volume [*Barr and Macdonald*, 1979] is of the order of 2 km$^3$. Trace element profiles are characterised by incompatible element enrichments similar to DUPAL ocean island basalts [*Liu et al.*, 1994]. Isotopic compositions clearly show the role of the DUPAL components EM1 and EM2 in the generation of the basalts. (Figures 3, 4). EM1 predominates in the eastern China and Mongolia provinces, whereas EM2 predominates in Indochina. Lead isotopic compositions lie above the Northern Hemisphere Reference Line of *Hart* [1984] and most would be classified as DUPAL according to the $\Delta 8/4 > +60$ criterion of *Hart* [1988]. Nonetheless, there has been some uncertainty [*Mukasa et al.*, 1996] as to whether the signatures are directly equivalent to those in the southern hemisphere DUPAL belt on account of $^{87}Sr/^{86}Sr$ ratios, particulary in the Indochina province, falling below the ratio of 0.7050 defined by *Hart* [1988].

Mantle xenoliths are common in the Miocene to Recent lavas [*Kiselev et al.*, 1978; *Preß et al.*, 1986; *Fan and Hooper*, 1989; *Song and Frey*, 1989; *Tatsumoto et al.*, 1992; *Chung et al.*, 1995b; *Zhang et al.*, 1996]. Xenolith types include dunite, harzburgite, spinel lherzolite, and garnet lherzolite, with the more-depleted compositions tending to characterise the mantle beneath the eastern continental margin [*Fan and Hooper*, 1989]. Amphibole and phlogopite are recorded in xenoliths and as megacrysts at many localities. Many xenoliths have DM isotopic compositions, although those containing hydrous minerals often have similar isotopic compositions to the basalts [*Stosch et al.*, 1986; *Song and Frey*, 1989; *Tatsumoto et al.*, 1992; *Chung et al.*, 1995b]. The frequent occurrence of mantle xenoliths, similarities in isotopic signatures between basalts erupted through continental lithosphere and those erupted through oceanic or severely attenuated continental crust, and oxygen isotope compositions within the range of mantle values have been used as arguments against crustal contamination [*Zhou et al.*, 1988].

## MODELS FOR THE ORIGIN OF INTRAPLATE VOLCANISM IN ASIA

### *Hotspots and Plumes*

Following the initial development of the hotspot hypothesis, 15 hotspots were assigned by *Burke and Wilson* [1976] to account for intraplate volcanism in Asia (Figure 5). Another could perhaps be added to account for the opening of the Sea of Japan [*Nakamura et al.*, 1989; *Iwamori*, 1991]. Sixteen hotspots corresponds to 13% of the world total in the compilation of *Burke and Wilson* [1976], although the number of, and what constitutes a hotspot is very subjective. *Crough and Jurdy* [1980] reduced the number of hotspots to 42. These have been reported as showing a good correlation with lower mantle P-wave velocity and the geoid, thereby lending support to the plume hypothesis [*Castillo*, 1988; *Duncan and Richards*, 1991]. As the basaltic volcanism in Asia is little different in terms of chemical composition and eruption morphology to intraplate volcanism in other parts of the world which has been ascribed to plumes, consistency of modelling then requires putting plumes under Asia. An absence of linear age progressions has not prevented application of plume models to ocean island chains such as the Cook-Austral-Marquesas islands [*Okal and Batiza*, 1987] so is not necessarily a fatal blow to the plume model in Asia. However, there is no correlation between seismically slow (hot) regions in the mantle below Asia with any of the depths that have previously been considered for plume generation (Figure 5). Thirteen of the 16 hotspots overlie cold regions at the base of the upper mantle and all overlie cold mantle at the core-mantle boundary. Moreover, a classic "Catch-22" situation emerges in that the addition of plumes to Asia would upset the correlations with the geoid and P-wave structure emphasized by *Duncan and Richards* [1991]. The ten plumes that would be required in the eastern China, eastern Russia, Mongolia, and northeast Siberia provinces would all be

