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Evolution of Damodar Fan Delta in the Western Bengal Basin, West Bengal

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ABSTRACT

Fan delta is formed when an alluvial fan prograde directly into the standing body of water from the adjacent highland. An ancient fan delta was developed 6-10m above from the present sea level at the lower course of Damodar river in the western part of Bengal basin. The present study attempted to represent the evolutionary history of Damodar fan delta in the context of many associative features favor to fan delta formation such as adjacent highland, basin margin faults, accommodation space and standing water body. These elements have been taken into consideration to identify the location, time and processes for the fan delta formation. Data related to tectonic and depositional history, sea level fluctuation and palaeodrainage network have been collected from various sources. These reveal that the western part of Bengal basin is characterized by numbers of north-south trending normal faults, shifting river courses and repeated marine transgression and regression phases. After collecting a huge amount of sediment from Chhotanagpur plateau, Damodar river deposited its sediment in the eastern side of these north-south trending faults in the subaerial and subaqueous environment throughout the geological period. In this region Chhotanagpur plateau, fault-dominated stable shelf and transgressed Bay of Bengal play the role of adjacent highland, accommodation space and standing water body respectively to develop Damodar fan delta. Sedimentation process started in late Cretaceous and still it is continuing in a subaerial environment. These fan forming processes led Damodar river to shift its course and make this region flood prone.

INTRODUCTION

Fan delta is an alluvial fan that progrades into a standing body of water from the adjacent highland (Holms, 1965; McGowen, 1970; Wescott and Ethridge, 1980; McPherson et al., 1987). According to Galloway and Hobday (1983), it is formed where braided river deposits sediment into standing water and its peripheral area is modified by the marine processes (McPherson et al., 1987). Nemec et al., (1988) defined fan delta as "a coastal prism of sediments delivered by an alluvial fan system and deposited mainly or entirely subaqueously, at the interface between the active fan and standing body of water". So, it is the resultant form of active alluvial fan forming processes and the marine or lacustrine processes. Fan delta has two depositional environments: (1) subaerial environment, above the mean sea level and (2) subaqueous environment, below the water level. The essential elements for the development of fan deltas are highland that is sediment source region, sediment load stream, accommodation space where a fan is developed, and a standing water body that is sea or lake. Sediment source region and accommodation space are separated by basin margin fault. Generally, these elements follow the linear sequence of high relief, fault-bounded basin margin, accommodation space, standing water body. Every fan delta has a very long evolutionary history. They developed through a wide range of geologic period from Precambrian to recent. There are several important work related to the ancient fan delta. Sneh (1979) studied about the fan deltas formed along the western fault scarp of the Dead Sea rift. This fan delta was formed during late Pleistocene under marine condition and exposed due to lake level fall at the end of Pleistocene. Backert et al. (2010) studied on Kerinitis Gilbert-types fan delta, Corinth Rift, Greece developed in the hanging wall of an active normal fault during early to middle Pleistocene. Wescott and Ethridge (1980) mentioned many ancient fan deltas from different parts of the world. Some of these are the alluvial fans deposited in Witwatersrand gold field (Pretorious, 1974) and Barberton mountain land of South Africa formed during the Precambrian, the fan deltas in south-eastern Missouri, USA developed during late Cambrian (Houseknecht and Ethridge, 1978), the San Onofre Breccia in the Los Angeles basin, California formed during Tertiary (Stuart, 1973; Friedman and Sanders, 1978), Liguanea gravel fan in Jamaica formed during Pleistocene (Wood, 1976). Damodar fan delta in western Bengal basin is an ancient alluvial fan delta that started to form since Cretaceous and now it is situated 6-10m above the mean sea level.

There are some important works on the geological settings of the western part of the Bengal basin (Sengupta, 1966; Mukhopadhyay, 1972, Kaila et al., 1992, Singh et al., 1998, Alam et al., 2003; S. Bandyopadhyay, 2007; Roy and Sahu, 2015) and the sedimentation processes over it by Das (1972), Mahapatra and Dana (2009) and Ghosh (2014) and Ghosh et al. (2014). Sengupta (1972) give the tectonics and depositional history of the West Bengal basin. Acharyya and Shah (2007, 2010) explain the morphostratigraphic settings of West Bengal including Damodar fan delta and adjoining areas. But all these work have given less attention to the Damodar fan delta and its formation. Changing courses of Damodar river in lower Damodar basin have been documented by Mukherjee (1938), Sen (1956) Bhattacharjjya (1959), Sen (1991), D. Bandyopadhyay (2007), Rudra (2010) and Bhattacharya (2011) but they have not discussed it in the context of Damodar fan delta formation. Mallick and Niyogi (1972), Deshmukh et al. (1973), Niyogi (1975), Acharyya and Shah, (2007) and Chakraborty and Nag (2015) denoted the different division of Damodar fan delta but their study do not incorporate the evolutionary history in the context of fan delta forming factors and elements.

The major objectives of this study is to review the tectonic and geomorphic settings of the western part of Bengal basin; to describe the fan delta forming factors and its existence in the western Bengal basin; to present the evolutionary history of the ancient Damodar fan delta since Cretaceous to the present day and to present the geomorphic characteristics of this ancient fan delta.

STUDY AREA

The Damodar river basin is a sub-basin of Ganga river system in eastern India (Fig. 1). This basin shares the area of Jharkhand (73.7%) and West Bengal (26.3%) having the total area of 23370.98

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km^2 (Majumder et al., 2010; Ghosh et al., 2014). Damodar river starts the journey from Palamu Hills of Chhotanagpur Plateau in Jharkhand and flows towards east up to Burdwan and then turn southwards and meet with river Hooghly near Chandipur. Previously it met river Hooghly at Falta. The total length of the river is about 540 km of which about 240 km is flowing in Jharkhand and rest of the course is flowing in West Bengal (Chandra, 2003). The basin is located in the transition zone of Chhotanagpur plateau and Bengal basin. The buried hill and north-south trending normal faults separate Bengal basin from the Chhotanagpur plateau (Sengupta, 1972). There is a considerable difference in lithology of upper and lower parts of the basin. The upper part is dominated by granite and granitic gneisses of the Archean, sandstone, and shale of Gondwana period and recent alluvium whereas the lower part is characterized by Tertiary rock deposits and alluvium (Singh et al., 1998). The basement of this alluvium deposits formed by the outpouring of lava during late Jurassic to late Cretaceous (Sengupta, 1972; Alam et al., 2003; Ghosh, 2014).

