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The kinematics of extension and inversion in the Malay Basin, offshore Peninsular Malaysia

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Abstract: The evolution of the Malay Basin, a Tertiary extensional basin offshore Peninsular Malaysia, is explained in terms of a simple kinematic model that accounts for the following key observations: (1) Major basement faults along the basin axis are E-trending rather than NW-trending, (2) Through-going strike-slip faults are absent from the basin axis and margins, and (3) *En echelon* fold pattern in postrift strata seems to have been influenced by the geometry of underlying extensional half-grabens. Basin development during late Eocene-early Oligocene began with sinistral transtensional shear of a broad NW-trending shear zone (axial shear zone) which contains pre-existing E-trending basement faults. The shearing caused crustal blocks that are bounded by the faults to rotate anticlockwise and form E-trending half-grabens between them. Reversal of shear during the early to middle Miocene, from sinistral to dextral, caused transpressive deformation and inversion of the half-grabens. The intensity of deformation increases southeastwards towards the West Natuna Basin as a result of the buttressing effect of the Natuna basement ridge which resisted the dextral motion along the axial shear zone.

INTRODUCTION

The tectonic origin of the Malay Basin, a Tertiary basin located offshore east of Peninsular Malaysia (Fig. 1), has been the subject of speculation for many years as much of the petroleum industry data remain unpublished. In this paper, a kinematic model for the evolution of the Malay Basin is proposed based on a study of available structural data. Kingston *et al.* (1983), among others, postulated that lithospheric tension that caused extension in the Malay Basin was the result of forces associated with subduction of the Indian Plate beneath Sumatra. Back-arc extension is probably not the main cause of extension in Sundaland during the early Tertiary, for the following reasons. First, the subduction along the Sumatra Arc has been in progress since Jurassic times (Wajzer *et al.*, 1993) whereas extension did not begin until Paleocene-Oligocene times. Second, the Malay Basin is more than 1000 km away from the Sumatra trench, which is too far to have been influenced by the subduction. Third, studies of the so-called "back-arc" basins in Sumatra (e.g. Moulds, 1989, Situmorang *et al.*, 1991) have shown the importance of pre-existing basement strike-slip faults in controlling extensional basin formation. The highly-oblique convergence between the down-going Indian plate and the Southeast Asian lithosphere, and the apparent lack of a Benioff-Wadati zone beneath Sumatra (see Hutchison, 1989, p. 23), apparently truncated at the Sumatra Fault Zone, suggest that slab-pull forces have contributed little to the extension in the overriding Sundaland lithosphere.

The major structural features in the Malay Basin, described by previous papers (e.g. Khalid Ngah *et al.*, 1996), may be explained in terms of a simple kinematic model, which will be discussed below. The extensional development of the basin is interpreted as being the result of continental intraplate deformation influenced by far-field tectonic tectonics at plate boundaries, in particular, the India-Asia collision. The occurrence of numerous extensional basins within a relatively broad zone of continental extension, extending from Thailand to the Natuna sea, suggests that basin development was related to distributed deformation of the Sundaland continental basement. Basin extension during the Oligocene took place within an overall dextral shear regime, induced by the collision whereas basin inversion seems to have been caused by a change to a sinistral shear regime during the Miocene.

REGIONAL FRAMEWORK

The central theme in many tectonic models for SE Asian extensional basins is the extrusion tectonics hypothesis (Tapponnier *et al.* , 1982), in which it was postulated that the India-Asia collision during the middle-late Eocene had caused the eastward-extrusion of large continental slivers along major strike-slip fault zones (Fig. 2). This hypothesis has been applied to the Thai, Malay, Penyu, and West Natuna basins (e.g. Daines, 1985; Polachan and Sattayarak, 1989; Mazlan Madon *et al.*, 1997). These extensional basins are thought to have formed as pull-apart basins along one of the major strike-slip faults, the Three Pagodas Fault, which extends from onshore Thailand to the Natuna area (the Malay-Natuna-Lupar Shear of Daines, 1985). Other strike-slip faults are also associated with Tertiary extensional basins, e.g. Wang Chao Fault (Mekong Basin) and the Red River Fault (Yingghei Basin).

Some workers believe that the indentation of India is accommodated predominantly by crustal thickening in Tibet and that lateral extrusion was insignificant (Dewey *et al.* , 1989). Other workers (e.g. Tapponnier *et al.* , 1986) have presented field and aerial photographic evidence for left-lateral motion on the Red River, Wang Chao, and Three Pagodas Faults during the mid-Tertiary. Field studies by Lacassin *et al.* (1993) give minimum estimates of Oligocene-Miocene left-lateral displacements of about 330 ± 60 km on the Red River Fault but only about 35 ± 20 km on the Wang Chao Fault. Left-lateral motion on the Wang Chao Fault has been dated to have occurred at about 30 Ma (Maluski *et al.* , 1993) whereas that on the Red River Fault is about 35–24 Ma (Scharer *et al.* , 1990, 1993, 1994). Right-lateral slip on faults such as the Red River occurred during the Quaternary (Allen *et al.* , 1984).

