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Amount and timing of extension along the continental margin off central Vietnam

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Key words. – Continental margin, Extension, Transform fault, Extrusion, Marginal basin, Vietnam, South China Sea.

Abstract. – As part of the 1993 French-Vietnamese PONAGA cruise, profiles comprising swath bathymetric profiling, six-channel reflection seismics, gravity and magnetic data were acquired across the N-S trending margin off Central Vietnam. These data enable us to recognise structural features striking N060°E. The seismic data show progressive crustal thinning from NW to SE : large tilted blocks in shallow water (Triton ridge), smaller blocks under a thin sedimentary layer (terraces), a buried structural high, and a deep basin (Nha Trang basin) with a thick sedimentary fill, a sequence typical of a passive margin. In map view all these structures branch in horsetail fashion onto the N-S striking Vietnam scarp, suggesting that the stretching is accommodated by N-S dextral motion with respect to the Indochina peninsula. Estimated crustal thicknesses of about 19 km for the lower terrace and 11 km for the Nha Trang basin correspond to extension factors of 1.7 and 2.9, respectively, if the crust is of continental origin. The total amount of extension then must have been at least 165 km and must have ended by anomaly 6 (20.5 Ma), age of the oldest oceanic crust adjacent to the basin. Assuming steady state symmetrical rifting, it must have started near anomaly 8 (~ 28 Ma), corresponding to ~ 165 km of opening prior to anomaly 6. Alternatively, strongly asymmetrical rifting implies a slightly younger age, near anomaly 7 (~ 26 Ma), while additional stretching further north leads to an older age, possibly up to 29 Ma. This result would then imply that the opening of the South China Sea after 29 to 26 Ma occurred along the right-lateral Vietnam scarp and was not primarily controlled by the extrusion of the Indochina.

Amplitude et âge de l'extension le long de la marge continentale du Vietnam central

Mots clés. – Marge passive, Extension, Faille transformante, Extrusion, Bassin marginal, Vietnam, Mer de Chine méridionale.

Résumé. – Au cours de la campagne franco-vietnamienne PONAGA en 1993, des données de bathymétrie multifaisceaux, sismique réflexion 6 traces, gravimétrie et magnétisme ont été acquises le long de la marge N-S du Vietnam central. Ces données nous permettent d'identifier des éléments structuraux d'orientation N060°E dont la succession est typique d'une marge passive. Les données sismiques montrent un amincissement progressif du NW vers le SE, avec de grands blocs basculés sous la ride du Triton, des blocs plus petits sous une couverture sédimentaire mince (terrasses), un haut structural enfoui, et un bassin profond, le bassin de Nha Trang, avec un remplissage sédimentaire épais. Ces structures se branchent suivant une géométrie en queue de cheval sur l'escarpement N-S, ce qui suggère que l'amincissement est accommodé par un jeu dextre N-S par rapport à l'Indochine. Les épaisseurs crustales sont estimées à environ 19 km sous la terrasse inférieure et 11 km pour le bassin de Nha Trang, correspondant à des taux d'extension respectifs 1.7 et 2.9, si la croûte est bien d'origine continentale. La quantité totale d'extension doit donc être d'au moins 165 km. L'extension doit avoir cessé à l'époque de l'anomalie 6 (20.5 Ma), qui est la plus ancienne anomalie océanique adjacente au bassin. En supposant le régime tectonique permanent et symétrique pendant le rifting, il doit avoir débuté à l'époque de l'anomalie 8 (~ 28 Ma), correspondant à ~ 165 km d'ouverture avant l'anomalie 6. Un rifting fortement asymétrique impliquerait un âge plus jeune, vers l'époque de l'anomalie 7 (~ 26 Ma), tandis qu'une extension significative plus au nord ferait remonter le début de l'extension vers 29 Ma. Ce résultat implique donc que l'ouverture post 29 à 26 Ma de la mer de Chine méridionale s'est produite le long de l'escarpement dextre N-S longeant le Vietnam central, et n'est donc pas principalement liée à l'extrusion du bloc indochinois.

VERSION FRANÇAISE ABRÉGÉE

Introduction

La marge continentale du Vietnam est un élément clé pour la compréhension des relations entre l'ouverture de la mer de Chine méridionale (MCM) et la tectonique du bloc indochinois. Deux modèles principaux ont été proposés : pour Taylor et Hayes [1980, 1983], l'ouverture de la MCM est due à la traction du panneau plongeant de la proto-Mer de Chine et la marge continentale N-S du Vietnam central est une marge décrochante dextre, alors que Tapponnier *et al.* [1982] proposent que l'extrusion du bloc indochinois le long de la faille du Fleuve Rouge, à jeu décrochant senestre, soit le moteur de l'ouverture. Récemment, il a été suggéré que les deux jeux, senestre puis dextre, auraient pu se succéder lors de l'ouverture de la MCM [Huchon *et al.*, 1994; Rangin *et al.*, 1995a]. Cet article présente de nouvelles données acquises le long de la marge du Vietnam central, permettant de discuter la géométrie, l'âge et la quantité d'extension de la marge afin de les comparer à celles du bassin océanique et de mieux définir le cadre cinématique de la MCM.

I. – Les données géophysiques

Au cours de la campagne PONAGA sur le N/O L'Atalante (6-30 mai 1993) (fig. 1), nous avons acquis des données bathymétriques multifaisceaux (Simrad EM 12), ainsi que des profils de sismique réflexion verticale 6 traces, de gravimétrie, magnétisme, sondeur de sédiments 3,5 kHz et quelques dragages. Les données sismiques ont été traitées et migrées avant interprétation.

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II. – Principales structures cartographiées

Les structures cartographiées (fig. 2) sont typiques d'une marge continentale en extension. Le bassin de Hoang Sa est bordé au sud par la ride du Triton, de direction N060°E. A son sommet, de faible profondeur (350 m), nous avons dragué des calcaires semblables à ceux constituant les récifs de Macclesfield. Sur le flanc sud de la ride, on trouve deux terrasses. Sous la terrasse supérieure (profondeur 800 m), la sismique ne révèle que quelques petits blocs basculés (fig. 3), tandis que la terrasse inférieure, vers – 2 000 m, est caractérisée par des blocs basculés avec un remplissage syn-rift atteignant 700 m d'épaisseur (fig. 4). La terrasse inférieure est séparée du bassin de Nha Trang par un haut topographique partiellement enfoui, interprété comme une ride volcanique compte tenu des anomalies magnétiques atteignant 100 nT (fig. 5). Enfin, le bassin de Nha Trang est un bassin profond (2 800 m) rempli d'environ 2 000 m de sédiments (fig. 5 et 6). Ces structures de direction N060°E viennent se brancher vers l'ouest sur l'escarpement N-S [Deffontaines *et al.*, 1994] suivant une géométrie dextre [Roques *et al.*, 1997b] (fig. 2).

