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Tectonic patterns and Cenozoic basalts in the western margin of the South China Sea

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Abstract: The allochthonous fragments — Indosinia, Sibumasu, East Malaya, and Southwest Kalimantan — rifted from Gondwanaland and drifted northward. Indosinia collided with the Yangzi-Huanan terranes in Devonian or Early Carboniferous period and became part of the East Asia continent. Sibumasu collided with East Asia continent and East Malaya during the Indosinian Orogeny (220–200 Ma). The Southwest Kalimantan terrane probably rifted from the northeast margin of Indosinia in the Cretaceous. At about 50 Ma the collision of the Indian continent into the Eurasian continent led to the fragmentation of Asia and was followed by the opening of the Andaman Sea, the clockwise rotation of the Indochina plate, and the rifting and the opening of the South China Sea. The Late Cretaceous alkaline intrusions in the Red River area of northern Vietnam formed during initial stage of rifting of the South China Sea. The Indian-Eurasian collision has successively pushed the Indochina Peninsula in the east-southeast direction. Most of the Middle Tertiary movements probably occurred along the left-lateral Red River, Tonle Sap-Mekong faults concurrent with the opening of most of the eastern South China Sea. The extensional tectonics along these predominantly strike-slip faults may be responsible for the Pliocene-Pleistocene alkaline basalts, which extend from the Mekong Delta northwestward into Thailand. Some basalt outcrops in Thailand, Kampuchea and Vietnam appear to trend north-south. The composition of basalts ranges from tholeiitic to alkalic. The basanitoid basalts contain abundant megacrysts of zircon, ruby, sapphire, and spinel. The megacrysts probably originated through assimilation of metamorphic rocks deep in the continental crust. The cores from the South China Sea indicate that the increase in subsidence rate appears in wells during the Quaternary. It may be related to the increase in Quaternary basalt and high heat flow in the western part of the South China Sea basin.

INTRODUCTION

The continental allochthonous continental fragments — Indosinia (east Thailand, Laos, Vietnam), Sibumasu (Shan States of Myanmar, northwest Thailand, Peninsular Myanmar and Thailand, western Malaya and northwest Sumatra), East Malaya and Southwest Kalimantan — rifted from Gondwanaland and drifted northward. Indosinia has a Precambrian basement overlain by Paleozoic shallow marine and Mesozoic deposits. Located at eastern margin of Gondwanaland, Indosinia collided with the Yangzi-Huanan terranes along the Songma Suture in Devonian or Early Carboniferous period and became part of the East Asia continent (Fig. 1). Sibumasu consists of Precambrian basement, Paleozoic sequence, Triassic shallow-marine limestone, radiolarian, chert and turbidites; and Jurassic-Cretaceous continental redbeds and shallow marine deposits (Metcalfe, 1988, 1990). Subumasu collided with the East Asia continent and East Malaya during the Indosinian Orogeny (220–200 Ma). The East Malaya terrane has a Proterozoic basement, Paleozoic shallow marine strata, overlain by Triassic marine volcaniclastics to the west and Jurassic and Cretaceous continental rocks to the east (Metcalfe, 1990). The Southwest Kalimantan terrane consists of Devonian, late Carboniferous, early Permian, late Triassic, and late Jurassic-Cretaceous marine deposits. The Southwest Kalimantan terrane probably rifted from the northeast margin of Indosinia in the Cretaceous during the opening of the proto-South China Sea (Ben-Avraham and Uyeda, 1973; Metcalfe, 1988).

During the Mesozoic time, the Hainan Island terrane on the northeast was added to the Southeast Asia. The stratigraphy and paleontological data indicate that the central and southern part of the Hainan Island were probably part of Gondwanaland (Fan, 1985, 1993; Yu, 1989; Yu *et al.*, 1990).

