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Structure of the Northern Bay of Bengal offshore Bangladesh: Evidences from new multi-channel seismic data

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Abstract :

New multi-channel seismic data were acquired in the northern part of the Bay of Bengal and at the northernmost termination of the 90°E Indian Ridge offshore Bangladesh. This survey was coupled with a seismic refraction experiment indicating this offshore basin is here floored by a thinned (15 km thick) continental crust, injected by Mesozoic volcanism. This attenuated continental crust is interpreted as formed during Gondwana super-continent fragmentation during a syn-rift period. The dominant tectonic pattern is marked by NE-SW trending tilted blocks filled by syn-rift sediments clearly identified on seismic profiles. The uppermost part of this continental crust (3–4 km thick) shows a complex assemblage of dipping reflectors and west-facing tilted blocks injected by volcanic build-ups. The lower crustal sequence (11–12 km thick) does not reveal significant reflectors. This syn-rift fabric is attributed to the Mesozoic up to the Early Cretaceous by correlation with published seismic data along the eastern coast of India. Opposite normal faults vergency on the Indian and Burma sides indicate an asymmetrical rifting (simple shear) creating a wide COT on the Burma side and a short COT on the opposite Indian side, a geometry typical of continental crust stretching.

This crustal fabric is overlain disconformably by a thin reflector attributed to the Late Cretaceous-Paleocene pelagic sequence deposited during India/Bay of Bengal drift phase, before the Cenozoic-India Asia collision marked by thick clastic sedimentation associated with the Ganges delta southward progradation.

Below this delta, this Mesozoic rift closes axially and is affected by the incipient Late Miocene shortening of the Shillong Plateau. The NE-SW fabric of this attenuated crust might be traced southward to 15°N, close to magnetic chron 34, where steady state spreading of the Central Indian Ocean occurred.

Keywords : Bengal basin, Seismic analysis, Basin structure, Bengladesh

Introduction

The Bay of Bengal extends into the northernmost part of the Indian Ocean. It is 1500 km wide at 15°N, between the East India passive margin to the west and the Sunda plate margin to the East. This basin was formed during two successive spreading episodes. Its northern part is generally accepted as floored oceanic crust formed during the Cretaceous and is characterized by NE-SW trending magnetic anomalies and possible NW-SE trending transform faults (Curray *et al*., 1982**;** Subrahmanyam *et al*., 1999). However Brune and Singh (1986) suspected the presence of continental crust flooring this basin. Southward, the Central Indian Ocean is clearly oceanic with E-W trending magnetic anomalies and N-S trending transform faults (Royer *et al*., 1988). According to Gibbons *et al*. (2013) the transition from the NE-W to E-W trending magnetic lineations occurred at 100 Ma (Figure 1), testifying for a possible transition between the termination of the Gondwana rifting and the onset of the incipient drift of India.

Previous basement studies in the northern Bay of Bengal

Magnetic anomalies identification and ages in the northern Bay of Bengal are still a matter of debate among the scientific community. The supposedly oceanic crust is generally accepted as Early Cretaceous in age and then developed during the magnetic quiet period (Ramana *et al.,* 1994).

Curray and Munasinghe (1991) suspected magnetic anomalies M4 and M5 in this basin, meanwhile Ramana *et al.* (1994) proposed a M11-M0 magnetic model for this basin, with a half-spreading rate of 3.5 cm/yr. More recently, Desa *et al.* (2013) considered the Bengal basin as the drifted half part of the Early Cretaceous Enderby basin. Barnerjee *et al.* (1995) proposed the rifting of this basin was generated above the same hot spot (Rajmahal/Kerguelen) induced by the Barremian India/Antarctica rifting. The crust of the basin could be then considered as a drifted part of the Kerguelen Large Igneous Province (LIP). In the eastern part of the basin, gravity data revealed the presence of NE-SW trending highs and lows along the coast of Krishna-Godavari and Mahanadi. The gravity lows correspond to the infilling of Permian, Triassic and Early Cretaceous sediments (Bastia and Radhakrihna, 2012; Nemcok *et al.*, 2012 and Sandwell *et al.*, 2014) with NE-SW trending lows and highs truncated and offset by NNW-SSE transverse zones that could be interpreted as oceanic fracture zones.

Rao *et al.* (1997) proposed that the oldest sediments deposited on the supposed oceanic crust are Early Cretaceous in age along the East India coast, and have identified eight distinct overlying sedimentary sequences ranging from Eocene to Late Pleistocene. Curray *et al.* (1982) compiled all seismic refraction data set available at this time. They found crustal velocities of 6.4 km/s in the Cauvery basin at 10°N and 13° N with an onset of sedimentation during Albian (or older) age and Early Cretaceous, respectively. Desa *et al.* (2013) suggest an Early Cretaceous age for the onset of rifting in the Bengal basin along the eastern margin of India. An eastward transition with a possible oceanic crust was proposed by Nemcok *et al*. (2012).

The eastern part of the basin, where the 90°E Ridge is largely present, was drilled during DSDP leg 22 (Site 217, Moore *et al.,* 1974). A rather continuous sequence from Quaternary to Middle Late Miocene was drilled down to the bottom of the 600 m thick basal Campanian chalks and cherts deposited on the 90°E Ridge basement. Between 10°N and 17°N, a Quaternary to Eocene sedimentary sequence was locally deposited on these volcanic rocks. These volcanics were attributed to the drifted Kerguelen hot spot LIP (Coffin *et al.,* 2002, Figure 1), but are frequently younger than the LIP itself. Royer *et al.* (1988) on drilling sites ODP leg 121, show a N to S decreasing age for this ridge volcanism (90 to 38 Ma), from 35°N to 10°N respectively (Duncan and Storey, 1993). This fits rather well the decreasing age of the South Bengal basin and Wharton spreading centers on both sides of the ridge. However, part of this Cretaceous and Cenozoic volcanism could be interpreted as MORB volcanism injected along the 90°E transform fault during the active South Bengal/Wharton basins spreading center migrations (Sclater and Fisher, 1974).

Mukhopadday and Krishna (1991), Klootwijk *et al*. (1991) and Duncan and Storey (1993) also suggested that part of this ridge volcanism has a MORB signature, which could have been injected from this spreading center over an attenuated ridge crust estimated 25-km thick by Greyvemeyer *et al.* (1999).

Le Pichon and Heirtzler (1968) have noticed exhumed gabbro along the 90°E Ridge. Consequently, the 90°E Indian Ridge is a topographic high probably formed during early Cenozoic intraplate shortening facilitating doming and exhumation of mantle, and underplated spreading center volcanism injected along the previously existing transform boundary. Maurin and Rangin (2009a) were able to trace the 90°E Ridge up to 20°N in our study area.

Data on the pre-Cenozoic stratigraphy, the nature and age of the northern Bay of Bengal acoustic basement are scarce, due to the lack of deep seismic penetration lines and deep well data. The most reliable seismic and drilling data were acquired in the western part of the basin, along the Eastern continental margin of the India micro-continent. Multi-channel seismic (MCS) data, calibrated by wells, were published by Bastia and Radhakrishna (2012*).* They interpret the western flank of this basin as a starved passive margin. Here, the deepest seismic horizons were reached by drilling and sediments were dated Valanginian.

Eastward, recent oil and gas exploration is presently intensifying offshore Bangladesh and Myanmar, but most of the wells did not reach the Paleogene and still remain confidential. Part of our new MCS data collected offshore western Myanmar in 2006 (Maurin and Rangin, 2009b) and partly used in this paper, were only calibrated for the Neogene.

On land, the most representative sequence that could be eventually correlated with the studied offshore area, crops out in the Rajmahal area, which has a special significance for the rifting and drifting history of the Bay of Bengal. Here, Precambrian metamorphosed continental rocks and tholeiitic lava trap flows *(Rajmahal volcanic traps)* were found. Hornblende and olivine basalts, andesite and intercalations of tuffs and ashes dated between 118 and 115 Ma mainly form this hot spot volcanism (Kent *et al.,* 2002). It is generally interpreted as a drifted fragment of the Kerguelen Large Igneous Province (LIP). In Bangladesh, this volcanism is disconformably covered by a few hundred meters of coarse sandstones and argillites (Alam *et al.,* 2003) reworking the underlying volcanic rocks.

