ELSEVIER

Tectonophysics 333 (2001) 9–34

TECTONOPHYSICS

www.elsevier.com/locate/tecto

Mantle contamination and the Izu-Bonin-Mariana (IBM) 'high-tide mark': evidence for mantle extrusion caused by Tethyan closure

M.F.J. Flower[a,*], R.M. Russo[b], K. Tamaki[c], N. Hoang[c,d]

[a]Department of Earth and Environmental Sciences, University of Illinois at Chicago (m/c 186), 845 W. Taylor Street, Chicago, IL 60607-7059, USA
[b]Department of Geological Sciences, Locy Hall, Northwestern University, Sheridan Road, Evanston, IL 60201, USA
[c]University of Tokyo, Ocean Research Institute, 1-15-1 Minamidai, Nakano, Tokyo 164, Japan
[d]Institute of Geological Sciences, National Center for Science and Technology of Vietnam, Tu Liem, Hanoi, Viet Nam

Received 30 October 1999; revised 31 March 2000

Abstract

Western Pacific basins are characterized by three remarkable attributes: (1) complex kinematic histories linked to global-scale plate interactions; (2) DUPAL-like contaminated mantle; and (3) rapid post-Mesozoic rollback of the confining arc-trench systems. The coincidence of slab steepening, extreme arc curvature, and vigorous basin opening associated with the Mariana convergent margin suggests that rollback continues in response to an east-directed mantle 'wind'. Against a backdrop of conflicting kinematic and genetic interpretations we explore the notion that eastward asthenospheric flow driven by diachronous Tethyan closure caused stretching of eastern Eurasia and concomitant opening of western Pacific basins. Marking the eastern boundary of the latter, the Izu-Bonin-Mariana forearc may be regarded as a litho-tectonic 'high-tide mark' comprising igneous and metamorphic products from successive episodes (since ca. 45 Ma.) of arc sundering and backarc basin opening. The forearc also forms an isotopic boundary separating contaminated western Pacific mantle from the N-MORB Pacific Ocean reservoir. While the isotopic composition of western Pacific mantle resembles that feeding Indian Ocean hotspot and spreading systems, its spatial–temporal variation and the presence of subduction barriers to the south appear to preclude northward flow of Indian Ocean mantle and require an endogenous origin for sub-Eurasian contaminated mantle. It is concluded that the extrusion of Tethyan asthenosphere, contaminated by sub-Asian cratonic lithosphere, was a major cause of western Pacific arc rollback and basin opening. The model is consistent with paleomagnetic and geologic evidence supporting independent kinematic histories for constituent parts of the Philippine Sea and Sunda plates although interpretation of these is speculative. Compounded by effects of the Australia–Indonesia collision, late-Tethyan mantle extrusion appears to have produced the largest DUPAL domain in the northern hemisphere. © 2001 Elsevier Science B.V. All rights reserved.

Keywords: backarc basin; arc rollback; asthenosphere; ophiolite; isotopic anomaly; mantle wind; extrusion

1. Introduction

Recent decades have seen intensive study of backarc basins (Sleep and Toksöz, 1971; Karig, 1971; Uyeda and Kanamori, 1979; Crawford et al., 1981; Hussong and Uyeda, 1981; Tamaki and Honza, 1991; Taylor, 1995 and references therein; Taylor and Natland, 1995) yet despite an accumulation of data from swath bathymetry, side-scan acoustic imagery, multichannel seismics, manned submersibles, and ocean drilling, there is little consensus concerning their genesis. We still

---

* Corresponding author.

0040-1951/01/$ - see front matter © 2001 Elsevier Science B.V. All rights reserved.
PII: S0040-1951(00)00264-X

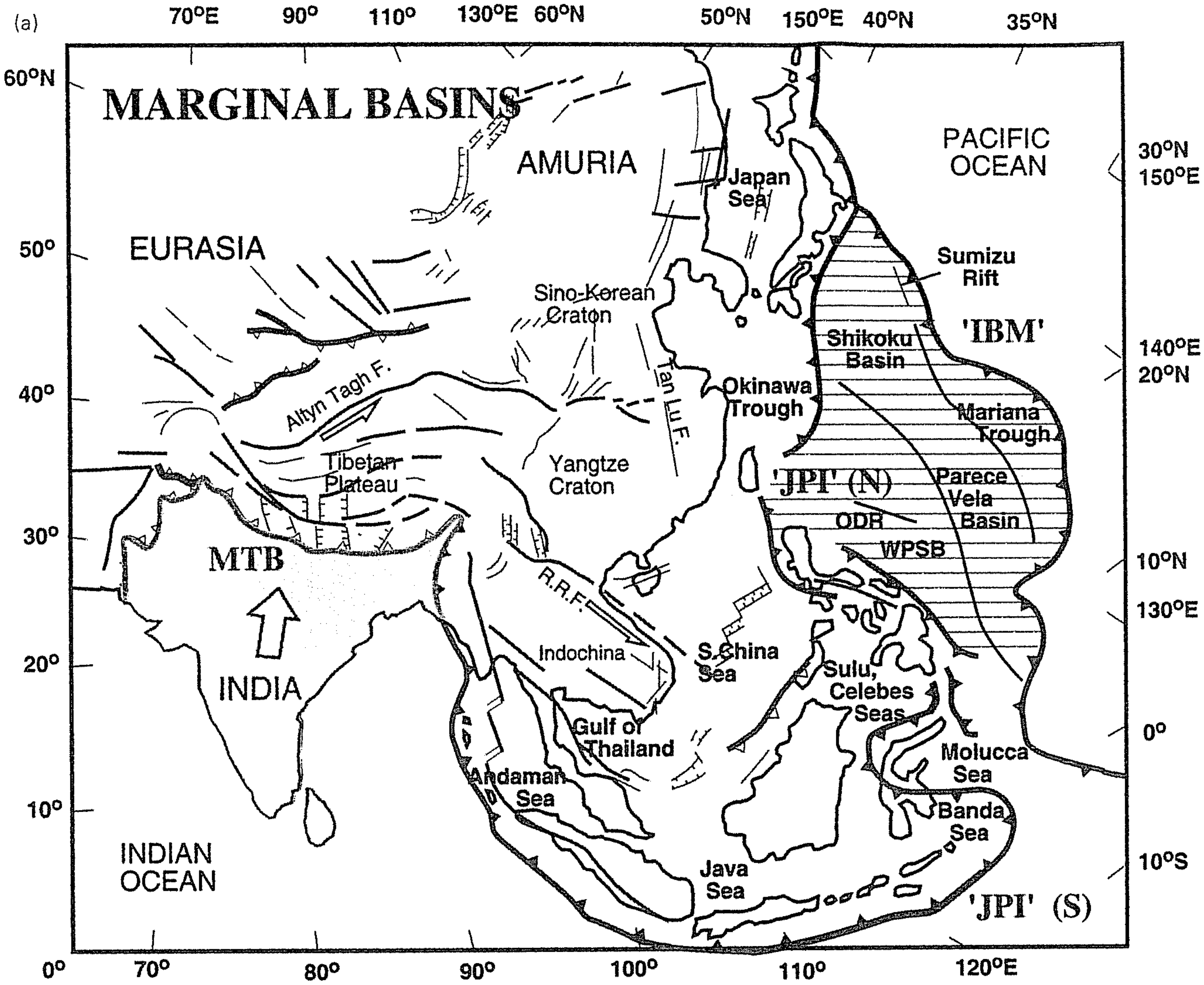

Fig. 1. Maps of eastern Eurasia: (a) marginal basins; (b) volcanic arcs, showing major tectonic features in eastern Eurasia, the western Pacific and northeastern Indian Ocean, Indian indentor (shaded) and Philippine Sea plate (horizontal lines); Major faults shown by thin grey lines, subduction zones (with solid barbs) and thrust zones (open barbs) by thick grey lines. IBM — Izu-Bonin-Mariana line; JPI — Japanese–Philippine–Indonesian line; MTB — Main Thrust Belt of the India-Asian collision; RRF — Red River Fault; WPSB — West Philippine Sea Basin; ODR — Oki Daito Ridge.

debate whether basin opening is an active or passive process with respect to the convecting upper mantle and whether sinking of subducting slabs beneath overriding plates is a cause or effect of backarc basin opening. In many respects these problems are analogous to those addressed by continental dynamic studies. Thin-viscous sheet and extrusion tectonic models (England and Houseman, 1989; Houseman et al., 1981; Houseman and England, 1992; also cf. Tapponnier et al., 1982, 1986) tacitly assume collision-induced plate motions are mechanically decoupled from the convecting asthenosphere (cf. Forsythe and Uyeda, 1975; Alvarez, 1982) although shear-wave splitting (Makeyeva et al., 1992; McNamara et al., 1994; Gao et al., 1994; Russo and Silver, 1996; Russo et al., 1996; Davis, 1996) and numerical buoyancy models (Alvarez, 1982; Davies and von Blanckenburg, 1995; Liu et al., 2000) now suggest collision effects such as crustal thickening and shortening, lateral block displacement, and slab detachment may strongly perturb the ductile mantle.

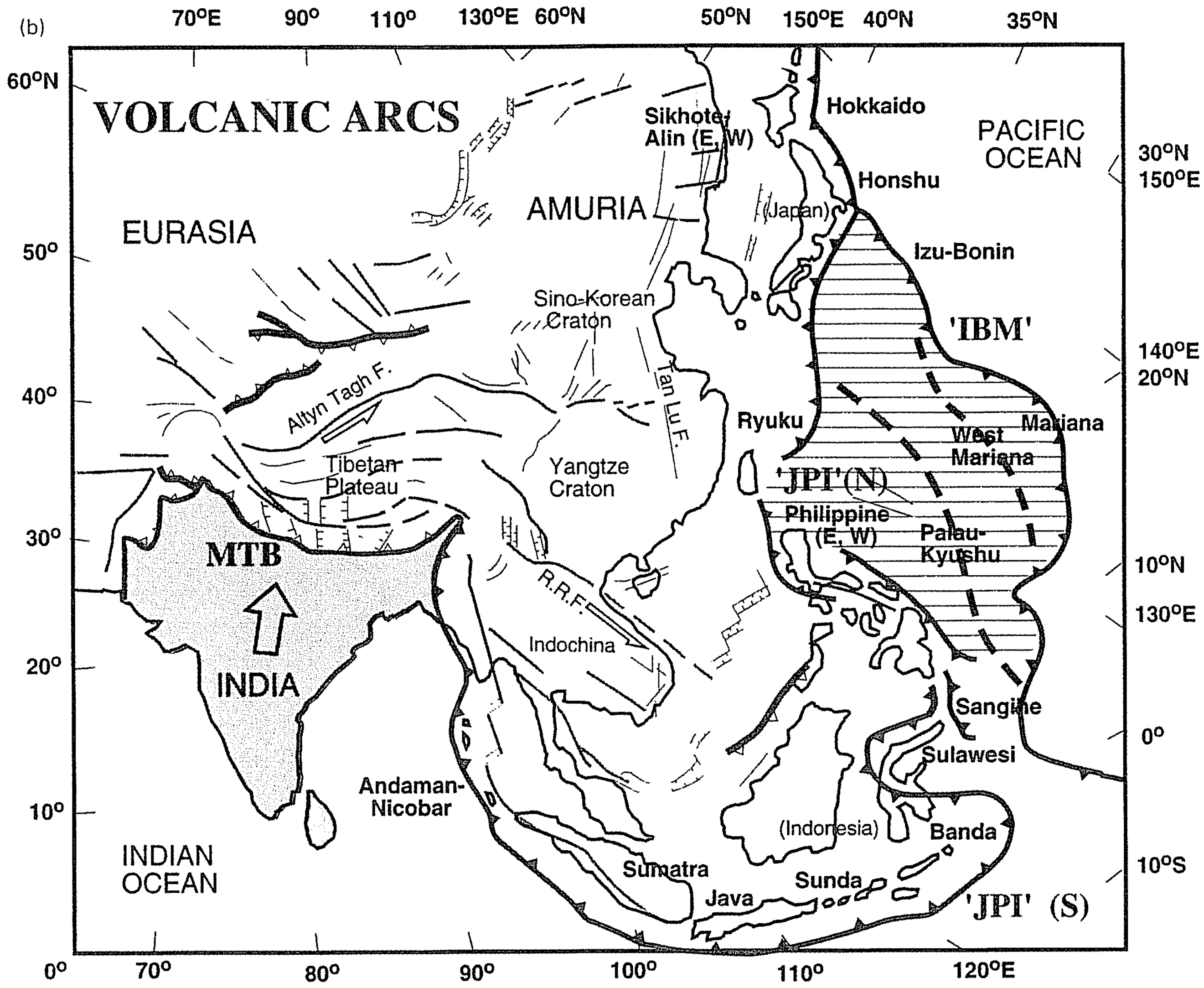

Fig. 1. (*continued*)

After considering possible relationships between the spatial–temporal patterns of western Pacific arc-trench rollback, the petrologic character of the Izu-Bonin-Mariana (IBM) forearc terrane, and the distribution of DUPAL-like (isotopic EM1-rich) mantle (after Dupré and Allegre, 1983; Hart, 1984), we propose a hypothesis that ascribes these features to the eastward extrusion of craton-contaminated asthenosphere during latter stages of Tethyan closure.

2. Backarc basins and subduction rollback

Backarc basins and marginal seas continue to be enigmatic features of subduction-related settings, often difficult to reconcile with the plate tectonic paradigm (Karig, 1971; Uyeda and Kanamori, 1979). Although not all arc-trench systems are complemented by backarc spreading the latter process is invariably associated with the subduction of oceanic lithosphere (Karig, 1971; Uyeda and Kanamori, 1979). In some cases, best exemplified in the western Pacific (Fig. 1a and b), basin opening and arc-trench rollback are propagated by the splitting or 'sundering' of arcs into active and relict components separated by newly opening basins. The precise relationship of backarc basin evolution to subduction is elusive, however, and competing models (reviewed by Uyeda and Kanamori, 1979; Tamaki and Honza, 1991; Taylor, 1995 and references therein; Taylor and Natland, 1995) are usually predicated on the tenuous balance between the velocities of overriding and retreating plates and their respective ages and density characteristics. While some models invoke conventional plate tectonic mechanisms, ascribing back-arc basins to slab-induced mantle upwelling as an exclusive product of subduction (Karig, 1971) (Fig. 2A) or regional plate kinematics (Sleep and Toksöz, 1971) (Fig. 2B), others appeal to random hot cells (Miyashiro, 1986; Tatsumoto and Nakamura, 1991) (Fig. 2C) or passive responses to asthenosphere-driven arc-trench 'rollback' (Uyeda and Kanamori, 1979; Doglioni, 1993; Smith, 1998; Smith and Lewis, 1999) (Fig. 2D and E).

The rollback phenomenon is in any case a problematic feature of convergent margins (Tamaki and Honza, 1991; Royden, 1993, 1996) and appears in various forms in the Mediterranean, Caribbean, and South Scotia Seas, and the western and southwestern Pacific Ocean. The most common explanation invokes gravitational effects resulting from the greater density of older, subducting oceanic lithosphere, and the pressure-induced reaction of basalt to eclogite as a subducting slab sinks, supported by the correspondence of deviatoric stress orientations with the dips of subducting slabs, (Isacks and Molnar, 1971). Royden (1993) invoked 'slab-pull' effects to explain the, often rapid, escape of subduction boundaries into oceanic regions where they form near-isolated, local tectonic systems. In contrast, the coincidence of slab steepening, extreme arc curvature, and vigorous back-arc basin opening in the IBM Mariana sector has suggested to others (Uyeda and Kanamori, 1979; McCabe and Uyeda, 1983) that rollback may reflect an east-directed mantle 'wind'. Arc-trench rollback is conspicuously absent from older and more mature subduction systems although it is particularly active where younger, less dense backarc lithosphere is being subducting (Taylor and Natland, 1995; Taylor, 1995, and references therein). Slab-pull and subduction rollback effects are also seen to diminish sharply or cease altogether following the arrival at a trench of less-dense continental lithosphere (Isacks and Molnar, 1971; Royden, 1993).

The extrusion tectonics hypothesis (Tapponnier et al., 1982, 1986) proposed to explain post-collision lithosphere 'escape' — implies that some marginal basins are generated as a passive response to 'lithosphere-push' escape, and arc–backarc mobility has been linked accordingly (Royden, 1993; Doglioni et al., 1999). For example, western and eastern Mediterranean basins have been attributed to the combined effects of slab-pull and lithosphere extrusion (Faccenna et al., 1996) although others — the South Scotia Sea, the Caribbean, and western and southwestern Pacific basins — are not obviously associated with plate collisions. The classic extrusion model assumes that propagation of motion is confined to the lithosphere, implying that extruded lithospheric blocks drag the underlying plastic asthenosphere (Lavé et al., 1996) rather than undergo traction resulting from mantle flow. Marginal basins such as the South China and Ionian Seas would have opened between discrete blocks of extruded lithosphere thus representing an extensional tectonic effect of 'lithosphere-push' extrusion (Briais et al., 1993; Chung et al., 1997; Lundgren et al., 1998).