About 50 Ma the collision of the Indian continent into the Eurasian continent led to the fragmentation of Asia (Fig. 2) and was followed by the opening of the Andaman Sea (Rodolfo, 1969), the clockwise rotation of the Indochina terrane (Haile *et al.*, 1977),

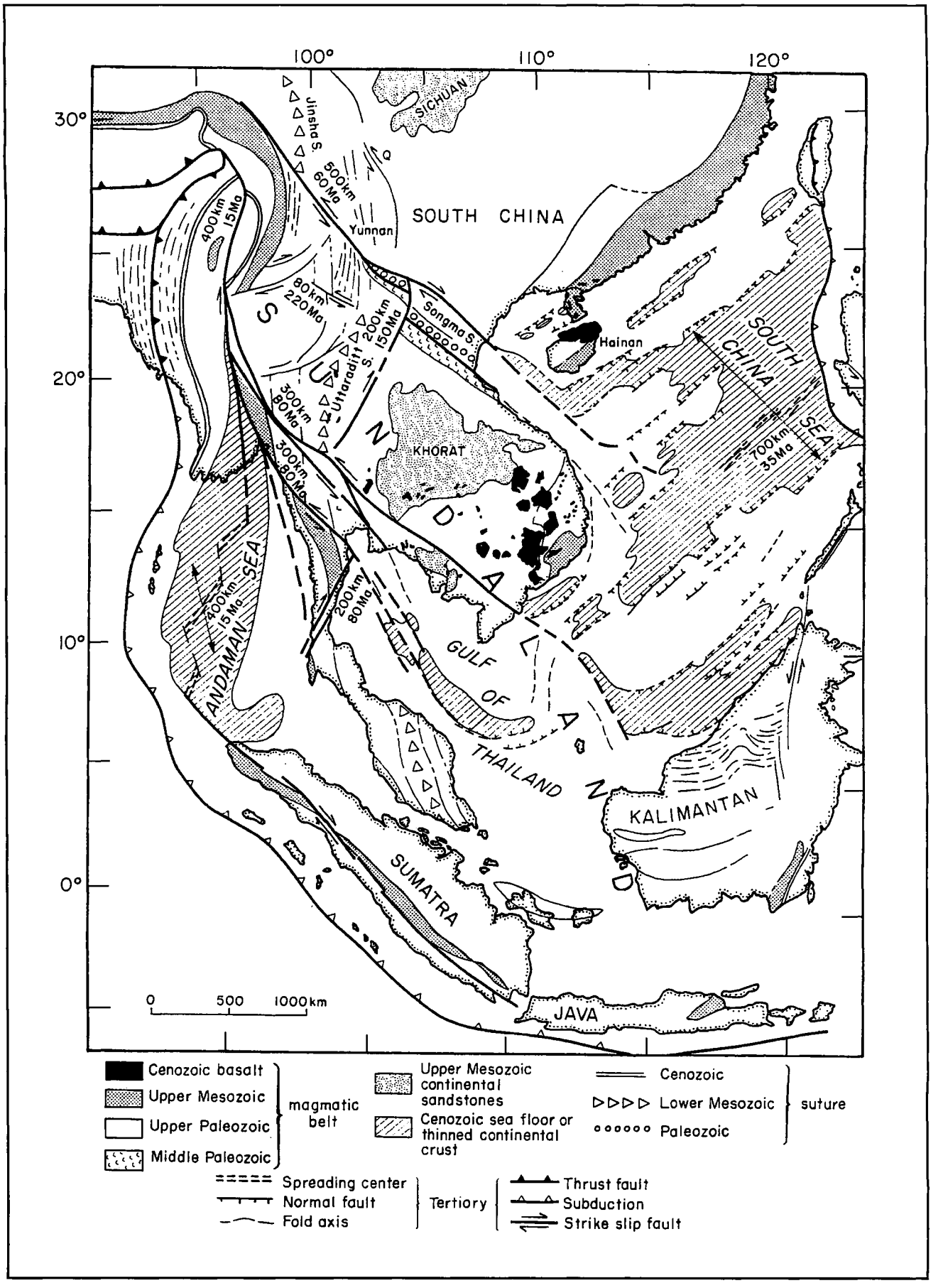

Figure 1. Tectonic setting of Southeast Asia (modified from Briais *et al.*, 1989; Barr and MacDonald, 1981).

