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Cenozoic magmatism in Indochina: lithosphere extension and mantle potential temperature

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Abstract: Cenozoic magmatism in southeast Asia, initiated at ca. 15 Ma and peaking between ca. 5 and 0.5 Ma, post-dates opening of the South China Sea Basin and is associated with lithospheric extension in Indochina, Thailand, and southern China. Geochemical data allow modelling of the relationship between melting and lithosphere extension in the region and documenting enrichment history of the continental lithosphere mantle. In Vietnam, geological relationships suggest that larger (tholeiite) melt fractions were generated within pull-apart basins along extensional N50°E- and N160°E-trending faults, while lower (alkali basalt and basanite) melt fractions were associated with conjugate strike-slip faults. Petrogenetic conditions interpolated from experimental data suggest quartz tholeiites were generated at ca. 1250°C and < 10 kbar pressure (plagioclase/spinel lherzolite), olivine tholeiites at ca. 1300°C, 10-15 kbar (spinel lherzolite), and alkali basalts and basanite at ca. 1350°C, < 30 kbar (spinel/garnet lherzolite), close to, or below, the thermal boundary layer of lithospheric mantle. Assuming uniform (pure shear) lithosphere extension, stretching factors needed to produce such melts at normal asthenospheric potential temperatures appear to exceed those believed to characterise recent extension in Indochina. This may suggest an elevated potential temperature resulting from (incipient) mantle plume activity.

INTRODUCTION

The extrusion tectonics hypothesis attempts to explain the geodynamic evolution of southeast Asia as a direct effect of the Indo-Eurasian collision through extensive strike-slip movement along the Red River, Chao Praya, and Tonle Sap-Mekong faults (Tapponnier *et al.*, 1986). While mechanical and kinematic effects of the model are much debated there have been few attempts to explain widespread mantle melting that accompanied, or post-dated, the extrusion process (Barr and McDonald, 1981; Whitford-Stark, 1986; Tu *et al.*, 1992; Flower *et al.*, 1992). In general, such excess passive margin volcanism may result from: 1) mantle decompression resulting from lithosphere stretching (McKenzie and Bickle, 1988; Latin and White, 1990; Tu *et al.*, 1991; 1992), 2) mantle plumes rising from the core-mantle boundary (Richards *et al.*, 1989; Griffiths and Campbell, 1990; Castillo, 1988; Silver *et al.*, 1988) or 670 km discontinuity (McKenzie and Bickle, 1988; White and McKenzie, 1989), $Tp >> 1280°C$, or 3) asthenospheric overturn induced by rifting (Mutter *et al.*, 1988; Buck *et al.*, 1988), $Tp \geq 1280°C$, cf. McKenzie and Bickle (1988).

At first sight these all present difficulties in southeast Asia. On the one hand, the extrusion model implies compression in regions where basalts are most prolific. On the other, there are few geophysical signs of an active plume although convective upwelling cannot be ruled out. Convective plume models may be distinguished from stretching or asthenospheric overturn by estimates of mantle potential temperature (Tp) (an adiabat extrapolated from the lithosphere thermal boundary layer) from basalt major element compositions (McKenzie and Bickle, 1988) and thermobarometric estimates from xenoliths. Shallow plumes may also be distinguished from those of deep origin from source trace element and isotopic enrichment signatures of plume-induced basalt melts (Hart, 1988; cf. Hanan and Schilling, 1986; Tu *et al.*, 1991; 1992).

Most examples of volcanism at passive margins *pre*-date crustal rupture and (in some cases) seafloor spreading, and are often evidenced by seaward-dipping seismic reflector sequences (Hinz, 1981; Vierck *et al.*, 1990). In contrast, dipping reflector sequences or other evidence of precursive volcanism have not been observed around the South China

Basin where regional intra-plate volcanism *post*-dates the main phase of extension. In this paper, we present preliminary interpretations of major element data for Vietnamese basalts with estimates of melting pressure and temperature conditions based on the interpolated experimental data for natural basalts.

CENOZOIC VOLCANISM: TIMING AND TECTONIC AFFINITY

Southeast Asia was probably extruded along major strike-slip faults between the early and late Tertiary in response to the Indo-Eurasian collision (Tapponnier *et al.*, 1986) with transform motion along the Red River and Tonle Sap-Mekong faults which confine much, but not all, volcanism in the region. The question as to whether the South China Sea (SCS) opened as an effect of extrusion (Tapponnier *et al.*, 1986) or independently as a back-arc feature associated with Pacific plate subduction (Taylor and Hayes, 1983) is controversial. In either case intra-plate magmatism, penetrating oceanic and continental lithosphere, was associated with newly-activated extension that followed the mid-Miocene cessation of SCS spreading. The activity marks a distal region behind the circum-Pacific subduction system and coincides with extensional rifted basins and strike-slip faults transgressing remnants of earlier Mesozoic subduction-related activity.