In seeking an alternative to lithosphere-push or slab-pull mechanisms, the dominance of backarc basins at eastern rather than western continental margins has been ascribed by some workers (Volpe et al., 1990; Doglioni, 1993; Smith and Lewis, 1999) to global-scale mantle 'wind' produced by the Earth's rotation. Although retreating Euro-Mediterranean plate boundaries appear to be both west- and east-directed, Doglioni et al. (1999) contend that western Mediterranean basins such as the Alboran Sea reflect eastward rollback of the west-directed Apennine-Adria subduction zone. Similarly, Smith and Lewis (1999) attributed western Pacific DUPAL-like mantle to asthenospheric drag resulting from westward displacement of the Eurasian and Australian plates. Recently, Tamaki (1995) proposed that backarc basin evolution in the western Pacific could be explained by the lateral displacement, or 'extrusion', of asthenospheric mantle in response to the closure of Tethys. This idea has far-reaching implications and was invoked by Flower et al. (1998) as a way to explain dispersed intraplate volcanism and the existence of widespread DUPAL-like mantle contamination beneath the eastern Eurasia–western Pacific region while Liu et al. (2000), on the basis of 2D numerical models, showed that lithosphere injection beneath Tibet causes significant mantle

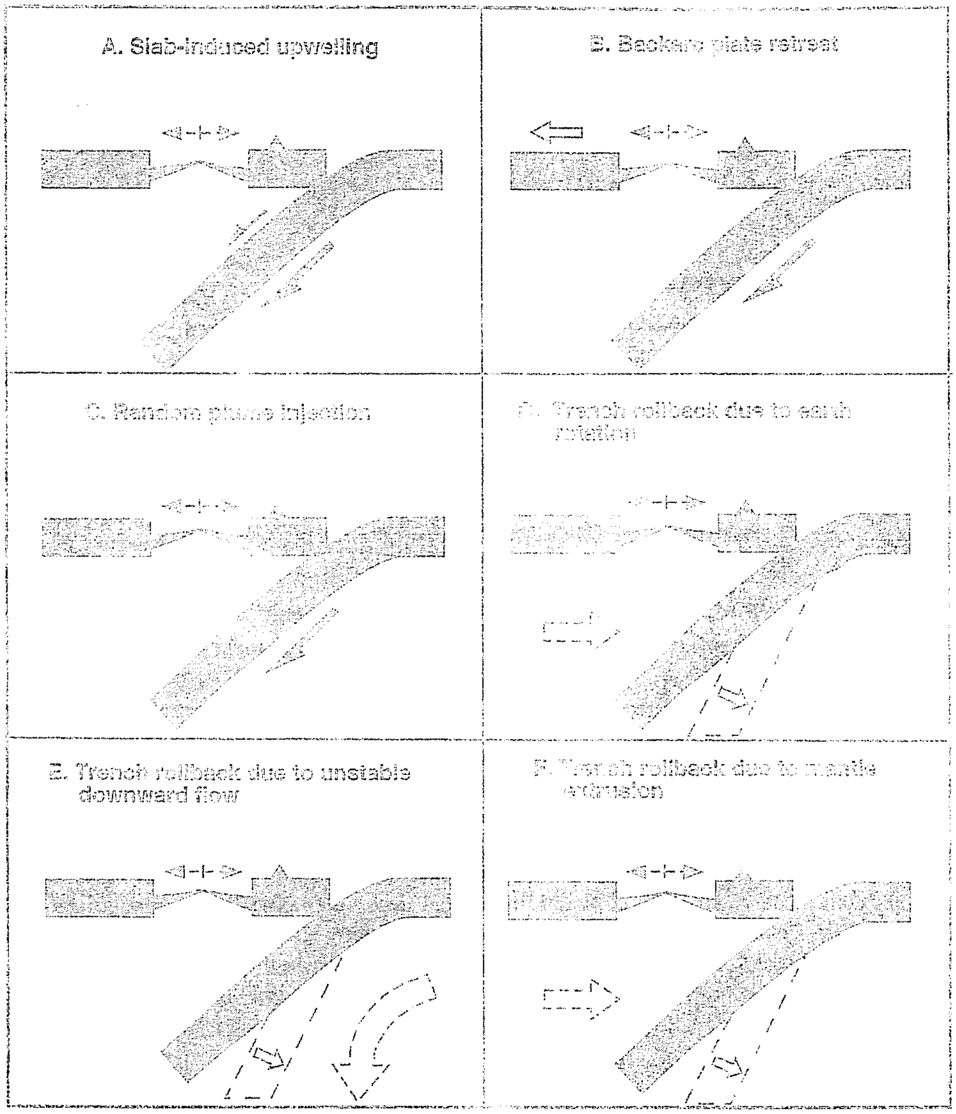

Fig. 2. Alternative mechanisms of back-arc basin formation (following Tamaki and Honza, 1991): (A) slab-induced asthenosphere upwelling (Karig, 1971); (B) backarc plate retreat effect as part of a global kinematic response (Sleep and Toksöz, 1971); (C) random plume injection from deeper mantle (Miyashiro, 1986; Tatsumoto and Nakamura, 1991); (D) eastward trench rollback due to earth rotation (Doglioni, 1993; Smith, 1998; Smith and Lewis, 1999, Doglioni et al., 1999); (E) trench rollback due to unstable downward flow (Uyeda and Kanamori, 1979); and (F) trench rollback due to mantle extrusion (Tamaki, 1995; Flower et al., 1998; this work).

extrusion, producing broad asthenospheric upwelling beneath east and southeastern Asia.

Thus mantle extrusion may provide an explanation for long-term stretching of the east Asian lithosphere (Armijo et al., 1989; Jolivet et al., 1990; England and Molnar, 1997a,b; Ren and Tamaki, 1999) and rollback of the western Pacific arc-trench systems (Karig, 1971; Crawford et al., 1981, 1986; Hussong and Uyeda, 1981; Tamaki and Honza, 1991; Stern and Bloomer, 1992; Bloomer et al., 1995), while providing a mechanism for driving lithospheric escape. Below, we outline how the notion of mantle extrusion is further supported by geologic and petrologic evidence from the IBM forearc — which may be viewed as a lithologic and geochemical 'high-tide mark' delimiting distal mantle extrusion effects — and by the spatial-temporal variation of isotopic mantle contaminants beneath the eastern Eurasia-western Pacific region. However, ambiguities regarding the provenance of older parts of the Philippine Sea and Sunda

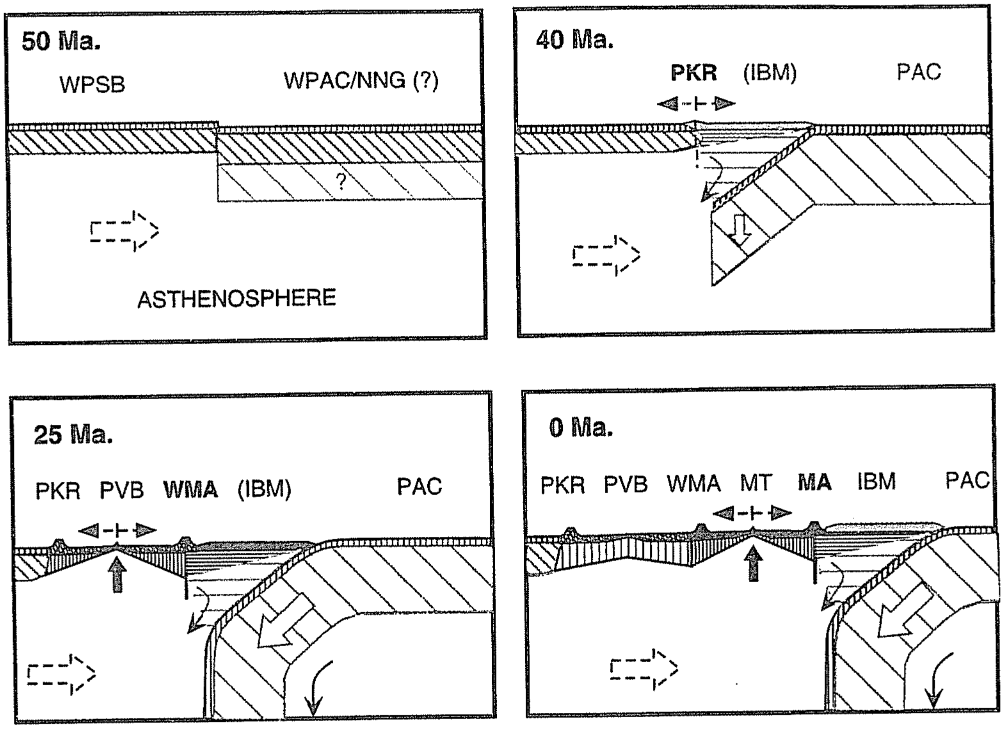

Fig. 3. Schematic history of the IBM forearc between ca. 50 Ma. and the present (after Karig, 1971; Crawford et al., 1981; Crawford et al., 1986; Hussong and Uyeda, 1981; Tamaki and Honza, 1991; Stern and Bloomer, 1992; Bloomer et al., 1995): (a) 50–40 Ma. Subduction initiation beneath West Philippine Sea Basin (WPSB) plate either by the Pacific (PAC) plate or (hypothetical) young North New Guinea (NNG) plate (Seno and Maruyama, 1984) (see Fig. 4a) along transform fracture zone in proto-WPSB spreading center. Boninite melt genesis accompanies early forearc development with inception of the calcalkaline arc forming the Palau-Kyushu ridge (PKR). (b) 40–25 Ma. Continued subduction with slab steepening of the Pacific plate, splitting of the Palau-Kyushu arc, Parece Vela basin (PVB) opening, and rollback of the active West Mariana arc (WMA). (c) 25–0 Ma. Continued subduction, Mariana Trough (MT) opening by splitting of the West Mariana arc, and rollback of the active Mariana arc (MA). (d) 0 Ma. Subduction beneath the modern Mariana arc-trench system with continued Mariana Trough opening by 'unzipping' of the West Mariana-Mariana arc to the north (Iwo Jima) (Stern et al., 1984, 1990).

plates need to be resolved before rigorous kinematic tests are applicable to the model. These are reviewed after considering the potential significance of IBM and other forearc terranes prior to discussing the isotopic evidence in support of mantle extrusion.

3. The Izu-Bonin-Mariana 'high-tide mark'

The IBM forearc comprises dislocated successions of boninite and tholeiite, and their respective intrusive and fractionation products, emplaced over at least 45 million years during repeated episodes of arc sundering, trench rollback, and basin opening. (Karig, 1971; Uyeda and Kanamori, 1979; Meijer, 1980; Crawford et al., 1981; Hussong and Uyeda, 1981; Reagan and Meijer, 1984; Hickey-Vargas and Reagan, 1987; Tamaki and Honza, 1991; Stern and Bloomer, 1992; Bloomer et al., 1995; DeBari et al., 1999). Fig. 3 shows that at least two episodes of magmatism and trench rollback were involved: (1) ca. 45–35 Ma., initial subduction at the seaward transform margin of the West Philippine Sea Basin, coinciding with the 'hard' collision of India, generating the Palau-Kyushu Ridge and earliest IBM forearc lithologies (Stern and Bloomer, 1992; Bloomer et al., 1995) (Fig. 3a and b); and (2) ca. 35–0 Ma., successive sundering of the Palau-Kyushu and West Mariana arcs with concomitant basin opening and trench rollback, preserving remnants of the relict Palau-Kyushu and West Mariana arcs, and intervening basins, in the modern IBM forearc (Karig, 1971; Bloomer et al., 1995) (Fig. 3c and d). The formation and amalgamation of IBM forearc components was accompanied by normal faulting, subsidence, dike intrusion, and diapiric emplacement of serpentinized harzburgite (Parkinson and Pearce, 1998), reflecting a dominantly extensional régime conducive to mantle decompression.

3.1. The forearc-ophiolite analogy

Several workers have drawn attention to lithologic and petrologic similarities between forearc and ophiolite lithologies, and the distinction of both from relatively homogeneous mid-ocean ridge-generated lithosphere (Bloomer et al., 1995 and references there in). Aside from the large age disparities between younger and older lithologic components and the structural complexities observed in forearc and ophiolite successions shared petrologic features include the partial or complete association of boninite, arc tholeiite, and (MORB-like) backarc basin eruptives and intrusives, common subduction-related LILE and LREE enrichment and HFSE depletions, refractory (high Mg- and Cr-nos.) mafic silicate and spinel phases, and refractory (harzburgite or CPX-poor lherzolite) mantle residua (Pearce et al., 1984, 1992a,b; Dick and Bullen, 1984; Reagan and Meijer, 1984; Hickey-Vargas and Reagan, 1987; Bloomer et al., 1995; Parkinson and Pearce, 1998).

The occurrence of boninite is particularly significant. These high-MgO, high-SiO_2 rocks are rare and virtually confined to ophiolites and early formed sections of some (but not all) forearc terranes (Meijer, 1980; Reagan and Meijer, 1984; van der Laan et al., 1989). They are rarely erupted from active arcs with the exception of recently initiated examples in the southwestern Pacific (Falloon and Crawford, 1991; Sobolev and Danyushevsky, 1994; Danyushevsky et al., 1995; Kamenetsky et al., 1997; Crawford et al., 1997). Boninite genesis appears to require a combination of refractory (melt-depleted), thermally anomalous mantle, an extensional tectonic régime, and relatively high P_{H_2O} conditions (van der Laan et al., 1989; Falloon and Crawford, 1991; Sobolev and Danuschevsky, 1994; Danyushevsky et al., 1995; Kamenetsky et al., 1997) and clearly reflects an unusual confluence of petrogenetic conditions.

The above observations support a growing consensus that many, if not most, ophiolites were initiated in thermally anomalous, 'early subduction' settings and, as progressively accreting forearc terranes, represent the magmatic and metamorphic products of repeated arc sundering and basin opening episodes (Pearce et al., 1984, 1992a,b; Stern and Bloomer, 1992; Bloomer et al., 1995). If correct, this view implies an intrinsic association between basin opening and arc rollback (on the one hand) and the 'imminent' collision of continental plates and incorporation of accreted forearc terranes as 'ophiolites' (on the other). It also implies that the lithologic and geochemical attributes of accreted forearcs are an unlikely product of intra-oceanic plate convergence (cf. Hall, 1996) unless the latter were thermally affected by collision-induced mantle flow and involved strongly refractory mantle.

During the Paleogene and Neogene the lateral margins of western and central Tethys were increasingly constricted as the African and Arabian plates moved northwards. Arc rollback and basin opening episodes were therefore short-lived, soon to be terminated by distal arc-(micro-) continent collisions, as evidenced by the histories of Appenine, Betic-Rif, Pyrrenean, and Carpathian cordilleras (Royden, 1993). Thus, as extension inexorably gave way to compression, MORB-like backarc basin lithosphere was consumed by subduction beneath the foreland plates. Following the inevitable 'hard' collision between continental plates, only non-subducted remnants of the arc–forearc would remain for incorporation into the orogenic suture. In contrast, the relatively unconstrained regions of eastern neo-Tethys, as represented by east Asia and the western Pacific allow arc rollback and basin opening to proceed almost indefinitely, constrained only by the rate of mantle flow and obstructions posed by cratonic keels, migrating microcontinents, and mobile, intra-oceanic subduction systems.

3.2. A uniformitarian approach

Uyeda and Ben Avraham (1972), Hilde et al. (1977) and Hilde and Lee (1984) proposed that early IBM volcanism appeared when subduction was initiated along north–south-trending transform dislocations, marked now by the Palau-Kyushu ridge (Fig. 1). Concurring with this interpretation, Stern and Bloomer (1992) suggested that initial subduction probably developed from 'leaky' transform fracturing associated with pre-existing West Philippine Sea

Basin seafloor spreading. In each case these models were able to explain the initiation of Palau-Kyushu arc volcanism in the Eocene, implying that relatively cool, old Pacific lithosphere was juxtaposed against the younger, thinner West Philippine Sea Basin plate. While conducive to the initiation of subduction this scenario is unlikely to offer the thermal-petrologic conditions needed for boninite genesis, a requirement for initiation of the IBM forearc (Reagan and Meijer, 1984; Hickey-Vargas and Reagan, 1987; Bloomer et al., 1995; Parkinson and Pearce, 1998; Shinjo, 1999). However, this problem may be resolved if subduction were initiated by younger, hotter lithosphere, since consumed prior to eventual juxtaposition of the Pacific and Philippine Sea plates (Seno and Maruyama, 1984; discussed in detail below).

Viewed in this context, and supported by pursuasive petrologic evidence (Geary and Kay, 1989; Evans et al., 1991; Pubellier et al., 1996; Monnier et al., 1995; Tamayo et al., 1998; Yumul et al., 1998; Shinjo, 1999), the putative JPI terrane (comprising the Japanese, Ryukyu, Philippine, and Indonesian archipelagos) (Fig. 1b), may be interpreted to reflect an analogous scenario, having separated from Eurasia prior to basin-opening similar to that producing the eastern part of the Philippine Sea plate. Depending on the kinematic interpretation of early Philippine Sea and Sunda plate assembly, major basin-opening episodes could have occurred: (1) ca. 65–40 Ma., probable detachment of Borneo and proto — Philippine and — Indonesian basement coeval with opening and rotation of the West Philippine Sea Basin; (2) ca. 30–15 Ma., further migration and rotation of the West Philippine Sea Basin, with successive opening of the Parece Vela Basin and the Mariana Trough; and (3) more-or-less contemporaneously with opening of 'inner' marginal basins — the South China and Japan Seas and the Okinawa Trough (Crawford et al., 1981). According to this scenario, the IBM, JPI, and other litho-tectonic 'high-tide marks' (including ophiolite lithologies embedded as in accreted microplates) delineate distal boundaries of 'far-field' mantle extrusion effects. We now explore the extent to which hypothetical arc rollback and forearc accretion processes may be reconciled with western Pacific lithosphere kinematic interpretations.

4. Western pacific plate kinematics

Western Pacific back-arc basins (Fig. 1a) opened during three main episodes of arc-trench rollback, shown with respect to the evolving Philippine Sea plate (Fig. 3). The West Philippine Sea and Celebes Sea Basins were established during the Eocene, the Japan, South China, Sulu, and Makassar Seas, and the Shikoku and Parece Vela Basins, between the Oligocene to Miocene, and Okinawa and Mariana Troughs, and Andaman Sea between the late Miocene to Quaternary (Karig, 1971; Zakariadze and Scott, 1979; Crawford et al., 1981, 1986; Hussong and Uyeda, 1981; Tamaki and Honza, 1991). A hiatus between the first and second episodes (ca. 45–40 Ma.) approximates the ca. 42 Ma. reorientation of Pacific plate spreading and 'hard' collision of India and Asia (Lee and Lawver, 1995). A second hiatus (ca. 15–10 Ma.) matches a number of microplate collisions in and around the South China Sea (of North Palawan, Reed Bank, Dangerous Grounds) (Taylor and Hayes, 1983; Pubellier et al., 1996), while a third, Quaternary hiatus coincides with consolidation of the Banda Sea (Milsom et al., 1996; Bergman et al., 1996; Vroon et al., 1996), opening of the the Okinawa and Mariana Troughs and the Sumisu Rift (Bloomer et al., 1995), initiation of east-directed subduction beneath the Philippines and Sulawesi, truncation of the Moluccan Sea (Rangin et al., 1996a,b, 1997), the Philippine–Taiwan collision. All phases were coeval with continued stretching of eastern Eurasia (Ren and Tamaki, 1999) and widespread appearance of 'dispersed' intraplate volcanism (Hoang et al., 1996). Philippine Sea and Sunda plate kinematics are clearly pivotal to understanding the relations between western Pacific basins and Eurasian and Australian plate motions.