The terminal stage for cessation of LIP Rajmahal volcanism was dated around 117 Ma (Kent *et al*., 2002). Consequently, the cessation of North Bay of Bengal rifting has to be of the same age. Drifting of India along the 90°E Ridge was dated 84-82 Ma (chron 34 to 38 Ma) into the South (Duncan and Storey, 1993). The oldest identified E-W magnetic anomalies of the India northern drift are dated Santonian (82 Ma, Royer *et al*., 1988), but incipient drift stage could have been initiated earlier, around 100 Ma according to Gibbons *et al*. (2013). This uncertainty is explained by the poor dating of the 118-84 Ma magnetic quiet zone.

Immediately south of our study area, at 18°N, the seismic data published by Basu *et al.* (2010) shows the same NE-SE Cretaceous tilted blocks in the basement that could be interpreted as stretched continental crust. Southward the imprint of the 90°E ridge is erasing this rift fabric.

However, this transition from rift to drift is supported by the new global marine model from CryoSat-2 and Jason-1 data (Figure 1) and reveal the easternmost N-S transform faults related to the drift stage extend up to 13°N, much farther North than the accepted boundary of Chron 34 as shown in Figure 1 (Sandwell *et al*., 2014).

In the present state of our knowledge, we think NW-SE trending Gondwana rift structures observed in the NE Bay of Bengal basin could be as young as 100 Ma. In conclusion, we suggest the transition from Gondwana rifting and India oceanic spreading could have occurred around 100 Ma or even before.

Interpretation of the multi-channel seismic lines acquired in the northern part of the Bay of Bengal

We have collected MCS data offshore Myanmar in 2006 B2 cruise (Maurin and Rangin, 2009a, 2009b) (Figure 2) using a 4.5 km long streamer with a 3000 in^3 air gun source. Some of these data were used in this study (Figure 2*).*

Late 2007-early 2008, we have collected new MCS data offshore Bangladesh. This B3 cruise was conducted on the R/V Osprey Explorer using a 10.05 km long streamer with 804 channels, towed at a water depth of 8 m and with a shooting interval of 50 m. The seismic source was a 6180 in^3 tuned air gun array of 64 air guns towed at a depth of 8 m. 3500 km of MCS data were acquired (Figure 2).

Refraction data were acquired during the B3 cruise along three MCS profiles (Figure 3) and results were recently published (Sibuet *et al.*, 2016)**.** Nine OBSs were deployed along each of the profiles, with a 20-km distance between OBSs. This refraction experiment using OBSs from Taiwan University and the air gun source of the ship was conducted during the acquisition of three MCS lines, one across the shelf break (B3-5), and two parallel to the shelf break, one north of it (B3-11) and one south of it (B3-02). The refraction processing was completed in the IFREMER Center of Brest. We have used part of the seismic velocities resulting from this refraction study to better constrain the seismic layers identified in the MCS lines.

To complement the tectonic understanding of the northern Bengal basin, we have also used the published works of Bastia and Radhakrishna (2012) and Nemcock *et al.* (2012) who have partly interpreted GXT MCS lines located along the East coast of India (Figure 2).

Lines across the northern termination of the Bengal basin

The 2007 B3 survey was concentrated along and across the shelf break area between 20° and 21°N (Figure 3). Two long seismic lines were also acquired along the west flank of the 90°E Ridge in the deepest part of the Bengal basin (Figure 2). The interpretation of the B3 seismic lines is presented here and complemented by the interpretation of some other seismic lines acquired during the 2006 B2 survey across the northernmost termination of the offshore Indo-Burma Ranges (Figure 3).

Seismic lines interpretation

We here discuss the results and interpretation of the B3 E-W and NW-SE trending lines complemented by some E-W trending B2 lines to illustrate the structure of the northernmost deep Bengal Basin. Then, we will discuss the N-S trending lines across the Bengal shelf break.

Line B3-02 (Figure 4) shows the most complete dated seismic sequences correlated with the easternmost GXT ION MCS line of the Mahanadi basin published by Bastia and Radhakrishna (2012)**.** The total thickness of the Cenozoic sediments reaches 7.5 s TWT and was conformably deposited on a thin (<1 s TWT) highly reflective seismic layer shown in green. This undisturbed layer was deposited disconformably on the complex crustal basement. It is attributed to the pelagic Latest Cretaceous-Paleocene sequence corresponding to the northern drift of India and was continuously mapped down to 17°N, all along the Bengal basin, blanketing the 90°E Ridge basement (Maurin and Rangin, 2009a). At this latitude, the B2-01 line is calibrated with DSDP drilling hole 217, indicating a Campanian-Maastrichian-Paleocene age for the pelagic sequence (Figure 5). No structures were observed below the upper crust brittle layer identified here as the lower crust.

Using these data, we propose that the overlying Cenozoic sedimentation on line B3-02 started in the late Paleocene-Eocene, at the time of the incipient collision of Greater India with Eurasia. The top Oligocene was deposited on a relatively thin sequence of late Paleocene-Eocene sediments, demonstrating that this basin was far away from the Himalayas and probably fed by eastward India/Sunda collision in Myanmar. These Early Paleogene sediments were deposited extensively along the eastern margin of the basin along the coast of Myanmar, particularly along the deep channels present along the Arakan range, offshore Myanmar (Rangin *et al.*, 2013).

A continuous and thin seismic sequence (less than 1 s TWT) is observed at the base of the thick Cenozoic sequence, and was deposited disconformably on the underlying crust. This thin undeformed seismic sequence was also deposited on the 90°E Ridge volcanic basement that fringes the Myanmar continental margin down to 16°N (Maurin and Rangin, 2009a). At this latitude (Figure 5), we were able to correlate the seismic sequence observed on lines B2-01 and B2-15 with DSDP Leg 22 Hole 217 located southward on the ridge (Moore *et al.*, 1974). At DSDP Site 217, the drilled pelagic section is mainly formed by Campanian-Maastrichian cherts, nanno-chalk and porcellanic limestone, all testifying a pelagic environment. Numerous blocks with the same lithology (*Globotruncana* sp., porcellanic limestone) engulfed in debris flows present along the southern side of the Arakan Range were observed and collected. These deformed and chaotic debris flows were interpreted by Maurin and Rangin (2009a) as 90°E Ridge fragments wrenched and incorporated along the Sunda plate margin in southern Myanmar.

In the northernmost part of the Bay of Bengal, the topographic and gravity signature of the ridge disappears rather completely (Figure 3). Here, the nature of acoustic basement imaged in Figure 4 is formed by two seismic layers: an upper and a lower crustal seismic layers differentiated on the refraction data (Sibuet *et al.*, 2016), the Moho being located at around 13 s TWT (Figure 4). Here, the upper brittle upper crust, with refraction velocities ranging from 4.7 to 5.5 km/s, is marked by eastward dipping reflectors that could represent eastward dipping volcanic reflectors or the shoulders of crustal tilted blocks with progressive sedimentary fanning during block tilting. We globally favor this later interpretation on the basis of the good axial correlation of these dipping reflectors showing a rather continuous NE-SW trend (Figures 6 and 7).

The upper crust layer lies on the thicker and opaque homogenous lower crust characterized by 5.5 to 7.7 km/s refraction velocities. These crustal velocities are too low for an oceanic basin floor and are interpreted as thinned continental crust intruded by volcanics (Sibuet *et al*., 2016). When transformed in depth, the thickness of the two crustal layers is 15 km suggesting the presence of a thinned continental crust formed during the crustal stretching associated with the Gondwana fragmentation.

Previously published data show that the crust was oceanic beneath the northern BoB. However, these results were not reliable as the sediment thickness is too large (Curray, 1994 ; Verma and Mukhopadhyay, 1977 and Uddin and Lundberg, 2004). SIbuet et al. (2016) refraction results clearly contradict this view. Their results do not fit also the velocity trends of the North Atlantic volcanic margins as discussed by Talwani et al. (2017). This view is also supported by deep seismic refraction and reflection profiles acquired across the Hatton bank, which show that the melt is intruded into the lower thinned continental crust as sills, which cross-cut the continental fabric, rather than as an 'underplate' of 100 per cent melt, as it was often assumed in the past (White et al., 2008). Therefore, the crust of the northern BoB is thinned continental crust with intruded volcanics wth a possibility that the high lower crustal velocity might be due to the presence of sills linked to the passage of the Kerguelen hot spot after the continental rifting of the northern BoB.

