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From partial to full strain partitioning along the Indo-Burmese hyper-oblique subduction

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Abstract

The Andaman–Nicobar Trench and its onshore prolongation—the Indo-Burmese wedge—is the least studied segment of the India–Australia subduction. New offshore geological and geophysical data have recently been collected along the Burma scarp during a marine survey conducted with the R/V *Marion Dufresne* (Andaman Cruise). Swath bathymetric mapping combined with shallow and deep seismic show that the dominant active tectonics is dextral strike-slip faulting accompanied by various amounts of shortening. The southern portion of the Burma scarp is transpressive (north Andaman Islands), the central portion is pure strike-slip on NNE-oriented segments (southern Myanmar), the northern portion shows sedimentary wedge growth along NW segments, both onshore and offshore (Arakan Yoma prism). Further north, the wedge bends to the west, while dextral shear faults more or less parallel to the Sagaing Fault develop within the internal part of the wedge and elongated NS folds form in its external part, abutting onto the Shillong Plateau. We propose a simple kinematic model involving evolution from partial to full partitioning from south to north along the West Burma Scarp (WBS), and we test it quantitatively using the most recent geodetic results. In the south, half of the 3.5 cm/year of India motion is taken at the trench itself, the other half being accommodated onto a single shear fault, the Sagaing Fault in Myanmar. In the north, where the Bangladesh fold system developed, dextral strike-slip faults are activated within the Arakan Yoma belt and at the accretionary prism–backstop contact, resulting in full partitioning there. Faults accommodating the oblique component of motion of India are progressively migrating in space from far field faults (Andaman–Sagaing) to near trench faults (Arakan Yoma belt and trench itself), the Burma sliver being "buttressed" by the Eastern Himalayas. This kinematic extends back to 4 Ma, which is the time of initiation of the last pulse of oceanic accretion in the Andaman Basin.

Keywords: Myanmar geology; Arakan Yoma belt; West Burma Scarp; accretionary wedge; oblique subduction; plate kinematics

1. Introduction

Northward motion of India with respect to SE Asia is accommodated along three main trenches: Java, Sumatra and Andaman–Nicobar. The curvature of these trenches implies a progressive increase of the

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obliquity of convergence, ranging from pure normal subduction at Java to oblique subduction at Sumatra and highly oblique motion towards the Andaman Islands and Myanmar (Fig. 1). The upper plate itself is shaped by this variation of obliquity. Off Sumatra, a large piece of crustal sliver is detached from the Sunda margin along the Great Sumatran, or Semangko, Fault. Northward, where obliquity becomes high, the Andaman Basin opened behind the Andaman–Nicobar Trench in a pull-apart setting between the northern tip of the Semangko Fault and the Sagaing Fault in Myanmar. The Andaman–Nicobar Trench is the least studied segment of the India–Australia subduction. The trench appears as a continuous trough from the northern tip of Sumatra to the southern extension of the Arakan Yoma accretionary prism, off Myanmar. It then vanishes towards the Bangladesh fold system.

Based on early versions of global plate kinematic models, Curray proposed the existence of an independent Burmese platelet absorbing the oblique motion of India with respect to SE Asia (Curray et al., 1979). The supposedly large NE motion of India (10 cm/year) was resolved, or partitioned (Fitch, 1972), into two large components: dextral strike-slip on the Sagaing Fault (>5 cm/year) and high rate normal subduction along the Indo-Burmese trench (>4 cm/year). Since these pioneering works, new constraints have been obtained from seismology, mantle tomography and GPS measurements. Seismicity and tomography delineate an eastward dipping Indian slab down to at least 250 km below the Andaman–Nicobar–Myanmar system (Verma et al., 1976a,b; Guzmàn-Speziale et al., 1987; Mukhopadhyay and Das Gupta, 1988; Guzmàn-Speziale and Ni, 1996). Seismicity distribution over the Burmese platelet and within the slab below indicate a more or less N–S trending P axis, suggesting that the entire area is subjected to north–south compression in relation to the nearby Himalayan Syntaxis (Le Dain et al., 1984; Guzmàn-Speziale and Ni, 1996). Virtually none of these studied focal mechanisms seemed to relate to the E–W subduction inferred by Curray. This absence of subduction earthquakes led Rao and Kumar (Rao and Kumar, 1999) to propose that although a deep lithospheric slab is indeed present at depth, subduction is now inactive. However, a recent re-examination of the seismicity suggests a still active oblique subduction (Satyabala, 2003). Satyabala further shows that the variation of slip vectors azimuths is compatible with a slip partitioning process similar to other oblique subductions, a conclusion that we share as will be shown later in this paper.

New kinematics constraints have recently been obtained through Global Positioning System (GPS) measurements. A major output of the GEODYSSEA Program was the discovery of a significant motion of a large Sundaland Block (Sumatra, Java, Vietnam, SE China, Borneo) with respect to Eurasia (Chamot-Rooke and Le Pichon, 1999; Simons et al., 1999; Michel et al., 2001). Global kinematics obtained by GPS (Holt et al., 2000; Kreemer et al., 2000a; Paul et al., 2001; Kreemer et al., 2003) as well as recent revision of India kinematics for the last 3 Myears (Gordon et al., 1999) also point to a slower than predicted motion of India. Finally, a local GPS network in Myanmar tied to other stations in SE Asia established a velocity of about 20 mm/year across the Sagaing Fault (Vigny et al., 2003), thus suggesting that only part of the motion of India is accommodated along the fault. A similar geological estimate was reached using the offset of a Quaternary volcano built on the fault (Bertrand et al., 1998; Bertrand, 1999).

Eastward motion of Sundaland, the new kinematics for India and slow shear on the Sagaing Fault put new kinematics constraints on the recent geodynamics of the Indo-Burma Trench. We report in this paper additional constraints based on a marine survey conducted along the Burma front (Andaman Cruise). The Burma scarp was surveyed in great detail between 14°N and 20°N, using swath mapping, shallow seismic and measurements of the gravity and magnetic fields. This new data set was combined with existing multichannel industrial lines from Compagnie Générale de Géophysique (CGG). We first describe the morphology of the Burma scarp and show that at present, the scarp is a major dextral strike-slip fault zone. Based on the pattern of active faults mapped both offshore and onshore (Myanmar), we further suggest that the degree of strain partitioning gradually increases from south Myanmar to north Myanmar, shearing being accommodated not only on the Sagaing Fault but also on additional strike-slip faults within the Arakan Yoma belt. We finally reconsider the general kinematic framework based

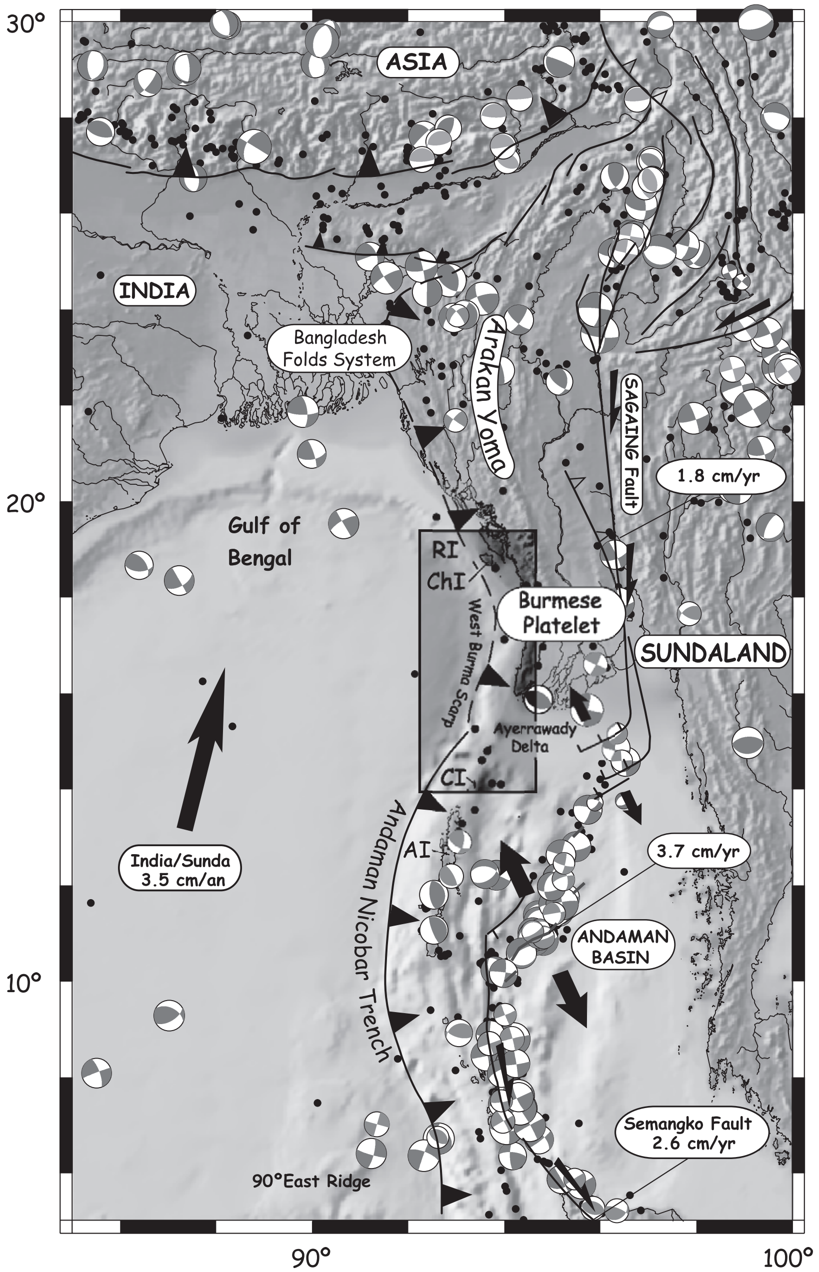
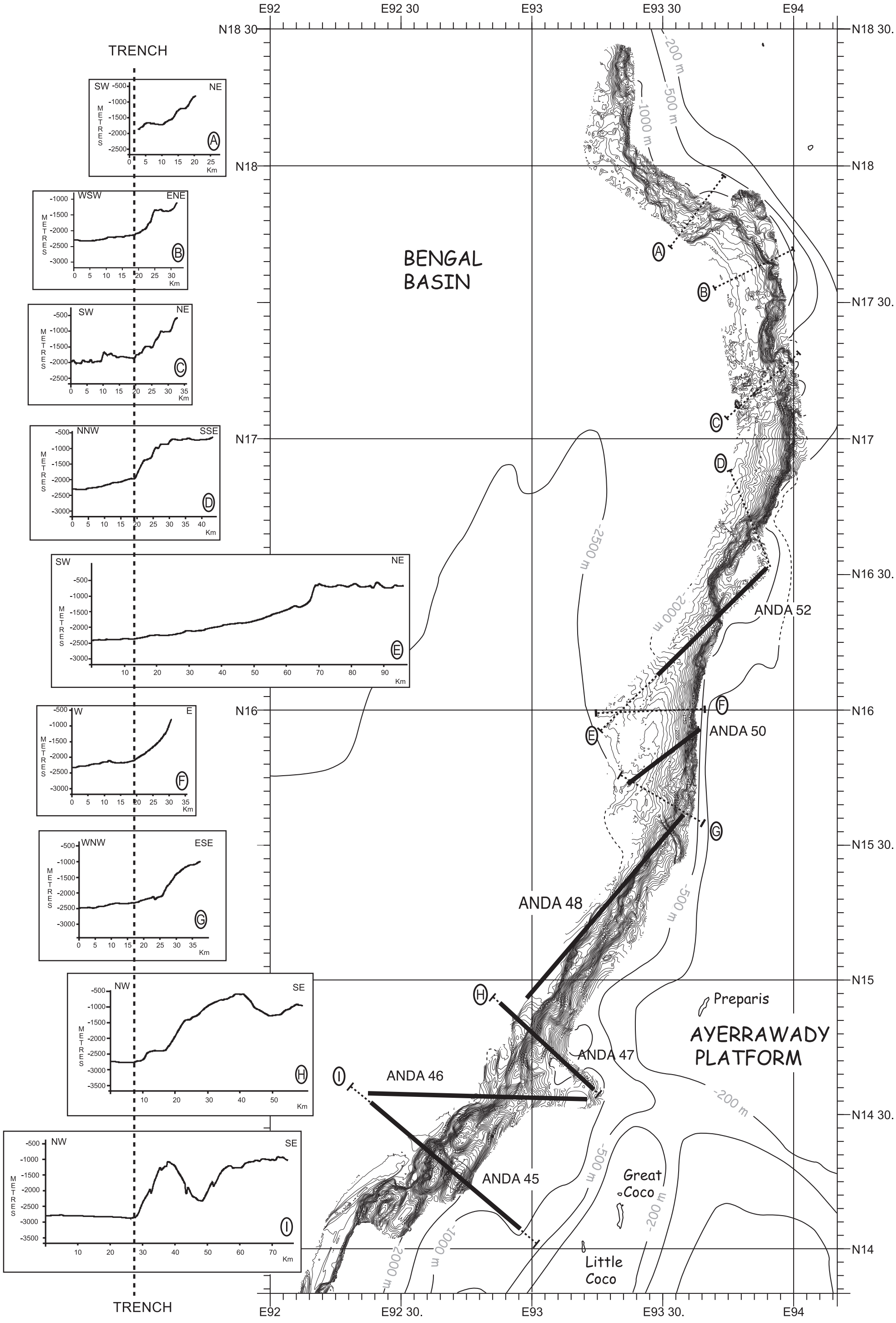