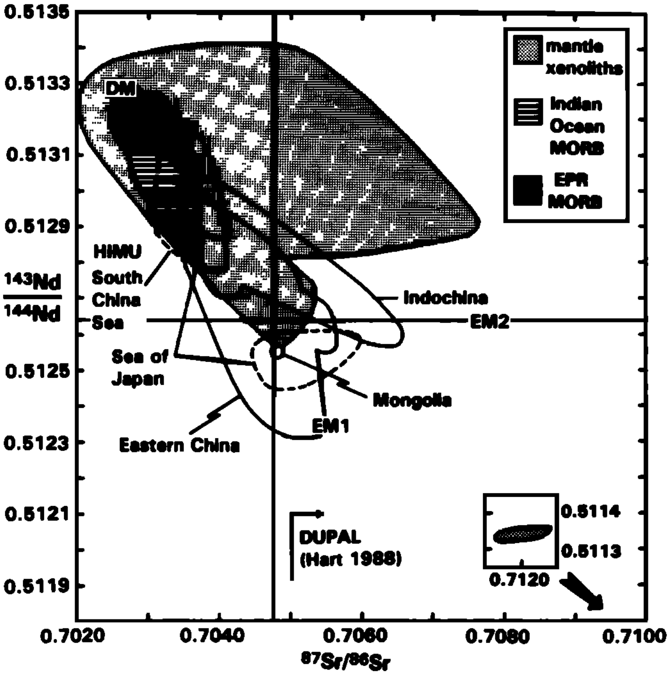


Fig. 3. Nd-Sr isotope compositions of intraplate volcanism, mantle xenoliths, and marginal basin basalts according to the domains depicted in Figure 2. The depleted mantle (DM), bulk Earth (BE), enriched mantle (EM1 and EM2), and high $\mu$ (HIMU) mantle components of *Hart* [1988] are shown for reference. Data sources: Indian Ocean MORB: *Ito et al.* [1987], *Dosso et al.* [1988], *Mahoney et al.* [1989]; eastern China: *Peng et al.* [1986], *Basu et al.* [1991], *Tatsumoto et al.* [1992], *Chung et al.* [1995a, b]; Mongolia: *Stosch et al.* [1986]; Indochina: *Tu et al.* [1991], *Intasopa et al.* [1995], *Mukasa et al.* [1996], *Hoang et al.* [1996]; Sea of Japan: *Tatsumoto and Nakamura* [1991]; South China Sea: *Jahn* [1986], *Chung and Sun* [1992], *Tu et al.* [1992].

associated with strongly negative (-20 to -60 m; Figure 1) geoid anomalies. Only in eastern Indochina and Borneo would hotspots be associated with a significant positive geoid anomaly, with the result that in the Pacific region there would be more hotspots associated with negative geoid anomalies than positive geoid anomalies.

### *Hotcell Models*

*Miyashiro* [1986] and *Zonenshain et al.* [1991] considered the thermal input for generation of intraplate volcanism in Asia to come from hotcells (hotfields at the surface) in the shallow mantle (Figure 6). Hotcells are large-scale features with dimensions much greater than the 1000-2000 km diameters [*White and McKenzie*, 1989; *Duncan and Richards*, 1991] postulated for plume heads, and are usually considered to arise due to thermal insulation from the continental lithosphere or from the absence of cooling of the mantle by subduction [*Anderson*, 1994]. The concept of large regions of thermally anomalous mantle under Asia is supported by high heat flow values [*Barr and Macdonald*, 1981; *Ye et al.*, 1985; *Liu*, 1987; *Tian et al.*, 1992] and observations from seismic tomography which indicate hot mantle at depths as shallow as 38 km in the Baikal, eastern China and Indochina provinces (Figure 6) [*Anderson et al.*, 1992a, b]. The thermal anomaly extending from northeast China to the Lake Baikal region correlates well with the extent of the Mongol-Okhotsk fold belt (Figure 7). Geothermobarometric studies of mantle xenoliths from eastern China indicate a thermal profile comparable to under oceanic lithosphere [*Fan and Hooper*, 1989] while in the Tariat region of Mongolia (Figure 2) the continental mantle geotherm [*Ionov and O'Reilly*, 1996] is equivalent to that under an ocean ridge (Figure 8).

### *Large-Scale Plate Interactions*

The intraplate volcanism in Asia shows an excellent correlation with lithospheric structure, with most basalts erupted along pre-existing lines of weakness through cratons, or along craton boundaries, sutures or fault systems (Figure 7). Most models [*e.g. Zhou et al.*, 1988; *Basu et al.*, 1991; *Zartman et al.*, 1991; *Tu et al.*, 1991, 1992; *Chung et al.*, 1994, 1995a, b; *Flower et al.*, 1996; *Hoang et al.*, 1996] have therefore focussed on generation of melts from continental mantle or enriched "plum pudding"-type asthenospheric sources formed by erosion of continental mantle, tapped in response to large-scale plate interactions. The latter may be divided into two principal events:

(1) Interactions between the Pacific and China plates. Early Cenozoic volcanism in the northeast Siberia and eastern China provinces lies in a back-arc setting relative to the Chukotki-Sikhote-Alin arc [*Parfenov and Natal'in*, 1979; *Whitford-Stark*, 1987; *Zonenshain et al.*, 1990] (Figure 2). Back-arc convection is likely to have played a role in the development of the extensional basins which generally followed pre-existing structures in these regions [*Gilder et al.*, 1991]. Arc activity declined along the Chukotki-Sikhote-Alin belt during the Eocene and Oligocene with the development of the present day convergent margin to the east, and by the Miocene the former arc region itself lay in the back-arc region [*Whitford-Stark*, 1987]. Intraplate volcanism associated with NE-SW trending faults of the Tan-Lu system and its northward extensions into Russia may mark the waning phases of the original back-arc convection regime.