Basalt plateaus in southern and central Vietnam are several hundred km in diameter, up to several hundred meters in thickness, and occupy approximately 23,000 km^2 (Fig. 1). They comprise voluminous tholeiite flows (up to 20 m thick) erupted from extensional pull-apart systems whose bounding strike-slip faults are marked by small alkali basalt, including basanite and nephelinite, volcanoes. The principal centers in Vietnam occur at: Song Be/Dalat, Pleiku, Buon Ma Thuot, and Xuan Loc. An embryo offshore complex (Phu Cuy) appears to be forming on the Con Son swell (e.g. the recently active Iles de Cendres) separating the Con Son and Cuu Long basins (Fig. 1), and a high heat flow belt along the eastern seaboard (Sapozhinkov *et al.*, 1979; Koloskov *et al.*, 1986; Han and Hoang, 1985; Hoang *et al.*, 1993) (Fig. 1), while a small pyroclastic eruption occurred in Pleiku in April 1993 (Dinh Toan, pers. comm.). Less voluminous basalts and plateau-like features appear intermittently between Dien Bien Phu in the north to Quang Ngai on the coast. These are largely controlled by the NNE-SSW-oriented Uttaradit-Luang Pratang-Dien Bien phu fracture system, in the west (Hutchison, 1989), and NNW-SSE-oriented Lai Chau-Quang Ngai system, in the east (Quang, 1986). In general, the basalts may be divided according to the character of penetrated lithosphere: 1) northern off-cratonic basalts, e.g. Dien Bien Phu, 2) a north-central cratonic group (penetrating the Kontum massif) e.g. Pleiku, Buon Ma Thuot, and Phuoc Long-Song Be, and 3) a southern off-cratonic group, e.g. Dalat, Xuan Loc, and Phu Cuy.

Undersaturated lavas carry mantle xenoliths, including garnet- and spinel-lherzolites, harzburgite, and megacrysts of pyroxene, olivine, plagioclase, garnet, zircon, and corundum, these assemblages resembling those reported from Cambodia, Thailand, and southern China (Barr and MacDonald, 1981; Finnerty and Boyd, 1987; Tu *et al.*, 1991; Flower *et al.*, 1988, 1992; Zhang *et al.*, 1993). Petrologic and geochemical studies include those of French and Vietnamese investigators (Lacroix, 1993; Lacombe, 1967; Carbonnel and Saurin, 1975; Quoc and Thuoc, 1979; Han and Hoang, 1985; Tung *et al.*, 1986; Hoang *et al.*, 1993) and, since 1975, Soviet investigators (see Whitford-Stark, 1987).

There is general agreement that Cenozoic volcanism in Indochina was controlled by regional lineaments (Tri *et al.*, 1986; Quoc and Thuoc, 1979; Tung *et al.*, 1986; Trinh and Yem, 1991) leading to paired development of basalt plateaus and sediment-filled depressions (Tung *et al.*, 1986; Bao and Hai, 1991). Rangin *et al.* (1993) showed that pre-Tertiary basement was affected by pervasive strike-slip and normal faulting and that two superposed fault systems were active during the Paleogene and Neogene. The older system consists of NW-SE left-lateral strike-slip faults parallel to the Red River fault, compatible with an east-west maximum compressional axis. In southern Vietnam conjugate SW-NE right-lateral faults are also present, reactivating pre-existing Paleozoic and Mesozoic faults (Fig. 1). The younger system consists of dominantly NNW-SSE to N-S right-lateral faults compatible with a north-south maximum compressional axis. Both systems were reactivated during uplift and basalt volcanism and indicate that Indochina did not behave as a rigid block during or after extrusion. Paleostress data (Rangin *et al.*, 1993) and paleomagnetic interpretations (McCabe and Harder, 1993) are consistent with a rotating stress field and the post-mid-Miocene westward translation of extension from the southwest SCS.

Progressive activation of tectonic lineaments suggests that eastern Indochina did not behave as a rigid block during the collision of India and Eurasia, and that substantial extension of the lithosphere occurred in a progressively changing stress field (Rangin *et al.*, 1993). These observations bear on the controversy concerning whether the

