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Marine and Petroleum Geology 15 (1998) 619–634

Marine and Petroleum Geology

Finite extension across the South Vietnam basins from 3D gravimetric modelling: relation to South China Sea kinematics

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Received 27 February 1998; revised 16 May 1998; accepted 28 May 1998

Abstract

We derive a crustal thickness map over the south Vietnam basins from a 3D inversion of gravity data that takes into account the sedimentary infill and its density variation with depth. This map is used to estimate the total amount of stretching across these basins, that varies from 190 km to the east (at 111°E) to 30 km to the west (at 107°E). Comparison with South China Sea kinematics (amount and timing of oceanic opening) implies large decoupling with respect to the Indochina block and supports the hypothesis of formation of the South China Sea in upper Oligocene to lower Miocene by southward subduction of the proto-South China Sea.

Keywords: Extension; Vietnam; Gravimetric modelling

1. Introduction

The South China Sea is one of the largest marginal basins in the western Pacific (Fig. 1). According to the analysis of magnetic anomalies, it opened from 32 to 15 Ma (Briais et al., 1993; Taylor & Hayes, 1980, 1983). While its eastern margin has disappeared by subduction beneath the Philippines islands, its northern and southern margins are typical passive margins which have recorded the rifting history of the basin. Since the oceanic basin has propagated toward the south-west, the timing for stretching of the continental crust to the west must be diachronous. In turn, this diachronicity is a key for understanding the mechanism of opening of the oceanic basin.

Several opening models have been proposed (Jolivet et al., 1989; Lee & Lawver, 1994; Rangin, 1996; Rangin et al., 1990; Tapponnier et al., 1982, 1986; Taylor & Hayes, 1980, 1983). They all correspond to two end-member models, implying either sinistral or dextral motion along the western margin, offshore central Vietnam. Taylor and Hayes (1980) first identified the magnetic anomalies in the South China Sea and observed their relative symmetry and their E–W orientation in the eastern part of the basin. Huchon et al. (1994) and Hall (1996) argued that extension was caused by slab-pull of a subducting proto-South China Sea located further south. Based on the analysis of the continental tectonics and on small-scale experiments, Peltzer (1983), Peltzer and Tapponnier (1988) and Tapponnier et al. (1982, 1986) suggested instead that the Indochina block was extruded southeastwards along the left-lateral Red River Fault during the India-Eurasia collision. According to radiometric data (Leloup et al., 1995; Shärer et al., 1990), the left-lateral motion was active up to early Miocene time and was coeval with the formation of the South China Sea which is then interpreted as a pull-apart basin related to the motion along the Red River Fault.

The northern margin of the South China Sea is relatively well known. The Beibu basin (Tonkin gulf) rifted mainly in the Oligocene as the termination of the Red River Fault, but its western part, close to the Red River Fault remained active until 5.5 Ma ago (Rangin et al., 1995b). South of the Beibu basin, the structure and age of the Song Hong (Yingghehai) basin is still debated, leading to divergent interpretations as a left-lateral (Le Pichon et al., 1995) or right-lateral (Harder et al., 1992) pull-apart basin during the Oligocene to lower Miocene. Further east, the Pearl River mouth basin also rifted during the Oligocene (Li Pinglu & Rao, 1994; Pigott & Ru, 1994; Ru & Pigott, 1986; Wang & Sun, 1994; Yu, 1994). Deep seismic soundings support the interpretation of the basin as located above a northward dipping crustal scale detachment (Hayes et al., 1995; Nissen et al., 1995a,

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PII: S0264-8172(98)00031-2

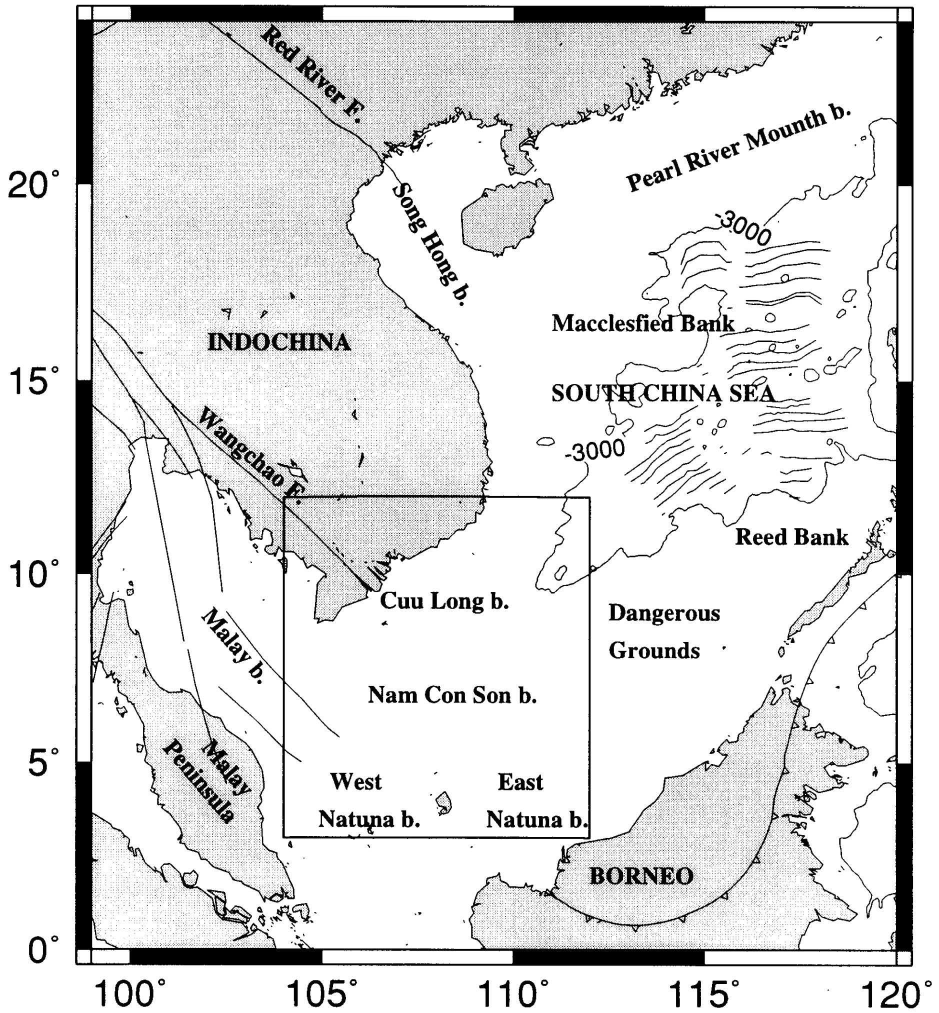

Fig. 1. Location map of the studied area. Rectangle: area of Figs 2, 3 and 4.

1995b). The geometry and timing of extension in these basins thus apparently supports Tapponnier et al.'s hypothesis. However, it has been shown that the oceanic spreading kinematics drastically changed around anomaly 7 (26 Ma) (Briais et al., 1989; Pautot et al., 1986), when the ridge reoriented from N–S to NW–SE spreading and started to propagate toward the south-west (Briais et al., 1993), until it reached the present-day location of the oceanic tip, near 9°N of latitude and 110°E of longitude (Coulon et al., 1995). The timing and kinematics of extension in the western margin of the South China Sea are thus crucial elements in determining the relationship of oceanic spreading to continental tectonics (Hayes, 1985).

Recent onshore and offshore data acquired in the Qui Nhon and Nha Trang basins (Marquis et al., 1997; Roques et al., 1997a, 1997b) support the Hayes' hypothesis of a dextral N–S margin offshore central Vietnam. On the basis of these data, Rangin et al. (1995a) have proposed that sinistral motion along the Red River fault system may be restricted to the area north of Danang, while partly coeval with dextral motion along the Vietnam margin south of Danang.

