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Morphotectonic evolution of the Majuli Island in the Brahmaputra valley of Assam, India inferred from geomorphic and geophysical analysis

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ABSTRACT

The Majuli Island, located in the upper reach of the Brahmaputra valley in Assam (India), has reduced in its areal extent from 787.9 km^2 to 508.2 km^2 during the period 1915–2005 (35.5% reduction). This amounts to severe average erosion of 3.1 km^2/yr. All efforts so far to save the island have failed to achieve the desired redress. The engineering approach of 'Save Majuli' action plans has focused on quarantining the island from the influence of the Brahmaputra River rather than designing long-term process-based solutions anchored on proper understanding of evolution of the relic island. The existing geomorphic model for the evolution of the Majuli Island related its genesis to the great earthquake (M 8.7) in 1750 during which a much smaller palaeo-Brahmaputra developed an anabranch and captured the Burhi Dihing River. The intermediate land-locked area thereby became the Majuli Island that is constituted primarily of the older floodplain deposits. We demonstrate that the evolution of the Majuli Island has been influenced by fluvial morpho-dynamics, as well as basement configuration and tectonic controls. Thus, the landform called the Majuli Island cannot be explained as a simple fluvial geomorphic feature. Rather, it represents an outcome of tectono-geomorphic process having strong subsurface control. We have investigated the influence of geomorphic parameters including channel belt area (CHB), channel belt width (W), braid bar area (BB), channel area (CH), thalweg changes and bankline migration on the trend of erosion of the Majuli Island. Integration of geophysical evidence from seismic data and the surface morphological changes suggest that the Majuli Island and other similar landforms represent structural 'highs'. Morphotectonic evolution of these islands has involved three stages- *pre-bypass uplift*, *Majuli formation* and *abandonment*. The Majuli Island in the Brahmaputra valley is presently passing through the abandonment stage and is gradually being incorporated within the flood plain of the valley.

1. Introduction

The Brahmaputra, considered as one of the top ten large anabranching mega-rivers of the world (Latrubesse, 2008), is the seventh largest tropical river (Hovius, 1998; Latrubesse et al., 2005; Tandon and Sinha, 2007) in terms of mean annual discharge (20,000 m^3/s in Bangladesh). It passes through three populous countries, China, India and Bangladesh. The mega-river acts as a conduit for transporting a very high sediment flux (852.4 t/km^2 year in Bangladesh) (Singh, 2006; Singh et al., 2006; Latrubesse, 2008) from a source representing broadly the active zone of continent-continent collision between the Indian and the Eurasian plates (Brookfield, 1998). The exceptionally high sediment flux of the Brahmaputra has been attributed to erosion of actively uplifting mountains of the Himalayas, slope erosion of the Himalayan foothills and movement of alluvial deposits stored in the Assam valley (Thorne et al., 1993; Garzanti et al., 2004). The influence of the Himalayan orogeny and large influx of the eroded materials from the hinterland on fluvial dynamics of the Brahmaputra River has been studied by several workers (Mathur and Evans, 1964; Coleman, 1969; Bhandari et al., 1973; Das Gupta and Nandy, 1982; Goswami, 1985; Ahmed et al., 1993; Das Gupta and Biswas, 2000; Kent and Das Gupta, 2004; Sarma, 2005). Available data also suggest that the present-day Brahmaputra valley, a NE-SW trending intermountain alluvial relief, was earlier a part of the Assam-Arakan basin, and it constituted mainly the shelf part of the basin (Das Gupta and Biswas, 2000). Although basins undergoing active tectonic adjustments are not considered suitable for hydrocarbon prospects (Fielding, 2000), the Brahmaputra valley, in spite of intense seismic activities, has provided excellent hydrocarbon reservoirs.

The upper reach of the Brahmaputra (Fig. 1) trends northeast-southwest extending from the confluence of three rivers, the Siang, the Dibang and the Lohit, to the stretch adjacent to the Mikir Hills. One of the most diagnostic features of the alluvial reaches of the Brahmaputra is the presence of large alluvial islands and several of them are more than a century old and inhabited as well. One such island, Majuli, located in the upper reach of the Brahmaputra valley is the focus of this paper. Majuli is one of the largest riverine islands in the world and the largest in Asia with a population of 0.16 million

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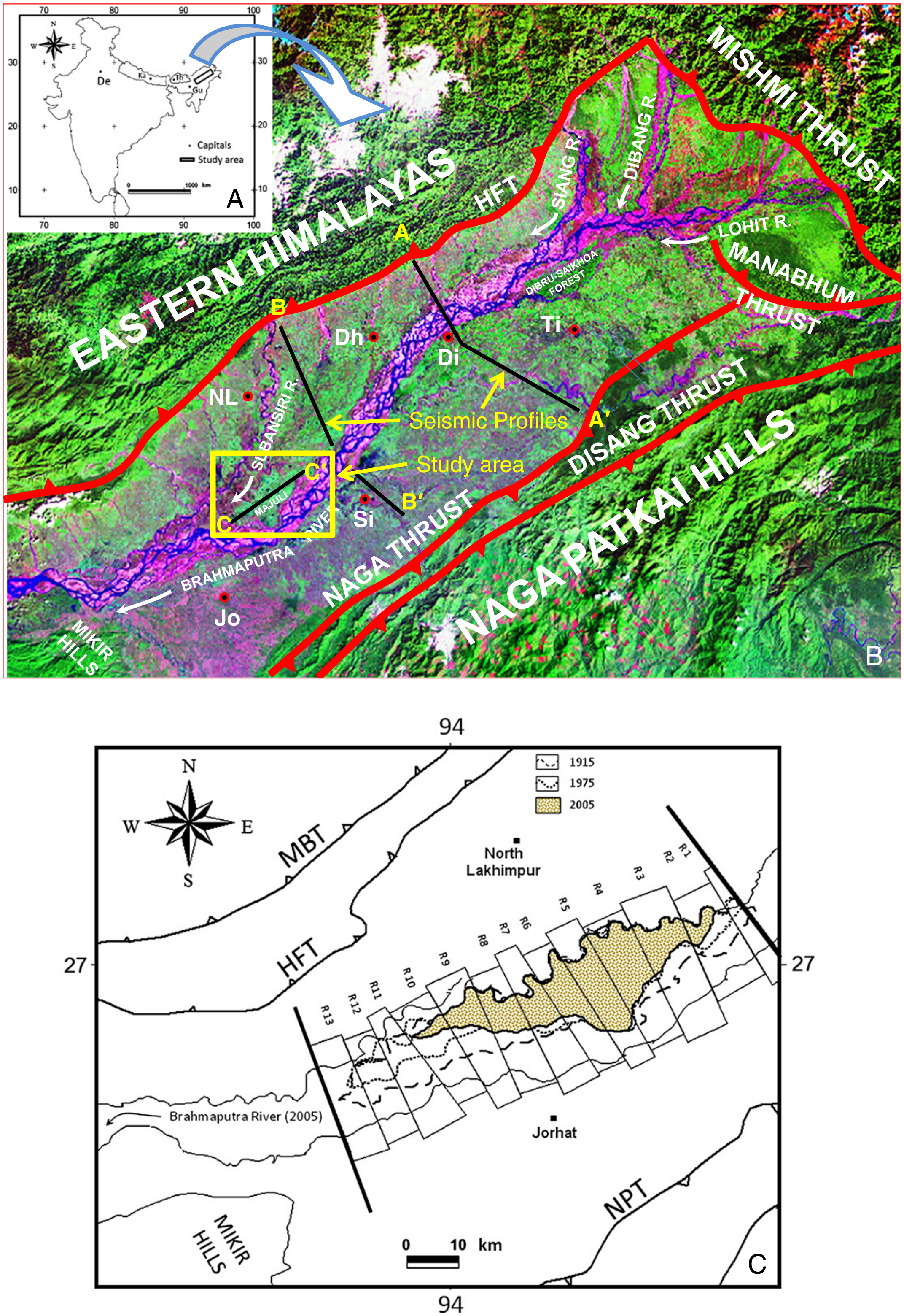


Fig. 1. Location map of the study area. (A) The upper reach of the Brahmaputra valley, situated in Assam, India, is a 280 × 80 sq.km area. (B) Three rivers, Siang, Dibang and Lohit meet to form the Brahmaputra River. Box shows the Majuli Island in the downstream reaches of the river. Important geological features and tectonic elements are shown to describe the study area. The area is sandwiched between the thrust belts of the Eastern Himalayas and the Naga Patkai Hills. The locations of three seismic profiles AA′, BB′ and CC′ are shown. (C) Thirteen reaches covering the Majuli Island where geomorphic measurements were done. (HFT- Himalayan Frontal Thrust; Jo-Jorhat; NL: North Lakhimpur; Si: Sibsagar; Di: Dibrugarh; Ti: Tinsukia; Dh: Dhemaji).

people and the site of ~64 Vaishnavite spiritual centres called ‘Satras’ (Fig. 1B-C). The literal meaning of ‘Majuli’ is the land locked between two rivers. The present length of the Majuli Island is ~64 km and the maximum width is ~20 km. This place, considered as a world heritage site that needs preservation, is under the threat of total extinction due to massive land erosion. The Majuli Island differs from other sandbars in the sense that the latter develop directly as the consequence of the sediment load redistribution whereas the former represents the remnant floodplain after sudden channel diversions and anabranching (Latrubesse, 2008). Formation of Majuli-like landforms is thus a part of river dynamics (Takagi et al., 2007) that might be related either purely to the variability in the sediment dispersal pattern or neotectonic influences and of course there might be interplay of both. Apart from Majuli, there are a few other islands in the Brahmaputra system including one in the upstream reaches close to the old confluence of Siang, the Dibang and the Lohit. Locally called 'new Majuli', this new island has developed during the last two decades only and about 300 km^2 of forested area (Dibru-Saikhoa Reserve Forest) has now become an island (Fig. 1B). This has resulted in an unprecedented increase in the width of the channel belt of the Brahmaputra in this reach and has also impacted the morphodynamics of the tributaries.

