

## **Internal structure of the 85°E Ridge, Bay of Bengal: Evidence for multiphase volcanism**

**M. Ismaiel<sup>1,2</sup>, K.S. Krishna<sup>1,2\*</sup>, K. Srinivas<sup>3</sup>, J. Mishra<sup>4</sup>, D. Saha<sup>5</sup>**

<sup>1</sup>Academy of Scientific and Innovative Research, CSIR-National Institute of Oceanography,  
Dona Paula, Goa - 403004, India

<sup>2</sup>Geological Oceanography, CSIR-National Institute of Oceanography,  
Dona Paula, Goa -403004, India

<sup>3</sup>CSIR-National Institute of Oceanography, Regional Centre, 176,  
Lawsons Bay Colony, Visakhapatnam 530 017, India

<sup>4</sup>KDM Institute of Petroleum Exploration, Oil and Natural Gas Corporation Ltd, 9,  
Kaulagarh Road, Dehradun - 248195, India

<sup>5</sup>Oil and Natural Gas Corporation Ltd, Geophysical Services, A&AA Basin,  
Luit Bhavan, Cinnamara, Jorhat – 785704, India

**\*Corresponding author:** K.S. Krishna (krishna@nio.org)

### **Key Points:**

- 1. High-quality seismic data image the internal structure of the 85°E Ridge**
- 2. Volcanic conduit and series of lava deltas identified within the 85°E Ridge reveal nature of the ridge**
- 3. Tectonic model proposed for the emplacement of the 85°E Ridge and its growth through time**

### **Abstract**

The 85°E Ridge, located in the Bay of Bengal of the northeastern Indian Ocean is an enigmatic geological feature as it possesses unusual geophysical signatures. The ridge's internal structure and mode of eruptions are unknown due to lack of deep seismic reflection and borehole data control. Here, we analyze 10 km of long-streamer seismic reflection data to unravel the ridge's internal structure, and thereby to enhance the understanding of how the ridge was originated and grew over a geologic time. Seismic facies analysis reveals the ridge structure consisting of volcanic vent and several stratigraphic units including packs of prograding clinoforms. The clinoform sequences are interpreted as volcanic successions, and led to the formation of lava-delta fronts. Interpreted features of lava-fed deltas and intervening erosional surfaces, and mass flows along ridge flanks suggest that the 85°E Ridge is a volcanic construct, and was built by both subaqueous and multiphase sub-marine volcanism during the Late Cretaceous (approximately from 85 to 80 Ma). At later time, from Oligocene-Miocene (~23 Ma) onwards the ridge was buried under the thick sediments of the Bengal Fan system.

**Keywords:** 85°E Ridge, aseismic ridge, Bay of Bengal, volcano-stratigraphy, multiphase submarine volcanism, lava deltas, carbonate sequence

## **1. Introduction**

The 85°E Ridge, one of the enigmatic aseismic ridges of the world oceans extends from the Mahanadi Basin in the northern Bay of Bengal to location of the Afanasy Nikitin seamount (ANS) in the equatorial Indian Ocean (inset map, Figure 1). The northern part of the ridge is buried under thick sediment sequences of the Bengal Fan system, whereas the southern part intermittently exposes to the seafloor. The ridge in the Bay of Bengal region is associated with prominent negative free-air gravity anomaly and alternative streaks of positive and negative magnetic anomalies (Figure 1). On the whole, the 85°E Ridge is an unusual aseismic ridge and its geophysical signatures contrastingly differ from that of many of the well-studied aseismic ridges of world oceans. Earlier geophysical studies over the 85°E Ridge have brought out morphology of the ridge's exterior surface and discussed possible sources contributing to the anomalous geophysical fields of the ridge (Liu et al., 1982; Curray and Munasinghe 1991; Gopala Rao et al., 1997; Ramana et al., 1997; Subrahmanyam et al., 1999; Subrahmanyam et al., 2001; Krishna, 2003; Anand et al., 2009; Krishna et al., 2009a; Bastia et al., 2010; Michael and Krishna, 2011; Sreejith et al., 2011; Radhakrishna et al., 2012; Desa et al., 2013; Krishna et al., 2014a; Choudhuri et al., 2014; Srinivasa Rao et al., 2016; Talwani et al., 2016). Although a range of theories for the origin of the 85°E Ridge have been discussed, the mantle source (volcanic eruptions) hypothesis is the preferred one that reasonably explains the ridge structure and anomalous geophysical signatures associated with it. However, its internal structure, mode of volcanism and deposition pattern yet remained unclear as the ridge is buried at great depths below the thick pile of fan sediments; also all previous seismic data acquired over the ridge were not capable enough of retrieving details of the ridge's internal structure. So, it is believed that internal structure of the ridge may provide some important insights for detail understanding of mode of eruption/ volcanism and lava flows within the ridge. In the present study, we carried out detailed analysis of exceptionally high-quality long streamer seismic reflection data across the 85°E Ridge to map its internal structure and to understand how the ridge was initiated and evolved through time.

## **2. Geological Setting of the Bay of Bengal**

The ocean floor in most part of the Bay of Bengal was accreted by the Early Cretaceous seafloor spreading between two landmasses of the Eastern Gondwanaland, Greater India and Australian-Antarctic block (Curray et al., 1982; Royer and Coffin, 1992; Gaina et al., 2007; Krishna et al., 2009a; Veevers, 2009; Talwani et al., 2016). Its conjugate part is believed to exist beneath the western Enderby Basin off East Antarctica continental margin. At around 118 Ma, there was a major ridge jump towards the northeastern part of the Indian subcontinent to split the continental fragments

of Elan Bank and part of the present Kerguelen Plateau (Talwani et al., 2016). As a result, age of the oceanic floor in the Western Basin of the Bay of Bengal is older than the other parts. In southeastern quarter of the Bay of Bengal, the ocean floor was evolved with a N-S spreading fabric by the India-Antarctica and Wharton ridge-systems during the Mid-Cretaceous period (Royer et al., 1991; Krishna et al., 1995, 1999, 2012; Krishna and Gopala Rao, 2000). Subsequently, the ocean floor in the Bay of Bengal was modulated into elongated basinal parts with the emplacement of two linear aseismic ridges, called the 85°E and Ninetyeast ridges along 85°E and 90°E meridians, respectively (Curry et al., 1982; Gopala Rao et al., 1997; Michael and Krishna, 2011). While the origin of the Ninetyeast Ridge was clearly deciphered due to the Kerguelen hotspot volcanism, but in the case of 85°E Ridge, despite huge efforts put forth by several researchers, the debate on contributing source is still undergoing. Eventually, the basement topography across the Bay of Bengal, i.e. from the Eastern Continental Margin of India (ECMI) to the Andaman Islands is manifested as alternate rises (85°E and Ninetyeast ridges) and wide depressions (Western, Central and Nicobar basins). Numerous river systems from the Indian subcontinent have almost continually discharged terrigenous sediments into the Bay of Bengal right from beginning of break-up of the Indian landmass from the Eastern Gondwanaland. The Indian peninsular rivers including the Mahanadi, Krishna–Godavari and Cauvery rivers have transported the eroded materials from land to the continental margin and beyond before and even after formation of both the linear aseismic ridges (Krishna et al., 2016). In a later phase (since the Oligocene-Miocene time), as a consequence of on-going interactions between the Himalayan tectonics and Asian climate, the Ganges and Brahmaputra river systems have discharged a huge volume of sediments into the Bay of Bengal (Krishna et al., 2016) and they have been extended up to 7°40'S over a distance of ~3000 km (Krishna et al., 1998, 2001). During the Mid- to Late Miocene the oceanic lithosphere and overlying sediment strata in the distal Bengal Fan were systematically folded and faulted in E-W direction as a response to the continuous collision between the continents, India and Asia (Krishna et al., 2001, 2009b; Bull et al., 2010).

### **3. Geophysical Dataset and Analysis**

In the present study, 2-D multi-channel seismic reflection data acquired by ION/GX Technology as part of deep-water exploration over the 85°E Ridge and adjacent regions were investigated (Figure 1) to delineate the internal structure and evolutionary mechanism of the aseismic ridge. The parameters of 10 km long offset streamer, 18 sec TWT (two-way travel time) recording time, 2 ms sampling rate, source volume >7000 cu. in, 25 m group interval, 400 channel and 170 bar-m (peak to peak) strength of energy source were used during the field experiments for acquisition of seismic reflection data. We also utilized satellite-derived free-air gravity data (Sandwell et al., 2014) as a

supplementary dataset to show the presence of various tectonic features of the Bay of Bengal and for discussions (Figure 1). The results of two industry drilled wells: Well "A" drilled at water depth 2678 m with a recovery of 4416 m core samples; and Well "B" drilled at water depth 2841 m with a total recovery of 3735 m core samples, were also utilized for lithological correlations and as well as assigning ages to interpreted seismic horizons. At both sites, the wells have penetrated the granitic basement. Recently, Krishna et al. (2016) have interpreted eight seismic sequences within the sediment strata following the regional continuity of prominent seismic reflections and their character. The correlations between seismic and well results allowed assigning ages to all eight sequence boundaries starting from the Early Cretaceous to present (Krishna et al., 2016). Within the sedimentary column, variable thicknesses of sequences are observed, i.e. the older sequences are thicker in the shelf region and become thinner towards deep-water region, while the younger sequences deposited since the Oligocene-Miocene time show a reverse trend with the increase of thickness in deep-water region (Krishna et al., 2016).