The west facing normal faults bounding these tilted blocks are difficult to image on our seismic data but lines B3-14 and B3-02 (Figure 6) also reveal the presence of NE-SW trending faults bounding the dipping reflectors. The correlation between these tilted blocks across the whole studied area confirms this interpretation (Figure 7). The density of B3 seismic lines is sufficient to support the hypothesis that these NE-SW rifting trends were created by NW-SE continental crustal extension simultaneously with the occurrence of a LIP volcanism. The major volcanic centers identified in our survey are located along some of these major fault traces suggesting volcanism and faulting are intimately linked during the continental extension processes.

A similar highly faulted brittle crust basement was evidenced offshore Myanmar by Basu *et al*. (2010), immediately south of our study area, between 17.5°N and 19°N. From their seismic data, half-grabens affecting the northernmost part of the 90°E Ridge were described. Grabens are filled by synrift clastic sediments indicating potential reservoir plays. This fractured basement is disconformably covered by a thin layer similar to our Late Cretaceous-Paleocene layer. In the same area, Lines B2-11 and B2-02 (Figure 2) reveal a similar geometry on top of the ridge (Maurin and Rangin, 2009a). We were able to trace the ridge structural basement fracturation between 14°N and 15°N, in the Coco Channel area located along the maritime border with India (Line B2-15, Figure 2). We conclude that the highly fractured Mesozoic Bengal basin basement disconformably covered by the pelagic Late Cretaceous sediments extends all along the Myanmar coast from Bangladesh to Andaman Islands.

A synthetic cross-section across the northern Bengal basin

On the basis of previous observations, a synthetic cross-section of the northern Bengal basin was built (Figure 8). We think the N-W facing normal fault system affecting the thinned Bay of Bengal continental crust in its western part, is the conjugated passive margin for the basins developed along the Indian eastern coast showing east facing normal faults. The Mahanadi basin is clearly N-E trending as well as the facing west Bengal basin in our study area, and most of this narrow basin is floored by thin continental crust affected major S-E facing detachments (Nemcok *et al*., 2013) and blanketed by thick Mesozoic and Cenozoic sediments.

In this synthetic cross-section, the eastern part of the basin on the Myanmar side is much wider than its counterpart in the Mahanadi basin, suggesting an asymmetric rift geometry probably created by simple shear, a classical model for continental crust extension (Wernicke, 1985). No oceanic crust has been clearly emplaced in the axis of this asymmetric rift that fits the deepest part of the northern Bengal basin in the S-W prolongation of the "Swatch no Ground" canyon. Flat reflectors covered by Late Cretaceous sediments are interpreted by Nemcok (2013) as mantle domes tops and oceanic crust, with a well imaged Moho. We interpret this narrow rift axis segment as the site of mantle dome exhumation only at the axis of this continental rift axis. In this NW-SE synthetic cross-section, the asymmetric northern Bengal rift is bordered eastward by the 90°E Ridge. No strike-slip faults have been detected along the transect between the East India Coast and the 90°E Ridge, suggesting the whole rift was drifted without internal deformation. Major active strike-slip faults are present eastward of the 90°E ridge along its boundary with the Arakan Belt (Maurin *et al*., 2009a and b; Rangin *et al*., 2013). The Arakan Belt is a complex system formed by distinct amalgamated terranes to the Sunda plate, such as the Burma continental block. This complex Early Paleocene-Eocene India/Sunda collision zone is illustrated in the right hand-side of the section.

Then, we assume that the northern Bengal basin floored by attenuated continental crust was not deformed since the end of the Gondwana rifting and was preserved in its structural integrity since then. The Bay of Bengal crust at the latitude of our study appears as rigid. It was never affected by significant post-rift and post-drift deformation at the latitude of our study. This suggests the hydrocarbon potential of this rift sealed by the continuous syn-drift pelagic Late Cretaceous Paleocene sequence is large. The presence of intense heat flow affecting this thin continental rift zone during stretching of the continental crust was enhanced by the volcanic intrusion of the Kerguelen hot spot volcanism during the fragmentation of Gondwanaland.

Termination of the Bay of Bengal below the Bengal delta in Bangladesh

The B3 N-S trending seismic lines crosscut the Bengal delta fan, which trends constantly E-W over 200 km, from the Swatch No Ground Canyon into the west, to the Indo-Burma ranges into the east (Figures 2 and 3). From West to East, the E-W linearly prograding delta front was surveyed along the N-S trending lines B3-01, B3-10, B3-09, B3-09, B3-06, B3-05 B3-04, B3-03 and B3-15 (Figure 3). The shelf break appears to be perfectly aligned along these sections.

Line B3-05 (Figure 9) is representative of the numerous N-S transects across the recent southward progradation of the Ganges delta as well as the structure of the thinned continental crust at depth. It is also one of the lines selected for the seismic refraction experiment. Below the sedimentary pile, the southern part of this profile shows a small high interpreted as a pre-Late Cretaceous volcano probably built during the Bengal basin Mesozoic rifting phase. It could be one of the numerous LIP volcano injected through the thinned continental crust. Deep reflectors of the upper continental crust are gently flexured below the volcano, indicating the volcano load was emplaced after the thinning of the continental crust.

On the time section, the Late Cretaceous-Paleocene thin layer (3 in Figure 9) was clearly deposited disconformably on the deeper sequences. Reflectors of sequence 4 are gently folded just below the present-day delta front. These reflectors are similar to those observed northward in the Sylhet basin or westward, along the east India continental margin and could represent a rather thick Mesozoic Gondwana syn-rift sedimentary unit.

Northward, the upper Neogene and Quaternary sedimentary sequence 1 clearly shows the delta front southward progradation, where at depth, the Paleogene-Early Neogene and Late Cretaceous sequence 3 is gently flexured. All these sediments appear to onlap disconformably a basement high (delta front high) exaggerated by the seismic pull-up on this time section. However, when the section was flattened at the base of sequence 1 the basement high is still observable. The pull-up effect on this time-section does not also entirely explain the gentle folding affecting sequence 2. This deep rooted folding could be interpreted as recent, and could explain the 200 km E-W trending delta shelf break. This linear delta front could be guided at depth by an active E-W trending crustal uplift comparable to the Shillong plateau uplifted since a longer time.

However, onlaps of the Cretaceous sequence 4 on this delta front high suggest that this basement high existed before its recent tectonic reactivation. This large anticline could be inherited from the Precambrian E-W trending structures present in the Indian craton, in the Singhum area (Geological map of India). It confirms that the crust below the delta front and the onshore Bengal basin is continental. We propose this tectonic reactivation is coeval with the Shillong plateau uplift initiated around 5 Ma (Bilham and England, 2001). We think that both the EW alignment of the recent delta shelf break above the delta basement high at depth as well as the Shillong plateau uplift are controlled by the tectonic reactivation of old Indian craton structures.

In Figure 11, the Bay of Bengal extends northward below the Bengal onshore delta. Westward, it is bounded east of the Indian Precambrian craton by the so-called “Hinge zone” (Uddin and Lundberg, 2004) characterized by Nummulites bearing Eocene shelf limestone (Johnson and Alam, 1991). We have sampled the same neritic limestone on the Myanmar side in Ramree (at 19°N) and Buruanga Islands (at 20°N) along the Kaladan shear zone running along the outer Indo-Burma belt (Maurin and Rangin, 2009b). A possible interpretation is that the Bay of Bengal and the Bengal basin northward now bordered eastward by right-lateral strike-slip fault belt along the Indo-Burma Ranges, was closing axially “en doigt de gant” during the Mesozoic, before the India/Sunda collision and dextral wrenching. In this hypothesis, the paleogeographic closure of the Bay of Bengal and its onshore extension in the Bengal Basin was acquired during the Mesozoic rifting of Gondwana as shown in the simple sketch of Figure 12. Thus, the studied area (marked by a square) could have been located at the northern termination of a larger rift basin opened between the Indian craton and the Elan Bank continental sliver. The basin was filled by Mesozoic clastic sediments injected by volcanism of the large LIP of the Kerguelen hotspot (KHS on Figure 12). This hot spot volcanism crops out in the Rajmahal (RJT) and Sylhet traps north of the present Bengal basin drifted away from Gondwanaland. In the mid-Cretaceous time, the Bengal basin was progressively detached from Antarctica and Australia. The drifted part of the Bay of Bengal attached to India was sealed by pelagic sediments during its Late Cretaceous and Paleocene drifting migration toward Eurasia. The Bay of Bengal is considered as a new challenge for hydrocarbon exploration, the source rocks being probably located below the Late Cretaceous unconformity.