Damodar river has a number of tributaries like Barakar, Konar, and Bokaro. They supply a huge amount of water and sediment to the lower reach area during the monsoon. It has only two distributaries, i.e. Amta Channel and Mundeswari. Earlier it had many distributaries like Khari, Banka, Behula, Gangur, Ghia, Kana, Kunti, Kana Damodar and Moja Damodar (Sen, 1991; D. Bandyopadhyay, 2007; Rudra, 2010, p.61). Damodar River had a right bank distributary named Dakshin Saraswati which met with Darakeswar river (Chakraborty and Nag, 2015). These channels create a radiating drainage network from different apexes (Fig. 1c). All these channels enter into the Hooghly River while two southernmost channels Moja Damodar and Kanki- Mundeswari meet the Rupnarayan. These are now disconnected from the main channel and act as an independent river. Agricultural fields become the source of these channels (Khari, Banka, Ghia) and some channels (Behula, Gangur, Kana and Kana Damodar) are sustaining from feeder canal of DVC project. Saraswati was a distributary of Hooghly river. It comes out from the Hooghly river at Tribeni and again met with Hooghly river at Sankrail. Previously it had a branch which flowed through Amta and met Rupnarayan river at Kolaghat (Rudra, 2010, p.41). The present study includes the entire region between Khari river to the north and Darakeswar to the west.

METHODOLOGY

Tectonic, depositional, and erosional history and sea level condition throughout the geological period has been tabulated (Table 1) using data from various sources and the events have been arranged from bottom to top in chronological way. The geological time scale has been taken from Monroe et al. (2007). Basement profile from Beliator to Bongaon has been modified from Kaila et al. (1992). The presence of an alluvial fan in the lower Damodar basin has been identified from the radiating slope, radiating palaeodrainage pattern and outward convex contour pattern from plateau front. Many associated features favored the formation of fan delta like basin margin fault, subsidence of land, accommodation space, and presence of water body have been taken into consideration to identify the location, time and processes involved in fan delta formation. The entire fan delta has been separated into three segments, i.e. Panagarh-Silla fan delta, Memari fan delta and Recent active fan based on the radiating drainage pattern in three different places and direction.

Location of the sea level has been plotted on the map of western part of Bengal basin for the Quaternary period after Bakshi (1972), Bera and Banerjee (1991, 2001), Banerjee (2003), Stanley et al. (2000), Banerjee and Sen (1987) and Gupta (1988) cited by Banerjee (2016). Location of sea level for the Tertiary period has been plotted based on the information after Das (1972), Mukhopadhyay (1972), Sengupta (1972) and S. Bandyopadhyay (2007). Das (1972) mentioned that NNE to SSW trending fault scrap to the east of Kuldiha Formation was the western limit of marine transgression in the Eocene. The 50m contour follows this fault scarp. That's why 50m contour line has been taken to demarcate the sea level for Eocene. According to Sengupta (1972), during the Oligocene estuarine condition was active near Burdwan area and shallow marine condition was existing near Memari. 20m contour line which goes between Memari and Burdwan has been taken to determine the sea level of Oligocene. Contours are extracted from the SRTM data using spatial analyst tools of ArcGIS 10.1.