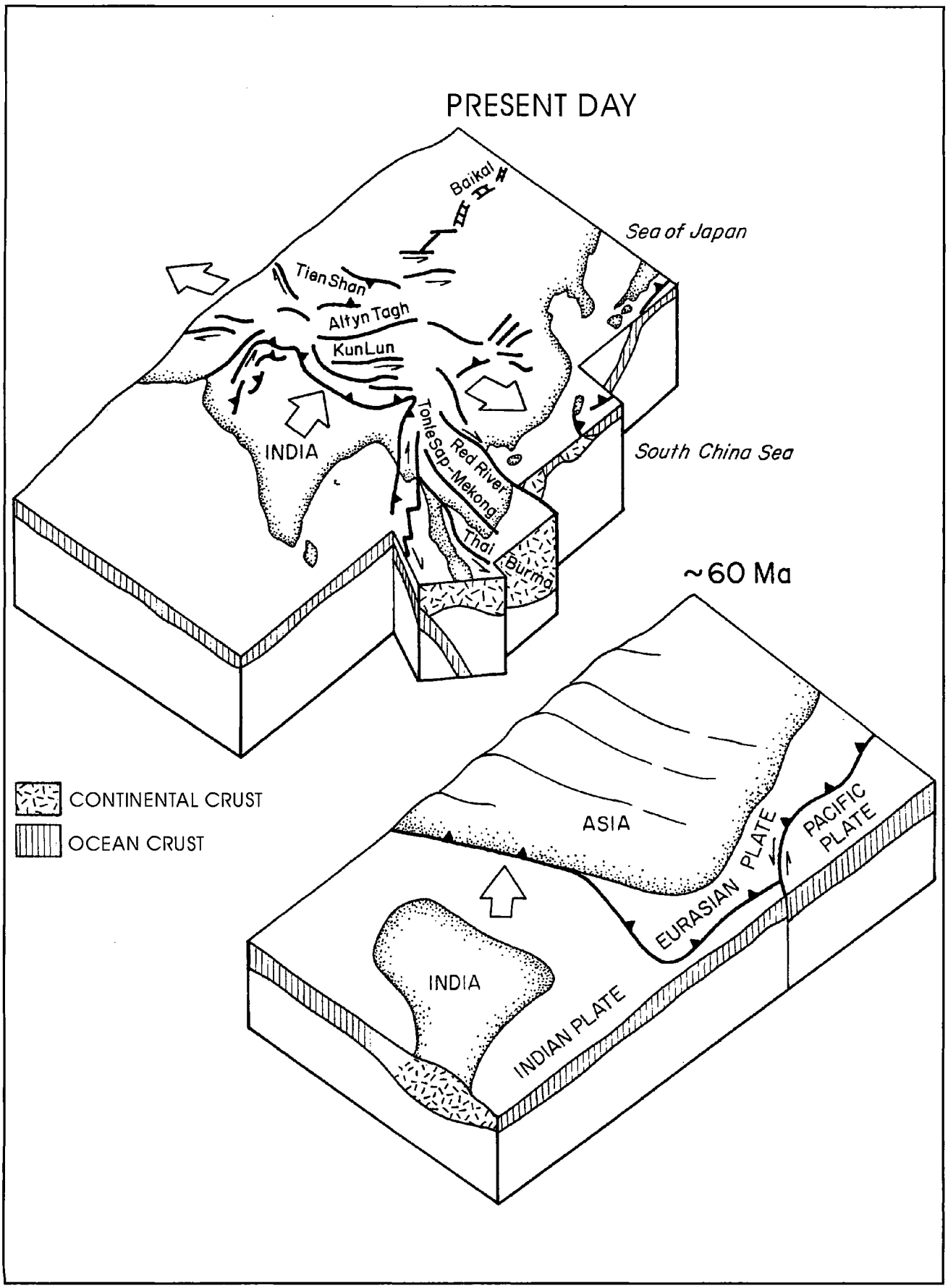

Figure 2. Block diagrams showing before and after the Indian continent collided with the Asian continent (modified from Armijo *et al.*, 1986; Howell, 1989).

and the rifting and the opening of the South China Sea (Molnar and Tapponnier, 1975, Tapponnier *et al.*, 1982, Taylor and Hayes, 1983). Several events that occurred on the Southeast Asia mainland would explain synchronous events to the west of the South China Sea: (1) the Late Cretaceous alkaline intrusions in the Red River area of northern Vietnam forming during the initial stage of rifting of the South China Sea; (2) formation of Tertiary basins in the southeast by tensional exploitation of older structural trends; and (3) initiation of alkalic magmatic activity in Vietnam during the Miocene (Barr and MacDonald, 1978).