To improve our current understanding on mode of volcanism and evolution of the 85°E Ridge, we carried out volcano-stratigraphic analysis of sediment depositions and reflection patterns within the ridge following the procedures adopted earlier (Kiørboe, 1999; Planke et al., 1999, 2000). The analysis led to identify various volcanic seismic facies units and edifices within the ridge structure and chaotic reflection sequence on ridge flanks. Details of geometry and seismic facies of stratigraphic units one to five and their interpretations are indicated in Table 1. Then, the seismic facies units and edifices are discussed in detail in terms of growth of the ridge structure (Planke et al., 1999, 2000).

#### **4. Structure and Volcano-stratigraphy of the 85°E Ridge**

The seismic dataset over the 85°E Ridge has provided a unique opportunity to image hitherto unidentified lava deposition patterns within the ridge structure, and this led to enhance our current understandings on structural architecture and genesis of the ridge. Previous seismic studies of the 85°E Ridge have just outlined the top-surface of ridge structure, but could not elucidate detailed subsurface information (Curry et al., 1982; Gopala Rao et al., 1997; Bastia et al., 2010; Michael and Krishna, 2011; Sreejith et al., 2011; Desa et al., 2013; Choudhuri et al., 2014). In the present work a few seismic transects crossing the 85°E Ridge (Figure 1) were investigated in order to obtain new details related to accretion pattern of erupted lava flows and build-up processes within the ridge structure. The main geological units/ formations observed within the ridge and on its flanks are: volcanic vent/ feeder like feature, basal volcanism, lava-fed deltas, wave-cut terraces/ eroded topsets, caldera, reworked volcano-clastic material, carbonate build-up, etc. (Figures 2-5). It is believed that

structural architecture and lava flows within the ridge may add important new insights for detail understanding of mode of eruption/ volcanism and lava accretion deposition pattern. Hence, internal architecture and style of lava accretions within the ridge are discussed in detail below.

#### **4.1 Morphology and Internal Architecture of the 85°E Ridge**

In order to examine topography and internal structure of the 85°E Ridge, the seismic profiles (E1240, E1290, E1300X, E1400, E4000 and E6000) that cross the ridge at different azimuths (Figure 1) were investigated. The morphology of the ridge's outer surface reveals that its dimension and geometry are quite variable from one location to the other (Krishna et al., 2014b). Along the profile E1240, mostly the western part of the ridge is imaged. On adjacent profiles E1290 and E6000, the ridge is observed as a broad dome-like feature with internal features (Figures 2 and 3), whereas the profile E1300X shows only the eastern fringe of the ridge with a less volume of material. Further northward on profiles E1400 and E4000, the ridge is imaged as a prominent basement high sitting adjacent to another structural high (Figure 4). The ridge structure is more symmetrical with a greater relief compared to the eastern mound. Earlier Bastia et al. (2010) have mapped the geometry of two structural high configurations for about 150 km extent between 16°N and 17.5°N latitudes. Following the morphological manifestation of the volcanic edifices described by Calves et al. (2011), the western high can be classified as a hyaloclastic mound, while the eastern high as a shield volcano. Along coast-parallel deep-waters profile E6000, the ridge structure is imaged as a single basement high, but with a smaller dimension (Figure 3). In general, on north of 16°N the ridge structure is culminated with other volcanic structural mound, while towards south the ridge manifests as a single dome like volcanic structure. It is also observed that reflection patterns within the ridge provide a much better scope for understanding the development of internal structure. Hence, coast-perpendicular profiles (E1290 and E1400) and coast-parallel profiles (E4000 and E6000) crossing the 85°E Ridge are investigated in detail (Figures 2-5) to derive useful information for understanding the build-up of the internal ridge structure.

The seismic images of the 85°E Ridge extracted from profiles E1290, E6000, E4000 and E1400 and their stratigraphic interpretations are shown in Figures 2 to 5, respectively. The ridge top-surface is shaped, in general, as a dome-like feature and buried below the thick Bengal Fan sediments. On profile E1290, the buried ridge has a width of about 80 km and relief of approximately 2.5 sec TWT (between depths 6.0 and 8.5 sec TWT, Figure 2). This part of the ridge is associated with a distinct negative magnetic anomaly signature (Krishna et al., 2014b), suggesting that the ridge is composed of magmatic material accreted during a reversed magnetic field. A high-amplitude prominent seismic reflection (Figures 2, 4 and 5) resembling the signature of oceanic basement is seen continuing from

one end to the other across the 85°E Ridge. The reflector lies at around 8.5 sec TWT on profiles E1290 and E4000, and 9.0 sec TWT on profiles E4000 and E1400, coincides with the oceanic basement surface and with the base of ridge structure. Approximately a cylindrical shaped body is noticed right below the apex of the ridge (Figures 2, 4 and 5) and found disrupting the continuity of pre-existing oceanic basement surface and ascending into the overlying volcanic strata. The pierced body is interpreted as a volcanic vent/ plug-like structure, which may have served as a volcanic conduit for ejection of lava material from mantle to the ocean floor. On top of the volcanic vent, a small basin-like feature is noticed, indicating the presence of crater/ caldera and it may have formed during the last phase of volcanism (Figure 2). Further, it is also observed the presence of various seismic reflection units on either side of the volcanic vent. The reflectors continuity within each stratigraphic unit seems to terminate in close vicinity of another unit of a volcanic body. Seismic character of each unit along with the mode of formation is discussed below and also elaborately detailed in Table 1.

The presence of a thick volcanic body (marked as unit 1 in Figure 2) above the basement is interpreted following the seismic characters of chaotic, high to moderate amplitude, semi-continuous reflection pattern. This unit has a horizontal spread of about 80 km and thickness up to 1.3 sec TWT (~2500 m thick) in the vicinity of the volcanic plug (Figure 2). As this unit possesses distinct reflection characteristics that are different from sub-aerial volcanism, it is inferred that the unit was accreted during the deep-water subaqueous volcanism. Initial phase of the ridge volcanism may have started with the formation of extrusion of subaqueous basaltic flows from central volcanic plug and fractures within the basement rock. Further, the lava material that flowed horizontally away from the conduit also filled the pre-existing basement undulations; therefore, this phase is marked as "basal volcanism". At the end of this phase of volcanism, the edifice has become a structural high like feature and reached close to the sea surface.

Over the sub-aqueous basaltic body, two discrete volcanic bodies (termed as unit 2 in Figure 2) are found having seismic reflections with moderate to low amplitude, dipping and prograding towards the ridge flank and down-lapping on the underlying deeper reflections in foreset. The observed reflection configuration may resemble the progradational oblique-tangential delta formed in siliciclastic environment (Vail et al., 1977) or sub-aerially erupted material prograded as lava flows in sub-aqueous environment forming the hyaloclastites breccia and depositing in downslope (Kjørboe, 1999; Planke et al., 2000; Spitzer et al., 2008; Wright et al., 2012; Abdelmalak et al., 2016). The base of these volcanic bodies (top-surface of unit 1) appears as undulated (eroded) surface interpreted as a platform for the formation of prograding clinoform sequence. The clinoform

sequence, in general, develops when the lava deposits shift basinward with respect to the sequence below as a result of high supply of magma material and relatively constant availability of accommodation space (Kjørboe, 1999; Wright et al., 2012). During this process the lava flows interacts with water and undergo quenching and fragmentation process, and eventually formed the steep delta escarpments of hyaloclastic breccias (Kokelarr, 1986; Kjørboe, 1999; Spitzer et al., 2008). Thus, the prograding clinoform reflections may have recorded transition phase from sub-aerial to shallow submarine deposition and directly related to the rate of lava supply, syn-volcanic subsidence and available accommodation space (Kjørboe, 1999; Wright, et al., 2012). Towards east of the vent, unit 2 has different seismic reflection character compared to the adjacent unit 1 and separated by an interface, which marked as "gap or orifice" for lava dispersion at different levels (marked as cyan circles in Figure 2). The clinoform packs in unit 2 correspond to the progradational lava delta and also represent the volcanic formations/ massive lava flows from the volcanic feeder to build a hyaloclastic mound. Similar type of seismic patterns were also noted in other oceanic regions, Shatsky Rise oceanic plateau (Sager et al., 2013), Hawaiian Islands (Walker, 1993), NE Atlantic-Rockall region (Archer et al., 2005), and NE Arabian Sea (Corfield et al., 2010) and interpreted as prograding clinoform sequences.

Presence of two small seismic sequences having high to moderate amplitude, semi-continuous and inclined reflections is noticed on either side of the upper part of the volcanic plug and termed them as unit 3 (Figure 2, Table 1). The unit with geometry of 5-10 km horizontal distance and ~400 m height shows the vertical build-up of volcanic succession. Its reflection pattern and geometry vary distinctly from that of other units 1 and 2, suggesting that this unit was formed in sub-aerial environment with the eruption of highly viscous magma material from the conduit.