The southern margin of the South China Sea has a more complex history, probably because it recorded not only the Oligo-Miocene rifting, but also the Paleocene events (Hinz & Schlüter, 1985; Shaoren et al., 1994). Hamilton (1979) first suggested that the opening of the South China Sea caused the separation of the Dangerous Grounds, Reed Bank and Palawan blocks from mainland China. From a comparison between the northern and southern margins of the South China Sea, Kanyuan et al. (1994) concluded with striking differences, due, however, to the overprint of compressional events to the south. Although of the scope of this paper, we may notice that most authors now recognize the former existence of a proto-South China Sea which has been subducted beneath northern Borneo (e.g., Holloway, 1982). In Sabah, the main compressional event was initiated in Middle Miocene (Rangin et al., 1990) and corresponds to the collision that followed the complete close of the proto-South China Sea (Tongkul, 1994).

Oil exploration has extensively covered the southern Vietnam basins since the early 70s and their general structure is well known, except for the deepest parts which have never been reached by exploration wells due to the very thick sedimentary infill (more than 10 km). The thickness and nature of the sediments, including their densities, are thus reasonably well known, although not yet published. In addition, satellite altimetry now provides an homogeneous data set of the gravity field. Its resolution (a few km) is enough for regional studies and can therefore be used to estimate the thickness of the crust underlying the basins, and therefore provides new constraints on their stretching mechanism.

2. Structure and history of the southern Vietnam basins

The southern Vietnam offshore is characterised by a shallow platform, less than 200 m of water depth, formed by the prograding Plio-Quaternary sediments of the Mekong delta (Figs 2 and 3). Beneath this recent sedimentary cover, oil industry exploration has revealed the presence of two main basins, the northern Cuu Long basin and the southern Nam Con Son basin, separated by a basement high named Con Son ridge. Further south are the Natuna basins, which are located west and south of the southern Vietnam shelf.

2.1. The Cuu Long basin

The Cuu Long basin is the continuation of the onshore Mekong basin and is about 400 km long and 100 km wide, with a NE–SW trend (Fig. 3) (Le, 1986). It mainly shows NE–SW normal faults (Mai, 1995) active until the end of Oligocene (Truong et al., 1991), and E–W trending faults in the central part of the basin. The syn-rift sequence is divided into the Ca Coi formation of Eocene age and the Oligocene Tra Tan formation (Do et al., 1993). It comprises fluviatile to deltaic sediments: sandstones, shales and silts (CCOP, 1991). The post-rift sequence is divided in the Bac Ho (Lower Miocene), Con Son (Middle Miocene), Dong Nai (Upper Miocene) and Bien Dong (Plio-quaternary) formations, all marine but with a slight uplift in Middle Miocene, due to depositional rates exceeding the thermal subsidence in the basin. The total sediment thickness reaches 9 km in the centre of the basin (Fig. 3). The general structure of the

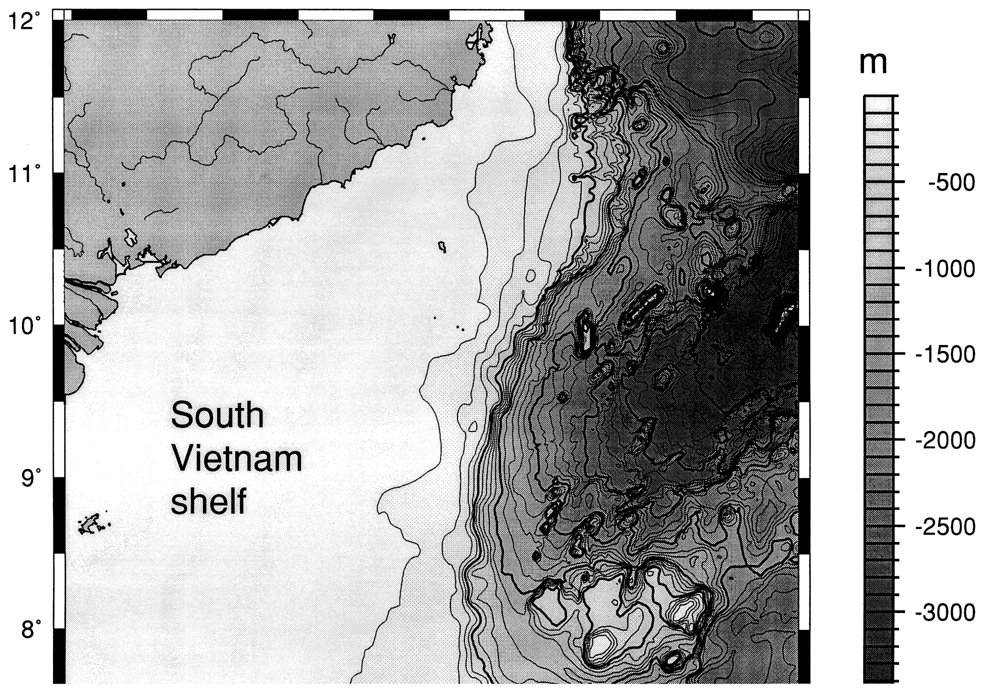

Fig. 2. Bathymetric map of the southern Vietnam shelf and adjacent oceanic basin (location: see inset in Fig. 1).

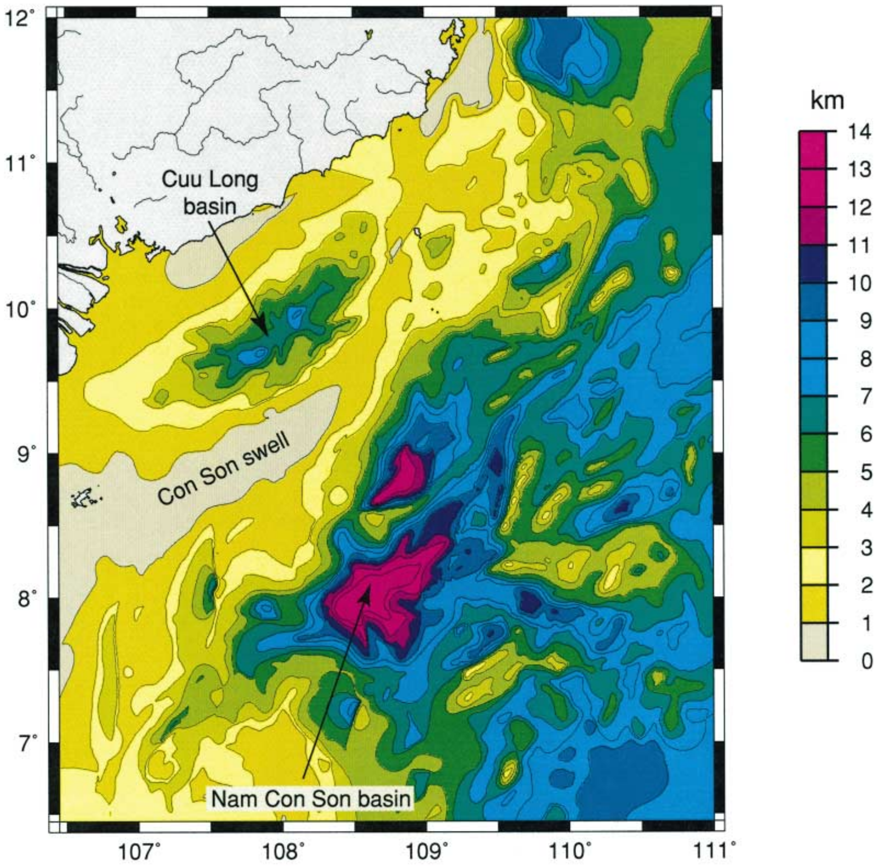

Fig. 3. Basement depth map (compiled from various industrial sources and from the PONAGA'93 cruise).

basin is attributed to the termination of the left-lateral Wang Chao fault (Tapponnier et al., 1986).