Fig. 1. Myanmar geodynamic setting. India–Sundaland convergence and shear motion on the Sagaing Fault are taken from the latest geodetic measurements (Vigny et al., 2003). The rectangle locates the Andaman Cruise survey along the Indo-Burma Margin. Focal mechanisms are from the HARVARD Catalogue and bibliographic references (Le Dain et al., 1984; Guzmàn-Speziale and Ni, 1996; Holt et al., 2000). AI: Andaman Islands. CI: Coco Islands. ChI: Cheduba Island. RI: Ramree Island.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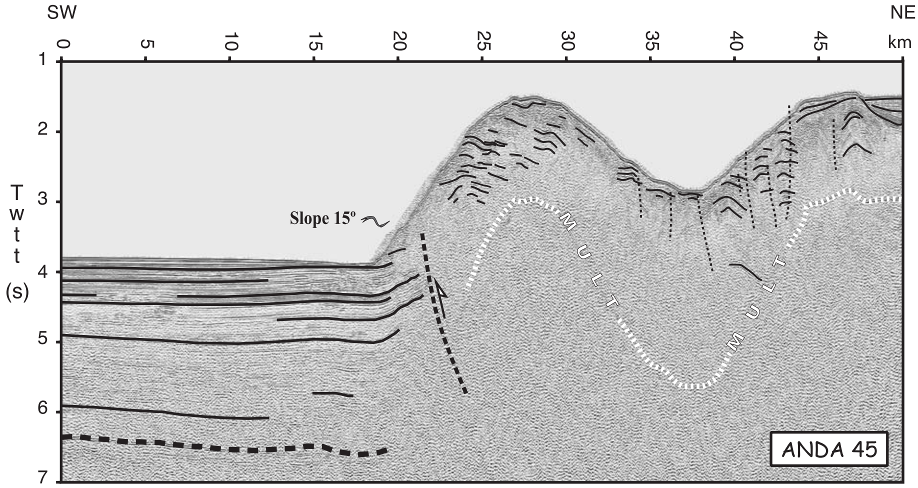


Fig. 3. Profile Andaman 45 and its interpretation. Track is located in Figs. 2 and 4. The Andaman seismic is a "light" seismic acquired at 10 knots (six channels, threefold). All Andaman profiles shown are migrated sections.

on the most recent plate tectonics models constrained by GPS measurements.

2. Morphology of the Indo-Burma trench along the West Burma Scarp (WBS)

The Andaman survey along the West Burma Scarp covers the Indo-Burma trench north of the Andaman Islands and south of the Arakan Yoma wedge in Myanmar (Fig. 1). The surveyed area is a 6–7-mile-wide strip extending from 14°N to 18°30′ N (Fig. 2). A single ship track was also run along the trench axis further South, so that the total length of trench surveyed is over 700 km. Morphologically, the WBS is a narrow and steep scarp between the flat 3000-m-deep Bengal Basin to the west and the bathymetric highs of the Coco Ridge to the east (Coco Islands and their extension, see Fig. 1). East of the Coco Ridge, the Ayerrawady platform and basins system is largely blanketed by fast infill of the prograding Ayerrawady delta.

A set of bathymetric sections across the West Burma Scarp (Fig. 2) clearly shows that the morphology is not typical of a trench. Most of these sections reveal the presence of a narrow and sharp slope break. Cross-sections B–H present wall morphology at short distance from the flat Bengal Basin. The slope of this narrow front is unusually high for a stable sedimentary wedge (12–15°), at contrast with the gentle slope observed at other accretionary prisms with a similar thick incoming section. Direct comparisons can be made with the Barbados and Eastern Mediterranean prisms, both being fed by large deltas (the Amazon and the Nile cones, respectively). The taper for those prisms does not exceed a few degrees (Lallemand et al., 1994; Chaumillon and Mascle, 1997). The steep gradient of the WBS actually shows more similarities with strike-slip dominated margins, such as the Puysegur Trench (Delteil et al., 1996; Lamarche and Lebrun, 2000; Lebrun et al., 2000) and the Hikurangi Trench (Collot et al., 1996, 2001) in New Zealand. The Burmese scarp swings south to north from a N40°E direction immediately north of the Andaman Islands to a N40°W trend at the location where the Arakan Yoma belt widens. This south to north swing coincides with three main tectonic styles, from trans-

Fig. 2. Andaman Cruise multibeam mapping along the Western Burma Scarp, contoured every 25 m. Contours lines outside the multibeam survey were merged with the GEBCO database. Seismic tracks are shown as thick black lines. A series of bathymetric profiles across the Western Burma Scarp are displayed to the left (sections A–I, dotted lines on the map). Notice that some, but not all, of these sections follow the seismic profiles.

pressive to pure dextral strike-slip in the south to accretion combined with dextral shear in the north.

2.1. The southern part of West Burma Scarp: a transpressive segment

South of 14°40′ N, the WBS morphology is characterized by a set of three N10°–N35°E *en échelon* highs. These blocks are bounded eastward by N30°E trending basins. One of these highs was imaged by seismic profile Andaman 45 (bathymetric section I in Fig. 2 and seismic line in Fig. 3). Thrusting onto the flat cover of the Bengal fan is suggested by the discrete flexure of the sediment pile deposited on the downgoing plate. The deepest reflector identified within the trench gently dips eastward and the section above shows clear fanning in relation to active thrusting (Fig. 3). The frontal thrust at the very base of the slope is buried beneath a sedimentary talus and thus does not break to the surface, the talus being probably fed by the unstable steep slope hanging above. The internal structure of the hanging wall shows rare eastward dipping reflectors. Although we cannot totally rule out that this tilting corresponds to the inherited structure of the upper margin (such as tilted blocks), a link with the recent activity of the bounding thrust is more likely. The simplest interpretation is that this set of *en échelon* highs are faulted wrenched anticlines. *En échelon* folds in a similar position (frontal wedge) and with similar orientation of their elongated axis have been observed south and north, although they all show less severe deformation. Estimate of the amount of shortening is difficult to obtain. On seismic line Andaman 45 (Fig. 3), the rare reflectors seen within the hanging wall may correspond to the well-stratified reflectors recognized in the trench, but the poor quality of the seismic does not allow a direct and reliable correlation. Furthermore, part of the hanging wall has clearly been eroded. The Neogene to Quaternary sedimentation rates in the area remain largely speculative. Based on multi-channel seismic data across the Bay of Bengal at 13°N latitude (150 km south of our survey), Gopala Rao et al. (1994) estimated a 250 m Ma^{-1} accumulation rate. Borehole data in the southern Bangladesh at 22°N latitude (about 400 km away from the northern tip of our survey) indicate a mean rate of 520 m Ma^{-1} for the post-Pliocene period (Alam et al., 2003). Using these rates as lower and upper bounds, and taking the sound velocity in the sediment in the range 1800–2000 m/s, the deepest reflector recognized on line Andaman 45 would be 5–10 Myears old (i.e., Early Pliocene or Late Miocene). The entire sequence above this reflector shows regular fanning towards the trench and upward folding at the slope break. This pattern is compatible with steady state thrusting since at least this age. The systematic *en échelon* disposition of those large anticlines (Figs. 2 and 4) strongly suggests that this portion of the WBS is an active transpressive dextral zone.

Between 14°N and 15°40′ N (Fig. 4), the WBS is a N40°E trending wall linking the flat Bengal Basin with the very shallow Burma shelf. North of 14°30′ N, the toe of the slope is affected by N10°E trending folds and thrusts with again an *en échelon* geometry (Fig. 5). The WBS is crosscut there by seismic profiles Andaman 46, 47 and 48 (Figs. 6, 8 and 9). We also show in Fig. 7 the line drawing of an unpublished CGG multichannel profile.

Along the east–west trending Andaman 46 profile (Fig. 6), a narrow elongated slice (slice A), thrust bounded west and east, occupies the base of the scarp. The internal structure of this slice shows again a series of small-scale *en échelon* folds trending N10°E. The CGG multichannel profile (Fig. 7) has a much better penetration than Andaman seismic lines, close to 3 twtt. The entire front of the wedge is affected by steep thrusts with double vergence. This reverse fault system is interpreted as the trace of a major N35°E trending dextral strike-slip fault. Part of this fault system is buried, as shown by dotted lines in Fig. 6, below 0.8–1 s twtt thick sediments. Profile Andaman 47 (Fig. 8) shows another pop-up structure (tectonic slice B). A small mound associated with a nascent strike-slip fault west of tectonic slice B is interpreted as a mud volcano. Although sediments are actively deformed at the toe of the slope, undeformed sediments blanket the scarp immediately east of the slope break, pointing again to localized deformation at the very base of the Burma scarp.

We interpret tectonic slices A and B (Fig. 5) as the surface expression of a dextral wrenched fault system at depth. The area thus appears as a positive flower structure, presently active only at the base of the scarp. The abyssal plain of the Bengal Basin is moderately affected by the *en échelon* structures. This could be the result of high sedimentation rate versus low deformation rate. In any case, the shearing component seems to be higher than the frontal accretionary component.