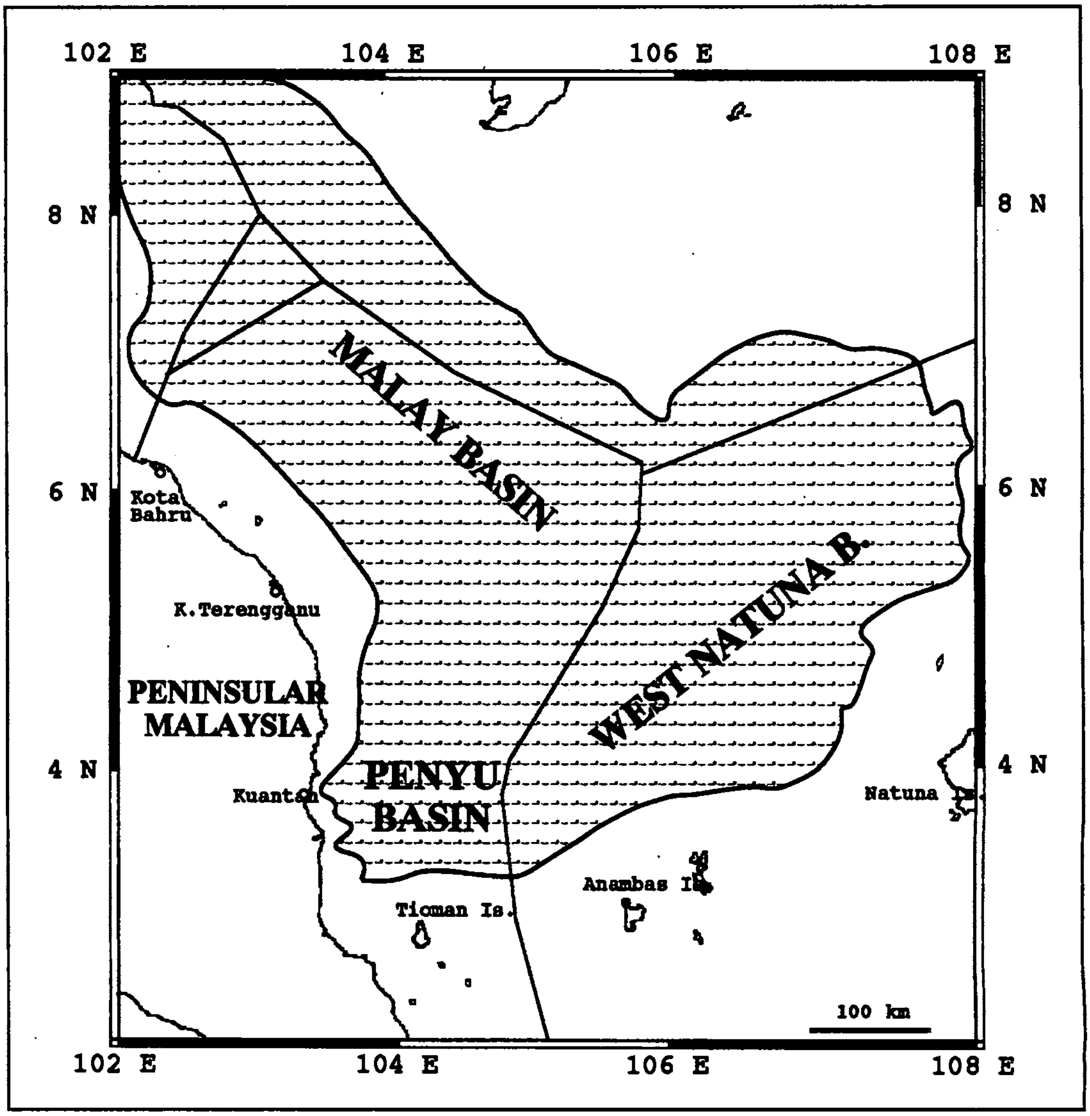

Figure 1. Tertiary basins off the east coast of Peninsular Malaysia.

Left-lateral motions on these major NW-trending faults may be explained by regional dextral shear of SE Asia during the early Tertiary (Fig. 3). From the late Cretaceous to about 45 Ma BP., India moved roughly northeastwards at an average velocity of about 10 cm/a, but changed to roughly northwards at the onset of the collision with Eurasia, with an average velocity of 5 cm/a (Dewey *et al.* , 1989). Before the collision, the convergence between India and Eurasia was roughly orthogonal and was accommodated by subduction beneath a volcanic arc along the southeastern margin of Eurasia. A change in relative motion at about 45 Ma resulted in oblique convergence, which is accommodated by lithospheric thickening in the collision zone and by broadly dextral transpressional shear in Southeast Asia (Dewey *et al.* , 1989). Oroclinal bending of the Sumatra-Java volcanic arc (Hutchison, 1992) is probably related to oblique convergence.

Regional dextral shear in Southeast Asia may have caused the reactivation of the NW-trending Mesozoic basement faults as left-lateral strike-slip faults whose motion was accommodated by clockwise rotation of fault-bounded blocks (Fig. 3). Tertiary extensional basins, including the Malay and Penyu Basins, may have developed along these reactivated strike-slip fault zones (Khalid Ngah *et al.*, 1996; Mazlan Madon *et al.* , 1997).

BASEMENT FAULTS AND ANTICLINES

Basement faults seem to have exerted a strong influence on the formation of the Malay and Penyu basins (Khalid Ngah *et al.* , 1996; Mazlan Madon *et al.*, 1997). Major NW-trending and E-trending basement faults have been identified from seismic data in the basins off the east coast of Peninsular Malaysia (Fig. 4A). Most of the NW-trending faults occur at the southwest margin of the Basin and, like the NW-trending faults onshore in Peninsular Malaysia, could have originated during the late