4.1. The Philippine sea plate

The Philippine Sea plate is moving ca. 2 cm/year westwards relative to stable Eurasia, partitioned between the strike-slip Philippine Fault and relatively larger trench-normal convergence at the Philippine and Manila Trenches (Heki, 1996; Kreemer et al., 2000), expanding eastwards by spreading in the Mariana Trough and Sumizu Rift and concomitant IBM rollback (Seno et al., 1993). Meanwhile, the

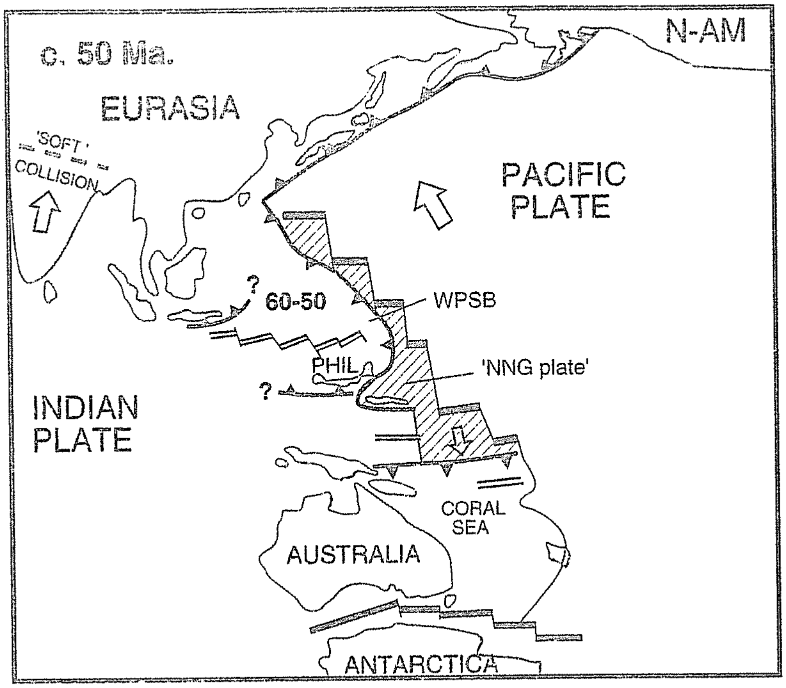

Fig. 4. Schematic plate geometry at ca. 50 Ma: showing origin of the West Philippine Sea Basin (WPSB), subduction of hypothetical North New Guinea plate (NNGP) prior to initiation of Palau-Kyushu (PKR) subduction (after Seno and Maruyama, 1984), with possible initiation of the Sunda plate formation indicated.

Amuria and China blocks are moving east and east-southeast, respectively (Wei and Seno, 1998; Koto et al., 1998), accomodated, despite Okinawa trough spreading, by Philippine Sea Plate subduction beneath the east Philippine, Ryuku, and Japanese subduction systems. While Philippine Sea Plate evolution east of the Palau-Kyushu ridge is relatively well understood (see Fig. 3), origins of the older West Philippine Sea Basin (WPSB) are more controversial.

Most interpretations of WPSB provenance accomodate paleomagnetic evidence for large clockwise rotations both prior to and after ca. 45 Ma. (Haston and Fuller, 1991; Fuller et al., 1991; Hall et al., 1995) suggesting the Palau-Kyushu boundary was approximately east–west at its inception and that the NNW-moving Pacific plate was not subducting beneath Palau-Kyushu. Most workers have attempted to resolve this by ascribing the initiation of Philippine Sea Plate formation and that of attached Philippine terranes, to a region north of present-day New Guinea from which they subsequently migrated to the west with consumption of a 'proto' — South China Sea basin (Fuller et al.,1991; Haston and Fuller, 1991; Hall, 1996, 1998; Hall et al., 1995). While consistent with the paleolatitudes required by paleomagnetic data, this interpretation is problematic for several reasons. Firstly, it requires the ad hoc inception of subduction and arc-trench rollback in a region of old Pacific lithosphere unlikely to have been associated with colliding or convergent plate margins. Secondly, it is extremely unlikely a priori for boninite to be generated in this setting (see discussion below).

An alternative solution is offered by the proposal of Seno and Maruyama (1984) that a relatively young (hypothetical) North New Guinea plate, generated at a northwest–southeast trending western Pacific axis, was subducting SSW-ward beneath 'proto' West Philippine Sea Basin, the latter having formed behind the northern half of Palau-Kyushu (Jolivet et al., 1989) (Fig. 4a and b). This interpretation is credible considering the common 'disappearance' of marginal basins and presence of ophiolites in the region (Hall, 1999). According to the 'retreating trench' version of this model the IBM trench migrated from south to northeast since ca. 45–50 Ma (Seno and Maruyama, 1984). The 48 Ma. ages of northern Palau-Kyushu Ridge and Chichi-Jima in the Bonin Islands indicate there was subduction beneath the northern part of the ridge since at least this time.

4.2. *The sunda plate*

The Sunda plate is rotating clockwise with respect to Eurasia with an eastward velocity of ca. 10 mm/year on its southern boundary increased to ca. 16–18 mm/year in the north (Chamot-Rooke and Le Pichon, 1999; Kreemer et al., 2000). The Australia-Sunda plate boundary follows the Java Trench west of Sumba and is accomodated to the east by combined northward translation of the Banda arc, shortening on the Flores and Wetar thrusts, and shearing within the Banda Sea and Sulawesi trench (Genrich et al., 1996; Honthaas et al., 1998; Kreemer et al., 2000). In New Guinea most Pacific-Australia motion occurs as strike-slip deformation and trench-normal convergence at the New Guinea Trench (Kreemer et al., 2000).

The Sundaland geologic record suggests an even more complex history than that of the Philippine Sea Plate and the region between Borneo and New Guinea is crucial to unraveling the interplay of Indo-Asian and Australian collision effects. Paleocene (61–59 Ma.) arc activity in West Sulawesi was succeeded in the Eocene by MORB (50–40 Ma.) resembling Celebes Sea basement (Polvé et al., 1997). Further arc build-up in the Oligocene and Miocene was followed by Mid-Miocene docking of Australian microplates in Central Sulawesi, and Late Miocene (ca. 13 and 10 Ma.) potassic and ultrapotassic activity, continuing in the south until the Pleistocene (0.77 Ma.) (Polvé et al., 1997; Rangin et al., 1997). The east Sulawesi ophiolite represents a back-arc remnant, similar but not necessarily equivalent to Celebes Sea basement (Monnier et al., 1995). In Borneo, the calcalkaline Sintang intrusives (19.2–16.5 Ma.) are coeval with early southeast-directed subduction while later activity may coincide with closure of a 'proto' South China Sea Basin (Prouteau et al., 1996).

Paleomagnetic data for western Sunda suggest a relatively simple picture, however. Chi et al. (1998) show virtually no rotation of Indochina since the Late Mesozoic and Lumadyo et al. (1993) show Borneo has not rotated since the Mid-Tertiary (cf. Fuller et al., 1991). In contrast, the north arm of Sulawesi has rotated ca. 20–25° since ca. 5 Ma., implying 200 to 250 km ca. 4 cm/year left-lateral displacement along the Palu-Koro fault and equivalent subduction of Celebes Sea lithosphere at the north Sulawesi trench along with opening of the Gulf of Tomini and northwest migration of arc volcanism (Polvé et al., 1997; Walpersdorf et al., 1998). Meanwhile, the Banda arc moved rapidly eastwards accomodated by the north-bounding Sorong Fault, blocking the northward approach of Australia (Milsom et al., 1996; Vroon et al., 1996; Guillou et al., 1998). Symmetrical geologic relations and regional shear zone motions — left-lateral to the north (Ailao Shan-Red River, Philippine, and Sorong faults), right-lateral to the south (Sumatra fault, Gulf of Thailand) — suggest that micro-continents enclosed by the Banda, Sunda, Sulawesi, and Sangihe arcs are unlikely to derive from the Australian plate. Likewise, microcontinents associated with Halmahera and the Molucca Sea (Bergman et al., 1996) may represent either allochthonous Australian fragments (Audley-Charles et al., 1988) or pieces of New Guinea transported westward by left-lateral motion (van Bergen et al., 1993; Hall et al., 1995; Vroon et al., 1996).

4.3. *Implications of 'fossil' slabs*

Post-Mesozoic accretion histories of Philippine Sea and Sunda plate fragments thus share numerous common features, including the repeated opening and consumption of marginal basins, microplate collisions, and ophiolites, well represented in Borneo, Sulawesi, the Philippine islands, an IBM forearc (Geary and Kay, 1989; Arcilla et al., 1989; Santa Cruz et al., 1989; Encarnacion et al., 1993; Evans et al., 1991; Pubellier et al., 1996; Rangin et al., 1996a,b; Bloomer et al., 1995). However, uncertainties about the extent of marginal basin consumption preclude true kinematic reconstructions (cf. Hall, 1996) and limit application of the latter in tests for mantle extrusion. Paradoxically, kinematic ambiguities may be better resolved on the basis of extrusion model predictions.

Seismic tomographic studies are providing new insights on the geometry of previously subducted slab material. For example, tomography shows that IBM subduction is essentially continuous although varying from near-vertical beneath the Marianas (penetrating the mantle transition zone) to near-horizontal beneath the Bonin arc to north (accumulating above the transition zone) (Fukao et al., 1992; van der Hilst and Seno, 1993; Takenaka et al., 1999). In contrast, subduction beneath the Indonesian and Philippine arcs is complicated by post-collision slab detachment and associated perturbations of mantle flow (Widiyantoro and van der Hilst, 1997). Slab geometries beneath the Banda and Molucca seas reflect combined effects of the Australia-Sunda continent-arc and Sangihe-Halmahera arc-arc collisions, Banda arc slabs forming a spoon-like structure above the transition zone and opposing Molucca Sea slabs dipping steeper to the west than to the east (Widiyantoro and van der Hilst, 1997). Interpreted in the light of geologic data, tomographic studies suggest that subduction was also more-or-less continuous between Taiwan and Java prior to the Miocene (Rangin et al., 1999), consistent with our interpretation of related 'high-tide mark', forearc lithologies characterizing the putative JPI line (Geary and Kay, 1989; Evans et al., 1991; Pubellier et al., 1996; Monnier et al., 1995; Tamayo et al., 1998; Yumul et al., 1998; Shinjo, 1999). As discussed above, if ophiolites represent conjugate components of subducted marginal basins, considerable internal compaction of the Sunda and Philippine Sea plates, and related precursive platelets, almost certainly occurred. Accordingly, while closure of the Sulu and Celebes basins is clearly recent, the presence of a 300 km-long slab below Borneo, with possible detached fragments to the east, may be interpreted as relicts of 'proto' South China Sea lithosphere (Rangin et al., 1999), hypothetical entities such as the North New Guinea plate (Seno and Maruyama, 1984), or early formed fragments of the Philippine Sea Plate (see above).

While reluctant to attribute western Pacific basins exclusively to the effects of either Australian or Indian indentors (Fuller et al., 1991; Hall et al., 1995; also cf. Tapponnier et al., 1990; Briais et al., 1993; Lee and Lawver, 1995) we recognize a series of lobe-shaped lithosphere domains apparently related to both (Fig. 1). An inner lobe series bounded by the Japan–Philippine–Indonesia (JPI) line-Indonesian and Philippine arcs (enclosing the South China Sea and Indochina), the Ryuku arc (enclosing the Okinawa Trough and mainland China), and Japanese arc (enclosing the Japan Sea, Korea, and southeastern Siberia), corresponds respectively with the Sunda, Chinese, and Amurian 'plates' (Tapponnier et al., 1986; Wei and Seno, 1998). Tentatively, an outer, Philippine Sea Plate, lobe bounded by the Izu-Bonin-Mariana (IBM) line — the Izu-Bonins enclosing the Sumisu Rift and Shikoku Basin, and Marianas enclosing the Parece Vela basin and Mariana Trough — may also be related to Indo-Asian collision effects. More speculatively, lobes bounded by the New Hebrides-Tonga-Kermadec line, enclosing the Manus, Solomon, Woodlark, Coral, Loyalty, Fiji and Lau basins (Bloomer et al., 1995; Chung et al., 1997; Crawford et al., 1997), may define mantle-perturbed regions associated with the approaching Australian plate. If these record the sum of processes associated with post-collision arc-trench rollback, the structural and petrologic histories of western Pacific forearc terranes assume a new significance.

5. Western pacific mantle contamination

5.1. DUPAL provenance

A seminal paper by Hart (1984) showed that isotopically anomalous (DUPAL) asthenosphere underlies oceanic lithosphere within much of the southern hemisphere. In particular, Indian Ocean mid-ocean ridge basalt (I-MORB) is isotopically distinguishable from most basalts emplaced at Pacific and northern Atlantic Ocean spreading centers. More recently, it has been shown that I-MORB-like asthenosphere is widespread beneath eastern Eurasia and western Pacific marginal basins (Mukasa et al., 1987; Hochstaedtler et al., 1990; Tatsumoto and Nakamura, 1991; Tu et al., 1991a,b; Hickey-Vargas et al., 1995; Crawford et al., 1997; Kepezhinskas et al., 1995; Castillo, 1996; Spadea et al., 1996) and much of east and southeastern Asia (Zhou et al., 1988; Basu et al., 1991; Tu et al., 1991a,b; Chung et al., 1992; Chung et al., 1994; Chung et al., 1995; Mukasa et al., 1995; Peng et al., 1995; Zhang et al., 1995; Hoang et al., 1996; Hoang and Flower, 1998; Flower et al., 1998; Okamura et al., 1998) (Fig. 1a). The IBM litho-tectonic 'high-tide mark' also represents a geochemical boundary between this province and isotopically 'normal' Pacific mantle to the east.

However, it is debated as to whether the former represents a mantle flow continuum with Indian Ocean mantle, a pre-existing flow system terminated by subduction beneath the Andaman Nicobar and Indonesian arcs, or a physically distinct (if geochemically similar) flow régime separated by subduction from the Indian Ocean domain. Whichever the case, the coincidence of isotopically anomalous mantle beneath east Asia and the western Pacific with a region combining sheared and stretched continental lithosphere and the earth's largest marginal basin plexus has gone largely unremarked in the literature.

Northward flow of Indian Ocean mantle (Mukasa et al., 1987; Hickey-Vargas et al., 1995; Hickey-Vargas, 1998; Smith, 1998) has to contend with a potential flow barrier posed by Indian Ocean subduction beneath Sundaland, especially where arc-trench roll-back occurred with slab steepening (Widiyantoro and van der Hilst, 1997). Of models appealing to endogeneous enrichment — a western Pacific DUPAL plume (Tatsumoto and Nakamura, 1991) or delaminated Sino-Korean cratonic mantle (Hoang et al., 1996), the second is preferred for several reasons. Firstly, western Pacific thermal anomalies are shallow and not indicative of deep plume activity (Lebedev et al., 1997; Zhang, 1998). Secondly, mantle contamination is strongest beneath the Japan Sea, proximal to the Sino Korean craton, where volcanics and mantle-derived xenoliths show extreme enrichment in an EM1-like contaminant (Basu et al., 1991; Tatsumoto et al., 1992), and to a lesser extent Taiwan and Indochina, and concentration gradients inconsistent with either north–south flow or provenance beneath western Pacific basins (Fig. 11; see below). Thirdly, there are strong indications that Archean lithospheric mantle has been removed from the Sino-Korean craton (Griffin et al., 1992, 1998; Tatsumoto et al., 1992; Zhang, 1998; Liu et al., 1990; Cheng et al., 1991). Thus asthenospheric EM1 may have been incorporated by east-flowing asthenosophere associated with Tethyan closure (Hoang et al., 1996; after McKenzie and O'Nions, 1983) producing EM1-rich, 'plum-pudding' asthenosphere beneath eastern Eurasia and contiguous marginal basins (Tatsumoto et al., 1992; Chung et al., 1995; Hoang et al., 1996) to produce EM1-rich 'plums' locally undigested in a dilute matrix (cf. Kellogg and Turcotte (1990).

5.2. *Mantle mixing*

To test this model we compare variation of western Pacific basin isotopic data with that predicted by this model in terms of broadly accepted, hypothetical mantle components. Following Hoang et al. (1996) we assumed that mantle isotopic variation may be explained by: (1) variable EM1-like enrichment of DMM-HIMU hybrids; and followed by (2) contamination of the asthenosphere (or partial melts thereof) by crust-derived EM2. Using endmembers defined by Sr, Nd, and Pb elemental contents and isotopic ratios of ^{87}Sr/^{86}Sr, ^{143}Nd/^{144}Nd, ^{208}Pb/^{204}Pb, ^{207}Pb/^{204}Pb, and ^{206}Pb/^{204}Pb (Zindler and Hart, 1986) (or natural compositional analogues such as (EM1-like) 'SKC' (derived from Sino-Korean cratonic lavas and xenoliths), we show the data plotted in terms of ^{208}Pb/^{204}Pb vs. ^{206}Pb/^{204}Pb, ^{207}Pb/^{204}Pb vs. ^{206}Pb/^{204}Pb, ^{87}Sr/^{86}Sr vs. ^{206}Pb/^{204}Pb, and ^{143}Nd/^{144}Nd vs. ^{206}Pb/^{204}Pb (Figs. 5–10).

In each case, model 1 approximates the Northern Hemisphere Reference Line of Hart (1984), indicating mixing of HIMU and DMM, and appears to be a fundamental constraint on global sub-oceanic mantle (Hart et al., 1992). East Pacific Rise (13–23°N) N-MORB compositions lie on the model 1 mixing curve, and an average of these is taken as the N-MORB endmember for east Asian-western Pacific asthenosphere. Model 2 simulates development of the east Asia-western Pacific domain by addition of EM1 to N-MORB (Mukasa et al., 1987; Tu et al., 1991a,b; Chung et al., 1992) prior to its contamination by, or mixing with, lithospheric EM2, as represented by model 3 (a-f) (Figs. 5–10). East Asia-western Pacific asthenospheric compositions may thus reflect EM1-enriched N-MORB mantle with, for example, small, subducting slab-derived additions of fluid and sediment melt.