Unlike the other sequence units, the unit 4 has strong continuous horizontal reflections with a thickness of around 400 m and horizontal spread of about 40-50 km and fills the pre-existing basin/ depression before reaching the paleo-offlap break (Figure 2). Further, the sequence is associated with caldera type feature (saucer type reflector) lying on top of the volcanic conduit. The lava flows in this unit formed as parallel bedded reflectors may have erupted sub-aerially, hence unit 4 may be classified as sub-aerial plateau basalt successions. The pre-existing ridge topography prior to the formation of unit 4 may have provided a suitable setting to propagate lava flows towards SE direction (Figures 2 and 5). A small seismic pack (labeled as unit 5 in Figure 2) lying on west of the volcanic conduit consists of prograding reflections similar to those observed in unit 2. Also, this indicates the last phase of formation of prograding hyaloclastite deltas before cessation of the ridge volcanism in this region.

With some minor exceptions, almost similar packs of reflection sequences are observed within the ridge structure on other profiles E6000, E4000 and E1400 too (Figures 3 to 5). The seismic sequence representing the retro-gradational style of volcanic succession (unit 3) and mainly restricted around the volcanic conduit is found only on profiles E1290 and E1400 (Figures 2 and 5). The prograding clinoform reflections interpreted on profile E6000 (unit 2 in Figure 3) are dipping in opposite direction, indicating the possibility of flow of volcanic eruptions in all directions.

It is also interpreted that the ridge structure is composite of series of lava flows stacked vertically and separated by stable platforms (Figures 2 to 5). The seismic sequences with distinct spatial distribution of internal reflection geometry and thickness indicate that there were large variations in magma flux effusion rates and lava depositional environments. During the initial phase of volcanism (unit 1), the ridge edifice may have been built in sub-aqueous conditions, but in subsequent phases (units 2-5) the ridge was further built, but in sub-aerial conditions. Therefore, it is inferred that the 85°E Ridge structure was built by multiple phase volcanism in different depositional environments.

#### **4.2 Formation of Erosional Surfaces within the 85°E Ridge and Carbonate Build-up over the ridge-top**

Interpreted seismic sequences within the 85°E Ridge are further analyzed for understanding the development of interfaces/ boundaries between the sequence units. The geometry and reflectivity of the interfaces within the ridge structure may also be considered as another useful proxy for understanding the mode of volcanism during the accretion of the ridge. The study led to identify, at least, four eroded flats on top-surface of each volcanic succession within the ridge and marked as bottom-set/ Base of the Lava Delta (BSL) (Figure 2). The topsets of each prograding clinoform unit is observed as high amplitude, horizontal and occasionally wrinkle-like reflections (Table 1). The flat-surface features, termed as erosional platform/ wave-cut terraces, were generally formed by physical processes of waves, tides, and/ or storms, thereby the eroded material may have transported downslope of the ridge (Winker and Howard, 1977; Muhs, 2000). These sub-marine surfaces are inferred to have formed due to erosion of the edifice during the stable tectonic conditions and/ or migration of lava feeder system to other location, leading to cessation of development of lava-fed delta (Coleman, 1988; Correggiari et al., 2005). During these processes, bottom water currents may have carried the eroded material to the basin and deposited on pre-existing sediment strata for the development of bounding reflections within the volcanic succession units. Hence, it is found the horizontal reflectors onlapping against inclined reflector surface at different depths on western flank of the 85°E Ridge (Figure 2). It is also observed that inclined reflectors appear to terminate on the flank of the ridge. Nearly flat-reflectors are inferred to have been formed from the terrigenous



source, whilst the inclined reflectors may represent the eroded material traveled downslope from the summit of the ridge. A complex mass wasting material deposited on downslope of the ridge flank is also observed on both profiles E6000 and E4000 (Figures 3 and 4). Erosion of volcanic ridge summits and collapse of flanks in several of the world volcanic provinces were well documented (Oehler et al., 2008; Le Friant et al., 2015).

The presence of inferred wave-cut terraces and volcano-clastic sediments deposited on ridge flanks led to interpret that, at end of each volcanic episode, the volcanic surfaces were subjected to erosion, and then followed by next phase of volcanism. Collapse of volcanic flanks and deposition of eroded debris, in general, shape the geometry and evolution of volcanic edifices, and then the setting plays a role in controlling the deposition of subsequent erupted material (Pinel and Jaupart, 2000; Boudon et al., 2013).

Following correlations of seismic sequences to both deep drill wells “A” and “B” (Krishna et al., 2016), it is found that the prominent seismic sequence above the basement has been deposited during the Cretaceous period (prior to 65 Ma) (Figures 2 to 5). This together with deposition of eroded debris suggest that the ridge structure was in shallow water conditions in the geological past, at least, up to Oligocene-Miocene time (~23 Ma), and then it underwent for erosion and re-deposition of sediments. Subsequently, the Lower Miocene sequence began to deposit over the ridge, with which the ridge structure was completely submerged. On top of the 85°E Ridge (on profiles E1290, E1400, E4000 and E1400) nearly reflection free zone in the form of a lens bounded by high amplitude reflection pattern is observed (Figures 2 to 5). Earlier similar seismic sequences lie over the 85°E Ridge were interpreted as carbonate bank (Gopala Rao et al., 1997; Karuppuswamy, 2013), therefore, we too conjecture the lens shaped reflection free zone identified on our profiles as a carbonate bank, and this may have formed when the defunct volcanic structure was subsiding through shallow water conditions at around ~80 Ma.

### **4.3 An Evolutionary Model for the Formation of the 85°E Ridge**

Seismic sections across the 85°E Ridge (Figures 2 to 5) helped us to interpret that each seismic sequence within the ridge formed during the phase of an individual volcanic activity. Thus, it is believed that multiphase volcanism emanated from volcanic vent may have constructed the 85°E Ridge. Using the constraints drawn from deposition of lava sequences in time domain, a generalized six-stage evolutionary model is proposed for the formation of the 85°E Ridge (Figure 6). During the initial phase, the volcanic vent ejected magmatic material, thereby the material has spread for long distance (~40 km away from the vent) on top of the oceanic basement, and then the deposited

material gave a shape of a structural high (stage 1, Figure 6). We refer this stage of volcanism as "basal volcanism" and indicative of high effusion rate and low viscosity eruption following the reports of many volcanic provinces in the world (Keszthelyi and Self, 1998; Gregg and Fornari 1998; Shipboard Scientific Party Leg 192, 2001). A strong cliniform reflection pack is observed as main edifice of the 85°E Ridge on either side of the volcanic vent (stage 2, Figure 6). In order to facilitate progradational lava-delta volcanism the structural high may have remained close to the sea surface. The base of this feature is marked as erosional surface and can be represented as a period of hiatus. During this phase of volcanism, the lava material spread for ~20 km on either side of the vent. The progradational lava-delta may form, in general, by low rates of effusion, change in magma properties and supply rates (Ballard et al., 1979; Wright et al., 2011; McClinton et al., 2013). Similar type of cliniform packs have been observed as lava-fed delta systems in onshore outcrops lying in Iceland and Greenland regions (Furnes and Fridleifsson, 1974; Pedersen et al., 1997). During the third phase of volcanism, volcanic source was most probably above the sea level and magma deposition took place in near vicinity of the conduit as the rate of magma flux was minimal (stage 3, Figure 6). Subsequently, there seems to be a cessation of volcanic activity for a short period as no lava-fed delta was recognized over the previous bed or topset of earlier stratigraphic unit (unit 3, Figure 2). After stage 3, volcanic activity was in dormant stage that may have led to the subsidence of the ridge system until exposed sub-aerial ridge part reached the shallow marine conditions. The fourth phase of volcanism appeared to have formed as subaerial lava flows to attain cliniform sequence on slopes of previous volcanic unit (stage 4, Figure 6). During this eruptive phase, the lava-fed delta system establishes major period of progradation due to increase in lava flux, led to migration of shoreline (a distance of ~25 km in SE direction, see Figure 2). In the last phase of volcanism, lava supply was significantly reduced, which caused retrogradation of the delta (stage 5, Figure 6). The volcanism in all stages except the one above the basement is characterized by lava-fed delta systems, which strongly support the growth of the volcanic edifice through sub-aerial eruptions. On top of ridge structure, a set of high amplitude reflection pattern resembling a "cap" is inferred to be the last stage formation. This is possibly made up of carbonate buildup formed during the post-volcanic subsidence in shallow water conditions. Afterward, ridge structure is subsided due to the post-volcanic subsidence and subsequently buried completely under the fan sediments (stage 6, Figure 6).