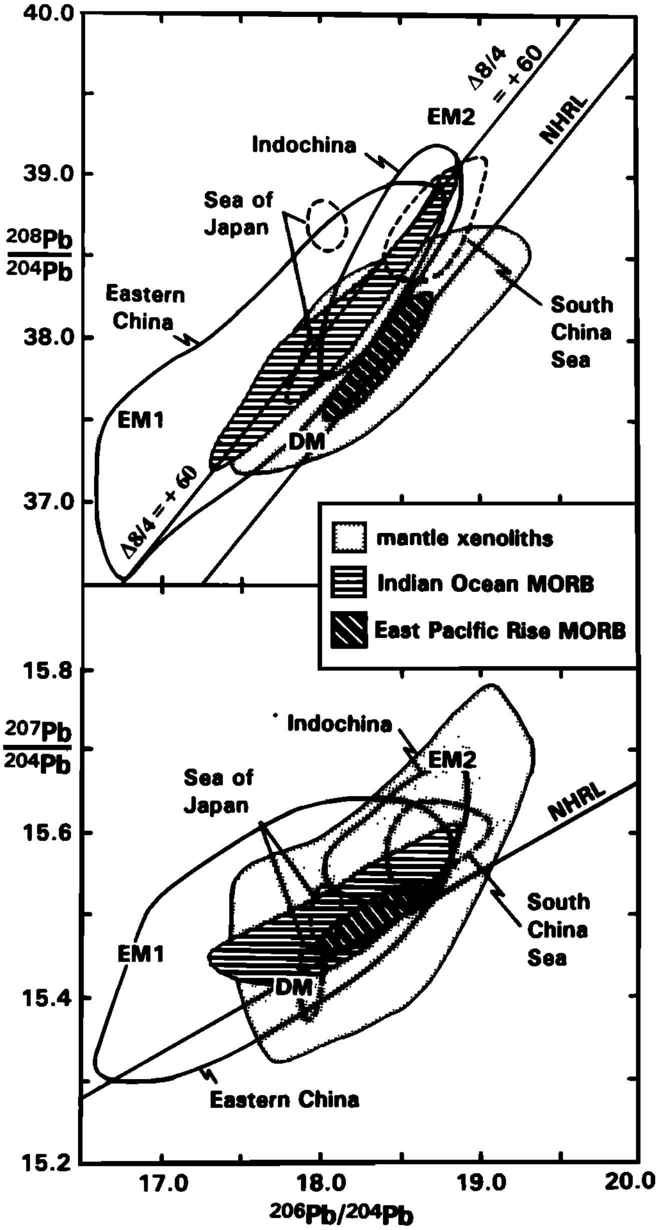


Fig. 4. Pb-Pb isotopic signatures of intraplate volcanism, mantle xenoliths, and marginal basin basalts according to the domains depicted in Figure 2. The Northern Hemisphere Reference Line (NHRL) and Δ8/4 = + 60 definition of *Hart* [1984] are shown for reference. Data sources as for Figure 3. Compositions of mantle components are from *Hart* [1988] except for EM1 which is depicted to lower $^{206}Pb/^{204}Pb$ as suggested from the data for basalts in eastern China.

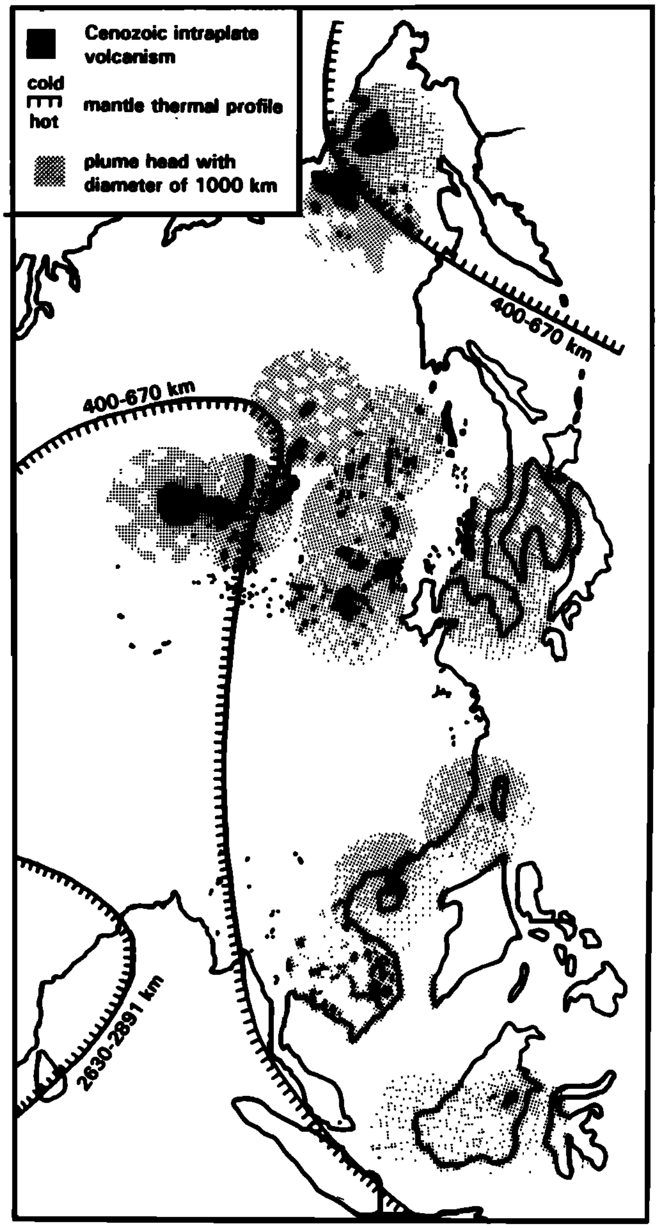


Fig. 5. Distribution of Cenozoic intraplate volcanism in Asia portrayed in terms of arrival of circular plume heads of 1000 km diameter (cf. *White and McKenzie* [1989]). At least 16 plumes are required. Positions of plumes has been interpreted from *Stefanick and Jurdy* [1984] and *Nakamura et al.* [1989]. Hatched contours indicate the extent of seismically slow (hot) regions at potential plume source depths at the base of the upper mantle and core mantle-boundary as deduced by seismic tomography (after *Tanimoto* [1990]).