2.2. *The Nam Con Son basin*

The Nam Con Son basin is deeper and more complex than the Cuu Long basin (Fig. 3). It shows E–W, NE–SW, NNE–SSW as well as N–S normal faults. The oldest sediments are attributed to Eocene and Early Oligocene, but only the Late Oligocene (Cau Formation or composite sequence T20 of Matthews et al., 1997) has been reached by exploration wells on structural highs. As in the Cuu Long basin, the Oligocene sediments which have accumulated in E–W trending half-graben are fluviatile to deltaic, but here the Oligo-Miocene unconformity is not well marked (Matthews & Todd, 1993). The syn-rift formations are Early to Middle Miocene, thus younger than in the Cuu Long basin. The Dua formation (Early Miocene, composite sequence T30) is marine (sub-littoral) and constituted by black shales intercalated with sandstones. It was deposited in NE–SW to N–S graben (Matthews et al., 1997) as were the Thong and Mang Cau formation (Middle Miocene, composite sequences T40 and T60), which contain mainly sandstones associated to shallow water limestones (reefs). The boundary between the Dua and Thong formations is an unconformity which seals most of the NE–SW normal faults. However, some of the faults continue into the Middle Miocene up to another unconformity dated at about 10 Ma. The Late Miocene (Nam Con Son formation, composite sequence T85) is represented by deeper marine sediments which, with the prograding Plio-quaternary Bien Dong formation, form the post-rift sequence with average subsidence rates of 50 m Ma^{-1} typical of thermal subsidence, contrasting with the faster subsidence rates (<700 m Ma^{-1}) recorded from 19.5–16 Ma.

A major difference in age therefore exists between the Cuu Long (Oligocene) and the Nam Con Son (Lower to Middle Miocene) basins. Their respective structural settings are also different: while the Cuu Long basin seems to be associated with NW–SE trending left-lateral faults (with more or less NNW–SSE extension), the structure of the Nam Con Son basin, although also characterised by NE–SW normal faulting, is not. Rather, several NE–SW to NNE–SSW normal faults appear to branch in a horse-tail fashion onto N–S faults. This structural relationship suggest that the N–S faults are right-lateral strike-slip faults. This tectonic pattern is also compatible with NNW–SSE extension, but no obvious structural link exists between the two basins. Finally, it is worthwhile noting that the structure of the Nam Con Son basin appears to be in the continuation of the deeper oceanic basin located further east (Fig. 2). This basin, up to 4000 m deep (water depth) corresponds to the tip of the southwestward propagating South China Sea, which reaches longitude 110°E about 15.5 Ma ago, according to the interpretation of the magnetic anomalies.

2.3. The West Natuna basin

The West Natuna basin is located to the west of the Natuna arch and is the south-eastward extension of the Malay basin. It is controlled by two main fault directions: NE–SW to ENE–WSW normal faults and WNW–ESE faults considered as left-lateral strike-slip faults (Letouzey et al., 1988; Mingard & Willett, 1993; Nga et al., 1996). Extension on NE–SW normal faults started during the Oligocene (near the top of the Benua Lama formation) and continued during the Early Miocene. Near the top of Barat formation (about 21 Ma ago), normal faults show numerous inversions sealed by the 10 Ma unconformity (Ginger et al., 1993).

2.4. The East Natuna basin

The East Natuna basin is located to the south of the Nam Con Son basin and is separated from the West Natuna basin by the N–S trending Natuna arch (Fig. 1). It has a similar history to the West Natuna basin during the Oligocene and Early Miocene, but no inversion is recorded in this basin. Rather, the NE–SW normal faults are systematically associated with N–S faults on which they branch in a horse-tail fashion, suggesting a dextral motion on these N–S faults. The most developed N–S dextral graben is the Komodo graben.

Three different types of basins thus characterise the continental margin west of the tip of the oceanic crust of the South China Sea: (1) the Cuu Long basin, Oligocene in age; (2) the West Natuna basin, Oligocene to Early Miocene and inverted in Middle Miocene; (3) the Nam Con Son and East Natuna basins, mainly of Early Miocene age and without Middle Miocene inversion, excepted a few localised gentle inversions in its south-eastern part. Their period of tectonic subsidence and their structural patterns form the basis for the interpretation of the crustal structure that we shall derive from gravimetric modelling in the next section.

3. Gravimetric modelling

3.1. 3D gravity inversion for Moho depth

The inversion procedure is a two-step processing of the free-air gravity anomaly. The first step consists of calculating a Bouguer anomaly reduced to the mantle by evaluating the contribution of the various bodies from the observation plane (sea surface) to the top of the crystalline basement (water and sediment contributions). In a second step, the obtained Bouguer anomaly is inverted to recover undulations of the Moho discontinuity. Details of the procedure can be found in Chamot-Rooke et al. (1997). The mantle Bouguer is calculated using a 3D analytic solution for thin sheets contribution (Talwani & Ewing, 1960). The inversion is then performed using Fourier domain gravity expansion (Parker, 1972).

In practice, the mantle Bouguer calculation requires knowledge of the geometry and density contrast (with respect to crystalline basement) of the various surface bodies. Since density increases with depth, it is necessary to consider several sedimentary layers. At this stage, and provided the geometries and densities of sedimentary layers are correctly estimated, the only unknown parameter is the density of the basement. We used a constant density of 2.75 g cm^{-3} for the basement density throughout the calculations, which is a typical mean value for continental crust.

The second step consists in determining the geometry of the Moho from the mantle Bouguer. The main assumption is that the residual Bouguer anomaly (free-air corrected for surface bodies) can be totally attributed to variations of the Moho depth. The inversion is based on Fourier transform methods. The gravimetry effect $g(x,y)$ produced by the periodic undulation $h(x,y)$ of an interface separating two layers with a density contrast $\Delta\rho$ at depth $d \gg h(x,y)$ is:

$$g(x,y) = 2\pi G\Delta\rho h(x,y)e^{-\mathrm{kd}} \tag{1}$$

where G is the gravitational constant and k the wave number, and high order terms in the gravity expansion have been ignored. In the Fourier domain, this equation becomes:

$$G(k_x,k_y) = 2\pi G\Delta\rho H(k_x,k_y)e^{-\mathrm{kd}} \tag{2}$$

where $H(k_x,k_y)$ is the Fourier transform of $h(x,y)$. One can then obtain the geometry $h(x,y)$ of the Moho by:

$$h(x,y) = TF^{-1}\left\{\frac{TF[g(x,y)]}{2\pi G\Delta\rho e^{-\mathrm{kd}}}\right\} \tag{3}$$

where TF and TF^{-1} denotes the Fourier and inverse Fourier transforms, respectively, and where $\Delta\rho$ is the density contrast between mantle and basement. Notice that the inversion procedure requires a reference level d for Moho undulations. This level can be determined by additional constraints at some specific location (such as Moho depth obtained from seismic refraction). However, mathematically, the Fourier expansion requires d to be as close as possible to the mean depth of the undulations. A full discussion of this problem is found in Chamot-Rooke et al. (1997). A safe procedure is to recalculate *a* *posteriori* the Moho contribution using the above mentioned 3D analytical solution. The residual (observed minus calculated gravity) can in turn be resolved through some minor adjustments of the Moho depth around the inverted solution.

3.2. Data set used

Data compilation has been done from latitude 6.45°N to 12°N and from longitude 106.45°E to 111°E. The bathymetric grid (Fig. 2) is a combination of the ETOPO5 database complemented with high accuracy multibeam data obtained over the propagating tip of the South China Sea during the PONAGA'93 cruise of R/V L'Atalante (Coulon et al., 1995). Over the southern Vietnam shelf, the water depth is generally less than 200 m. The shelf edge is marked by a 1000 m scarp, with a general N–S trend. East of it, the water depth increases toward the oceanic basin, reaching nearly 4000 m.

Sediment isopachs were obtained from various industrial sources and merged after checking regional multichannel seismic lines. The two-way travel times T (in s) obtained from seismic data were converted to depth Z (in m) using the following relationship, based on the compilation of data from about 30 wells:

$$Z = 16.8 + 759.5T + 247T^2 \tag{4}$$

The obtained basement depth map is shown in Fig. 3. The basement depth varies from 2–8 km in the Cuu Long basin and from 3–13 km in the Nam Con Son basin. It is less than 1 km on the Con son ridge.