This paper puts forward a critical review of the available hypothesis for the evolution of the Majuli Island and presents new insights based on geophysical evidence. We offer an alternative mechanism for the evolution of the Majuli Island taking into consideration its morpho-tectonic setting and fluvial processes.

2. The upper Brahmaputra valley and the Majuli Island

In the present study, we focus on the upper Brahmaputra valley situated in the extreme north east corner of India in the foothills of eastern Himalayas (Fig. 1A). This part of the valley belongs to the Assam Arakan foreland basin system (DeCelles and Giles, 1996) and the Majuli Island and the adjacent areas are a part of the foredeep having some of the thickest depocenters. The upper Brahmaputra valley is 280 km long and 80 km wide (Fig. 1B) sandwiched between NE-SW bound Himalayan Frontal Thrust (HFT) and the Naga-Patkai Thrust (NPT). The Mishmi hills, belonging to the syntaxial zone of the Himalayas mark the north-eastern boundary and the Mikir hills, having basement metamorphic rocks exposed, are located close to the south-western boundary.

The stratigraphy deciphered from different deep wells close to the Majuli Island shows the oldest sediment of Paleocene-Eocene age (Ranga Rao, 1983). The geo-tectonic setting of the Majuli Island (Fig. 2) shows that the place is situated between the Bouguer gravity anomaly contours 220–240 mGal and first order basement depth contours 3.6-5.0 km (Narula et al., 2000). It clearly shows a prominent 'Low' in the NW part of the Majuli Island. As per the first order tectono-geomorphic zonation of the intermontane valley into *central uplift*, *slope* and *depression* (Lahiri and Sinha, 2012), the Majuli Island falls into the lower part of the 'central uplift' zone. Seismological evidence suggests that the eastern Himalaya to the west and the Indo-Burma thrust areas to the east of the Majuli Island have recorded several large earthquakes (greater than magnitude 4) during 1964–1993 (Narula et al., 2000). However, the Brahmaputra valley area where the Majuli Island is located is practically aseismic. This observation is in line with the study of the Coda waves (Hazarika et al., 2009) for the smaller earthquakes (Magnitudes varying from 1.2 to 3.9). A quality index of the coda waves 'Qc' is supposed to have higher values for the lesser decay. Unconsolidated material highly fractured or otherwise, is supposed to cause greater degree of attenuation of the waves and that is why it will show lower values of 'Qc'. The eastern Himalayan side nearer to the Majuli Island represents highly unconsolidated materials thereby causing a higher degree of seismic energy attenuation in all ranges of frequencies (1–18 Hz).

3. Method & approach

To understand the nature of the recent morphological changes around the Majuli Island area, the 23.5 m resolution IRS-P6-LISS-3 image, taken on 15 December 2005, was compared to the topographic maps prepared during 1912–1926 seasons (scale 1: 253,440) and 1977 (scale: 1:250,000) topographic maps of the Survey of India. Standard methods of digitization, image to image registration by selecting proper Ground Control Points (GCPs) and ground verification were followed using ERDAS software for co-registration of all data. Different thematic maps including geomorphology and structure of the Majuli Island and surroundings were integrated with images and toposheets in a GIS environment. Channel belt of the Brahmaputra River, including the Majuli, was divided into 13 reaches (Fig. 1C) of length varying from 4.5

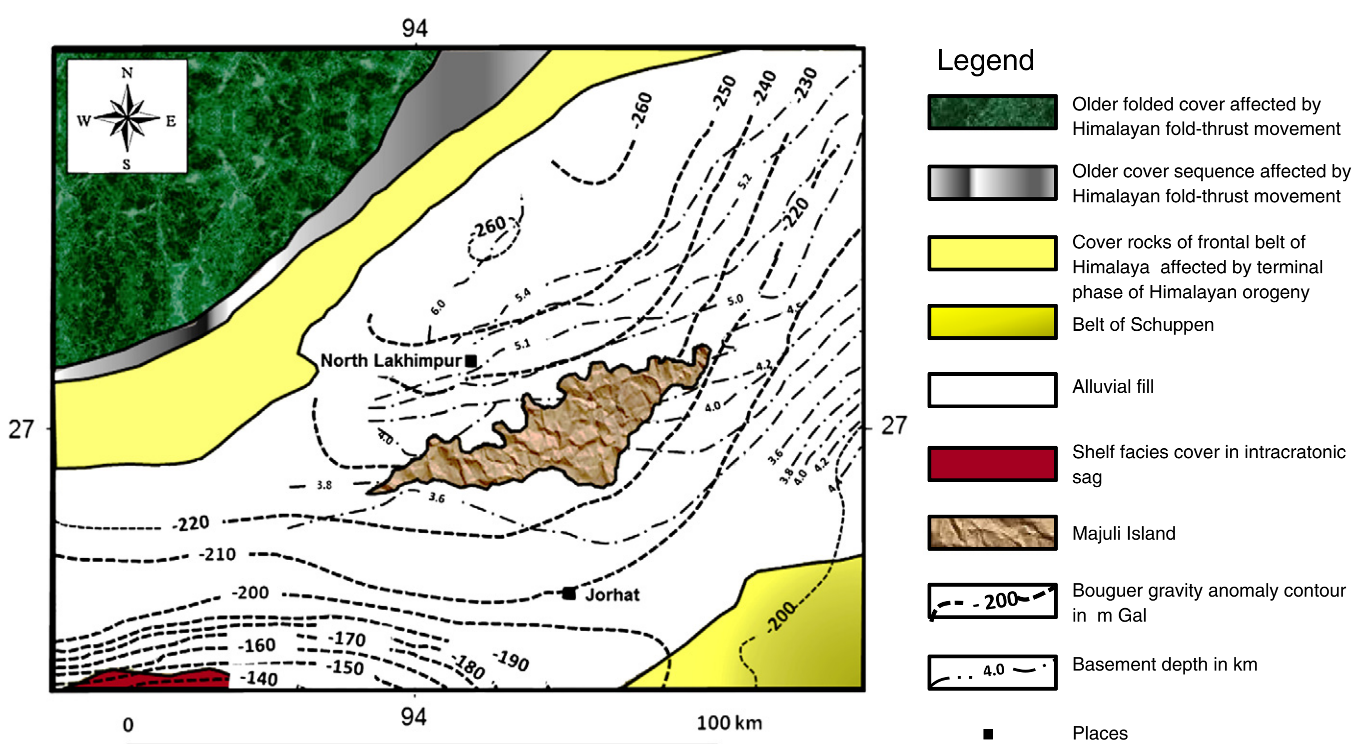


Fig. 2. Geotectonic setting of the Majuli Island and the surrounding area with Bouguer gravity contours in mGal and basement depths are shown in km. Deeper the basement, thicker is the sediment thickness and more negative Bouguer anomaly.