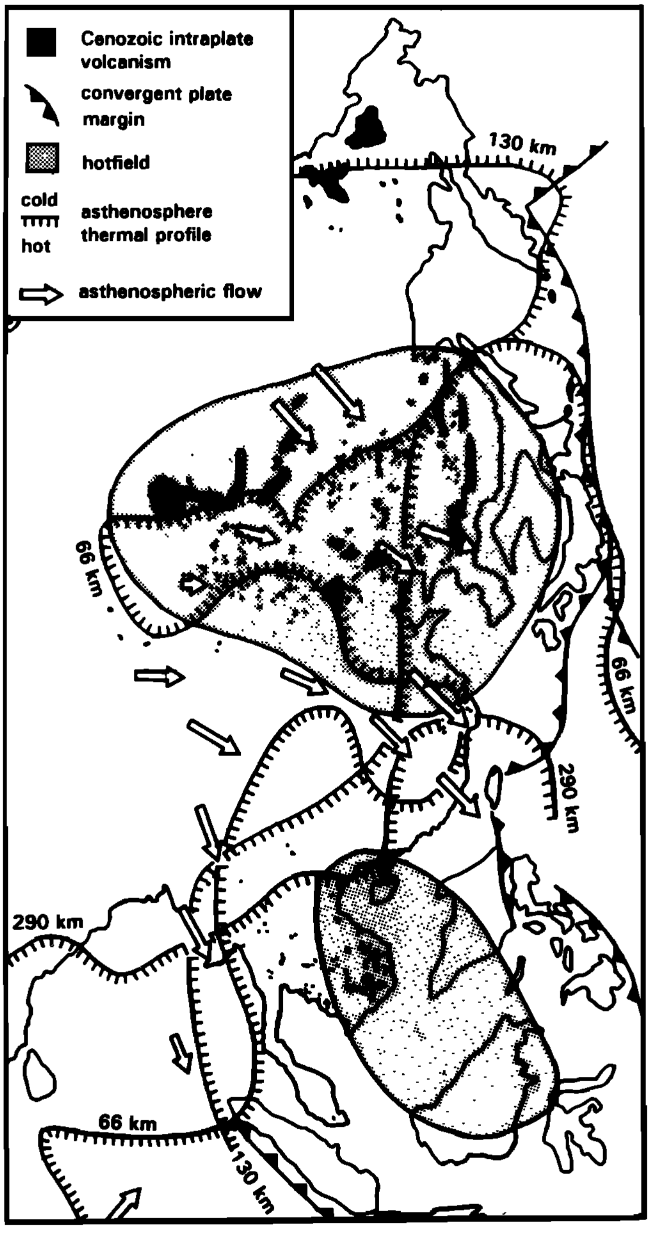


Fig. 6. Intraplate volcanism in Asia relative to the hotcell models of *Miyashiro* [1986] and *Zonenshain et al.* [1991]. Hatched contours indicate the extent of seismically slow (hot) asthenosphere as deduced by tomography (after *Anderson et al.* [1992a, b]). Asthenospheric flow directions (length of arrow indicates relative velocity) are based on the azimuthal anisotropy directions of *Montagner and Tanimoto* [1991].

(2) Fracturing of the China plate in response to the collision of India. The response of continental blocks to the impact of India into southern Asia in the Eocene has been termed "extrusion tectonics" [*Molnar and Tapponnier*, 1975]. Due to the rigidity of the Eurasian plate, deformation propagated through the China plate reactivating boundaries between recently amalgamated continental blocks. The microplates thus formed underwent rotation and easterly or southeasterly extrusion. The northern limit of deformation corresponds to the margin of the Siberian platform. *Zonenshain and Savostin* [1981] postulated fracturing followed this line because of lithospheric weakening by pre-existing asthenospheric upwelling in the Lake Baikal region. Interactions along microplate boundaries were complex with some becoming compressional while others acted as transform boundaries [*Zonenshain and Savostin*, 1981]. Intraplate volcanism in the Mongolian province largely followed the latter type of microplate boundary. The Baikal province represents the only region where the movement on the microplate boundaries was purely extensional, hence the greater amounts of volcanism in this region. To the east of the collision zone, the Indochina microplate underwent southward translation and clockwise rotation. The impact of India also led to the development or reactivation of several suture and fault systems in southeast Asia. Despite the presence of P-MORB compositions in the South China Sea [*Jahn*, 1986], a ready structural explanation exists whereby opening of this basin takes place by left-lateral motion along the Red River fault, and the tectonics of the basin have not been ascribed to plumes as for the Sea of Japan. In Thailand volcanism was associated with graben development and largely follows the Dien Bien Phu suture [*Whitford-Stark*, 1987]. Volcanism in Burma accompanied strike-slip motion on the Sagaing fault system which can be considered the boundary between the Indian and China plates (Figure 7).

## COMPATIBILITY OF MODELS

A combination of the hotcell and large-scale plate interaction models above would appear to offer the most comprehensive explanation for the volcanism, particularly from the correlations noted between hotcell outline and lithospheric structure. Most studies concur that the EM1 signature in Asia can be equated with ancient continental


Fig. 7. Distribution of Cenozoic intraplate volcanism relative to the principal tectonic and structural features of the continental lithosphere of Asia. Outlines of cratonic blocks (SP Siberian, SK Sino-Korean, OM Omolon, KB Khingan-Bureya, IC Indochina, YC Yangtze, TR Tarim, KZ Khazakstan, IN Indian) are from *Maruyama et al.* [1989], *Zonenshain et al.* [1990], and *Goodwin* [1991]. Fault systems (1 Taihang, 2 Tan-Lu, 3 Red River, 4 Sagaing) and sutures are from *Hutchison* [1989], *Zonenshain et al.* [1990], *Tian et al.* [1992], and *Xu et al.* [1993]. The China plate can also be divided into microplates (DZ, Dzungarian, MN Mongolian, AM Amurian) formed by the impact of India into southern Asia (after *Zonenshain and Savostin* [1981]). Other plates: PA Pacific, PH Philippine Sea, NA North American, OK Okhotsk microplate. Fold belts: VKB Verkhoyansk-Kolymian belt, MOFB Mongol-Okhotsk fold belt, SCFB South China fold belt. Section X-Y (Siberian platform to Philippine Sea) is shown in Figure 9.