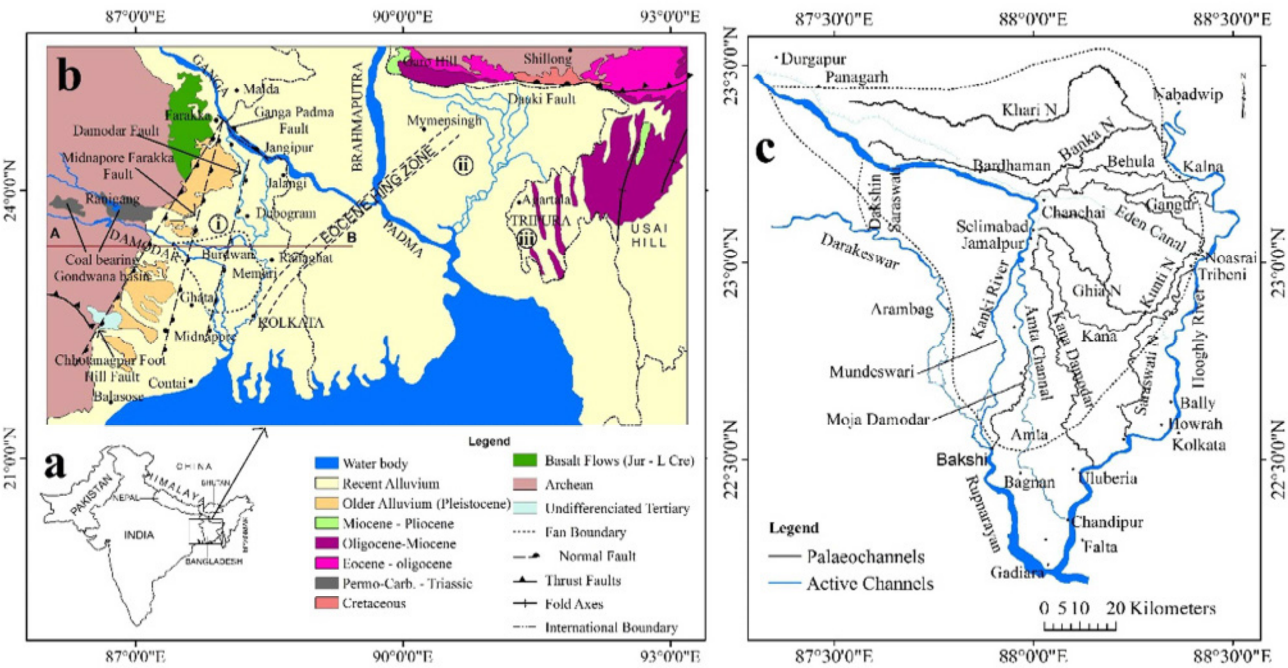

Fig.1. Location of the study area (**(a)** Location of Bengal Basin in Eastern India, **(b)** Location of Lower Damodar Basin in Western Bengal Basin, **(c)** Lower Damodar Basin) and Geological settings of Bengal Basin; Source: The base map is modified from Sengupta et al., 1972. Chhotanagpur Foothill fault, Midnapore- Farakka Fault, and Damodar fault incorporated from Singh et al., 1998)

Table 1. Tectonic, depositional, erosional history and sea level condition in western part of Bengal basin

Period	Epoch	Tectonic, deposition and erosional events	Condition of Sea level (Transgression/Regression)
Quaternary	Holocene (0.01Ma BP- recent)	Human intervention (construction of embankment, Dams etc) on channel dynamics. Upliftment of this block (block between Midnapore-Farakka fault and Damodar Fault) along the part of Damodar fault (Singh et al. 1998) Subsidence of continental block between Midnapore-Farakka fault and Damodar Fault (Singh et al. 1998)	After 6 ka the sea level started to fall and reached the present level. In 7-6 ka Marine transgression occurred in lower Gangetic plain (Banerjee and Sen 1987; Singh et al. 1998). This time sea level was confined within 10-6 m above present sea level (Merh 1992; Singh et al. 1998)
	Pleistocene (1.8- 0.01 Ma BP)	Re-activation of normal fault (Singh et al. 1998) Lateritization of sediment took place (Das, 1972) Erosional work taking place on the late Tertiary deposition due to fall of sea level (Mukhopadhyay, 1972; Sengupta, 1972)	In late Pleistocene period sea receded from the Bengal Basin (Sengupta 1972; Mukhopadhyay 1972) In Early Pleistocene small-scale marine transgression occurred due to re activation of normal fault (Singh et al. 1998) but the sea level was confined in the deeper portion of the Bengal Basin (Mukhopadhyay 1972; Sengupta 1972)
Tertiary	Pliocene (5-1.8 Ma BP)	Formation of Rajmahal Garo-gap (Alam, 1989; Khan, 1991; S. Bandyopadhyay, 2007)	Small scale marine transgression occurred in part of West Bengal (Mukhopadhyay 1972) Marine Regression (Das 1972; Mukhopadhyay 1972)
	Miocene (23-5 Ma BP)	Starting of the formation of Bengal delta on the Bengal Basin (Rudra 2010) Formation of Bengal Basin was completed Collision between Indian plate and Burma Plate (Alam et al. 2003; Rudra 2010)	Marine transgression took place at east of Memari- Ghatal trend area (Mukhopadhyay 1972; Alam 1989; S. Bandyopadhyay 2007) Major Marine Regression occurred (Das 1972; Alam, 1989; S. Bandyopadhyay 2007)
	Oligocene (34-23 Ma BP)	Erosion took place on the preceding deposition due to fall of sea level. Deposition occurred at Burdwan under freshwater to Estuarine environment (Sengupta, 1972)	Shallow marine condition was active at Memari and Pandua. (Sengupta 1972)
	Eocene (56-34 Ma BP)	Start of hard collision between Indian shield and South Asia and starting of the formationof Himalayan mountain (Alam et al. 2003) Continuation of north and NNE journey of India (Alam et al. 2003) Basin-wide subsidence due to movement of Basin Margin fault zone (Mukhopadhyay 1972)	The western limit of marine transgression was confined by the Midnapore- Farraka Fault (Das 1972). Sea level reached at maximum level (Sengupta 1972; Mukhopadhyay 1972; S. Bandyopadhyay 2007) and then started to fall.
	Palaeocene (66-56 Ma BP)	Soft collision occurred between north-western edge of India and south Tibet (Alam et al. 2003) The suture of India- Tibet plate was completed at this time due to anti clock wise movement of Indian plate (Klootwijk et al. 1992; Alam et al. 2003)	Transgression process was continuing
Cretaceous (146- 66 Ma BP)	Late Cretaceous	Starting of northward journey of India towards the Asia (Lawver et al. 1985; Powell et al. 1988; Scotese et al. 1988; Fowler 1990; Ducan 1992; S. Bandyopadhyay 2007) Slow Subsidence of Bengal shelf area (Mukhopadhyay 1972)	Marine transgression started (Roybarman 1983; Singh et al. 1998; Rudra 2010)
	Early Cretaceous	Out pouring of basic lava on Bengal shelf (Mukhopadhyay 1972) and formation of Rajmahal trap (Morgan 1972; Mahoney et al. 1983; MacDougall 1992; Ingley et al. 2002; Kent et al. 2002; S. Bandyopadhyay 2007) Freshwater and fluviatile sedimentation started in Durgapur area (Kuldiha Formation; Das 1972) Sedimentation started on the Stable Self Zone (Alam et al. 2003) Commencement of the formation of The Stable Shelf and Central Deep Basin (Alan et al. 2003) India was separated from the Gondwanaland (S. Bandyopadhyay 2007)	—
Jurassic (200-146 Ma BP)	200 -146 Ma BP	Evolution of Bengal Basin was started (S. Bandyopadhyay 2007) Formation of normal faults (Alam et al. 2003). Break up of Gondwanaland (Alam et al. 2003)	—

Mukhopaphyay (1972) mentioned that the Miocene transgression occurred at the east of Memari- Ghatal trend. A line connecting Ghatal-Memari parallel to 20m contour consider as Miocene sea level.