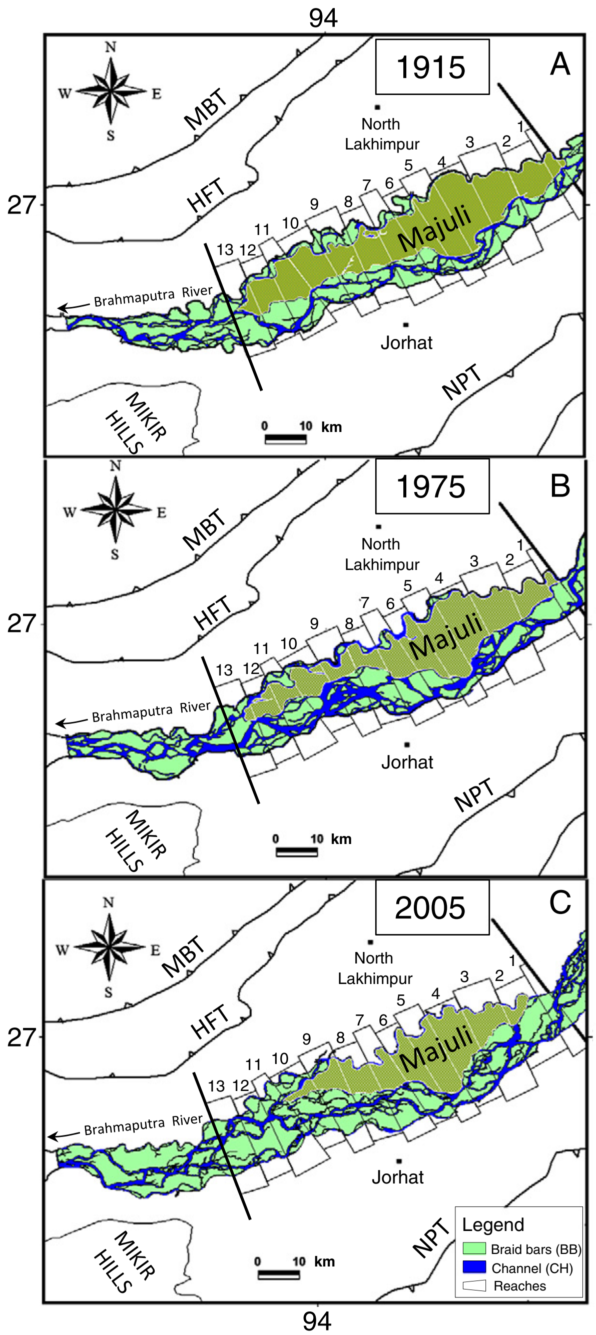


Fig. 3. Reach scale planform changes in the Brahmaputra and Majuli island during (A) 1915, (B) 1975 and (C) 2005.

to 8.5 km. A variable reach length was preferred to locate places of local significance and the computation was done for changes per unit areas or lengths.

To investigate the interrelationships of the erosion characteristics of the Majuli Island with other geomorphic parameters, we measured the planform parameters such as channel belt area (CHB), braid bar area (BB) excluding the Majuli Island, Channel area (CH), average widths (W), and thalweg and bankline shifts for three different years 1915, 1975 and 2005.

Seismic sections obtained from the Oil India Limited, Duliajan were interpreted after identifying different reflectors based on the lithological information and the geophysical log data (mostly natural gamma ray logs and the deep resistivity data). Some of the interesting findings of other workers were also used to interpret Quaternary-scale basin evolution.

4. Results and interpretation

4.1. Geomorphology and erosional history of the Majuli Island

The spindle-shaped Majuli Island, in spite of the recent surge in the rate of erosion, is a fairly steady landmass within the channel belt of the Brahmaputra River. Unlike other smaller islands located in the adjacent areas, the Majuli never submerges completely even during maximum flooding. Majuli is also a *relic* island because it is older than the Brahmaputra River (Sarma and Phukan, 2004).

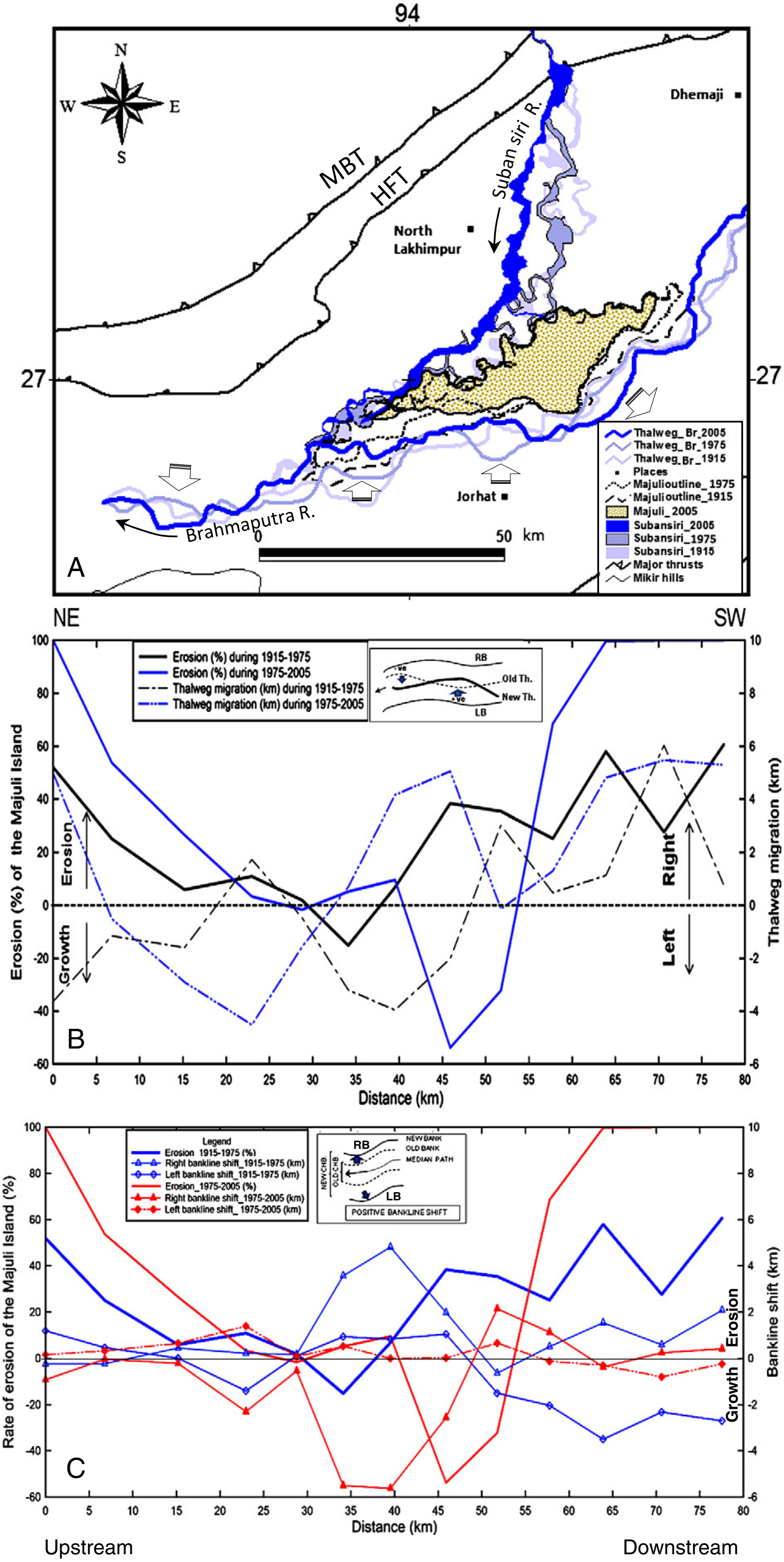
Geomorphic mapping of the Majuli Island and the surrounding reaches of the Brahmaputra river (Fig. 3A–C) using multi-date satellite images and toposheet covering a period of about 90 years reflects a highly dynamic regime and a very high rate of erosion of the island. Between 1915 and 1975, the surface area of the island reduced from 787.87 km^2 to 640.5 km^2 (18.7% reduction) and then to 508.2 km^2 by 2005 (35.5% reduction as compared to the 1915). The average rate of erosion in the last thirty plus years has increased considerably from 2.46 km^2/yr (1915–1975) to 4.40 km^2/yr (1975–2005). The length of this island has also reduced greatly from 79.7 km in 1915 to 75.16 km in 1975 and then 63.33 km in 2005 (about 20.5% reduction compared to 1915). Our initial observations suggest significant spatial variability in terms of erosion of the Majuli Island in the upper, middle and lower parts.

Although it is often difficult to define the thalweg line on maps and images, we mapped the median path of the widest channel to represent the temporal variability of thalweg line (Fig. 4A). In the upper as well as the middle parts of the Majuli, the thalweg line of the Brahmaputra shows an eastward shift away from the island during the period 1915–2005. In the lower parts of the Majuli, the thalweg line moved closer to the Majuli (Fig. 4B). Further, the Subansiri, a major tributary of the Brahmaputra, shifted SW after the 1950 earthquake and now joins the Brahmaputra close to the western edge of the Majuli (Fig. 4A).

Bankline shift along the right and left banks (Fig. 4C) shows different and at places opposite trends with respect to erosion of Majuli. The right bankline is very close to the western edge of Majuli. Over the years, due to human interventions and migration of the Subansiri River further downstream, channel flow along the right bank has been fairly stable and erosion has also decreased rapidly on the western end. On the other hand, the left bankline has moved closer to the Majuli Island, particularly in the lower part and has accelerated erosion of the island.