#### **4. Summary and Conclusions**

Sequence stratigraphy of high-quality seismic reflection data of the 85°E Ridge deciphered the ridge internal structure consisting of no more than five volcanic successions deposited during multiple phases of volcanism. The ridge architecture clearly supports the volcanic origin and was constructed

from massive lava flows that emanated from volcanic conduits. The major part of the volcanism appeared to have begun sometime during the Late Cretaceous (~85 Ma) and may have continued up to 80 Ma in sub-aerial conditions. The interpreted prograding clinoforms and their eroded top surfaces within the ridge and reworked volcano-clastic sediments (mass wasting) on flanks of the ridge suggested that the 85°E Ridge was built initially by subaqueous basal volcanism and subsequently by sub-aerial multiphase volcanism. Once the volcanic activity has ceased, the sub-aerial ridge structure (considered to be an island feature) began to subside, but on the whole, the ridge structure remained in shallow water conditions probably for around 2-3 million years, which eventually facilitated the formation of lenticular shape carbonate sequence over the apex of the ridge. Subsequently, the sediments deposited until Oligocene-Miocene time (~23 Ma) totally covered the ridge structure, and from then onwards the feature remained below the seafloor and buried under the Bengal Fan sediments. Therefore, we conclude that the 85°E Ridge was constructed by a multiphase volcanism with short discrete time intervals during the Late Cretaceous, and then submerged and buried under the thick fan sediments. The present study is the first of its kind in detailing the internal structure of the 85°E Ridge and to bring out important new insights for understanding the accretion of the ridge.

## **Acknowledgements**

Authors are greatly indebted to D.K. Pande and S.V. Rao, former Directors (Exploration), ONGC, for their keen interest and immense support for initiation of R&D collaborative project between CSIR-NIO and ONGC-KDMIPE. The present work is a part of this collaboration project. MI is thankful to UGC, New Delhi for awarding the research fellowship (JRF). We thank all three anonymous reviewers for their critical comments and suggestions for improving the manuscript. This is NIO contribution number...

## **References**

- Abdelmalak, M.M., S. Planke, J.I. Faleide, D.A. Jerram, D. Zastrozhnov, S. Eide, and R. Myklebust (2016), The development of volcanic sequences at rifted margins: New insights from the structure and morphology of the Vøring Escarpment, mid-Norwegian Margin, *J. Geophys. Res.*, 121, doi:10.1002/ 2015JB012788.
- Anand, S.P., M. Rajaram, T.M. Majumdar, and R. Bhattacharya (2009), Structure and tectonics of 85°E Ridge from analysis of Geopotential data, *Tectonophysics.*, 478(1-2), 100-110.doi:10.1016/j.
- Archer, S.G., S.C. Bergman, J. Iliffe, C.M. Murphy, and M. Thornton (2005), Palaeogene igneous rocks reveal new insight into the geodynamic evolution and petroleum potential of the Rockall Trough, NE Atlantic Margin, *Basin Res.*, 17(1), 171–201, doi:10.1111/j.1365 2117.2005.00260.x.
- Ballard, R.D., R.T. Holcomb, and T.H. van Andel (1979), The Galapagos Rift at 86°W: 3. Sheet flows, collapse pits, and lava lakes of the rift valley, *J. Geophys. Res.*, 84: doi:

10.1029/JB080i010p05407.

Bastia, R., M. Radhakrishna, S. Das, A.S. Kale, and O. Catuneanu (2010), Delineation of the 85°E ridge and its structure in the Mahanadi offshore basin, Eastern Continental Margin of India (ECMI), from seismic reflection imaging, *Mar. Petrol. Geol.*, 27, 1841–1848.

Boudon, G., B. Villemant, A. Le Friant, M. Paterne, and E. Cortijo (2013), Role of large flank-collapse events on magma evolution of volcanoes. Insights from the Lesser Antilles Arc, *J. Volcanol. Geotherm. Res.*, 263, 224–237, doi:10.1016/j.jvolgeores.2013.03.009.

Bull, J. M., C. DeMets, C., K.S. Krishna, D.J. Sanderson, and S. Merkouriev (2010), Reconciling plate kinematic and seismic estimates of lithospheric convergence in the central Indian Ocean, *Geology*, 38, 4, 307-310.

Calvès, G., A.M. Schwab, M. Huuse, P.D. Clift, C. Gaina, D. Jolley, A. R. Tabrez, and A. Inam (2011), Seismic volcanostratigraphy of the western Indian rifted margin: The pre-Deccan igneous province, *J. Geophys. Res.*, 116, B01101

Choudhuri, M., M. Nemeok, C. Stuart, C. Welker, S.T. Sinha, and D. Bird (2014), 85°E Ridge, India – Constraints on its development and architecture, *J. Geol. Soc. Ind.*, 84, 513-530.

Coleman, J.M. (1988), Dynamic changes and processes in the Mississippi River delta, *Geol. Soc. Am. Bull.*, 100, 999-1015.

Corfield, R.I., S. Carmichael, J. Bennett, S. Akhter, M. Fatii, and T. Craig (2010), Variability in the crustal structure of the West Indian Continental Margin in the Northern Arabian Sea, *Petroleum Geoscience*, Vol. 16, 257–265, doi: 10.1144/1354-079309-902.

Correggiari, A., A., Cattaneo, and F. Trincardi (2005), The modern Po Delta system: lobe switching and asymmetric prodelta growth, *Mar. Geol.*, 222-223, 49-74.

Curray, J.R., F.J. Emmel, D.G. Moore, and R.W. Raitt (1982), Structure, tectonics and geological history of the northeastern Indian Ocean. In: the Ocean Basin and Margins, Vol. 6, The Indian Ocean, edited by Narin, A. E., Stehli, F. G., Plenum, New York, 399-450.

Curray, J.R., and T. Munasinghe (1991), Origin of the Rajmohal Traps and the 85°E Ridge: Preliminary reconstructions of the trace of the Crozet hotspot, *Geology*, 19, 1237-1240.

Desa, M.A., M.V. Ramana, T. Tamprasad, M. Anuradha, M.V. Lall, and B.J.P. Kumar (2013), Geophysical signatures over and around the northern segment of the 85°E Ridge, Mahanadi offshore, Eastern Continental Margin of India: Tectonic implications, *J. Asian Earth Sci.*, 73, 460–472.

Elliott, G. M., and L. M. Parson (2008), Influence of margin segmentation upon the break-up of the Hatton Bank rifted margin, NE Atlantic, *Tectonophys.*, 457, 161–176, doi:10.1016/j.tecto.2008.06.008

Furnes, H., and I.B. Fridleifsson (1974), Tidal effects on the formation of pillow lava/ hyaloclastite deltas, *Geology*, 2, 381- 384.

Gaina, C., R. D. Müller, B. Brown, T. Ishihara, and S. Ivanov (2007), Breakup and early seafloor spreading between India and Antarctica, *Geophys. J. Int.*, 170, 151–169.

Gopala Rao, D., K.S. Krishna, and D. Sar (1997), Crustal evolution and sedimentation history of the Bay of Bengal since the Cretaceous, *J. Geophys. Res.*, 102, 17, 747-17, 768, doi:10.1029/96JB01339.

Gregg, T.K.P., and D.J. Fornari (1998), Long submarine lava flows: Observations and results from numerical modeling. *J. Geophys. Res.*, 103, 27517–27531.