The most recent version (7.2) of the free air anomaly map derived from satellite altimetry (Sandwell & Smith, 1992) was used (Fig. 4). Although less precise at short wavelength than shipboard measurements, the satellite derived map is sufficient for our purpose. Comparison with ship data on small areas shows a fair agreement at wavelengths greater than 10 km.

Finally, sediment densities were obtained from a compilation of several industrial wells, from which we constructed a density versus sediment thickness chart (Fig. 5). The density contrast between the basement and the overlying sediments becomes negligible below 5–6 km thickness.

3.4. Results

The Bouguer anomaly map reduced to mantle is shown in Fig. 6. A first approximation of the Moho depth was obtained through the inversion procedure described

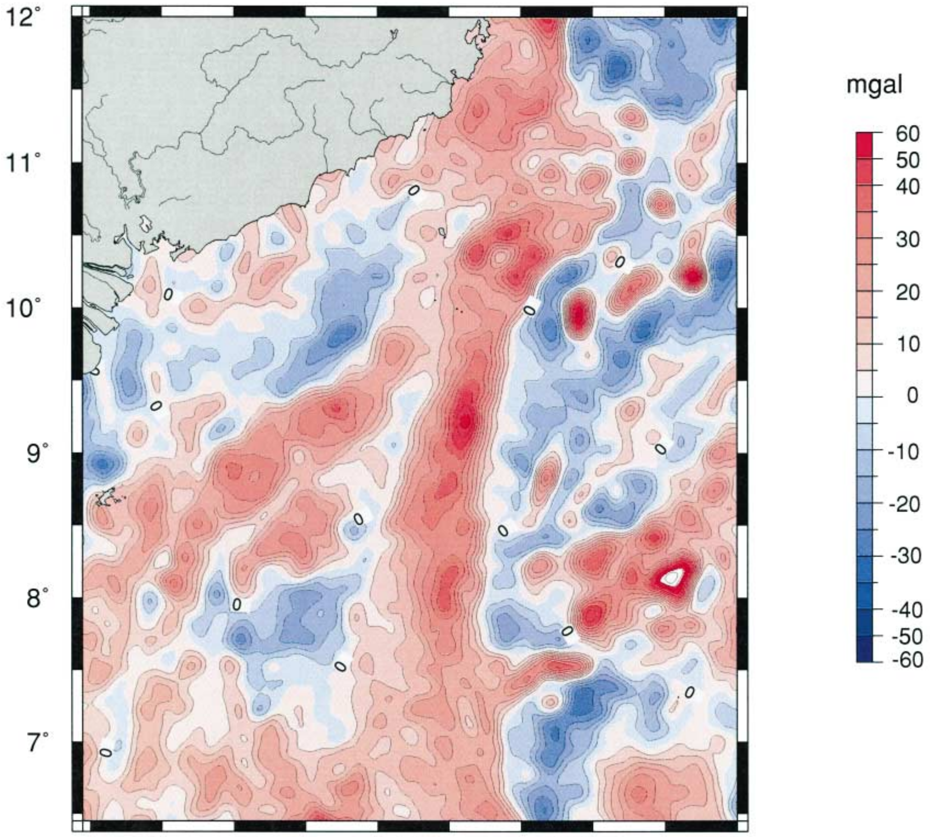

Fig. 4. Free air gravity anomaly map, derived from altimetry (Sandwell, version 7.2).

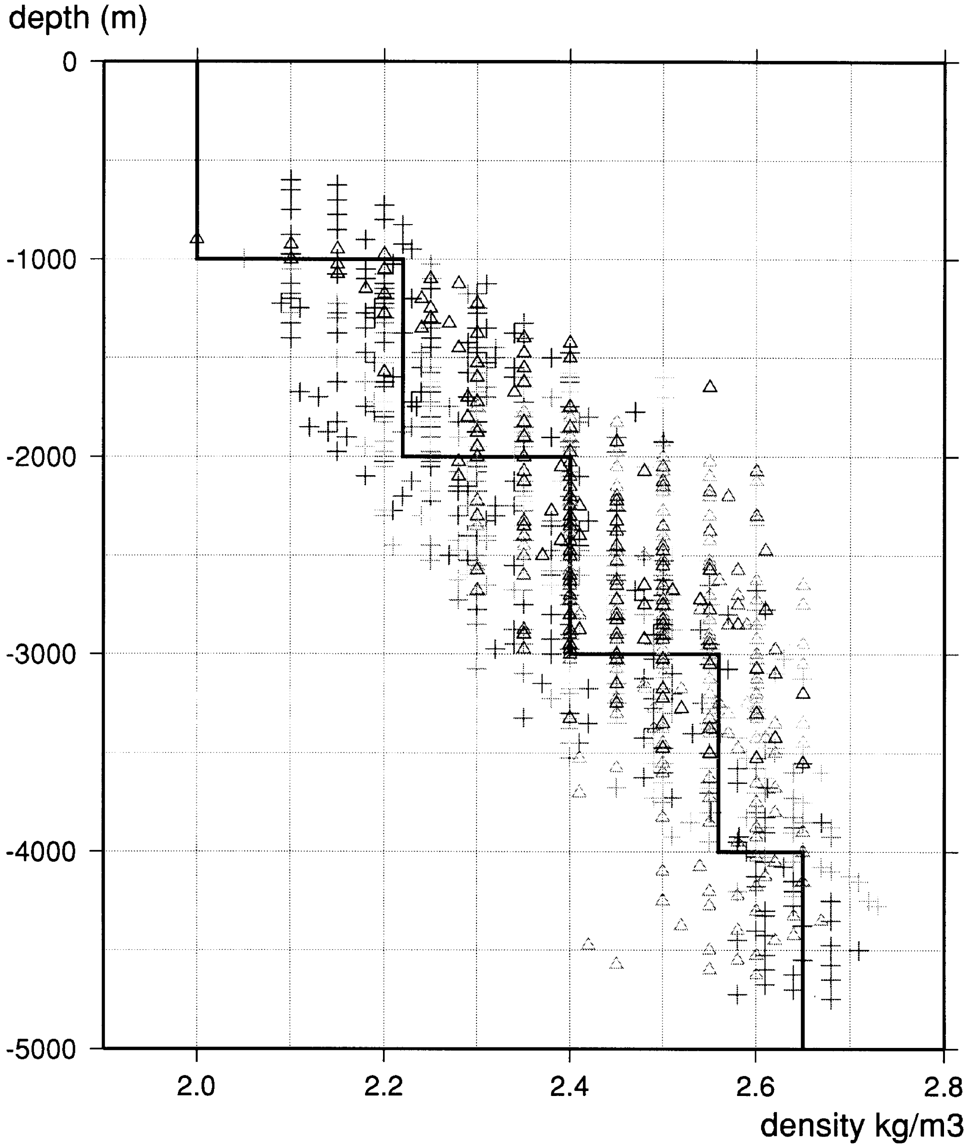

Fig. 5. Density vs depth determined from about 30 wells in the South Vietnam basins. The bold line is the mean curve that we used for the gravimetric computations.

above. The re-calculated signal (forward modelling based on 3D exact solution rather than Fourier approximation) showed differences locally reaching 30 mgal. These residuals (differences between observed and recomputed gravity signals) were in turn used to adjust the first order solution by minor depth corrections of the Moho. The final Moho depth map (Fig. 8) leads to residuals less than 4 mgal (rms), with maximum not exceeding 12 mgal (Fig. 7). The crustal thickness map (Fig. 9) shows that the minimum thickness corresponds to the oceanic propagating tip of the South China Sea (less than 8 km), while continental crust is thinnest (10–12 km) beneath the Nam Con Son basin. By contrast, the Cuu Long basin is much less thinned (20 km).