Fig. 5 shows changes in planform parameters in the reaches of the Brahmaputra river around the Majuli Island. There is a remarkable shift in the relative trend of channel area (CH) and the braid bar area (BB) changes. During 1915–1975, CH and BB often show opposite trends although CHB follows a trend similar to that of BB (Fig. 5A). Also, the average amplitude of change in CH was higher than that of BB and the CHB. This suggests that channel reduction outpaced channel aggradation during this period. However, during 1975–2005, CH and BB show similar trends but BB has a much higher amplitude of change in the reaches along the Majuli Island (Fig. 5B). As we move downstream, the amplitude difference between BB and CH keeps on increasing, suggesting a rising trend in channel aggradation. The BB/CH ratio reduces

Fig. 4. (A) Thalweg locations of the Brahmaputra channel belt and the shifting tendency of the Subansiri River before it confluences with the Brahmaputra River in the lower part of the Majuli Island during 1915, 1975 and 2005, (B) Comparison between the nature of thalweg migration and the percentage of erosion of the Majuli Island during 1915–1975 and 1975–2005.(C) Comparison between the bankline migration of the Brahmaputra channel belt and the nature of erosion of the Majuli Island during two different periods as mentioned above. Positive migration of both the banklines amounts to increase in the width of the channel belt for a given location.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Subansiri_1975
Subansiri_1915
Major thrusts
Mikir hills
NE
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Erosion (%) during 1915-1975
Erosion (%) during 1975-2005
Thalweg migration (km) during 1915-1975
Thalweg migration (km) during 1975-2005
RB
Old Th.
New Th.
LB
Erosion (%) of the Majuli Island
Thalweg migration (km)
Erosion
Growth
Right
Left
B
Distance (km)
Legend
Erosion 1915-1975 (%)
Right bankline shift_1915-1975 (km)
Left bankline shift_1915-1975 (km)
Erosion_1975-2005 (%)
Right bankline shift_1975-2005 (km)
Left bankline shift_ 1975-2005 (km)
NEW BANK
OLD BANK
MEDIAN PATH
NEW CHB
OLD CHB
POSITIVE BANKLINE SHIFT
Rate of erosion of the Majuli Island (%)
Bankline shift (km)
C
Distance (km)
Upstream
Downstream

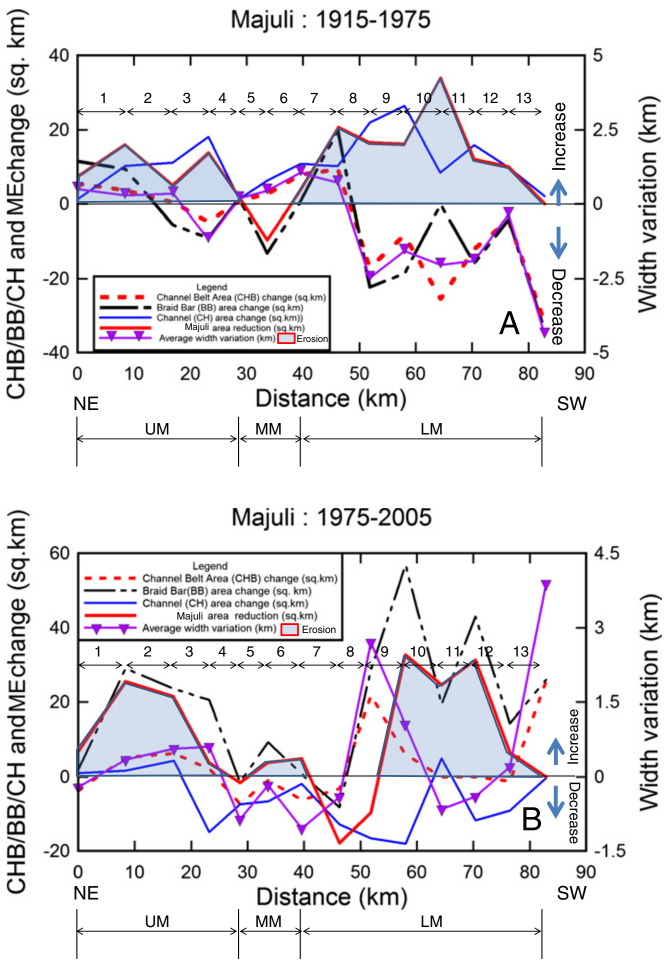

Fig. 5. Quantitative analysis of the geomorphic parameters observed in relation to the temporal variability of planform erosion of the Majuli Island. (A) Absolute changes in the channel belt areas, average widths of different smaller units, cumulative areas of braid bars (Majuli excluded), cumulative channel areas and amount of erosion of the Majuli Island during 1915–1975, (B) same parameters plotted during 1975–2005.

from 2.34 in 1915 to 1.24 in 1975 but increases again to 2.49 in 2005 suggesting an overall aggradation during 1915–2005.

Trends of variation in the channel belt area (CHB) and the average widths (W) show a close similarity and are negatively correlated to the reduction of the Majuli Island for the period 1915–1975. This correlation is a bit unclear during the period 1975–2005 as erosion occurred even when channel belt expanded or remained stable. However, the rate of Majuli erosion was much higher in reaches where channel belt shows a narrowing tendency (due to human intervention in the form of construction of embankments etc. or otherwise). Within the channel belt, new braid bars formed in some reaches but the cumulative braid bar area (BB) in different geomorphic units (excluding the area covered by the Majuli Island) shows an overall decreasing trend (about 9.3% decrease during 1915–1975). However, during 1975–2005, the trend was reversed, and there was an exceptionally large increase in braid bar area by ~53% with a simultaneous increase in severity of erosion of the Majuli Island.

Further, the upstream reaches of the Brahmaputra, close to the confluence of the Lohit, the Dibang, and the Siang, have undergone significant changes in the last two decades and a major island with an area of around 300 sq. km has emerged (locally called 'new Majuli', see Fig. 6). A comparative study of the temporal changes in channel configuration indicates a three-phase evolution of this new island: (a) bifurcation of the Siang River and its north-westward shift, (b) confluence shift and positive stretching of the Brahmaputra channel belt, and (c) avulsion of the Lohit River by channel capturing. From 1995 onward, the Lohit River started to divert its flow from the western flank of the Dibru-Saikhoa reserve forest along the Dangori River and eventually the Dibru River channel was captured by the Lohit River. The Dibru-Saikhoa Reserve Forest became an island (New Majuli) by 1998 and the Siang-Dibang-Lohit (SDL) confluence point (from which onward the flow regime is known as the Brahmaputra River) shifted further downstream.

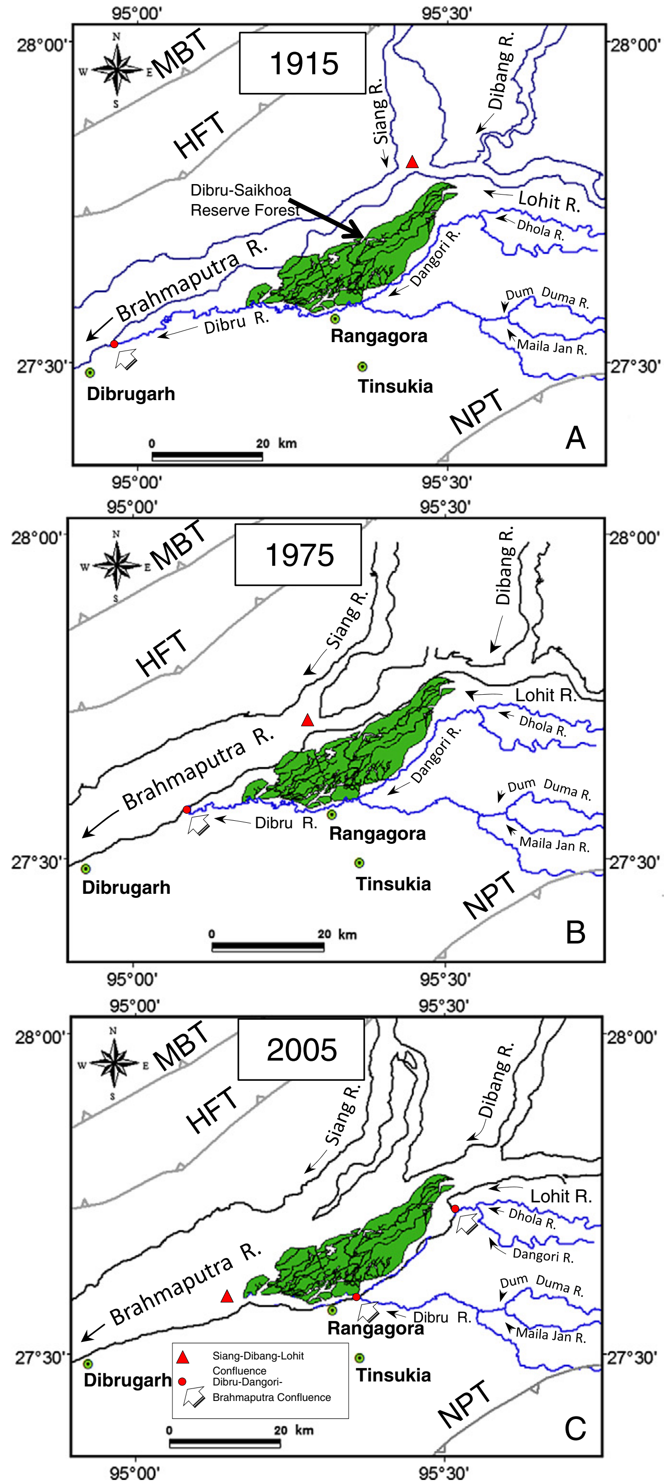

Fig. 6. Sequence of development of new Majuli island in the upper reaches of the Brahmaputra. The Dibru-Saikhoa Reserve Forest has become a new river island within the last two decades. Siang-Dibang-Lohit confluence point shifts in the downstream direction. Confluence point of the Dibru River shifts in the upstream direction.