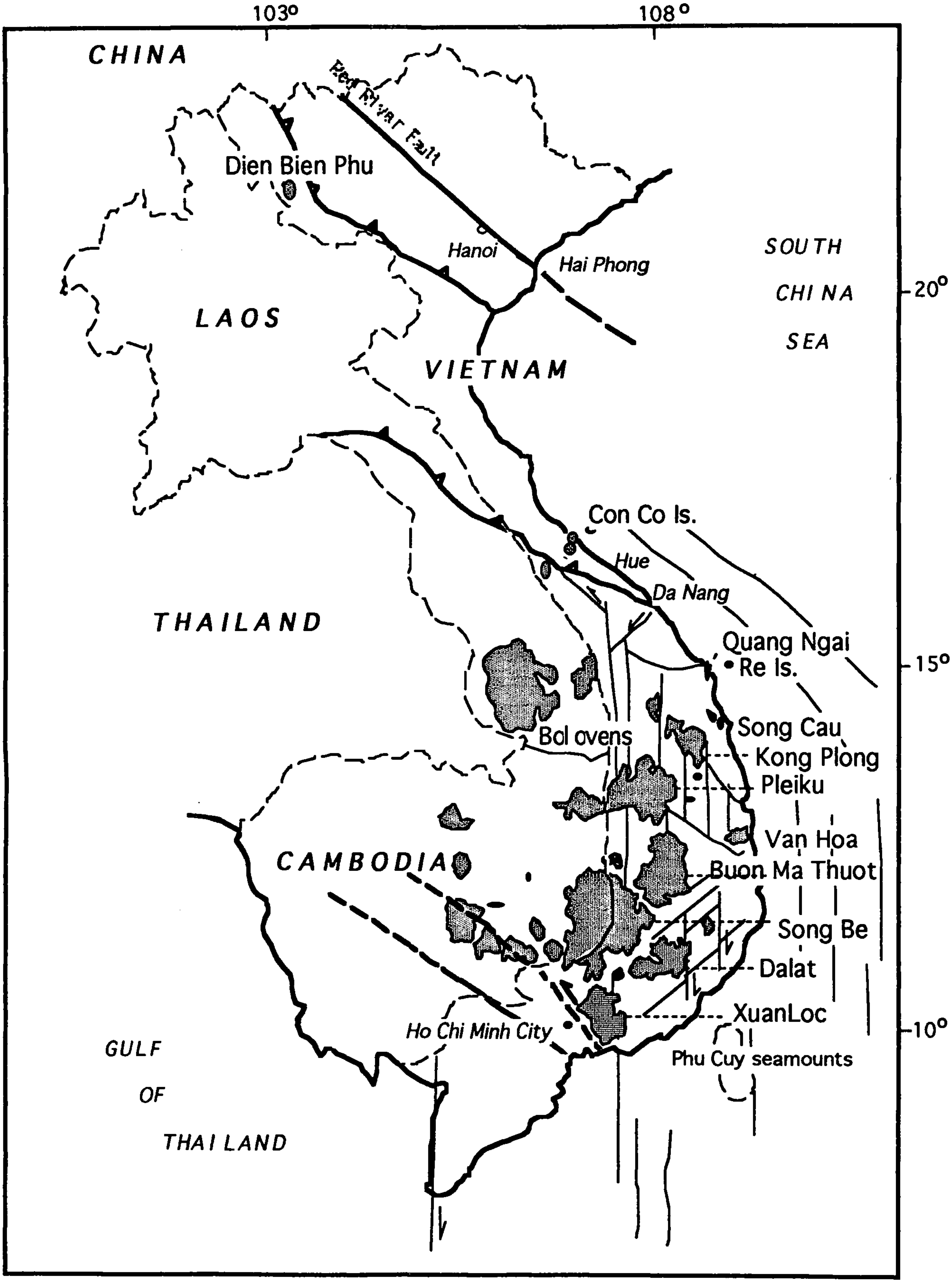


Figure 1. Sketch map of Indochina showing Cenozoic basalt plateaus (stippled). Igneous centers studied are: Song Be/ Dalat (10-1.2 Ma), Buon Ma Thuot (5.8-1.1 Ma), Pleiku (4.3-0.8 Ma), Xuan Loc (1.3-0.85), and Phu Quy seamounts (0.8-0 Ma). Tectonic fabric was interpreted from landsat imagery and geological studies by Rangin *et al.* (1983), the Vietnamese National Center for Scientific Research, and Geological Survey of Vietnam.

South China Sea evolution resulted from slab pull of the subducting proto-South China Sea (Taylor and Hayes, 1983) or from the extrusion of Indochina with respect to Eurasia (Tapponnier *et al.*, 1986). Gravity models based on integrated geologic and geophysical data for several basins associated with tectonic extrusion provide further constraints on the extent and orientation of extension (Harder *et al.*, 1993). Models for the Malay, West Natuna, and Nam Conson basins (all associated with the Three Pagodas strike-slip fault system) and Mekong basin (associated with the Mae Ping-Tonle Sap-Mekong strike-slip fault) suggest combined strike-slip extension of about 118 km (Harder *et al.*, 1993), significantly less than previous minimum estimates of 300 km (Tapponnier *et al.*, 1986).

Available K-Ar age data (Arvanne *et al.*, 1990; Rangin *et al.*, 1993) reflect activation of the centers as follows: Song Be/Dalat (10-1.2 Ma) > Buon Ma Thuot (5.8-1.1 Ma) > Pleiku (4.3-0.8 Ma) > Xuan Loc (1.3-0.85 Ma) > Phu Quy (0.8-0 Ma), matched by secular changes from dominant quartz tholeiite (with subsidiary olivine tholeiite and alkali basalt) to dominant alkali basalt and basanite (with subsidiary tholeiite) at younger centers (Thi, 1991; Quoc and Giao, 1980; Hoang and Han, 1990). Each plateau marks the intersection of regional fractures, several of which are aligned along eroded remnants of Mesozoic and earlier calc-alkaline rocks, reflecting pre-South China subduction Sea (Taylor and Hayes, 1983).

PARTIAL MELTING AT A COOL PASSIVE PLATE MARGIN

On the basis of parameterized data for basalt phase equilibria, mantle thermal conductivity, and viscosity, McKenzie and Bickle (1988) proposed that basalt melt fractions and compositions are simple functions of the stretching factor β (assuming uniform stretching) and mantle *Tp*. While this model explains the volume and composition of melt generated at ocean ridges (Fujii and Scarfe, 1985; Falloon and Green, 1988; Kinzler and Grove, 1992a,b) at β values > 50, uniform stretching is controversial for lower β values associated with passive margins and intra-continental rifts, in view of suggestions that extension may occur through 'simple shear' (along low-angle extensional fractures) rather than 'pure shear' (uniform extension throughout the lithosphere) (Wernicke, 1985; Lister *et al.*, 1986; Buck *et al.*, 1988). Attempts to distinguish these models have been based on geologic and seismic reflection investigations and are for the most part contentious or inconclusive.

Latin and White (1990) considered the problem with respect to mantle melting and showed that decompression associated with simple shear is not enough to produce melt at realistic mantle pressure unless *Tp* is anomalously high. For pure shear extension, in contrast, significant melt fractions are possible at upper mantle pressures at relatively modest β factors. Figure 2 shows models calculated for uniform (bulk shear) stretching of the lithosphere at (a) normal *Tp* (1280°C) and (b) elevated *Tp* (1480°C) (after Latin and White, 1990), indicating melt fractions calculated for a range of β. At normal *Tp* melting occurs at β values between 2 and 3 and pressures of ca. 1.5 GPa. A melt fraction of 1.5 requires a β value of about 5 and pressures less than 1 GPa. In contrast, for a *Tp* of 1480°C melting may occur at $\beta < 1.5$ and pressures up to 3 GPa. A 1.5 melt fraction can be generated at β factors of less than 2. On the basis of basalt geochemical data we can interpret melt generation conditions from the interpolated phase equilibria of primitive compositions, hence establish depths and degrees of melting of compositionally distinct magma batches. Thus, estimates of *Tp* derived from petrologic data can be useful in constraining estimates of β from: 1) gravity and heat flow modeling, 2) subsidence estimates from backstripped sedimentary sections, and 3) deep penetration seismic experiments.