III. – Quantité d'extension

Dans un premier temps, nous avons restitué, après décharge isostatique des sédiments, la profondeur du socle acoustique sous les terrasses et dans le bassin de Nha Trang, déterminée sur les profils sismiques. En supposant une épaisseur de croûte continentale initiale de 30 km, la formulation de Le Pichon et Sibuet [1981] conduit à un taux d'extension de 1,7 sous la terrasse inférieure et de 2,9 dans le bassin, ce qui correspond à une épaisseur crustale de 10 km. Nous avons ensuite modélisé les profils d'anomalie gravimétrique à l'air libre, en utilisant la géométrie déduite des profils sismiques (fig. 7). Les valeurs d'épaisseur crustale obtenues sont très proches de l'estimation précédente : 19 km sous la terrasse inférieure, 11 km pour le bassin. La restoration de l'ensemble de la coupe à son épaisseur initiale de 30 km implique une extension totale horizontale de 165 km sur une direction N150°E, soit 190 km projeté sur l'escarpement N-S. Cette valeur est comparable aux estimations proposées récemment pour le bassin de la Rivière des Perles, sur la marge nord de la MCM [Hayes *et al.*, 1995].

IV. – Age de l'extension dans le bassin de Nha Trang : conséquences sur le mécanisme d'ouverture de la mer de Chine méridionale

D'après la carte des anomalies magnétiques de Briais *et al.* [1993], l'anomalie 6 (20 Ma) est située immédiatement au sud-est du bassin de Nha Trang (fig. 8). Par conséquent, l'extension a dû cesser il y a 20 Ma. Comme le pôle de rotation de l'ouverture anté 20 Ma est très éloigné, et si l'extension est symétrique, les 165 km d'extension sur la marge doivent correspondre à la même quantité d'ouverture océanique plus à l'est. La reconstruction de la figure 9 montre que le début de ces 165 km d'extension correspondent à l'anomalie 8, soit 28 Ma. Cependant, si l'extension est asymétrique, cet âge est un peu plus récent : 26 Ma si seulement 50 km d'extension ont affecté la marge sud de la MCM (Dangerous Grounds). Enfin, toute extension significative au nord de la ride du Triton impliquerait au contraire un âge sensiblement plus ancien, probablement vers 29 Ma.

Comme nous avons montré que l'extension a accommodé un jeu dextre le long de la marge N-S, la transition du jeu senestre au jeu dextre proposé par Huchon *et al.* [1994] date au minimum de 26 à 29 Ma, qui est aussi l'âge de la « break-up unconformity » au nord du bassin de Nam Hai Nam (Qiong Dong Nan) situé au nord de la ride du Triton [Ru *et al.*, 1994].

Le Pichon *et al.* [1994] ont montré qu'un changement cinématique majeur s'est produit en mer de Chine méridionale entre l'anomalie 9 (29 Ma) et l'anomalie 7 (26 Ma). Cette cinématique et la géométrie du bassin de Song Hong (Yinghehai) suggèrent un mouvement senestre post 28 Ma de 100 km au maximum le long de la faille du Fleuve Rouge, à comparer aux 450 km d'ouverture océanique plus à l'est, ce qui est incompatible avec un jeu senestre le long de l'escarpement N-S. Par ailleurs, les données radiochronologiques sur la faille du Fleuve Rouge [Shärer *et al.*, 1994] indiquent que le jeu senestre est actif jusqu'à 23 Ma. Par conséquent, le mécanisme d'extrusion et l'ouverture océanique le long du décrochement dextre longeant le Vietnam central ont pu être actifs simultanément.

V. – Conclusion

La quantité totale d'extension sur la marge du Vietnam central est d'environ 165 km. Cette extension s'est produite principalement entre 26-29 et 20 Ma, donc pendant l'ouverture océanique plus à l'est. Or les données bathymétriques ainsi que les études à terre suggèrent un jeu dextre le long de l'escarpement N-S longeant le Vietnam central. Par conséquent, mais sans exclure que l'extrusion de l'Indochine ait pu induire le rifting de la mer de Chine méridionale, son ouverture océanique post 29 à 26 Ma apparaît comme cinématiquement indépendante de l'extrusion, et probablement liée à la subduction plus au sud de la proto-mer de Chine.

INTRODUCTION

The relationship of the Cenozoic evolution of the Indochina peninsula to the formation of the South China Sea (SCS) is still debated (fig. 1). Is the extrusion of the Indochina peninsula, related to the Indian-Eurasian collision, directly responsible for both the early rifting and the later sea-floor spreading, between 32 and 16 Ma, of the South China Sea?

Although several models of opening of the South China Sea have been discussed in relation to the surrounding tectonics [Taylor and Hayes, 1980, 1983; Tapponnier *et al.*, 1982, 1986; Jolivet *et al.*, 1989; Rangin *et al.*, 1990; Huchon *et al.*, 1994], the two main end models are the following: Taylor and Hayes [1980, 1983], observing the

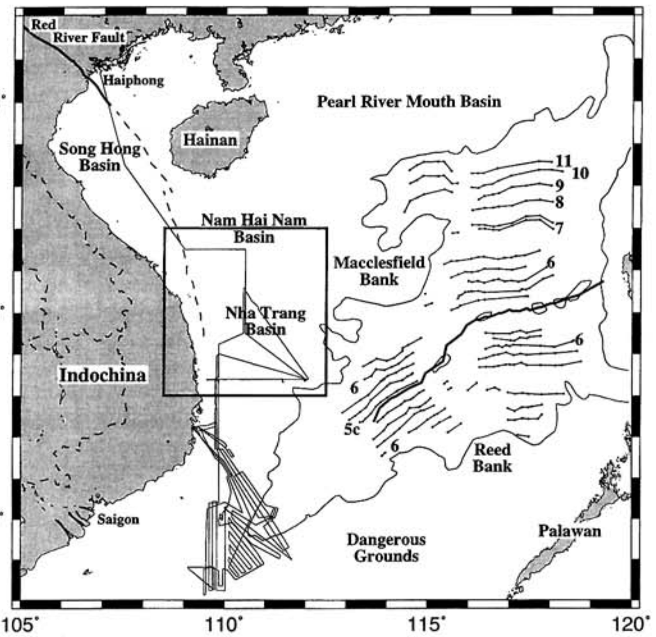

FIG. 1. – Location map of the surveyed area within the general framework of Indochina and South China Sea. The tracklines of the 1993 PONAGA cruise, as well as the oceanic magnetic anomalies [from Briais *et al.*, 1993] and the approximate continent-ocean boundary, are shown. The boxed area is shown in more detail in figure 2.

FIG. 1. – *Localisation de la zone d'étude et contexte général du bloc Indochinois et de la mer de Chine méridionale. Les routes de la campagne PONAGA 1993, ainsi que les anomalies magnétiques océaniques [d'après Briais* et al., *1993] et la limite approximative continent-océan, sont indiquées. Le rectangle indique la localisation de la figure 2.*

relative symmetry and the E-W orientation of the magnetic anomalies in the eastern part of the SCS, argued that extension was caused by slab-pull of a subducting proto-SCS located further south. Tapponnier *et al.* [1982] suggested instead that the Indochina block was extruded south-eastwards due to the India-Eurasia collision. This extrusion, which was accommodated by large sinistral motion along the Red River Fault (RRF) up to early Miocene time [Shärer *et al.*, 1990, 1994] induced the formation of a pull-apart responsible for both the early rifting and the early stage of oceanization of the South China Sea.