Alkali basalts from Sikhote-Alin (SAS-3,-4) show strong enrichment in EM1 and resemble K-rich basalts from northeastern China and the Japan Sea associated with disaggregation of the eastern Sino-Korean craton (Zhou et al., 1988; Basu et al., 1991; Peng et al., 1995; Zhang et al., 1995; Okamura et al., 1998) (Fig. 5a–d). Subduction-related lavas from Sikhote-Alin (SAS-1), Sakhalin Island (SAS-2), and the Kamchatka peninsula show relatively strong EM2 enrichment (as represented by crust-derived sediments

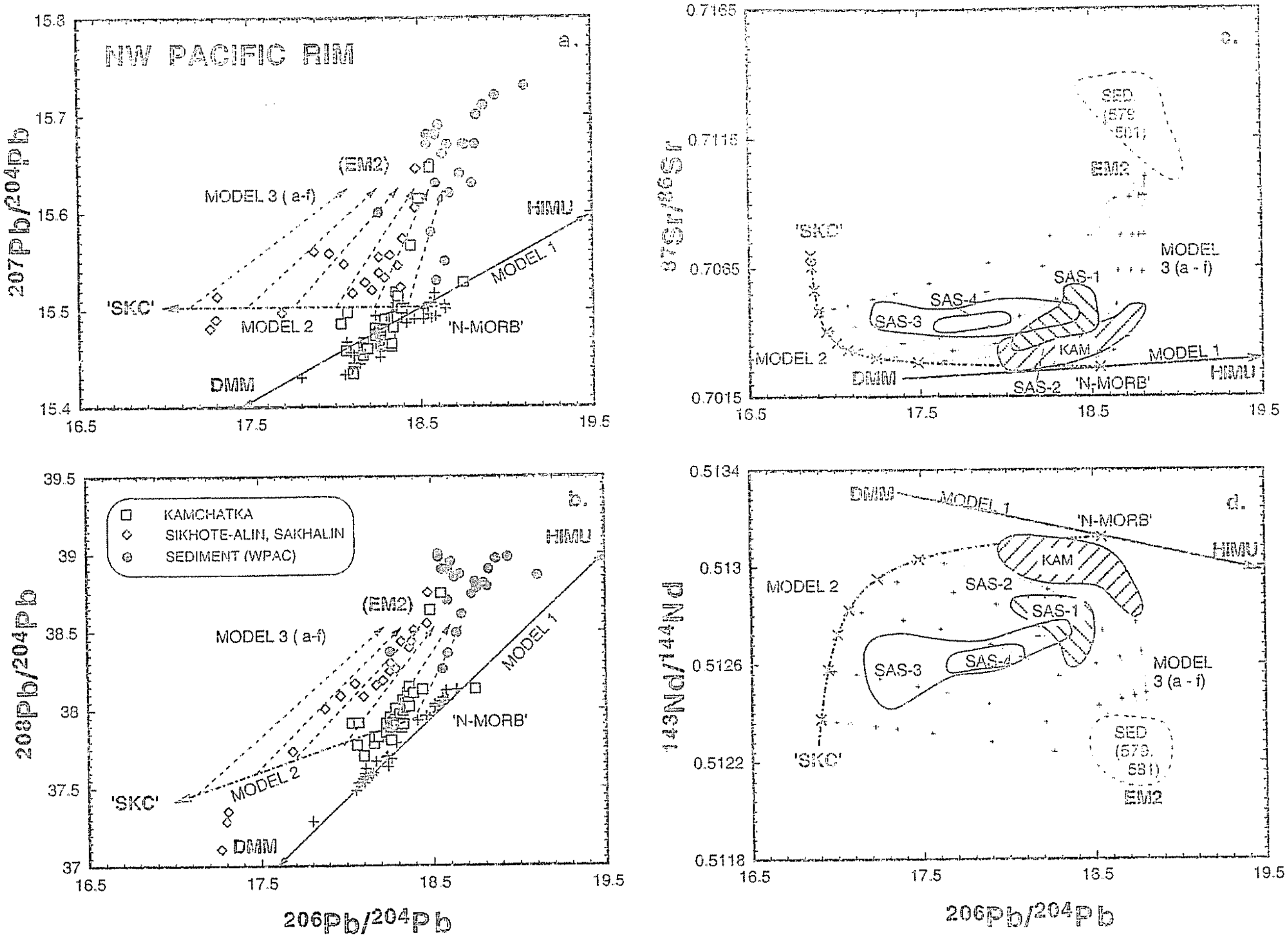

Fig. 5. Plots of ^{207}Pb/^{204}Pb, ^{208}Pb/^{204}Pb versus ^{206}Pb/^{204}Pb, and ^{87}Sr/^{86}Sr. ^{143}Nd/^{144}Nd versus ^{206}Pb/^{204}Pb for Neogene-Quaternary eruptives from the Northwestern Pacific 'rim', including Sikhote-Alin and Sakhalin (SAS 1–4) (Okamura et al., 1998) and the Kamchatka peninsula (Kepezhinskas et al., 1995) in relation to sediment compositions from ODP Sites 579 and 581, by comparison with hypothetical mantle mixing models (1–3) (see text). EM2, DMM, HIMU oceanic mantle endmember compositions are taken from Zindler and Hart (1986) as modified by Hoang et al. (1996) Hoang et al. (1998). 'SKC' is the average cratonic mantle component interpolated for the Sino-Korean craton from northern Chinese basalts and xenoliths (refs.). 'N-MORB' is average MORB for the East Pacific Rise 13–23°N. (Mahoney et al., 1994).

from ODP Sites 579 and 581) (Plank and Langmuir, 1998) of variably EM1-rich primitive melts (Fig. 5a–d). Basalts from the Japan Sea comprise (a) asthenosphere-derived tholeiite forming oceanic basement (ODP Sites 794, 795, and 797) which reflect EM2 addition to primitive EM1-rich melts; and (b) seamount and island alkali basalts resembling northeastern Chinese and Sikhote-Alin intraplate basalts (Basu et al., 1991; Peng et al., 1995; Zhang et al., 1995, 1998; Okamura et al., 1998), possibly affected by EM1-rich, cratonic wallrock reaction (Cousens and Allan., 1992; Pouclet et al., 1995; Flower et al., 1998) (Fig. 6a–d). Compositions from Honshu Island (Japan) are clearly related to subducted sediment but suggest such sediments may be compositionally intermediate between EM2- and EM1-types (Kersting et al., 1996), resembling South China Sea sediments (McDermott et al., 1993) (Fig. 6a–d).

Marginal sea basement to the south comprises backarc spreading crust (the Celebes and Sulu Seas and Marinduque Basin (Spadea et al., 1996), intraplate seamounts and islands (South China Sea), (Tu et al., 1991a,b), and a possibe relict ridge (the Cagayan Ridge), (Spadea et al., 1996), all showing significant EM2 enrichment of EM1-enriched primitive melt (Fig. 7a–d). Eruptive compositions from the

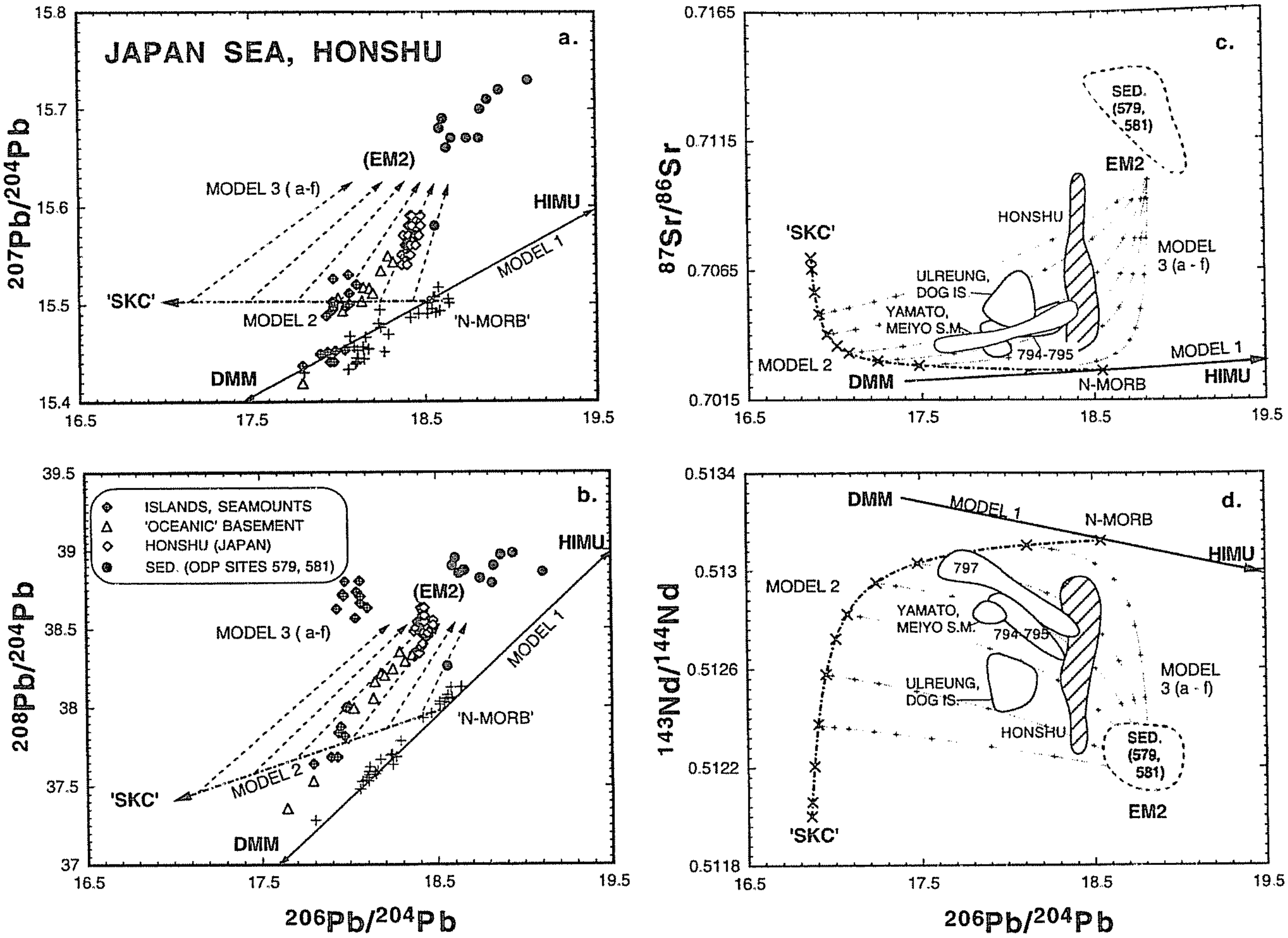

Fig. 6. Plots of $^{207}Pb/^{204}Pb$, $^{208}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$, and $^{87}Sr/^{86}Sr$, $^{143}Nd/^{144}Nd$ versus $^{206}Pb/^{204}Pb$ for Neogene-Quaternary eruptives from Japan Sea islands, seamounts, and 'oceanic' basement (ODP Sites 794, 795, 797) (Nakamura et al., 1989; Tatsumoto and Nakamura, 1991; Cousens and Allan, 1992) and Honshu Island (Japan) (Kersting et al., 1996) in relation to sediment compositions from ODP Sites 579 and 581 and South China Sea (McDermott et al., 1993), compared with hypothetical mantle mixing models 1–3 (see text).

Philippine archipelago can all be attributed to more-or-less uniform EM1-rich asthenosphere (X) (Fig. 8a–d) variably contaminated by EM2-like sediment (Mukasa et al., 1987; Chen et al., 1990; McDermott et al., 1993). Mixing relations computed between pre-subduction asthenosphere (X) and hypothetical sediments X′ and X″ (Fig. 8a–d) suggest that compositions from the Bicol Peninsula — associated with Philippine Sea Plate subduction at the Philippine Trench-result from adding relatively high-$^{206}Pb/^{204}Pb$ sediments, as sampled from Philippine Sea ODP Site 801 (Plank and Langmuir, 1998) (Fig. 8c and d). In contrast, those from the Bataan peninsula or localities near the Luzon–Taiwan and Palawan–Mindoro collision zones-associated with subduction and collision at the Manila Trench-appear to be affected by lower $^{206}Pb/^{204}Pb$ (EM1-rich) sediments of South China Sea type (McDermott et al., 1993), similar to Honshu Island compositions (Fig. 6a–d). The isotopic diversity of Philippine eruptives can therefore be largely attributed to a range of sediment compositions variably added to the asthenosphere via two opposed subduction zones enhanced by proximity to both the late Neogene Palawan–Mindoro and Luzon–Taiwan collisions (Mukasa et al., 1987; Chen et al., 1990).

The relatively few data for West Philippine Sea Basin basement (ca. 50–53 Ma. ODB-1 and WPSB in Fig. 9a–d) indicate that EM1-enriched asthenosphere existed prior to the 'hard' collision of India

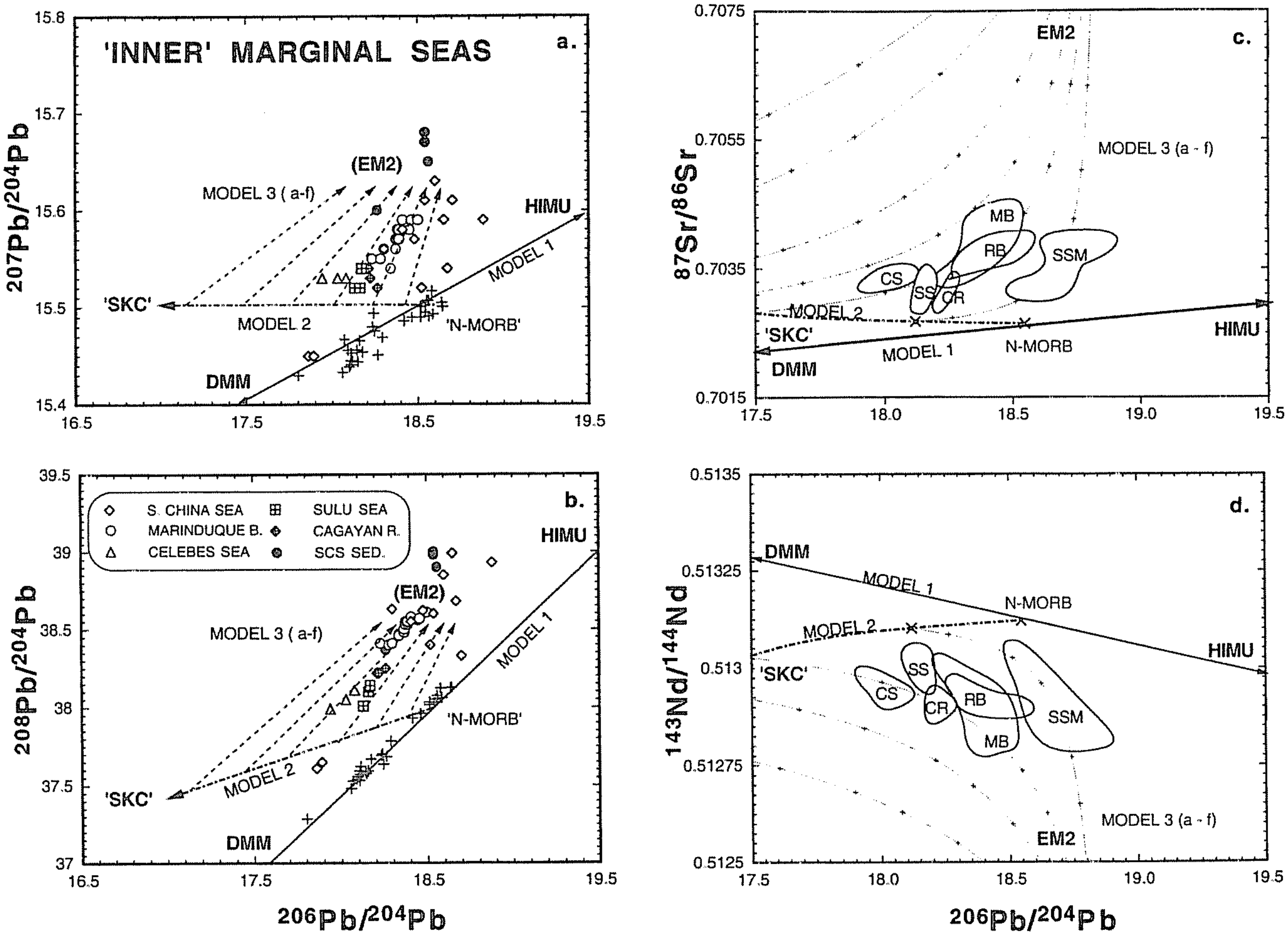

Fig. 7. Plots of $^{207}Pb/^{204}Pb$, $^{208}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$, and $^{87}Sr/^{86}Sr$, $^{143}Nd/^{144}Nd$ versus $^{206}Pb/^{204}Pb$ for 'inner' marginal basins, including South China Sea (SCS) seamounts (Scarborough Seamounts-SS, Reed Bank-RB) and islands (Tu et al., 1991; Tu et al., 1991), Marinduque Basin (MB) (Philippines), Celebes Sea (CS), Sulu Sea (SS), and Cagayan Ridge (Sulu Sea) (CR) (Spadea et al., 1996), compared with hypothetical mantle mixing models 1–3 (see text).

and Asia and suggest that EM1 contamination of ambient asthenosphere may, after all, have been unrelated to the collision (discussed below). However, relatively high-$^{206}Pb/^{204}Pb$ compositions of Oki-Daito Basin (50 Ma.) and Benham Rise (36 Ma.) basalts (ODB-2 and BR in Fig. 9a–d) resemble those of Pacific domain oceanic plateaus while Palau-Kyushu Ridge (45 Ma.) and Oki-Daito Ridge (19 Ma.) arc eruptives (PKR and ODR in Fig. 9a–d) reflect progressive EM2 additions to (slightly) EM1-rich asthenosphere. Basement compositions from the Parece Vela and Shikoku Basins, Sumisu Rift, and Mariana Trough are mostly consistent with small EM2-like additions (of ODP Site 801 sediment) to EM1-rich asthenosphere (Hochstaedtler et al., 1990; Hickey-Vargas, 1991, 1998; Hickey-Vargas et al., 1995) although mixing between anomalous western Pacific and Pacific N-MORB reservoirs is apparent in the northern Mariana Trough (MT1, MT2 in Fig. 10a–d) (Stern et al., 1990; Volpe et al., 1990; Gribble et al., 1998). Mixing with Pacific N-MORB also appears to have affected the Mariana and Izu-Bonin arc sources (IB1, IB2, and MA in Fig. 10a–d) (Pearce et al., 1992a,b; Elliot et al., 1997). Thus, with the exception of Oligocene Oki-Daito and Benham Rise plateau basalts in the West Philippine Sea Basin and hybrid sources at or close to the IBM line itself, western Pacific arc and backarc mantle reservoirs conform closely to compositions modeled by mixing (Hoang et al., 1996).