- Karuppuswamy, G. (2013), Play prospects and emerging scenarios: K-G Basin, *Bull. ONGC*, 48 (2), 18-56.
- Keszthelyi, L., and S. Self (1998), Some physical requirements for the emplacement of long basaltic lava flows. *J. Geophys. Res.*, 103, B11, 27447–27464.
- Kiørboe, L. (1999), Stratigraphic relationships of the Lower Tertiary of the Faeroe basalt plateau and the Faeroe–Shetland Basin. *In: Fleet, A.J. & Boldy, S.A.R. (eds) Petroleum Geology of Northwest Europe: Proceedings of the 5th Conference, Geol. Soc.Lond.* 559–572.
- Kokelarr, P. (1986), Magma-water interactions in subaqueous and emergent basaltic volcanism, *Bull. Volcanol.*, 48, 275-289.
- Krishna, K.S., D. Gopala Rao, M.V. Ramana, V. Subrahmanyam, K.V.L.N.S. Sarma, A.I. Pilipenko, V.S. Shcherbakov, and I.V. Radhakrishna Murthy (1995). Tectonic model for the evolution of oceanic crust in the northeastern Indian Ocean from the Late Cretaceous to the Early Tertiary, *J. Geophys. Res.*, 100, 20,011-20,024.
- Krishna, K.S., M.V. Ramana, D. Gopala Rao, K.S.R. Murthy, M.M. Malleswara Rao, V. Subrahmanyam, and K.V.L.N.S. Sarma (1998), Periodic deformation of oceanic crust in the central Indian Ocean. *J. Geophys. Res.*, 103, 17,859-17,875.
- Krishna, K.S., D. Gopala Rao, L.V. Subba Raju, A.K. Chaubey, V.S. Shcherbakov, A.I. Pilipenko, and I.V. Radhakrishna Murthy (1999), Paleocene on-axis hot spot volcanism along the Ninetyeast Ridge: An interaction between the Kerguelen hot spot and the Wharton spreading center, *Proc. Indian Acad. Sci. (Earth Planet. Sci.)*, 108, 255–267.
- Krishna, K.S., and D. Gopala Rao (2000), Abandoned Paleocene spreading center in the northeastern Indian Ocean: Evidence from magnetic and seismic reflection data, *Marine Geology*, 162, 215-224
- Krishna, K.S., J.M. Bull, and R.A. Scrutton (2001), Evidence for multiphase folding of the central Indian Ocean lithosphere, *Geology*, 29, 715-788.
- Krishna, K.S. (2003), Structure and evolution of the Afanasy Nikitin seamount, buried hills and 85°E Ridge in the northeastern Indian Ocean, *Earth Planet. Sci. Lett.*, 209, 379-394, doi:10.1016/S0012-821X(03)00081-5.
- Krishna, K.S., L. Michael, R. Bhattacharyya, and T. J. Majumdar (2009a), Geoid and gravity anomaly data of conjugate regions of Bay of Bengal and Enderby Basin: New constraints on breakup and early spreading history between India and Antarctica, *J. Geophys. Res.*, 114, B03102 doi: 10.1029/2008JB005808.
- Krishna, K.S., J.M. Bull, and R.A. Scrutton (2009b), Early (pre-8 Ma) fault activity and temporal strain accumulation in the central Indian Ocean, *Geology*, 37, 3, 227-230.
- Krishna, K.S., H. Abraham, W.W. Sager, M. Pringle, F.A. Frey, D. Gopala Rao, and O.V. Levchenko (2012), Tectonics of the Ninetyeast Ridge derived from the spreading records of the contiguous oceanic basins and age constraints of the ridge, *J. Geophys. Res.*, 117 B04101, doi:10.1029/2011JB008805.
- Krishna, K.S., J. M. Bull, O. Ishizuka, R.A. Scrutton, S. Jaishankar, and V.K. Banakar (2014a), Growth of the Afanasy Nikitin seamount and its relationship with the 85°E Ridge, northeastern Indian Ocean, *J. Earth Syst. Sci.*, 123(1), 33-47.
- Krishna, K.S. et al., (2014b), Structural style and tectonic evolution of Bay of Bengal from Eastern Continental Margin of India (ECMI) to Andaman with special reference to hydrocarbon

- prospectivity, *Technical Report (unpublished) submitted to KDMIPE, ONGC, Dehradun* pp. 1-344.
- Krishna, K.S., M. Ismaiel, K. Srinivas, D. Gopala Rao, J. Mishra, and D. Saha (2016), Sediment pathways and emergence of Himalayan source material in the Bay of Bengal, *Current Science*, 110(3), doi:10.18520/cs/v110/i3/.
- Le Friant, A., et al., (2015), Submarine record of volcanic island construction and collapse in the Lesser Antilles arc: First scientific drilling of submarine volcanic island landslides by IODP Expedition 340, *Geochem. Geophys. Geosyst.*, 16, doi:10.1002/2014GC005652.
- Liu, C.S., D.T. Sandwell, and J.R. Curray (1982), The negative gravity field over the 85°E Ridge, *J. Geophys. Res.*, 87, 7673-7686.
- McClinton, T., S.M. White, A. Colman, and J.M. Sinton (2013), Reconstructing lava flow emplacement processes at the hotspot-affected Galapagos spreading center, 95°W and 92°W, *Geochem. Geophys. Geosys.* 14, 2731–2756.
- Michael, L. and K.S. Krishna (2011), Dating of the 85°E Ridge (northeastern Indian Ocean) using marine magnetic anomalies, *Current Science*, 100, 1314-1322.
- Muhs, D.R., (2000), Dating Marine Terraces with Relative-Age and Correlated-Age Methods. Quaternary Geochronology: Methods and Applications, *AGU Reference Shelf 4*.
- Oehler, J.F., J.F. Lenat, and P. Labazuy (2008), Growth and collapse of the Reunion Island volcanoes, *Bull. Volcanol.*, 70, 717–742, doi: 10.1007/s00445-007-0163-0.
- Pedersen, A.K., M. Watt, W.S. Watt, and L.M. Larsen (1997), Structure and stratigraphy of the early Tertiary basalts of the Blosseville Kyst, East Greenland, *J. Geol. Soc.*, 154, 565-570.
- Pinel, V., and C. Jaupart (2000), The effect of edifice load on magma ascent beneath a volcano, *Philos. Trans. R. Soc. London A*, 358, 1515– 1532.
- Pinel, V., and F. Albino (2013), Consequences of volcano sector collapse on magmatic storage zones: Insights from numerical modeling, *J. Volcanol. Geotherm. Res.*, 252, 29-37.
- Planke, S., E. Alvestad, and O. Eldholm (1999), Seismic characteristics of basaltic extrusive and intrusive rocks, *Leading Edge*, 18, 342–348, doi:10.1190/1.1438289.
- Planke, S., P.A. Symonds, E. Alvestad, and J. Skogseid (2000), Seismic volcanostratigraphy of large-volume basaltic extrusive complexes on rifted margins, *J. Geophys. Res.*, 105, 19335-19351.
- Radhakrishna, M., G. Srinivasa Rao, S. Nayak, R. Bastia, and D. Twinkle (2012), Early Cretaceous fracture zones in the Bay of Bengal and their tectonic implications: Constraints from multi-channel seismic reflection and potential field data, *Tectonophysics*, 522–523, 187-197, doi:10.1016/j.tecto.2011.11.026.
- Ramana, M.V., V. Subrahmanyam, A.K. Chaubey, T. Ramprasad, K.V.L.N.S. Sarma, K.S. Krishna, M. A. Desa., and G.P.S. Murthy (1997), Structure and origin of the 85°E Ridge, *J. Geophys. Res.*, 102, 1799-18012.
- Rey, S.S., S. Planke, P.A. Symonds, and J.I. Faleide (2008), Seismic volcanostratigraphy of the Gascoyne margin, Western Australia. *J. Volcanology and Geothermal Res.*, 172, 112-131, <http://dx.doi.org/10.1016/j.jvolgeores.2006.11.013>
- Royer, J.-Y., J.W. Peirce, and J.K. Weissel (1991), Tectonic constraints on the hotspot formation of Ninetyeast Ridge: *In Proceedings of the Ocean Drilling Program Scientific Results*, College Station, Texas, Ocean Drilling Program, 121, 763- 776.

- Royer, J.-Y., and M.F. Coffin (1992), Jurassic to Eocene plate tectonic reconstructions in the Kerguelen Plateau region, in: W.S. Wise, R. Schlich, et al., *Proc. Ocean Drill. Prog., Scientific Results 120, College Station, TX, 1992*, pp. 917-928.
- Sager, W.W., J. Zhang, J. Korenaga, T. Sano, A.A.P. Koppers, M. Widdowson and J.J. Mahoney (2013), An immense shield volcano within the Shatsky Rise oceanic plateau, northwest Pacific Ocean, *Nat. Geosci.*, 6, 976-981.
- Sandwell, D.T, R.D. Müller, W.H.F. Smith, E. Garcia, and R. Francis (2014), New global marine gravity model from CryoSat-2 and Jason-1 reveals buried tectonic structure, *Science*, 346 (6205), 65-67. Shipboard Scientific Party Leg 192 Summary, (2001), *Proc. ODP, Init. Repts.*, 192, 1-72.
- Spitzer, R., R.S. White, and P.A.F. Christie (2008), Seismic characterization of basalt flows from the Faroes margin and the Faroe-Shetland basin, *Geophys. Prospect.*, 56, 21-31.
- Sreejith, K.M., M. Radhakrishna, K.S. Krishna, and T.J. Majumdar (2011), Development of negative gravity anomaly of the 85°E Ridge, northeastern Indian Ocean- A process oriented modelling approach, *J. Earth Sys. Sci.*, 120 (4), 605-615.
- Srinivasa Rao, G., M. Radhakrishna, K.M. Sreejith, K.S. Krishna, and J.M. Bull, (2016), Lithosphere Structure and upper mantle characteristics below the Bay of Bengal, *Geophys. J. Int.*, 206, 675-695.
- Subrahmanyam, C., N.K. Thakur, T.G. Rao, R. Khanna, M.V. Ramana, and V. Subrahmanyam (1999), Tectonics of the Bay of Bengal: new insights from satellite-gravity and ship-borne geophysical data, *Earth Planet. Sci. Lett.*, 171, 237-251.
- Subrahmanyam, V., K.S. Krishna, I.V.R. Murthy, K.V.L.N.S. Sarma, M. Desa, M.V. Ramana, K.A. Kamesh Raju (2001), Gravity anomalies and crustal structure of the Bay of Bengal, *Earth Planet. Sci. Lett.*, 192, 447-456.
- Talwani, M. M.A. Desa, M. Ismaiel, and K.S. Krishna (2016), The Tectonic Origin of the Bay of Bengal and Bangladesh. *J. Geophys. Res.* (in press).
- Vail, P.R., R.G. Todd, and J.B. Sangree (1977), Seismic stratigraphy and global changes of sea level, part 5: chronostratigraphic significance of seismic reflections. In: *Seismic Stratigraphy; Applications to Hydrocarbon Exploration* (Ed. C.E. Payton), *AAPG Mem.*, 26, 99-116.
- Veevers, J.J. (2009), Palinspastic (pre-rift and -drift) fit of India and conjugate Antarctica and geological connections across the suture, *Gondwana Research*, 16, 90-108.
- Walker, G.P.L. (1990), Geology and volcanology of the Hawaiian Islands, *Pac. Sci.*, 44(4), 315-347.
- Weber, G.E., (1983), Geologic investigation of the marine terraces of the San Simeon fault zone, San Luis Obispo County, California. *Technical Report to the U.S. Geological Survey*, Contract #14-08-001-18230.
- West, B.P., S.R. May, J.E. Eastwood, and C. Rossen (2002), Interactive seismic facies classification using textural attributes and neural networks. *Leading Edge*, 21, 1042-1049.
- Winker, C.D., and J.D. Howard (1977), Correlation of tectonically deformed shorelines on the southern Atlantic coastal Plain, *Geology*, 5, 123-127.
- Wright, K.A., R.J. Davies, D.A. Jerram, J. Morris, and R. Fletcher (2012), Application of seismic and sequence stratigraphic concepts to a lava-fed delta system in the Faroe Shetland Basin, UK and Faroes. *Basin Res.*, doi:10.1111/j.1365-2117.2011.00513.x

