Sediment pathways and emergence of Himalayan source material in the Bay of Bengal

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The sediment succession in the Bay of Bengal (BoB) records the signatures corresponding to India–Asia collision, regional climate change, and erosional processes of both the Himalayan orogen and Indian subcontinent. The Bengal Fan – the world's largest submarine fan – has long been studied to understand the link between the Himalayan tectonics and Asian monsoon. But, lack of detailed information on corresponding signals hampered the understanding of related processes of tectonics, climate and erosion. The present study of long-streamer seismic reflection profile data and information from deep drill well logs in the western BoB has revealed two different phases of sediment deposition. In the first phase, until Oligocene–Miocene (~23 Ma), Indian peninsular rivers discharged sediments to the BoB which accumulated at a rate ~20 m/m.y. with an aberration of two fairly enhanced sediment pulses during the periods from 65 to 54 Ma and 34 to 23 Ma. In second phase, since 23 Ma, the Ganges and Brahmaputra rivers added huge volumes of sediments to the bay at variable rates ranging from 40 to >1000 m/m.y. A distinct increase in sediment discharge (~140 m/m.y.) during the Oligocene–Miocene (~23 Ma) together with the development of regional onlap unconformity and the start of turbidity system provide an important age marker corresponding to rapid exhumation of the Himalaya, which intensified the erosional process and commencement of Bengal Fan sedimentation. Further rise in the rate of sedimentation during the period 6.8–0.8 Ma is coincident with the change in monsoon intensity, but surprisingly not in agreement with the decrease in sediment rate reported at ODP Leg 116 sites in the distal Bengal Fan. Here we provide well-constrained ages for the commencement and growth of the Bengal Fan, which can serve as benchmark information for understanding the interaction between the Himalayan exhumation and Asian climate.

Keywords: Asian climate, Bengal Fan, Continental collision, Himalayan tectonics, Ganges and Brahmaputra Delta

CONTINENTAL collision between India and Asia during the early Tertiary[1–3] led to the formation of the highest mountain range in the world – the Himalaya – which in turn was responsible for major changes in regional and global climatic conditions[4,5]. Interactions between the Himalayan mountain range and Asian climate initiated the erosional process in the Himalayan and Tibetan region and transported enormous volumes of terrigenous material to the Arabian Sea and Bay of Bengal (BoB) to form the Indus and Bengal submarine fans respectively. Sediment records of the BoB were earlier studied[6–8] to retrieve information on the linkage among Himalayan tectonics, Asian climate and erosional history of the Himalaya. There is a general belief that the sediment discharge from the Himalaya to the BoB had begun around the Eocene (~40 Ma)[9–11], but this was not constrained by drill well (DSDP Site 218 and ODP Leg 116 sites) information from the BoB region as the Eocene horizon lies at a greater depth. One of those wells, ODP Site 718 in the distal Bengal Fan penetrated up to ~17 Ma sedimentary strata, but that did not reach the base of fan sediments; therefore, the issue of early phase of the Bengal Fan sedimentation is still debated[7,8]. The recent drilling – International Ocean Discovery Expedition (IODP) 354 – in the southern BoB pointed to the record of early fan deposition between 10 Ma and late Oligocene[12]. The rate of Himalayan erosion is governed principally by monsoon climate and exhumation, but reduction in the Himalayan sediment erosion has also been reported at ca. 8 Ma, despite the intensified Asian monsoon[8,13–15].

The sediment deposition pattern, including rate, direction and lithology in the BoB has continually changed due to coupled process of Himalayan tectonics, sub-continent volcanism and regional climate[6–10,15–18].

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Therefore, to address some of these fundamental processes, we studied exceptionally high-quality long streamer seismic reflection profile data acquired from the Indian shelf to deep-water region and correlated the seismic startigraphy with the stratigraphic column in two industrial deep-water bore holes (*A* and *B*; Figure 1). In the present study, we document the sediment dispersal patterns in time and space in the bay for reconstructing sediment accumulation rates during the Cenozoic period, which eventually addresses long debated issues of time of initiation of Bengal Fan deposition and consequences of monsoon strengthening on sediment accumulation rates.

Geological setting of the Bay of Bengal

The oceanic lithosphere beneath the BoB, particularly close to the Eastern Continental Margin of India (ECMI) was accreted during the first-phase of seafloor spreading activity (Early Cretaceous) of the northeastern Indian Ocean. Its conjugate lithosphere is believed to exist beneath the Enderby Basin at the margin of East Antarctica[19,20]. During the initial stages of break-up of eastern Gondwanaland, the Indian land mass experienced multiple splits of small continental fragments such as Elan Bank and Southern Kerguelen Plateau[21–23]. A major change in spreading direction from NW–SE to N–S occurred in the mid-Cretaceous period. Subsequently, two prominent aseismic ridges, viz. 85°E and Ninetyeast were emplaced on the oceanic crust of the BoB[9–11]. Afterwards, during the early Cenozoic period the Indian subcontinent collided with the Asian continent and this led not only to closure of the Tethys Sea, but also brought out dramatic changes in tectonics and climate in the Asian region[4,5].