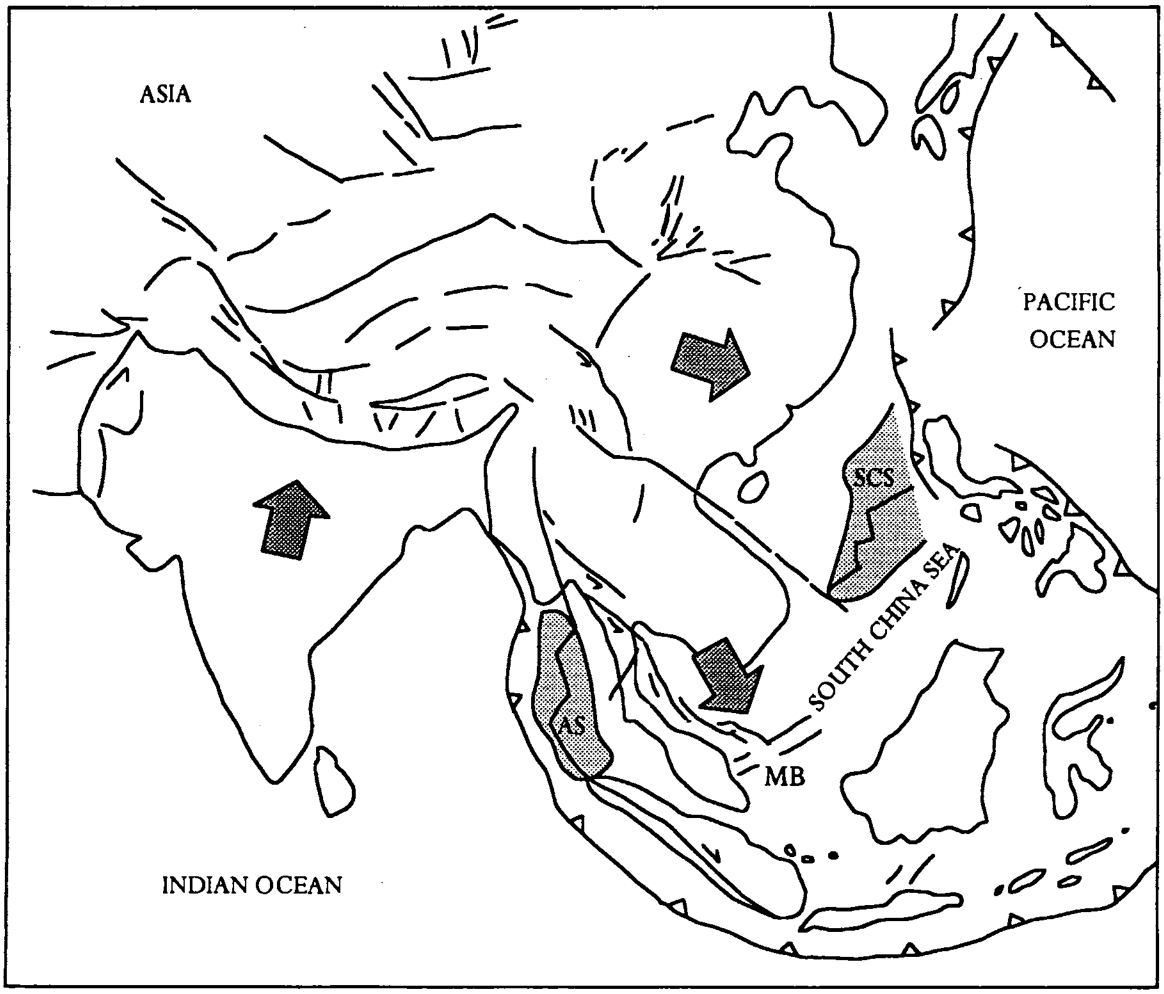

Figure 2. Regional tectonic setting of Southeast Asia during early Tertiary times. The collision of India with Asia caused eastwards extrusion of continental blocks (arrows) along major strike-slip faults resulted also in the development of pull-apart basins in the Gulf of Thailand, Andaman (AS), and South China Sea (SCS). MB-Basins offshore Peninsular Malaysia. After Tapponnier *et al.* (1982).

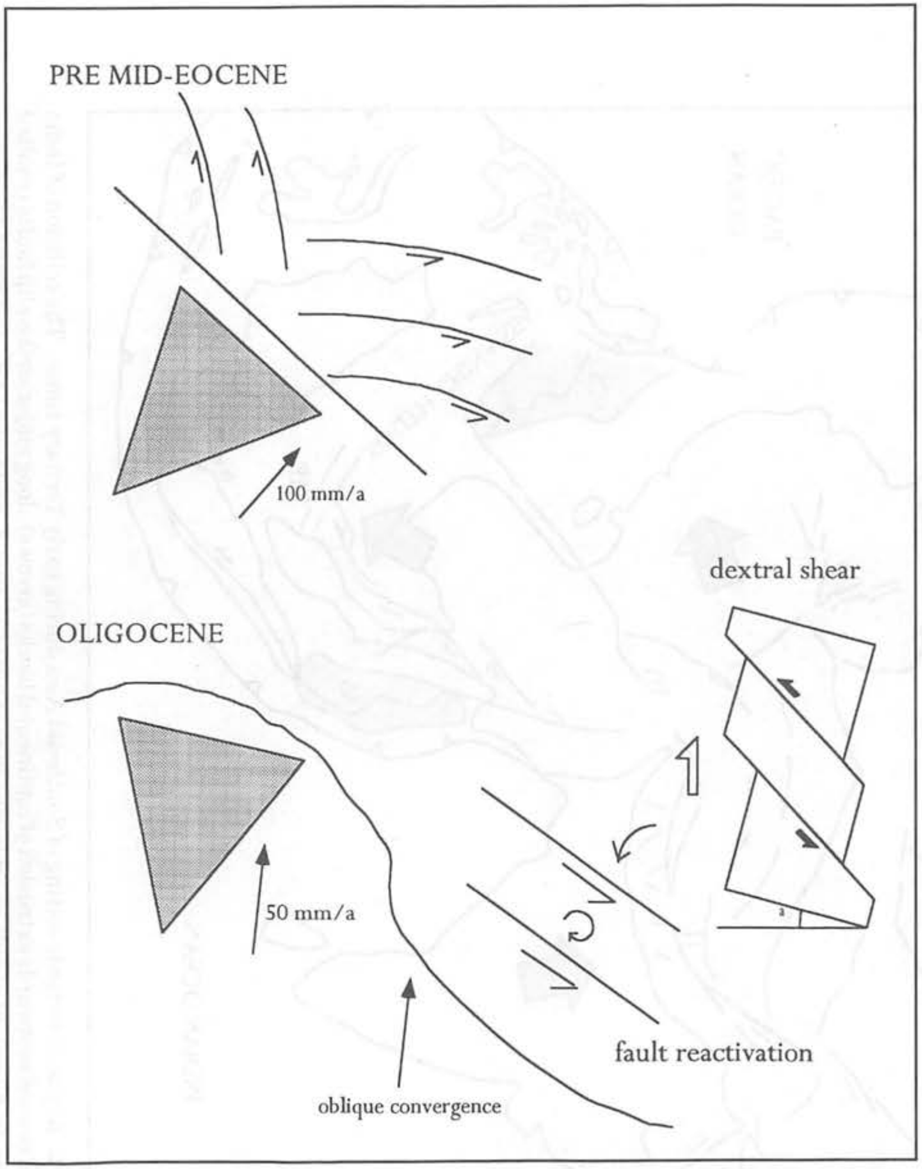

Figure 3. Effects of India-Asia collision on SE Asian tectonic evolution. Pre-mid Eocene times: orthogonal convergence phase, as India moves northeastwards. Major left-lateral strike-slip faults initiated. Model for strike-slip faults based on slip-line field theory (Tapponnier and Molnar, 1976). Oligocene: India's motion northwards, resulting in oblique convergence in Southeast Asia. Dextral shear causes reactivation of pre-existing faults and shear zones. India's velocities from Dewey *et al.* (1989).