## Figure and table Captions:

**Table 1:** Details of seismic facies, geometry and geological interpretation of the volcanostratigraphic units of the ridge structure. Classification scheme is followed from Planke et al. (1999, 2000), West et al. (2002), Rey et al. (2008), and Elliott and Parson (2008)

**Figure 1:** Satellite free-air gravity anomaly color code map of the 85°E Ridge and adjacent area of the Bay of Bengal (Sandwell et al., 2014). Black dotted lines show the network of ION/GXT multi-channel seismic profiles investigated in the present work. The solid red circles with white star show the locations of industry (ONGC) drill wells “A” and “B” located on Eastern Continental Margin of India. Thick black lines show the locations of seismic sections illustrated in Figures 2, and 3. The inset map shows the satellite derived bathymetry image of the Bay of Bengal and trace of the 85°E Ridge from the Mahanadi Basin in the north Bay of Bengal to the Afanasy Nikitin seamount in the equatorial Indian Ocean.

**Figure 2:** The section of the seismic profile E1290 illustrates the internal structure of the 85°E Ridge. And its interpreted line diagram is shown below. The section displays characteristic of volcanic plug, lava-fed delta units, etc. The ridge structure is completely buried under the thick Bengal Fan sediments deposited since the Oligocene-Miocene time (~23 Ma). SP shown along the horizontal-axis and BSL marked within the ridge structure indicate the shot-point and Bottomset/Base of the Lava Delta, respectively.

**Figure 3:** The coast parallel deep-water seismic profile E6000 crossing the 85°E Ridge and its interpretation are shown (for location, see Figure 1). The profile nearly orthogonally crosses the profile E1290.

**Figure 4:** The coast parallel offshore Mahanadi Basin profile E4000 depicting the two peaks of the 85°E Ridge. Packs of volcanic clinoform reflectors within the ridge structure and mass-wasting on west flank of the ridge are clearly seen.

**Figure 5:** The coast perpendicular seismic profile E1400 and its interpretation depict the internal structure of the northern segment of the 85°E Ridge.

**Figure 6:** Schematic illustration showing the development of the 85°E Ridge through geological age.



	Geometry	Seismic facies			Interpretation
		Top reflections	Internal reflections	Base reflections	
Unit 1	Bidirectional Wedge shaped	Moderate to low amplitude, horizontal to sub horizontal, planer, disrupted	High to moderate amplitude, horizontal to sub horizontal, semi-continuous, hummocky reflections	High amplitude, sub horizontal, parallel, varies from semi-continuous to disrupted reflections	Basal volcanism erupted from a source that created a basin floor topographic feature
Unit 2	Sheet-like to wedge shaped	High to moderate amplitude, horizontal and semi-continuous, parallel to sub parallel reflections	Moderate to low amplitude, inclined, parallel to sub parallel, continuous to semi-continuous prograding clinoform reflections	Low amplitude, sub horizontal, sub parallel reflections	Topsets composed of sub-aerial lava flows and foresets beds formed as transition from lava flow to hyaloclastic breccias by the quenching and fragmentation of lava with water and rapid deposition on downslope
Unit 3	High angle wedge shaped	Moderate to low amplitude, parallel to sub parallel, disrupted reflections	Moderate amplitude, inclined, parallel to sub parallel, continuous to semi-continuous reflections	High amplitude, parallel to sub parallel, horizontal to sub horizontal reflections	Foresets beds are sub-aerial eruption and bottom sets is composed of reworked and remobilized deposits of lava flow due to the collapse of the delta front
Unit 4	Sheet-like to wedge shaped	High amplitude, parallel, varying continuity with strong layered horizontal and continuous reflections	Low to moderate amplitude, inclined, semi-continuous prograding clinoform reflections	Moderate amplitude, parallel to sub parallel, sub parallel reflections	Topsets are horizontal basalt successions and forests are hyaloclastic breccias with a large component of volcanic material
Unit 5	Wedge	Low amplitude, horizontal to sub horizontal, parallel reflections	Low to moderate amplitude, inclined, semi-continuous prograding clinoform reflections	Low amplitude, horizontal to sub-horizontal, parallel, reflections	Foresets beds composed of hyaloclastic breccias due the interaction of lava flows with water