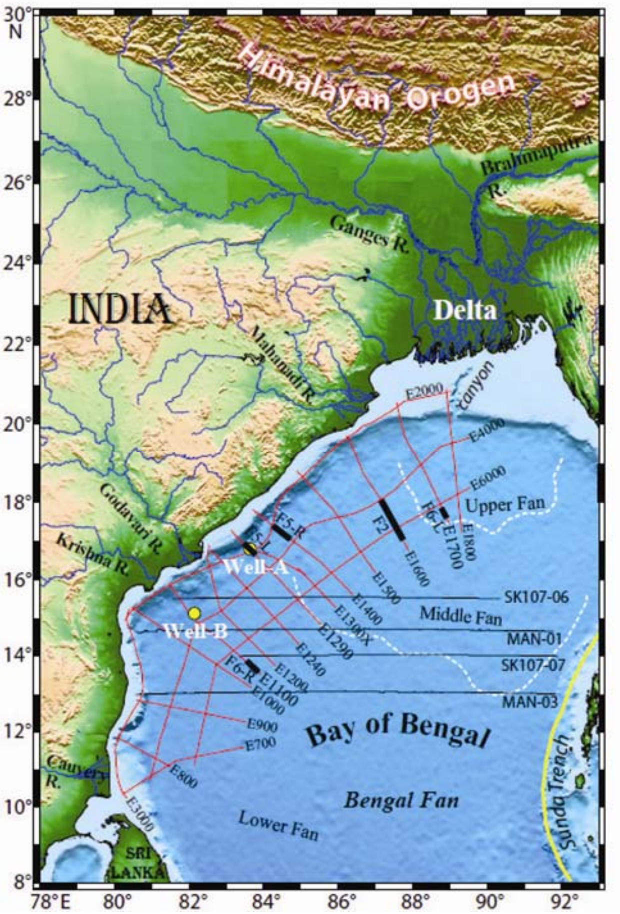


Figure 1. Seafloor topography of the Bay of Bengal (BoB) and reliefs of the Himalayan belt and Indian continental shield. Major peninsular and Bengal Basin rivers are shown with light blue lines. White dashed line separates upper, middle and lower fan provinces of the Bengal Fan. Thin red and black lines show the network of multi-channel seismic profiles investigated in the present work. Solid yellow circles show the locations of industry (ONGC) drill wells *A* and *B* on continental margin. Locations of seismic sections presented in Figures 2, 5 and 6 are shown with thick black lines.

Enormously thick sequences of sediments were deposited in the BoB, initially by the Indian peninsular river systems (Cauvery, Krishna–Godavari, Vamsadhara–Nagavali, Mahanadi, etc.) and thereafter by the Bengal Basin river systems (Subaranarekha, Damodar, Ganges and Brahmaputra) (Figure 1). The latter deposition eventually led to the formation of the world’s largest deltaic plain referred as the Bengal Fan[24,25]. During the initial phase of sediment deposition, two aseismic ridges – 85°E and Ninetyeast – were emplaced on the ocean floor in near N–S direction. Thus the basement topography in the BoB was shaped by alternate sharp structural highs and wide depressions. In the younger phase, during the Miocene the crust and overlying sediment strata in the distal Bengal Fan were deformed together, resulting in long-wavelength folds and high-angle reverse faults[6,26–29]. Both basement and sediment undulating topographies developed at different times have played a role in controlling the sediment dispersal pattern in the BoB.

Seismic data – stratigraphy and correlation to drill wells

The collaborative project between the National Institute of Oceanography (NIO) and Oil and the Natural Gas Corporation Limited (ONGC) facilitated to integrate seismic reflection profile data of the BoB (Figure 1), and correlate them with the results from two deep drill holes, which helped in assigning ages to the interpreted seismic horizons. The profiles labelled *E* were acquired using 10 km long streamer by ION/GX Technology under the India Span programme, while the regional profiles (MAN-01 and 03; SK 107-06 and 07) between central ECMI and Andaman Islands were acquired by ONGC and NIO respectively.

Seismic stratigraphic analysis was carried out on 14 coast-orthogonal and three coast-parallel profiles of the western BoB (Figure 1). In addition, four regional seismic profiles across the BoB described by Gopala

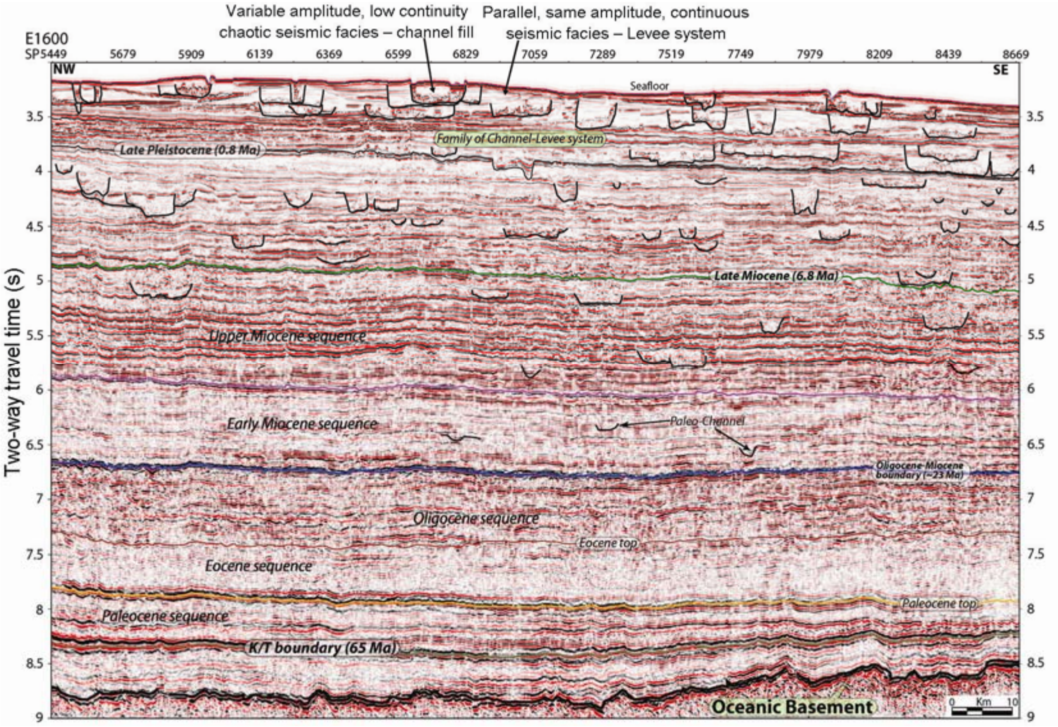
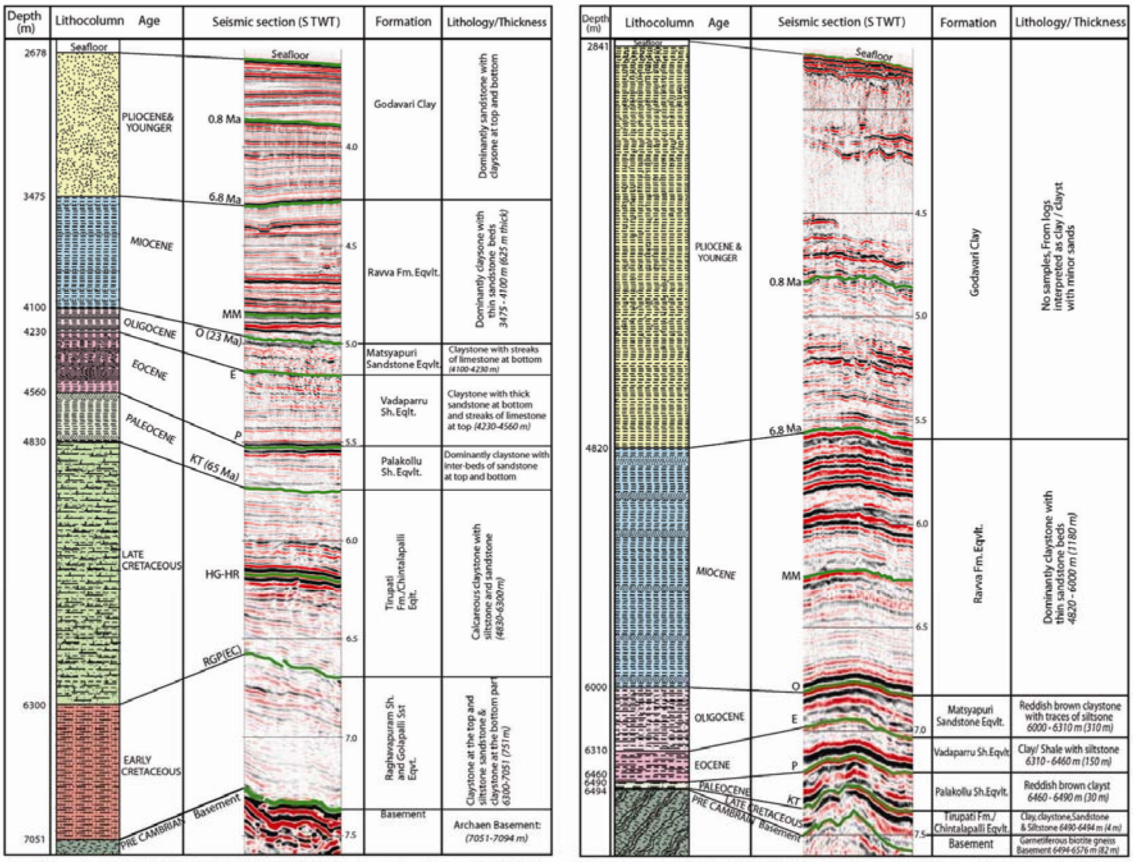