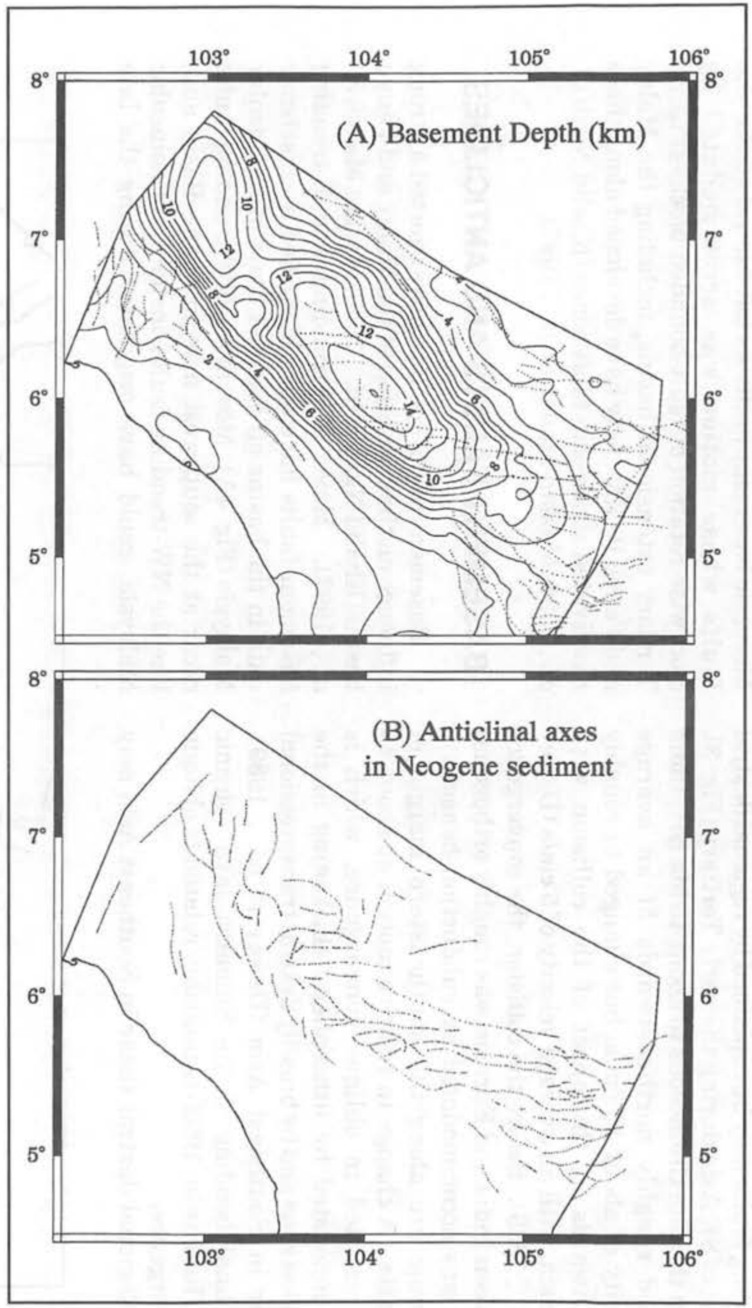

Figure 4. (A) Basement depth in the Malay Basin. Contours in km. Dotted lines represent major basement faults. (B) Axial traces of major inversion anticlines in the Neogene strata of the Malay Basin.

Mesozoic. Although the onshore faults were mainly sinistral strike-slip faults (Tjia, 1972), Liew (1994) and Tjia (1994b) showed that the offshore faults have been reactivated dextrally during the early Tertiary to form small pull-apart basins, such as the Dungun Graben.

The Malay Basin is clearly not a simple rift basin formed by orthogonal NE-SW extension because most of the axial basement faults strike E-W, oblique to the overall basin trend. The east-trending basement faults may have originated by sinistral shear of a broad NW-trending axial zone. Tjia (1994a) named the zone the Axial Malay Fault. In this paper, however, I shall refer to it rather informally as the axial shear zone (ASZ) because it is not a single fault but represents a broad zone of shear deformation.

Large folds occur within the Neogene postrift succession in the Malay Basin (Fig. 4B). These inversion structures overlie extensional half-grabens that are bounded by the E-trending basement faults (Fig. 5). One of these faults (F2 in Fig. 6) has been reactivated as a reverse fault as a result of almost complete inversion of the underlying half-graben (see Line 153). Some inversion structures, especially those in the south, resemble flower structures, which suggests that shortening across the half-grabens may have involved significant oblique slip along the E-trending basement faults. A change from sinistral to dextral motion may have caused the basin to be inverted.

Hamilton (1979) proposed that NW-trending right-lateral shear was responsible for the apparently en echelon pattern of the inversion anticlines in the Malay Basin. According to the classical wrench fault model (Fig. 7A, B), the anticlines could have formed by dextral simple shear above a principal displacement zone. Alternatively (Fig. 7C), the anticlines could have formed simply by deformation involving pre-existing E-trending en echelon half-grabens in response N-S shortening associated with the dextral shear. I prefer the latter model because no through-going basement strike-slip fault has been identified in the basin. Because the anticlines developed by shortening across the half-grabens, apparently as a result of transpressive oblique motion on the E-trending faults, their geometry and orientation merely conform to those of the underlying half-grabens (Fig. 8A).

EXTENSION AND INVERSION

One possible mechanism for the development of the Malay Basin is by pull-apart at a releasing bend of a strike-slip fault (Fig. 8B), with the E-trending faults being extensional fractures (normal faults) formed between two crustal blocks that were pulled apart as a result of local NW-SE transtension at the fault bend. Because the faults occur within a broad axial zone of deformation, however, it is more likely that the Malay Basin was formed by distributed shear deformation of the axial zone rather than by pull-apart along a discrete strike-slip fault (Fig. 8C).

The "block" model of McKenzie and Jackson (1986), originally applied to the Aegean region (Greece), is used here to illustrate the role of distributed continental deformation in the formation of extensional basins (Fig. 9A). The model may be constructed easily using pieces of wood and screws as pivots. The model is rather simplistic because it assumes that the ends of the fault-bounded blocks remained attached to the zone boundary during deformation but, yet, are free to rotate about their respective pivots. In nature, however, deformation at the boundaries is accommodated by distributed deformation (McKenzie and Jackson, 1986).

On a basinal scale, the small pull-apart basins within the Hinge Fault Zone of the Malay Basin (Tjia, 1994b) could be the effect of distributed deformation along the southwestern boundary of the ASZ. The E-trending basement faults within the ASZ are envisaged as a set of parallel faults oriented obliquely to the basin boundaries. During sinistral shearing, the crustal blocks bounded by these faults rotate anticlockwise, forming half-grabens between them. Because the length of the crustal blocks and of the deforming zone remain the same after deformation, the half-grabens must be a direct result of the internal rotation of the crustal blocks. The relative motion between any two points on adjacent blocks are always perpendicular to the zone boundary and, hence, the slip on the faults are oblique to their boundaries as they move apart. Note, also, that the strike-slip component of displacement is opposite in sense to that of the external shear couple. The model suggests, therefore, that the half-grabens in the Malay Basin were probably formed by dextral oblique motion between the fault-bounded blocks, as a result of sinistral transtension of the whole zone.