Presently, the entire flow of the Lohit River, partial flow of the Dibang River and a number of smaller streams from the southern bank are passing through the old Dangori-Dibru course. Moreover, in contrast with the downward shift of the SDL, the confluence of the Dibru and the Brahmaputra River shifted by 14 km in between 1915–1975 and during 1975–2005, the shift was about 27 km in the upstream direction (Fig. 6). Thus, within a period of ninety years, the net upward shift of the confluence was more than 40 km. At present, due to the channel capture by the Lohit River, two independent confluence points emerged - one between the Dangori and the Lohit and another between the Dibru and the Lohit. Both of these south bank rivers, besides the upward shift of the confluence, have also gone through substantial reduction in length - the Dibru River reduced by about 64 km and the Dangori River by 24 km.

4.2. Sub-surface geology of Majuli Island based on seismic profiles

Of the three seismic profiles taken up in this study, the first one AA′ (Fig. 7A, see Fig. 1B for location), located ~60 km upstream of the tip of the Majuli, is a merged section generated from two smaller sections. Criss-crossing the entire valley, the net length of this profile is about 80 km. The NW-SE bound segment of the profile, about 25 km long, begins near the HFT where the Simen River joins the valley and then, ends

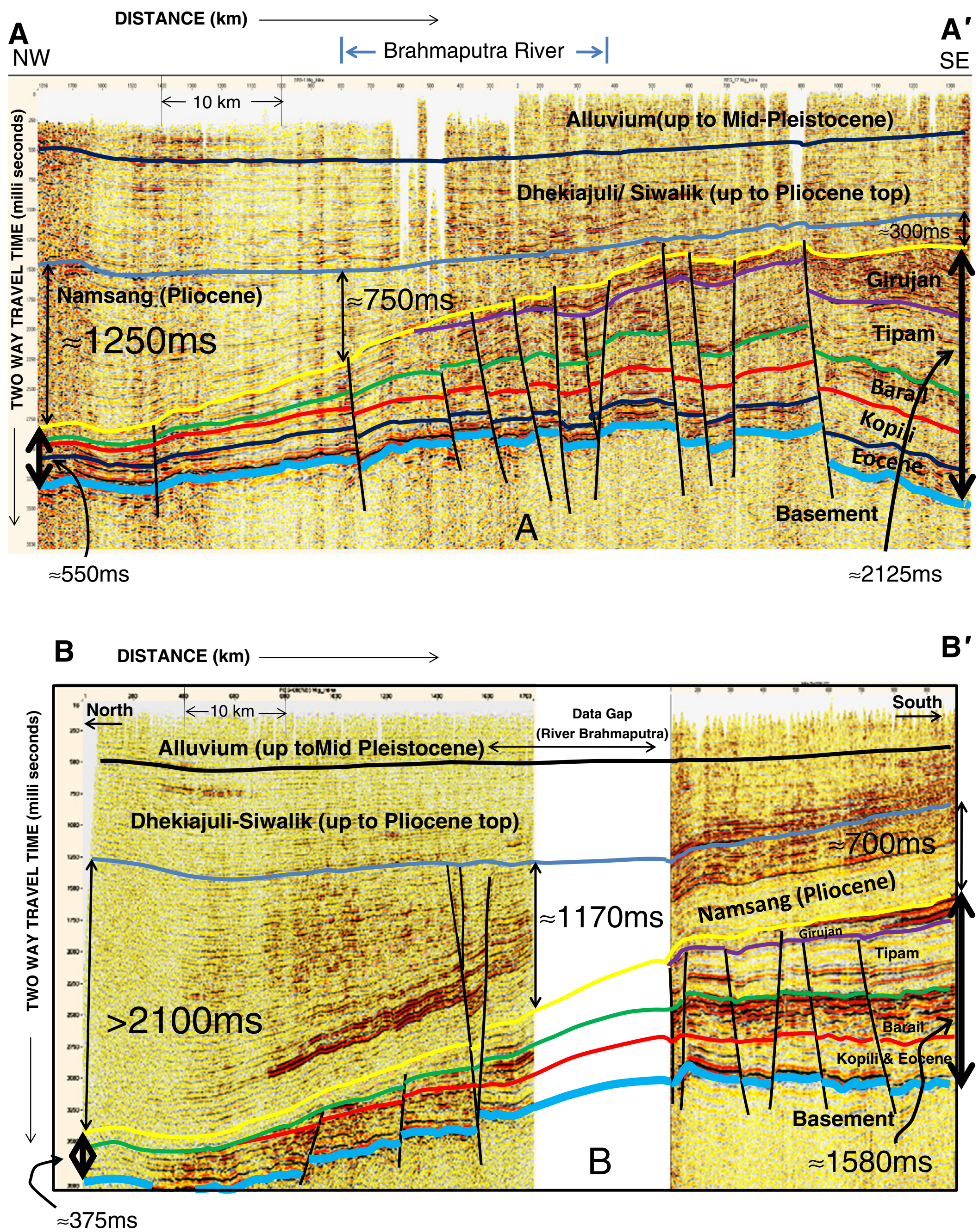

Fig. 7. Subsurface interpretation from the seismic sections. (A) An integrated seismic section AA/ across the upper reach of the Brahmaputra valley. The section shows clearly the basement topography and the stratigraphy. This is a Two Way Travel Time (TWTT) section. The great thickness of sediments having fluvial origin near the Himalayan Frontal Thrust (HFT) is remarkable and equally remarkable is its nature of thinning towards the Naga Patkai Thrust (NPT) belt. (B) Seismic section BB′, very close to the upper tip of the Majuli Island, shows the deepening and thickening of the fluvial sediments in the Himalayan foredeep compared to section AA′. (C) Seismic section CC′ below the Majuli Island shows clearly the bending caused by thrust belt tectonics and the convexity of the near surface bed boundaries.

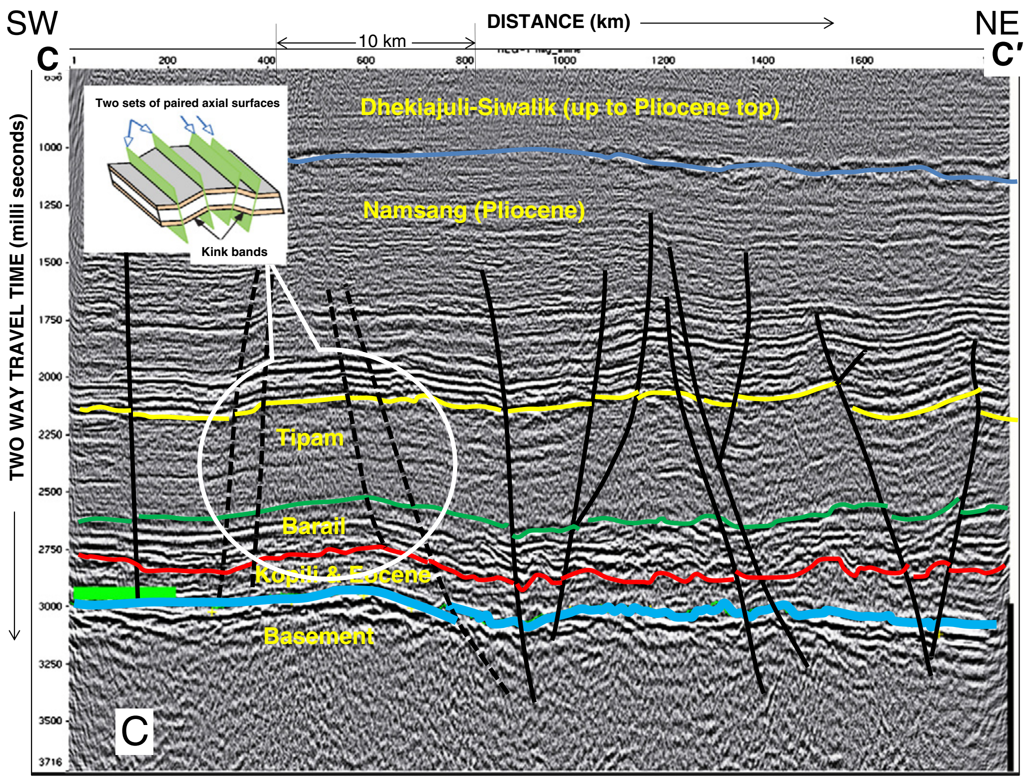

Fig. 7 (*continued*).

at Dibrugarh crossing the Brahmaputra River. The second segment of the section, starts at Dibrugarh, proceeds towards the Naga Patkai Thrust (NPT) and ends near the place where the Burhi Dihing River emerges into the valley. This section, besides subsurface stratigraphy of Miocene-Pliocene sequences shows the basin configuration and tectonic framework (discussed later). Interestingly, the Miocene top in the eastern Himalayan side is located at about 2.8 s whereas in the NPT side this is located at about 1.3 s. Thus, there is a difference of about 1.5 s suggesting large variation in sedimentary thickness between the Himalayan and NPT side.