Bed level differences of feeder channel and channels of old delta plain has been measured through levelling by the Dumpy level and the total station. The signatures of active fan forming processes of the Recent Active Fan and inactive Memari fan delta are presented by the field photographs.

An elevation map has been constructed from the SRTM (downloaded from http://glcf.umd.edu/data/srtm/) data using ArcGIS 10.1. The data related to earlier channels or palaeochannels of Damodar river have been collected from various literature and maps. These channels have been identified from topographical maps (73M/11, 73M/12, 73M/16, 73N/13-73N/16, 79A/4, 79A/8, 79B/1-79B/6) of Survey of India and Google Earth imagery and plotted these on the map using Arc GIS 10.1. Different parts of Damodar fan delta and the major fault line has been shown by the Landsat 8 imagery. Longitudinal and transverse profile of the fan delta has been prepared from SRTM data using 3D analyst tools of ArcGIS.

RESULTS

Geological Background

Formation of the Damodar fan delta and development of drainage system on it are very much associated with the tectonic and sedimentary history of Bengal basin. Bengal basin has formed at the junction of Indian, Tibetan (Eurasian) and Burma plates (Alam et al., 2003). The collision of these three plates took place in middle Eocene to early Miocene (Alam et al., 2003; S. Bandyopadhyay, 2007; Rudra, 2010, p.12), although the evolution of Bengal basin was started in the Jurassic (160Ma BP) with the breakup of Gondwanaland (S. Bandyopadhyay, 2007). The Bengal basin has three main geo-tectonic divisions, i.e. the Stable Shelf, the central deep basin and the Chittagong Tripura fold belt (Fig. 1b; Alam et al., 2003). Sengupta (1972) divided the western part of Bengal Basin (West Bengal) from west to east into four units i.e. (1) The shield area, (2) The basin margin zone characterized by subsurface hill, (3) The stable shelf zone and (4) The deeper part of the basin (Fig. 2). The zone between basin margin fault and Eocene hinge zone is known as stable shelf zone. The stable shelf zone takes an elongated shape from NNE to SSW direction. The northern part of the stable shelf covers the north-western part of Bangladesh and southern part comprises the south West Bengal. The Damodar fan delta has been developed on the stable shelf zone of West Bengal. SW to NE trending (Kolkata to Mymensingh) 'hinge zone', a zone of normal faults at a depth of 15500 feet (4724.4 meter; Sengupta, 1966) in the basement (Alam et al., 2003) that separates the stable shelf from the central deep basin (Sengupta, 1972; Goswami, 1979; Alam et al., 2003). The area east of this 'hinge zone' represents the transition between Indian continental crust and the oceanic crust (Fig. 1b; Alam et al., 2003). So the Damodar fan delta is formed in the north-eastern edge of Indian continental crust.

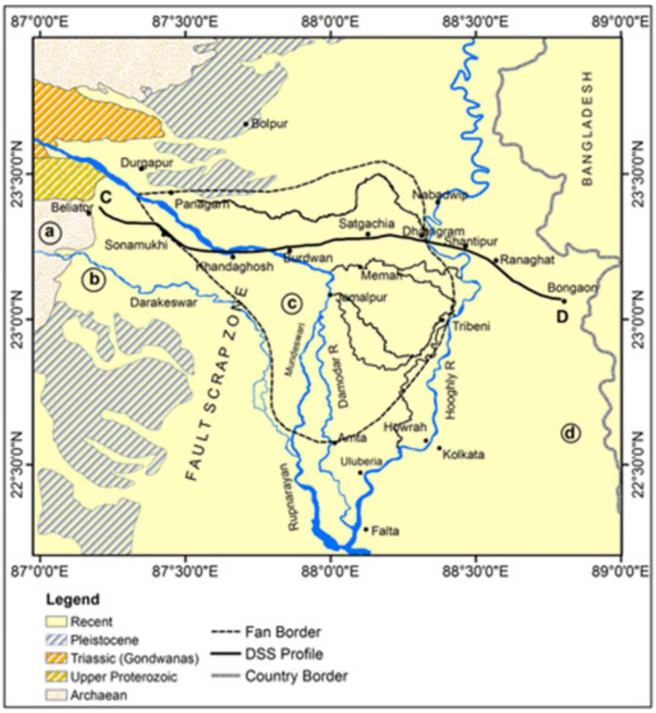

Fig. 2. Geological setup of western part of Bengal Basin (a The Shield Area, b The Basin Margin Zone, c The Stable Shelf Zone, d the deeper Part of Bengal Basin; Along the CD line Deep Seismic Sounding (DSS) study was carried out by Kaila et al., 1992. Reproduced from Kaila et al., 1992)

Basement Configuration of the Stable Shelf

In the western side, a series of sub-surface basement hills and basin margin fault-scarp zone divides the stable shelf from the shield area (Fig. 2; Sengupta, 1966, 1972; Rudra, 2010). The stable shelf is characterized by some basement faults i.e. Chhotanagpur foot hill fault, Medinipur-Farakka fault, Damodar fault and Ganga-Padma fault (Fig. 1b; Singh et al., 1998). Presence of these faults gives the characteristics of a shelf, a flat horizontal surface used for storage. These faults have been formed after the breakup of Gondwanaland in the Jurassic and during the downwarping of continental crust in the Cretaceous (Das, 1972; Singh et al., 1998; Alam et al., 2003). Since Cretaceous, these faults were reactivated in different geological periods (Das, 1972; Singh et al., 1998) and extended into the sedimentary cover deposited during Cretaceous to Tertiary (Fig. 2) due to reactivation (Singh et al., 1998).