As the structural evidence suggests, the inversion of the half-graben in the Malay Basin may have been accompanied by significant strike-slip displacement along the half-graben border faults. Figure 9B shows a how the half-grabens may have been inverted. If the originally sinistral shear is reversed, as was suggested also by Tjia (1994a, b) and Tjia and Liew (1996), so that the crustal blocks rotate clockwise, sinistral oblique-slip will occur along their bounding faults. This induces a N-S component of shortening across the

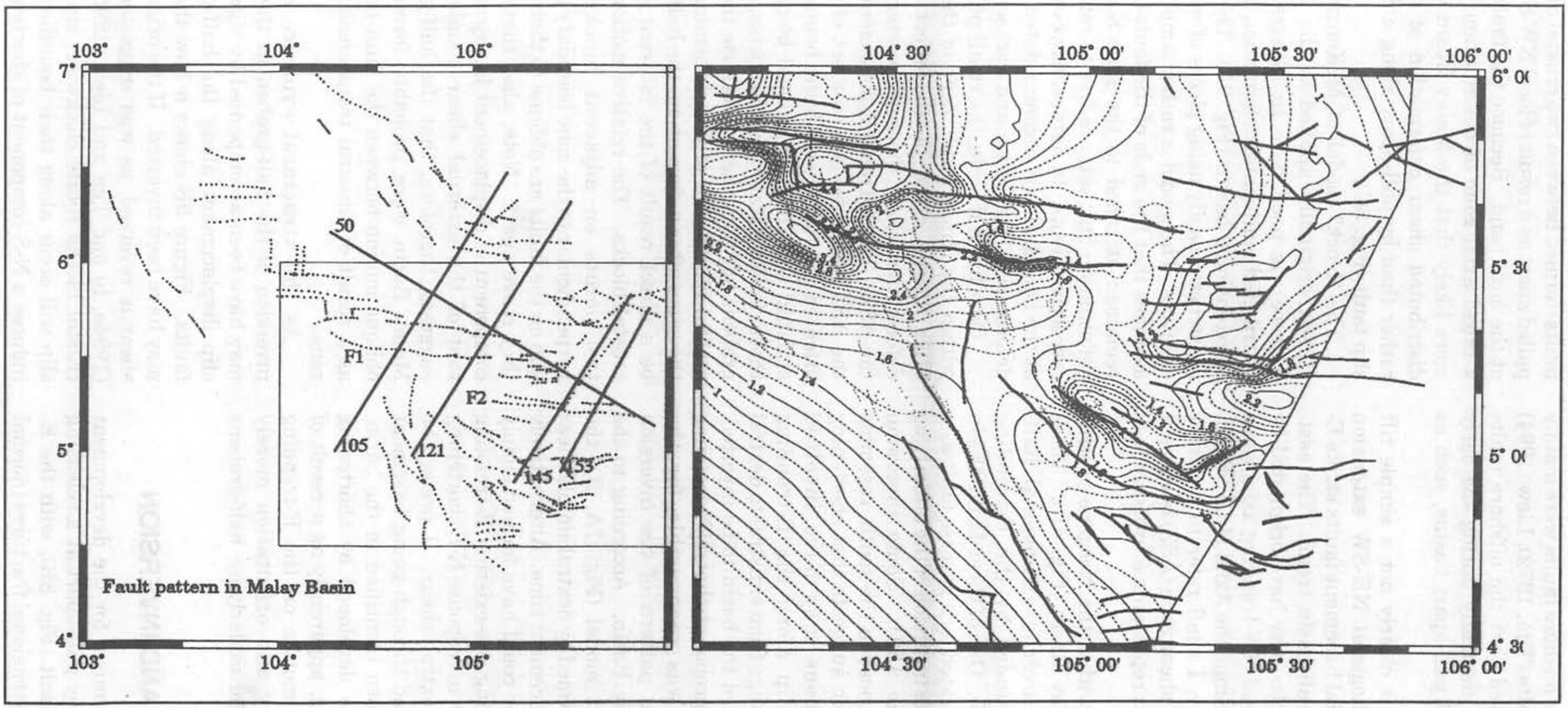

Figure 5. Relationship between basement faults and inversion anticlines in the southern Malay Basin. Left: Major basement faults and location of seismic lines shown in Fig. 6. Rectangular box represents area shown on the right. Right: detailed structural map of southern Malay Basin showing the structure at the top of Group I (depth in km), superimposed on the basement fault map shown on the left. Note that the geometry of inversion is strongly influenced by the presence of underlying basement faults.