4. Kinematics of continental stretching

4.1. Amount of stretching across the Nam Con Son basin

The crustal thickness over the South Vietnam basins (Fig. 9) obviously shows a close relationship to the tip of the South China Sea oceanic crust. In spite of the complexity introduced by the presence of two sub-basins in the Nam Con Son basin, the deepest part of these basins clearly lies at the south-western continuation of the fossil oceanic propagating tip (Coulon et al., 1995). Subsidence analysis, both in the Nam Con son basin and in the Zengmu basin, shows that the tectonic subsidence phase started 21–22 Ma ago (Academia Sinica, 1989),

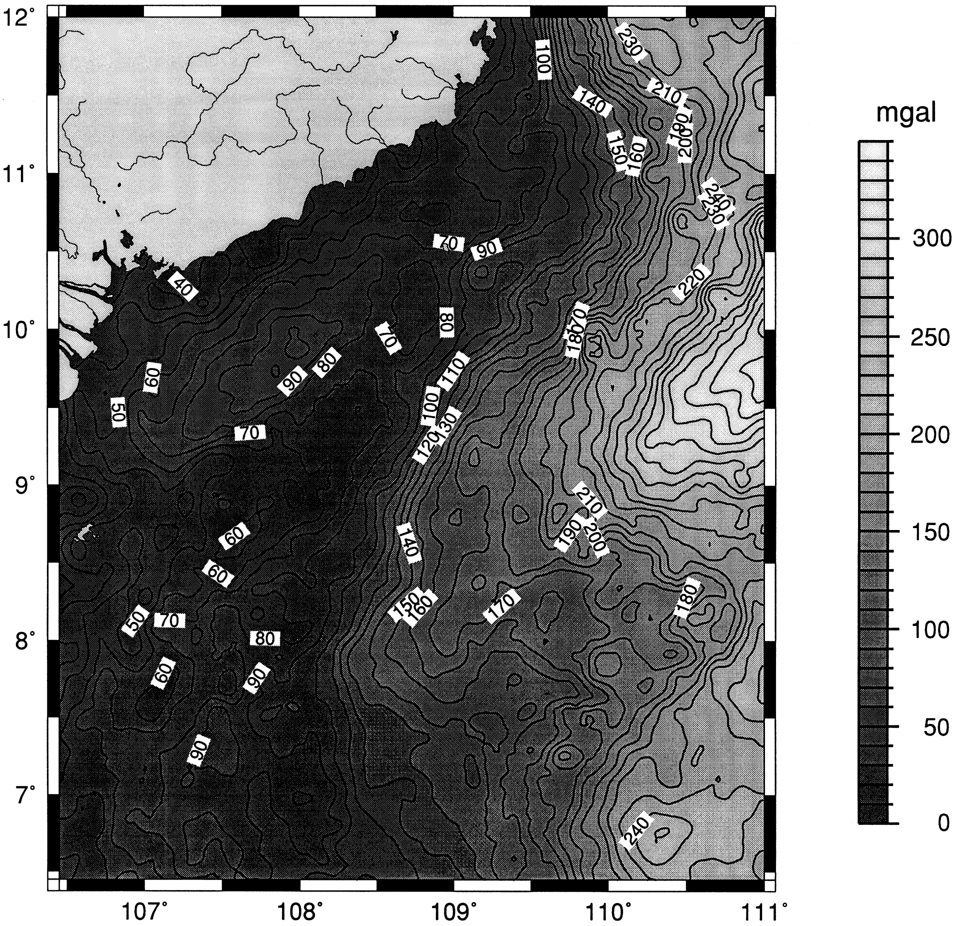

Fig. 6. Computed mantel Bouguer anomaly (explanation: see text).

and ended shortly after spreading ceased in the South China Sea, 15–16 Ma ago.

To further compare the synchronous amounts of oceanic opening in the South China Sea and of continental extension over the South Vietnam basins, we systematically computed from the crustal thickness map the total amount of stretching along small circles about Briais et al.'s (1993) South China Sea pole of opening for this period (21–15 Ma) (Fig. 10). This was done by assuming an initial crustal thickness of 30 km before stretching, inferred from the observed crustal thickness along the coast of Vietnam (Bui, 1993), and assuming further conservation of crustal volume during stretching. Ru and Pigott (1986) emphasized that the South China Sea region records several episodes of stretching, so that the assumption of a 30 km constant crustal thickness, prior to the Miocene stretching, may not be valid. However, we show in a further section that the stretching across the Cuu Long basin, which records the Oligocene stretching, is much less than in the Con Son basin. Note that we did not include the Cuu Long basin in the calculations since this basin is older than the period into consideration (21–15 Ma).

The poles of rotation of Briais et al. (1993) for the corresponding period of time—anomalies 6 (20.5 Ma[2]), 6a (21.7 Ma) and 6b (23.4 Ma)—are rather close to each other, and far from the South Vietnam basins, and they result in nearly the same small circles. Figure 11 shows the total amount of stretching computed from the crustal thickness map along these small circles, as a function of longitude. It ranges from 30 km to the south-west to 190 km to the north-east. This south-westward decrease is fairly linear and would correspond to a pole of rotation located very close to the south-west (at about 6°30′N, 106°30′E), assuming that stretching accommodates a rigid rotation of Vietnam with respect to the southern margin of the South China Sea. The formation of the basins consequently does not obey the same kinematics as the oceanic opening of the South China Sea, the westward decrease in continental stretching being faster than that predicted by the oceanic kinematics.

This rapid decrease of stretching toward the south-west is also in good agreement with the basin inversion

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[2] Using Harland et al.'s (1990) timescale.

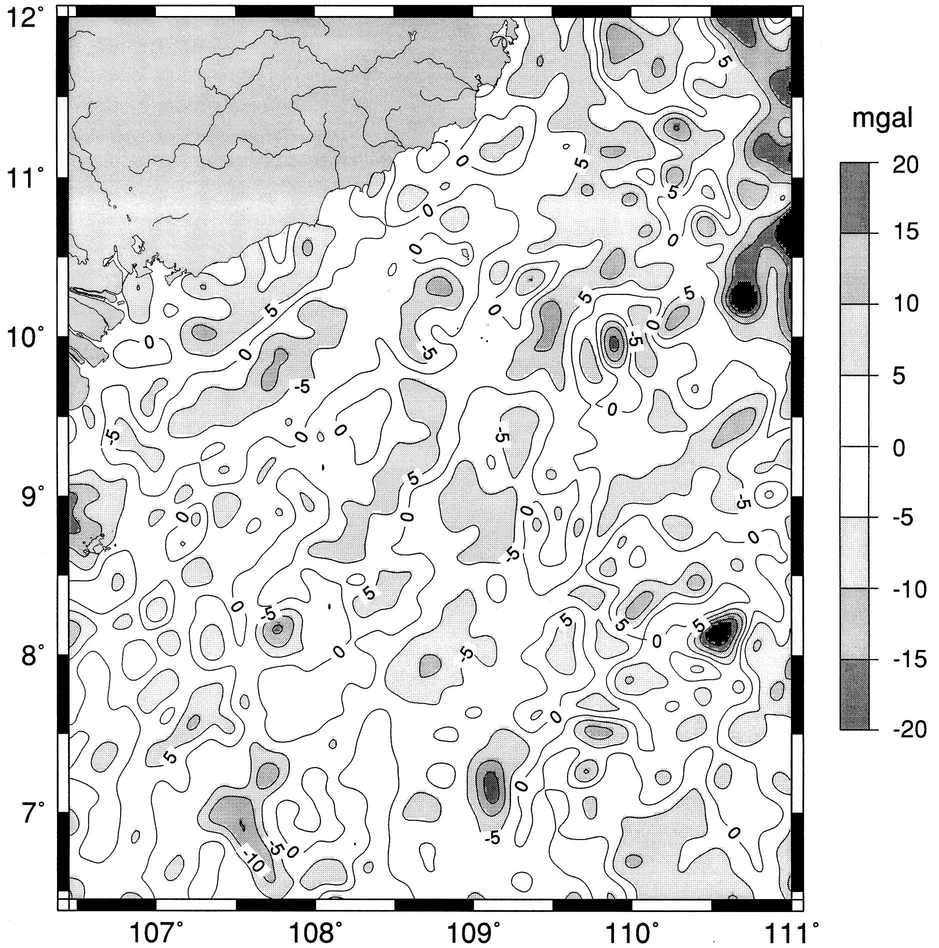

Fig. 7. Residual free air gravity anomaly (difference between the free air anomaly computed from the model and the observed anomaly).

which occurred 21 Ma in the West Natuna basin (Nga et al., 1996; Ginger et al., 1993). Extension to the north-east of Natuna arch and slight compression to the south-west being kinematically compatible, it suggests a common cause, which, concerning the inversion of the West Natuna basin, can be considered as the propagation of compression in the Rajang-Crocker belt of north Borneo (Bénard et al., 1990; Prouteau et al., 1996). We shall see in the last section that this explanation is consistent with the hypothesis of Taylor and Hayes (1980) for the formation of the South China Sea.