A large Cenozoic continental alkalic basaltic province extends through Thailand, Laos, Kampuchea and Vietnam, covering an area of about 70 square kilometers (Barr and MacDonald, 1979) (Fig. 1). Alkalic basalts are also present in Leizhou Peninsula and northern Hainan Island of southern China (Zhou and Chen, 1981; Fan, 1985, 1993), where they occur as isolated pockets and large plateaus. Several locations are important sources of sapphire, ruby, and zircon, and they are mined from nearby alluvial deposits (Berrange and Jobbins, 1976; Fontaine and Workman, 1978; Mitchell and Garson, 1981). The purpose of this paper is to examine the relationship of the Cenozoic basalts and tectonic activity in the western South China Sea.

TECTONICS

The association of alkalic basalts with continental regions of Cenozoic uplift, extension tectonism, and high heat flow is worldwide, such as in the southwestern U.S. and southern Australia (Christiansen and Lipman, 1972; Barr and MacDonald, 1979) and the East Africa rift (Gass, 1970).

The late Cenozoic basalts of southeast Asia are probably an expression of complex tectonic phenomena, the opening of the Andaman Sea, rotation of parts of Southeast Asia, opening of the South China Sea, and regional interactions between the India and Eurasian plates (Barr and MacDonald, 1981) (Fig. 1).

The Indian-Asian collision has successively pushed Indochina Peninsular, then Tibet and South China toward the ESE direction (Fig. 2). Most of the middle Tertiary movements probably occurred along the left-lateral Red River fault zone together with the opening of most of the eastern South China Sea (Tapponnier *et al.*, 1986).

The region of continental Southeast Asia that migrated to the south-southeast during Cenozoic time is assumed to have maintained an essentially extensional tectonic environment. This enabled the development and formation of the basins. The alkalic basalt migration continued to late Tertiary. The close association among the basins, reactivated faults, lineaments and alkalic basalts reflects their genetic relationship (Bunopas and Vella, 1978).

The extensional tectonics along this predominantly strike-slip faults may be responsible for the Pliocene-Pleistocene alkalic basalts, which extend from the Mekong Delta northwestward into Thailand (Hutchison, 1989a). In Thailand, most of the basalt outcrops are widely dispersed with no obvious pattern, but some outcrops appear to be elongated on a north-south trend (Barr and MacDonald, 1978, 1979). McCabe *et al.* (1988) studied the paleomagnetism of the basins of central Thailand as a major phase of east-west extension occurred during the late Neogene. The paleomagnetic direction from the central Chao Phraya basin and vicinity is rotated nearly 25° clockwise with respect to Khorat Plateau (Fig. 3). The magnetic delineation from the Khorat Plateau are similar in Vietnam. The areas studied are having high heat flow. The Pliocene-Pleistocene basalt is associated with rhyolite and they are the late stage biomodal waning phase of basin extension. There are late Neogene north trading normal faults in the area studied, and they are located along the margins of the basin. The late Neogene basalts have similar age to the major basin bounding faults (Hamilton, 1979; Nieuwland, 1984; Travena and Clark, 1986) suggest that the basalts were erupted at the same time as the formation of the basins. The extensive outcrops of basalt in Kampuchea and Vietnam (Workman, 1972, 1975; Fontaine and Workman, 1978) also appear to be in north-south trends, although not associated with any mapped faults (Fig. 3). All these basalts are considered to represent tensional episode during the late Cenozoic Era.

Ru and Pigott (1986) studied the cores from the South China Sea and observed that the increase in subsidence rate appears in wells during the Quaternary, perhaps indicating a more recent but subdued stage of rifting. The increase may be related to the increase in Quaternary basalts and the high heat flow in the western part of the South China Sea basin.