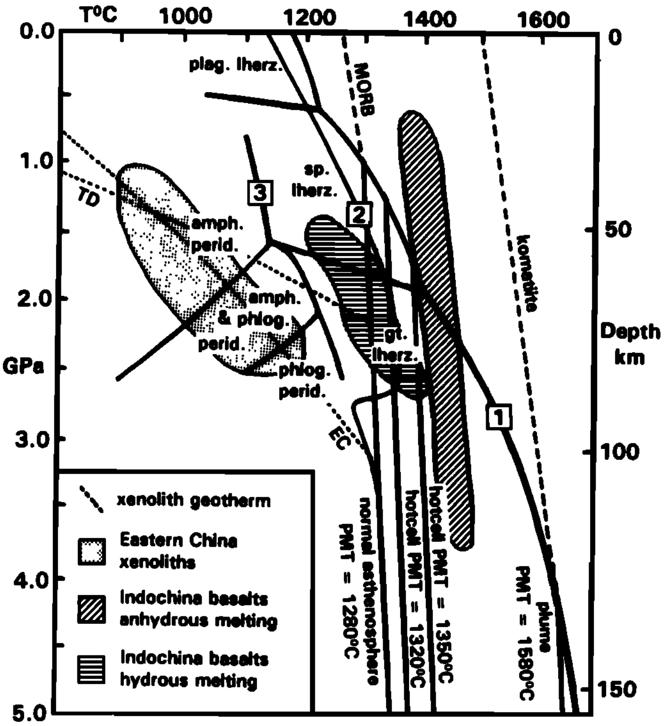


Fig. 8. Pressure-temperature estimates for mantle xenoliths [*Fan and Hooper*, 1989] and primitive basaltic melts [*Flower et al.*, 1996] from eastern China and Indochina relative to the anhydrous (1), carbonated (2), and hydrous (3) peridotite solidii (after *Morse* [1980], *Takahashi* [1990], and *Menner and Dunn* [1995]). Continental mantle geotherms for eastern China and Mongolia (Tariat Depression) are from *Fan and Hooper* [1989] and *Ionov and O'Reilly* [1996], respectively. Interaction of even a normal asthenospheric adiabat (potential temperature 1280°C; e.g. *Takahashi* [1990]) with continental mantle in either of these two regions would have been sufficient to initiate melting of hydrous peridotite. The elevation of asthenospheric temperatures by 40-70° under Indochina is attributed to development of hotcell conditions. In contrast, a plume rising to the base of the continental mantle beneath Asia (80 km depth) would be expected to produce komatiite from the equivalence of the plume geotherm (potential temperature 1580°C; *Saunders et al.* [1992]) and komatiitic liquid line of ascent of *Takahashi* [1990].

mantle from under the cratonic regions of the continental blocks [*Tatsumoto et al.*, 1992; *Chung et al.*, 1994, 1995a; *Hoang et al.*, 1996; *Zhang et al.*, 1996]. The margins of cratons would be subject to metasomatism during subduction events. While amphibole and phlogopite are expected to be stabilised in the mantle wedge, phlogopite would be more likely to survive the thermal rebound following removal of the slab after the cessation of subduction. Breakdown of amphibole and its recrystallisation at shallower depths is suggested as one possible cause of generation of EM1 signatures on account of the lower Rb/Sr ratios of this mineral relative to phlogopite. Alternatively, EM1 may be related to metasomatism by carbonate-rich melts [e.g. *Brandon et al.*, 1995].

The origin of the EM2 component has been more problematic since this signature more typically characterises arc volcanism. In the classic arc model the mantle wedge is infiltrated by fluids containing large ion lithophile elements and light rare earth elements while high field strength elements (HFSE) are retained in the subducting slab. The high Nb abundances of basalts in Asia have therefore been attributed to contamination of the continental mantle sources with subducted sediment [*Tu et al.*, 1991; *Flower et al.*, 1992; *Mukasa et al.*, 1996]. However, recent models [*Kelemen et al.*, 1992, 1993] have suggested that the fluids/melt migrating from the slab are not depleted in HFSE, but that the depletion in such elements observed in arc magmas is a result of their retention in the mantle wedge. In this model, olivine rich melts undergo a series of reactions with the mantle wedge peridotite to form clinopyroxene-rich melt plus a dunite or harzburgite residue in which HFSE are retained in minerals such as orthopyroxene. High abundances of Nb in mantle xenoliths from regions where subduction has taken place [*Sun and Kerrich*, 1995], and evidence for equilbration of primitive arc and intraplate melts with harzburgitic rather than lherzolitic residues as for MORB [*Francis*, 1995], are consistent with this model. The isotopic compositions of mantle xenoliths from Asia [*Stosch et al.*, 1986; *Tatsumoto et al.*, 1992] demonstrate that phlogopite carries and retains an EM2 signature for hundreds of millions of years. After the cessation of subduction, the remnant arc source would thus have an EM2 signature and be enriched in HFSE such that it is not necessary to invoke mixing of sediment into the continental mantle.