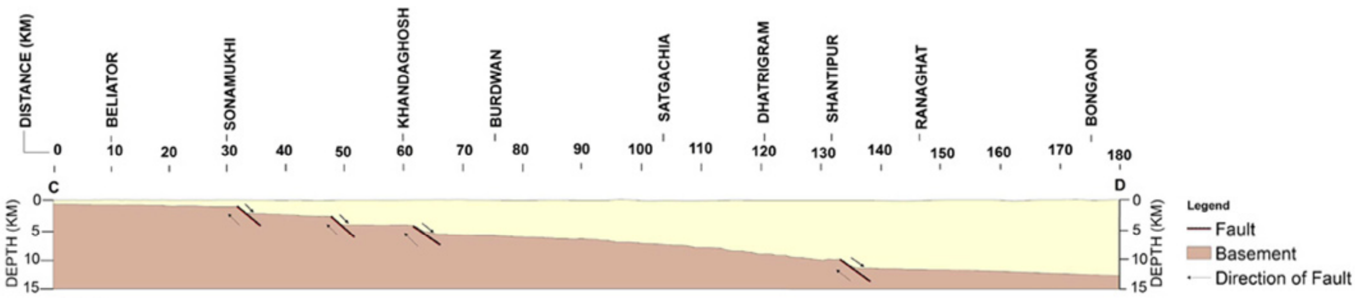

Fig.3. Basement configuration along the CD line: Beliator- Burdwan- Bongaon (There is a steep flexure in the basement at the east of Khandaghosh where the depth of basement increases about 5 km. From Sonamukhi to Khandaghosh the depth of the basement increase about 4 km where the horizontal distance between two places is 30 km. The first fault from the west has affected the entire sedimentary column from basement to surface and the second fault only affected the basement. Kaila et al., 1992)

The evolution of the stable shelf started after the breakup of Gondwanaland (Alam et al., 2003). The depth of the basement increases from west to south-east (Fig. 3; Sengupta, 1972; Das, 1972; Kaila et al., 1992). Kaila et al. (1992) identified two basement faults between Sonamukhi and Khandaghosh through deep seismic sounding (DSS) study (Fig. 2). From west Beliator to east of Khandaghosh the depth of basement increases about 5 km (Fig. 3; Kaila et al.,1992) which indicate the very steep slope between Beliator to Khandaghosh.

Sea Level Fluctuation

Since the Cretaceous to the Holocene, the stable shelf experienced a number of marine transgression and regression (Fig. 4; Sengupta, 1966; Mukhopadhyay, 1972; Roybarman, 1983; Singh et al., 1998; S. Bandyopadhyay, 2007). The tectonic factor is more responsible for the transgression and regression of the sea. Marine transgression occurred in the Cretaceous after the downward movement of the tectonic block (Alam et al., 2003). The magnitudes of the marine transgressions were different in different geological periods. During the Eocene, marine transgression reached the highest level (Sengupta, 1966; S. Bandyopadhyay, 2007) due to movement of basin margin fault (Mukhopadhyay, 1972) or Chhotanagpur foothill fault. The western limit of the sea level was marked by Midnapore-Farakka fault-scarp (Das, 1972). After the Eocene, the magnitude of the marine regression gradually reduced. During the middle Miocene, the sea level was in the east of Memari-Ghatal trend (Mukhopadhyay, 1972; Sengupta, 1972). Large-scale marine transgression occurred in late Miocene and Pliocene (Mukhopadhyay, 1972). After this transgression period, two small-scale marine transgressions took place in the Bengal basin, one in early Pleistocene and the other in early Holocene (7-6 ka BP) due to the reactivation of the faults (Singh et al., 1998). The early Pleistocene marine transgression was limited in the deeper portion of the Bengal basin (Mukhopadhyay, 1972; Sengupta, 1972), while the early Holocene transgression was confined within 10-6 m above the present sea level (Merh, 1992; Singh et al., 1998). The sea level finally retreated from the Bengal basin during the regression phase in 6 ka (Singh et al., 1998) and reached the present level. Nowadays due to global warming again sea level has started to rise at a rate of less than 1 mm per year (Rudra, 2010, p.14).

Fig. 4. Location of Sea Level in different geological period. Source: Reproduced from Banerjee, 2016 (Late Pliocene to Early Pleistocene after Bakshi (1972), Early to Middle Pleistocene after Bera and Banerjee (1991, 2001), Late Pleistocene after Banerjee (2003), Holocene (8800 ybp) after Stanley et al. (2000), Holocene (7000-6500 ybp) after Banerjee and Sen (1987, 1988), Holocene (4500-3000ybp) after Gupta (1988)) and location of sea level from Eocene to Early Pliocene has been plotted based on the information after Das (1972), Mukhopadhyay (1972), Sengupta (1972) & S. Bandyopadhyay (2007).

DISCUSSION

The environment, favorable for both alluvial fan and delta, is required to form a fan-delta. The evolution of alluvial fan and its morphology and dynamics are influenced by the three main factors i.e. (1) tectonics, (2) climate and (3) base level (Bull, 1977; Harvey, 2002). Interaction of these three factors forms the major thrust of the alluvial fan research.Whereas a standing water body is required to get the characteristics of a fan-delta, the tectonics factors influence the architectural elements of a fan, like adjacent highland, basin margin fault, accomodation space (Bull, 1978; Harvey, 1987; Silva et al., 1992; Harvey, 2002; Goudie, 2004). This may also influence the base level characteristics and slope through upliftment and subsidance of the tectonics block (Calvache et al., 1997; Harvey, 2002). The chhotanagpur plateu, Chotanagpur foothill fault and the stable self region act as the adjacent highland, basin margin fault and accomodation space respectively to form the Damodar fan delta. The climatic factors plays major role in controlling the sediment supply, sediment transportation power of the feeder channel, water and sediment ratio (Harvey, 2002). The laterites or ferrecretes deposits of Peninsular India is the vital indicator of the onset of monsoon climate in the Bengal basin and the development of this ferruginous material began at the end of the Cretaceous (Ghosh, 2014) which indicates that monsoon climate existing in the Bengal basin since Cretaceous. Base level change controls the fan dynamics and morphology (Harvey, 2002). Reactivation of the basement faults in different geological periods and Pleistocene glaciation played the main role for the base level change in the stable shelf area of Bengal basin. At present average annual rainfall is about 1300 mm (Chandra, 2003). Beside these three major factors, fans are also controlled by the size, geology and relief of the catchment (Harvey, 2002; Goudie, 2004). Damodar river has funnel-shaped large catchment area about 23370.98 km^2. This river has steep slope about 1.86 m/km for the first 241 km in upper catchment area while in the middle and lower course it has moderate to the gentle slope (Chandra, 2003). Every controlling factor and architectural elements such as adjacent highland, basin margin fault, accommodation space, and standing waterbody were involved to develop a fan delta at the lower Damodar basin or the eastern part of Bengal basin. Existence of all these factors like basin margin fault (Alam, 2003), existence of Damodar river (Das, 1972), onset of monsoon (Ghosh, 2014), and changes of sedimentation characteristics from Gondowana basin deposits to continental deposits (Das, 2014) in Cretaceous reveal that the Damodar fan delta started to developed during Cretaceous period.