Figure 2. Seismic reflection record (profile E1600) imaging the sediment succession of the BoB. Eight sedimentary layers deposited since the Early Cretaceous are interpreted.



Correlation of well "K-1" (16°47' 44.22"N; 83° 37' 57.52"E) lithology to the seismic section (E1290)

Correlation of well "UD-1" (15°07' 0.28"N; 82° 08' 36.00"E) lithology to the seismic section (E1100)

Figure 3. Litho-column and age of the drill wells *A* and *B* and their ties to interpreted sequence boundaries.

Rao *et al.*[10], and Michael and Krishna[11] were also used in the study. Since the present study is aimed to understand the sediment deposition in space and time, the main attention was focused on sediment strata of the region. Following the regional continuity of prominent seismic reflectors and their character, eight sedimentary sequences starting from the Early Cretaceous to the Present (Figure 2) have been mapped along all the reflection profiles. In addition we have also kept litho-column of the wells *A* and *B* (drilled in the Krishna–Godavari (K–G) Basin) in view for identification of sedimentary layers (Figure 3).

Two industrial wells, *A* and *B*, were drilled in deep waters of the K–G Basin (Figures 1 and 3). Well *A* was drilled in continental rise region (about 50 km seaward of the foot-of-the-slope) in water depth of 2678 m. The bore hole penetrated a thickness of 4373 m of sediments and went into the Precambrian basement for 43 m. The second well *B* is located at a water depth of 2841 m at the northern periphery of the K–G Basin. This has cut through 3653 m sediment cover and entered the 82 m of Precambrian garnetiferous biotite gneiss basement rocks.

Biostratigraphic studies of core samples were carried out by ONGC; the age results thus obtained were assigned to interpreted seismic horizons of profiles E1290, E1300 and E2000, which lie in close proximity of drill hole *A*, and another set of profiles E1100 and E4000 that run in the vicinity of drill hole *B* (Figure 1). Thereby the calibrated ages were extended to the network of all seismic profiles. Thus this comprehensive seismic study in the BoB that utilizes perfect ties between the reflection profile data and two deep-penetrating bore holes. The ages assigned to the seismic horizons from basement to seafloor are – *KT* boundary (65 Ma), Paleocene–Eocene boundary (~55 Ma), Eocene–Oligocene boundary (~34 Ma), Oligocene–Miocene boundary (~23 Ma), middle Miocene (~16 Ma), late Miocene (6.8 Ma) and late Pleistocene (0.8 Ma) (Figures 2 and 3).

Regional sediment deposition rates in the BoB are still not known, hence we have calculated linear sedimentation rates (m/m.y.) at both drill wells *A* and *B* located in the western BoB following the age–depth model discussed in the Initial Report of the ODP Leg 208 (ref. 30). Subsequently, to obtain reliable information on sedimentation rates for the entire study region, we have divided it into a number of geological provinces (northern BoB, Central Basin, 85°E Ridge, Western Basin and ECMI), following the structural architecture of the BoB. The velocities obtained from the present dataset (wide–angle seismic reflections and drill wells *A* and *B*) and from published refraction data[31] were largely followed to calculate the thickness of each seismic sequence for all geological provinces. We also considered six pseudo-wells within each geological province to obtain a best representative average sedimentation rate profile. The process followed for determination of sediment deposition rates for each geological province is most reasonable and represents the actual sedimentation history.

Subsequently, each sequence horizon from the interpreted seismic reflection data was digitized for the purpose of preparation of sediment isopach maps for different geological periods. The gridded data for all the horizons were brought to the GMT (Generic Mapping Tools) platform for preparation of time (two-way travel time; TWT) structure map of the western BoB. Isopach maps thus prepared for different geological periods were interpreted for understanding the sediment dispersal pattern and deposition history.