The seismic section BB′ (Fig. 7B, see Fig. 1B for location) consists of two parts; there is a data gap in the Brahmaputra channel belt. The section starts close to the source of the Subansiri River; runs SE to the northern tip of the Majuli Island, and then covers the south bank of the valley towards the east running almost parallel to the Dikhau River. The section showing the maximum two-way-travel-time (TWTT) of 4.16 seconds (or, 4160 ms) covers a depth of around 6 km. The basement complex shows a general dipping trend towards the Eastern Himalayan side and a number of normal faults. Also, Paleocene-Miocene sediments of mostly marine origin thicken as reflected by increase in TWTT from 375 ms to 1580 ms towards the SE direction. The overlying sediments, Late Miocene and younger, are mostly fluvial. Pliocene sediments are much thicker on the Himalayan side than the topographic boundary of the Naga Patkai Thrust belt. Moreover, as we compare AA′ with BB′, it is observed that the depozone in the north bank in the downstream direction of the Brahmaputra keeps on deepening (from 2850 ms to 3400 ms) as well as thickening (1250 ms to 2100 ms) below the topographic boundary of the Himalayan thrust belt.

The SW-NE trending seismic section along CC′ (Fig. 7C, see Fig. 1B for location), parallel to the strike direction of the Majuli Island, clearly shows the presence of a multiple-hinge anticline formed due to the contractional fault related fold (Bally, 1983) in the basement complex itself. The hinge lines propagate in the upward direction. However, as we move up, massive sediment dumping seems to attenuate the hinge line bends. The isopach map surrounding the Majuli Island, integrated mainly from the seismic surveys done by the ONGCL and the well data information, shows that the thickness of sediments is ~6.0 km close to the foothills of the eastern Himalayas (Fig. 2) and 3.5-4.4 km below the Majuli Island. Sediment thickness decreases rapidly between the Majuli Island and the Mikir Hills, and ultimately the hard basement complex crops up. The basement shows highly faulted and fractured condition.

Seismic data have also been integrated with topographic and basement configuration. The topographic map of the Majuli Island (Fig. 8A) shows a prominent high in the central part with a sharp break in slope (Average slope changes from 0.17 m/km to 0.73 m/km). This topographic break closely matches with a break in the basement slope along the same profile (Fig. 8B). The basement depth was computed with the average velocity of 3000 m/s from the seismic section shown in the Fig. 7C. Fig. 8C shows the isopach map of the region around Majuli. There is a very prominent E-W bound fault called 'Jorhat Fault', passing through the tail end of the Majuli Island. A number of NE-SW bound faults are running parallel to the strike of the Majuli Island. This evidence suggests that the position of the Majuli Island is structurally controlled and such geomorphic highs are guided by basement topography. We have also verified this hypothesis with a seismic section for a NE-SW bound profile running near parallel along the eastern margin of the Dibru Saikhoa Reserve Forest (the quality of which is not good enough to be presented in the paper). The seismic section shows unmistakably a prominent basement upliftment around the 'New Majuli' area.

5. Discussion

Sarma and Phukan (2004) suggested that the old Brahmaputra, called Lohit, was flowing through the northern side of the present day Majuli ~250 years back as a considerable low-energy meandering river. The width of the Lohit was comparable to one of the present-day tributaries, the Burhi Dihing (200-500 m wide). It is important to note that the average width of the Brahmaputra River in the upper Assam valley was 9.74 km in 1915 over a 240 km long channel belt

(Lahiri and Sinha, 2012). An older version of the Dihing River (pre-1750) was flowing along the present course of the Brahmaputra River south of the present-day Majuli Island. The great flood of 1750 changed the earlier low-energy, meandering Lohit into a very high-energy braided river, the present day Brahmaputra. Sarma and Phukan (2004) also suggested that the sudden rise in the magnitude of discharge necessitated development of anabranches in the Brahmaputra to improve channel efficiency (Nanson and Huang, 1999; Richardson and Thorne, 2001; Jain and Sinha, 2004). The anabranch flowing through the earlier course of the Dihing formed a land locked area, the Majuli, has developed further during the last 250 years while the discharge through the main Brahmaputra has kept on decreasing very fast.

The geomorphic model proposed by Sarma and Phukan (2004) raises a number of questions: (a) Why was the Brahmaputra flowing as a low-energy meandering river ~250 years back? (b) Was it due to much lesser volume of water discharge from the catchment area? (c) Did the catchment area for the Brahmaputra valley witness a drastic change in the monsoonal precipitation 250 years back? Ice-melt water constitutes a significant component of the discharge into the Brahmaputra. However, it is mainly the monsoonal precipitation in the catchment which is responsible for the large volumes of water and sediment transport. Although the following sections do not answer these questions, we propose an alternative model for the development of Majuli-like landforms in the alluvial reaches of the Brahmaputra.

5.1. Role of basin configuration and tectonic setting

New geophysical evidence, especially high resolution seismic sections, have provided us an opportunity to understand the morphotectonic evolution of Majuli. Fig. 10A shows a schematic and generalized stratigraphy based on the seismic profiles AA′ and BB′ shown in Fig. 7A and B. Marine sediments below the fluvial sediments show a distinct trend of thickening from the HFT margin towards the present day NPT line. On the other hand, the non-marine sediments, mostly fluvial, are thickest around the HFT and much thinner towards the SE with respect to the location of the Majuli Island (Fig. 10A).

Seismic section presented in Fig. 7A shows that the Miocene top (top of the marine sediments) is at about 2.8^{+}s near the HFT and the same near the NPT is 1.3 s. This time difference of 1.5 s being a Two Way Travel Time (TWTT), for an average velocity of 3000 m/s, it amounts to a depth interval of about ~2.25 km. One possible explanation for such differences in basin depth could be stronger subduction along the Himalayan Frontal Thrust (HFT) and generation of larger accommodation space for fluvial sediment deposition. A comparison between the seismic sections BB′ and AA′ shows that the Pliocene sediments have thickened from 1250 ms to 2100 ms below the topographic front of the Himalayan thrust belt. Another NE-SW bound running seismic line (CC′) along strike direction of the Majuli Island shows (Fig. 7C) a multiple-hinge anticline which usually forms due to contractional fault-related folds. These observations indicate that three major geological elements, surrounding the Majuli Island, namely, the Eastern Himalayas, the Naga-Patkai Hills and the Mikir Hills, are undergoing differential tectonic activities. Isopach map around the Majuli Island shows (Fig. 8C) a prominent 'Jorhat Fault' (Prasad and Mani, 1983), representing most probably the local tectonic boundary of the Mikir Hills about which the 'Pop-up' phenomenon (Bilham and England, 2001) continues and the tail end of the Majuli Island is affected by a subsidence that has caused its rapid erosion in the last ninety years.