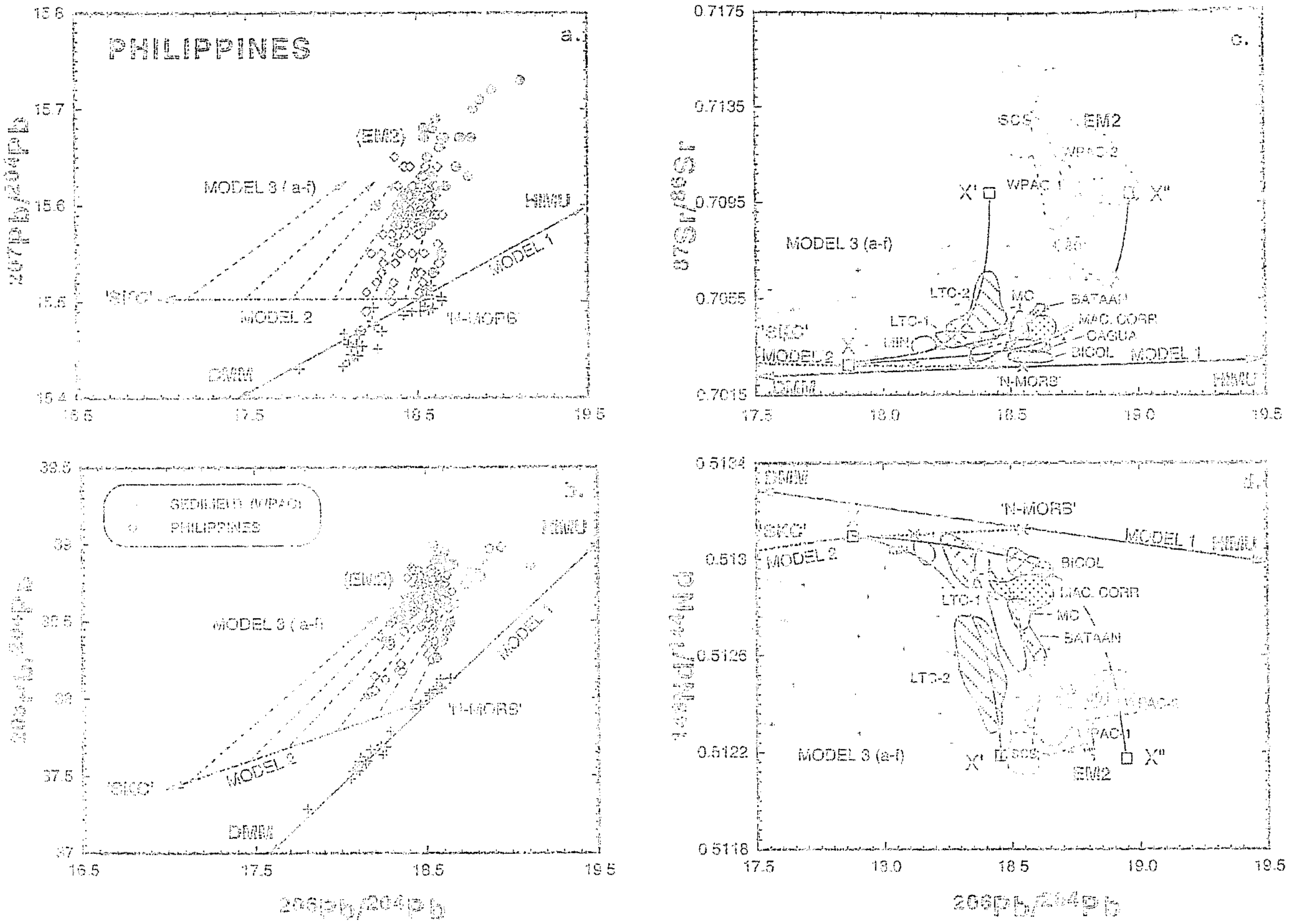

Fig. 8. Plots of ^{207}Pb/^{204}Pb, ^{208}Pb/^{204}Pb versus ^{206}Pb/^{204}Pb, and ^{87}Sr/^{86}Sr, ^{143}Nd/^{144}Nd versus ^{206}Pb/^{204}Pb for the Philippine archipelago, including compositions from the Luzon-Taiwan collision (LTC-1, 2) zone, Mindoro Collision (MC) zone, Macalod Corridor, Bicol and Bataan peninsulas, Cagua, and Mindoro (MN) (Mukasa et al., 1987) in relation to sediment compositions from ODP Site 801 (Plank and Langmuir, 1998), WPAC- (western Pacific-) 1, -2, (Vroon et al., 1995) and South China Sea (McDermott et al., 1993). Computed mixing curves are shown between X (ambient WPAC asthenosphere) and hypothetical sediment compositions X′ and X″ (see text), compared with hypothetical mantle mixing models 1–3 (see text).

5.3. Pre-collision DUPAL mantle

While western Pacific marginal basins mostly postdate the 'hard' India-Asia collision, early phases of (e.g.) Sunda and Phlippine Sea plate formation were in fact well underway during 'soft-' even 'pre-collision' stages. Relicts of these, represented by WPSB and Celebes Sea basement (ca. 50–60 Ma.) and Eocene and Late Cretaceous ophiolites in the Philippines, Borneo, and Sulawesi, nonetheless show DUPAL-like signatures (Hickey-Vargas et al., 1995; Hickey-Vargas, 1998). However, these observations are not in conflict with the hypothesis that DUPAL-like mantle was generated via sub-Asian cratonic delamination, for reasons elaborated below. DUPAL-like mantle was also associated with the Tethyan Yarlung-Sangpo (Tibet) and Semail (Oman) ophiolites, dated respectively at ca. 110 and 95 Ma. (Gopel et al., 1984; Mahoney et al., 1992, 1998), and can be traced back to at least ca. 140 Ma. in the western Indian Ocean itself (Mahoney et al., 1998). In contrast the ca. 150 Ma. Tethyan Masirah ophiolite (Arabia) and Early Cretaceous Indian Ocean lithosphere (ODP Site 261; Weis and Frey, 1996) lack the DUPAL isotopic character, suggesting that a secular change in Tethyan asthenospheric composition must have occurred before ca. 160 Ma., as Indian Ocean opening allowed for linkage with the

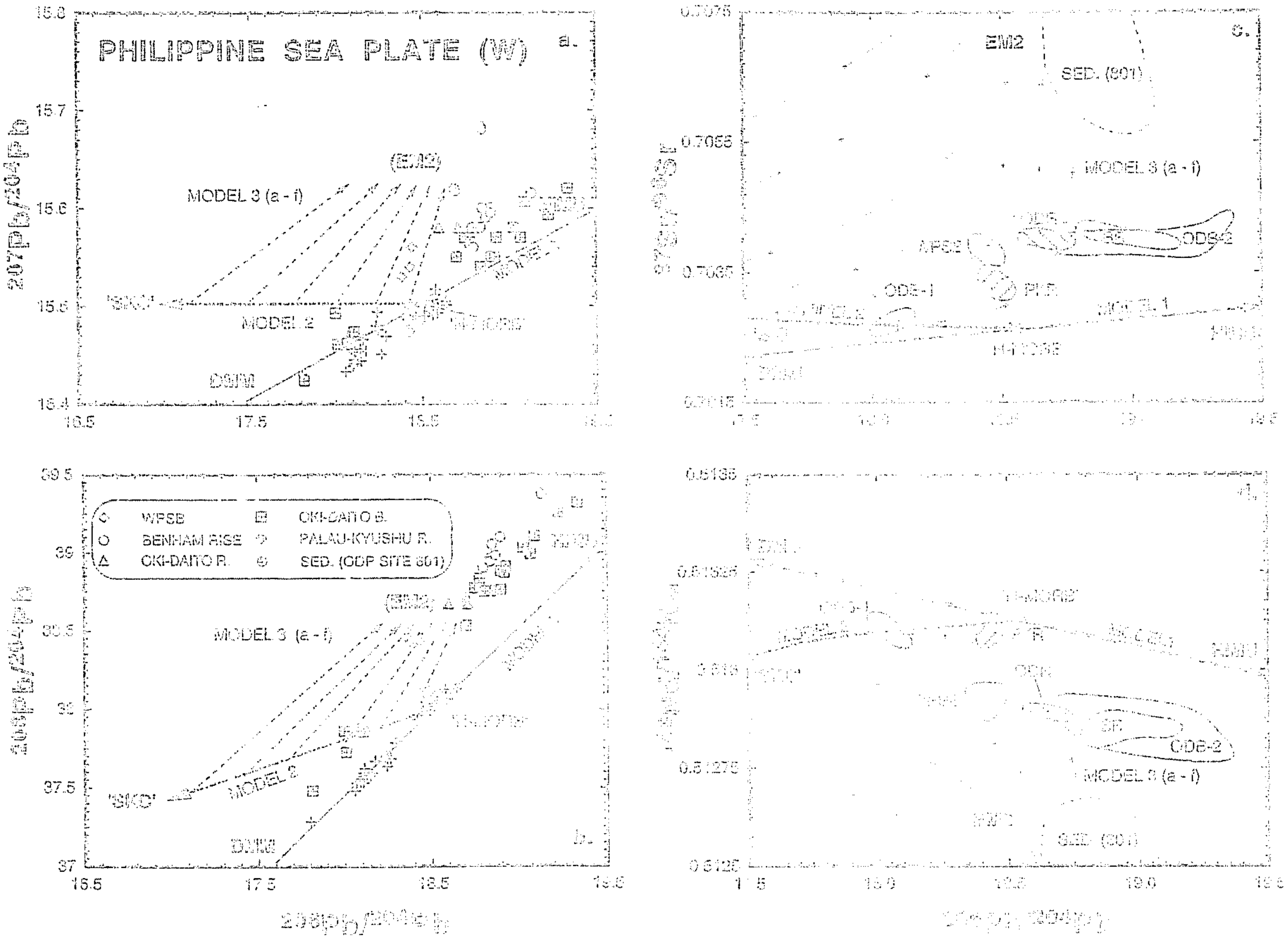

Fig. 9. Plots of $^{207}Pb/^{204}Pb$, $^{208}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$ and $^{87}Sr/^{86}Sr$, $^{143}Nd/^{144}Nd$ versus $^{206}Pb/^{204}Pb$ for the Philippine Sea plate (west), including drilled and dredged samples from West Philippine Sea Basin (WPSB) basement (DSDP Site 291, ca. 54 Ma) (Hickey-Vargas, 1991; Hickey-Vargas et al., 1995), the Benham Rise (BR) (ca. 36 Ma), Palau-Kyushu Ridge (PKR) (ca. 45 Ma), Oki-Daito Ridge (OKR) (ca. 19 Ma), and Oki-Daito Basin (OKB) (ca. 50 Ma) (Hickey-Vargas, 1998) in relation to sediment compositions from ODP Site 801, compared with hypothetical mantle mixing models 1–3 (see text).

contracting Tethyan mantle reservoir (Lawver and Gahagan, 1993; Mahoney et al., 1998).

Significantly, I-MORB-type mantle existed in at least part of equatorial Tethys by 110 Ma., as the oceanic sector between Arabia and India narrowed and India–Asia collision became increasingly imminent The advent of DUPAL-like mantle was accompanied by a secular decrease in isotopic diversity, further suggesting increased homogenization by mixing of the relatively young Indian Ocean mantle reservoir (Mahoney et al., 1998). This pattern raises at least two possiblities which are not mutually exclusive: (1) DUPAL-like Indian Ocean mantle flowed into Tethyan reservoirs as the latter became linked to the former (Mahoney et al., 1998); and (2) DUPAL signatures were generated in situ by interaction of squeezed 'proto' Tethyan mantle with Eurasian cratonic lithosphere. However, the first of these cannot be a unique solution to the generation of anomalous western Pacific mantle as the distinct spatial–temporal pattern of the latter indicates that at least part of the anomaly was generated north of the Tethyan suture, probably beneath northern China (Fig. 11). While some eastern Chinese basalt compositions reflect reaction between asthenospheric melts and cratonic wallrock others may reflect asthenosphere delamination of the cratonic substrate (Hoang et al., 1996), confirmed by the high-EM1

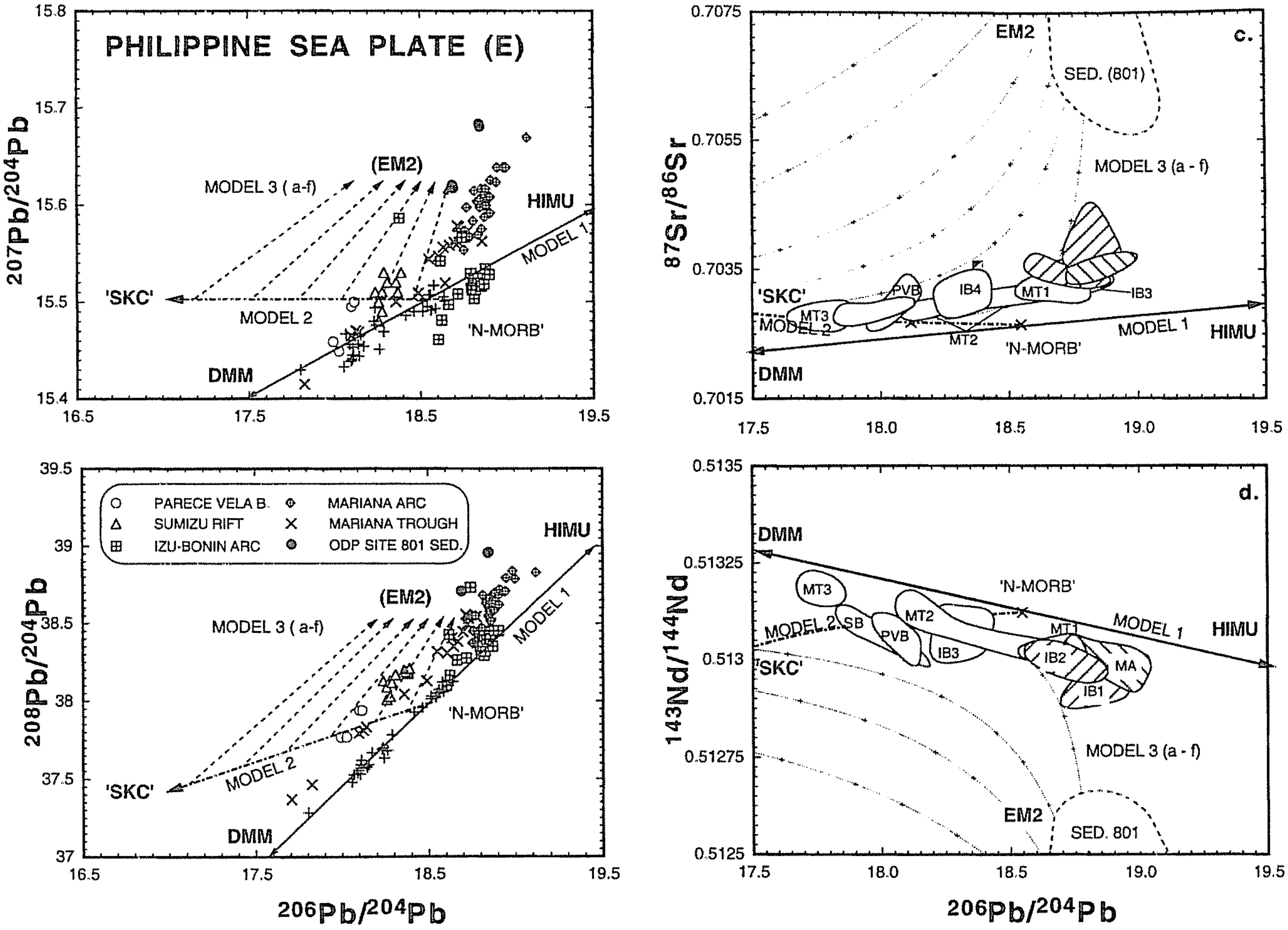

Fig. 10. Plots of $^{207}Pb/^{204}Pb$, $^{208}Pb/^{204}Pb$ versus $^{206}Pb/^{204}Pb$, and $^{87}Sr/^{86}Sr$, $^{143}Nd/^{144}Nd$ versus $^{206}Pb/^{204}Pb$ for the Philippine Sea plate (east): including compositions for the Parece Vela Basin (PVB), Mariana Trough (MT1 — northern trough; MT2-northern ridge; MT3-southern ridge) (Volpe et al., 1990; Stern et al., 1984; Stern et al., 1990), Shikoku Basin (SB) (Hickey-Vargas, 1991), Sumizu Rift (SR) (Hochstaedtler et al., 1990; Fryer et al., 1990), the Mariana arc (MA) (Elliot et al., 1997), and Izu-Bonin arc (IB1 — ca. 41 Ma.; IB2 — ca. 35 Ma.; IB3 — ca. 17 Ma.; IB4 — ca. 10 Ma.) (Pearce et al., 1992a; Pearce et al., 1992b), compared with hypothetical mantle mixing models 1–3 (see text).

concentrations in 'asthenospheric' basalts from the Japan and South China Seas and (to a leasser extent) Taiwan, Indochina, and Tibet, relatively distal to identified margins of the Sino-Korean craton.

Direct evidence for mantle flow is sparse although seismic shear-wave splitting studies are consistent with east–west-oriented mantle anisotropy (Makeyeva et al., 1992; McNamara et al., 1994; Gao et al., 1994; Davis, 1996) and seismic tomography (Liu et al., 1990; van der Hilst et al., 1991; Zhang and Tanimoto, 1991; Su et al., 1994; Davis, 1996; Zhang, 1998; Liu et al., 2000) indicate lobe-shaped low-velocity anomalies, corresponding to clusters of Late Neogene to Quaternary volcanism within the inferred extrusion lobes.