Recently, Huchon *et al.* [1994] argued on the basis of observations of superposed tectonic regimes in central Vietnam [Rangin *et al.*, 1995a] and of oil industry data, that both mechanisms (i.e. extrusion *and* opening along a dextral transform) could have been operating successively, or even have been partly coeval. The anomaly 6b reorientation of the oceanic accretion in the SCS from E-W to NE-SW [Pautot *et al.*, 1986; Briais *et al.*, 1993] suggests that a major kinematic reorganisation occurred near 23 Ma, which could be the change from sinistral to dextral motion along the Vietnam scarp [Rangin *et al.*, 1995a]. On land, Huchon *et al.* [1994] showed that there was a northward migration of the transition from sinistral to dextral motion from ~ 30 Ma in the south (Lat. 10°N) to ~ 5 Ma in the north (Lat. 25°N), and related this change to the decreasing influence of the extrusion as India moved north and to the relative increasing influence of the slab-pull forces along the Sunda trench. This change from sinistral to dextral motion within the SCS should have affected the tectonics of the margin itself.

While there are field studies on the Indochinese peninsula [Rangin *et al.*, 1995a; Phan *et al.*, 1994] addressing the extrusion phase, as well as marine studies of the oceanic portion of the South China Sea [e.g. Taylor and Hayes, 1980; Pautot *et al.*, 1986] documenting the spreading phase, there is little information available on the structure of the Vietnamese margin which is most likely to have recorded both phases. In this paper, we present new data on the deep basins developed along the Vietnamese margin. The data were acquired during the French-Vietnamese project PONAGA. The main objective of this paper is to provide an estimate of the amount of extension along the continental margin and to discuss its timing in relation to the opening of the South China Sea.

GEOPHYSICAL DATA ACQUISITION AND PROCESSING

The new data presented here have been acquired during the PONAGA cruise on R/V l'Atalante from May 6th to 30th 1993 (fig. 1). The main scientific objectives of the project were to study the tectonics of the Vietnamese continental margin and its relationship with the opening of the South China Sea. We focus here on the results from the northern part of the Vietnamese margin between 13° and 17°N (inset fig. 1). Results from the southern part of the survey, which covers the southwestern tip of the propagating spreading center of the SCS, will be presented in another paper.

The acquired data consist of swath bathymetry, six-channel reflection seismics, 3.5 kHz echosounding, gravity and magnetics. We also dredged rock samples at locations where basement rocks were shown to outcrop on the echo-sounder and over a few volcanic structures. The Simrad EM 12 dual echosounder enabled us to obtain data in a corridor up to 12 km wide at great water depth and hence to determine

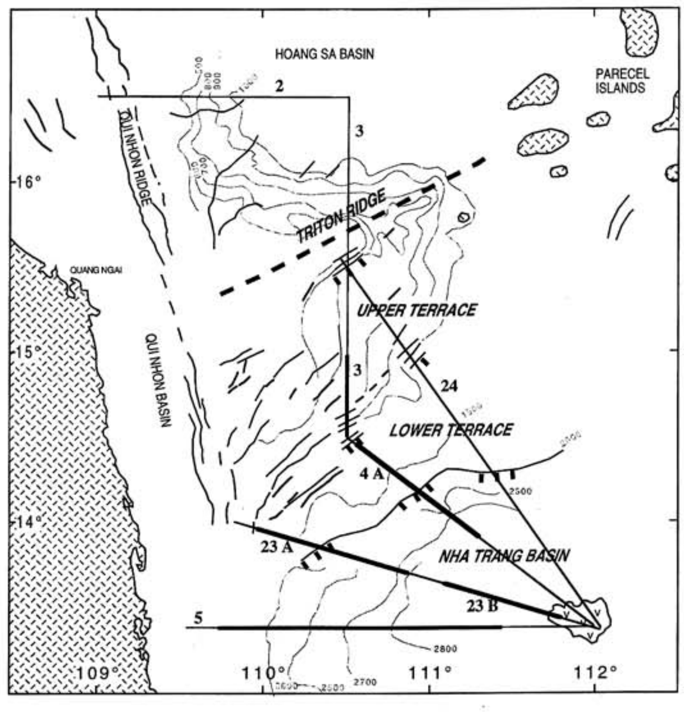

FIG. 2. – Major structural elements, simplified bathymetry and locations of identified fault segments in the studied area. The most remarkable features are the general N060°E trend of the units east of the Qui Nhon Ridge and their horsetail-like branching into it. Ship tracks of the 1993 PONAGA cruise are shown with their numbers as referred to in the text.

FIG. 2. – *Principaux éléments structuraux, bathymétrie simplifiée et localisation des segments de failles identifiées dans la zone d'étude. Les structures les plus remarquables sont la direction générale N060°E des unités structurales à l'est de la ride de Qui Nhon et leur branchement en queue de cheval sur celle-ci. Les profils de la campagne PONAGA 1993 sont indiqués avec leur numéro tel qu'appelé dans le texte.*

the orientation of structures with reasonable accuracy (fig. 2). The seismic data have been processed through a standard sequence : trace editing, CMP gathering, pulse-shaping and predictive deconvolution, band-pass filtering, stack and f-k migration. The gravity measurements have been corrected from navigational effects and converted to free-air anomalies.

OVERVIEW OF MAPPED STRUCTURES

A series of structures are recognised on all the profiles (fig. 2) and can reasonably be correlated between the profiles using both bathymetry and geophysics. In the northwest, the Hoang Sa basin is bordered to the south by the Triton ridge culminating at 350 m depth and its two southern terraces. The first terrace (upper terrace) is fairly flat and is located just SE of the ridge at a depth of about 800 m while the second one (lower terrace) has a gentle SE-trending slope, gets as deep as about 2 000 m, and is underlain by small, shallow tilted blocks. The boundary between the lower terrace and the 2 800 m-deep Nha Trang basin is systematically associated with volcanic mounts. The overall structure is typical of a passive continental margin with progressive crustal thinning from the shallow Triton ridge to the deep Nha Trang basin. The system is bounded to the west by the Vietnam scarp (VNS).

The overall NE-SW trend in the bathymetric data (fig. 2), especially where the N060°E Triton ridge and the terraces branch into the Vietnam scarp, suggests the existence of NW-SE extension. Thus, assuming that the VNS has been a transcurrent system for most of its existence, the motion along it appears to be dextral since a sinistral motion would be expected to give birth to NW-SE extensional structures. The progressive westward widening of the Triton ridge at the expense of the upper terrace, associated with horse-tail structures, also supports a contemporaneous right-lateral displacement along the Vietnamese margin. A similar pattern of N060°E normal faults branching into right-lateral transcurrent faults has been observed on land [Rangin *et al.*, 1995a; Roques *et al.*, 1997b].

The Triton ridge

The Triton ridge separates the Hoang Sa basin to the north from the Nha Trang basin to the south (fig. 2). The ridge strikes about N060°E [Trinh, 1981], branches in a horse-tail fashion into the Qui Nhon ridge and rises up to a depth of 350 m. Its width is about 25 km at the longitude of profile P3, but it widens to the west. The 3.5 kHz sounder profile shows a very strong reflection indicating a highly reflective bottom as well as a few small normal faults on the southern flank. The shallow water and the relatively poor quality of the seismic profile prevent from seeing more structural information.

A sample of blackish, clayey limestone, collected by dredging on the southern scarp between 440 and 380 metres water depth, indicates that the amount of subsidence may be quite important. Structures similar and parallel to those of the Triton ridge, with large southeast dipping normal faults, are located further north [Roques *et al.*, 1997b], evidencing that the Triton ridge is part of a series of large tilted blocks that were formed during the early extensional stage of the area, and that it was eroded before subsiding to its present depth.