Although geophysical evidence for a long-standing plume beneath southeast Asia is lacking (cf. Watts *et al.*, 1985; Courtney and White, 1986; White and McKenzie, 1989) the possibility of elevated *Tp* must be considered if lithosphere stretching is unable to account for the volume of melt generated. Experimental studies of natural and synthetic analogue systems (Kushiro, 1975; Takahashi and Kushiro, 1983; Fujii and Scarfe, 1985; Kinzler and Grove, 1992a, b) clearly demonstrate that basaltic melts show increasing CaO/Al_2O_3 and decreasing Na_2O/CaO with increasing *Tp* (at a given pressure), and increasing FeO and decreasing SiO_2 with increasing pressure (at given *Tp*) (*Langmuir* and Hanson, 1980; Klein and Langmuir, 1987). Viereck *et al.* (1989) used mass balance calculations to show that melt compositions reflect both melt fraction (i.e. *Tp*) and buffering phases in the residue. Thus mantle *Tp* and melting pressure can be interpreted from basalt composition, assuming the latter to represent a primary mantle melt fraction.

EVIDENCE FROM MANTLE SOURCE COMPOSITIONS

Incompatible trace element and radiogenic/non-radiogenic isotopic ratios in basalts can also be used to monitor enrichment and depletion histories of the source and provenance of added enrichment component. For example, Sr, Nd, and Pb isotopic and trace element signatures may be used to distinguish primitive non-depleted (Schilling *et al.*, 1982; Hanan and Schilling, 1986) or enriched ('Dupal'-type) (Hart, 1988; Loubet *et al.*, 1988) plumes from the lower or intermediate-level mantle. Enriched continental lithosphere mantle (CLM) or extended passive margin sources such as the South China Basin signatures may resemble either of these and are therefore more controversial, models invoking lower mantle or asthenospheric enrichment (Jochum *et al.*, 1989; McDonough, 1990) contrasting with others (Fitton *et al.*, 1988; Hawkesworth *et al.*, 1990) suggesting the involvement of a subduction slab-derived component.

Recognition of *Dupal*-like isotopic and Th-enriched signatures in post-spreading South China Sea and Hainan Island basalts (part of the same regional magmatic episode as Vietnamese basalts) led to the suggestion that extended CLM had been enriched via shallow level subduction prior to disaggregation and basin opening (Tu *et al.*, 1991, 1992, in review; Flower *et al.*, 1988, 1992) rather than by a deep mantle plume and supported by trace element data for xenolith pyroxene separates (Zhang *et al.*, 1993). Further interpretation suggested that CLM enrichment was superimposed on a mantle source resembling that of Central Indian Ridge (CIR-) MORB (Tu *et al.*, 1991, 1992), shared by the least-radiogenic SCS basalts and basalts from the proto-SCS East Taiwan Ophiolite