6. Conclusions

(1) Backarc opening, arc-trench rollback, and forearc accretion processes recorded by the Izu-Bonin-Mariana (IBM) and, more speculatively, components of the Japanese–Philippine–Indoenisan (JPI) lithotectonic 'high-tide marks', provide a uniformitarian model for explaining early Philippine Sea and Sunda plate formation, and the significance of collision-embedded ophiolites.

(2) The spatial-temporal EM1 concentration gradients in the asthenosphere beneath western Pacific basins relative to the Sino-Korean craton are consistent with the interpretation that western Pacific mantle

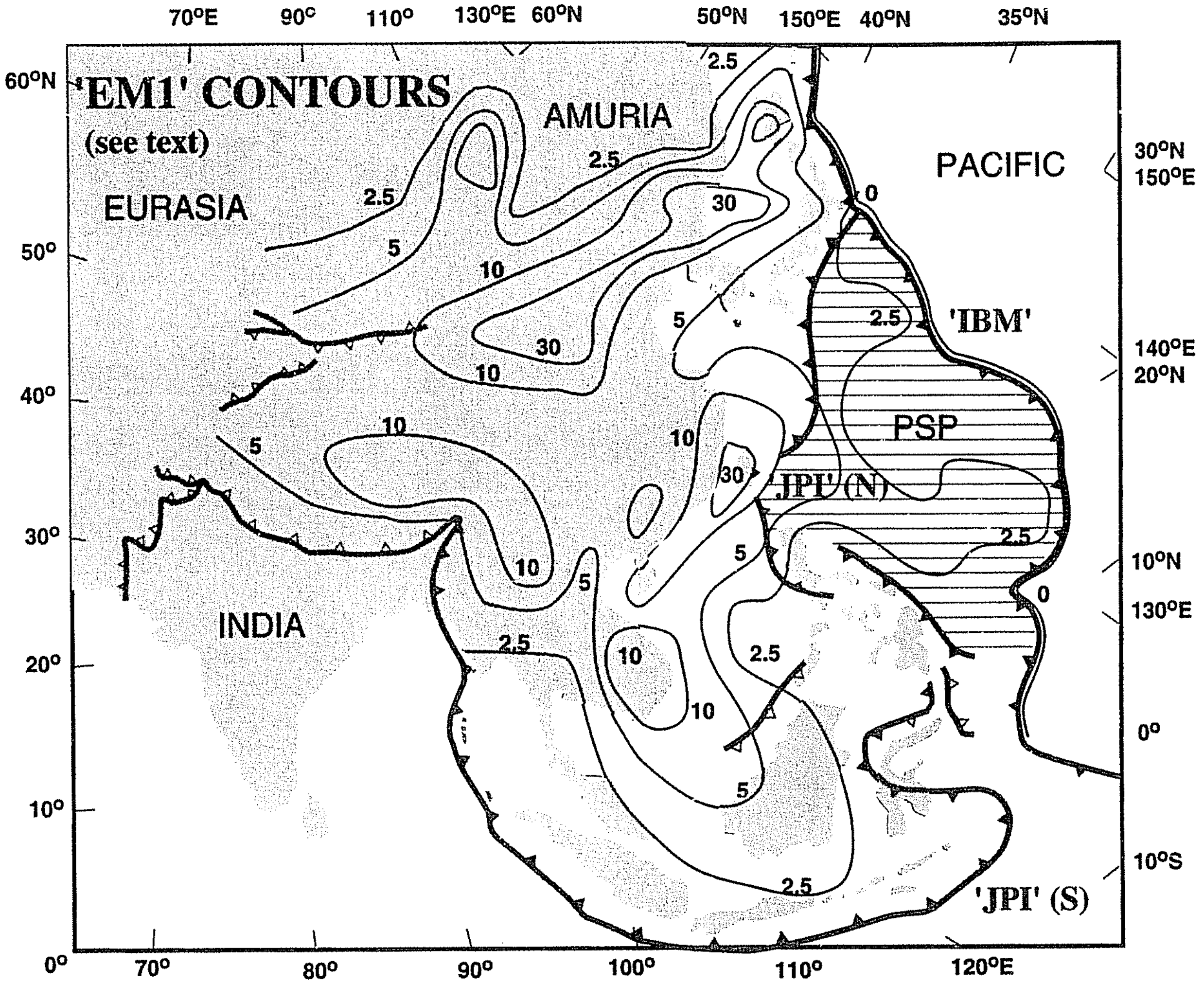

Fig. 11. Asia-western Pacific 'EM1' (i.e. the EM1-like 'SKC' component) distribution as a proportion of binary mixing between 'N-MORB' (DMM + HIMU) and EM1-computed from basalt trace element and isotopic compositions assuming bulk mantle comprises DMM, HIMU, EM1, and EM2 (Zindler and Hart, 1986; Flower et al., 1998) within the east Asia-western Pacific mantle isotopic province. Because DUPAL compositions (strictly defined; Hart, 1984) may include both oceanic EM1 and EM2 mantle endmember components), we have computed 'contaminant' contents in terms of such endmembers rather than the more conventional Δ8/4Pb and Δ7/4Pb parameters ('vertical' deflections of ^{208}Pb/^{204}Pb, and ^{207}Pb/^{204}Pb from NHRL on isotopic 'Pb–Pb' diagrams). To the east, a broad Pacific domain is dominated by isotopically 'normal' mid-ocean ridge basalt (N-MORB) consistent with simple mixing of DMM and HIMU mantle components. Sr, Nd, and Pb isotopic data for Neogene and Quaternary basalt eruptives in the east Asia-western Pacific region show that isotopically-anomalous mantle extends from Indonesia in the south to eastern Siberia, and that its eastern rim (EM1 = 0) is marked by the (Kurile), Japanese, Izu-Bonin, and Mariana volcanic arcs. These accreted active and relict subduction-related complexes reflect a diachronous pattern of arc sundering, trench rollback, and concomitant basin opening and may be interpreted as litho-tectonic 'high-tide marks'. To the south and southwest the east Asia-western Pacific province is separated from the Indian Ocean by the Andaman-Nicobar and Indonesian archipelagoes, while to the east and northeast of Australia, the New Hebrides, Tonga, and Kermadec arcs separate analogous DUPAL-like basins from the Pacific N-MORB domain.

could have resulted from contamination by delaminated sub-Asian cratonic lithosphere of N-MORB asthenosphere extruded during late stages of Tethyan closure.

(3) Mantle extrusion is also supported by preliminary tomographic and shear-wave splitting results, and 2D numerical models of collision-related mantle flow suggesting at least two mantle flow paths for sub-Asian asthenosphere-north and south of the Sino-Korean craton.

(4) During the second phase of Philippine Sea Plate evolution mantle may have been extruded via

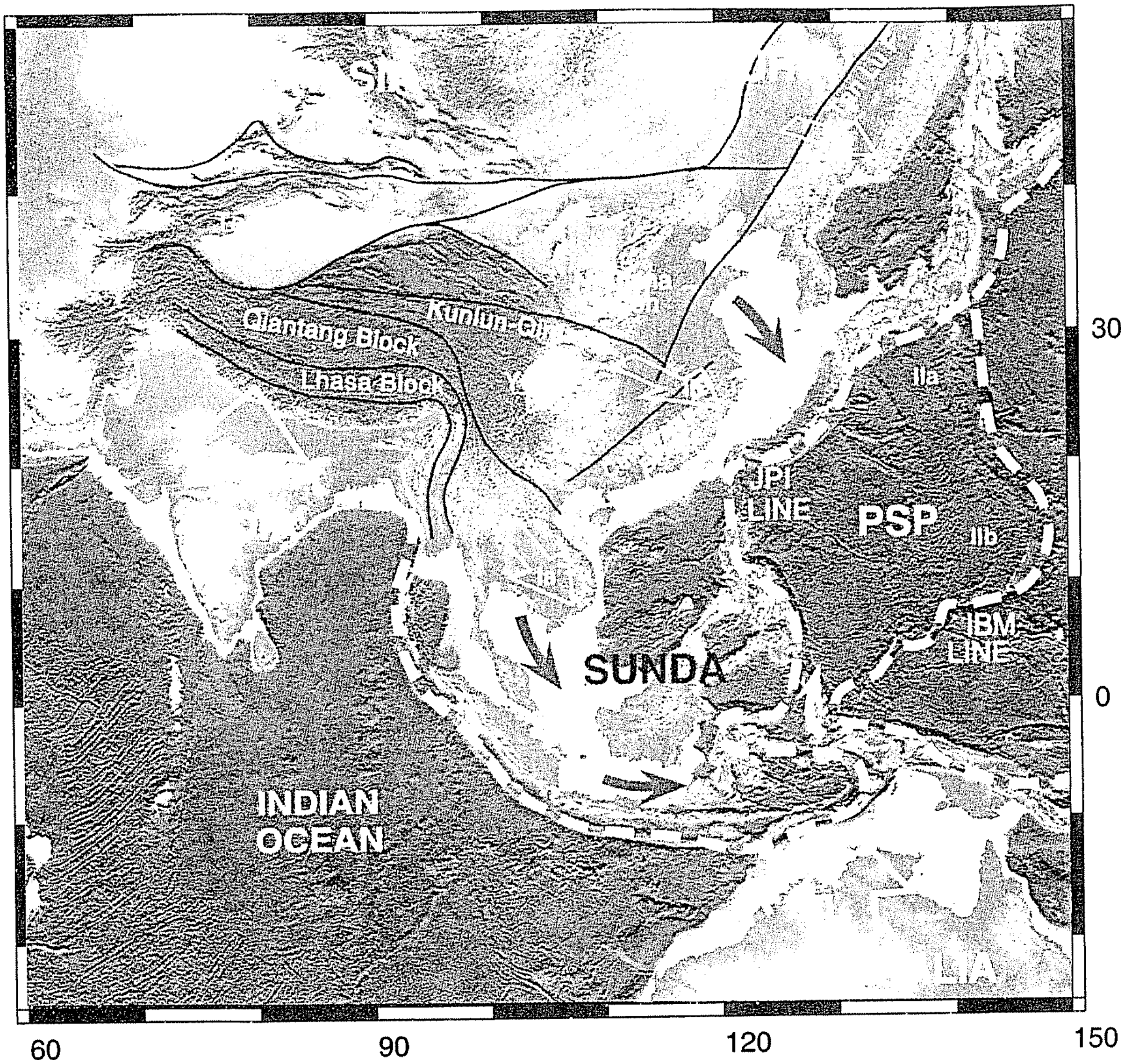

Fig. 12. Topographic map of eastern Eurasia, Australia, western Pacific, and northeastern Indian Ocean, showing inferred tectonic 'lobes'. An inner lobe series (Ia-c) is bounded by the Japan–Philippine–Indonesia (JPI) line-Indonesian and Philippine arcs (enclosing the South China Sea and Indochina), the Ryuku arc (enclosing the Okinawa Trough and mainland China), and Japanese arc (enclosing the Japan Sea, Korea, and southeastern Siberia), corresponding respectively with the Indochinese, Chinese, and Amurian 'plates'. An outer lobe (IIa, b) bounded by the Izu-Bonin-Mariana (IBM) line — the Izu-Bonins enclosing the Sumisu Rift and Shikoku Basin (IIa), and Marianas (IIb) enclosing Parece Vela and the Mariana Trough — may also be related to Indo-Asian collision effects.

asthenospheric 'windows' in the vicinity of the East China and South China Seas. Indian Ocean mantle influx may have occurred beneath the Moluccan Sea (Fig. 12).

(5) Ambiguities in western Pacific plate kinematic models need clarification before their rigorous application in testing the mantle extrusion model.

Acknowledgements

We acknowledge support from the National Science Foundation, University of Illinois (Chicago), Texas A and M Indochina Research Consortium, and Midwest Universities Consortium for International Activities. We appreciate extensive discussions with Rick Carlson, Sun-Lin Chung, Deng Jinfu, Tony Lee, Mian Liu, Ching-Hwa Lo, and Liz Widom. We particularly thank Serge Lallemand and co-organizers of the symposium "Active Subduction and Collision in Southeast Asia" at the Université de Montpellier for the opportunity to air the ideas presented in this paper. Louis Briqieu, Laurent Jolivet, and Brian Taylor are also thanked for their careful, constructive reviews.

References

Alvarez, W., 1982. Geological evidence for the geographical pattern of mantle return flow and the driving mechanism of plate tectonics. J. Geophys. Res. 87, 6697–6710.

Arcilla, C.A., Ruelo, H.B., Umbal, J., 1989. The Angat ophiolite, Luzon, Philippines; lithology, structure, and problems in age interpretation. In Flower, M.F.J., Hawkins, J.W. (Eds.), Ophiolites and Crustal Genesis in the Philippines. Tectonophysics 168, 127–135.

Armijo, R.P., Tapponnier, P., Mercier, J.L., Han, T., 1989. Quaternary extension in southern Tibet: field observations and tectonic implications. J. Geophys. Res. 94, 2787–2793.

Audley-Charles, M.G., Ballantyne, P.D., Hall, R., 1988. Mesozoic–Cenozoic rift–drift sequence of Asian fragments from Gondwanaland. Tectonophysics 155, 317–330.

Basu, A.R., Wang, J.W., Huang, W.K., Xie, G.H., Tatsumoto, M., 1991. Major element, REE, and Pb, Nd, and Sr isotopic geochemistry of Cenozoic volcanic rocks of eastern China: implications for their origin from sub-oceanic type mantle reservoirs. Earth Planet. Sci. Lett. 105, 149–169.

van Bergen, M.J., Vroon, P.Z., Hoogewerff, J.A., 1993. Geochemical and tectonic relationships in the East Indonesian arc-continent collision region: implications for subduction of the Australian passive margin. Tectonophysics 223, 97–116.

Bergman, S.C., Coffield, D.Q., Talbot, J.P., Garrard, R.A., 1996. Tertiary tectonic and magmatic evolution of western Sulawesi and the Makassar Strait, Indonesia: evidence for a Miocene continent–continent collision. In: Hall, R., Blundell, D.J. (Eds.), Tectonic Evolution of Southeast Asia. Geol. Soc. Spec. Publ. 106, 391–429.

Bloomer, S.H., Taylor, B., MacLeod, C.J., Stern, R.J., Fryer, P., Hawkins, J.W., Johnson, L., 1995. Early arc volcanism and the ophiolite problem: a perspective from drilling in the western Pacific. In: Taylor, B., Natland, J. (Eds.), Active Margins And Marginal Basins of the Western Pacific. AGU Geophysical Monograph, vol. 88. American Geophysics Union, Washington, DC, pp. 1–30.

Briais, A., Patriat, P., Tapponnier, P., 1993. Updated interpretation of magnetic anomalies and seafloor spreading stages in the South China Sea, implications for the Tertiary tectonics of SE Asia. J. Geophys. Res. 98, 6299–6328.

Castillo, P.R., 1996. The origin and geodynamic implication of the Dupal isotopic anomaly in volcanic rocks from the Philippine island arcs. Geology 24, 271–274.

Chamot-Rooke, N., Le Pichon, X., 1999. GPS determined eastward Sundaland motion with respect to Eurasia confirmed by earthquakes slip vectors at Sunda and Philippine trenches. Earth Planet. Sci. Lett. 173, 439–455.

Chen, C.-H., Shieh, U.-N., Lee, T., Chen, C.-J., Mertzman, S.A., 1990. Nd–Sr–O isotopic evidence for source contamination and unusual component under Luzon arc. Geochim. Cosmochim. Acta 54, 2473–2483.

Cheng, G.-Y., Song, Z.-H., An, C.-Q., Cheng, L.-H., Zhuang, Z., Fu, Z.-W., Lu, Z.-L., Hu, J.-F., 1991. Three-dimensional crust and upper mantle structure of the north China region. Acta Geophys. Sin. 34, 172–181.

Chi, C.T., Dorobek, S., Richter, C., McCabe, R., Flower, M.F.J., 1998. Paleomagnetism of late Neogene basalts in Vietnam and Thailand; implications for the post-Miocene tectonic history of Indochina. In: Mantle Dynamics and Plate Interactions in East Asia. Geodynamics Series, AGU, vol. 27, pp. 289–299.

Chung, S.-L., Sun, S.-S., new, A., 1992. genetic model for the East Taiwan ophiolite and its implications for Dupal domains in the northern hemisphere. Earth Planet. Sci. Lett. 109, 133–145.

Chung, S.-L., Sun, S.-S., Tu, K., Chen, C.-H., Lee, C.-Y., 1994. Late Cenozoic basaltic volcanism around the Taiwan Strait, SE China: product of lithospere–asthenosphere interaction during continental extension. Chem. Geol. 112, 1–20.

Chung, S.-L., Jahn, B.-M., Chen, S.-J., Lee, T., Chen, C.-H., 1995. Miocene basalts in NW Taiwan: evidence for EM-type mantle sources in the continental lithosphere. Geochim. Cosmochim. Acta 59, 549–555.

Chung, S.-L., Lee, T.-Y., Lo, C.-H., Wang, P.-L., Chen, C.-Y., Yem, N.T., Hoa, T.T., Wu, G.-Y., 1997. Intraplate extension prior to continental extrusion along the Alao Shan-Red River shear zone. Geology 25, 311–314.

Cousens, B.L., Allan, J.F., 1992. A Pb, Sr, and Nd study of basaltic rocks from the Sea of Japan, Legs 127/128. In: Tamaki, K., Suyehiro, K., Allan, J., McWilliams, M. et al. (Eds.), Proc. ODP, Sci. Results, 127/128, Part 2. Ocean Drilling Program, College Station, TX, pp. 805–817.

Crawford, A.J., Beccaluvca, L., Serri, G., 1981. Tectonomagmatic evolution of the west Philippine-Marianas region and the origin of boninites. Earth. Sci. Planet. Lett. 54, 346–356.

Crawford, A.L., Beccaluva, L., Serri, G., Dostal, J., 1986. Petrology, geochemistry and tectonic implications of volcanics dredged from the intersection of the Yap and Mariana trenches. Earth Planet. Sci. Lett. 80, 265–280.

Crawford, A.J., Verbeeten, A., Eggins, S., Danyushevsky, L.V., Maillet, P., Sigurdsson, I.A., Monzier, M., 1997. Hot subduction; magmatism along the Hunter Ridge. SW Pacific, State-of-the-arc'97. Island Arc Magma Genesis workshop, vol. 45, pp. 9–12.