The continental slope

The upper terrace (fig. 2) has undergone minor amounts of extension as shown by some normal fault blocks and half-grabens (fig. 3). The small (~ 10 mgal) short-wavelength oscillations in the free-air anomalies on profiles P3 and P24 correlate with a series of small grabens (fig. 3). The upper terrace becomes narrower and disappears westwards as a consequence of the widening of the Triton ridge as the latter branches into the Vietnam scarp.

As expected, the amount of extension is more important on the lower terrace, as normal faults bounding small blocks with syn-rift sediment thicknesses as large as 700 m are identified (fig. 4). The SE section of profiles P4 and P24 show small SE-dipping tilted blocks. Syn-rift sedimentary sequence is thicker than at the upper terrace. On the other hand, the profile P23 shows only a large block producing a half-graben filled by a much thicker (> 1 km) sedimentary sequence (fig. 5). The syn-rift sequence is sealed by a low-frequency horizon that has been recognised on oil industry data, north of the Triton ridge and dated at approximately 21 Ma [Roques *et al.*, 1997a].

The lower terrace is separated from the Nha Trang basin by a small topographic high with peak-to-peak 100 nT magnetic anomalies which is interpreted as a series of small volcanic edifices. The magnetic anomalies can be seen on all profiles where the assumed volcanic rocks presumably have intruded preexisting extensional structures (figure 4 between CDP 2400 and 2600 and figure 5 near CDP 1400).

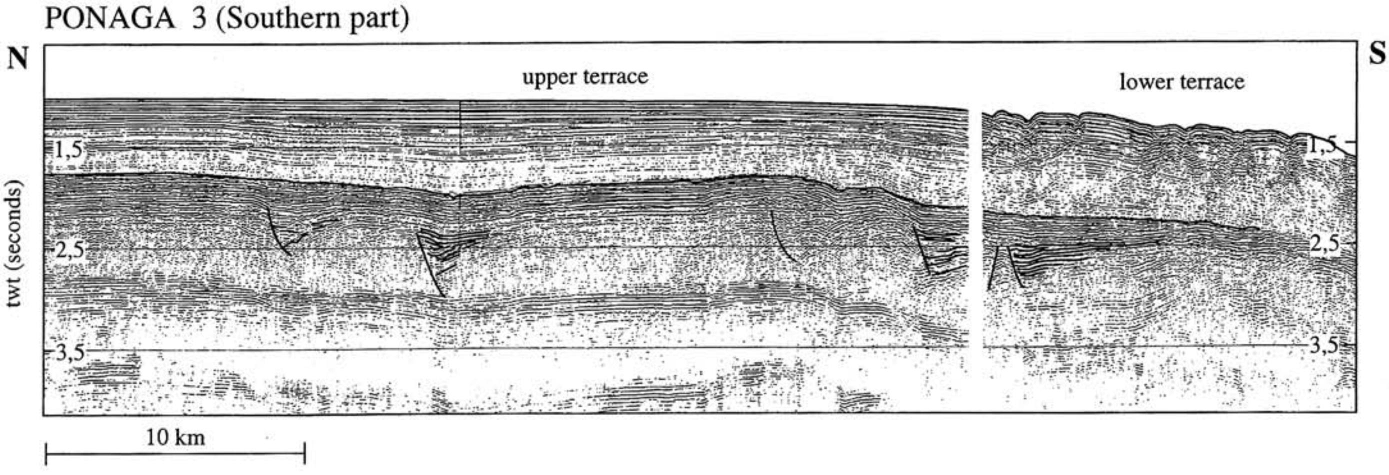

FIG. 3. – Southern part of seismic profile P3 showing the shallow-dipping upper terrace.

FIG. 3. – *Partie sud du profil sismique P3 montrant la terrasse supérieure.*

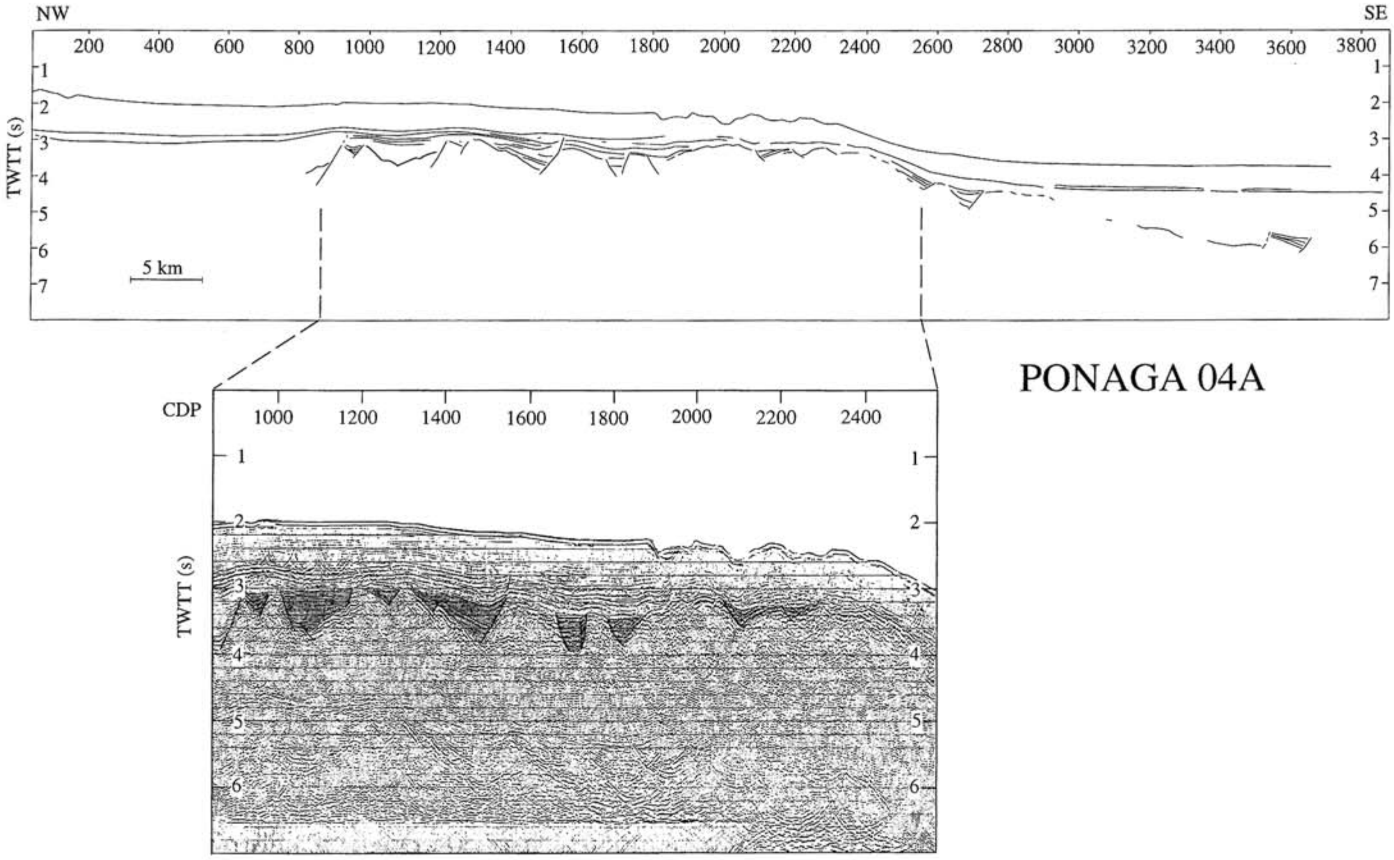

FIG. 4. – Top : line drawing of seismic profile P4 showing the transition from the lower terrace to the Nha Trang basin. A series of grabens and half grabens underlain the lower terrace. At the transition they are uplifted by recent volcanism. Syn-rift sedimentation is present under the basin indicating its continental nature. Bottom : detail of profile P4 showing the geometry of the tilted blocks and the sedimentation pattern within the half-grabens under the lower terrace.