Conclusions

This study of MCS data in the northernmost part of the Bay of Bengal reveals the presence of a continental rift formed during the fragmentation of Gondwana, before the Late Cretaceous. The refraction data collected during the same cruise indicate that the crust is of continental origin and strongly thinned (15-km thick) during the Gondwana rifting. Offshore Bangladesh, the SE flank of this rift zone was only imaged in our study area. This western rift flank is present along the eastern coast of India but is here very narrow, indicating a strongly asymmetric continental rift created by simple shear extension mechanism in the Gondwana continental crust. During the Bay of Bengal opening, some of the rift normal faults were injected by pre-late Cretaceous LIP volcanism. We suggest this volcanism is part of the Rajmahal and Sylhet volcanic traps, considered as drifted fragments of the Kerguelen LIP province, cropping out immediately north of the study area and injected in the thick continental crust of the Indian craton. We think the northern Bay of Bengal attenuated crust was formed immediately southward of the drifted Rajmahal and Sylhet traps LIP volcanism, detached during the mid-Cretaceous from its mother land, the Kerguelen hot spot plateau in Gondwana.

The northern termination of the Bay of Bengal crust extends very far to the north, below the onshore Bengal delta, where it was interpreted as oceanic crust (Uddin and Lunberg, 2004). We believe this crust is here attenuated continental crust, flexuring below the uplifted continental Shillong plateau.

Eastward, this basin disappears below the wrenched fold and thrust belt of the Indo-Burma Ranges. We interpret this wedge as related to combined effect of N-S dextral wrenching along the India/Sunda plates boundary and S-W directed East Himalaya crustal flow of the East Himalaya syntaxis, and not to an active subduction of the Bay of Bengal below Sunda. Consequently the northern Indo-Burma wedge is just a wide WSW directed Neogene gravitational flow and not an active subduction zone (Rangin *et al.*, 2013). This implies the northern paleogeographic closure of the Bay of Bengal floored by attenuated continental crust was not significantly modified, but just blanketed by this sedimentary East Himalaya sedimentary and crustal flow related to the East Tibetan plateau collapse.

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Figure captions

Figure 1: Transition from rifting to spreading in the Bengal basin plotted on Mercator projected 1-min satellite derived free-air gravity field map (Sandwell *et al.*, 2014). Chron 34 (Santonian in red) and younger magnetic anomalies southward fit the steady state drift of India and attached Bengal basin. The satellite image reveals deep buried

structures in this basin: Some of the N-S transform faults can be traced up to 13° N, much farther than chron 34, suggesting India drifting was initiated much earlier, during the Mid-Cretaceous. In the northernmost part of this basin, NE-SW trending structures can be detected East and South of the study area, and can be part of the Gondwana continental rifting stage.

Old magnetic lineaments proposed by Gibbons *et al*. (2014) are also plotted on the figure. The frame indicates the study area discussed in this paper.

Stars indicate DSDP and ODP drill sites: DSDP 217, ODP 758 and DSDP 216 from N to S respectively.

Figure 2: Multi-channel reflection seismic data recently acquired in the northern Bengal basin. Our seismic lines acquired in 2006 (labeled B2) and 2007 (labeled B3) are in red and GXT lines (acquired by ION GXT and ONGC) partially published by Desa *et al.* (2013) and Nemcock *et al*. (2013) along the coast of India are in blue. Track-lines are plotted on the GEBCO shaded bathymetry map.

Figure 3: B3 cruise seismic survey at the northern termination of the Bengal basin offshore Bangladesh. Acquired seismic lines are plotted on the free-air gravity map (Sandwell *et al*., 2014). Refraction data were acquired along lines B3-02, B3-05 and B3-11 (Sibuet *et al*., 2016). The north Indo-Burma ranges fold belt anticlines are plotted in red.

Figure 4: Top: Line drawing interpretation of Line B3-02. Cenozoic sediments (Late Paleogene to present-day) were dated by correlation with the East Indian passive margin dated sequences. The Cenozoic sediments overlain a thin but highly reflective seismic sequence attributed to the Late Cretaceous. This highly reflective sequence

could represent the condensed pelagic sequence deposited during drifting of India with the attached Bengal basin. The drifted sequence was deposited disconformably on tilted fault blocks dissecting Early Cretaceous (or older) deposited sediments during the rifting phase of Gondwana. Bottom: Corresponding refraction time-section with distinct thinned continental crustal layers obtained by refraction (Sibuet *et al*., 2016). Two main crustal layers were identified, a brittle upper crust and a lower crust with a total thickness of 15 km.

Figure 5: Correlation between Line B2-01 offshore south Arakan in Myanmar and Drill Site 217 (DSDP Leg 22, Moore *et al*., 1974). The high reflective layer observed on the B2-01 line crossing the 90°E Ridge can be precisely dated Campanian, Maastrichian and Paleocene.

Figure 6: Correlation of tilted blocks on lines B3-14, B3-02 and B2-11 supporting the N50°E trend of the Northern Bengal crust fabric.

Figure 7: N50°E trending tectonic fabric of this area plotted on free-air gravity anomaly map. Dominant NE-SW trending listric normal faults are shown in green as well as the northernmost termination of the 90°E Ridge discussed by Maurin and Rangin (2009a). The N50°W Arakan fold and thrust belt front is marked by a strong positive anomaly. This gravity collapsed fold belt extends westward along the E-W trending Bengal delta shelf break (Maurin and Rangin, 2009b). Free-air gravity anomaly map is used as background. Tilted sequences are dipping SW and are truncated by the following normal fault (barbed green lines). Main volcanic centers are shown in blue and were injected along some normal faults.

Figure 8: NW-SE trending synthetic cross-section of the northern Bay of Bengal. This section was drawn perpendicularly to the NE-SW extension direction of the basin. The N-E part of this section represents the observed data in our study area. In this cross-section, we have used the B2-11 and B3-02 time sections transformed to depth using refraction data. To the west, the synthetic section of the Mahanadi basin was built following Bastia and Radhakrishna (2012), Desa *et al*. (2013) and Nemcok *et al*. (2013). The onshore Myanmar cross-section was simplified from Rangin *et al.* (2013). Location of cross-section is plotted on the Bengal basement map insert (s. TWT).

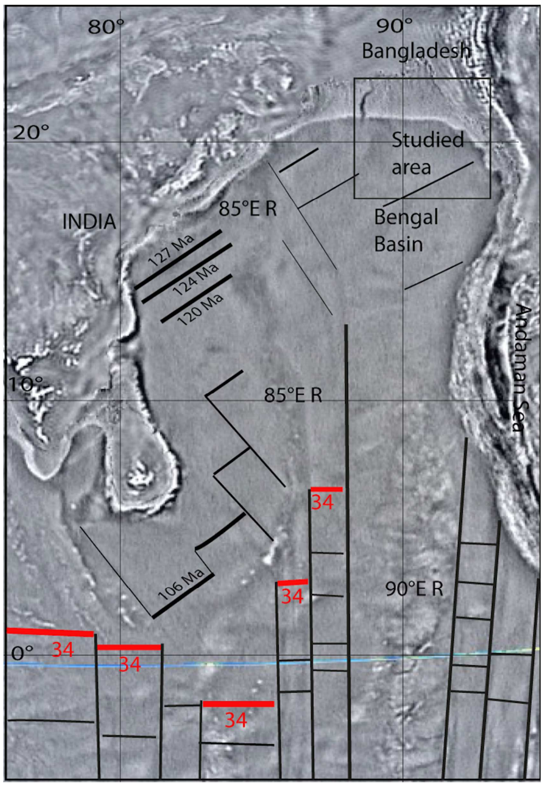
Figure 9: Line B3-05 interpretation showing the recent (late Miocene to present) progradation of the Delta front (1) and the Paleogene-Lower Neogene (2) gently folded with the late Cretaceous sediments (3) just below the delta progradation. The E-W basement delta front high (4) cannot be only explained by a pull-up artifact. Location of Line B3-05 on Figure 3. * indicates mass-sedimentary flows. m=multiples.