4.2. Comparison with the kinematics of the South China Sea spreading ridge

We now compare our estimate of continental stretching to the predicted amount of oceanic opening during the same period of time (Fig. 12). The oceanic motion since anomalies 6, 6a and 6b was obtained using the corresponding poles of rotation of Briais et al. (1993). To the north-east, close to the oceanic tip, the predicted oceanic motion since anomaly 6 (20.5 Ma) is smaller by more than 40 km than our continental stretching estimate. On the other hand, the predicted motion since anomaly 6b (23.4 Ma) is larger by about 30 km than our estimate. A good fit is obtained for anomaly 6a (21.7 Ma), suggesting that continental stretching is kinematically compatible with oceanic spreading if extension started 21.7 Ma ago. This falls into the range of ages for the onset of tectonic subsidence in the South Vietnam basins. In other words, the present day crustal thickness estimated in the north-eastern region, close to the oceanic tip, is fully explained by the kinematics describing the oceanic spreading in the South China Sea since 21.7 Ma.

However, we showed that further west continental stretching decreases more rapidly and does not conform with the oceanic kinematics. This observation implies strong decoupling between the South China Sea and the continental block west of Natuna arch. The estimated amount of offset (about 160 km) is simply the difference between the continental stretching to the south-west (not more than 30 km) and the relative motion predicted by kinematics (190 km). This decoupling may either correspond to a northward motion of Vietnam with respect to the southern margin of the South China Sea, if the latter is attached rigidly to the continental block west of

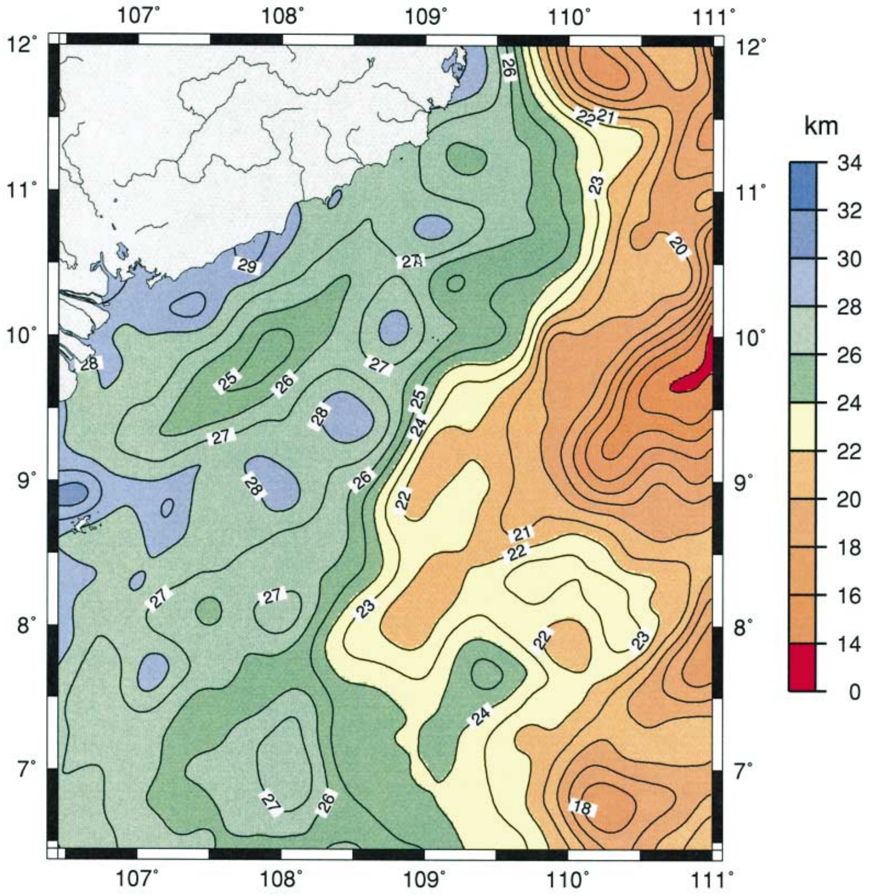

Fig. 8. Computed Moho depth.

Natuna arch, or to a southward motion of the southern margin of the South China Sea with respect to Vietnam if the latter is attached rigidly to the continental block west of Natuna arch.

Since this decoupling implies left-lateral or right-lateral strike-slip motions, respectively, it can be compared to known tectonic features which may accommodate such a motion. While the Cuu Long basin might be interpreted as a horse-tail termination of the Wang Chao fault, and the Malay basin as connected to the Three Pagodas fault system (Tapponnier et al., 1986), no NW–SE trending faults appear to connect with the Nam Con Son basin. On the other hand, N–S trending faults along the Natuna arch are good candidates for accommodating dextral motion, as well as NW–SE trending strike-slip faults recognised off Sarawak (Mat-zin & Swarbrick, 1997) (Fig. 13). It suggests that, at least from 22–15 Ma, south Vietnam was attached to the continental block west of Natuna arch. Consequently, our analysis suggests that a total of 160 km of dextral N–S motion may have occurred (from 22–15 Ma) in a distributed way to the south-west of the Nam Con Son basin.

Furthermore, rifting of the south Vietnam basins is coeval with the southward subduction of the proto-South China Sea beneath Borneo as inferred from the 18–19 Ma Sintang adakites (northwest Borneo) (Prouteau et al., 1996) that mark the early stage of subduction, followed by calc-alkaline magmatism and collision in Middle Miocene (Rangin et al., 1990). This time relationship thus favors the model in which the slab pull is the driving force for the opening of the South China Sea (Hall, 1996).

Independent estimates based on gravity modelling in the Nha Trang basin (Marquis et al., 1997) suggest that 190 km of dextral motion occurred along the N–S Vietnam scarp from 26–29 Ma to 20.5 Ma. In total the southern margin of the South China Sea seems to have been displaced with respect to Vietnam by about 350 km from 26–29 Ma up to the end of spreading, a value close to the total amount of opening of the South China Sea since 26–29 Ma (325–440 km measured along the margin, according to Briais et al.'s (1993) kinematics).

4.3. *Amount of stretching across the Cuu Long basin*

The same analysis of stretching has been done for the Cuu Long basin. However, South China Sea kinematics before 30 Ma would predict NE–SW trending extension, incompatible with the overall structure of the basin (Fig. 3) and its link with the NW–SE trending left-lateral Wang