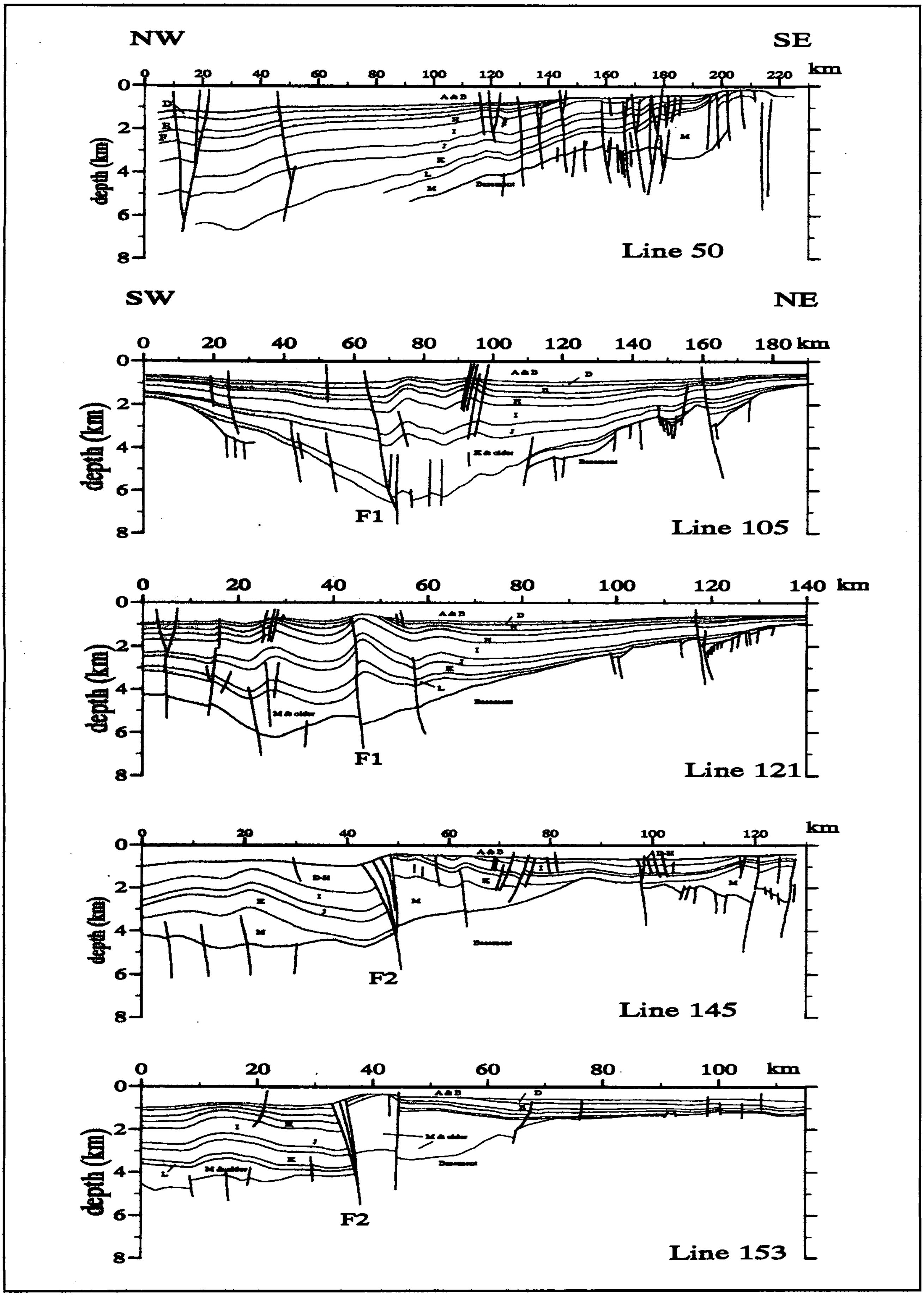

Figure 6. Geoseismic sections (depth-converted) from the southern Malay Basin (location map in Fig. 5). The topmost line is oriented NW-SE while the rest are NE-SW. Notice how the deformation, which produced the inversion structures at the centre of the basin, increases from NW to SE. Two major basement faults are shown as F1 and F2 (see Fig. 5).

grabens, which was observed in seismic sections as reverse dip-slip reactivation of the faults. Hence, we may interpret the flower structures in the southern Malay Basin as having been produced by sinistral oblique-slip reactivation of the E-trending half-graben border faults as a result of reversal in the shear direction.

THE ROLE OF THE NATUNA RIDGE

The degree of inversion in the Malay Basin increases from north to south, resulting in different structural styles (Fig. 7D). Mildly inverted structures are typical of those in the north/central part of the basin (see Fig. 6, Line 105), whereas strongly and completely inverted half-grabens are typical of the southern part of the basin (Lines 145, 153). Further south, in the West Natuna Basin, thrusts and reverse faults are not uncommon (Ginger *et al.* , 1993), implying yet more intense deformation. The deformation resulted in massive basement uplift, thinning of the postrift strata, and truncation by the regional middle-late Miocene Unconformity in the southeastern part of the Malay Basin (Fig. 6). Available stratigraphic and structural data suggest that the timing of uplift coincides with the basin inversion phase during the middle-late Miocene. Hence, basin inversion has resulted in, not only local inversion of individual half-grabens, but also in a regional basement uplift in the southeastern part of the Malay Basin and in the West Natuna Basin. Sedimentation seems to have been continuous in the northeastern part of the Malay Basin; the uplifted southeastern region providing the sediment supply to the northeast. Contemporaneous subsidence, sedimentation, and deformation in different parts of the basin, is a typical feature of many strike-slip basins, such as the San Joaquin Basin, central California (Nilsen and Sylvester, 1995, p. 448–449).

Figure 10 shows how the southern Malay Basin and the West Natuna Basin may have been uplifted during the middle Miocene inversion phase. The inversion of half-grabens in the Malay Basin, as explained in the block model, is the result of regional dextral shear. The increasing intensity of deformation towards the south is caused by the buttressing effect of the Natuna Ridge which, effectively, resisted the dextral motion of the block on the northwestern side of the ASZ. Furthermore, the northward subduction of the Indian Plate beneath the Java Trench to the south may have contributed also to the deformation. The southern part of the Malay Basin and almost the entire West Natuna Basin are situated, effectively, between two converging crustal blocks. This has resulted in