Other than for Asia, continental mantle has only rarely been invoked as an important source for intraplate volcanism. The reluctance to consider such material can be attributed in part to this reservoir having generally been equated with lithosphere, which by definition is strong, cold, and hence likely refractory. The volcanism in Asia might thus appear consistent with the image of the continental mantle perpetuated in plume models, with the low volumes of basalt reflecting the absence of the thermal input of a plume. However, similar isotopic signatures are then required to reside at greatly different levels (plume source and continental mantle) in the mantle. At first sight a possible solution to this problem would be to follow the model of *McKenzie and O'Nions* [1983] and envisage the continental mantle of Asia to represent evolving DUPAL material which could potentially be delaminated and incorporated into a plume source [*Basu et al.*, 1991; *Tatsumoto and Nakamura*, 1991; *Mukasa et al.*, 1996]. However, numerically there are more examples of intraplate volcanism dominated by the EM endmembers rather than HIMU which is supposed to be recycled oceanic crust. EM1 predominates in the most voluminous examples of intraplate volcanism such as the Ontong Java oceanic plateau [*Mahoney and Spencer*, 1991] and flood basalt provinces such as the Deccan Traps [*Peng and Mahoney*, 1995] whereas the HIMU endmember is found in only a few, volumetrically minor ocean islands such as St. Helena and Mangaia. Considering that the concentrations of Nd, Sr, Pb are thought to be comparable in the various isotopic components [*Hart*, 1988], the implication is that delaminated continental mantle would have to be more prevalent in the plume source than subducted oceanic crust. And even if incorporation of continental mantle into a plume source was a plausible process, the volcanism in Asia would still require that it be necessary to generate identical types of melt by plume and non-plume mechanisms. No other category of volcanism (ocean ridge or arc) requires such duplication of models.

A much more straightforward possibility is that continental mantle is merely eroded into the asthenosphere to form shallow-level domains of enriched mantle which are then tapped by non-plume processes [*Smith*, 1993; *Anderson*, 1994, 1996]. Such domains would become displaced from the continent under which they form by westward migration of lithosphere relative to the underlying mantle. This effect is a consequence of Earth rotation and produces a net eastward mantle flow of up to 5 cm $y^{-1}$ depending on latitude [*LePichon*, 1968; *Doglioni*, 1990; *Ricard et al.*, 1991; *Smith*, 1993]. Such domains can be tapped to generate intraplate volcanism by shear melting in response to stress fields imposed by large-scale plate interactions [e.g. *Jackson and Shaw*, 1975; *Lewis and Smith*, 1995] such that deep-seated sources (plumes) become unnecessary to account for the occurrence of intraplate volcanism in either the oceanic or continental regime. In this type of model, the isotopic provinciality of Asia becomes a function of the history of the lithospheric blocks which make up the region, while the "differential rotation" mechanism offers an explanation for the generation and location of volcanism.

## EVOLUTION OF THE CONTINENTAL MANTLE UNDER ASIA

In the early Paleozoic, most of the cratonic fragments now lying south of the Siberian platform were part of eastern and northeastern Gondwana. The North China block comprising the Sino-Korean craton and surrounding early Paleozoic belts, lay to the east of Antarctica, with which it had collided in the Ordovician [*Smith et al.*, 1997]. The South China and Tarim blocks, along with Indochina and Indonesia, are usually placed adjacent to Australia [e.g. *Coney*, 1990]. Fragmentation of eastern Gondwana began in the early Devonian with the rifting of the North China block from the region [*Coney*, 1990; *Smith et al.*, 1997], and continued through the Permian and Triassic when the terranes of southeast Asia migrated across Tethys [*Hutchison*, 1989]. *Menzies et al.* [1993] have shown that the eastern part of the North China block lost more than 120 km of continental mantle at some stage between the Ordovician and Cenozoic. While the tendency has been to regard this loss as a late Mesozoic or Cenozoic event [e.g. *Liu*, 1987], analogy with the model of *Mahoney et al.* [1989] for the Indian Ocean suggests loss of continental mantle would be more likely to have taken place during the breakup of Gondwana. The detached thermal boundary layer material is suggested as the source of South Pacific intraplate volcanism [*Lewis and Smith*, 1995].

Amalgamation of Asia began with the accretion of massifs in the Mongol-Okhotsk fold belt to the Siberian platform in the mid Paleozoic, followed by the collision of South China and North China in the Permian and Triassic [*e.g. Zonenshain et al.*, 1990]. Subsequent interactions with the Farallon and Izanagi plates led to NNW-directed subduction along the eastern margin of Asia from the late Jurassic to the early Cretaceous [*Parfenov and Natal'in*, 1979]. The highly oblique nature of the plate interactions has been suggested as a cause for faulting in the Tan-Lu system [*Xu et al.*, 1993]. Subduction orientated WNW resumed in the late Cretaceous [*Liu*, 1987; *Maruyama et al.*, 1989; *Zonenshain et al.*, 1990; *Tian et al.*, 1992] producing the Chukotki-Sikhote-Alin belt. The presence of a subducting slab along the eastern continental margin would have restricted mantle flow thereby trapping an asthenospheric domain under Asia. Along the eastern continental margin any rise in temperature due to thermal insulation would be countered by the cooling effect of the subducted slab. But under central Asia and Indochina there would be no such cooling effect, allowing a progressive rise in asthenospheric temperatures. Alternative models proposed by *Miyashiro* [1986] involving northward migration of a hotcell now located under eastern China causing the successive opening of the Philippine Sea, South China Sea, and Sea of Japan, or migration of Indian Ocean asthenosphere under Asia [*Hickey-Vargas*, 1995] are considered unlikely. While the differential rotation mechanism offers an explanation for why Indian Ocean asthenosphere should be moving under the western Pacific, mantle flow directions under Asia (Figure 6) as inferred from azimuthal anisotropy are toward the southeast [*Montagner and Tanimoto*, 1991], perpendicular to the direction required for either hotcell or Indian Ocean asthenosphere migration. Subduction of the Indian plate under southwest Asia from at least the middle Jurassic to the late Cenozoic [*Besse and Courtillot*, 1988; *Maruyama et al.*, 1989] would likely have impeded any northwesterly movement of Indian Ocean asthenosphere since flow directions indicate deflection of asthenosphere to the southeast by the current Indonesian subduction zone .