FIG. 4. – Haut : interprétation du profil sismique P4 montrant la transition de la terrasse inférieure au bassin de Nha Trang. Une série de grabens et de demi-grabens caractérisent la terrasse inférieure. La zone de transition apparaît soulevée par du volcanisme récent. La sédimentation syn-rift est présente sous le bassin indiquant sa nature continentale. Bas : détail du profil P4 montrant la géométrie des blocs basculés et le mode de sédimentation dans les demi-grabens sous la terrasse inférieure.

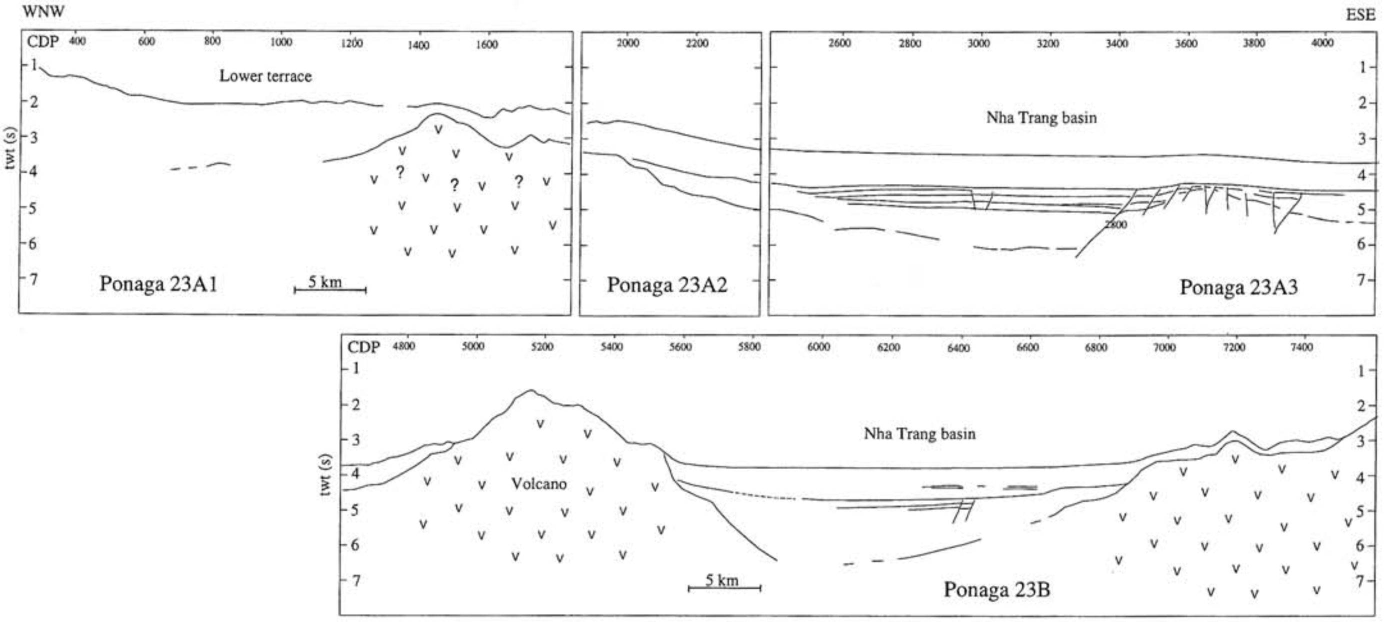

FIG. 5. – Line drawing of seismic profile P23 showing the volcanic nature of the transition between the lower terrace and the Nha Trang basin. Another volcanic feature outcrops in the centre of the basin, probably alkalic material that migrated upwards through reactivated normal faults.

FIG. 5. – Interprétation du profil sismique P23 montrant la nature volcanique de la transition entre la terrasse inférieure et le bassin de Nha Trang. Une autre structure volcanique apparaît au milieu du bassin, correspondant probablement à du matériel alcalin mis en place le long de failles normales réactivées.

The Nha Trang basin

The deep Nha Trang basin is a large extensional basin bounded to the north by the lower terrace and to the west by the Vietnam scarp. The scarp is separated from the basin by a fault (fig. 6) since the slope between the two structures is very steep, suggesting that the Vietnamese margin is transcurrent in this area [Deffontaines *et al.*, 1994]. There is however no convincing evidence anywhere of the presence of a fault between the lower terrace and the basin. Profiles P4, P23, and P24 show a smooth transition from the terraces to the basin and syn-rift sediments are recognized under the NW edge of the basin on profile P4 (fig. 4), suggesting that continental crust underlies the Nha Trang basin.

Volcanic seamounts were recognized under the Nha Trang basin on the seismic profiles. They coincide with short-wavelength gravity and magnetic anomalies. One of these volcanoes may be seen on profile P23, in the centre of the basin (fig. 2 and 5), as well as at the extremity of profiles P4, P5, P23 and P24. Alkalic volcanic material dredged at that locality has been dated at 170 ka by the K/Ar method [Bellon *et al.*, 1994]. It is thus unrelated to the oceanic spreading in the South China Sea, but the intrusion may have risen through older faults re-activated under NE-SW compression, as shown, for instance, by the October 7, 1965 earthquake located 200 km further to the ESE.

AMOUNT OF EXTENSION

The average free-air anomaly under the terraces and the Nha Trang basin is small, favouring isostatic equilibrium. We have therefore used local isostasy to constrain the amount of crustal thinning under the terraces and the basin, and hence determine whether the thickness is closer to oceanic or continental ones. We picked the acoustic basement two-way travel time under flat portions of both water-bottom and basement and converted it to depth using standard velocities. Knowing the water depth and the sediment thickness we removed the effect of the post-rift sedimentary load and obtained the true subsidence. Then, we calculated the extension factor β following the formulation of Le Pichon et Sibuet [1981]. We used the constants adopted by these authors and assumed an original crustal thickness of 30 km. The thermal cooling following the instantaneous stretching was considered to last for 30 Ma. Applying this method to profile P4 yields extension rates of 1.7 for the lower terrace and of 3 for the Nha Trang basin. Similar values are obtained for profiles P23 (1.7, 2.9) and P24 (1.8, 2.9). A larger original crustal thickness would decrease the estimated β value. A 10 % uncertainty on thickness results in a 10 % uncertainty on β, thus about +/– 0.2. The corresponding crustal thickness is about 10 km under the Nha Trang basin, which seems too thick for an oceanic crust. We thus suggest that the crust is a highly thinned continental one, intruded by recent volcanism as can be observed on profiles P4 and P24.

The crustal thicknesses and extension factors estimated above were based on simple 1-D isostatic equilibrium calculations. To check these estimates, we made simple 2-D models of the free-air gravity data for profiles P4 and P23 (fig. 7). The data require a substantial amount of crustal thinning (~ 5 km) at the boundary between the lower terrace and the Nha Trang basin. The crustal thickness is about 20 km under the lower terrace and 13 km under the basin.