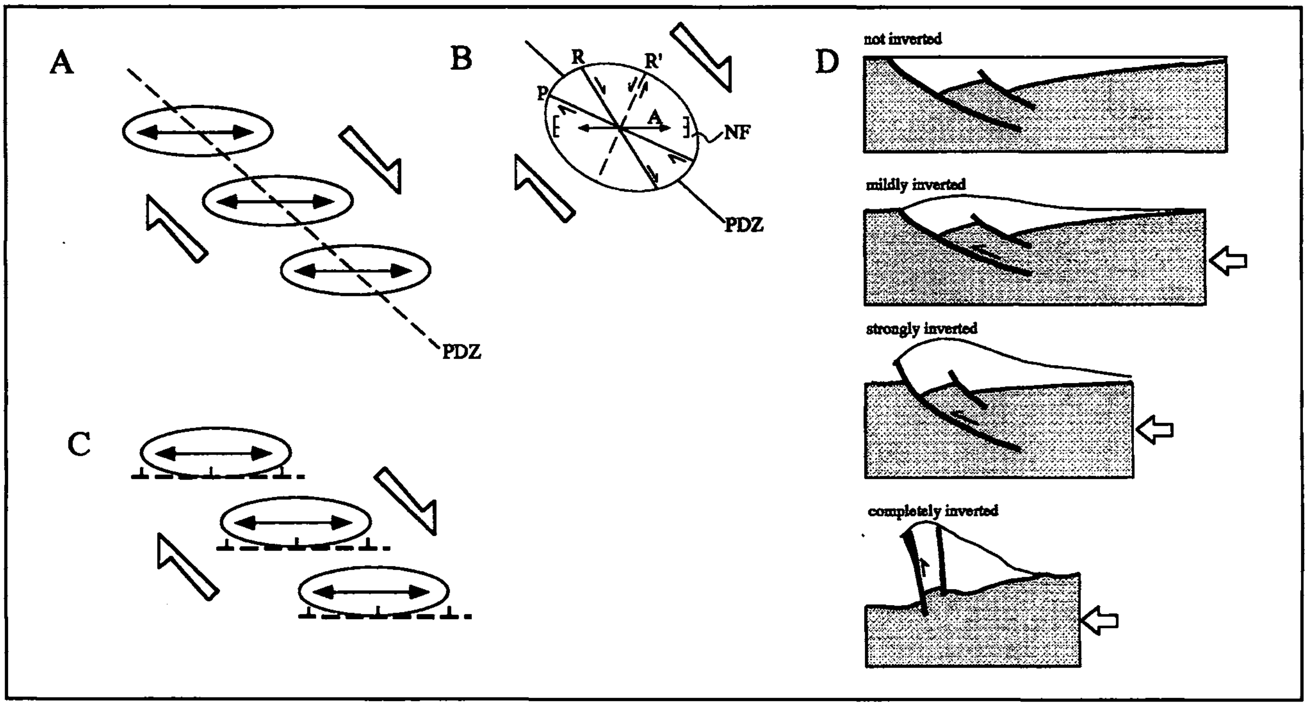

Figure 7. Conceptual models of en echelon folding involving a right-lateral wrench system. (A) Fold configuration (ellipse with plunging arrows) in a sedimentary layer above a principal displacement zone (PDZ) at depth (dashed line). (B) Strain ellipse representation of a right-lateral wrench fault (after Christie-Blick and Biddle, 1985). NF – normal fault, A – anticlinal axis, R – Riedel shear, P – P shear. (C) Folds developed above north-dipping, en echelon normal faults that bound half-grabens by buckling of sedimentary cover in response to distributed deformation resulting from right-lateral shear. (D) Structural styles produced by, from top to bottom, increasing degrees of inversion involving half-graben basins.

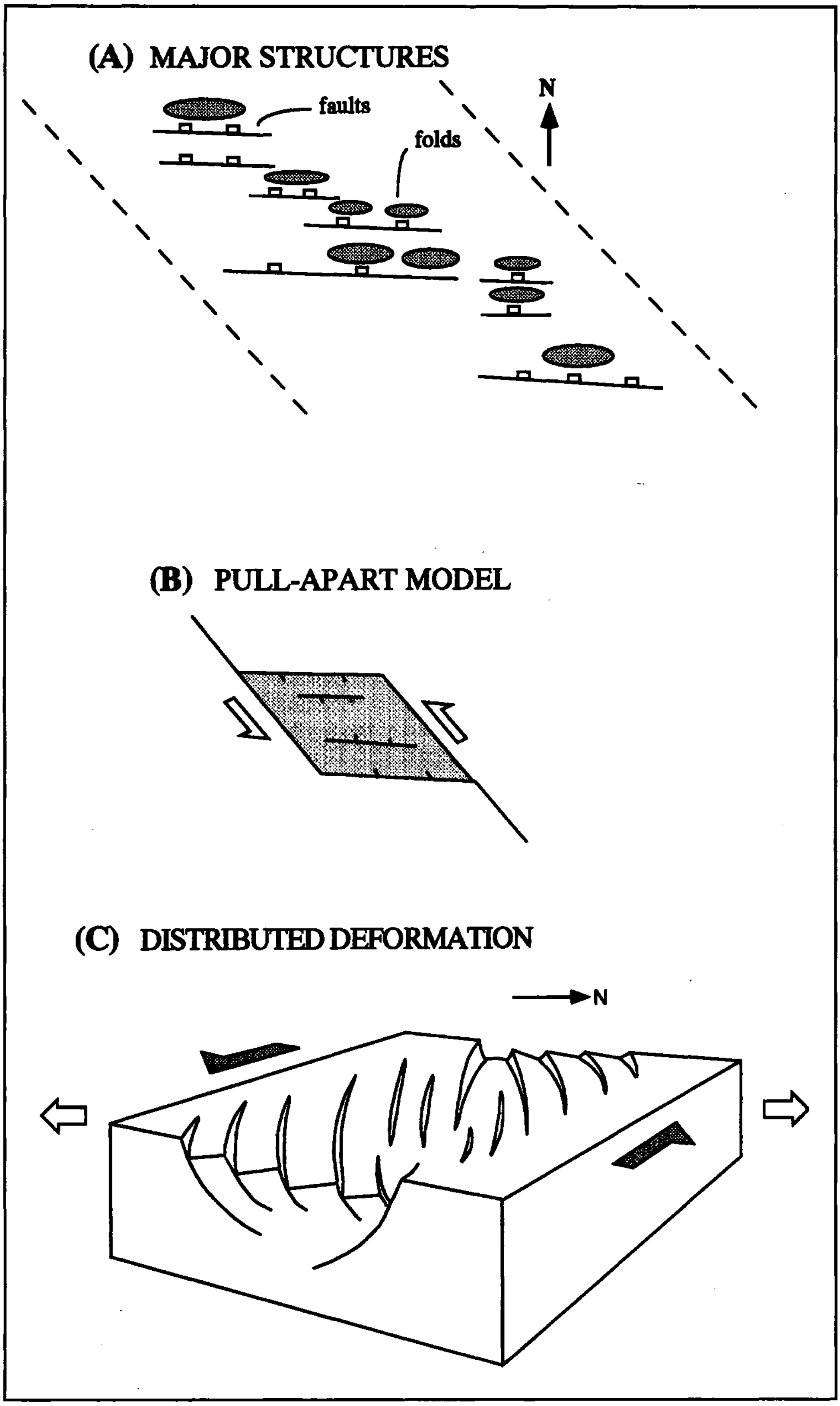

Figure 8. Pull-apart model for the Malay Basin. (A) Schematic illustration of en echelon array of E-trending faults and associated inversion anticlines. (B) Pull-apart basin formed by extension at a releasing bend of NW-trending strike-slip fault. (C) Schematic illustration of the geometry of the Malay Basin during the early stages of development. Note the obliquity of the basement faults and half-grabens as a result of left-lateral shearing of a broad zone of deformation.