Basement morphology, regional onlap unconformity and palaeo-buried channels

Interpreted seismic results of the western BoB were utilized for preparation of depth to basement map and various sediment isopach maps for examining the basement morphology, possible correlations to onshore structural lineaments and sediment dispersal pattern. The basement topography reveals that the margin, particularly in shelf and slope region, is traversed by nearly coast perpendicular major grabens G1 to G5, indicating the continuity of onshore graben/shear zone structures into offshore region (Figure 4). The graben G1 having a dimension of about 70 km width and 125 km length, runs nearly E–W between onshore Ponnaiyar and Palar river systems, and shows the offshore continuity of the Cauvery rift zone. Using the airborne magnetic data of the southern Indian Shield and marine magnetic data of the Cauvery offshore basin, Subrahmanyam *et al.*[32] have mapped the continuity of two prominent shear zones known as the Moyar–Bhavani shear zone and Palghat–Cauvery shear zone into the offshore area in the vicinity of graben G1. The graben G2, 70 km wide and 100 km long, lies in the vicinity of onshore crustal boundary between two major geological provinces, viz. the Southern Granulites Terrain (SGT) and the Dharwar Craton. The graben may indicate the offshore extension of suture zone associated with the SGT and Cuddapah greenstone belt (Figure 4). The NW-SE G3 graben represents offshore continuity of the Pranhita–Godavari graben. The grabens G4 and G5 are relatively smaller in dimension and show the offshore continuity of the Vamsadhara–Nagavali and Mahanadi shear zones respectively. All graben features are seen to extend from coastline to seaward for about 100–125 km; thereafter, the graben features terminate at the rifted continental blocks evolved during the last phase of continental break-up. The location of the rifted thinned continental blocks, in general, is considered as inward Continent–Ocean Transition (COT) zone or beginning of the COT. The basement gradient beneath the continental slope of the southern segment of the ECMI is significantly steep than in the northern segment (Figure 4). In addition,

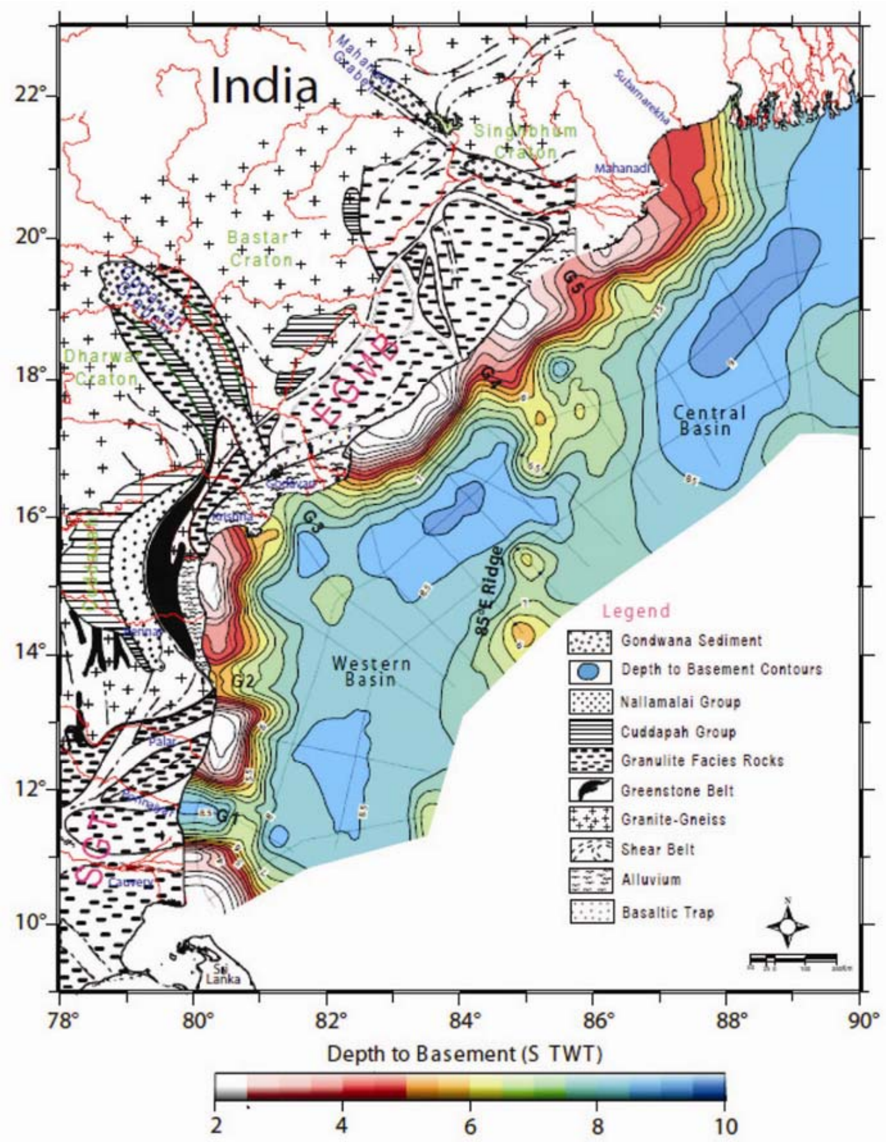


Figure 4. Depth to the basement map of the ECMI and adjacent deep-water region. Contour interval is 0.5 S TWT. Coastal geology and structural features, including the Gondwana grabens are adopted from Chetty[48].