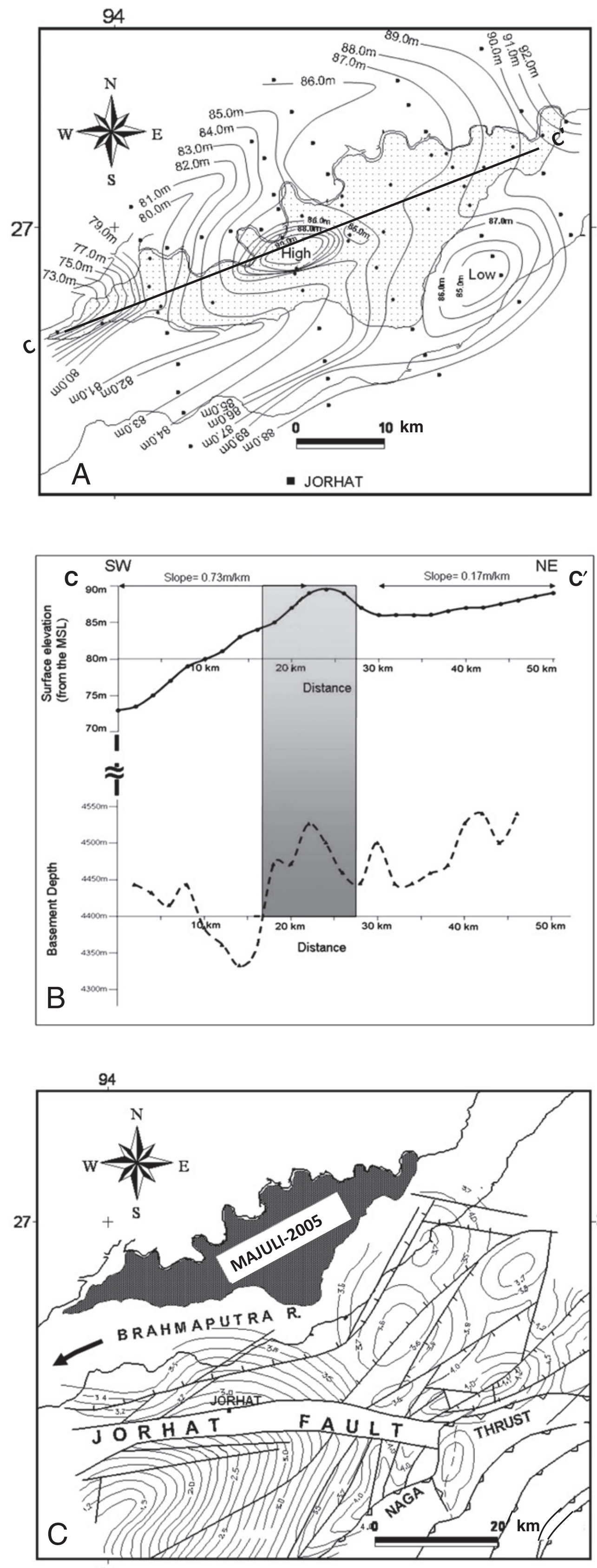

Fig. 8. (A) Topographic contours around the Majuli Island. From NE direction to the SW, the elevation falls from 92 m to 73 m above the mean sea level. However, there are a prominent 'High' in the middle portion of the island and a 'Low' adjacent to it. (B) Surface elevation change and the basement depth variation below the seismic profile CC′. For the sake of simplicity in comparison, the scale of basement depth variation has been compressed ten times. The normal gravity fault of basement origin is distinctly manifested on the surface. (C) Isopach map (modified from Prasad and Mani, 1983) showing the basement depth or sediment thickness variation (in km) in the eastern and the south eastern boundary of the Majuli Island. The Jorhat fault is supposed to control the south eastward bank migration of the Brahmaputra River.

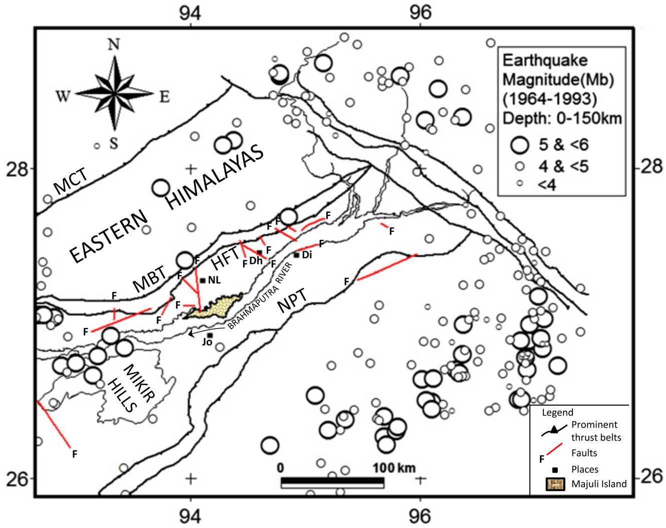

Fig. 9. Seismicity of the area surrounding the Majuli Island for the period 1964–1993 with considerably higher range earthquake magnitudes ($4.0 \geq M_b \leq 6.0$) and mostly shallow (0-40 km) in origin is shown. Earthquakes belonging to 41–70 km depths have also been clubbed up. The valley area is mostly aseismic.

Seismicity of the area (Fig. 9) shows major seismic activities about the marginal part of the basin as well as at the rim of the 'Pop-up' structures. The thick sediment blanket in the valley area acts as a dampener to keep it mostly aseismic. This is also substantiated by the study of Coda waves. However, the presence of lateral compression suggests that there are possibilities of stress accumulation of different magnitudes in different parts of the valley.

5.2. Role of geomorphic factors in evolution of the Majuli Island

Two geomorphic factors have influenced the evolution of the Majuli Island in a major way – thalweg migration and bankline shift of the Brahmaputra River and its tributaries. Apart from the Majuli Island under study, a similar feature has developed in the upper reaches of the Brahmaputra as reflected from reconstruction of drainage lines for the last 50 years (Fig. 6).

A comparison of rate of erosion in different parts of the Majuli Island reveals that the rate of erosion in the lower Majuli (~32.3%) was twice of that in the upper Majuli (~16.3%) during the period 1975–2005. We also note that the thalweg in the Brahmaputra channel migrated towards the lower Majuli reaches whereas it moved away from the Majuli Island in its upper and middle stretch. Further, the left bankline of the Brahmaputra River has been shifting towards Majuli and this has accelerated the erosion rate significantly. In addition, the channel dynamics of one of the important northern tributaries, the Subansiri, has also influenced the erosion of the lower Majuli. Before the 1950 earthquake, the Subansiri used to join the Brahmaputra with a much reduced flow in the central part of the Majuli Island. During the 1950 earthquake, the coseismic subsidence of the *Subansiri depression* (Lahiri and Sinha, 2012) resulted in migration of the Subansiri to SW and the river now joins the Brahmaputra much downstream close to the western edge of the Majuli. The combined flow of the Brahmaputra and the Subansiri along with northward migration of the thalweg and the left bankline of the Brahmaputra have acted in unison to accelerate the rate of erosion of the Majuli Island.

Our data have also demonstrated that temporal variations of various planform parameters such as CHB, W, BB, CH, LB, and RB are strongly correlated to the rate of erosion of the Majuli Island. While the channel belt area and width are negatively correlated to the rate of erosion, braid bar (BB) and channel (CH) areas are positively correlated particularly in

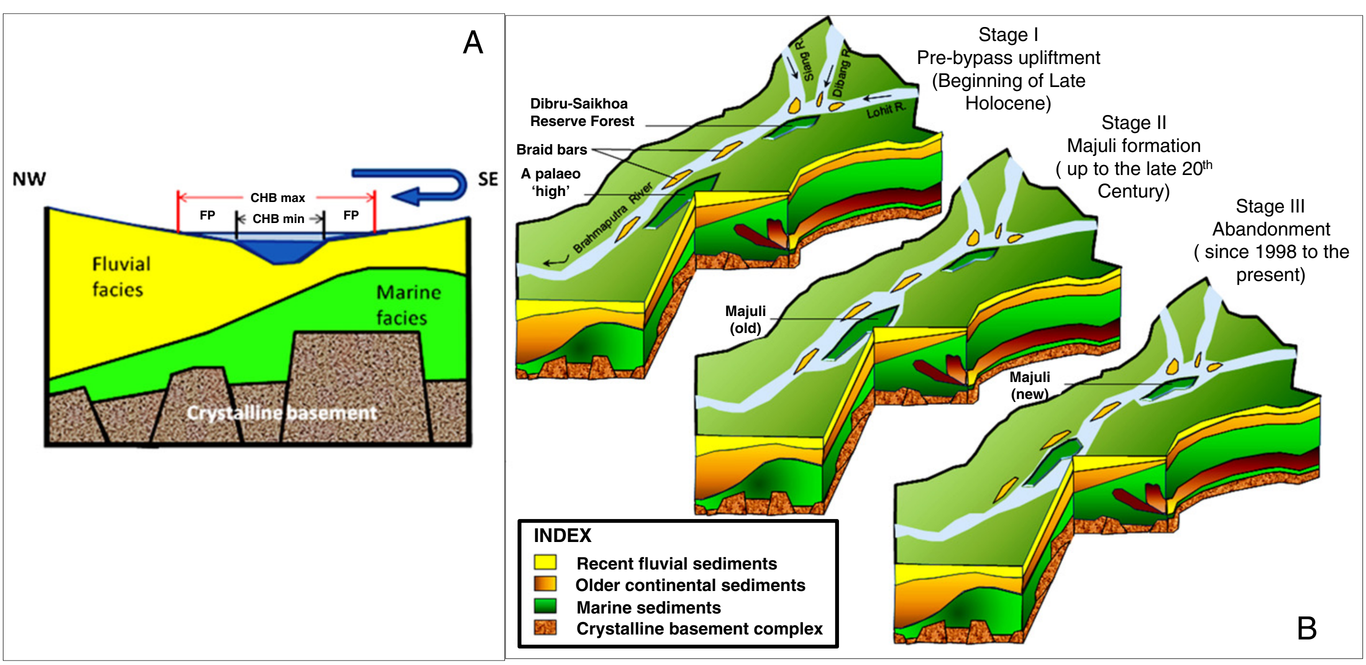

Fig. 10. Conceptual model summarising the evolution of the Majuli Island in the backdrop of the generalized basin evolution (A) A vertical cross sectional view across the basin merging the intra-stratification of the fluvial and marine sediments in the subsurface. A routine to and fro movement of a major river system like the Brahmaputra across the valley cannot explain the uneven nature of the thickness of the fluvial sediments unless tectonics associated with the frontal thrust systems in the convergent basin margins are brought into the picture. (B) A three stage model describing the behaviour of a specific geomorphic 'high' in response to the lateral bankline shift of a large river like the Brahmaputra. In the process demonstrated the Brahmaputra is migrating laterally from west to east. Stage I shows the upliftment of landforms due to tectonic control; Stage II shows avulsive characteristics of the Brahmaputra channelbelt when confronted with a structurally controlled geomorphic 'high' in the form of emergence of the old Majuli. Stage III shows unabated bankline migration that resulted in the abandonment of the old Majuli. A similar kind of three stage evolution has begun for the Dibru Saikhoa Reserve Forest causing emergence of a new Majuli.

the lower Majuli reaches. We argue that increase in braid bar areas in the lower reaches of the Brahmaputra particularly during 1975–2005 is clearly related to increased erosion of the Majuli Island.