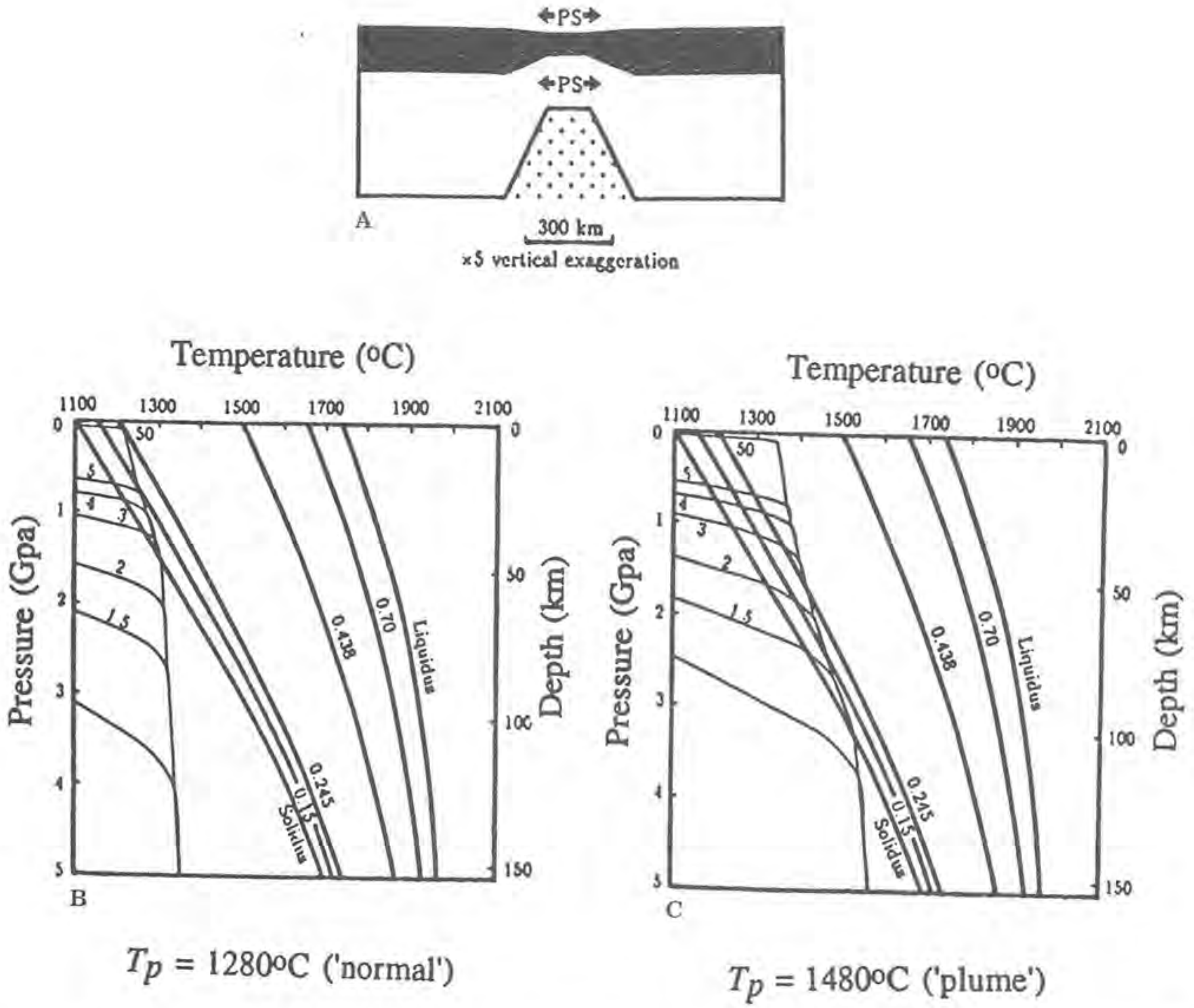


Figure 2. Uniform stretching model: A: Cartoon illustrating geometry produced by a stretching factor (b) = 2, B: Pressure-temperature diagram showing effects of adiabatic upwelling due to stretching of convective geotherm by different values of b (e.g. 1.5, 2, 3, 4, 5) for an interior potential temperature (Tp) = 1280°C, in relation to mantle peridotite solidus and liquidus. Curves between solidus and liquidus show different melt fractions by weight (0.15), 0.245, 0.438, 0.7). C: As for B with interior Tp = 1480°C (modified from Latin and White, 1990)

(Chung *et al.*, 1993), and Philippine Sea plate (Hickey-Vargas, 1991), and suggesting pervasive northward extension of the Indian Ocean asthenospheric reservoir. This conclusion has significant implications for mantle dynamics in the region. If the Indochina basalts share the SCS, CIR-MORB (etc.) asthenospheric source character (superimposed by subduction-derived enrichment of CLM) *and* require elevated potential temperatures, there is a clear indication of hot plume upwelling, albeit from an undefined mantle depth.

BASALT COMPOSITIONS AND MELTING CONDITIONS

Previous studies of Vietnamese basalts include geochemical overviews (Thi, 1991; Quoc and Giao, 1980), and more detailed investigations of Xuan Loc basalt chemistry (Hoang and Han, 1990). Most authors concur that two regional eruptive episodes produced lava associations of tholeiite, alkali basalt, basanite, and nephelinite, together with relatively small amounts (< 5%) of evolved lavas and pyroclastics. Several authors have studied megacrysts and mantle xenoliths entrained in undersaturated lavas, especially at Xuan Loc, and offshore localities (Han and Hoang, 1985; Hoang and Han, 1990).

Major element analyses of Vietnamese basalts from the basalt plateaus in southern and central Vietnam (to be published and interpreted in detail by Hoang *et al.*, 1993) allow some preliminary observations. The analysed samples were sampled stratigraphically from cored sections of the Song Be/Dalat, Pleiku, Buon Ma Thuot, and Xuan Loc basalt plateaus (Fig. 3), and by dredging from the embryo submarine complex, Phy Cuy (Fig. 1). Together with the interlayered sedimentary formations, the chemical data and section logs allow correlation of eruptive units over wide areas at each centre (Fig. 3).

The data suggest: Dalat basalts are slightly evolved quartz and olivine theoliites with subsidiary alkali basalt (MgO 6-9 wt%) and include interlayered high-K and low-K types. K_2O of the former is more than twice that of the low-K types. Basalts from Pleiku are dominated by olivine tholeiite, with subsidiary quartz tholeiite, alkali basalt, and basanite. These also reflect low-, moderate-, and high-K types, reflecting a heterogeneous source rather than products of magma system diversification, and range from moderately evolved (5-6 wt% MgO) to primitive (9-12 wt% MgO) character. Buon Ma Thuot basalts are relatively primitive (9-12 wt% MgO) and comprise moderate-K olivine tholeiite and (lesser) alkali basalts, similar in K content to Pleiku types. Xuan Loc basalts comprise olivine tholeiite and basanite which are quite primitive (8-11 wt% MgO) including interlayered high- low-K types. Offshore volcanics comprise similar proportions of olivine tholeiite, alkali basalt, and basanite, and range from primitive (up to 12 wt% MgO) to moderately evolved (ca. 6 wt% MgO). They include similar high- and moderate-K types for the Phu Cuy seamounts, matched by Quang Ngai olivine tholeiite types and moderate-K alkali basalt types from Re and Conco Islands. The apparent temporal progression of: Son Be/Dalat > Pleiku/Buon Ma Thuot > Xuan Loc > Phu Cuy complexes, is matched by basalt compositional changes, respectively, from dominant quartz tholeiite (with subsidiary olivine tholeiite and alkali basalt) in older centres to dominant alkali basalt and basanite (with subsidiary tholeiite) in younger volcanics, suggesting a decrease in ambient melt fraction and increase in mantle segregation pressures with time as a function of the evolving regional stress field.