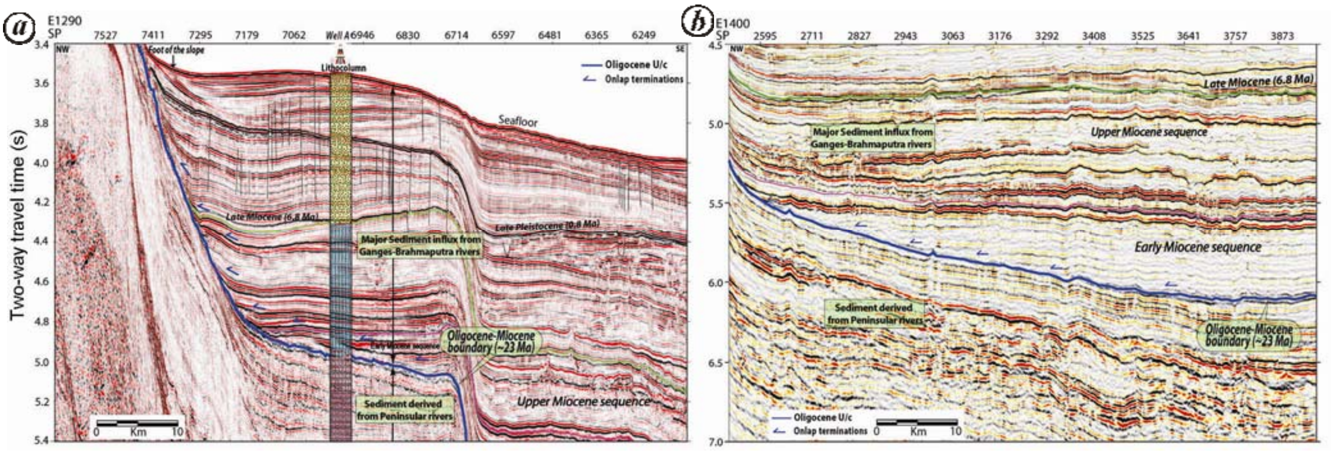


Figure 5. Seismic sections of profiles E1290 (***a***) and E1400 (***b***) show important constraint of Oligocene–Miocene regional unconformity that separates two different depositional sediment sections delivered by different sets of river systems. The drill well *A* on profile E1290 penetrates through the entire sediment column, including the unconformity and sub-basement strata. A significant change in lithology is observed at depth of 23 Ma and again at 6.8 Ma sediment horizons.

we have also identified the presence of the 85°E Ridge with a considerable elevation of up to 2.5 sec TWT from the adjacent basement floor on either side. It is further found that the ridge structure is discontinuous in the vicinity of 16°N lat. and finally terminates at around 18°N lat. The presence of the ridge in the BoB divides the region into two major oceanic basins (Central and Western basins), and also controls the sediment distribution delivered from the peninsular and Bengal Basin river systems.

Detailed analysis of reflection data led to the identification of a regional unconformity developed at the Oligocene–Miocene boundary (~23 Ma) along the ECMI. The unconformity is identified largely based on onlaps of seismic reflectors (Figure 5). Thus it reveals the presence of two different sedimentation regimes in the past – the lower sediment package thinning from the shelf region to deep waters, and the upper sediment package showing a reverse trend of thinning towards the shelf (Figure 5). We suggest that the sediments below the unconformity were transported from the Indian shield by peninsular rivers, while those above the unconformity were deposited dominantly by the Ganges and Brahmaputra river systems. The unconformity is mapped over the large extent of the ECMI, except in the vicinity of the Cauvery (profiles E700, E800) and K–G (E1000, E1100, E1200) basins, and off Bangladesh coast (E1800), as they were influenced by nearby river discharges. Thus, the interpreted unconformity (Oligocene–Miocene time) is considered to be an important geological time marker in the sedimentation history of the BoB. Further examination of reflection data led to the identification of buried paleo-channels, which may be considered as the earliest turbidity current channels that were active around the time of formation of Oligocene–Miocene horizon (Figure 6). Since then, prevalence of sediment filled paleo-channels has significantly increased as noted earlier[25,33].

Sediment dispersal pattern and growth of the Bengal Fan

Earlier Curray[34], and Radhakrishna *et al.*[31] have prepared a sediment thickness map for the BoB using a few regional seismic profiles for understanding the sediment pattern and depositional history. The maps provide low-resolution information on basement morphology and total sediment thickness of the BoB. The present study using good network of high-quality deep seismic data over the ECMI and deep-water region provides more realistic information on basement morphology and sediment distribution patterns at different times.

Sediment isopach trends (Figures 7 and 8), and accumulation rates (Figure 9) of the BoB have reveal that sediment sources/pathways and depositional rates have greatly varied in space and time. The peninsular rivers were discharging sediments at a rate c. 20 m/m.y. with the thickness of sediments reducing from margin to deep-waters until 65 Ma and again between 56 and 34 Ma (Figure 7). During the periods from 65 to 56 Ma and again from 34 to 23 Ma, the BoB received sediment inputs from the rivers of Bengal Basin as well as some peninsular rivers at an average rate of 70 m/m.y. The enhanced rate of sediment deposition may have occurred during the early Cenozoic era due to emplacement of large Deccan volcanic sequence, which resulted in change in relief of the Indian subcontinent, and again during the Oligocene Epoch due to changes in convergence, particularly the rate and steepness of subduction between the colliding plates[35]. This implies that, from the early Cretaceous rift-stage to Oligocene–Miocene (~34 Ma), peninsular rivers were a major source of sediments. In later phase up to ~23 Ma, the sediments seem to have been discharged from both the peninsular Indian and Bengal Basin rivers. Therefore, we are of the view that there may be a possibility of proto-fan sediment deposition during the Eocene–Oligocene (~34 Ma) at lower rates (Figures 7 *b* and 9).

Subsequently, from Oligocene–Miocene (~23 Ma) to 6.8 Ma, the BoB received huge volumes of sediment from the Ganges–Brahmaputra delta through a large network of channels (Figure 8 *a*). The change in direction of sediment source and high accumulation rate resulted in onlapping of the entire Miocene sequence on the Oligocene–Miocene boundary in the shelf-slope region (Figure 5), suggesting that the Bengal Fan sedimentation increased about fourfold starting at 23 Ma and dominated the sediment deposition in the entire BoB. Thus the age marker is identified with strong supportive evidences – onlap unconformity, buried channels, fan architecture and apex location – for discharge of sediments through the Ganges–Brahmaputra delta to the BoB. Around this time in the Himalayan foreland basin, a major Oligocene–Miocene unconformity was identified as a consequence of intensification of the Asian summer monsoon[36]. Structural and thermo-chronological studies of southern Tibet suggest that most significant deformation in the Greater Himalaya regime is the evolution of Main Central Thrust since 23 Ma (ref. 37), and this must have triggered the discharge of eroded sediments to the ocean[38].