PETROLOGY

The distribution, petrography and geochemistry of Cenozoic basalts in Indochina were first described by Lacroix (1933), and the regional synthesis was only recently presented by Barr and MacDonald (1981). They showed that the Cenozoic basalts cover thousands of square kilometers in the southern part of Vietnam, in the eastern part of

Kampuchea and on the Bolovens Plateau of southern Laos. There are also smaller outcrops in western Kampuchea, north central Vietnam, Thailand, and northwestern Laos (Fontaine and Workman, 1978).

Cenozoic basalts found in Leizhou Peninsula and Hainan Island of Guangdon province comprise over 600 volcanoes and cover an area of 6,000 square kilometers (Sun, 1987). A company on Hainan island recently was designated to handle the export of gem corundum. The occurrence of sapphire and ruby in Hainan island had been mentioned by Shih (1989).

Basalts of mainland Southeast Asia show wide variety in composition, ranging from tholeiite to alkalic. Hawaiite seem to be the most abundant,

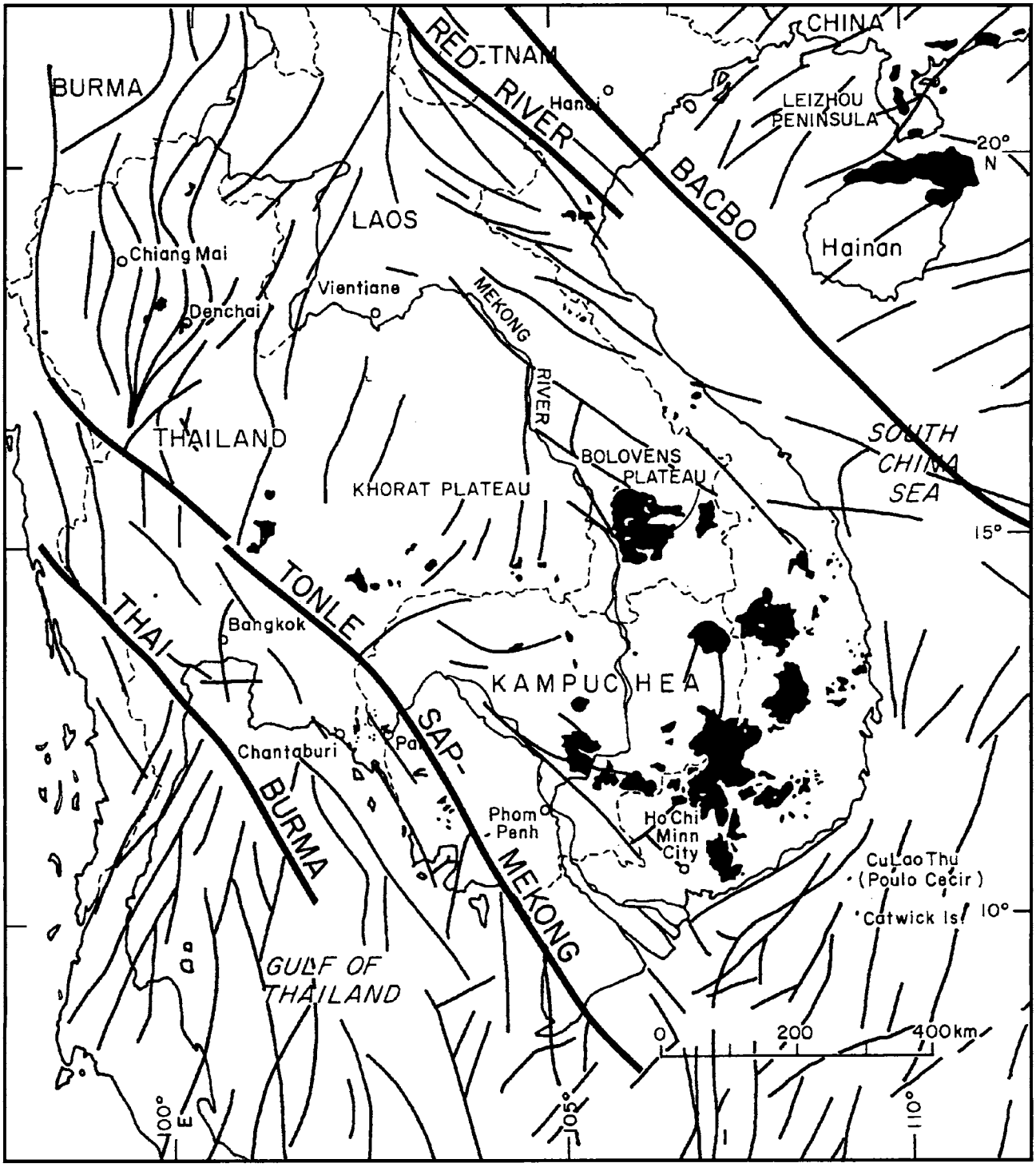

Figure 3. Fault systems and the distribution of Cenozoic basalts (solid black) of continental Southeast Asia (from Wood, 1985; Barr and Macdonald, 1981).

tholeiite is also abundant, whereas basanitoid basalts are relatively minor. Xenoliths are generally associated with basanitoid basalts (Barr and MacDonald, 1981; Vichit, 1978; Aranyakanon and Vichit, 1983), and consist of eclogite, dunite, peridotite, spinel peridotite and lherzolite. Megacrysts consist of corundum, zircon, garnet, titanomagnetite, ilmenite, spinel, olivine, pyroxene, nepheline, anorthoclase, and plagioclase.

The Denchai basalt of northern Thailand was erupted from a single vent; K-Ar dating yields an age of 5.64 Ma (Pliocene). The composition of the basalt changed in time from continental tholeiite, through hawaiite to basanite (Barr and MacDonald, 1979). The basalts in southeastern Thailand are olivine basalt and basanitoid basalt. The basanitoid basalt probably is the source of the sapphire that is mined from placer