Basalt compositions were projected on to planes in the 'CMAS' system (O'Hara, 1968), respectively from MS to C_2S_3-A_2S_3-M_2S and M_2S to CS_{60}-A_{30}-MS (where C = CaO, M = MgO, A = Al_2O_3, S = SiO_2, MS = enstatite, M_2S = forsterite, etc.) (Fig. 4). Experimentally-determined solid-liquid equilibria in the pressure range 1 atm - 30 Kbar were projected for comparison. In general, trace element and mass balance constraints preclude a genetic association of alkali basalts and tholeiites and suggest their derivation at contrasting depths and melt fractions. Assuming whole-rock compositions represent magmatic liquids the interpolated phase equilibria are interpreted as follows:

Dalat: Quartz tholeiites with Mg-numbers (100 Mg/[Mg + Fe''] < ca. 60) project close to low pressure (i.e. << 10 Kbar) pseudoquaternary eutectic and cotectic phase boundaries, reflecting extensive low-pressure fractionation of olivine, ± clinopyroxene, plagioclase. Olivine tholeiite and alkalic basalts have primitive Mg-numbers (> 65) and project close to 10 and 15 Kbar eutectics, indicating segregation from the mantle at these pressures (Fig. 4a).

Buon Ma Thuot: Tholeiitic and alkali basalts are relatively unfractionated and correspond to 10-15 Kbar (and rarely higher pressure) pseudoquaternary eutectics, suggesting melt segregation at these conditions. Low pressure olivine fractionation was not significant (Fig. 4b).

Pleiku: Most quartz and olivine tholeiites fractionated olivine, clinopyroxene, and plagioclase at low pressures. Primitive variants (Mg-numbers ca. 70) correspond to 10 Kbar eutectic or cotectic equilibria suggesting this as a lower pressure limit for melt segregation. Alkali basalts are mostly