During the younger phase, 6.8–0.8 Ma, a further rise in sediment deposition (~210 m/m.y.) is clearly observed in the BoB (Figure 9), but this is surprisingly not in agreement with the decrease in sediment rate reported at ODP Leg 116 sites in the distal Bengal Fan[7,13–15]. In the distal Bengal Fan the ODP Leg 116, wells were drilled over the crest of the Late Miocene intraplate deformation-related fold[29]. Therefore, the undulated Miocene topography did not allow the location to receive the complete sediment section, which resulted in underestimation of sediment depositional rates during the period 6.8–0.8 Ma. It is well known that syn-deformational sediments are relatively thin over the fold-crests than in the trough regions[28,29]. The increased accumulation rates determined in the

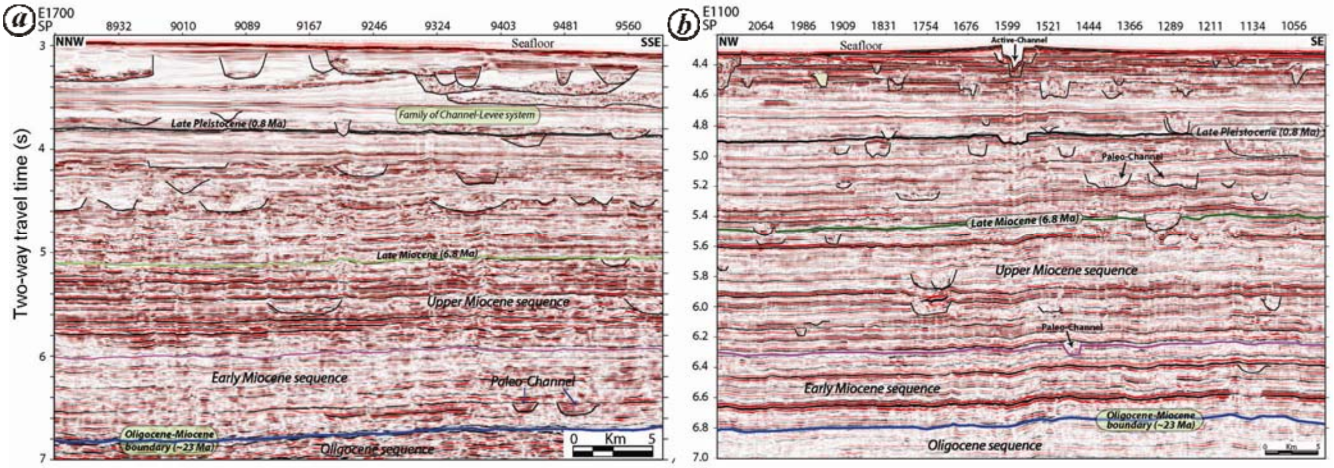


Figure 6. Seismic sections of profiles E1700 (***a***) and E1100 (***b***) showing the presence of sediment-filled, buried paleo-channels from Early Miocene to the Present.

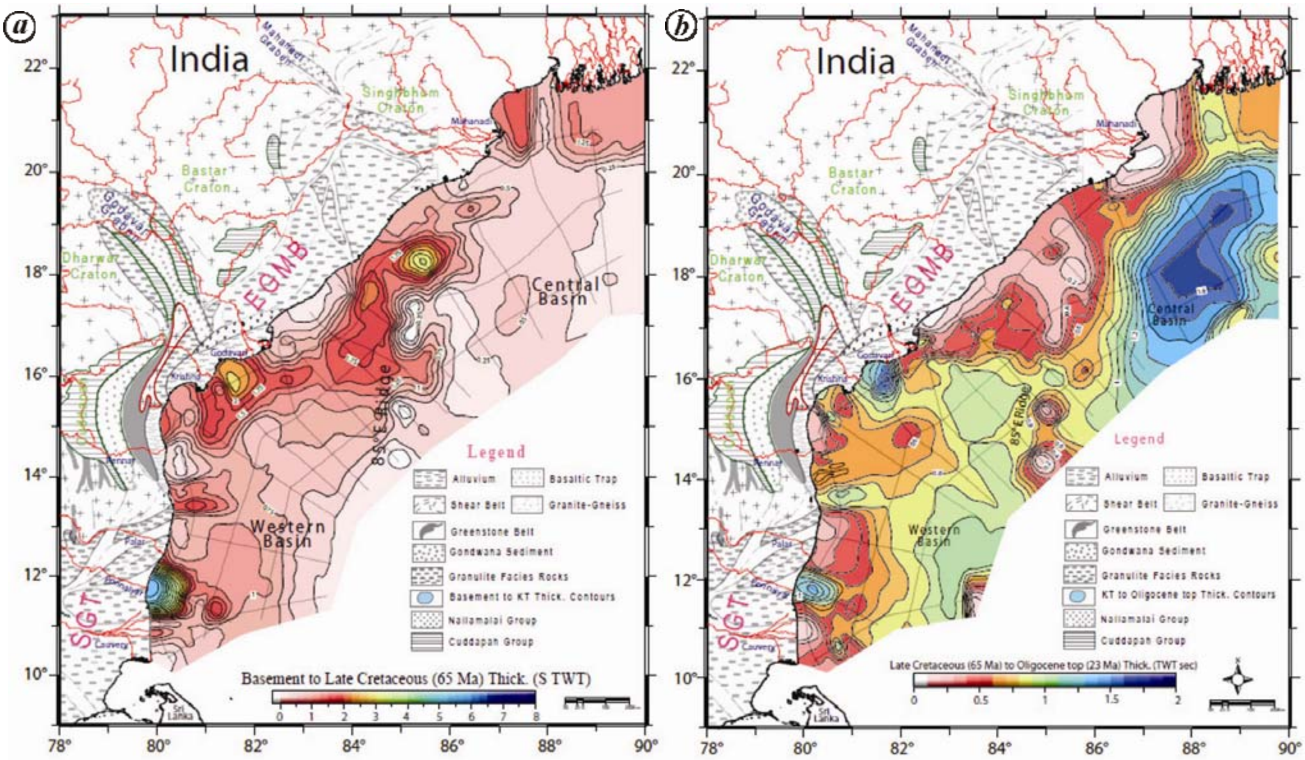


Figure 7. Sediment isopach maps prepared from the interpreted seismic reflection results. ***a***, From basement to 65 Ma seismic horizon (contour interval 0.25 sec). ***b***, For sediment layer deposited between 65 and 23 Ma (contour interval 0.1 sec).

present work may generally indicate the occurrence of monsoon intensification event in the Asian region, but the variability (strengthening/weakening) of the Asian monsoon during the late Miocene is still under debate[39–42].