Mantle flow has been suggested as the cause of steepening of westward- as opposed to eastward- directed subducting slabs [*Doglioni*, 1990] and thereby offers a mechanism for extension in the Bohai Gulf and eastern Russia regions which culminated in the opening of the Sea of Japan. As the slab steepened and the subduction zone retreated eastwards, asthenosphere would appear to be injected [cf. *Nodha et al.*, 1988; *Tatsumi et al.*, 1990] into the back-arc region (Figure 9a). Elsewhere in the region, correlation of volcanism with microplate boundaries and cratonic keels suggests the influence of topographic heterogeneites, some of which may date back to the rifting of continental blocks from Gondwana, at the asthenosphere-continental mantle boundary (Figures 9b, c). Rifts which advance furthest toward the basin opening stage tend to be those associated with deep topographic structures lying perpendicular to mantle flow [*Doglioni*, 1990]. Mantle flow around topographic features will set up secondary convection cells within which adiabatic decompression may give rise to the generation of flood basalts [*King and Anderson*, 1995]. A considerable proportion of the volcanism in eastern China lies along the northern boundary of the Sino-Korean craton where a significant change in lithospheric thickness is expected. Similarly, volcanism in northeast Siberia lies along the northwestern margin of the Omolon block (Figure 7). Rifting in the Baikal province occurred perpendicular to the edge of the Siberian craton [*Gao et al.*, 1994] (Figure 7). The structure of this region [*Burmakov et al.*, 1987] suggests a step in lithospheric thickness from ca. 150 km under the Siberian platform to less than 100 km under the Mongol-Okhotsk fold belt. The long-lived asthenospheric upwelling inferred beneath this region by *Zonenshain and Savostin* [1981] becomes a consequence of this variation in lithospheric thickness. Volcanism in the Vitim and Udokan regions areas to the northeast of Lake Baikal fits a model of a melt generation from a convection cell induced by this topographic feature (Figure 9b,c). Convection cells of the asthenospheric dimensions suggested in Figure 9 have been modelled from seismic tomography to the southwest of the Baikal province [*Kulakov et al.*, 1995].

The convection regimes induced by the topography would serve to erode an already thin continental mantle section such that the thermal anomalies in Figure 6 may represent both the effects of insulation and the rise of asthenosphere to high levels. The xenolith geotherms from the Tariat region and eastern China would be compatible with ascent of normal asthenosphere (potential temperature 1280$^0$C) to depths of 75 to 100 km. The association of EM components with fluid-rich phases suggested earlier results in large thermal anomalies not being necessary for melting. The hydrous (EM2?) and carbonated (EM1?) peridotite solidii lie to significantly lower temperature than the solidus for anhydrous lherzolite and interaction with asthenosphere would be sufficient to induce melting (Figure 8). Hydrous melting conditions under Indochina were favoured by *Flower et al.* [1996]. Calculations for anhydrous conditions in this region yielded asthenospheric potential temperatures of 1480$^0$C but gave an unrealistically large, and often too low a range for the depth of melt segregation. The same pressure-temperature estimates for hydrous melting conditions indicate asthenospheric potential temperatures of less than 1320$^0$C for all but one locality where the potential temperature is 1350$^0$C (Figure 8). The temperature differences for the sources of these basalts at $\Delta T$=40-70$^0$ above the normal asthenosphere adiabat are much lower than the $\Delta T$=300$^0$ estimates [*Saunders et al.*, 1992] for plumes. In contrast, a plume with a potential temperature 1580$^0$ rising to the base of the continental mantle as under Asia, would be expected to produce komatiite from even anhydrous peridotite (Figure 8), and so becomes totally unsuitable for the generation of the small volumes of basalt as found in Asia.

## CONCLUSION

There is no requirement for, and several reasons against interpreting the Cenozoic intraplate volcanism in Asia in