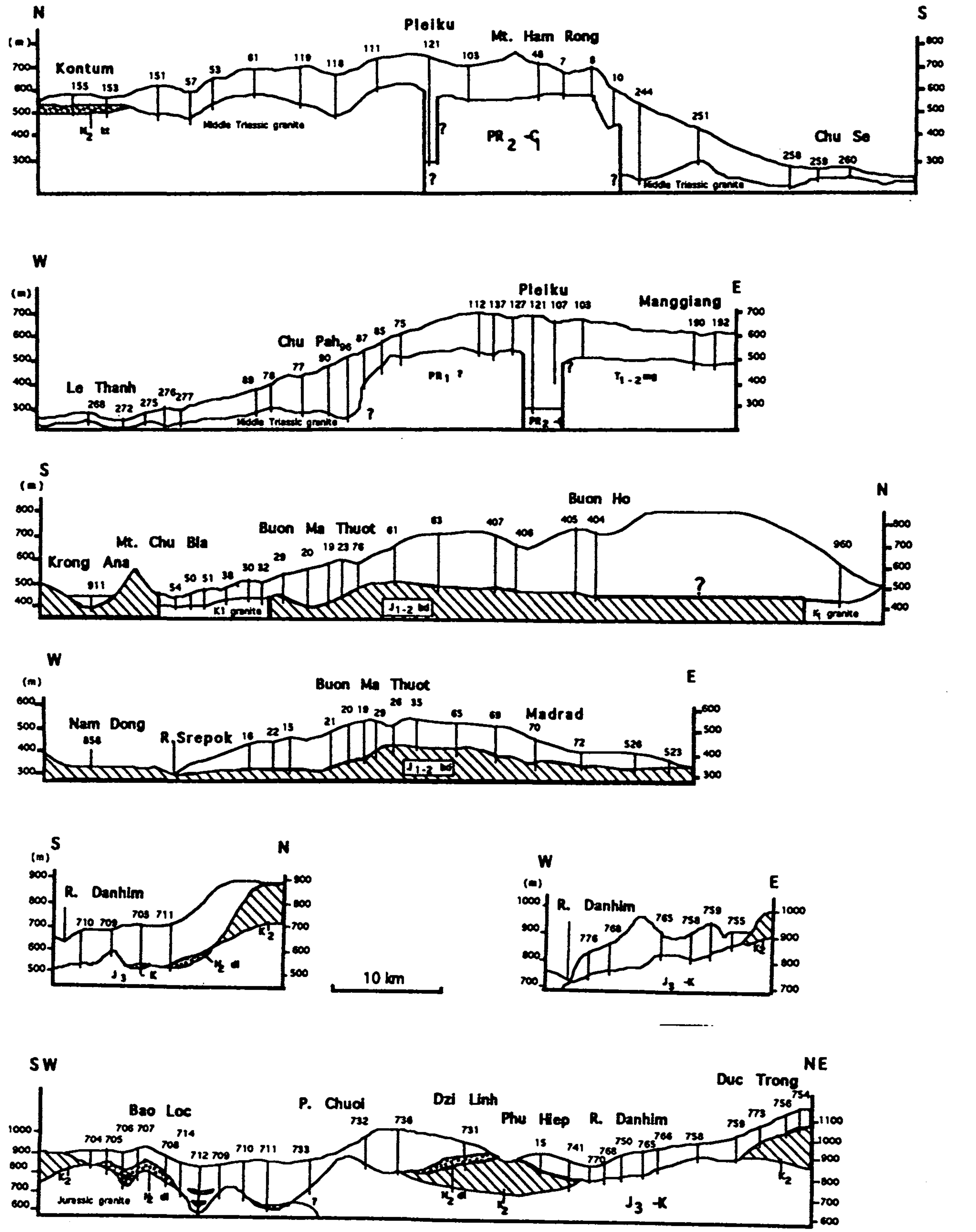


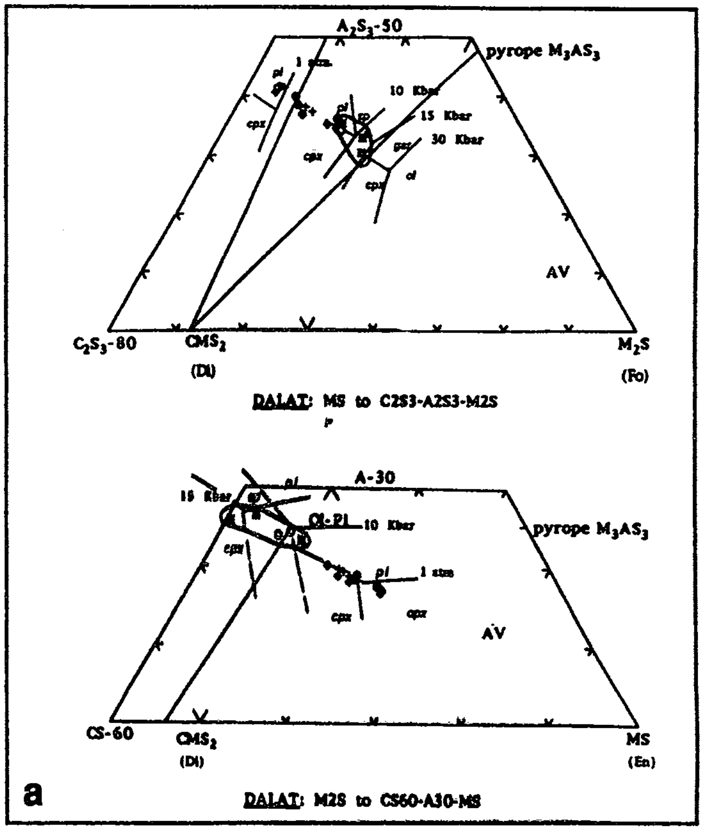
Figure 3. Geological cross sections of Vietnamese basalt plateaus: Pleiku, Buon Ma Thuot, and Dzi Linh/Dalat, compiled from hydrologic drill sections (indicated) of the Vietnamese Geological Survey.

primitive and correspond to higher pressure (> 15 Kbar) equilibria (Fig. 4c).

Xuan Loc: Basalts are dominantly alkalic and primitive, corresponding to 20-30 Kbar melt equilibria. Subsidiary olivine tholeiite was fractionated at lower pressures (Fig. 4d).

Phu Quy: Offshore basalts are consistently primitive (Mg-numbers > 65) hence simplest to interpret in terms of phase equilibria. Tholeiites project close to 10 Kbar equilibria with undersaturated (alkalic) compositions projecting at higher pressure (15-20 Kbar) pseudoquaternary equilibria (Fig. 4e).

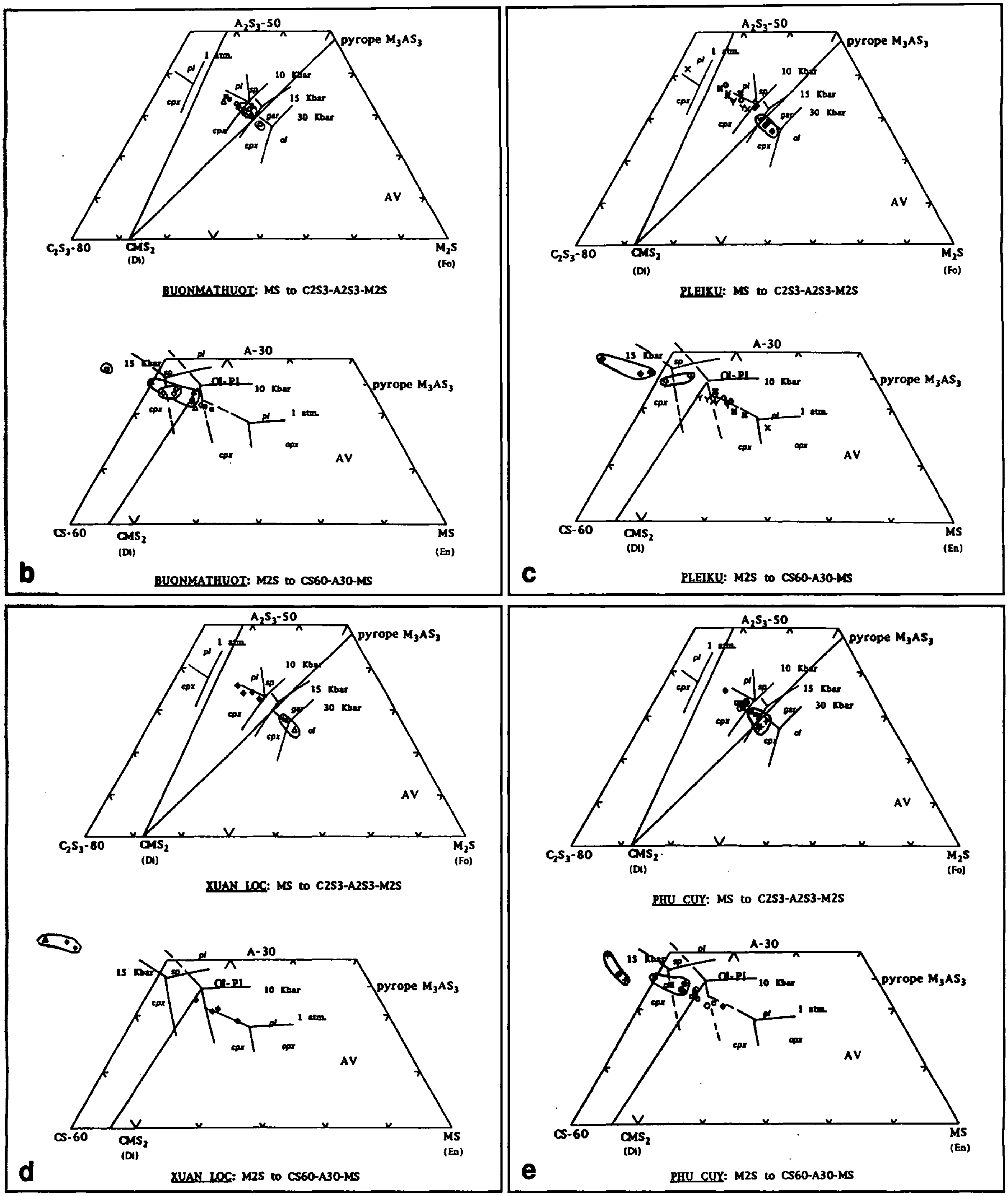
This preliminary graphical treatment suggests that in general melts segregated from solid mantle matrices at pressures between ca. 10 and 30 Kbar (30-90 km depth), respective melt temperatures (from experimental data, Kinzler and Grove, 1992a, b) being in the range ca. 1290-1380°C. Melt fraction has clearly decreased and depth of partial melting increased with time. Unless ambient β values were in excess of 2-3, which seems unlikely, asthenospheric *Tp* was probably higher than normal. However, until definitive β values are available this is unconfirmed. In general terms the progression of activity and its compositional character could reflect a decrease in either β or *Tp*.