Profile Andaman 48 (Fig. 9) is very oblique to the trend of the WBS. Its orientation parallels the trend of the scarp and helps to better confirm the fault dips. The westernmost fault (fault A) is subvertical, at least in the top of the section, and shows a minor thrust component towards the east close to the mudline. This fault is more or less in line with the westernmost fault identified on profile Andaman 47, but with opposite vergence. Another active fault can be observed immediately east of fault A in the middle part of profile Andaman 48 (Fig. 9) and is also probably a vertical strike-slip fault, marked by a discrete mud volcano.

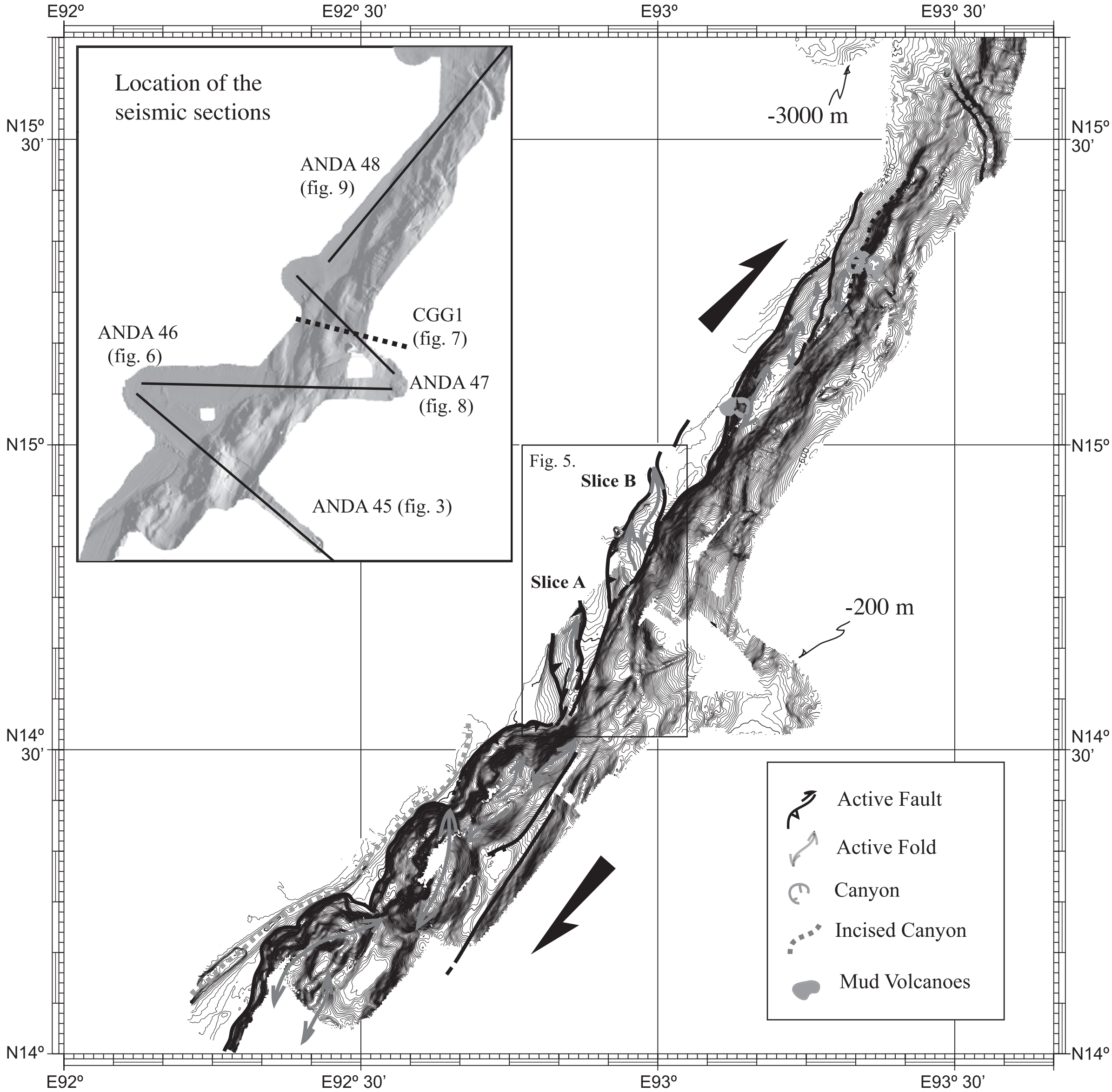


Fig. 4. Tectonic sketch for the southernmost portion of the surveyed Western Burma Scarp. Bathymetric data are contoured every 20 m.

Fault zone B below the lower terrace has a clear strike-slip component as indicated by its change of vergency approaching the surface. Eastward, the profile crosscuts fault zone C, which seems to be less active than fault zone B on profile Andaman 48. However, the bathymetric map confirms that fault zone C becomes the active one northward. Active deformation is thus concentrated along the two frontal *en échelon* duplex, less than 20 km wide, located at the base of the slope. Steepness and localization of the active structures support the fact that the deformation is concentrated in a narrow band at the base of the slope. The interpretation is that fault zones A, B and C are part of a larger *en échelon* dextral strike-slip system trending N35°E.

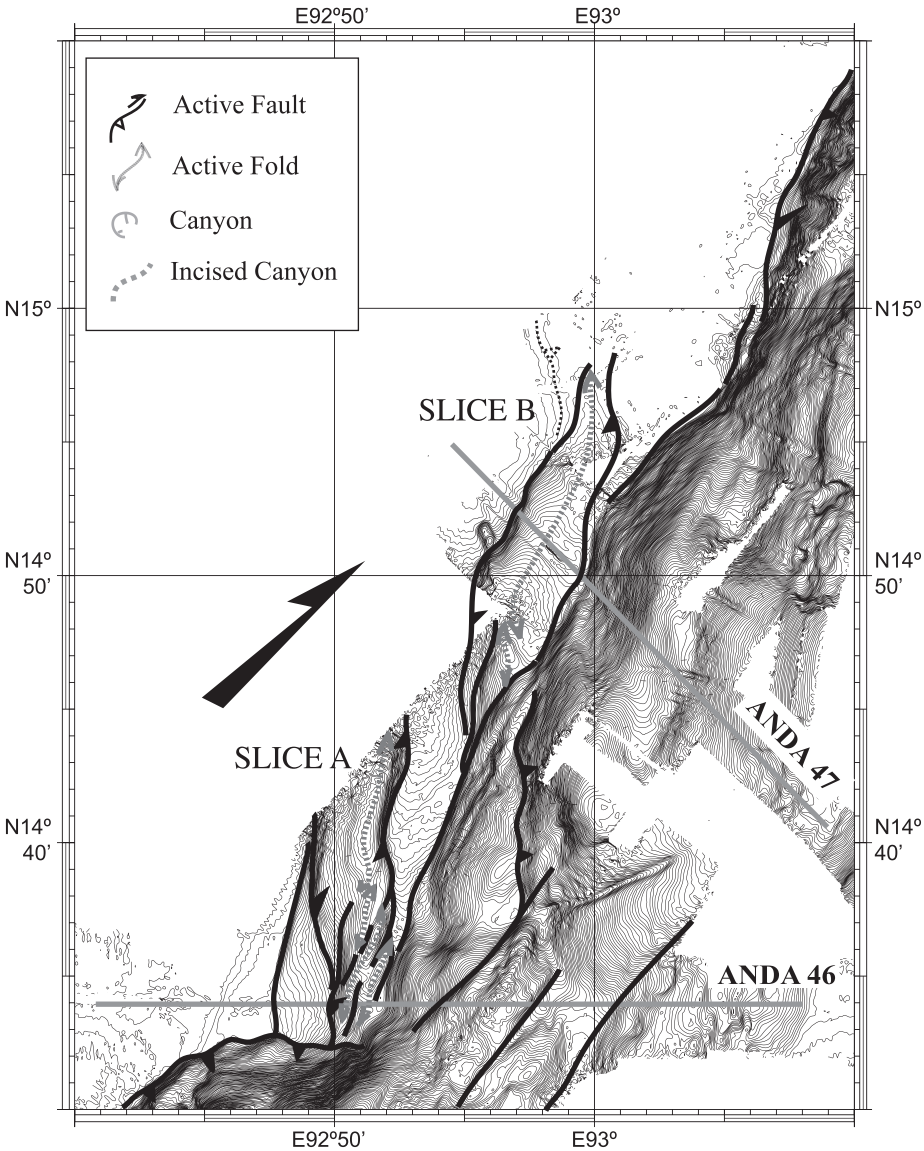


Fig. 5. Extract of the southern area showing *en échelon* tectonic slices at the base of the slope of the Western Burma Scarp. See location of the extract in Fig. 4.

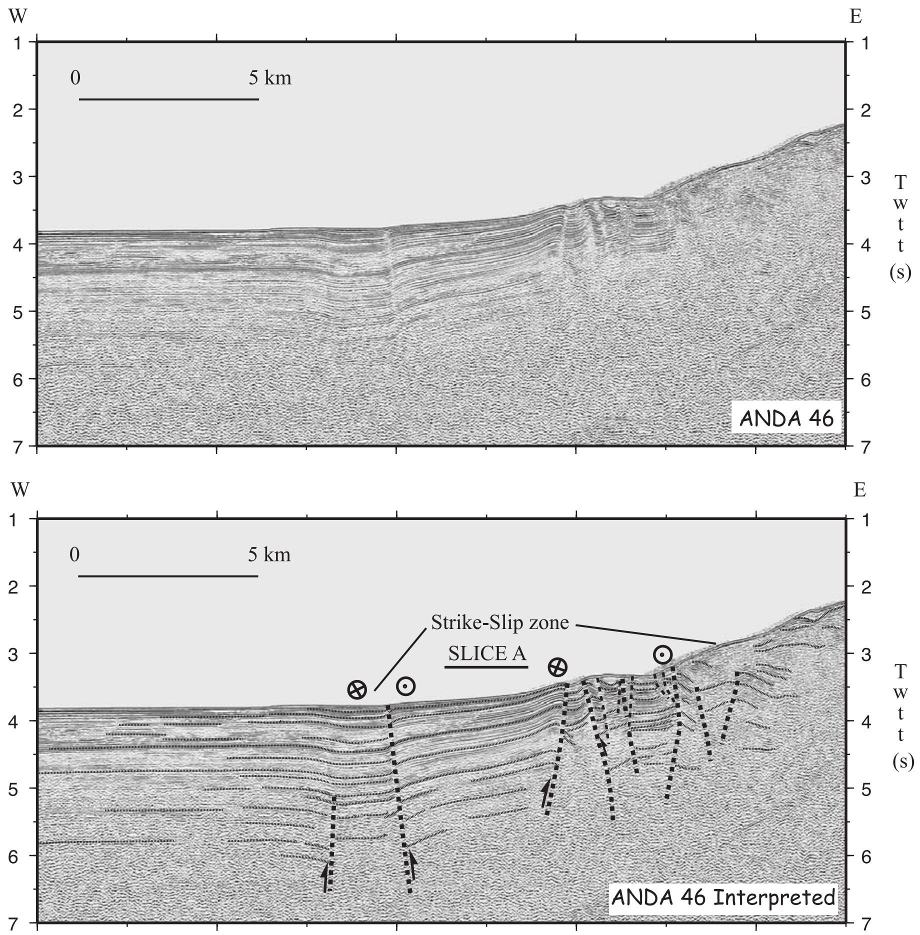


Fig. 6. Profile Andaman 46 and its interpretation. Track line position in Fig. 4.