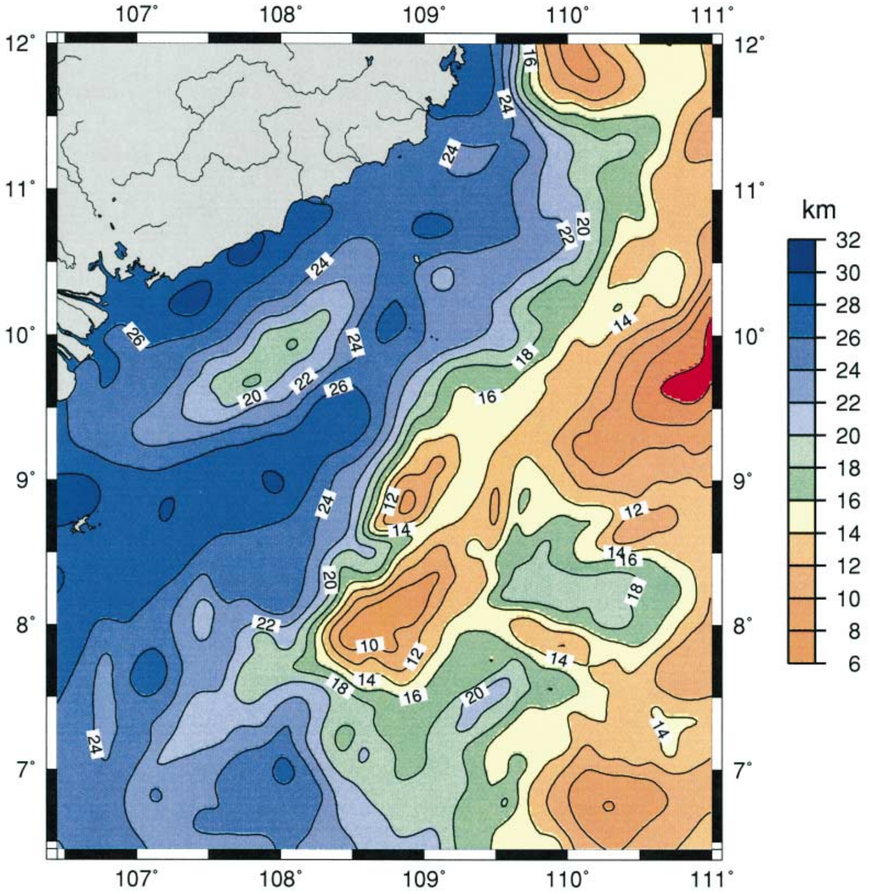

Fig. 9. Computed crustal thickness.

Chao fault. Crustal sections perpendicular to the basin axis indicate a maximum amount of stretching of 30 km (Fig. 11), in good agreement with the 20–27 km computed by (Mauri, 1993). As can also be seen from the crustal thickness map, the stretching across the Cuu Long basin is by far less than across the Nam Con Son basin. Moreover, it bears no obvious link with the early phase of opening of the South China Sea, both in terms of direction and amount of extension. Recent estimates (Hayes et al., 1995; Nissen et al., 1995a) of the extension across the Pearl River Mouth basin, along the northern margin of the South China Sea, show large values, up to 300 km, consistent with possible hundreds of kilometres of left-lateral displacement along the Red River Fault (Tapponnier et al., 1982, 1990). By contrast, the limited amount of extension across the Cuu Long basin does not favour the 140 km of displacement along the Wang Chao fault postulated by Tapponnier et al. (1986).

5. Conclusion

Our analysis suggests that a clear link exists between the formation of the Nam Con Son basin and the oceanic opening of the South China Sea between 21 and 15 Ma, the period during which the spreading centre rapidly propagated toward the south-west. However, the more rapid decrease in stretching toward the south-west, compared to the prediction of oceanic kinematics, has two important consequences: first, it explains the inversion of normal faults in the West Natuna basin, which occurred 21 Ma ago. Second, it leads us to conclude that the southern margin of the South China Sea moved by some 160 km with respect to the Indochina block, in the way suggested by Taylor and Hayes (1980) in their dextral Vietnam margin model, as opposed to the left-lateral model of Tapponnier et al. (1982).

Acknowledgements

This work was initiated in the framework of a collaborative research project between Ecole Normale Supérieure, University Paris 6 and several Vietnamese institutions, including the National University of Vietnam in Hanoi. We warmly thank Prof. Tong Dzuy Thanh and Xavier Le Pichon for leading the project. TOTAL Oil & Gas provided us with invaluable help, including logistic support and access to data. This work benefited from discussions with P. Gérard and B. Simon (TOTAL),

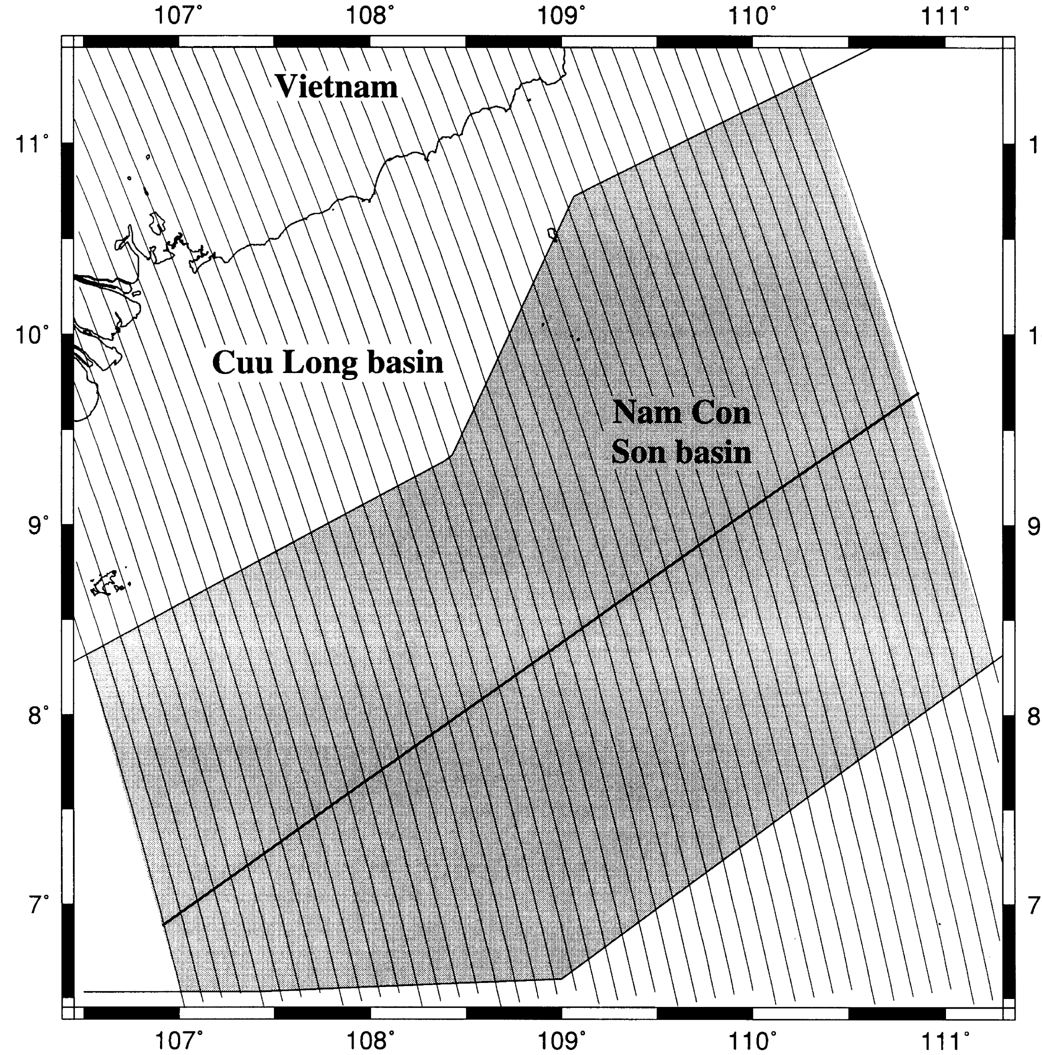

Fig. 10. Location of 'sections' (small circles about Briais et al.'s (1993) rotation pole for anomaly 6a) used for the computation of the amount of stretching in Fig. 11. The area used for the computation is shaded. Bold line: x-axis of Fig. 11.