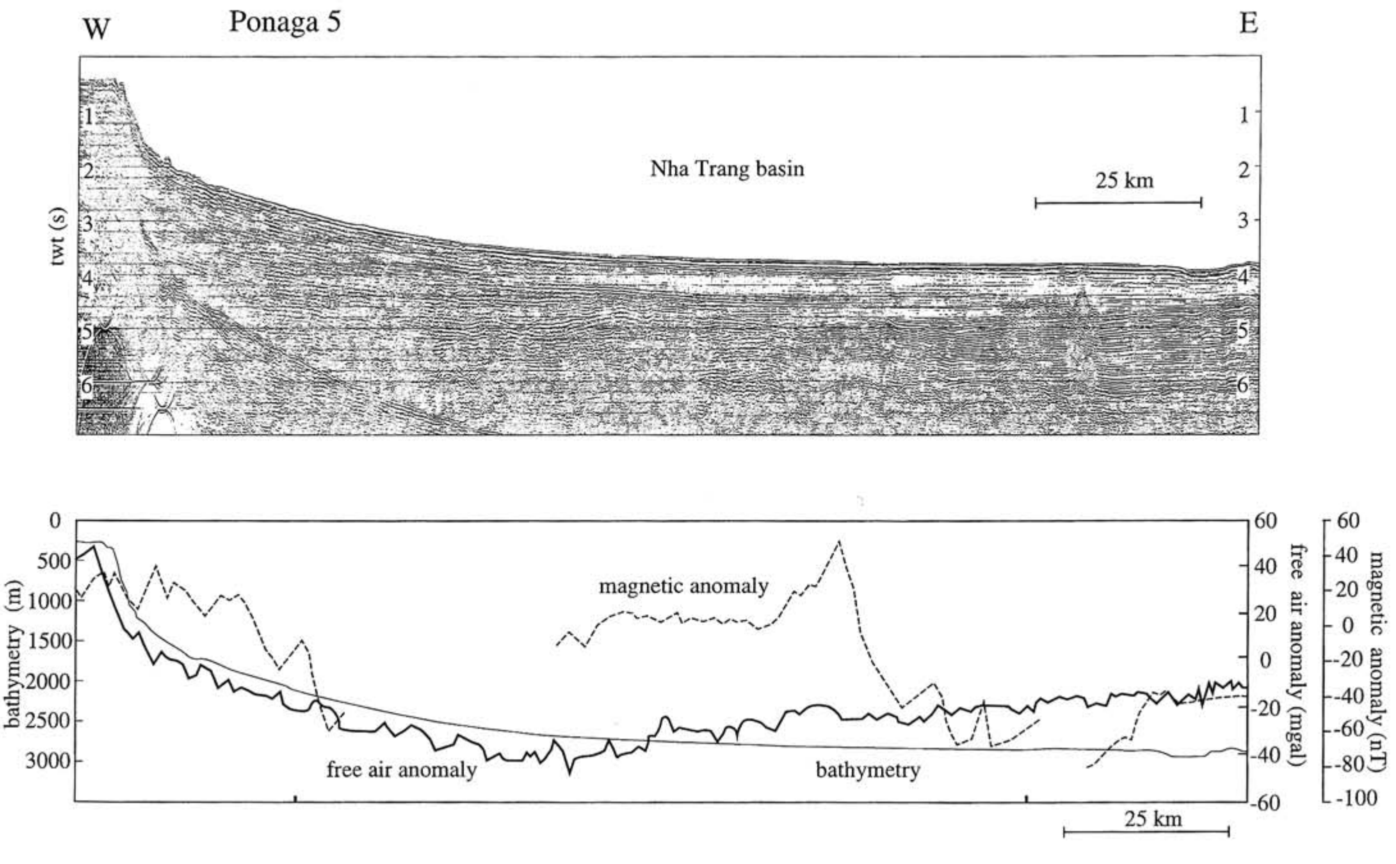

FIG. 6. – Seismic profile (P5) across the NS-striking Vietnam scarp and the Nha Trang basin.
FIG. 6. – *Profil sismique (P5) montrant l'escarpement N-S du Vietnam et le bassin de Nha Trang.*

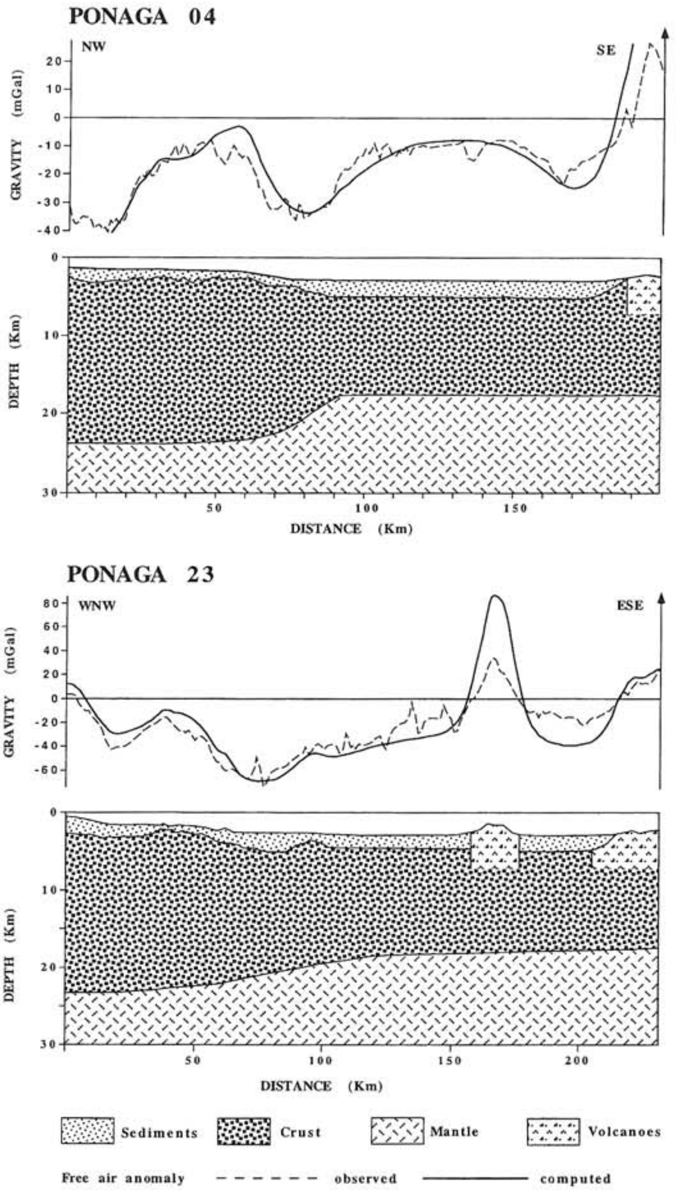

FIG. 7. – 2.5-D gravity models of profiles P4 (top) and P23 (bottom). The crust is ~ 20 km thick under the lower terrace and ~ 13 km thick under the Nha Trang basin. The small misfit between the model (solid line) and the data (dashed line) is caused by the presence of volcanic structures.