deposits in the vicinity (Barr and MacDonald, 1978). Panjasawatwong and Yaowanoiyothin (1993) reported that the young basaltic flow (post Triassic, possible Cenozoic) form a discontinuous narrow belt, superimposing on the Uttaradit-Nan Suture along the Thailand and Laos border (Fig. 1). The chemical composition of the alkaline basalt, hawaiite, and mugeraite are comparable with the post shield stages of Haleakala (Hana and Kula series) in east Maui of the Hawaiian chain and are interpreted to have erupted in a continental environment as the late Cenozoic basalts in mainly southeast Asia. At Palin, western Kampuchea, the lavas are analcime basanite, containing augite, analcime and feldspar phenocryst in a clear glass matrix. They contain abundant megacrysts of magnetite, ilmenite, spinel, clinopyroxene, garnet, olivine, phlogopite, feldspar, zircon, ruby and sapphire (Fontaine and Workman, 1978). Placer deposits of gem-quality sapphire, zircon and spinel reported by Berrange and Jobbins (1976) are derived from deeply weathered Quaternary basanite from Pailin. Sapphire has been mined at Palin for at least 100 years (Fig. 4).

The basalts in Vietnam tend to be layered and more extensive (Tri and Quoc, 1990; Xinh, 1990). Tholeiites are most abundant, but alkalic suites are also present. In Vietnam, the basalts have been subdivided on the basis of age by Nguyen (1982) and Hutchison (1989b): (1) Miocene-Pliocene tholeiite and andesite; (2) early Pleistocene — tholoeiite, dolorite and rare alkalic olivine basalt; (3) late middle Pleistocene — alkalic olivine basalt, rare trachyte and phonolite; and (4) Holocene — alkalic tholeiite, basanite, and limburgite. A joint venture between the government of Vietnam and Thailand interests was formed to market the world-class rubies and sapphires, mostly from the Ha Tuyen province (Premoli, 1989). In 1923, a volcanic eruption occurred in the South China Sea off the Vietnamese coast near Cu Las Thu (Poulo Cecir) and Catwick islands; the volcanic rocks consist of basalt and nepheline andesine basalt (Workman, 1972).