Generally, a fan delta is formed when an alluvial fan prograde into standing body of water. But it is not necessary that the alluvial fan has

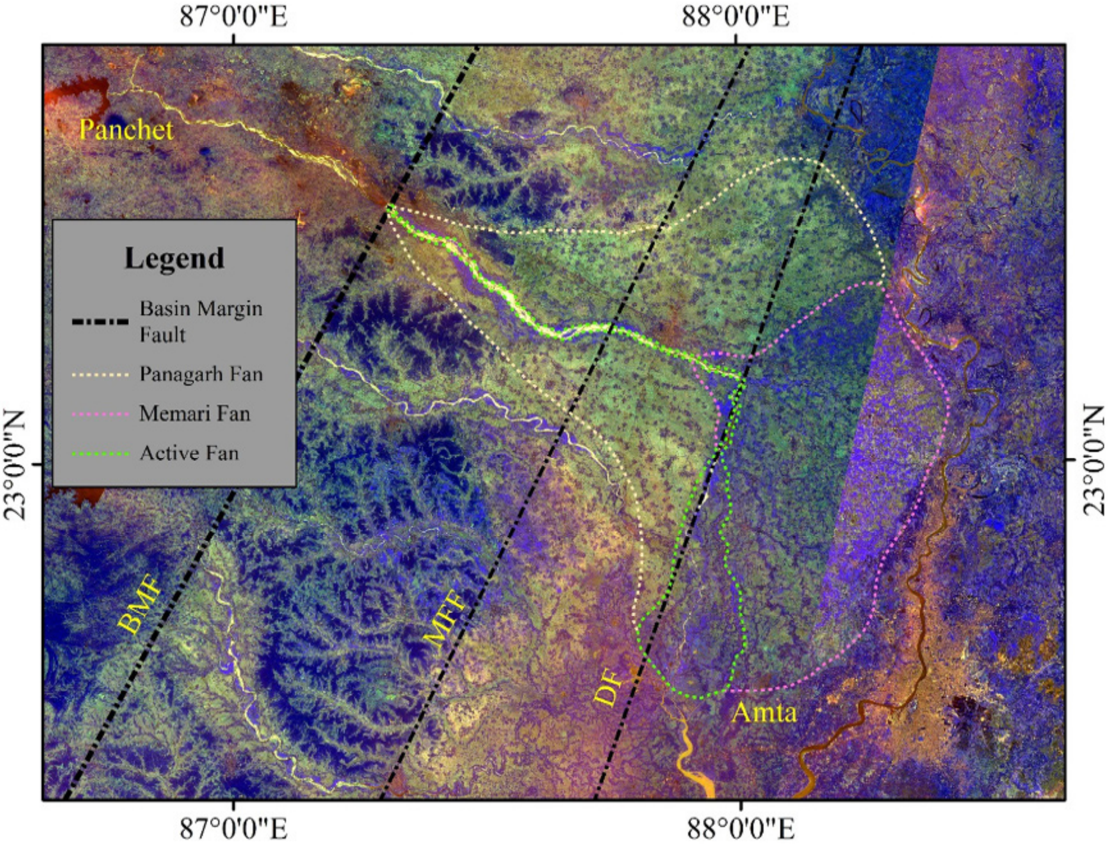

Fig.5. Landsat 8 Imagery showing three different depositional lobe of Damodar Fan Delta and the three major fault.

to prograde always to reach water body, inversely water body can encroach the fan area through transgression (Nemec and Steel, 1988). Damodar fan got contact with water body because of the transgression of the Bay of Bengal in different geological periods. Three subaerial mechanisms were mainly involved for the formation of an alluvial fan, i.e. (1) avulsing channelized rivers, (2) sheet flow and (3) debris flows (Schumm, 1977; Blair and McPherson, 1994; Parker et al., 1998). Existance of meander scar, paleochannels on the fan surface indicates that Damodar fan-delta has been formed by the avulsion of the channelized river and sheet flow. The present study divides it into three segments, i.e. (1) The Panagarh fan delta trending east, (2) Memari fan delta trending east and southeast (3) Recent active fan delta trending towards the south (Fig.5).