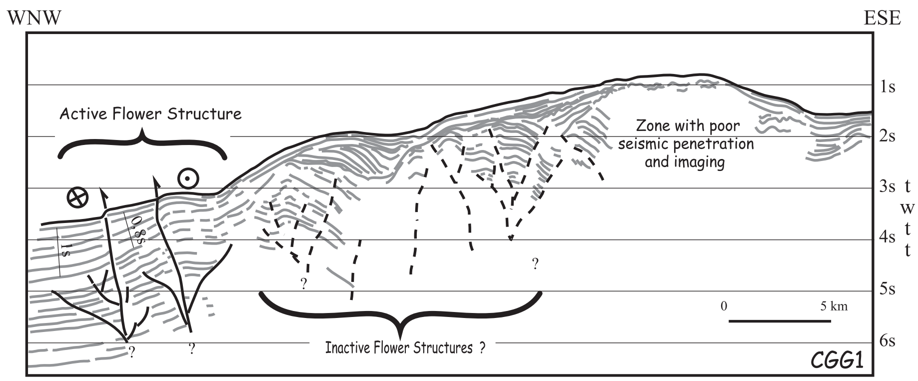


Fig. 7. CGG Profile interpretation. Track line position in Fig. 4.

2.2. The central part of the Western Burma Scarp: a transform segment

North of 15°30′N, the WBS swings westward and bends to a N10°E orientation. In contrast to the southernmost segment, no tectonic slices are observed seaward of this portion of the scarp. The morphology is simple and corresponds to a relatively undeformed area. Between 15°40′N and 15°50′N (Fig. 10) prominent canyons, well seen on back-scattering data, deeply incise the WBS. A large deep sea fan outlines the very unstable tectonic front, but no clear fault geometry can be observed there.

Absence of significant deformation at the toe of the scarp is illustrated along seismic line Andaman 50 (Fig. 11). The trench does not appear either in the morphology. The Bengal fan sediments actually lap gently the base of the WBS. This sequence is rather undeformed, with the exception of discrete strike-slip faulting affecting the Bengal fan sediments. The

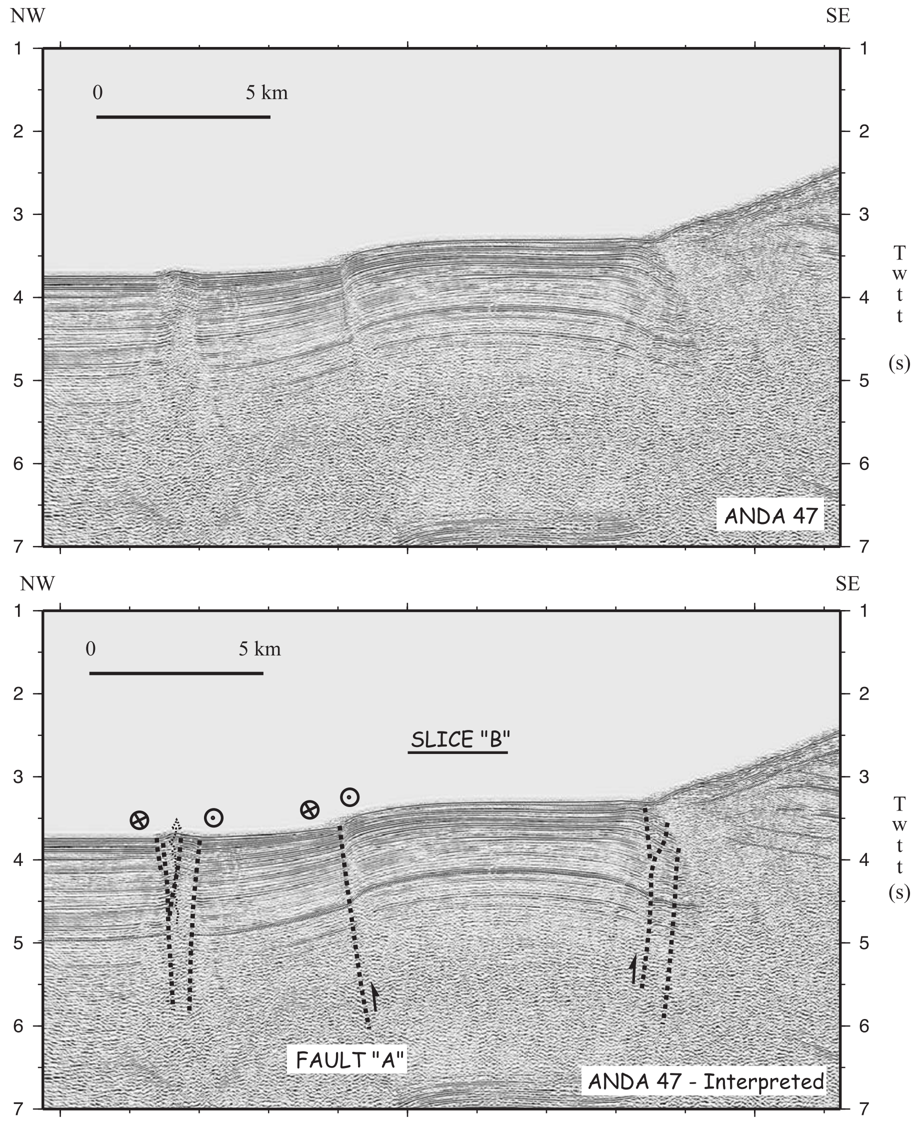


Fig. 8. Profile Andaman 47 and its interpretation. Fault A is followed on profile Andaman 48. Track line position in Fig. 4.

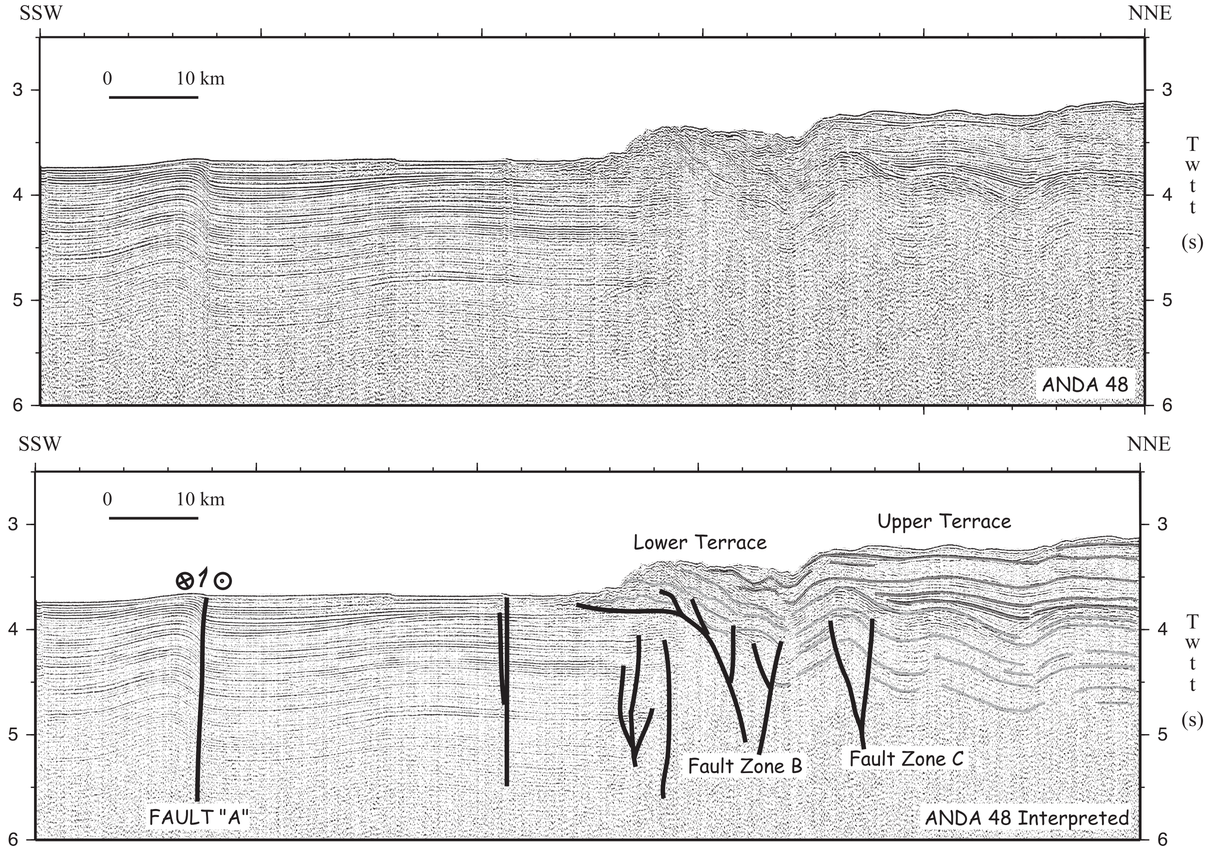


Fig. 9. Profile Andaman 48 and its interpretation. Track line position in Fig. 4.

sequence below is flexed upslope. This sequence was followed landward on a CGG multichannel line (Fig. 11) and forms the western flank of a high poorly imaged on seismic profiles.

A single active thrust was mapped east of the shelf break (CGG2, Fig. 11). The main orientation of this thrust is not well constrained due to poor spatial distribution of available seismic data. However, the regional tectonic orientations of the thrusts mapped northward, as well as correlation with onshore mapped structures along the Indo-Burma mountain ranges, indicate that this structure corresponds to a dogleg compressive arm (restraining bend) oriented in N140°E to 150°E, consistent with a N30°E to N40°E convergence.

Deformation is present north of 16°20′N where the WBS is clearly framed by dominos with N160°E and N40°E segments. Andaman 52 seismic line (Fig. 11) indicates that sediments are thrusted westward onto the Bengal Basin along the largest N160°E segments. Several potential décollement levels are observed within the Bengal sediments, possibly merging along a single main décollement at depth. Clear and intense deformation is found further upslope, at the northeastern end of profile Andaman 52. Active folding associated with N160°E trending thrusts affects the recent sediments supplied by the Ayerawaddy delta. Despite discontinuous bathymetric mapping due to shallow waters, folds appear rather sigmoid in shape and connect with the N40°E trending structures interpreted as strike-slip faults. The northwestward part of this "domino" pattern is relayed northward (between 16°30′N and 16°40′N, Fig. 10) by a rather continuous and narrow strike-slip zone marked by *en échelon* folds and mud volcanoes. Here, the deformation takes place along