Danyushevsky, L.V., Sobolev, A.V., Falloon, T.J., 1995. North Tongan high-Ca boninite petrogenesis; the role of Samoan plume and subduction-transform fault transition. J. Geodynam. 20, 219–241.

Davies, J.H., von Blanckenburg, F., 1995. Slab breakoff: a model of lithosphere detachment and its test in the magmatism and deformation of collisional orogens. Earth Planet. Sci. Lett. 129, 85–102.

Davis, P.M., 1996. Tomography and seismic anisotropy of Asia and present and past tectonics. In: An, Y., Harrison, T.M. (Eds.), The

Tectonic Evolution of Asia. Cambridge University Press, Cambridge, pp. 85–94.

DeBari, S.M., Taylor, B., Spencer, K., Fujioka, K., trapped, A., 1999. Philippine Sea Plate origin for MORB from the inner slope of the Izu-Bonin Trench. Earth Planet. Sci. Lett. 174, 183–197.

Dick, H.J.B., Bullen, T., 1984. Chromian spinel as a petrogentic indicator in abyssal and alpine-type peridotites and spatially associated lavas. Contrib. Mineral. Petrol. 86, 54–76.

Doglioni, C., 1993. Geological evidence for a global tectonic polarity. J. Geol. Soc. Lond. 150, 991–1002.

Doglioni, C., Harabaglia, P., Merlini, S., Mongelli, F., Peccerillo, A., Piromallo, C., 1999. Orogens and slabs vs their direction of subduction. Earth Sci. Rev. 45, 167–208.

Dupré, B., Allegre, C.J., 1983. Pb–Sr isotope variations in Indian Ocean basalts and mixing phenomena. Nature 303, 142–146.

Elliot, T., Plank, T., Zindler, A., White, W., Bourdon, B., 1997. Element transport from slab to volcanic front at the Mariana arc. J. Gerophys. Res. 102, 14991–15019.

Encarnacion, J.P., Mukasa, S.B., Obille Jr., E.C., 1993. Zircon U–Pb geochronology of the Zambales and Angat ophiolites, Luzon, Philippines: evidence for an Eocene arc-back arc pair. J. Geophys. Res. B: Solid Earth Planets 98, 19,991–20,004.

England, P., Houseman, G., 1989. Extension during continental convergence with application to the Tibetan Plateau. J. Geophys. Res. 94, 17561–17579.

England, P.C., Molnar, P., 1997a. Active deformation of Asia: from kinematics to dynamics. Science 278, 647–650.

England, P.C., Molnar, P., 1997b. The field of crustal velocity in Asia calculated from quaternary rates of slip on faults. Geophys. J. Int. 130, 551–582.

Evans, C.A., Casteneda, G., Franco, H., 1991. Geochemical complexities preserved in the volcanic rocks of the Zambales Ophiolite, Philippines. J. Geophys. Res. B: Solid Earth Planets 96, 16251–16262.

Faccenna, C., Davy, P., Brun, J.-P., Funiciello, R., Giardini, D., Mattei, M., Nalpas, T., 1996. The dynamics of back-arc extension; an experimental approach to the opening of the Tyrrhenian Sea. Geophys. J. Int. 126, 781–795.

Falloon, T.J., Crawford, A.J., 1991. The petrogenesis of high-calcium boninite lavas dredged from the northern Tonga Ridge. Earth Planet. Sci. Lett. 102, 375–394.

Flower, M.F.J., Tamaki, K., Hoang, N., 1998. Mantle extrusion: model for dispersed volcanism and DUPAL-like asthenosphere in east Asia and the western Pacific. In: Flower, M.F.J., Chung, S.-L., Lo, C.-H., Lee, T.-Y. (Eds.), Mantle Dynamics and Plate Interactions in East Asia. Geodynamics Series, vol. 27. American Geophysical Union, Washington, DC, pp. 67–88.

Forsythe, D., Uyeda, S., 1975. On the relative importance of the driving forces of plate motion. Geophys. J. R. Aust. Soc. 43, 163–200.

Fryer, P., Taylor, B., Langmuir, C.H., Hochsteadter, A.G., 1990. Petrology and geochemistry of lavas from the Sumisu and Torishima backarc rifts. Earth Planet. Sci. Lett. 100, 161–178.

Fukao, M.O., Inoue, H., Nenbai, M., 1992. Subducting slabs stagnate in the mantle transition zone. J. Geophys. Res. 97, 4809–4822.

Fuller, M., Haston, R., Lin, R.B., Schmidtke, E., Almasco, J., 1991. Tertiary paleomagnetism of regions around the South China Sea. J. SE Asian Earth Sci. 6, 161–184.

Gao, S., Davis, P.M., Liu, H., Slack, P.D., Zorin, Y.A., Mordvinova, N.A.V.V., Kozhevnikov, V.M., Meyer, R.P., 1994. Seismic anisotropy and mantle flow beneath the Baikal Rift Zone. Nature 371, 149–151.

Geary, E.E., Kay, R.W., 1989. Identification of an Early Cretaceous ophiolite in the Camarines-Norte islands basement complex, eastern Luzon, Philippines. Tectonophysics 168, 109–126.

Genrich, J.F., Beck, Y., McCaffrey, R., Calais, E., Stevens, C.W., Subarya, C., 1996. Accretion of the southern Banda arc to the Australian plate margin determined by Global Positioning System measurements. Tectonics 15, 288–295.

Gopel, C., Allegre, C.J., Xu, R.-H., 1984. Lead isotope study of the Xigaze ophiolite, Tibet: the problem of the relationship between magmatites and tectonites. Earth Planet. Sci. Lett. 69, 301–310.

Gribble, R.F., Stern, R.J., Newman, S., Bloomer, S.H., O'Hearn, T., 1998. Chemical and isotopic composition of lavas from the northern Mariana Trough: implications for magmagenesis in backarc basins. J. Petrol. 39, 125–139.

Griffin, W.L., S.Y. O'Reilly, Ryan, C.G., 1992 Composition and thermal structure of the lithosphere beneath South Africa, Siberia and China: proton microprobe studies. Symposium on Cenozoic Igneous Rocks and Deep-seated Xenoliths of China and its Environs. Program with Abstracts, vol. 20, Chinese Academy of Sciences, Beijing.

Griffin, W.L., Zhang, A., S, Y., 1998. Phanerozoic evolution of the lithosphere beneath the Sino-Korean craton. In: Flower, M.F.J., Chung, S.-L., Lo, C.-H., Lee, T.-Y. (Eds.), Mantle Dynamics and Plate Interactions in East Asia. Geodynamics Series, vol. 27. American Geophysical Union, Washington, DC, pp. 107–126.

Guillou, H., Arnaud, N., Honthaas, C., Rehault, J.P., Maury, R.C., Bellon, H., Hemond, C., Malod, J.A., Cornee, J.J., Villeneuve, M., Cotton, J., Burhanuddin, A., 1998. Neogene back-arc origin for the Banda Sea basins: geochemical and geochronological constraints from the Banda ridges (East Indonesia). Tectonophysics 298, 297–317.

Hall, R., 1996. Reconstructing Cenozoic SE Asia. In: Hall, R., Blundell, D. (Eds.), Tectonics Evolution of Southeast Asia. Geol. Soc. Spec. Publ. 106, 153–184.

Hall, R., 1998. The plate tectonics of Cenozoic SE Asia and the distribution of land and sea. In: Hall, R., Holloway, J.D. (Eds.), The Plate Tectonics of Cenozoic SE Asia and the Distribution of Land and Sea. Backbuys Publishers, Leiden, pp. 91–131.

Hall, R., 1999. When two arcs collide: Neogene history of collision in the Halmahera region, Indonesia, Program with Abstracts, International Conference on: Active Subduction and Collision in Southeast Asia: Data and Models. Mem. Geosci.-Montpellier 14, 181.

Hall, R., Fuller, M., Ali, J.R., Anderson, C.D., 1995. The Philippine Sea Plate: magnetism and reconstructions. In: Taylor, B., Natland, J. (Eds.), Active Margins and Marginal Basins of the western Pacific. AGU Geophysical Monograph, vol. 88. American Geophysics Union, Washington, DC, pp. 371–404.

Hart, S.R., 1984. The DUPAL anomaly: a large scale isotopic anomaly in the southern hemisphere. Nature 309, 753–756.

Hart, S.R., Hauri, E.H., Oschmann, L.A., Whitehead, J.A., 1992. Mantle plumes and entrainment: isotopic evidence. Science 256, 517–520.

Haston, R.B., Fuller, M., 1991. Paleomagnetic data from the Philippine Sea plate and their tectonic significance. J. Geophys. Res. 96, 6073–6098.

Heki, K., 1996. Horizontal and vertical crustal movements from three-dimensional very long baseline interferometry kinematic reference frame; implication for the reversal timescale revision. J. Geophys. Res. B, Solid Earth Planets 101, 3187–3198.

Hickey-Vargas, R., 1991. Isotope characteristics of submarine lavas from the Philippine Sea: implications for the origin of arc and basin magmas of the Philippine tectonic plate. Earth Planet. Sci. Lett. 107, 290–304.

Hickey-Vargas, R., 1998. Origin of the Indian Ocean-type isotopic signature in basalts from the Philippine Sea plate spreading centers: an assessment of local versus large-scale processes. J. Geophys. Res. 103, 20963–20979.

Hickey-Vargas, R.L., Reagan, M., 1987. Temporal variation of isotope and rare earth element abundances from Guam: implications for the evolution of the Mariana arc. Contrib. Mineral. Petrol. 97, 497–508.

Hickey-Vargas, R., Hergt, J.M., Spadea, P., 1995. The Indian Ocean-type isotopic signature in western Pacific marginal basins: origin and significance. In: Taylor, B., Natland, J. (Eds.), Active Margins and Marginal Basins of the Western Pacific. AGU Geophysical Monograph, vol. 88. American Geophysics Union, Washington, DC, pp. 175–197.

Hilde, T.W.C., Uyeda, S., Kroenke, L., 1977. Evolution of the western Pacific and its margin. Tectonophysics 38, 145–165.

Hilde, T.W.C., Lee, C.-S., 1984. Origin and evolution of the West Philippine basin: a new interpretation. Tectonophysics 102, 85–104.

van der Hilst, R., Seno, T., 1993. Effects of relative plate motion on the deep structure and penetration depth of slabs below the Izu-Bonin and Mariana island arcs. Earth Planet. Sci. Lett. 120, 395–407.

van der Hilst, R., Engdahl, R., Spakman, W., Nolet, G., 1991. Tomographic imaging of subducted lithosphere below northwest Pacific island arcs. Nature 353, 37–43.

Hoang, N., Flower, M.F.J., Carlson, R.W., 1996. Major, trace element, and isotopic compositions of Vietnamese basalts: interaction of enriched mobile asthenosphere with the continental lithosphere? Geochim. Cosmochim. Acta 60, 4329–4351.

Hoang, N.T., Flower, M.F.J., 1998. Petrogenesis of Cenozoic basalts from Vietnam: implication for origins of a diffuse igneous province. J. Petrol. 39, 34–50.

Hochstaedtler, A.G., Gill, J.B., Morris, J.D., 1990. Volcanism in the Sumisu Rift, II. Subduction and non-subduction related components. Earth Planet. Sci. Lett. 100, 195–209.

Honthaas, C., Rehault, J.-P., Maury, R.C., Bellon, H., Hemond, C., Malod, J.-A., Cornee, J.-J., Villeneuve, M., Cotten, J., Burhanuddin, S., Guillou, H., Arnaud, N., 1998. A Neogene back-arc origin for the Banda Sea basins; geochemical and geochronological constraints from the Banda ridges (East Indonesia). Tectonophysics 298, 297–317.

Houseman, G., England, P., 1992. Crustal thickening versus lateral expulsion in the Indian–Asian continental collision. J. Geophys. Res. 98, 12233–12249.

Houseman, G.A., McKenzie, D.P., Molnar, P., 1981. Convective instability of a thickened boundary layer and its relevance for the thermal evolution of continental convergent belts. J. Geophys. Res. 86, 6115–6132.

Hussong, D.M., Uyeda, S., 1981. Tectonic processes and the history of the Mariana arc: a synthesis of results from Deep Sea Drilling Project Leg 60. In: Hussong, D.M. (Ed.), Initial Reports of the Deep Sea Drilling Project, vol. 60. US Government Printing Office, Washington, DC, pp. 909–929.

Isacks, B.L., Molnar, P., 1971. Distribution of stresses in the descending lithosphere from a global survay of focal mechanism solutions of mantle earthquakes. Rev. Geophys. Space Phys. 9, 103–174.

Jolivet, L., Davy, P., Cobbold, P., 1990. Right-lateral shear along the Northwest Pacific margin and the India-Eurasia collision. Tectonics 9, 1409–1419.

Jolivet, L., Huchon, P., Rangin, C., 1989. Tectonic setting of western Pacific margin basins. In: Cadet, J.P., Uyeda, S. (Eds.), Subduction Zones, The Kaiko Project. International Kaiko Conference on Subduction Zones, vol. 60, pp. 23–47.

Kamenetsky, V.S., Crawford, A.J., Eggins, S., Muehe, R., 1997. Phenocryst and melt inclusion chemistry of near-axis seamounts. Valu Fa Ridge, Lau Basin; insight into mantle wedge melting and the addition of subduction components. Earth Planet. Sci. Lett. 151, 205–223.

Karig, D.E., 1971. Origin and development of marginal basins in the western Pacific. J. Geophys. Res. 76, 2542–2561.

Koto, T., Kotake, Y., et al., 1998. Initial results from WING, the continuous network in the Western Pacific area, GPS. Geophys. Res. Lett. 25, 369–372.

Kellogg, L.H., Turcotte, D.L., 1990. Mixing and the distribution of heterogeneities in a chaotically convecting mantle. J. Geophys. Res. 95, 421–432.

Kepezhinskas, P.K., Defant, M., Drummond, M., 1995. Progressive enrichment of island arc mantle by melt–peridotite interaction inferred from Kamchatka xenoliths. Geochim. Cosmochim. Acta 60, 1217–1229.

Kersting, A.B., Arculus, R.J., Gust, D.A., 1996. Lithospheric contributions to arc magmatism: isotopic variations along strike in volcanoes of Honshu, Japan. Science 272, 1464–1468.

Kreemer, C., Holt, W.E., Goes, S., Govers, R., 2000. Active deformation in eastern Indonesia and the Philippines from GPS and seismicity data. J. Geophys. Res. 105, 663–680.

Lavé, J., Avouac, J.-P., Lacassin, R., Tapponnier, P., Montgner, J.-P., 1996. Seismic anisotropy beneath Tibet-evidence for eastward extrusion of the Tibetan lithosphere. Earth Planet. Sci. Lett. 140, 83–96.

Lawver, L.A., Gahagan, L.M., 1993. Subduction zones, magmatism, and the breakup of Pangea. In: Stone, D.B., Runcorn, S.K. (Eds.), Flow and Creep in the Solar System: Observations Modeling, and Theory. Kluwer Academic, Dordrecht, pp. 225–247.

Lebedev, S., Nolet, G., van der Hilst, R.D., 1997. The upper mantle beneath the Philippine Sea region from waveform inversions. Geophys. Res. Lett. 24, 1851–1854.

Lee, T.-Y., Lawver, L., 1995. Cenozoic plate reconstruction of Southeast Asia. In: Hilde, T.W.C., Flower, M.F.J. (Eds.), Tectonophysics: Southeast Asia Structure, Tectonics, and Magmatism, vol. 251, pp. 85–138.

Liu, F.-T., Hua, W., Jian-hua, L., Ge, H., Qiang, L., Ke-Xin, Q., 1990. 3-D velocity images beneath the Chinese continent and adjacent regions. Geophys. J. Int. 101, 379–394.

Liu, Mian, Cui Xiaojun, Liu Futian, 2000. Mantle extrusion: a possible link between Indo-Asian collision and eastern China rifting. Submitted for publication.

Lumadyo, J.E., McCabe, R., Harder, S., Lee, T., 1993. Borneo: a stable portion of the Eurasian margin since the Eocene. J. SE Asian Earth Sci. 8, 225–231.

Lundgren, P., Giardini, D., Russo, R.M., 1998. A geodynamic framework for eastern Mediterranean kinematics. Geophys. Res. Lett. 25, 4007–4010.

Mahoney, J., LeRoex, A.P., Peng, Z., Fisher, R.L., Natland, J.H., 1992. Southwestern limits of Indian Ocean ridge mantle and the origin of low-^{206}Pb/^{204}Pb mid-ocean ridge basalt: isotope systematics of the central Southwest Indian Ridge (17°–50°E). J. Geophys. Res. 97, 19771–19790.

Mahoney, J., Sinton, J.M., Kurz, M.D., McDougall, J.D., Spencer, K.J., Lugmair, G.W., 1994. Isotope and trace element characteristics of a super-fast spreading ridge: East Pacific Rise (13°–23°S). Earth Planet. Sci. Lett. 121, 173–193.

Mahoney, J.J., Frei, R., Tejada, M.L.G., Mo, X.X., Leat, P.T., Nägler, T.F., 1998. Tracing the Indian Ocean mantle domain through time: isotopic results from old west Indian, east Tethyan, and south Pacific seafloor. J. Petrol. (7), 1285–1306.

Makeyeva, L.I., Vinnik, L.P., Roeker, S.W., 1992. Shear wave splitting and small-scale convection in the continental upper mantle. Nature 358, 144–147.

McCabe, R., Uyeda, S., 1983. Hypothetical model for the bending of the Mariana Arc. In: Hayes, D.E. (Ed.), The Tectonic and Geologic Evolution of Southeast Asian Seas and Islands: Part 2. AGU Geophysical Monograph 27, pp. 281–293.

McDermott, F., Defant, M.J., Hawkesworth, C.J., Maury, R.C., Joron, J.L., 1993. Isotope and trace-element evidence for three component mixing in the genesis of the North Luzon arc lavas (Philippines). Contrib. Mineral. Petrol. 113, 9–23.

McKenzie, D., O'Nions, R.K., 1983. Mantle reservoirs and oceanic island basalts. Nature 301, 229–231.

McNamara, D.E., Owens, T.J., Silver, P.G., Wu, F., 1994. Shear wave anisotropy beneath the Tibet Plateau. J. Geophys. Res. 98, 12003–12017.