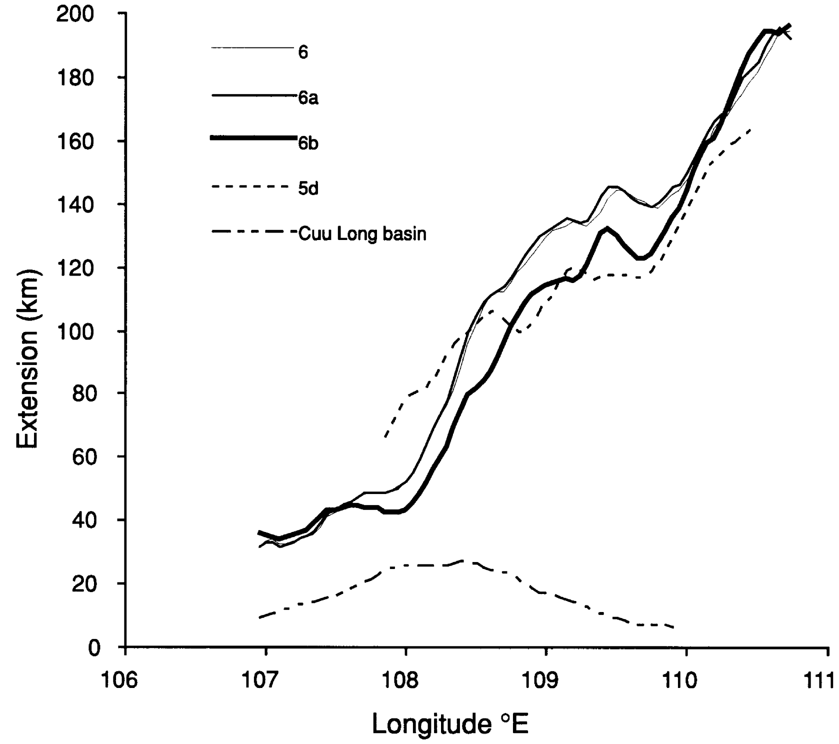

Fig. 11. Amount of stretching across the Nam Con Son basin, computed from Fig. 9 along small circles about the rotation poles of (Briais et al., 1993) corresponding to magnetic anomalies 5d, 6, 6a and 6b (see Fig. 10). The amount of stretching across the Cuu Long basin is also shown.

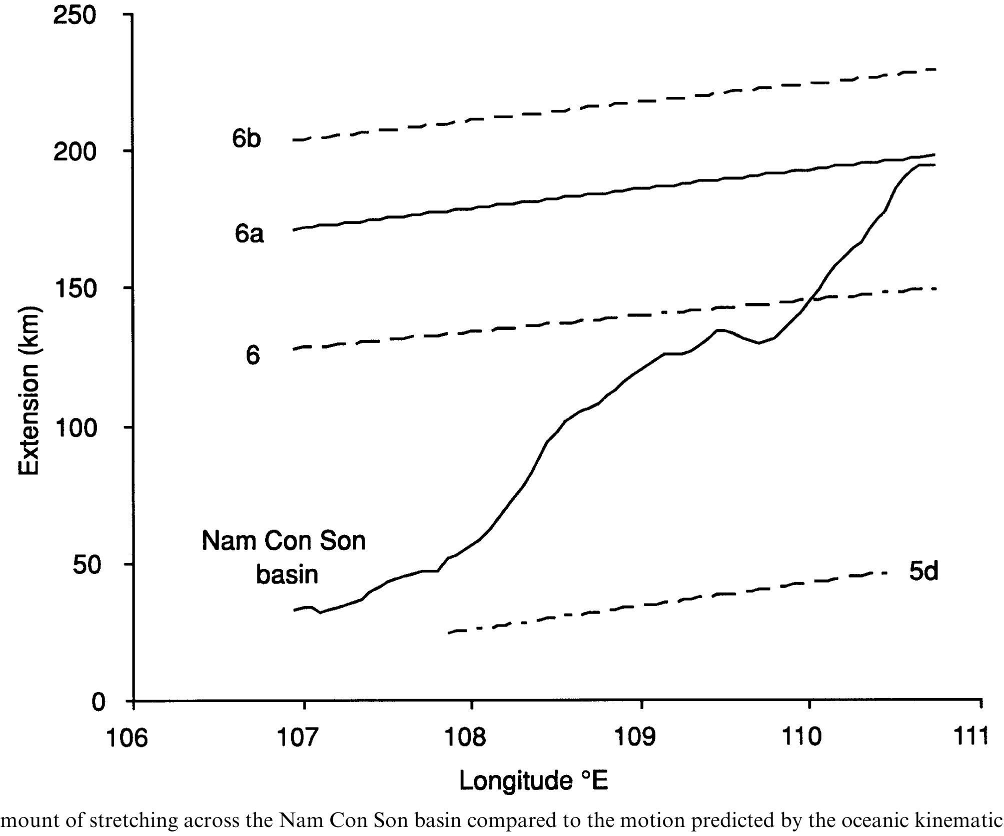

Fig. 12. Average amount of stretching across the Nam Con Son basin compared to the motion predicted by the oceanic kinematics for anomalies 5d, 6, 6a and 6b.

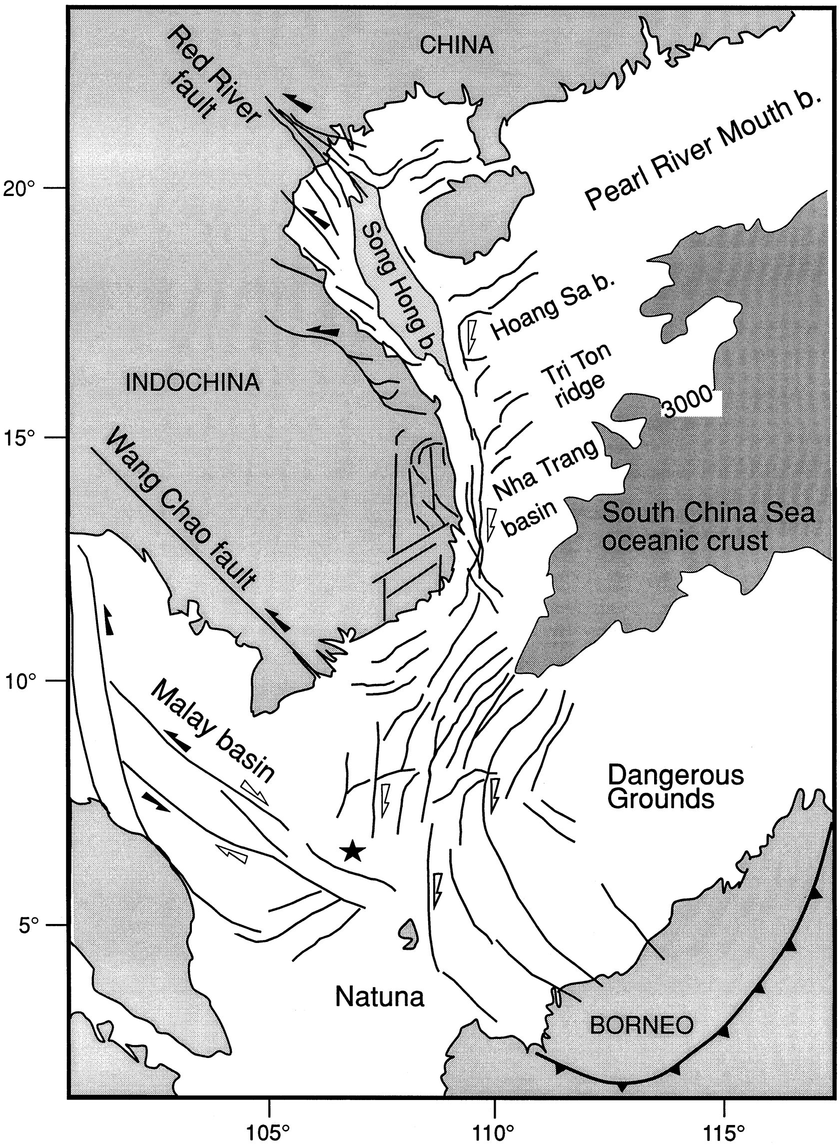

Fig. 13. Structural sketch showing the relationship between the south Vietnam basins and the South China Sea. Black arrows: Oligocene to Early Miocene strike slip motions. Open arrows: Early to Middle Miocene strike slip motions. Star: pole of opening of the South Vietnam basin.

and C. Rangin. The assistance of PetroVietnam in compiling the database is greatly acknowledged. Comments by R. Hall and an anonymous referee helped to improve the manuscript.

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