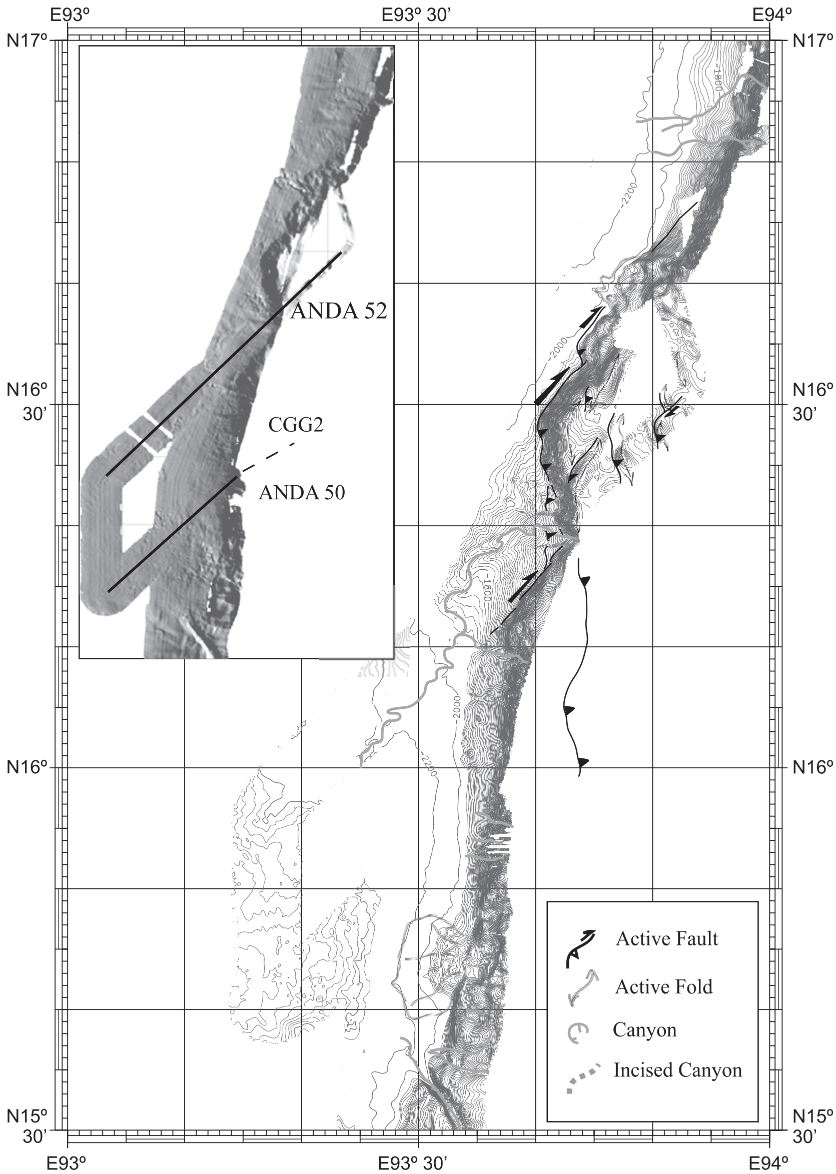


Fig. 10. Tectonic sketch of the central portion of the surveyed West Burma Scarp. Bathymetric data are contoured every 20 m.

short dogleg segments composed of N160°E trending thrusts and N40°E trending strike-slip faults. The same organization is followed northward where it guides the shape of the wall. Consequently, the entire central segment of the WBS corresponds to a multiscale dogleg system consistent at larger scale with a rather straight N35°E dextral shear zone in a N35–40°E convergence.

2.3. The northern part of the West Burma Scarp: from transform to accretion

This northernmost part of our survey covers the very southern tip of the Arakan Yoma wedge (Fig. 12). Structurally, it coincides offshore with the first clear evidences of significant wedge type accretion. We name it the Ramree lobe, from the nearby

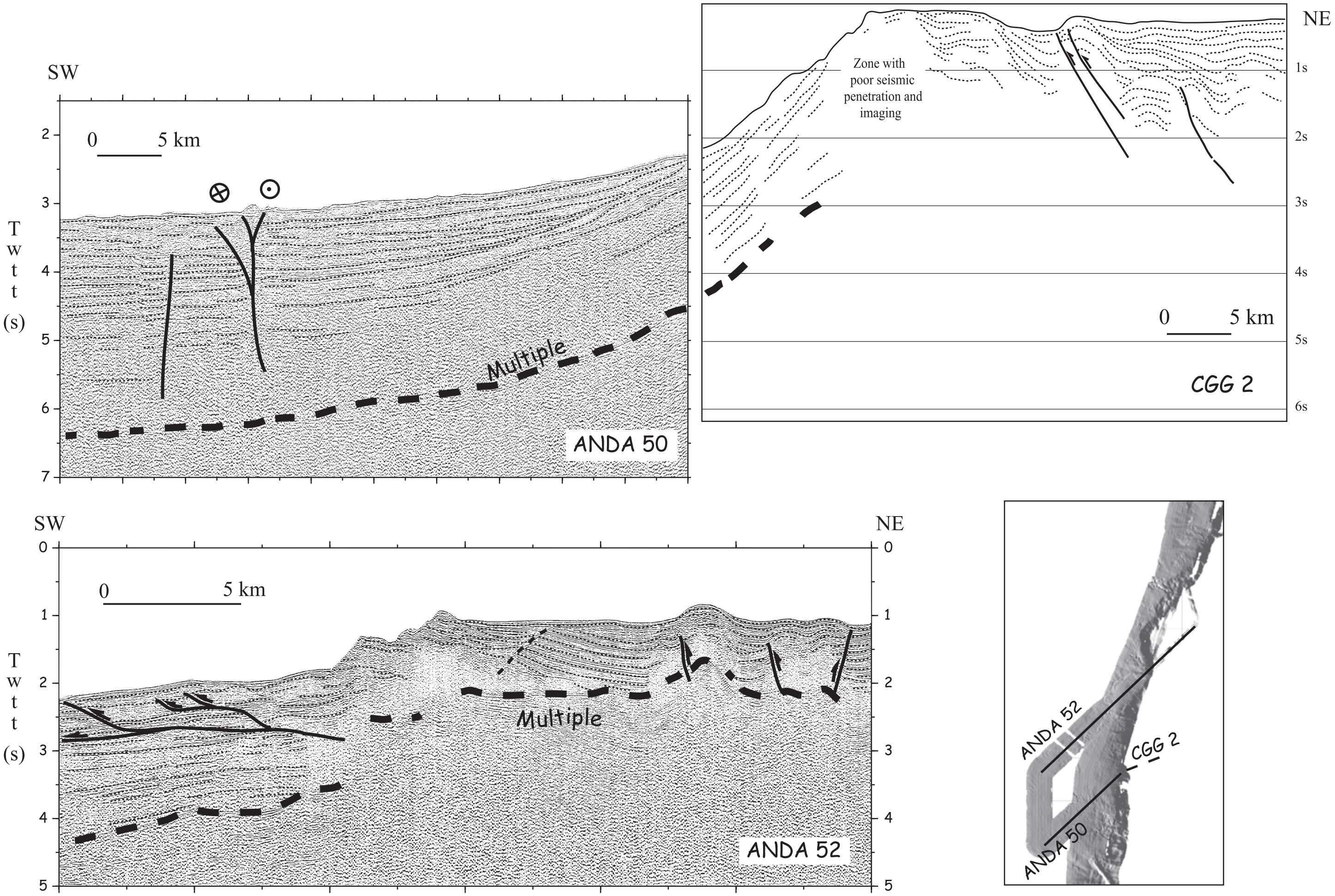


Fig. 11. Interpretations of seismic profiles Andaman 50, Andaman 52 and CGG2 multichannel line.

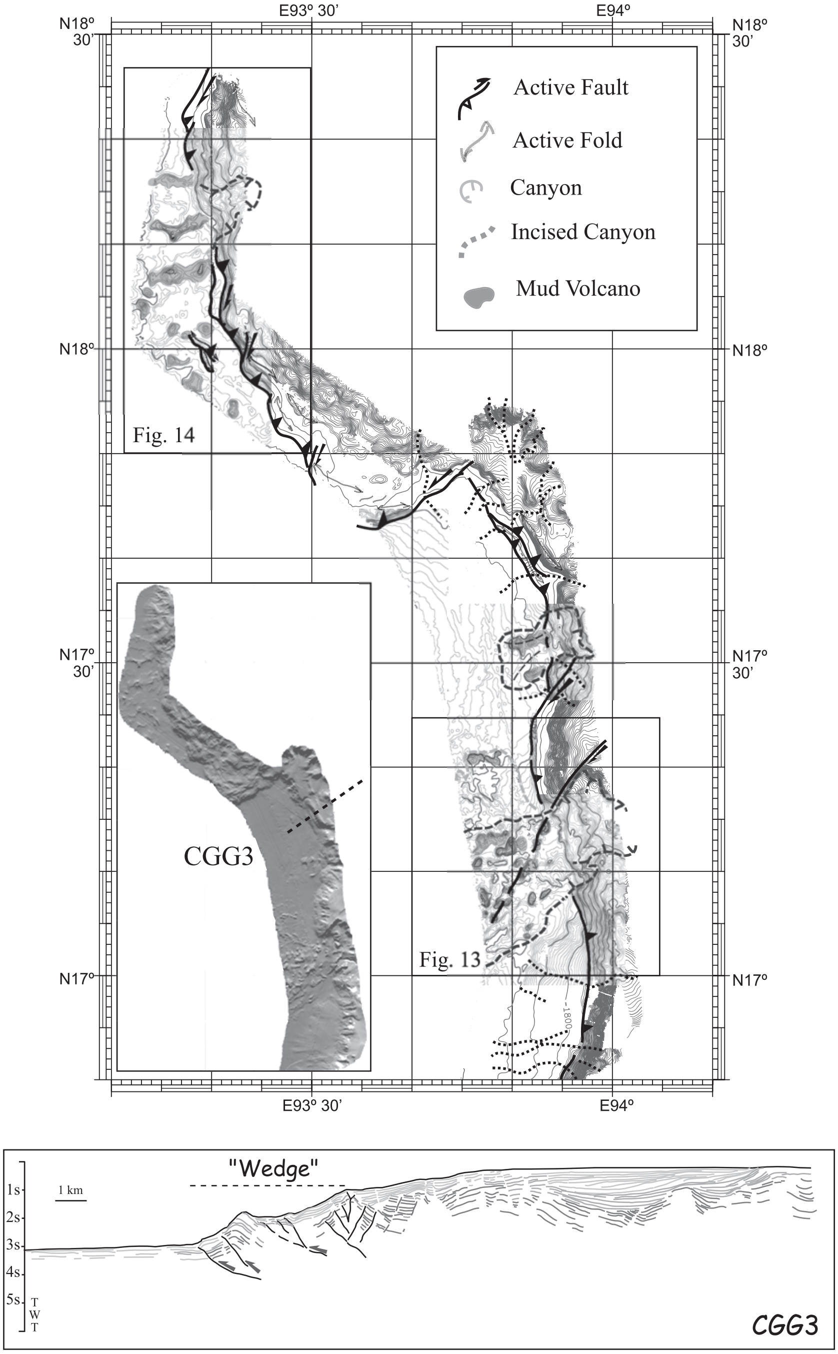


Fig. 12. (a) Tectonic sketch and bathymetric map of the northern portion of the Western Burma Scarp. Data are contoured every 20 m. (b) Interpretation of CGG3 multichannel line.

Ramree Island off Myanmar main coast. This is also the place of widespread mud diapirism and major gravity collapses, such as the Watthe Avalanche named from the closest city in Myanmar.