Meijer, A., 1980. Primitive island arc volcanism and a boninite series: examples from the western Pacific island arcs. In: Hayes, D.E. (Ed.), The Tectonic and Geologic Evolution of Southeast Asian Seas and Islands. The Tectonic and Geophysics Monograph Series, vol. 23. American Geophysics Union, Washington, DC, pp. 271–282.

Milsom, J., Kaye, S., Sardjono, 1996. Extension, collision and curvature in the eastern Banda arc. In: Hall, R., Blundell, D.J. (Eds.), Tectonic Evolution of Southeast Asia. Geol. Soc. London, Spec. Publ. 106, 85–94.

Miyashiro, A., 1986. Hot regions and the origin of marginal basins in the western Pacific. Tectonophysics 122, 195–216.

Monnier, C., Giradeau, J., Maury, R.C., Cotton, J., 1995. Back-arc basin origin for the east Sulawesi ophiolite (eastern Indonesia). Geology 23, 851–854.

Mukasa, S.B., McCabe, R., Gill, J.B., 1987. Pb-isotopic compositions of volcanic rocks in the West and East Philippine arcs: presence of the Dupal isotopic anomaly. Earth Planet. Sci. Lett., 153–164.

Mukasa, S.B., Fischer, G.M., Barr, S.M., 1995. The character of the subcontinentnal mantle in southeast Asia: evidence from isotopic and elemental compositions of extension-related Cenozoic basalts in Thailand. In: Hart, S.R. (Ed.), Earth Processes: Reading the Isotopic Code. AGU Geophysics Monograph, vol. 95. American Geophysics Union, Washington, DC, pp. 233–252.

Nakamura, E., Campbell, I.H., McCulloch, M.T., Sun, S.-S., 1989. Chemical geodynamics in a backarc region around the Sea of Japan: Implications for the genesis of alkaline basalts in Japan, Korea, and China. J. Geophys. Res. 94, 4634–4654.

Okamura, S., Arculus, R.J., Martynov, Y.A., Kagami, H., Yoshida, T., Kawano, Y., 1998. Multiple magma sources involved in marginal sea formation: Pb, Sr, and Nd isotopic evidence from the Japan Sea region. Geology 26, 619–622.

Parkinson, I.J., Pearce, J.A., 1998. Peridotites from the Izu-Bonin-Mariana forearc (ODP Leg 125): evidence for mantle melting and melt-mantle interaction in a supra-subduction zone setrting. J. Petrol. (9), 1577–1618.

Pearce, J.A., Lippard, S.J., Robberts, S., 1984. Characteristics and tectonic significance of supra-subduction zone ophiolites. Geol. Soc. London, Spec. Publ. 16, 77–96.

Pearce, J.A., Thirlwall, M.F., Ingram, G., Murton, B.J., Arculus, R.J., van der Laan, S., 1992. Isotopic evidence for the origin of boninites and related roks drilled in the Izu-Bonin (Ogasawara) forearc, Leg 125. In: Fryer, P., Pearce, J.A., Stokking, L.B. et al. (Eds.), Proc. ODP, Sci. Results, vol. 125, Ocean Drilling Program, College Station, TX, pp. 237–263.

Pearce, J.A., van der Laan, S., Arculus, R.J., Murton, B.J., Ishii, T., Peate, D.W., Parkinson, I.J., 1992. Boninite and harzburgite from Leg 125 (Bonin-Mariana forearc): a case study of magma genesis during the initial stages of subduction. In: Fryer, P., Pearce, J.A., Stokking, L.B. et al. (Eds.), Proc. ODP, Sci. Results, vol. 125, Ocean Drilling Program, College Station, TX, pp. 623–662.

Peng, Z.C., Zartman, R.E., Futa, K., Chen, D.G., 1995. Pb-, Sr-, and Nd-isotopic systematics and chemical characteristics of Cenozoic basalts, eastern China. Chem. Geol. 59, 3–33.

Plank, T., Langmuir, C., 1998. The chemical composition of subducting sediment and its consequences for the crust and mantle. Chem. Geol. 145, 325–394.

Polvé, M., Maury, R.C., Bellon, H., Rangin, C., Priadi, B., Yuwono, S., Joron, J.L., Atmadja, R.S., 1997. Magmatic evolution of Sulawesi (Indonesia): constraints on the Cenozoic geodynamic history of the Sundaland activemargin. Tectonophysics 272, 69–92.

Pouclet, A., Lee, Jin-Soo, Visal, P., Hervé Bellon, B., 1995. Cretaceous to Cenozoic volcanism in South Korea and in the Sea of Japan: magmatic constraints on the opening of the backarc basin. In: Smellie, J.L. (Ed.), Volcanism Associated with Extension at Consuming Plate Margins. Geol. Soc. Spec. Publ. 81, 169–191.

Prouteau, G., Maury, R.C., Rangin, C., Suparka, E., Bellon, H., Pubellier, M., Cotton, J., 1996. Miocene adakites from northwest Borneo and their relation to the subduction of the Proto South China Sea. Comptes Rendus Acad. Sci. Terre 323, 925–932.

Pubellier, M., Quebral, R., Aurelio, M., Rangin, C., 1996. Docking and post-docking escape tectonics in the southern Philippines. In: Hall, R., Blundell, D.J. (Eds.), Tectonic Evolution of Southeast Asia. Geol. Soc. Spec. Publ. 106, 511–523.

Rangin, C., Dahrin, D., Quebral, R., 1996a. Collision and strike-slip faulting in the northern Molucca Sea (Philippines and Indonesia); preliminary results of a morphotectonic study. In: Hall, R., Blundell, D.J. (Eds.), Tectonic Evolution of Southeast Asia. Geol. Soc. Spec. Publ. 106, pp. 29–46.

Rangin, C., Dahrin, D., Quebral, R., Scientific Party, MODEC, 1996. Collision and strike-slip faulting in the northern Moluccan Sea (Philippines and Indonesia): preliminary results of a morphotectonic study. In: Hall, R., Blundell, D.J. (Eds.), Tectonic Evolution of Southeast Asia. Geol. Soc. Spec. Publ. 106, 29–45.

Rangin, C., Maury, R.C., Polvé, M., Bellon, H., Priadi, B., Soeria-Atmadia, R., Cotten, J., Joron, J.-L., 1997. Eocene to Miocene backarc basin basalts and associated island arc tholeiites from northern Sulawesi (Indonesia): implications for the geodynamic evolution of the Celebes basin. Bull. Soc. Géol. Fr. 168, 627–635.

Rangin, C., Spakman, W., Pubellier, M., Bijwaard, H., 1999. Tomographic and geological constraints on subduction along the eastern Sundaland continental margin (South-East Asia). Bull. Soc. Géol. Fr. 170 (6), 775–788.

Reagan, M.K., Meijer, A., 1984. Geology and geochemistry of early arc-volcanic rocks from Guam. Geol. Soc. Am. Bull. 95, 701–713.

Ren, J., Tamaki, K., 1999. Late Mesozoic and Cenozoic episodic rifting of eastern Eurasia continent. Trans. Am. Geophys. Union, Eos (46), 1019.

Royden, L.H., 1993. The tectonic expression of slab-pull at continental convergent boundaries. Tectonics 12, 303–325.

Royden, L., 1996. Coupling and decoupling of crust and mantle in convergent orogens: implications for strain partitioning in the crust. J. Geophys. Res. 101, 17679–17705.

Russo, R.M., Silver, P.G., 1996. Cordillera formation, mantle dynamics, and the Wilson Cycle. Geology 24, 511–514.

Russo, R.M., Silver, P.G., Franke, M., Ambeh, W.B., James, D.E., 1996. Shear wave splitting in Northeast Venezuela, Trinidad, and the eastern Caribbean. Phys. Earth Planet. Inter. 95, 251–275.

Santa Cruz, J.R., Letargo, M.R.R., Samaniego, C.L., 1989. Petrography and chemistry of high-Mg, biotite-rich, pillow lavas from southwestern Panay, Philippines. In: Flower, M.F.J., Hawkins, J.W. (Eds.), Ophiolites and Crustal Genesis in the Philippines. Tectonophysics 168 (1–3), 137–149.

Seno, T., Maruyama, S., 1984. Paleogeographic reconstruction and origin of the Philippine Sea. Tectonophysics 102, 53–84.

Seno, T., Stein, S.A., Gripp, A.E., 1993. A model for the motion of the Philippine Sea Plate consistent with NUVEL-1 and geological data. J. Geophys. Res. 98, 17941–17948.

Shinjo, R., 1999. Geochemistry of high Mg andesites and the tectonic evolution of the Okinawa Trough-Ryukyu arc system. Chem. Geol. 157, 69–88.

Sleep, N.H., Toksöz, M.N., 1971. Evolution of marginal basins. Nature 33, 548–550.

Smith, A.D., 1998. The geodynamic significance of the DUPAL anomaly in East Asia. In: Flower, M.F.J., Chung, S.-L., Lo, C.-H., Lee, T.-Y. (Eds.), Mantle Dynamics and Plate Interactions in East Asia. Geodynamics Series, vol. 27, pp. 89–106.

Smith, A.D., Lewis, C., 1999. Differential rotation of lithosphere and mantle and the driving force of plate tectonics. Geodynamics 28, 97–116.

Spadea, P., d'Antonio, M., Thirlwall, M.F., 1996. Source characteristics of basement rocks from the Sulu and Celebes basins (western Pacific): chemical and isotopic evidence. Contrib. Mineral. Petrol. 123, 159–176.

Sobolev, A.V., Danyushevsky, L.V., 1994. Petrology and geochemistry of boninites from the north termination of the Tonga Trench; constraints on the generation conditions of primary high-Ca boninite magmas. J. Petrol. 35, 1183–1221.

Stern, R.J., Bloomer, S.H., 1992. Subduction zone infancy: examples from the Eocene Izu-Bonin-Mariana and Jurassic California arcs. Geol. Soc. Am. Bull. 104, 1621–1636.

Stern, R.J., Smoot, N.C., Rubin, M., 1984. Unzipping of the Volcano arc, Japan. Tectonophysics 102, 153–174.

Stern, R.J., Lin, P.N., Morris, J.D., Jackson, M.C., Fryer, P., Bloomer, S.H., Ito, E., 1990. Enriched backarc basin basalts from the northern Mariana Trough: implications for the magmatic evolution of backarc basins. Earth Planet. Sci. Lett. 100, 210–225.

Su, W.-J., Woodward, R.L., Dziewonski, A.M., 1994. Degree 12 model of shear velocity heterogeneity in the mantle. J. Geophys. Res. 99, 6945–6980.

Takenaka, S., Sanshadokoro, H., Yoshioka, S., 1999. Velocity anomalies and spatial distributions of physical properties in horizontally lying slabs beneath the Northwestern Pacific region. Phys. Earth Planet. Inter. 112 (16), 137–157.

Tamaki, K., 1995. Upper mantle extrusion tectonics of southeast Asia and formation of western Pacific backarc basins. In: International Workshop: Cenozoic Evolution of the Indochina Peninsula, Hanoi/Do Son, April, 1995, Abstract with Programs, 89 pp.

Tamaki, K., Honza, 1991. Review of global marginal basins. Episodes 14 (3), 224–230 (IUGS).

Tamayo Jr., R.A., Yumul Jr., G.P., Santos, R.A., Jumawan, F., Rodolfo, K.S., 1998. Petrology and mineral chemistry of a back-arc upper mantle suite; example from the Camarines Norte ophiolite complex, South Luzon. J. Geol. Soc. Philippines 53, 1–23.

Tapponnier, P., Peltzer, G., Le Dain, A.Y., Armijo, R., Cobbold, P., 1982. Propagating extrusion tectonics in Asia: new insights from simple experiments with plasticine. Geology 7, 611–616.

Tapponnier, P., Peltzer, G., Armijo, R., 1986. On the mechanics of the collision between India and Asia. In: Coward, M.P., Ries, A.C. (Eds.), Collision Tectonics. Geol. Soc. Spec. Publ. 19, 115–157.

Tapponnier, P., Lacassin, R., Leloup, P.H., Schärer, U., Zhong, D., Wu, H., Liu, X., Li, S., Zhang, L., Zhong, J., 1990. The Ailao Shan/Red River metamorphic belt: tertiary left-lateral shear between Indochina and South China. Nature 343, 431–437.

Tatsumoto, M., Nakamura, Y., 1991. DUPAL anomaly in the Sea of Japan: Pb, Nd, and Sr isotopic variations at the eastern Eurasian continental margin. Geochim. Cosmochim. Acta 55, 3697–3708.

Tatsumoto, M., Basu, A.R., Huang, W., Wang, J., Xie Sr., G., 1992. Nd, and Pb isotopes of ultramafic xenoliths in volcanic rocks of eastern China: enriched components and EMII in sucontinental lithosphere, EMI. Earth Planet. Sci. Lett. 113, 107–128.

Taylor, B. (Ed.), 1995. Backarc Basins: Tectonics and Magmatism Plenum Press, New York, 180 pp.

Taylor, B., Hayes, D.E., 1983. Origin and history of the South China Basin. In: Hayes, D.E. (Ed.), The Tectonic and Geologic Evolution of Southeast Asiam Seas and Islands. AUG Geophysics Monograph, vol. 27. American Geophysics Union, Washington, DC, pp. 25–26.

Taylor, B., Natland, J. (Eds.), 1995. Active Margins and Marginal Basins of the Western Pacific. AGU Geophysical Monograph, vol. 88, (350 pp.).

Tu, K., Flower, M.F.J., Carlson, R.W., Zhang, M., Xie Sr., G.-H., 1991a. Nd, and Pb isotopic compositions of Hainan basalts (south China): implications for a subcontinental lithosphere Dupal source. Geology 19, 567–569.

Tu, K., Flower, M.F.J., Carlson, R.W., Zhang, M., Xie, G.-H., 1991b. Magmatism in the South China Basin. 1. Isotopic and trace element evidence for an endogenous Dupal mantle component. Chem. Geol. 97, 47–63.

Uyeda, S., Ben-Avraham, Z., 1972. Origin and development of the Philippine Sea. Nature 240, 176–178.

Uyeda, S., Kanamori, H., 1979. Backarc opening and the mode of subduction. J. Geophys. Res. 84, 1049–1061.

van der Laan, S.R., Flower, M.F.J., Koster van Groos, A.F., 1989. Experimental evidence for the origin of boninite: near-liquiuds phase realtions to 7.5 kbar. In: Crawford, A.J. (Ed.), Boninites and Related Rocks. Unwin, Hyman, London, pp. 113–148.

Volpe, A.M., Macdougall, J.D., Lugmair, G.W., Hawkins, J.W., Lonsdale, P., 1990. Fine-scale isotopic variation in Mariana Trough basalts: evidence for heterogeneity and a recycled component in backarc basin mantle. Earth Planet. Sci. Lett. 100, 251–264.

Vroon, P.Z., van Bergen, M.J., Klaver, G.J., White, W.M., 1995. Strontium, neodymium, and lead isotopic and trace-element signatures of the East Indonesian sediments: provenance and implications for Banda Arc magma genesis. Geochim. Cosmochim. Acta 59, 2573–2698.

Vroon, P.Z., 1996. Pb and Nd isotope constraints on the provenance of tectonically displaced continental fragments in east Indonesia. In: Hall, R., Blundell, D.J. (Eds.), Tectonic Evolution of Southeast Asia. Geol. Soc. Spec. Publ. 106, 445–455.

Walpersdorf, A., Rangin, C., Vigny, C., 1998. GPS compared to long-term geologic motion of the north arm of Sulawesi. Earth Planet. Sci. Lett. 159 (1–2), 47–55.

Wei, D., Seno, T., 1998. Determination of the Amurian plate motions. In: Flower, M.F.J., Chung, S.-L., Lo, C.-H., Lee, T.-Y. (Eds.), Mantle Dynamics and Plate Interactions in East Asia. American Geophysical Union, (Geodynamics Series), vol. 27. Washington, DC, pp. 337–345.

Weis, D., Frey, F.A., 1996. Role of the Kerguelen Plume in generating the eastern Indian Ocean seafloor. J. Geophys. Res. B, Solid Earth Planets 101, 13831–13849.

Widiyantoro, S., van der Hilst, R., 1997. Mantle structure beneath Indonesia inferred from high-resolution tomographic imaging. Geophys. J. Int. 130, 167–182.

Yumul Jr., G.P., Dimalanta, C.B., Faustino, D.V., de Jesus, J.V., 1998. Translation and docking of an arc terrane; geological and geochemical evidence from the southern Zambales Ophiolite complex, Philippines. Tectonophysics 293, 255–272.

Zakariadze, G.S., Scott, R.B., 1979. Petrology and geochemistry of the Palau-Kyushu remnant arc, Site 448, DSDP Leg 59. Trans. Am. Geophys. Union, Eos 60, 94.

Zhang, M., Suddaby, P., Thompson, R.N., Thirlwall, M.F., Menzies, M.A., 1995. Potassic volcanic rocks in NE China: geochemical constraints on mantle source and magma genesis. J. Petrol. 36, 1275–1303.

Zhang, M., Zhou, X.H., Zhang, J., 1998. Nature of the lithospheric mantle beneath the Songliao Block, NE China: evidence from potassic rocks and Nature of the lithospheric mantle beneath the Songliao Block, NE China: evidence from potassic rocks and mantle xenoliths. In: Flower, M.F.J., Chung, S.-L., Lo, C., Lee, T.-Y. (Eds.), Mantle Dynamics and Plate Interactions in East Asia. Geodynamics Series, vol. 27. American Geophysical Union, Washington, DC, pp. 197–219.

Zhang, Y.-S., 1998. Three-dimensional upper mantle structure and plate tectonics under east Asia. In: Flower, M.F.J., Chung, S.-L., Lo, C.-H., Lee, T.-Y. (Eds.), Mantle Dynamics and Plate Interactions in East Asia. Geodynamics Series, vol. 27. American Geophysical Union, Washington, DC, pp. 11–23.

Zhang, Y-S., Tanimoto, T., 1991. Global Love wave phase velocity variation and its significance to plate tectonics. Phys. Earth. Planet. Inter. 66, 160–202.

Zhou, X.H., Zhu, B.Q., Liu, R.X., Chen, W.J., 1988. Cenozoic basaltic rocks in eastern China. In: MacDougall, J.D. (Ed.), Continental Flood Basalts. Kluwer Academic, Dordrecht, pp. 311–330.

Zindler, A., Hart, S., 1986. Chemical geodynamics. Annu. Rev. Earth Planet. Sci. 14, 493–571.