5.3. Morphotectonic evolution of Majuli

Based on our geophysical and geomorphological investigations, we propose a 3-stage evolution of the Majuli Island and similar landforms in the region (Fig. 10B). Stage I involved the development of geomorphic 'highs' guided by basement configuration. This is confirmed from the seismic sections and topographic data and we have mapped a basement high just below the existing Majuli Island. Although the quality of seismic data around the new Majuli region in the upstream reaches of the Brahmaputra is not so good, the basement configuration and the topographic data suggest the presence of a geomorphic high at this location as well. These 'highs' can either be due to the leading edges of the blind thrust fronts in the foreland areas of the valley or due to the normal faults and 'arching' of the basin along its central part.

Stage II involved the incorporation of the geomorphic high within the channel belt as a result of fluvial dynamics. In valleys with strong structural control, well-defined geomorphic highs generally force the river to bypass (Holbrook and Schumm, 1999). The development of the new Majuli Island in the upper reaches of the Brahmaputra clearly illustrates this stage where the southward migration of the Lohit River bypassed the geomorphic high and the forested floodplain was incorporated within the channel belt at a historical time scale. Further development of the island through erosion-deposition cycles occurs due to local geomorphic processes. Our study has also shown a close relationship between morphodynamics of the Brahmaputra River and erosional history of the Majuli Island.

Stage III involves the abandonment of the Majuli Island or incorporation of the island with the adjoining floodplain. This is again affected by fluvial dynamics as is illustrated by the configuration of the Majuli Island in 2005. The main channel of the Brahmaputra now flows south of the Majuli and the northern branch is nearly inactive. The Majuli Island is slowly getting incorporated in the northern floodplain of the Brahmaputra while the southern and downstream edge of the island is under severe erosion.

6. Conclusions

The Majuli Island is one of the most dynamic landforms in the Brahmaputra valley of Assam and has attracted a lot of attention for a number of reasons. Apart from a serious threat to very special Vaishnavite spiritual centres due to severe erosion of the island in recent years, the Majuli Island represents a geomorphic high sitting on 'high basement' topography. This is confirmed from seismic sections around the Majuli and correlation of geophysical and topographic data. We have proposed a 3-stage evolution of Majuli and similar landforms involving the development of a geomorphic high and fluvial dynamics of the main channel. We emphasize the role of basement configuration and tectonic setting in the evolution of such landforms rather than a merely geomorphic process.

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References

Ahmed, A.E., Murthy, R.V.S., Bharktya, D.K., 1993. Depositional environment, structural style and hydrocarbon habitat in Upper Assam Basin. In: Biswas, S.K., Dave, P., Garg, P., Pandey, J., Maithani, A., Thomas, N.J. (Eds.), Proceedings of the Second Seminar on Petroliferous Basins of India. , vol. 1. Indian Petroleum Publishers, Dehra Dun, pp. 437–458.

Bally, A.W., 1983. Seismic expression of structural styles: A picture and work atlas, American Association of Petroleum Geologists, Tulsa, Okla., U.S.A.(139 pp.).

Bhandari, L.L., Fuloria, R.C., Sastri, V.V., 1973. Stratigraphy of Assam valley. AAPG Bull. 57, 643–654.

Bilham, R., England, P., 2001. Plateau 'pop-up' in the great 1897 Assam earthquake. Nature 410, 806–809.

Brookfield, M.E., 1998. The evolution of the great river systems of southern Asia during the Cenozoic India-Asia collision: Rivers draining southwards. Geomorphology 22, 285–312.

Coleman, J.M., 1969. Brahmaputra River channel processes and sedimentation. Sediment. Geol. 3, 129–239.

Das Gupta, A.B., Biswas, A.K., 2000. Geology of Assam. , Geological Society of India, Bangalore (169 pp.).

Das Gupta, S., Nandy, D.R., 1982. Seismicity and tectonics of Meghalaya Plateau, NE India. Symp. on Earthquake Engineering, 7th. Univ. of Roorkee, India, pp. 19–24.

DeCelles, P.G., Giles, K.A., 1996. Foreland basin systems. Basin Res. 8, 105–123.

Fielding, E.J., 2000. Morphotectonic evolution of the Himalayas and Tibetan plateau. In: Summerfield, M.A. (Ed.), Geomorphology and global tectonics. Wiley, Chichester, pp. 201–222.

Garzanti, E., Vezzoli, G., Andò, S., Lanord, C.F., Singh, S.K., Foster, G., 2004. Sand petrology and focused erosion in collision orogens: The Brahmaputra case. Earth Planet. Sci. Lett. 220, 157–174.

Goswami, D.C., 1985. Brahmaputra River, Assam, India: Physiography, basin denundation and channel aggradation. Water Resour. Res. 21, 959–978.

Hazarika, D., Baruah, S., Gogoi, N.K., 2009. Attenuation of coda waves in the northeastern region of India. J. Seismol. 13, 141–160.

Holbrook, J., Schumm, S.A., 1999. Geomorphic and sedimentary response of rivers to tectonic deformation: A brief review and critique of a tool for recognizing subtle epeirogenic deformation in modern and ancient settings. Tectonophysics 305, 287–306.

Hovius, N., 1998. Controls on sediment supply by larger rivers. In: Shanley, K.W., McCabe, P.J. (Eds.), Relative role of eustasy, climate, and tectonism in continental rocks. SEPM Spec. Publ., 59. Society for Sedimentary Geology, pp. 3–16.

Jain, V., Sinha, R., 2004. Fluvial dynamics of an anabranching river system in Himalayan foreland basin, Baghmati River, north Bihar plains, India. Geomorphology 60, 147–170.

Kent, W.N., Das Gupta, U., 2004. Structural evolution in response to fold and thrust belt tectonics in northern Assam - A key to hydrocarbon exploration in the Jaipur anticline area. Mar. Pet. Geol. 21, 785–803.

Lahiri, S.K., Sinha, R., 2012. Tectonic controls on the morphodynamics of the Brahmaputra River system in the upper Assam valley, India. Geomorphology 169–170, 74–85.

Latrubesse, E., 2008. Patterns of anabranching channels: The ultimate end-member adjustment of mega rivers. Geomorphology 101, 130–145.

Latrubesse, E., Stevaux, J.C., Sinha, R., 2005. Tropical rivers. Geomorphology 70, 187–206.

Mathur, L.P., Evans, P., 1964. Oil in India. I.G.C. 22nd session, India, pp. 7–52.

Nanson, G.C., Huang, H.Q., 1999. Anabranching rivers: Divided efficiency leading to fluvial diversity. In: Miller, A.J., Gupta, A. (Eds.), Varieties of fluvial form. Wiley, Chichester, pp. 477–494.

Narula, P.L., Acharyya, S.K., Banerjee, J., 2000. Seismotectonic atlas of India and its environs. Special publication 59 , Geological Survey of India pp. 1–40.

Prasad, B.N., Mani, K.S., 1983. Distribution of seismic velocities as related to basin configuration in Upper Assam Valley. J. Assoc. Explor. Geophys. III (4), 25–33.

Ranga Rao, A., 1983. Geology and hydrocarbon potential of a part of Assam- Arakan basin and its adjoining region. Pet. Asia J. 6, 127–158.

Richardson, W.R., Thorne, C.R., 2001. Multiple thread flow and channel bifurcation in a braided river: Brahmaputra-Jamuna River, Bangladesh. Geomorphology 38, 185–196.

Sarma, J.N., 2005. Fluvial process and morphology of the Brahmaputra river in Assam, India. Geomorphology 70, 226–256.

Sarma, J.N., Phukan, M.K., 2004. Origin and some geomorphological changes of Majuli Island of the Brahmaputra river in Assam, India. Geomorphology 60, 1–19.

Singh, S.K., 2006. Spatial variability in erosion in the Brahmaputra basin: Causes and impacts. Curr. Sci. 90, 1272–1276.

Singh, S.K., Kumar, A., Lanord, C.F., 2006. Sr and $^{87}Sr/^{86}Sr$ in waters and sediments of the Brahmaputra river system: Silicate weathering, CO_2 consumption and Sr flux. Chem. Geol. 234, 308–320.

Takagi, T., Oguchi, T., Matsumoto, J., Grossman, M.J., Sarker, M.H., Matin, M.A., 2007. Channel braiding and stability of the Brahmaputra river, Bangladesh, since 1967: GIS and remote sensing analyses. Geomorphology 85, 294–305.

Tandon, S.K., Sinha, R., 2007. Geology of large rivers. In: Gupta, A. (Ed.), Large rivers: Geomorphology and management. Wiley, Chichester, pp. 7–28.

Thorne, C.R., Russell, A.P.G., Alam, M.K., 1993. Planform pattern and channel evolution of the Brahmaputra river, Bangladesh. Geol. Soc. Lond. Spec. Publ. 75, 257–276.