2.3.1. The Watthe Avalanche

Between 17°N and 17°35′ N, an important cinder cone abruptly cuts the linearity of the Western Burma Scarp. The area shows debris flows that poured out of large canyons. Bathymetric mapping reveals kilometer-size blocks lying on the flat seafloor of the Bengal Basin (Fig. 13). In addition to this blocky morphology, several mud volcanoes were identified on 3.5-kHz profiles. They appear as smoother bathymetric mounds within the Bengal plain. Our interpretation is that a large debris avalanche, the Watthe Avalanche, recently affected the steep and rather unstable slope of the Western Burma Scarp. Sudden loading of the non-

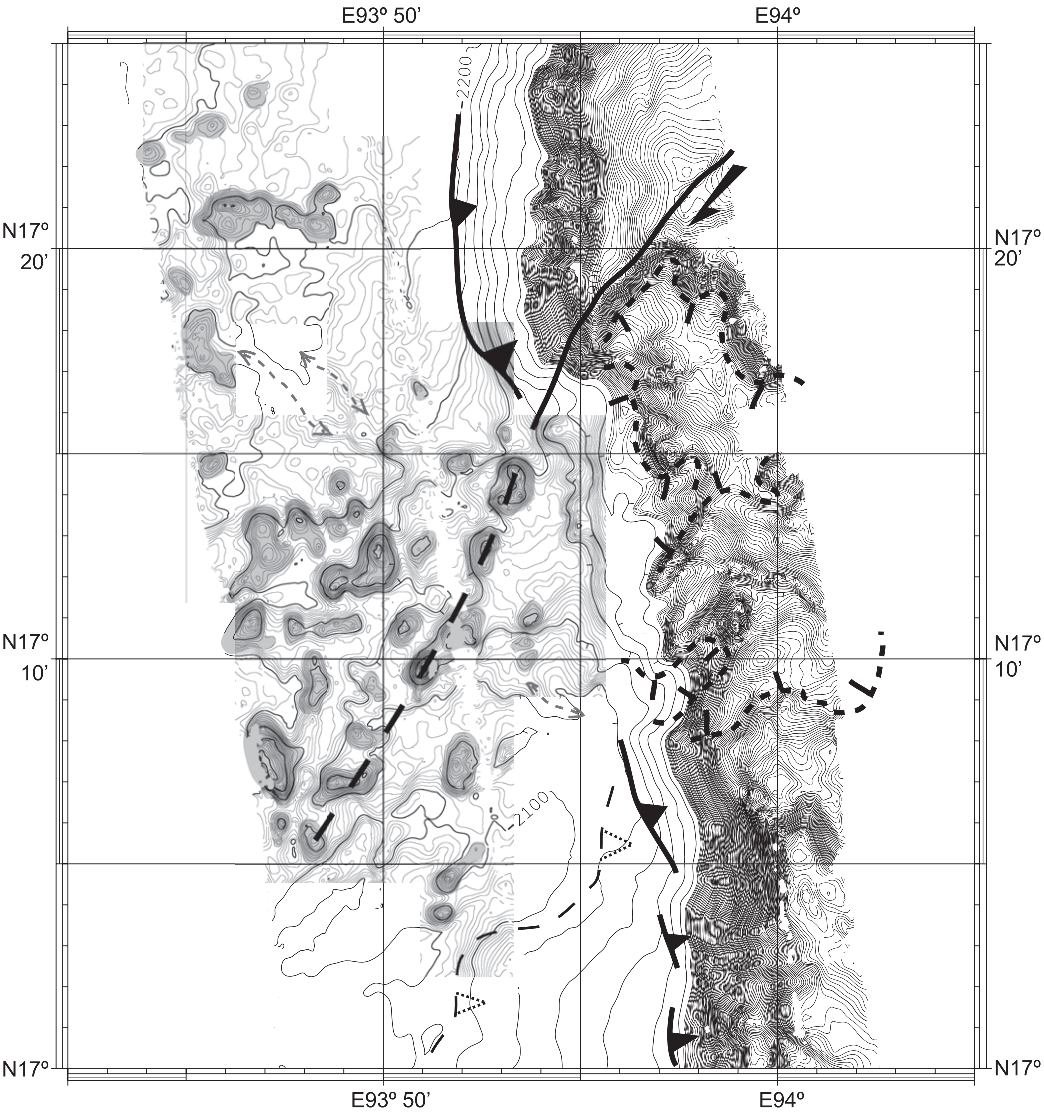


Fig. 13. Focus on the Watthe Avalanche and its debris cone. Mud volcanoes are in grey, black dotted lines are normal faults, black line is the strike-slip fault that generated the avalanche, and grey dotted lines are fold axis. Bathymetric data are contoured every 20 m.

compacted sediments of the Bengal fan probably resulted in the eruption of the mud volcanoes. Fast blanketing due to high sedimentation influx lead to rapid filling and progressive embedding of some of the debris, responsible for the peculiar "flat and blocks" morphology recognized by multibeam. Mud volcanoes are irregularly arranged into several N30°E trending ridges. Assuming that mud escaped through tension gashes, this orientation is compatible with stress orientation expected onto a more or less NS dextral strike-slip fault.

Similar avalanches have been observed along the Hikurangi Margin (Collot et al., 2001). The Ruatoria Debris Avalanche in New Zealand presents the same morphology, constituted by debris flows, with an almost circular indentation bounded by strike-slip scarp parallel to the Pacific Plate/Kermadec Arc convergence. The avalanche is interpreted there as resulting from the oblique subduction of a large seamount. The Watthe Avalanche seems to have occurred in a different tectonic setting, since the WBS shows no seamount-related indentation. The Avalanche would rather be the result of the high instability of the WBS along the main shearing segments. A similar instability, a large submarine olistostrome associated with the subduction motion, has been reported southward along the Sunda Arc subduction zone, facing the Andaman Islands (Moore et al., 1976).

2.3.2. The Ramree lobe

Offshore Ramree and Cheduba Islands, the Western Burma Scarp is a short accreting segment composed of imbricate folds and thrusts (Fig. 12). This portion of the WBS is the first clear evidence for wedge type accretion. The bathymetry shows a large semi-circular lobe sharply bounded to the southeast by a N55°E trending fault. Sigmoid folds there indicate sinistral motion compatible with the progressive outward growth of the wedge at the expense of the thick Bengal plain sediments. The main orientation of thrusting is N120°E, and a statistical study of the orientation of the imbricate slices and folds suggests a N35°E growth convergence.

North of 18°N (Fig. 14), although the overall course of the WBS generally trends northward, bathymetric details show dogleg segments with N140°E trending thrusts (accreting segments) and N10–20°E trending transfer faults (dextral strike-slip segments). However, the transfer faults do not show sharply in the bathymetry due to the soft and thick sediment cover.

Deformation also affects the flat sediments of the Bengal Basin, indicating outward propagation of the décollement level. The Bengal Plain facing this portion of the WBS is actually covered with mud volcanoes, either isolated or remarkably aligned along N70°E to EW trends. These mud ridges are particularly abundant in the northernmost part of the surveyed area. Notice that mud expulsion is also abundant upslope towards the continental margin, with Ramree and Cheduba Islands being the culminating points of larger mud volcano fields (Bender, 1983).

3. Tectonic interpretation of the Western Burma Scarp

The structures observed along a 700-km-long portion of the West Burma Scarp typically depict a dextral shear zone with wrenched accretionary wedge. The active tectonics evolves from transpression in the south to a multiscale restraining bend geometry in the north, connected by a localized strike-slip fault zone (Fig. 15). We do not see abrupt changes in the tectonic style, but subtle variations occur along the West Burma Scarp from south to north:

(1) In the south, the dominant tectonic process is dextral strike-slip faulting localized at the base of the slope, accompanied with significant shortening. Multiscale *en échelon* folds with axis trending N10°E to N35°E are compatible with NE convergence of the Indian plate with respect to the Burma margin.
(2) Further north, the WBS is shaped by a domino pattern framed by short N160°E and long N40°E segments. Motion along the N40°E trending segments is pure strike-slip.
(3) The WBS then swings N10°W, towards the Watthe Avalanche and N40°W towards the Ramree lobe. The WBS there shows a combination of N20°E dextral faults and NW–SE thrusts. The Ramree lobe itself shows discrete dogleg structures in its internal pattern.

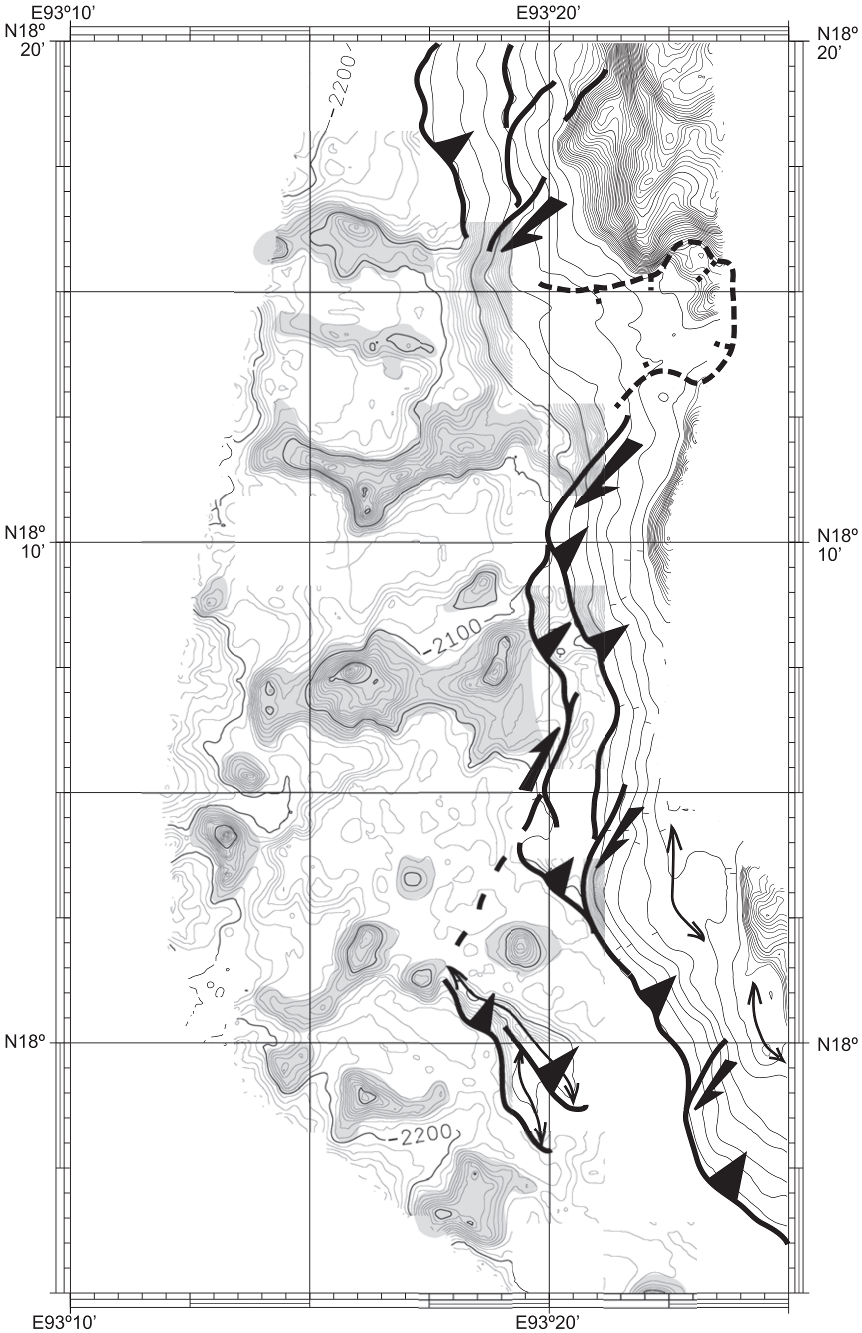


Fig. 14. Western flank of the Ramree Lobe, controlled by N10–20°E trending dextral strike-slip faults and N120–140°E trending thrusts. Bathymetric data are contoured every 20 m.