Another significant change in sediment deposition pattern and rates (290–1600 m/m.y.) was found during the late Pleistocene (0.8 Ma) to the Present (Figures 8 *b* and 9). During this phase, the K–G river system recommenced its activity and delivered sediments to the western part of the BoB, while the northern part of the Central Basin received sediments from the Mahanadi, Ganges and Brahmaputra river systems. Approximately similar sedimentation rates (1200 m/m.y.) were reported in the onshore Bengal delta region[43]; these may be the highest sedimentation rates in Earth's history. The younger event (0.8 Ma to the Present) is inferred to be associated with the second main phase of uplift of the Higher Himalaya[7] and/or onset of major glacial cycles[8].

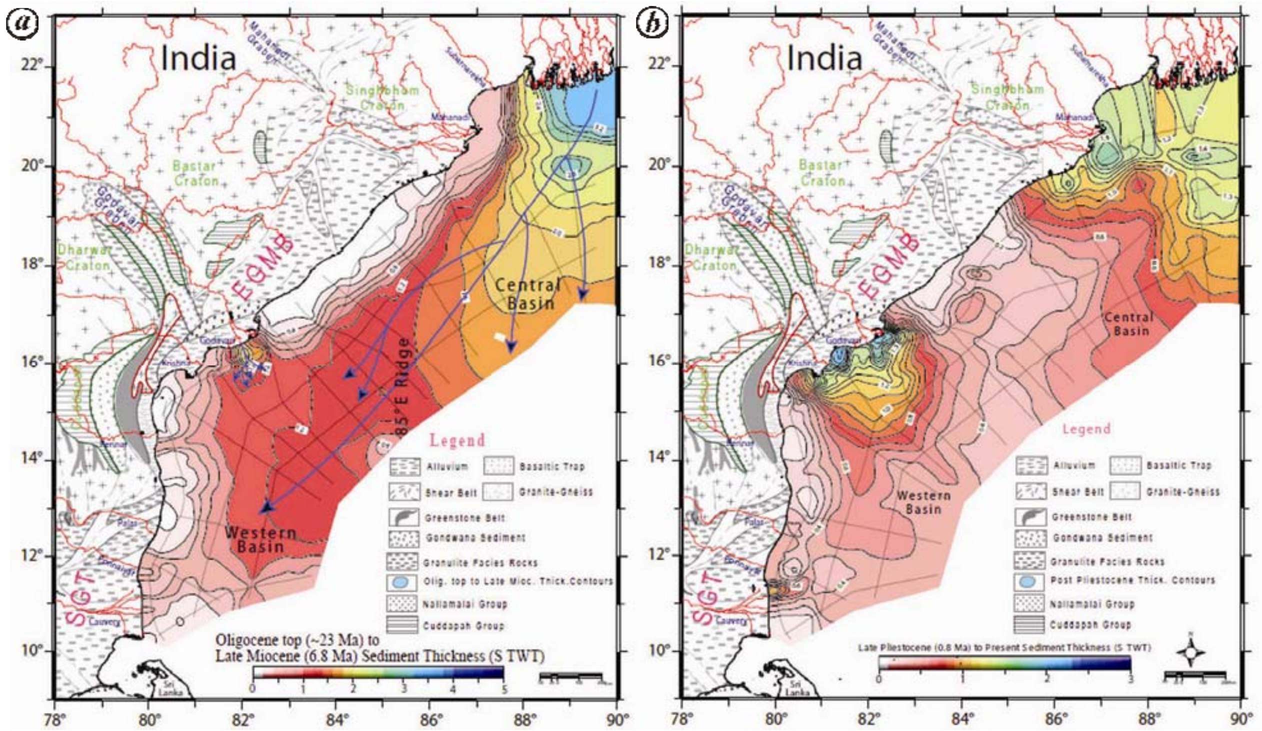


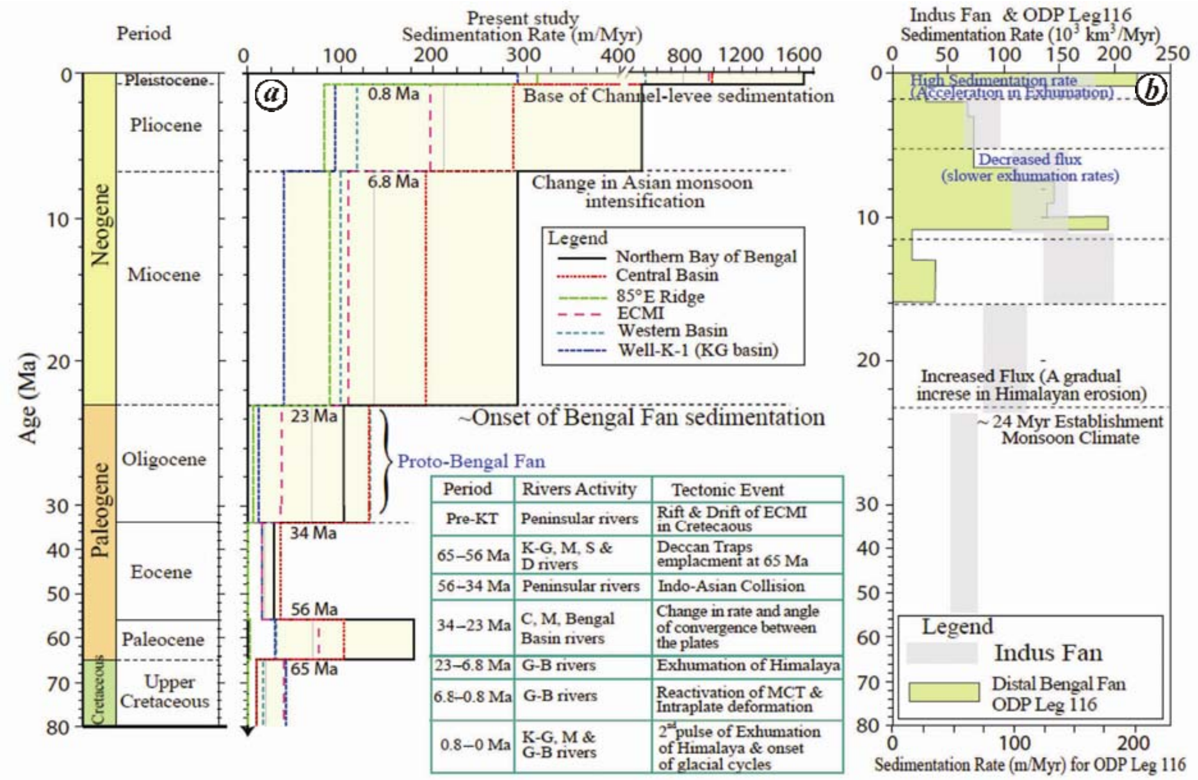
Figure 8. Sediment isopach maps prepared from the interpreted seismic reflection results. ***a***, For the period from 23 to 6.8 Ma (contour interval 0.2 sec). ***b***, For the period from 0.8 Ma to the Present (contour interval 0.1 sec).