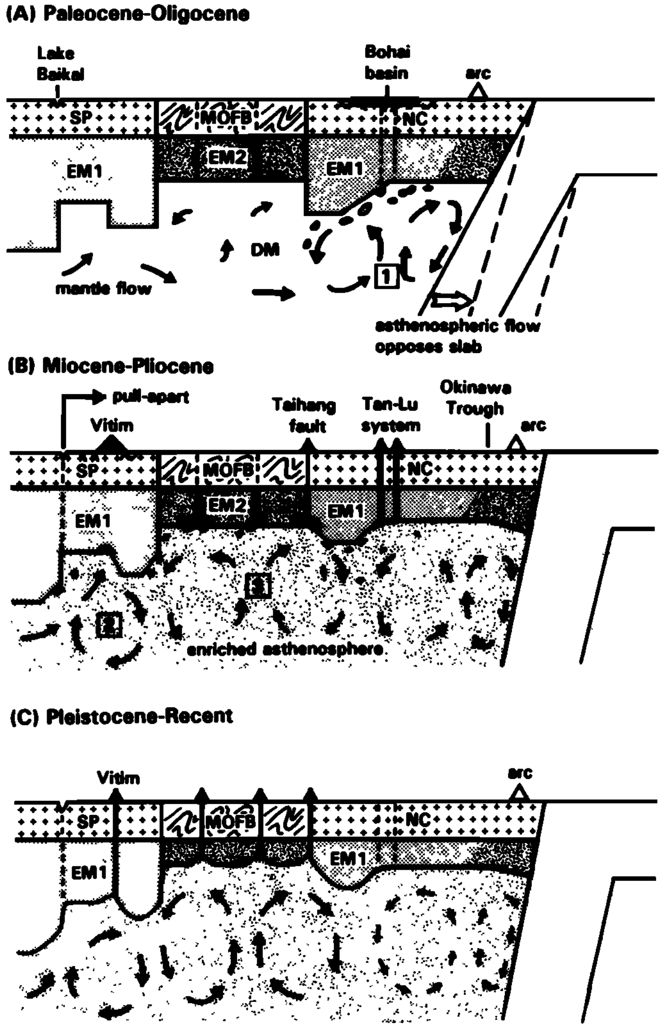


Fig. 9. Origin of intraplate volcanism along the 1700 km section X-Y in Figure 7, based on the model of *King and Anderson* [1995]. The lithosphere of Asia has been simplified into three crustal blocks, Siberian platform (SP), Mongol-Okhotsk fold belt (MOFB), and North China platform (NC), underlain by continental mantle characterised primarily by EM1 or EM2 isotopic signatures. (A) Paleocene-Oligocene. Eastward asthenospheric flow opposes the subducting Pacific plate leading to steepening of the slab and roll-back of the trench. Back-arc convection is accentuated by upwelling induced by a topographic "hole" in the continental mantle formed during the rifting of North China from Gondwana in the Paleozoic. The resulting convection cell (1) in combination with lithospheric stretching from slab roll-back reactivates pre-existing structural weaknesses, culminating in extension and tholeiitic-transitional basaltic volcanism in the Bohai Gulf region. The upwelling also causes a thermal anomaly and the erosion of continental mantle into asthenosphere creating the beginnings of a shallow-level enriched domain (stippled). (B) Miocene-Pliocene. Convection cell 1 wanes as the slab retreats. Basaltic volcanism associated with this cell becomes dominated by small melt fractions derived at deeper levels along the continental mantle-asthenosphere interface, and follows structural weaknesses of the Tan-Lu fault system. Further convection cells (2 and 3) are induced by the imposition of a lithospheric pull-apart regime following the collision of India into Asia on a heterogeneous continental mantle-asthenosphere boundary under the southeastern Siberian platform and Mongol-Okhotsk fold belt. Volcanism in the Baikal province occurs east of the microplate boundary due to the control on the location of melt generation by continental mantle topography. (C) Pleistocene-Recent. Volcanism occurs along sutures and faults throughout the Mongol-Okhotsk fold belt following thinning of the continental mantle. By the present time, the action of the three convection cells has produced an extensive thermal anomaly and enriched domain throughout the upper levels of the asthenosphere under Asia.

terms of mantle plumes. The premises on which the plume model are based make it self-defeating in that addition of hotspots to the region would upset correlations with the geoid which have been used in support of the plume model. The association of volcanism with extensional or transcurrent microplate boundaries and other lithospheric structural features, stand in stark contrast to hotspot models where the number of plumes required is judged from the spatial extent of the volcanism. Instead, the evidence suggests that large-scale interactions between the China, Pacific and Indian plates superimposed on developing hotcell conditions were important controls on the volcanism. The location and timing of volcanism was also influenced by asthenospheric convection cells induced by topographic variation at the continental mantle-asthenosphere boundary. The heterogeneity of this boundary reflects the lithospheric architecture of cratonic roots separated by collision zones. Subduction processes during the amalgamation of the continental blocks imparted an EM2 isotopic signature on an otherwise ancient continental mantle section dominated by EM1. Enrichment of HFSE in the mantle wedge makes amphibole- or phlogopite- bearing peridotite remnants from arc volcanism suitable sources for the generation of intraplate melts. There is therefore no need to invoke some process for the mechanical mixing of subducted sediment into the continental mantle to account for the EM2 signatures.

The model presented is in accord with previous suggestions that isotopic differences between the Asia and southern hemisphere DUPAL domains reflect a relatively recent (Phanerozoic) timing of production of the EM2 signature in Asia. However, considerations of the continental mantle of Asia as material which could potentially be incorporated into a plume source can not avoid the requirement for non-plume mechanisms to generate the intraplate volcanism in Asia. The test of a scientific hypothesis should be its ability to account for all observations to which it pertains. In this respect, it should be noted that plume models must acknowledge the generation of intraplate volcanism by non-plume mechanisms, and so fail to provide a unique geodynamic synthesis for intraplate volcanism worldwide. It is suggested that the only way to avoid duplication of petrogenetic models is to delaminate continental mantle directly into shallow-level domains and tap these by non-plume processes.

*Acknowledgements.* Funded by NSC83-0202-M-006-002. A.D. Brandon, S.-L. Chung, and M. Zhang are thanked for reviews.

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