**Table 1.**

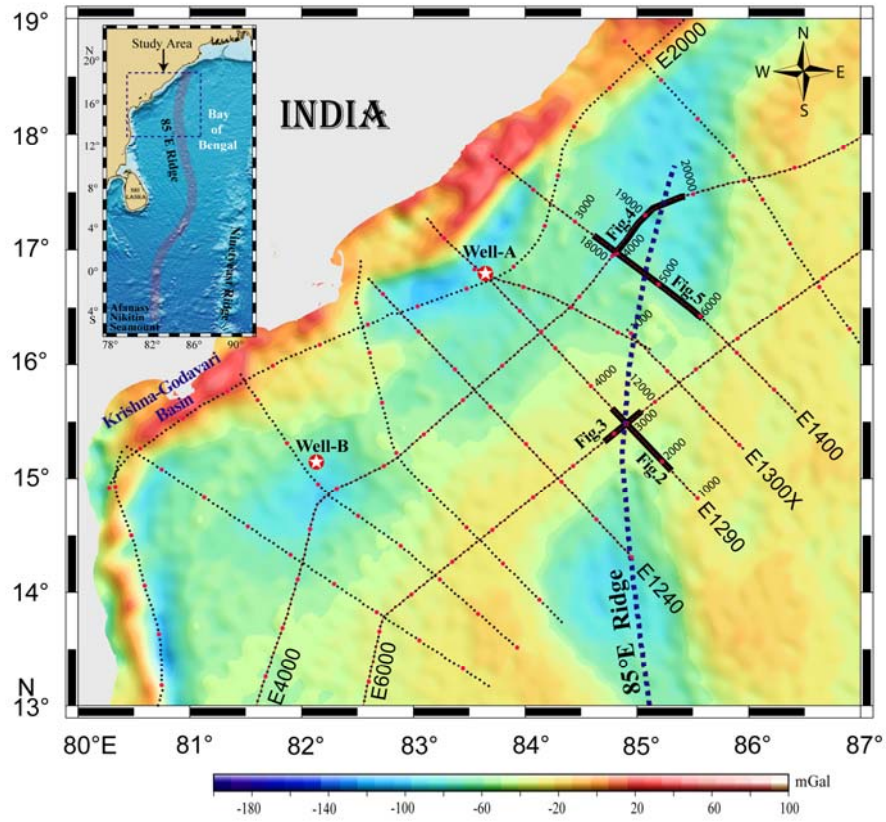


Figure 1

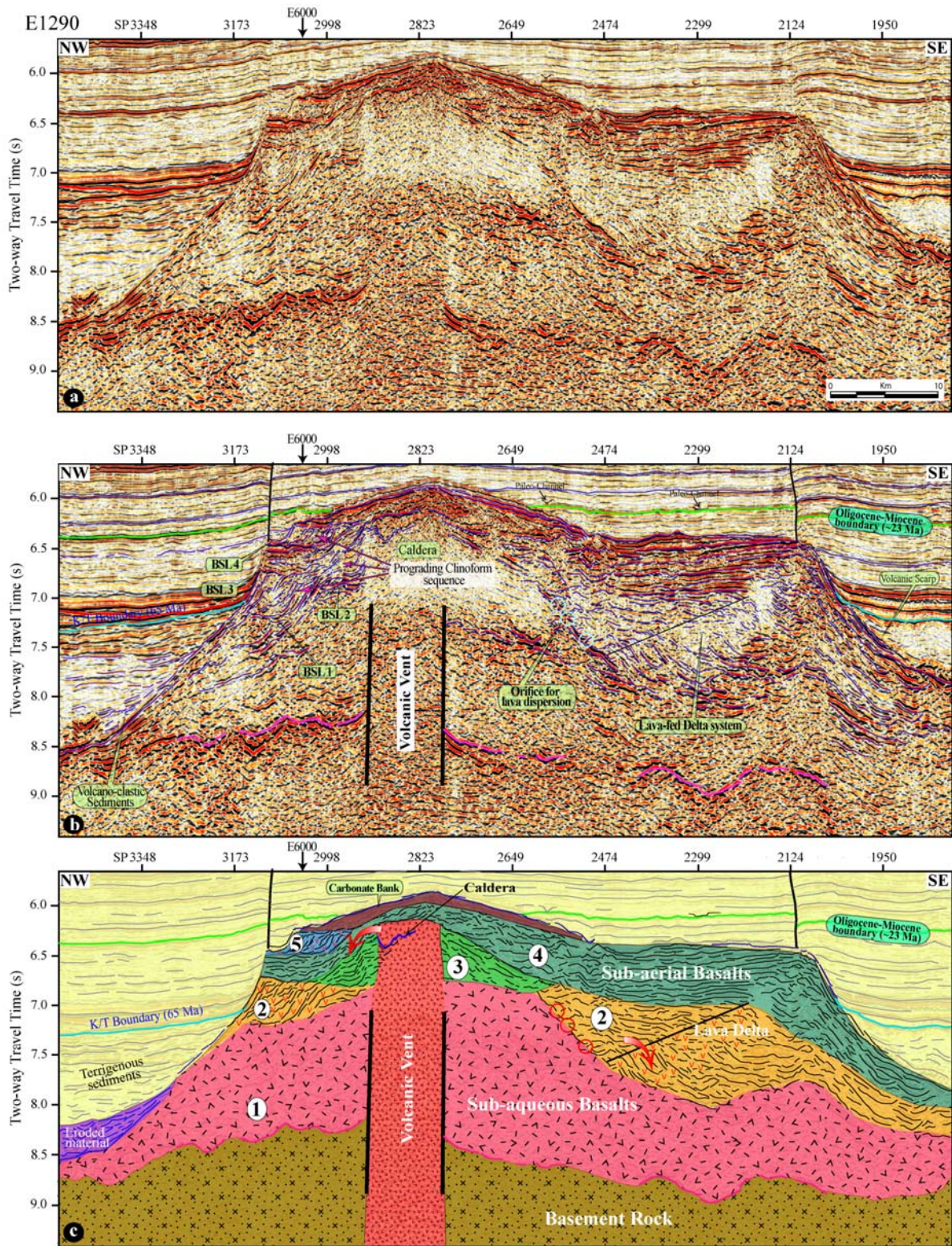


Figure 2

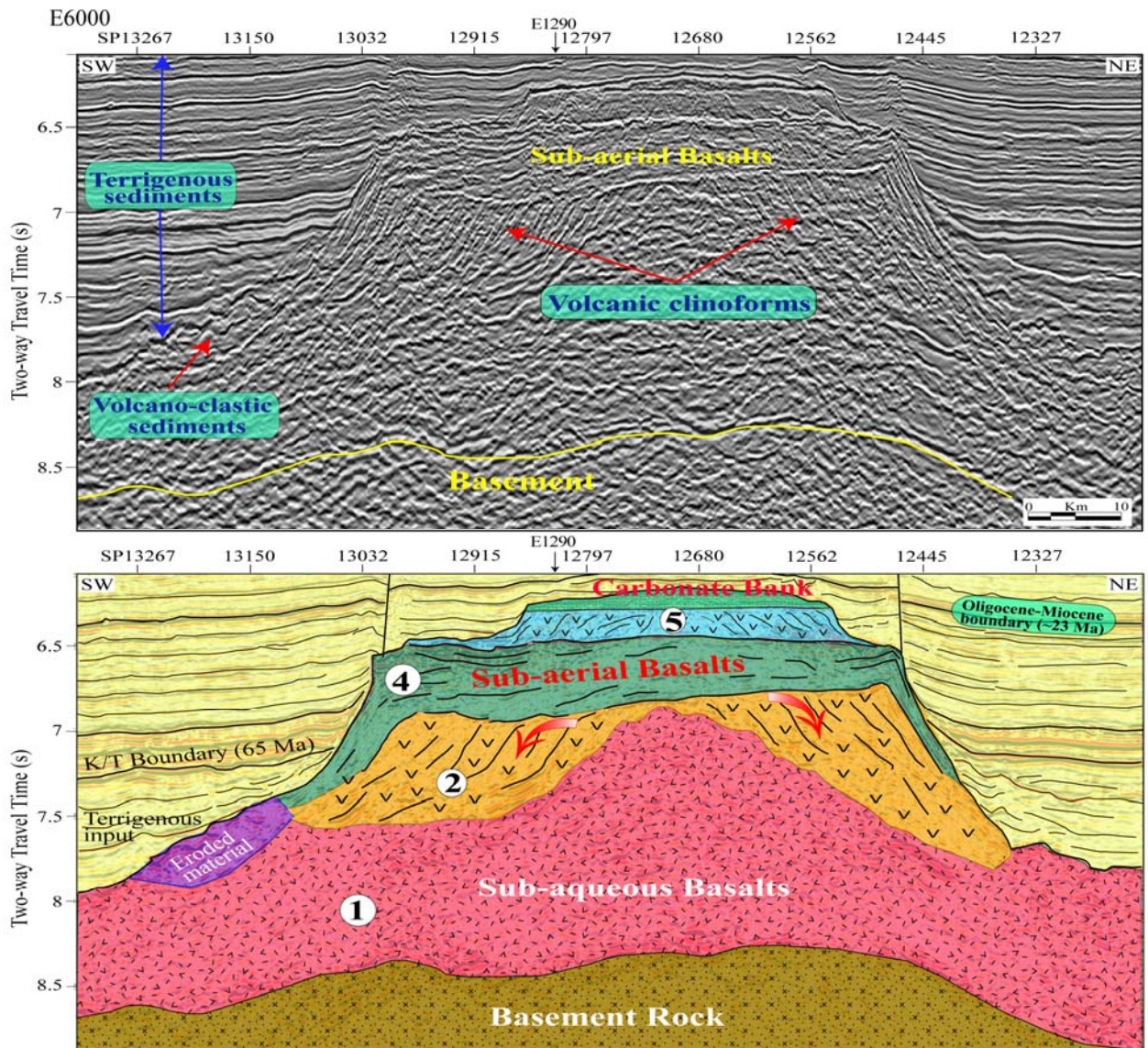