(4) Previous work on the offshore part of the Indo Burma wedge (Nielsen et al., 2001) also indicated, on the basis of industrial seismic data, that the same dogleg organization extends north outside the Andaman survey, up to 19°40′ N (Fig. 15). In this area, the Burma margin is controlled by

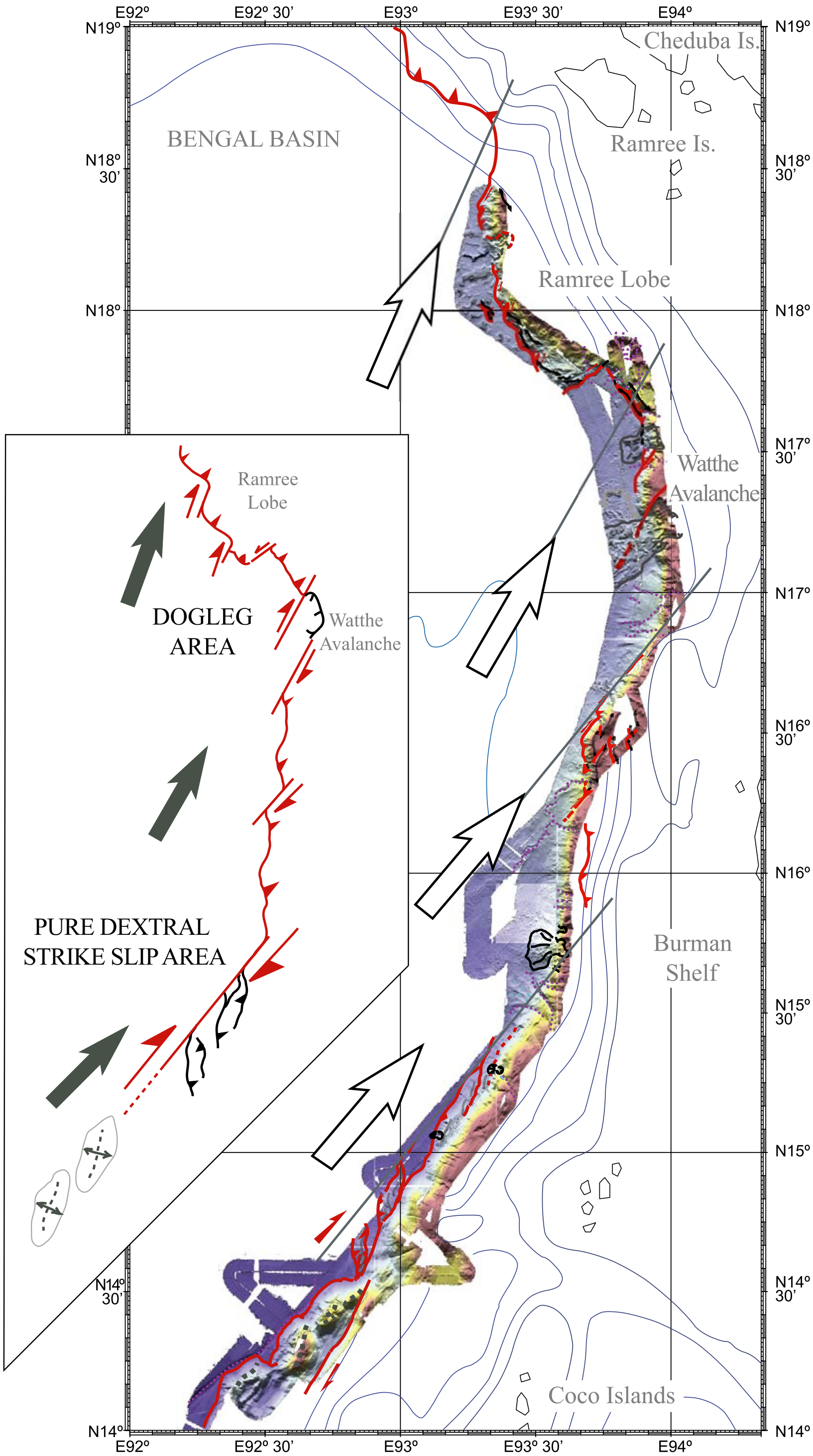


Fig. 15. Summary of the main tectonic features along the slope of the Western Burma Scarp. Arrows indicate inferred relative convergence between India and Burma margin.

N130°E thrust linked by NS to N20°E trending dextral transform segments, suggesting a N10–20°E relative convergence between India and Burma.

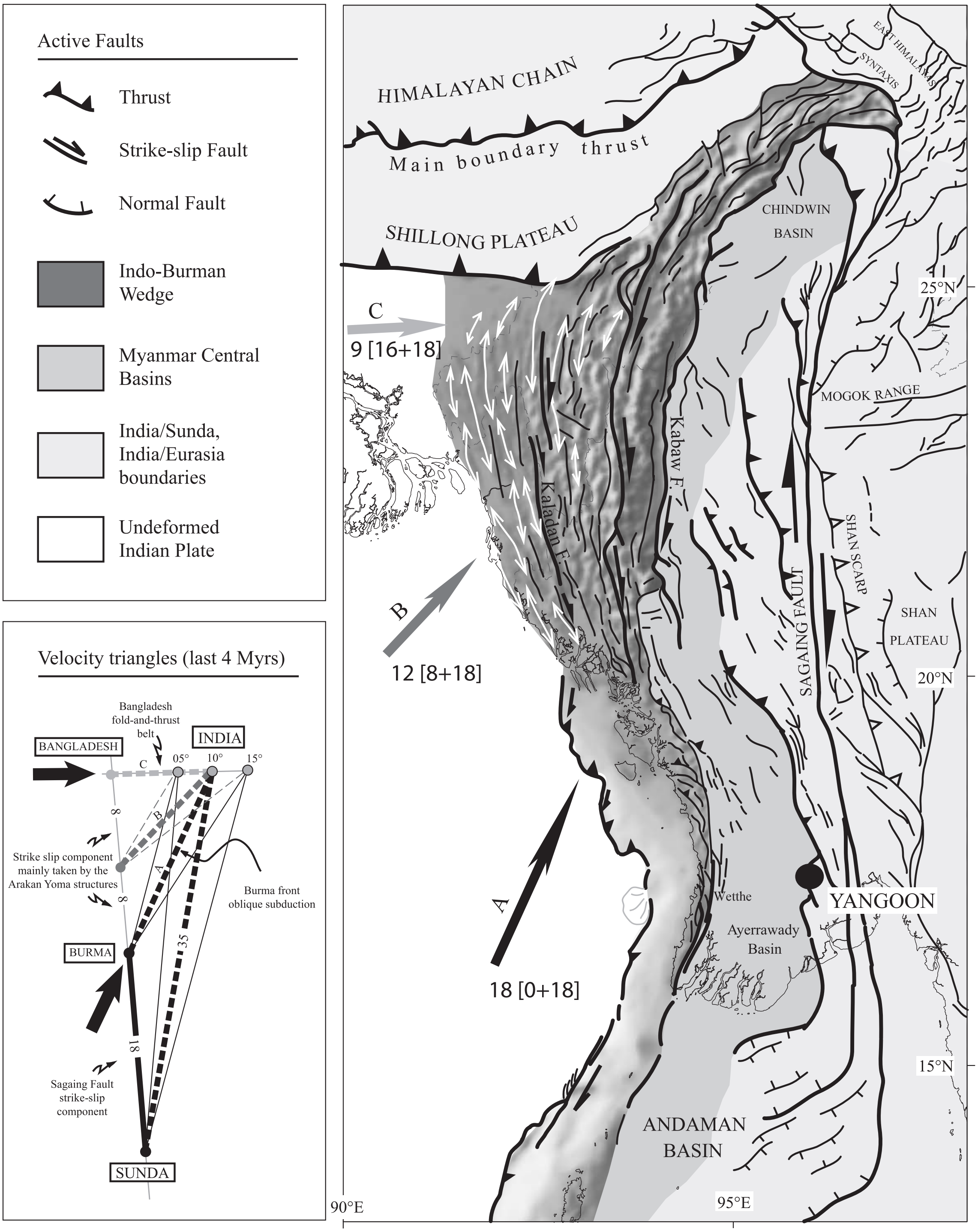
The mean N35°E trend of the pure shear segments, together with the N130–140°E trending thrusts, are compatible with a N30–40° convergence of India with respect to the Burma platelet. In details, the relative direction of convergence may evolve from N50° in the south to N20° in the north. We interpret those variations as resulting from latitudinal variations of the motion of the upper plate (or upper margin) with respect to India, either as an effect of rigid body rotation of the Burma platelet or as a result of internal deformation within it. The mean N30–40° convergence is to be compared to the predicted N10 ± 5° motion of India with respect to Sundaland. The main conclusion is that although the 20–30° clockwise rotation of the convergence vector does imply some amount of shear partitioning (if not relative convergence would be N10°), the degree of partitioning is rather small, at least along the portion of trench covered by the Andaman survey. We will show in a latter section that this observation is in agreement with reduced shearing motion on the Sagaing Fault.

4. Correlation of offshore data with seismicity and onshore structural fabric of the Indo-Burma range

Superficial as well as internal structures of the offshore Indo-Burmese wedge are poorly known. The active tectonic setting is mainly constrained by information provided by focal mechanisms of largest earthquakes (Harvard CMT and Engdahl catalogue) and some scarce morphological studies (Basu et al., 1992; Gopala Rao and Krishna, 1997). Off the Andaman Islands, seismicity indicates EW shortening, but strike-slip faulting is dominant. A few interplate earthquakes (i.e., slip on low-angle and east-dipping plane, see Fig. 1) suggest EW subduction (Kreemer et al., 2003). A recent model of the tsunami generated by the large 31/12/1881 submarine earthquake south of the Andaman Islands (Mw 7.9–10°N latitude) concludes to pure thrust slip onto an east-dipping plane (Ortiz and Bilham, 2003). Full partitioning would thus be reached there, in relation with the opening of the Andaman basin (Ortiz and Bilham, 2003). Immediately north of the Andaman Islands, major seismic events are absent, suggesting a seismic gap below the entire surveyed area. This gap was interpreted as further evidence for "locking" of the lower Indian and upper Burman plates (Le Dain et al., 1984; Guzmàn-Speziale and Ni, 1996). One large earthquake did occur recently quite close to the southern tip of our survey. This 13/09/2002 earthquake (Mw 6.5–13°N latitude), located west of the northern tip of the Andaman, is interpreted as oblique subduction of the Indian plate in a more or less northeast direction (Kayal et al., 2004). The subduction motion obtained solely from earthquakes would thus indicate gradual increase of the obliquity from southern to northern Andaman Islands.

North of 21°N in northern Myanmar, the core of the Arakan Yoma wedge is affected by strike-slip faults (Le Dain et al., 1984; Ni and Guzmàn-Speziale, 1989; Guzmàn-Speziale and Ni, 1996; Rao and Kumar, 1999). Faults seem to be distributed within the Arakan Yoma belt, but major ones may coincide with the main geological contacts (from west to east, Neogene prism-metamorphic Paleogene prism-Backstop formed by the Central Myanmar basin). At the same latitude, the toe of the Arakan Yoma wedge is exposed onshore and is characterized by NS trending folds and thrusts. Orientation of the maximum horizontal compressive stress from borehole breakouts suggests E–W compression in the external part of the Bangladesh fold system, although the data are somewhat scattered (Gowd et al., 1992). The E–W compression seems to be restricted to the sedimentary pile, since the mean P axis of earthquakes is only slightly east of north (Gowd et al., 1992, 1998). This would imply decoupling of the Tripura fold-and-thrust belt from the underlying basement.