FIG. 7. – *Modèles gravimétriques 2.5-D pour les profils P4 (en haut) et P23 (en bas). La croûte est épaisse de ~ 20 km sous la terrasse inférieure et ~ 13 km sous le bassin de Nha Trang. Les petits écarts entre le modèle (ligne continue) et les données (ligne tiretée) sont dus à la présence de structures volcaniques.*

The model shows a good fit to the long-wavelength anomalies, the main cause of misfit being the volcanoes, the effects of which cannot be properly modelled by the 2-D scheme used here. Note that we did not take into account the thermal effect during rifting since we considered a constant density for the lithospheric mantle. Applying this correction properly would need to know the distribution as well as the duration and age of extension [Alvarez *et al.*, 1984]. Instead, we made a simple correction by computing the approximate mantle density after instantaneous stretching followed by 30 Ma of thermal cooling. It results in corrected crustal thicknesses of 19 and 11 km beneath the lower terrace and the Nha Trang basin, respectively, corresponding to stretching factors of 1.6 and 2.7.

The thinning factors obtained can be used to roughly estimate the amount of extension that has to be accommodated by strike-slip motion along the Vietnamese margin, since the Nha Trang basin is bounded to the west by the transcurrent Vietnam scarp. We can obtain the original length along the N150°E direction perpendicular to the late spreading stage of the SCS by dividing the present-day length of the lower terrace and of the Nha Trang basin (80 and 200 km, respectively, see figure 8 for the geometry used in our calculations) by their respective extension factors, chosen here as 1.7 and 2.9, average values for the profiles studied. The initial length was then 116 km, leading to 164 km of stretching along the N150°E direction, and 189 km once projected along the N-S Vietnam scarp. This is a minimum estimate of the total motion since even more extension has probably happened within the Upper terrace and north of the Triton ridge, although the corresponding amount is probably small compared to the extension to the south.

Using deep seismic soundings and gravity modelling, Hayes *et al.* [1995] obtained estimates of the horizontal extension accomodated by crustal thinning in the Pearl River Mouth basin, along the northern margin of the South China Sea. These ranges from 175 km for the eastern transect (along long. 118°E) to 325 km for the western transect (along long. 113°E). The former transect reaches the oceanic crust were anomaly 11 (32 Ma) has been identified, while the later cuts accross the Macclesfield bank and reaches the continent-ocean boundary in the younger part of the basin, close to anomaly 6a (22 Ma). These data show that the amount of extension is much larger to the west, and that a significant amount of oceanic opening to the east, after 32 Ma, was coeval with continental extension to the west. We shall come back to this point when discussing the timing of extension.

We now attempt to relate the extension in the Nha Trang basin to the opening of the SCS, since both processes must have been contemporaneous for at least part of their respective durations.

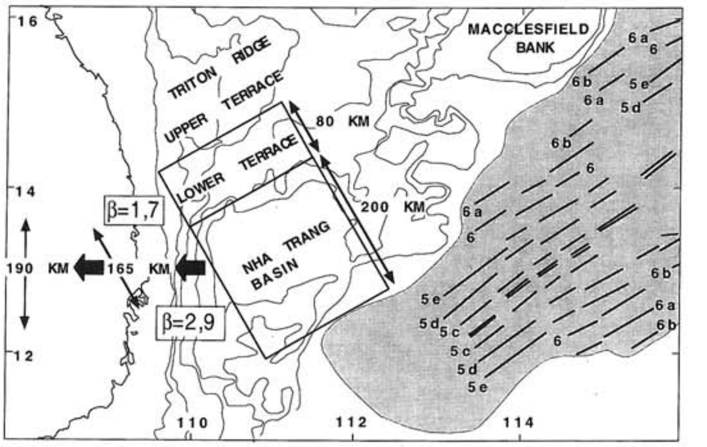

FIG. 8. – Geometry used for the calculation of the amount of crustal extension. The present-day lengths of the Lower terrace and the Nha Trang basin are divided by their respective extension factors β to recover their original lengths. The overall extension will be slightly underestimated because we do not take into account the extension in the upper terrace.

FIG. 8. – *Géométrie utilisée pour le calcul de la quantité d'extension crustale. Les longueurs actuelles de la terrasse inférieure et du bassin de Nha Trang sont divisées par leurs taux d'extension respectifs β pour obtenir les longueurs initiales. L'extension totale est sans doute légèrement sous-estimée car l'extension de la terrasse supérieure n'est pas prise en compte.*

AGE OF EXTENSION IN THE NHA TRANG BASIN : CONSEQUENCES FOR THE MECHANISM OF OPENING OF THE SOUTH CHINA SEA

The amount and timing of the extension must be discussed within the general tectonic framework of the area. According to Briais *et al.*'s [1993] magnetic anomaly map (fig. 8), the Nha Trang basin is limited to the south by magnetic anomaly 6. If we assume that stretching ceases as spreading begins, then extension has to have ended at about 20 Ma. If we assume steady-state symmetric distension, the ~ 165 km of extension obtained here for the terraces-basin system has to be accommodated by nearly the same amount of opening to the east, since the finite pole of rotation at this time is located far away from the area [Briais *et al.*, 1993]. This implies that we can recover the original pre-rifting configuration by closing all anomalies prior to 6 until 165 km have been removed. The corresponding reconstructions are shown in figure 9. They show that the extension must have begun near anomaly 8 (27.7 Ma) to obtain the same increase in length everywhere. Note that we took into account the ridge jump at anomaly 7 by using the average value between the age obtained for the northern and southern part of the South China Sea. Although we could not determine from our data the amount of extension north of the Triton ridge, any significant stretching there would imply an older age for the onset of extension : for example, 50 km would make it older by 1.5 Ma (again, based on the oceanic kinematics).

However, the bathymetric and crustal thickness maps [Chen and Lei, 1987] suggest that stretching has been larger offshore Vietnam than on the southern conjugate margin (Dangerous Grounds). The asymmetry in thickness of both margins could be due to a simple shear mechanism for crustal extension as suggested by Hayes *et al.* [1995] on the basis of deep seismic soundings and gravity modelling [Nissen *et al.*, 1995a, 1995b]. The smaller amount of total extension would imply a younger age for the beginning of rifting. For instance, assuming that stretching was only 50 km to the south (compared to 165 km in the Nha Trang basin) would result in an age of about 26 Ma (anomaly 7) for the beginning of rifting in the Nha Trang basin. Note that 26 Ma is also the age of the ridge jump [Taylor and Hayes, 1983; Briais *et al.*, 1993], as well as that of the reorientation of spreading and of the rapid propagation of the ridge toward the southwest. Finally, it appears that 26 Ma is the minimum age for the onset of extension, while 29 to 30 Ma remains plausible.