Summary and conclusion

Analysis of seismic stratigraphy of the BoB sediments clearly establishes that the rivers from peninsular India discharge sediments at a lower rate (~20 m/m.y.) from rift-drift stage to the Oligocene–Miocene (~23 Ma). During this time interval two sedimentary pulses – (i) from 65 to 54 Ma and (ii) 34 to 23 Ma – have been recognized with an increase in the rate of sedimentation to ~50 m/m.y. (Figure 9). During the first pulse period sediments were supplied by Subaranarekha and Damodar rivers of West Bengal, in addition to the Indian Peninsular rivers following the topographic changes of the Indian shield caused by the Deccan Trap volcanism. The later pulse from 34 to 23 Ma also witnessed a rise in sediment accumulation rates due to the changes in convergence angle rate between the plates, suggesting that the BoB may have received the sediments from both the peninsular India and Bengal Basin rivers. Therefore, it is interpreted that there may be a possibility of initial deposition of proto-fan sediments during the Eocene–Oligocene (~34 Ma) at lower rates (Figures 7 *b* and 9). Then a distinct increase in sediment flux up to 140 m/m.y. is observed at the time of Oligocene–Miocene transition (~23 Ma), which continued until about 6.8 Ma (Figures 8 *a* and 9). This observation, when collated with other constraints of Oligocene–Miocene unconformity (Figure 5) and sediment filled paleo-channels (Figure 6), becomes an important age marker representing rapid exhumation of the Himalaya and commencement of Bengal Fan sedimentation.

The Indus Fan too received the sediments at considerably increased rates around the Oligocene–Miocene[44], implying that both the Arabian Sea and BoB have well-recorded signals related to tectonic and climatic events associated with the Himalayan orogeny. It has been suggested by several workers[38,45,46] that a gradual increase in the rate of deposition of material eroded from the Himalaya in the sub-Himalayan for deep and distal basins began at ~24 Ma. This proposition agrees well with the observation of rapid deposition of sediments at ~23 Ma in both the BoB and Arabian Sea. However, post-23 Ma altogether different scenarios of sedimentation rate emerge in the Indus and Bengal fans (Figure 9), despite synchronous climatic conditions in the Cenozoic era. Sedimentation rate of the Indus Fan reached a peak between 24 and 15 Ma and remained high until ~10.5 Ma and reduced gradually till 3.5 Ma, before it began to increase again in the Late Pliocene and Pleistocene epochs[44]. Differential exhumation rate in the Himalayan belt[47] caused by change in the angle of convergence between India and Asia[35] seems to be mainly responsible for two different rates and styles of sediment deposition in the Indus and Bengal fans.

The present study allows reconstructing the history of sediment discharge from rivers of peninsular India and Bengal Basin, particularly the nature and intensity of erosion influx at millennial-scale during the Cenozoic. It is



Period	Rivers Activity	Tectonic Event
Pre-KT	Peninsular rivers	Rift & Drift of ECMI in Cretecaous
65–56 Ma	K-G, M, S & D rivers	Deccan Traps emplacment at 65 Ma
56–34 Ma	Peninsular rivers	Indo-Asian Collision
34–23 Ma	C, M, Bengal Basin rivers	Change in rate and angle of convergence between the plates
23–6.8 Ma	G-B rivers	Exhumation of Himalaya
6.8–0.8 Ma	G-B rivers	Reactivation of MCT & Intraplate deformation
0.8–0 Ma	K-G, M & G-B rivers	2nd pulse of Exhumation of Himalaya & onset of glacial cycles

Figure 9. Sediment rate versus age plots of the BoB, Indus Fan and distal Bengal Fan. ***a***, Sediment rates are calculated and shown for different geologic domains of the BoB. The grey line indicates the average sediment rate of all geologic domains of the BoB. ***b***, Sediment rates are compared to those of the Indus Fan[38] and distal Bengal Fan[7,13]. The table depicts major river activities in time domain since the Cretaceous and associated important tectonic events. C, K–G, M, S, D and G–B represent the Cauvery, Krishna–Godavari, Mahanadi, Subaranarekha, Damodar and Ganges–Brahmaputra rivers respectively.

further found that an abrupt change in sediment deposition in the BoB during Oligocene–Miocene (~23 Ma) has strong linkages with the rapid uplift of the Himalaya and establishment of present-day Asian monsoon. Subsequent rise in sediment deposition from 6.8 to 0.8 Ma is also strongly associated with the strengthening of the Late Miocene Asian monsoon[39–41]. Several earlier studies[4,39,40] suggested that the monsoon was strengthened after ~8 Ma, but recent reports[42,44] indicate a weaker monsoon in South Asia as well as South East Asia after 8 Ma.

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ACKNOWLEDGEMENTS. We thank D. K. Pande and S. V. Rao (former Directors (Exploration), ONGC for their interest and immense support in the initiation of R&D collaborative project between CSIR-NIO and ONGC-KDMIPE. The present work is a part of this collaboration project. We also thank Jon Bull and Manik Talwani for their comments and suggestions that helped improve the manuscript. This is NIO contribution number 5848.

Received 7 September 2015; revised accepted 31 December 2015

doi: 10.18520/cs/v110/i3/363-372