Figure 10: B3 lines across the Delta shelf Break. These profiles acquired along the 300 km long E-W shelf break perfectly fits the crustal uplift located at depth and the delta front above. Location of seismic lines in Figure 3. The N-S line B3-01 is located into the west and B2-03 into the east.

Figure 11: Northern paleogeographic closure of the Bengal basin onshore Bangladesh. Main active structures are shown in red. Simplified N-S cross-section along the axial termination of the Bengal basin. The map and the simplified cross-section below are modified from Uddin and Lunberg (2004).

Figure 12: Tentative reconstruction of the Bay of Bengal rift zone before detachment and northward drift of India. KHS: Kerguelen hot spot, RJT: Rajmahal LIP traps, ST:

Silhet LIP traps, BR: Broken Ridge. The green line is the speculated fracture zone along Elan Bank. The detachement of drifted India is supposed to be the future trace of the 90°E Ridge. KHS is supposed to be placed along the oceanic Enderby basin (shown in pink). The red star is the speculated India-Bengal /Eurasia rotation pole during the incipient India-Bengal drifting.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90°E R
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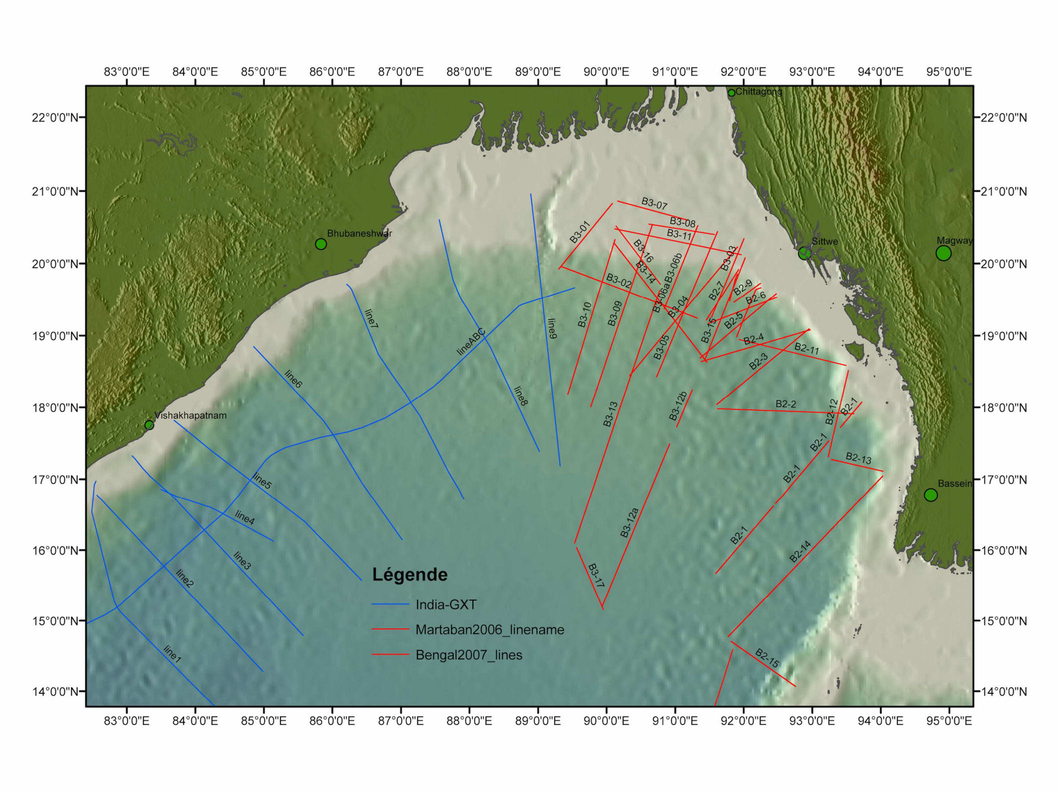

Légende
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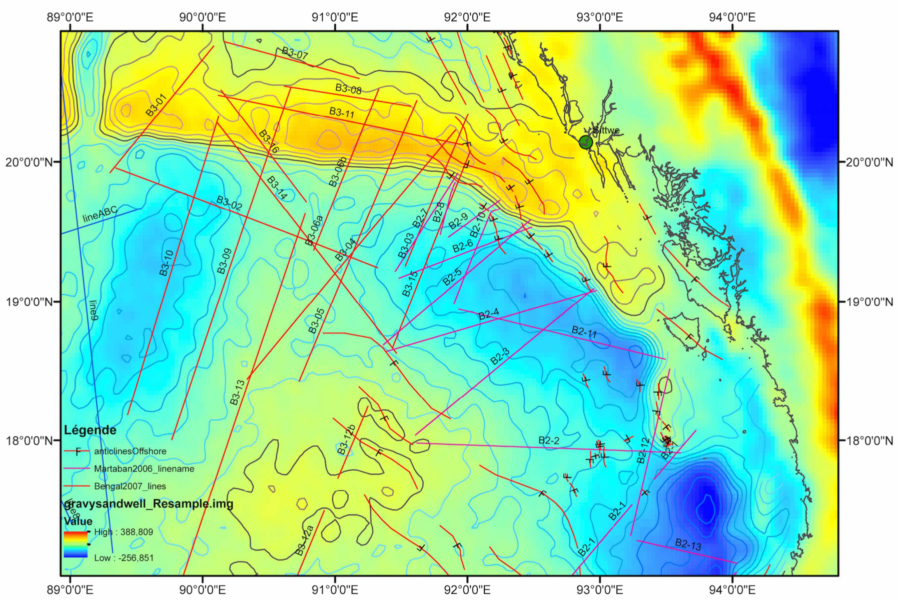
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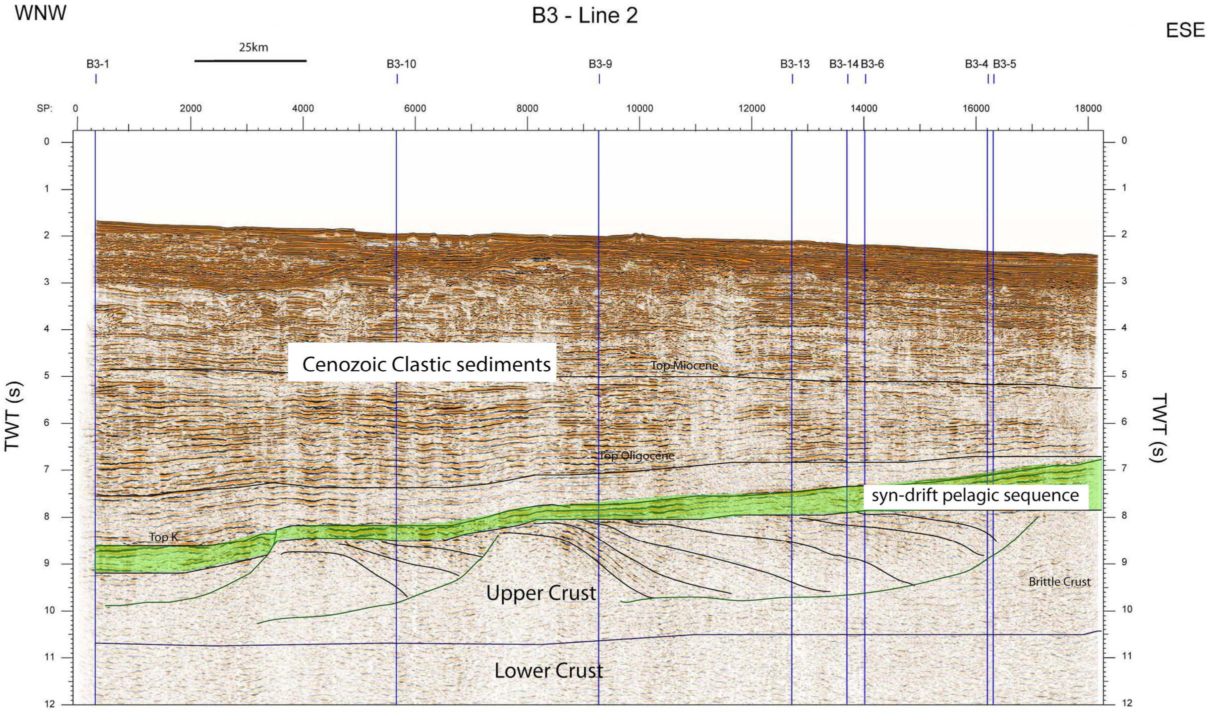
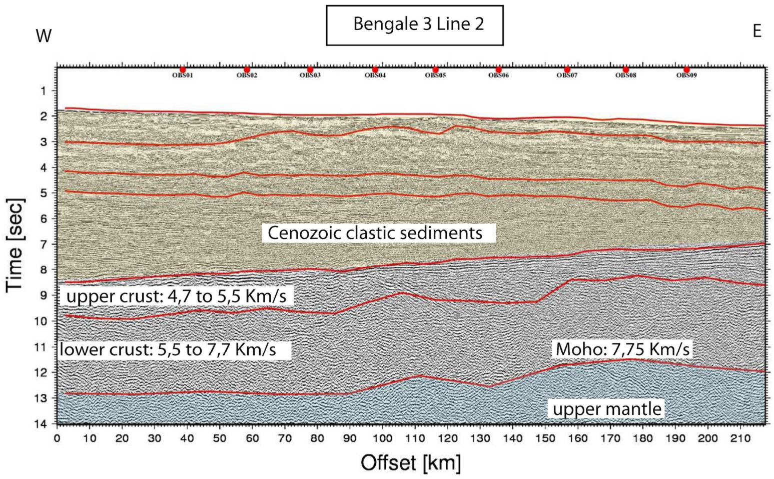