In Leizhou Peninsula and Hainan Island of Guangdong province, the volcanism began in the Pliocene (5.6–3.8 Ma) and was more widespread in the early Pleistocene (0.90–0.80 Ma) when it formed a large-scale lava platform. The middle-late Pleistocene (0.70–0.10 Ma) is an episode of central eruptions (Zhou *et al.*, 1988). Some eruptions were recorded as recently as during the historic time (Sun, 1987). The early volcanism yielded mainly quartz tholeiites and olivine tholeiites, indicative of an active continental margin environment. These volcanoes trend in the ENE and NE directions. The later phase yields alkaline olivine basalt and tholeiites, and the volcanoes trend in a NW direction. Ultramafic xenoliths are found in the alkaline olivine basalts. The volcanism occurred mainly in relation to the activity of deep faults (Zhou *et al.*, 1988). Late Tertiary basalts are widely distributed on the South China Sea sea floor and on small islands. Basalts of the South China Sea are alkaline basalts and tholeiites; the age in the northern part is Pliocene (3.5 Ma) (Zhou *et al.*, 1988).

PETROGENESIS

Tholeiite magma may represent large amounts of partial melting at a relatively shallow depth in the mantle. Alkalic magma may originate by lesser amounts of partial melting at relatively deeper levels in the mantle, followed by slower ascent to allow differentiation. A range of alkaline magma compositions may be produced by variations in the amount and depth of both partial melting and fractional crystallization during ascent (Barr and MacDonald, 1979). The tholeiite and hawaiite in Thailand do not contain megacrysts and may represent relatively shallow partial melting and slower ascent. The basanitoid basalts in southeastern Thailand are the hosts of the gemstone and are interpreted as high-pressure megacrysts formed with the basalts in the upper mantle and transported rapidly to the surface (Barr and MacDonald, 1978). The first flow of the Denchai basalts of Thailand appeared to be the most voluminous but changed in time from continental tholeiite, through hawaiite to basanite. The magma was probably generated by large amounts of partial melting. The magma probably ascended rapidly and carried spinel lherzolite nodules from depth as great as 50 km. Megacrysts such as corundum and zircon also accompanied the nodules (Barr and MacDonald, 1979). The basanitoid magma formed

by partial melting of the mantle at high-pressures of up to 20–30 kb and ascended rapidly to the surface. Megacrysts of corundum and zircon occur in the basanitoid basalts and are interpreted as high pressure cognate megacrysts (Barr and MacDonald, 1978; Barr and Dostal, 1986). Berrange and Jobbins (1976) suggested that the gem-bearing magmas were hybrid, having assimilated corundum-bearing metamorphic rocks deep in the continental crust. Lacroix (1933) proposed that corundum and zircon associated with basalts from Indochina are relict xenoliths that accompanied the basalt during the eruption through gneissic crustal rocks. Low alumina basaltic magma at 65–95 km (20–30 kb) moved to a more shallow level, approximately 25–35 km (7–10 kb) and could then have raised the