Field studies at the latitude of the Andaman survey have shown that the dogleg structural organization recognized at sea is also observed on land along the southern part of the Indo-Burma range (Fig. 16). In its southernmost part, this range is mainly framed by N30°E trending dextral strike-slip faults and rare thrust faults, as far north as 18°N. North of this latitude, the N20°E dextral faults are combined with N120°E northeastward and southwestward vergent thrusts. The deformed area widens and changes orientation gradually, forming a major restraining bend.



Active Faults
Thrust
Strike-slip Fault
Normal Fault
Indo-Burman Wedge
Myanmar Central Basins
India/Sunda, India/Eurasia boundaries
Undeformed Indian Plate
Velocity triangles (last 4 Myrs)
Bangladesh fold-and-thrust belt
BANGLADESH
INDIA
C
05°
10°
15°
B
A
8
8
Strike slip component mainly taken by the Arakan Yoma structures
Burma front oblique subduction
35
BURMA
18
Sagaing Fault strike-slip component
SUNDA
HIMALAYAN CHAIN
Main boundary thrust
EAST HIMALAYAN SYNTAXIS
SHILLONG PLATEAU
CHINDWIN BASIN
25°N
C
9 [16+18]
MOGOK RANGE
Kabaw F.
Kaladan F.
SHAN SCARP
SAGAING FAULT
SHAN PLATEAU
B
12 [8+18]
20°N
A
18 [0+18]
Wetthe
Ayerrawady Basin
YANGOON
15°N
ANDAMAN BASIN
90°E
95°E

North of 20°N, the active structures are more linear and are represented by N–S to N170°E trending steep strike-slip faults that dissect the internal part of the range. The shallow seismicity outlines these strike-slip faults, which are sub-parallel to the Sagaing Fault.

The main conclusion from land studies is that dextral strike-slip faulting within the core of the Arakan Yoma wedge gradually increases northwards, while the relative convergence vector at the toe of the wedge becomes gradually purely frontal forming the Bangladesh folds. Our general interpretation is that partitioning along the Indo-Burma margin progressively evolves from poorly partitioned in the Andaman survey area to highly partitioned in the north. We next test this hypothesis through a simple kinematic model.

5. From partial to full partitioning along the Indo-Burma margin

Partitioning is a major mechanism of accommodation of oblique convergence (Mc Caffrey, 1994) at SE Asia trenches (including the Sunda trenches, and also the Philippine Trench and Nankai Trough). Sumatra, in particular, was long recognized as a case study, oblique motion of the Indo-Australian plate being resolved into trench-normal and arc-parallel components (Mc Caffrey, 1991; Bellier and Sébrier, 1995). Partitioning at Sumatra is active as far north as the northern tip of the Semangko Fault, where the fault enters into the Andaman Sea and connects to the active Andaman spreading centers. The Andaman Basin itself is generally considered as a pull-part basin between the Semangko and the Sagaing Fault, thus suggesting that partitioning observed at Sumatra is more or less transferred to Myanmar. This rather simple scheme is challenged by a number of complexities. First, the offshore tectonic pattern shows significant amount of shearing along a sizeable portion of the trench itself, indicating that full partitioning does not hold there. Second, the rate of motion on the Sagaing Fault is only two thirds of the rate on the northern Semangko Fault. A geological velocity of 10–25 mm/year was proposed using the offset of a Quaternary volcano built right on the fault (Bertrand et al., 1998; Bertrand, 1999). This is in good agreement with geodetic estimates. A local GPS geodetic network in Myanmar tied to other stations in SE Asia established an instantaneous velocity of about 18 mm/year around the ancient city of Mandalay (Vigny et al., 2003). Full transfer of the 26 mm/year Semangko motion to the Sagaing Fault thus does not seem to apply. Third, the series of NS elongated folds in Bangladesh suggest that convergence is back to trench-normal there. The degree of partitioning thus strongly varies with latitude. Fourth, vertical partitioning may also be important, stress indicators (borehole breakouts and P axis of earthquakes) show that at least the frontal portion of the Arakan prism is decoupled from the underlying basement.

Regardless of the mechanisms at work, we find that a simple kinematic model involving evolution from partial to full partitioning from south to north along the West Burma Scarp is compatible not only with the offshore tectonic style, but also with the reduced amount of shearing on the Sagaing Fault and the activation of additional dextral strike-slip faults within the core of the Arakan Yoma belt. We take as a basis to our model the most recent up-to-date for the motion of India with respect to Sundaland (Chamot-Rooke et al., 1998; Chamot-Rooke and Le Pichon, 1999; Simons et al., 1999; Becker et al., 2000; Holt et al., 2000; Kreemer et al., 2000b; Vigny et al., 2003). Geodetic measurements confirmed that Sundaland acts as an individual plate, so that the India/Eurasia kinematics inaccurately describes subduction motion at Sundaland trenches. Global kinematics obtained by

Fig. 16. Combined offshore and onshore structural map of Myanmar and surroundings. Schematically, the main units from west to east are: Indian plate, highly deforming and westward prograding Arakan Yoma Range and Bangladesh folds and thrust belt, deforming Myanmar Central Basins, undeforming Sunda Block. Arrows (and numbers next to them) indicate relative convergence of India with respect to the upper margin (all rates in mm/year), progressively rotating from 035°/18 mm/year (South Myanmar) to due East–West/9 mm/year (Bangladesh folds and thrusts belt). This is the result of progressive evolution from partial (south) to full partitioning (north), in relation with shear on Sagaing Fault only (south) to shear on Sagaing Fault plus NS dextral strike-slip faults in the Arakan Yoma (north). Numbers in brackets indicate the amount of dextral shear taken in the Arakan belt (first number, 0–8 and 16 mm/year) and onto the Sagaing Fault (second number, constant 18 mm/year rate assumed). These numbers were derived from the velocity triangles shown to the left.

GPS also point to a slower than expected motion of India. NUVEL-1A estimation at the latitude of Myanmar was about 50 mm/year (DeMets et al., 1990, 1994) where GPS measurements as slow as 35 mm/year have been reported (Holt et al., 2000; Kreemer et al., 2000a; Paul et al., 2001). A recent revision of the kinematics of India for the last 3 Myears, using up-to-date magnetic anomaly identification, also concludes to a slower motion of India (Gordon et al., 1999). Taking into account these revisions, the India–Sundaland convergence vector at the latitude of Myanmar is close to 35 mm/year, in a N10 $\pm$ 5° direction.

We test in Fig. 16 velocity triangles that may apply to the Indo-Burma region. Since geodetic (instantaneous) and geologic (finite motion for the last 3–4 Ma) estimates of India motion converge to similar values, we infer that the kinematic we describe here is valid for the last 4 Ma. The 4-Ma period also corresponds to the last pulse of oceanic accretion in the Andaman basin (Chamot-Rooke et al., 2001). India–Sunda motion is set to 35 mm/year, but we allow for the direction to vary in the range N5° to N15°. Shearing on the Sagaing Fault is constrained to 18 mm/year. The basic idea is that partitioning evolves from partial in the south (i.e., shearing on the Sagaing Fault only) to full partitioning in the north (i.e., shearing on the Sagaing Fault plus additional strike-slip faults active within the Arakan Yoma). Shearing on the Sagaing Fault alone leads to predicted convergence motion at the Burma Trench in the range N10° to N40°, in agreement with the structures described along the WBS. Dextral shearing on additional faults west of the Sagaing progressively reorientates clockwise the direction of convergence to reach pure shortening in the very north (Bangladesh). The model requires an integrated rate of shear within the Arakan Yoma increasing northward (from small to 16 mm/year, see Fig. 16) which adds to the shear on the Sagaing Fault. We do not know at present whether this shear is located onto specific faults or distributed throughout the wedge. Major geologic discontinuities are likely to be activated. The Kabaw fault puts into contact the metamorphic rocks of the Paleogene accretionary complex with the Upper Cretaceous–Tertiary sediments of the Central basin. The fault is known to be reverse but with a strong right-lateral component (Pivnik et al., 1998). Other faults are active within the Indo-Burman Ranges, such as the Kaladan thrust, at the contact between the Paleogene accretionary complex and the Neogene accretionary prism, and additional east-dipping thrusts limiting successive slices of the accretionary prism (Sikder and Alam, 2003). We infer that these faults have a significant dextral strike-slip component.

Implicit in our kinematic model is that this additional shearing is taken in the Arakan Yoma belt rather than on the Sagaing Fault. If taken along the Sagaing Fault only, then the rate of strike-slip motion on it should increase northward. GPS measurements are restricted to Mandalay City, and at present, we do not know if the geodetic rate is constant along the entire Sagaing Fault. However, a northward rate increase would imply stretching of the Burma sliver, which is opposite to the observations. The Central basin in Myanmar is affected by transpression (see Fig. 16) active since Pliocene or Pleistocene time (Pivnik et al., 1998). This recent transpression followed a long period of extension, which led Pivnik et al. to suggest that northward motion of the Burma sliver is resisted by the Eastern Himalayas, following a "buttressing" model initially proposed by Beck (Beck et al., 1993). The entire variation that we see along the Burma front may actually be the result of this buttressing effect. Away from the Himalayas, obliquity of the subduction is fully accommodated by the opening of the Andaman basin. In Myanmar, motion of the sliver is resisted by the Himalayas, so that only half of the Andaman opening is transmitted to the Sagaing Fault. The remaining oblique component is then accommodated at the trench itself (this WBS study). In northern Myanmar, motion of the sliver may eventually drop, thus de-activating the Sagaing Fault. Dextral shearing would then migrate westward, re-activating major discontinuities found in the Arakan Yoma belt. In this extreme scenario, oblique motion of India is progressively transferred from a remote fault system (Andaman basin and eastern margin of the Central basin, i.e., the Sagaing Fault) to a close to trench fault system (Arakan belt and trench itself).

6. Conclusions

The West Burma Scarp is an active dextral strike-slip boundary accommodating part of the India–

Sunda motion. Detailed multibeam mapping and seismic imaging of the active structures found along the scarp suggests a relative convergence between India and Burma around N30°, implying pure strike-slip to pure shortening depending on the local orientation of the various segments of the margin. At a more regional scale, the Burma front progressively evolves to pure shortening northward towards the Bangladesh fold system. We infer that the evolution from shear (Burma scarp) to shortening (Bangladesh wedge) is the result of a gradual evolution from partial to full partitioning. Partial partitioning in the south is compatible with estimated motion of the Sagaing Fault, obtained from both instantaneous (GPS) and Quaternary (geological) fault slip rates (about 2 cm/year). The Sagaing Fault thus takes only half of the total India–Sundaland shear component of motion. Full partitioning in the north is the result of additional active strike-slip faults within the Arakan Yoma, localized at the prism–backstop contact but also within the Arakan Yoma belt. Faults accommodating the oblique component of motion of India are progressively migrating in space from far field faults (i.e., Andaman transforms/rift system and Sagaing Fault) to near trench faults (Arakan Yoma belt and the trench itself), as a result of the buttressing effect of the Eastern Himalayas that resist free escape of the Burma sliver.

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