Panagarh Fan Delta

Movement of tectonic blocks along the well-established faults and sedimentation process on stable shelf area of Bengal basin began in early Cretaceous (Alam et al., 2003). Probably from that time, the evolution of Damodar fan started. After draining the Chottanagpur plateau, Damodar river crossed the Chottanagpur foothill fault escarpment and developed an alluvial fan adjacent to the hilly area. Primarily the fan formation continued in the freshwater and fluviatile environment. Marine transgression started in late Cretaceous (Roybarman, 1983; Singh et al., 1998; Rudra, 2010) and reaches the maximum level in Eocene (Sengupta, 1972; S. Bandyopadhyay, 2007). The western limit of this marine transgression was NNE-SSW trending Midnapore-Farakka fault scarp (Das, 1972). This time fan forming process continued in both the subaerial and subaqueous environment. During the Eocene (50 Ma BP) when this fan forming process was going on, the Indian landmass was situated near the equator (Tardy et al. 1991). If the latitudinal rainfall distribution on that period was similar to the present day then the high amount of rainfall accelerated the fan formation. After the Eocene, sea level started to fall and shifted eastward (Fig. 4). During the Oligocene, the shallow marine environment was active in Memari and Pandua and deposition under freshwater to estuarine condition took place in Burdwan area (Sengupta, 1972). So, at that time the subaerial fan forming mechanism was active in the west of Memari and sub-surface process was active at the east of Memari. This type of environment again re-established in middle Miocene and middle Pleistocene in this area. The depositional process from Oligocene to Miocene was controlled by Midnapore- Farakka fault scrap (Das, 1972). Sedimentation process since late Cretaceous to Miocene occurred in an open marine environment because the formation of Bengal basin was not completed on that period (Table 1). In late Oligocene, to early Miocene major marine regression occurred (Das, 1972; Alam, 1989; Bandyopadhyay, 2007) which led to erosion and establishment of fluvial environment in this area (Das, 1972). Due to this negative base level changes erosion become active in the upper catchment area. The water divider between Damodar and Ajoy river formed from this extensive erosion (Das, 1972). This fan area lastly inundated by the by the sea during early Pleistocene. Since this period to the Holocene, the Panagarh Fan developed through fluvial environment because no subsequent marine transgression inundated this area in later period. The surface of the fan comprises with Quaternary fluvial deposit and from surface to the basement has a sequence of Quaternary, Miocene-Oligocene, Eocene limestone, Paleocene and Cretaceous (Fig 6). The Pliocene marine sedimentation is absent in the subsurface of the the Panagarh fan delta. Stratigraphic sequence of this region given in Table 2. A radial drainage pattern developed with the development of this fan. These channels changed their courses continuously by channel avulsion, neck cut off, chute cut and by the others fluvial processes. Only few channels of this fan can be traced now, i.e. Khari, Banka and Dakshin Saraswati. Off-take point of Khari river from Damodar river near Durgapur has been considered as the initiation of this fan (Fig. 1c).

Table 2. Stratigraphic sequence of Panagarh Fan Delta region (after Das, 1972)

Formation	Lithology	Thickness range (mertes)	Age
Ajay-Damodar	Sand, ferruginous, yellow, coarse to fine; silt; greyish yellow clay.	-	Recent
Bishtupur	Sand, ferruginous, yellow; lithomargic variegated clay: laterite; calcareous nodules.	26-45	Pliocene to Pleistocene
Alinagar	Sand and pebbles, greyish white; grey, sticky clays, with occational carbonaceous matter.	21-82	Miocene
5b Khatpukur (western parts)	Blueish grey claystones, siltstones, sandstones; calcareous shales, calcareous sandstones, argillaceous and arenaceous limestones, fragmental shell-limestones (eastern parts) 3-95.5	Carbonaceous shale, claystones grey and greyish black,with thin bands of lignite and layers of sand.(western parts) 1-20	Oligocene to Miocene
Kuldiha	Sand and pebbles; kaolinitic and ochreous sandstones; red, green and white clays.	2-45	Createaceous (?) to Oligocene
Durgapur	Felspathic sandstones, coarse to very coarse, gritty and pebbly; occasional red and green shales; carbonaceous sandstones, carbonaceous shales, and lenses of dull coal.	0.35-129	Middle Triassic (?) to Jurassic
Panchet	Felspathic sandstones, greyish green, greenish grey, medium to fine; red and green shales.	51.00	Lower Triassic
Raniganj	Felspathic sandstones, greyish white medium to fine; carbonaceous shales; grey shales; a thin lens of coal.	4.50	Permian

Memari Fan Delta

Memari fan is the extension of Panagarh fan delta. Most probably in the early Miocene, the deposition lobe of Damodar fan shifted towards the east and formed Memari fan-delta. Location of the sediment source area and the depositional lobe of fan delta depends on the upliftment of footwalls and subsidence of hanging wall (Leeder and Gawthorpe, 1987; Leeder et al., 1988; Gawthorpe and Colella, 1990; Hwang et al., 1995). Location of the depositional lobe of a fan depends on the following relationship as mention by Bull (1977)

$$\frac{\Delta u}{\Delta t} \geq \frac{\Delta w}{\Delta t} + \frac{\Delta s}{\Delta t} \quad \text{(i)}$$

$$\frac{\Delta u}{\Delta t} < \frac{\Delta w}{\Delta t} > \frac{\Delta e}{\Delta t} \quad \text{(ii)}$$

Where, u is the tectonics uplift, t is the time, w is the channel down cutting, s is the fan deposition, and e is the erosion of fan deposition. According to Bull (1977) If the amounts of uplift (u) equal or exceed the sum of the amounts of down cutting (w) and deposition (s), the fan will form adjacent to the mountain front or plateau front but when the rate of stream channel down cutting at the mountain or plateau front exceeds the rate of uplift at the mountain front, the deposition area shifted to the downslope area. In early Miocene, base level was changed due to sea level fall. This negative base level change probably increased the rate of downcutting. Possibly this rate of downcutting was more than the upliftment rate. That's why the loci of deposition shifted to Memari area where another radiating drainage network was formed. The early Miocene has been chosen for this shifting of deposition lobe because it was the immediate major marine regression stage after Eocene transgression. This time huge erosional event took place in the upper segment of the fan (Sengupta, 1972; Mukhopadhyay, 1972; Bandyopadhyay, 2007). This extensive erosion produced huge amount of sediment which help Panagarh fan delta to prograde. Progradation of Panagargh fan delta is more prominent during late Pleistocene regression. After the Oligocene, this area