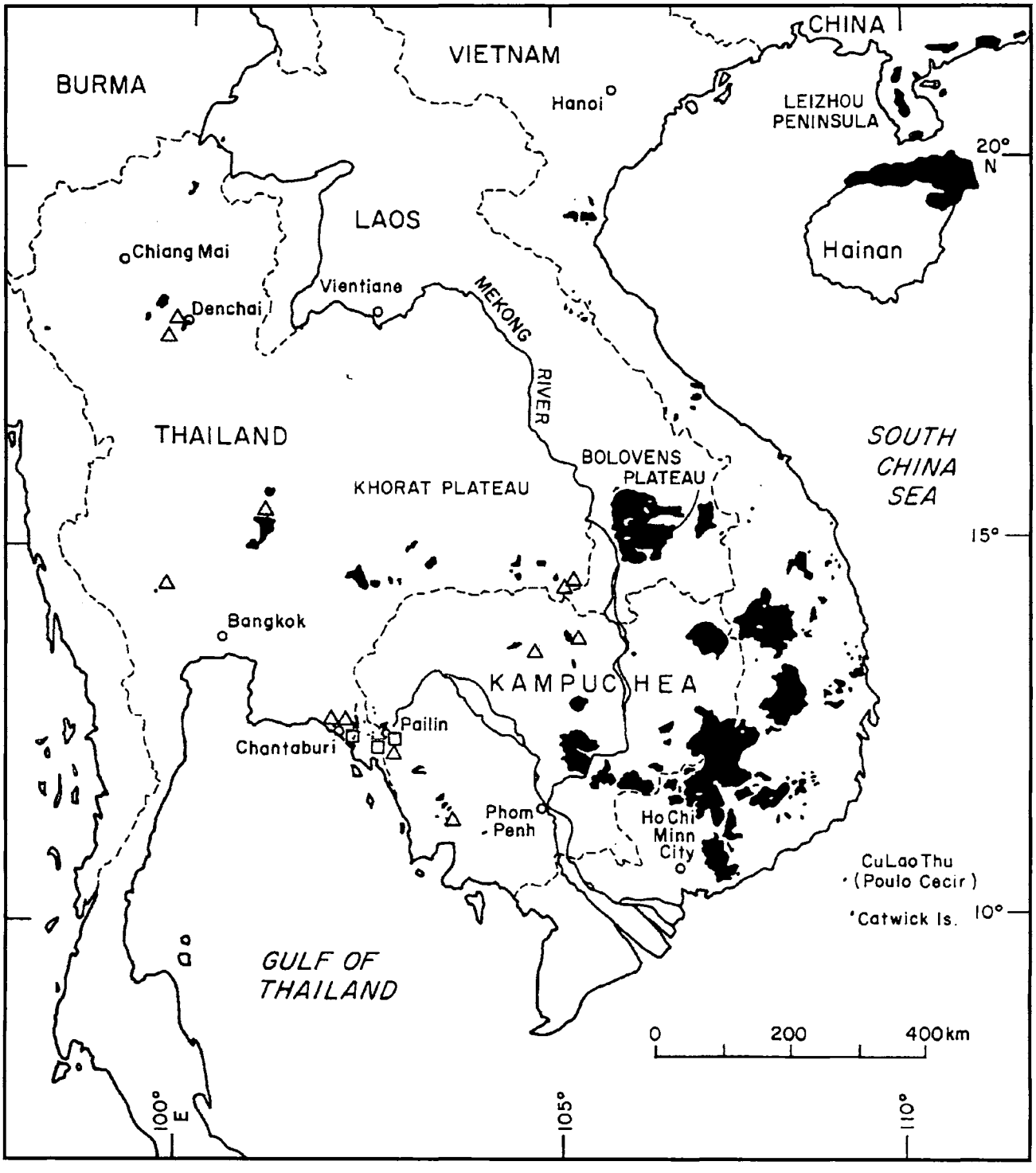

Figure 4. Occurrences of Cenozoic basalt (solid black), ruby (□), and sapphire (△) of continental Southeast Asia (from Aranyakanon and Vichit, 1983; Fontaine and Workman, 1978).

alumina content of the wall-rock in the crust. Basaltic magma must be kept in a holding chamber for a period of time for corundum to crystallize and then be erupted to the surface and quenched. The presence of sanidine and anorthoclase indicates that the sodic feldspar megacrysts probably formed later at shallow depths at pressures less than 12 kb (Vichit *et al.*, 1978). Rapidly ascending magmas are likely to carry xenoliths and megacrysts, whether exotic or cognate.

CONCLUSIONS

1. The allochthonous continental fragments — Indosinia, Sibumasu, and East Malaya among others drifted from Gondwanaland during the Paleozoic and Mesozoic periods and collided with South China to form the foundation of mainland Southeast Asia.
2. At about 50 Ma the collision of the Indian continent into the Eurasian continent led to the opening of the Andaman Sea and the South China Sea, and pushed the Indochina Peninsular into an ESE direction.
3. The extensional tectonics along the strike-slip faults may be responsible for the Pliocene-Pleistocene alkaline basalts, which extend from the Mekong Delta northward into Thailand.
4. The composition of basalts ranges from tholeiitic to alkalic. The basanitoid basalts contain abundant megacrysts of zircon, ruby, sapphire and spinel. They probably originated through assimilation of metamorphic rock deep in the continental crust.
5. The close association among the formation of basins, reactivated faults, and alkalic basalts reflect their genetic relationships.

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