WNW
B3 - Line 2
ESE
25km
B3-1
B3-10
B3-9
B3-13
B3-14
B3-6
B3-4
B3-5
SP:
TWT (s)
Cenozoic Clastic sediments
Top Miocene
Top Oligocene
syn-drift pelagic sequence
Top K
Upper Crust
Brittle Crust
Lower Crust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W
E
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Cenozoic clastic sediments
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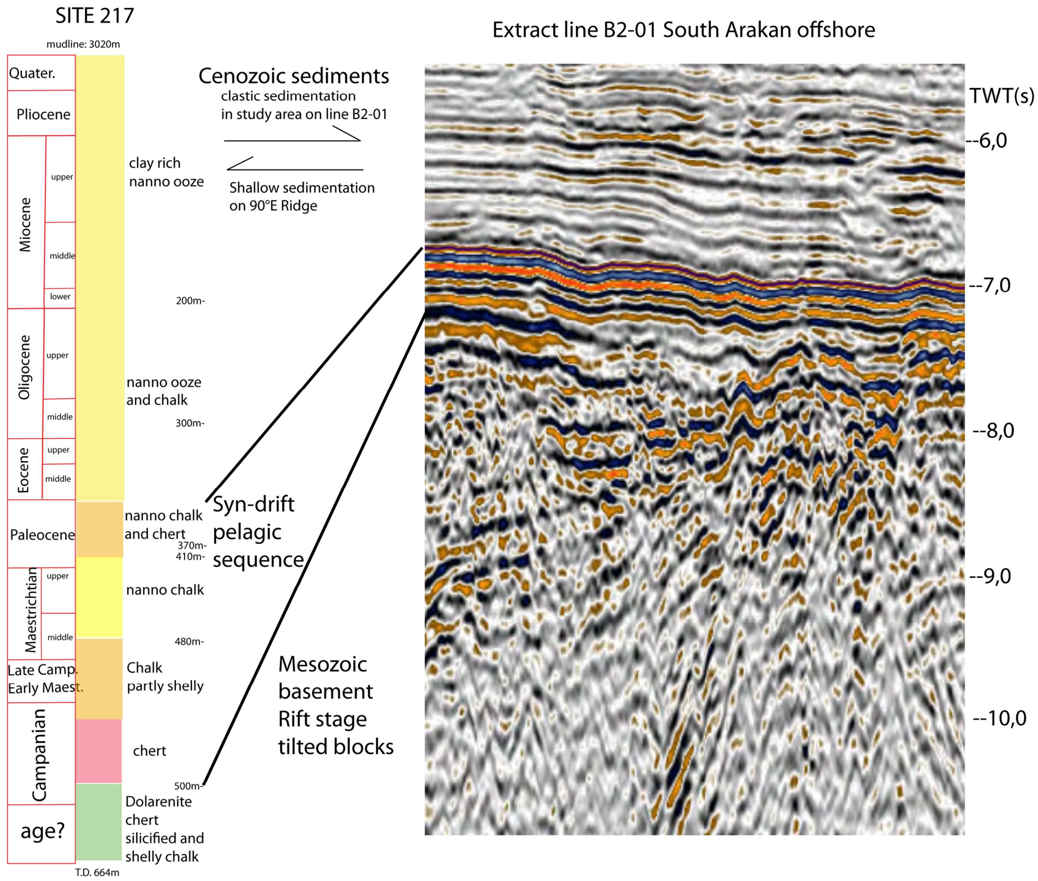
lower crust: 5,5 to 7,7 Km/s
Moho: 7,75 Km/s
upper mantle
Offset [km]