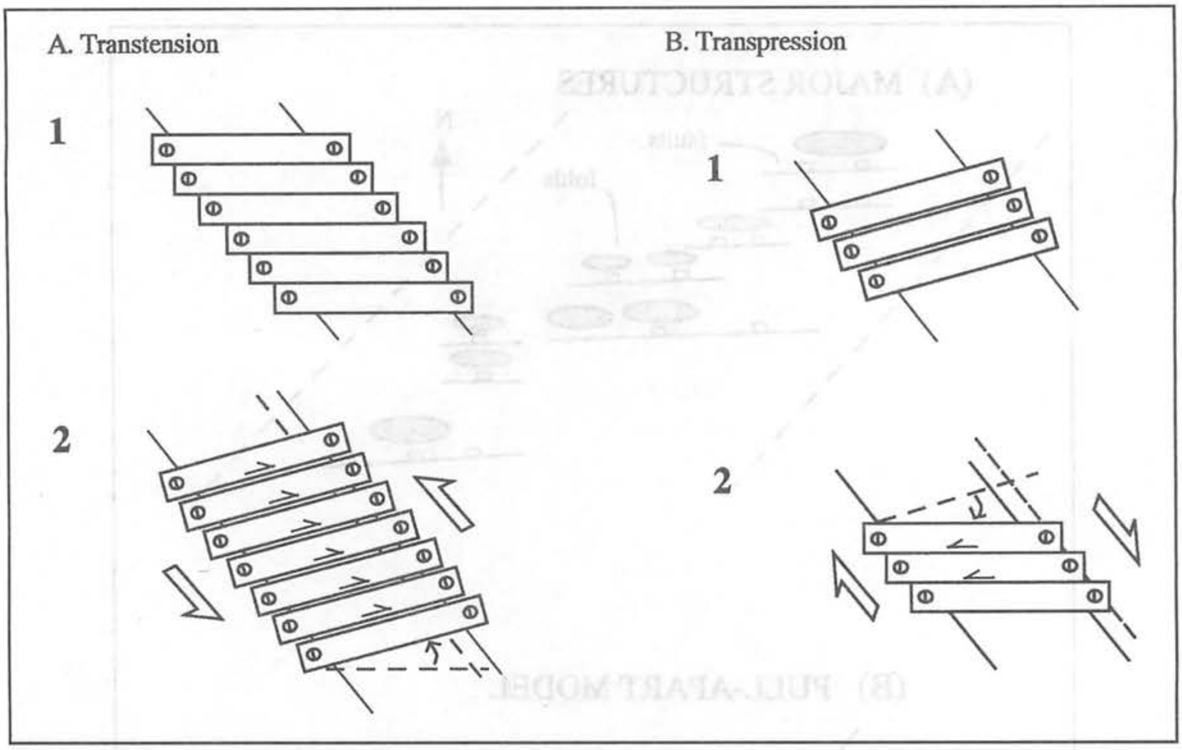

Figure 9. Block model for extension and inversion in the Malay Basin, based on the original concept of McKenzie and Jackson (1986). (A) Transtensional phase. (1) Initial geometry of shear zone, represented by crustal blocks (wooden slats) separated by en echelon faults. (2) Sinistral shear: blocks rotate anticlockwise about fixed axes (screws), causing dextral oblique slip of the faults and producing gaps (basins) between them. Note that the shear zone increases in width as a result of the deformation. (B) Transpressional phase. (1) Before inversion, geometry as in A2. (2) Reverse motion of the external shear couple, from sinistral to dextral, results in narrowing of the shear zone, closure of basins, and deformation of the sedimentary fill.

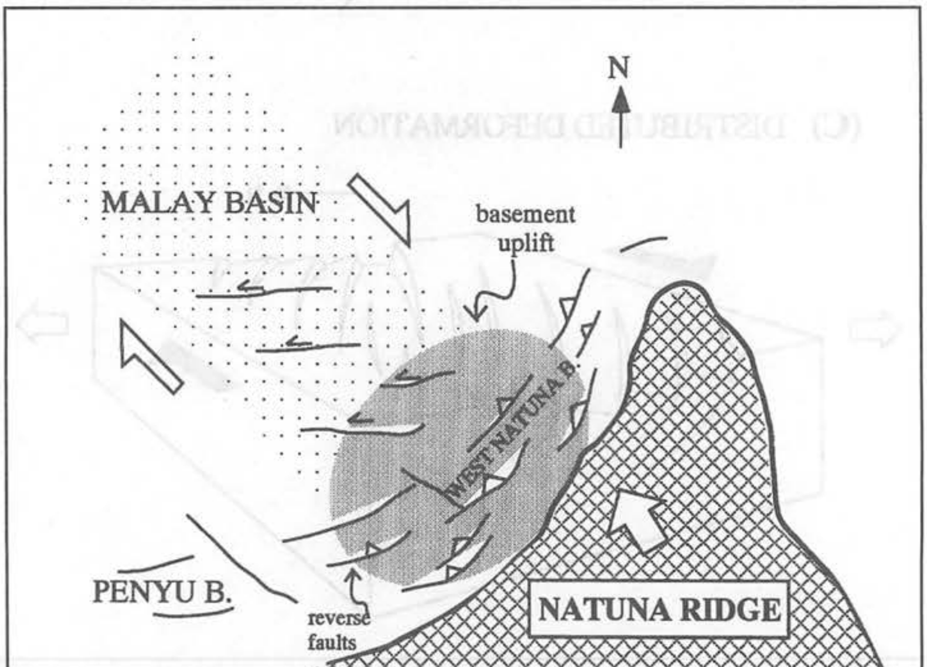

Figure 10. Cause of basement uplift in the southern Malay Basin and the West Natuna Basin. Uplift was caused by crustal thickening between two converging crustal blocks: 1. the northwestern side of the Malay Basin shear zone and 2. the Natuna Ridge, which acted as a buttress that resisted the southeastward motion of 1. Deformation in the sedimentary cover within the compressional zone (shaded area) is dominated by folding and reverse/thrust faults.

crustal shortening, thickening, and isostatic uplift.

SUMMARY

A simple kinematic model is proposed whereby the Malay Basin was formed by transtension of a NW-trending sinistral shear zone that contains pre-existing E-trending basement faults. During deformation, anticlockwise rotation of the fault-bounded blocks resulted in dextral oblique slip along the faults and produced a series of E-trending half-grabens. The formation of compressive anticlines over the half-grabens is explained as being the result of a reversal in the sense of shear. Dextral shear resulted in transpressive, sinistral oblique-slip reactivation of the E-trending basement faults and the formation of anticlines over the inverted half-grabens.

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