Figures 4a-e. Major element compositions of basalts from Vietnamese centers projected on to planes in the 'CMAS' system (O' Hara, 1968), from MS to C_2S_3-A_2S_3-M_2S and M_2S to CS_{60}-A_{30}-MS (where C = CaO, M = MgO, A = Al_2O_3, S = SiO_2, MS = enstatite, M_2S = forsterite, etc.):
(a) Dalat,
(b) Buon Ma Thuot,
(c) Pleiku,
(d) Xuan Loc, and
(e) Phu Cuy seamounts.
Alkali basalts are grouped by solid line. Experimentally-determined solid-liquid equilibria in the pressure range 1 atm - 30 Kbar (taken from the literature) are projected for comparison.

CONCLUSIONS

1) Cenozoic magmatism comprises voluminous (qz- and ol-normative) tholeiite and lesser amounts of Ne-normative (alkalic) basalts between ca. 12 m.y BP and the present. The activity postdates SCS opening and reflects westward transgression of extensional stress to the Indochina and southern China mainland.
2) The basalts occur as thick plateaus marking extensional 'nodes' at intersections of major fault systems, and appear to comprise two main episodes of eruption. Mg-numbers (100 Mg/[Mg + Fe'']) range 45-60 for early episode (Neogene-early Pleistocene) and 60-68 for later episode (middle Pleistocene to Holocene) basalts. While relatively few (e.g. mantle xenolith-bearing basalts) are unfractionated primary melts younger basalts tend to be more primitive.
3) Relations of the basalts to tectonic fabric suggest a progressive rotation of dominant extensional axes, e.g. Dalat (10-1.2 Ma, NW-SE), Buon Ma Thuot (5.8-1.1 Ma, ENE-WSW), Pleiku (4.3-0 Ma, NE-SW), Xuan Loc (1.3-0.85 Ma, E-W), and Phu Cuy (0.8-0 Ma, E-W) centres.
4) The implied stress rotation is accompanied by changes in dominant basalt composition from quartz tholeiite (Dalat), olivine tholeiite (Buon Ma Thuot, Pleiku), to alkali basalt (Xuan Loc,



b
BUONMATHUOT: MS to C2S3-A2S3-M2S
BUONMATHUOT: M2S to CS60-A30-MS
c
PLEIKU: MS to C2S3-A2S3-M2S
PLEIKU: M2S to CS60-A30-MS
d
XUAN LOC: MS to C2S3-A2S3-M2S
XUAN LOC: M2S to CS60-A30-MS
e
PHU CUY: MS to C2S3-A2S3-M2S
PHU CUY: M2S to CS60-A30-MS
A_2S_3-50
pyrope M_3AS_3
C_2S_3-80
CMS_2 (Di)
M_2S (Fo)
A-30
CS-60
MS (En)
1 atm.
10 Kbar
15 Kbar
30 Kbar
Ol-Pl
pl
sp
gar
cpx
opx
ol
AV

Phu Cuy), suggesting decreases in ambient melt fraction and increases in melt segregation pressure.

5) Tholeiite melts probably segregated from solid mantle matrices at pressures between ca. 10 and 30 Kbar (30-90 km depth), respective melt temperatures (from experimental data) being in the range ca. 1290-1380°C.
6) These conditions imply asthenospheric upwelling at elevated *Tp* (> 1280°C) unless stretching factors of > 2 prevailed. This is unlikely in view of geologic evidence for rapid uplift of Indochina during the past 10 Ma.

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