SITE 217
mudline: 3020m
Quater.
Pliocene
Miocene
upper
middle
lower
Oligocene
upper
middle
Eocene
upper
middle
Paleocene
Maestrichtian
upper
middle
Late Camp.
Early Maest.
Campanian
age?
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nanno ooze
200m-
nanno ooze
and chalk
300m-
nanno chalk
and chert
370m-
410m-
nanno chalk
480m-
Chalk
partly shelly
chert
500m-
Dolarenite
chert
silicified and
shelly chalk
T.D. 664m
Cenozoic sediments
clastic sedimentation
in study area on line B2-01
Shallow sedimentation
on 90°E Ridge
Syn-drift
pelagic
sequence
Mesozoic
basement
Rift stage
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Extract line B2-01 South Arakan offshore
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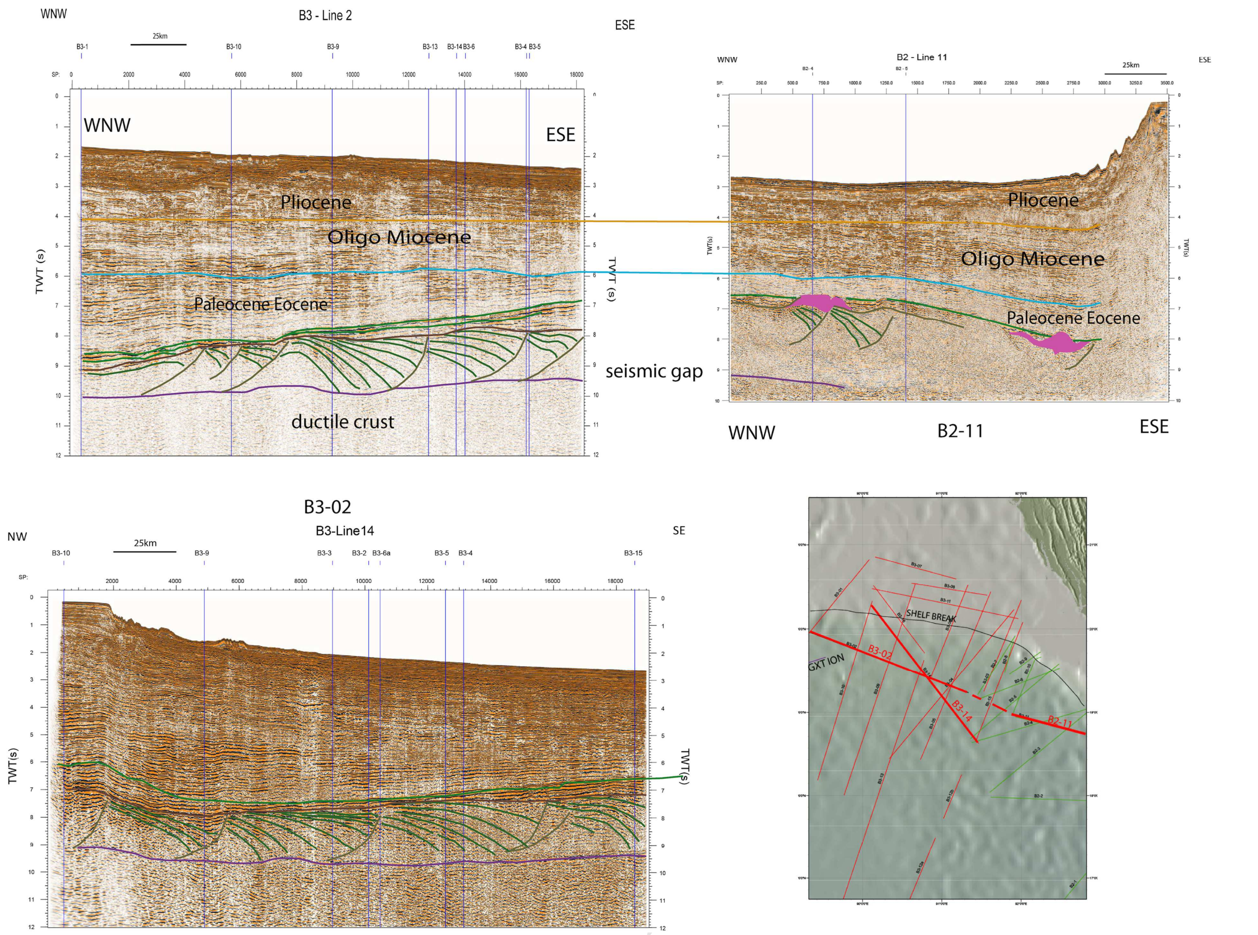
WNW
B3 - Line 2
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25km
WNW
ESE
Pliocene
Oligo Miocene
Paleocene Eocene
seismic gap
ductile crust
TWT (s)
B2 - Line 11
Pliocene
Oligo Miocene
Paleocene Eocene
WNW
B2-11
ESE
B3-02
B3-Line14
NW
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25km
TWT(s)
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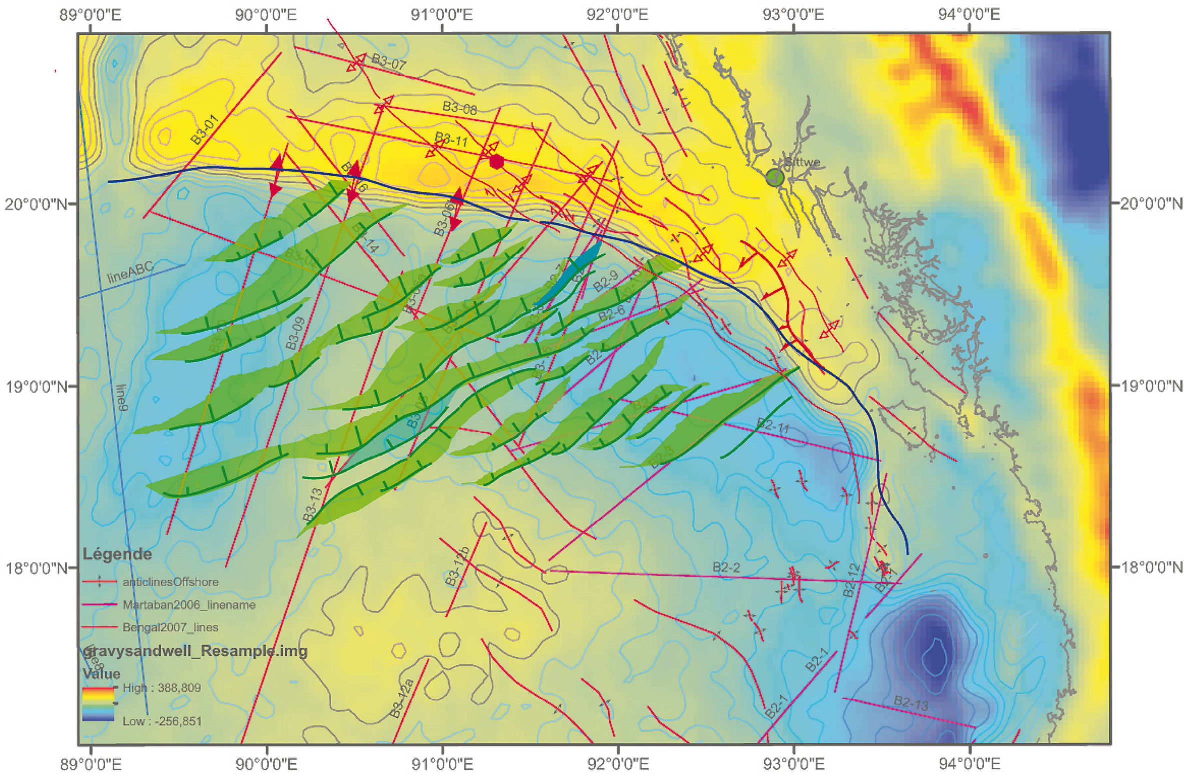
B3-02
B3-14
B2-11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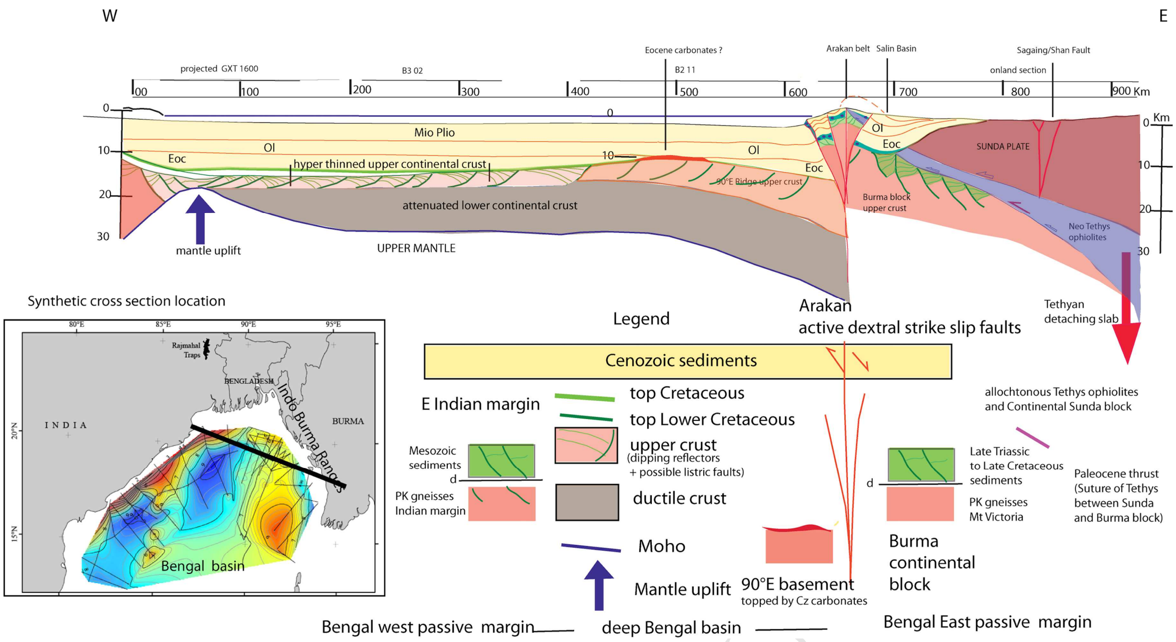
Low : -256,851