Our estimate of crustal extension in the Nha Trang basin (165 km) is much less than that of Hayes *et al.* [1995] across the western Pearl River Mouth basin and Macclesfield bank (325 km). This is because, as noted earlier, extension also occurred north of the Triton ridge, especially in the Nam Hai Nam basin, south of Hainan island. Here the free air gravity anomaly is very low (– 40 mgal) and reflects the large amount of thinning of the crust, creating a depression filled with several kilometres of sediments. No direct estimate of horizontal extension has been made across the Nam Hai Nam basin, but we can compare our estimated 165 km of horizontal extension between 26-29 Ma and 20 Ma to the values determined by Hayes *et al.* [1995]. Using the same rotation pole for the rifting as that of the oldest magnetic anomalies, the 175 km of pre-32 Ma extension along the eastern transect correspond to a rotation angle of 4.5°. The theoretical extension along the western transect for the same period is then about 135 km. The difference of 190 km between the measured extension (325 km) and the predicted 135 km of pre-32 Ma extension thus corresponds to the period from 32 to 23 Ma, the age

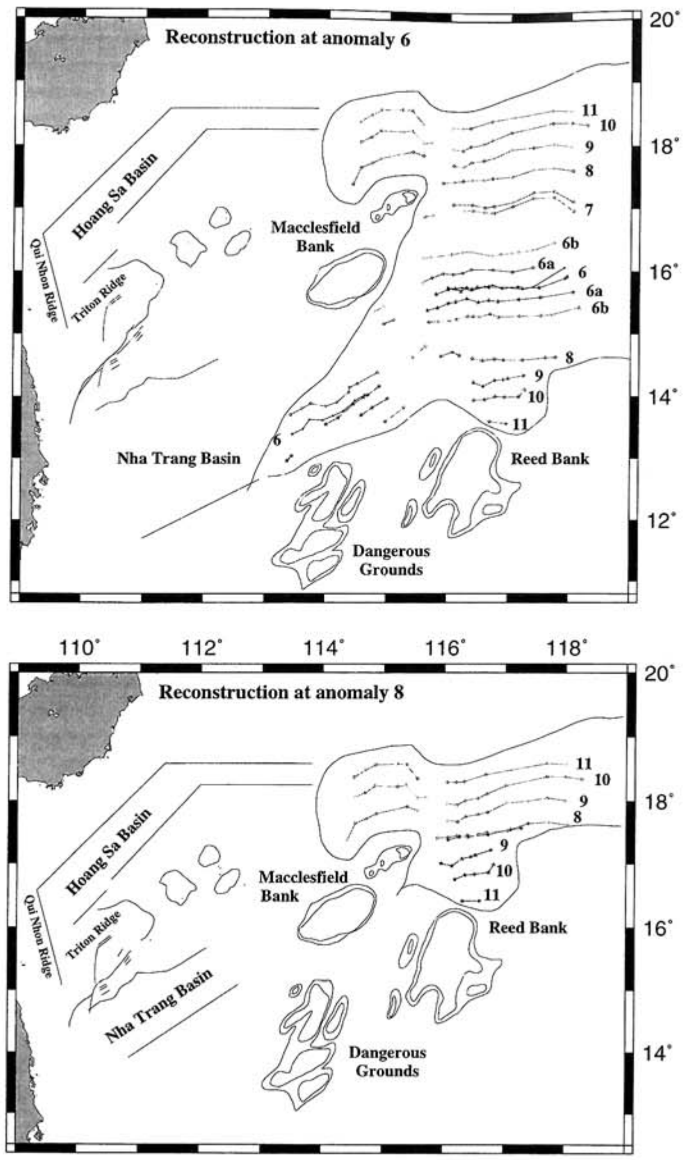

FIG. 9. – Top : reconstruction of the Triton Ridge-Nha Trang Basin system and South China Sea at anomaly 6 (20.45 Ma). Pole and angle of rotation : 0.1°N, 83.3°E, 2.8°. The age of the end of extension corresponds to the oldest oceanic crust adjacent to the Nha Trang basin. Bottom : reconstruction at the time of anomaly 8 (27.7 Ma). Pole and angle of rotation : 12.7°N, 98.4°E, 2.4°. Bringing back the extensional system to its original configuration results in closing the equivalent amount (165 km) of the eastern part of the SCS from at least anomaly 8 to anomaly 6. Magnetic anomalies from Briais *et al.* [1993]. Discussion : see text.

FIG. 9. – *En haut : reconstruction du système ride du Triton-bassin de Nha Trang et de la mer de Chine méridionale à l'anomalie 6 (20,45 Ma). Pôle et angle de rotation : 0,1°N, 83,3°E, 2,8°. L'âge de la fin de l'extension correspond à celle de la croûte océanique la plus ancienne adjacente à la marge. En bas : reconstruction à l'anomalie 8 (27,7 Ma). Pôle et angle de rotation : 12,7°N, 98,4°E, 2,4°. La restauration de la marge en extension à sa longueur initiale correspond à une extension de 165 km équivalente à l'ouverture du bassin océanique entre les anomalies 8 et 6. Anomalies magnétiques d'après Briais* et al. *[1993]. Discussion : voir texte.*

of magnetic anomaly 6b located in front of the western transect. This value well agree with our estimated value of 165 km for the Nha Trang basin during the period 20 to 26-29 Ma (21 km/Ma along the western transect, 18 to 27 km/Ma along the Nha Trang basin profil). Thus, the whole continental crust south of Hainan island appears to have been stretched in such a way as to correspond to the oceanic spreading further east.

Consequently, the central Vietnam margin must has been affected by right-lateral motion after 26-29 Ma and the transition from left- to right-lateral motion along the margin proposed by Huchon *et al.* [1994] had already happened at these latitudes by the time the rifting begins in the Triton ridge-Nha Trang basin system, i.e. by 26 to 29 Ma. This age agrees with the age of the break-up unconformity in the western Pearl River mouth and Nam Hai Nam (Qiong Dong Nan) basins [Ru *et al.*, 1994].

We now discuss the consequences for the mechanism of opening of the South China Sea with respect to the extrusion of the Indochina block. Le Pichon *et al.* [1994] pointed out a major kinematic change between anomaly 9 (29.3 Ma) and 7 (26 Ma). Before that time, the Red River Fault system followed a small circle about the average pole describing the pre-28 Ma rotation derived from magnetic anomalies [Briais *et al.*, 1993], whereas it departs significantly from that small circle afterwards. Based on the geometry of the Song Hong (Yingghehai) basin (fig. 1), Le Pichon *et al.* [1994] estimated a maximum of 100 km of post-28 Ma sinistral motion, compared to about 450 km of oceanic opening farther east. This difference can be explained only if we consider a right-lateral sense of motion along the Vietnam scarp. Therefore, this dextral motion is partly coeval with the sinistral motion along the Red River Fault, which was active up to ~ 23 Ma [Shärer *et al.*, 1994]. Our age estimate of 26-29 Ma for the beginning of extension in the Triton ridge – Nha Trang basin system coincides with the kinematic change, and is another line of evidence for the existence of dextral motion along the Vietnam scarp between 26-29 and 20 Ma.

Since the data in the southern Vietnam offshore also provide evidences for right-lateral motion up to 15 Ma ago [Coulon *et al.*, 1994; Nguyen Thi Ngoc Hai *et al.*, 1994], it then appears that most (from 26-29 to 15 Ma) of the opening of the South China Sea occurred along a dextral margin. Only the rifting stage and possibly the very first stage of opening (32 to 26-29 Ma) could have been induced by the left-lateral motion along the Red River Fault, as proposed by Tapponnier *et al.* [1982].

SUMMARY AND CONCLUSION

New geophysical and bathymetric data from the eastern Vietnamese margin show that the Triton ridge and Nha Trang basin are part of a N060°E-striking extensional system bounded the west by the N-S Vietnam scarp. The total amount of extension is of the order of 165 km and may have occurred between 26-29 and 20 Ma. This interval corresponds to most of the initial opening stage of the South China Sea. In addition, structural trends in the bathymetric data as well as geological field studies and regional syntheses support the inference of a dextral motion along the N-S Vietnam scarp. Hence we propose that the extrusion of the Indochinese block along the sinistral Red River Fault – whilst it might have been a factor in triggering the extension east of Indochina – is not controlling the main part of the opening of the SCS, i.e. both are independent, uncoupled processes as proposed earlier by Huchon *et al.* [1994].

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