Figure 3

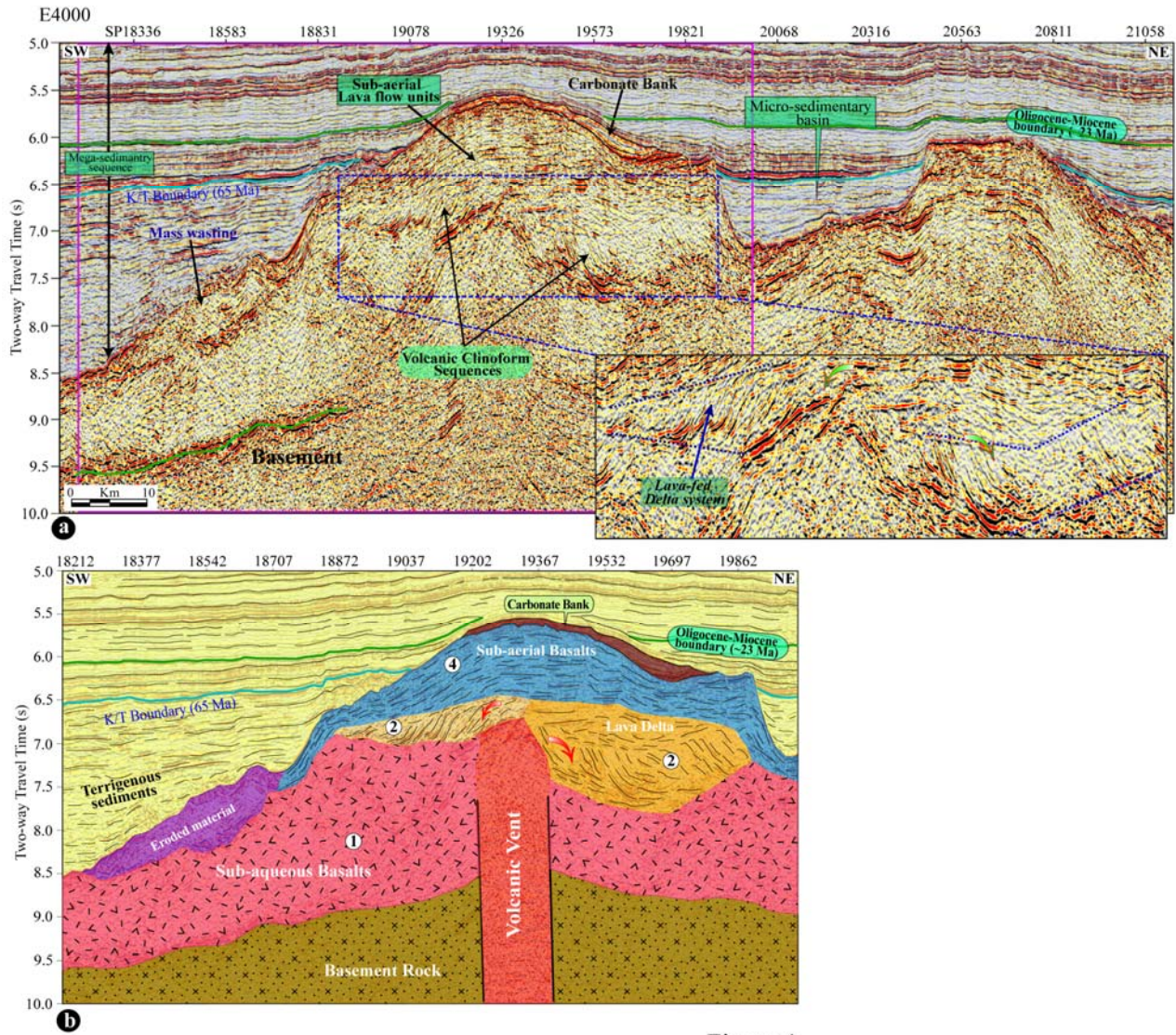


Figure 4

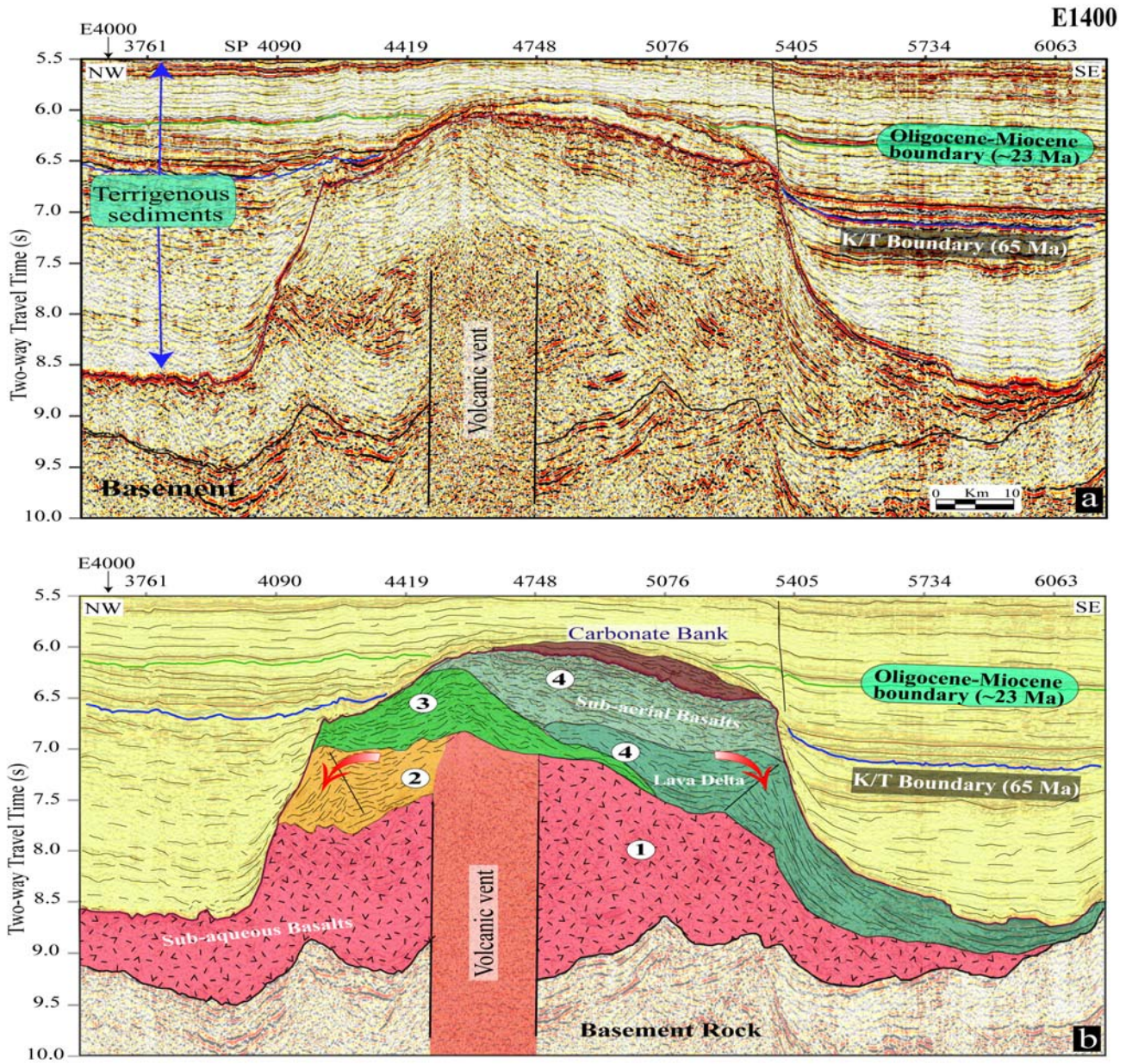


Figure 5

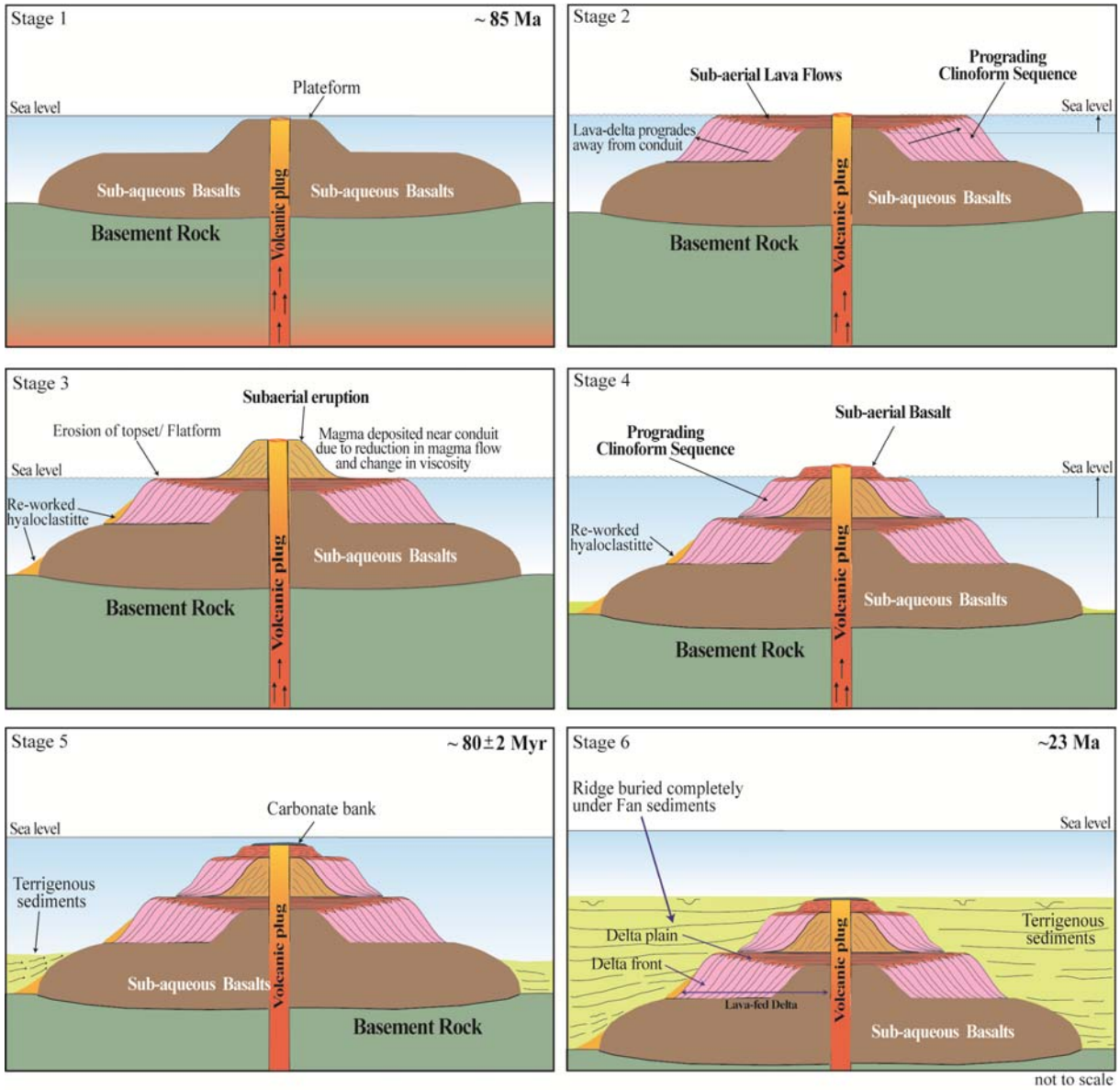


Figure 6