W
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B3 02
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B2 11
Arakan belt
Salin Basin
Sagaing/Shan Fault
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300
400
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800
900 Km
Mio Plio
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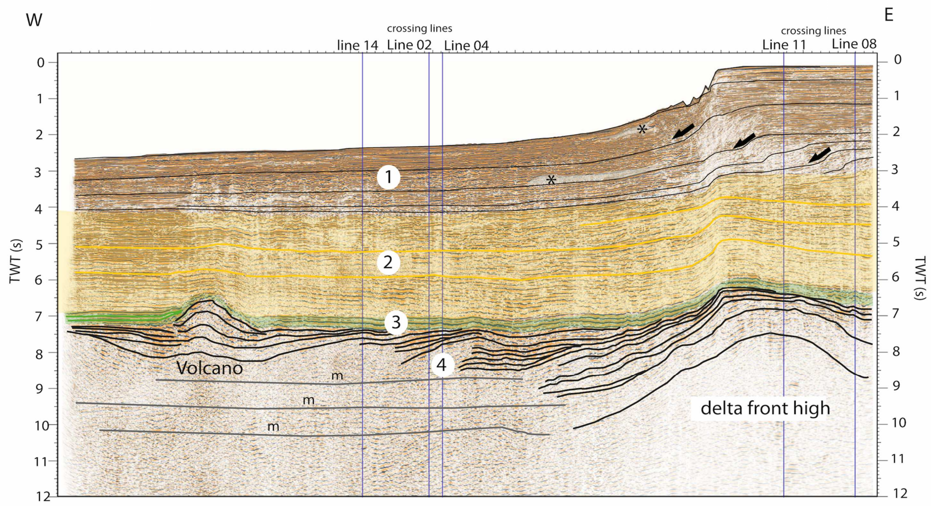
Ol
hyper thinned upper continental crust
attenuated lower continental crust
mantle uplift
UPPER MANTLE
90°E Ridge upper crust
Burma block upper crust
SUNDA PLATE
Neo Tethys ophiolites
Synthetic cross section location
INDIA
BANGLADESH
BURMA
Rajmahal Traps
Indo Burma Range
Bengal basin
Legend
Arakan
active dextral strike slip faults
Tethyan detaching slab
Cenozoic sediments
E Indian margin
top Cretaceous
top Lower Cretaceous
upper crust
(dipping reflectors
+ possible listric faults)
Mesozoic sediments
PK gneisses Indian margin
ductile crust
Moho
Mantle uplift
90°E basement
topped by Cz carbonates
allochtonous Tethys ophiolites and Continental Sunda block
Late Triassic to Late Cretaceous sediments
PK gneisses Mt Victoria
Paleocene thrust (Suture of Tethys between Sunda and Burma block)
Burma continental block
Bengal west passive margin
deep Bengal basin
Bengal East passive margin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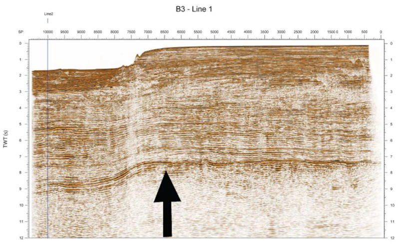

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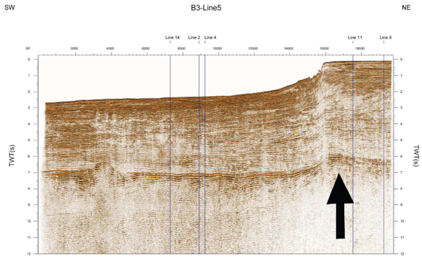

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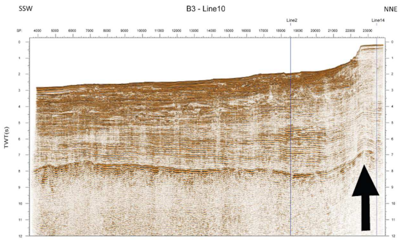

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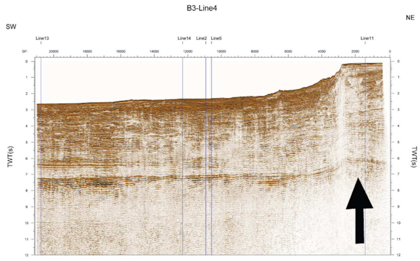

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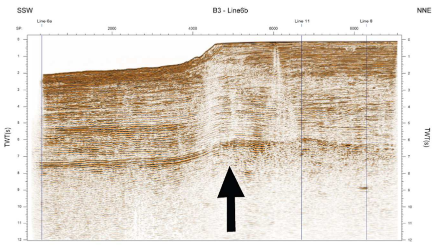

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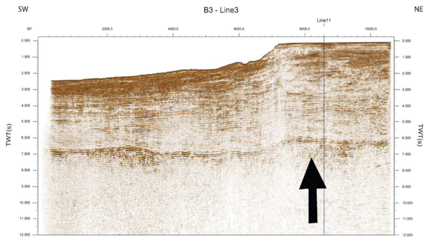

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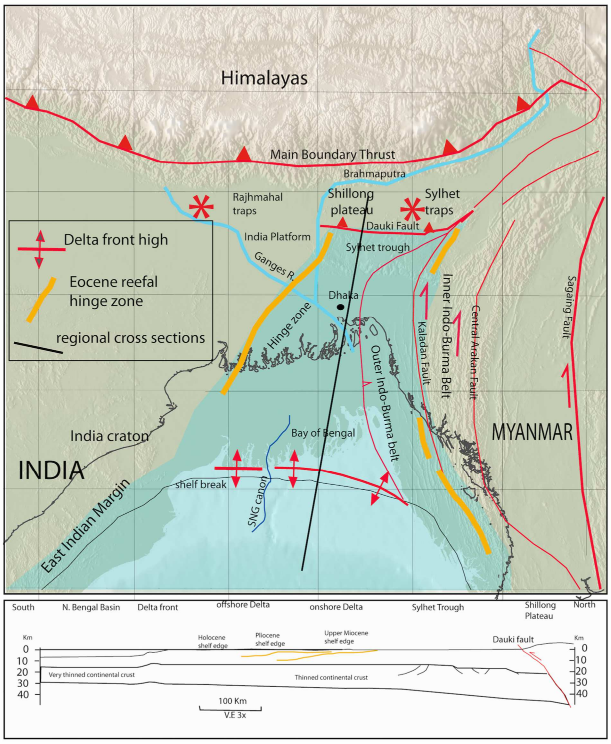
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Main Boundary Thrust
Brahmaputra
Rajhmahal traps
Shillong plateau
Sylhet traps
Dauki Fault
India Platform
Sylhet trough
Ganges R.
Delta front high
Eocene reefal hinge zone
regional cross sections
Hinge zone
Dhaka
Inner Indo-Burma Belt
Kaladan Fault
Central Arakan Fault
Sagaing Fault
Outer Indo-Burma belt
India craton
INDIA
Bay of Bengal
MYANMAR
East Indian Margin
shelf break
SNG canon
South
N. Bengal Basin
Delta front
offshore Delta
onshore Delta
Sylhet Trough
Shillong Plateau
North
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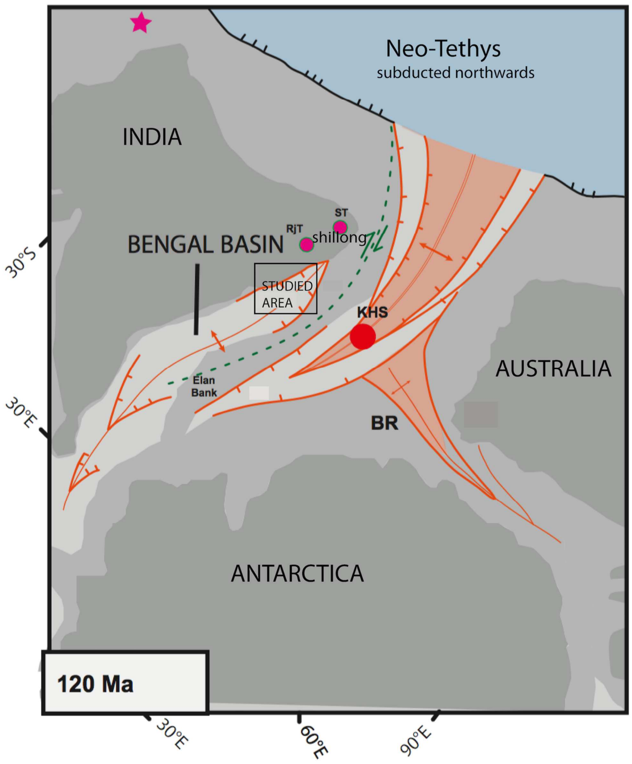
Pliocene shelf edge
Upper Miocene shelf edge
Dauki fault
Very thinned continental crust
Thinned continental crust
100 Km
V.E 3x


Neo-Tethys
subducted northwards
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120 Ma
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