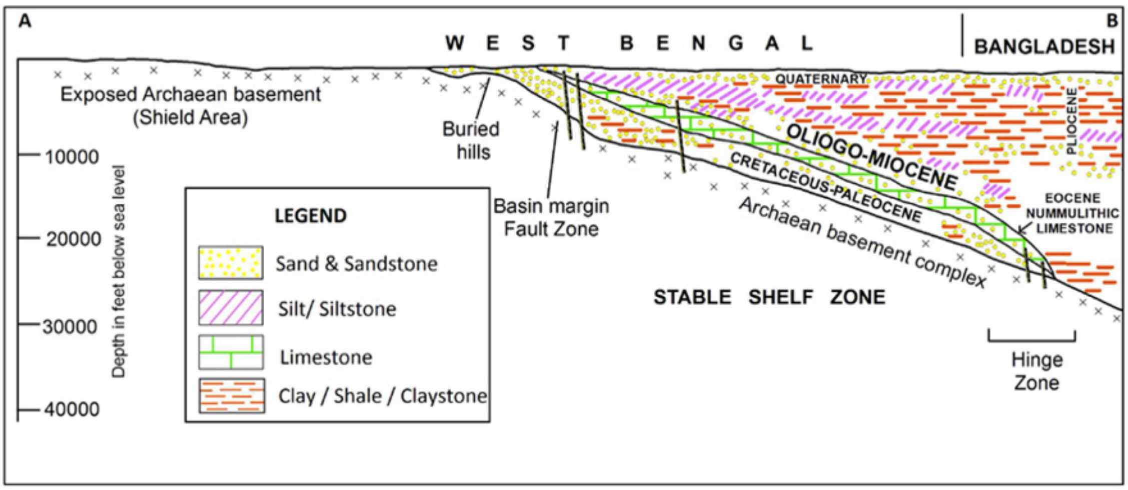

Fig. 6. Cross section along AB line (in Fig. 1b) to show subsurface configuration and broad change in lithofacies across the Basin. (Source: Modified from Sengupta, 1972).

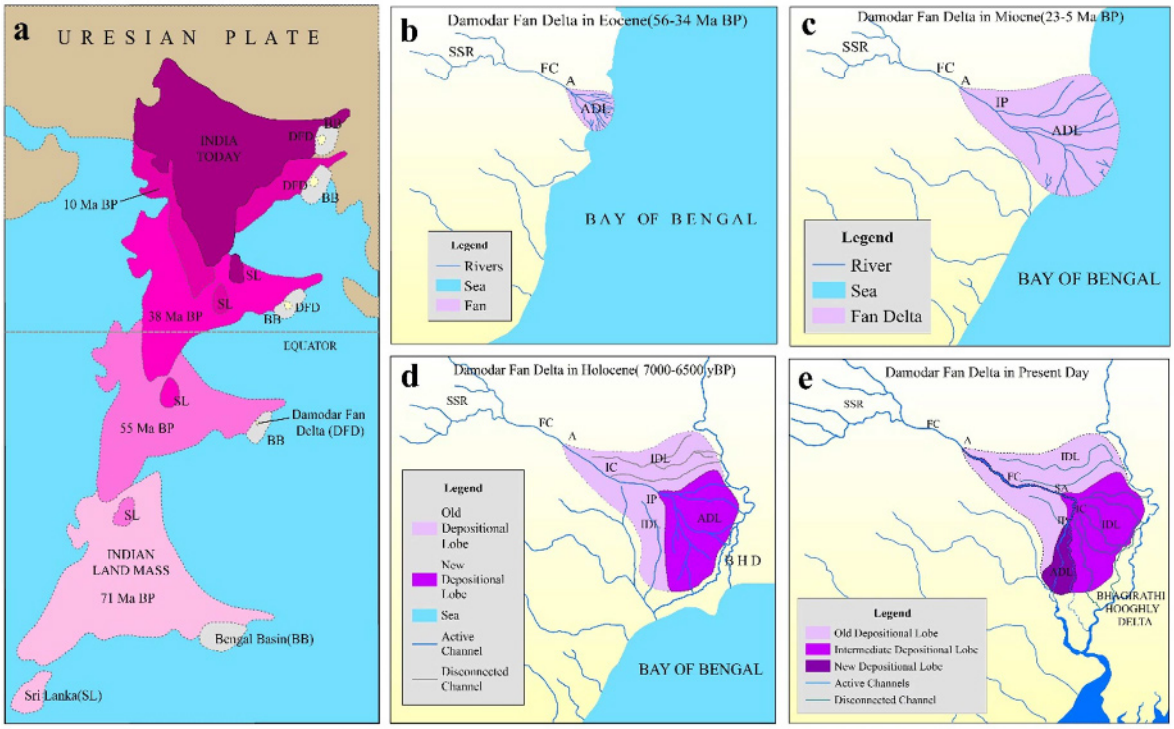

Fig.7. Conceptual schematic diagram showing evolution of Damodar Fan Delta. a) Migration of India in different geological period; b) Damodar Fan Delta in Eocene (56-34 Ma BP) c) Damodar Fan Delta in Miocene (23-5 Ma BP) d) Damodar Fan Delta in Holocene (7000-6500 yBP) e) Damodar Fan Delta in present day. Abbreviations are SSR= Sediment Source Region, A= Apex, FC= Drainage basin feeder channel, IC = incised channel on fan, IP = fan intersection point ADL= Active Depositional lobe, IDL = Inactive depositional lobe. (The maps have been produced based on the sea level in Fig 4)

was again inundated by the sea in middle Miocene and middle Pleistocene. There was a regression phase between these two periods. Thus this fan delta was formed through repetition of fluvial and marine processes.

The fan area was totally exposed during late Pleistocene regression. No marine transgression inundate this area in the subsequent period. During Pleistocene regression deposition lobe again shifted to the down fan area. Many geomorphological changes occurred in Panagarh fan delta and Memari fan delta on that time. Dissections of the Panagarh fan surface started from this time. Damodar river incised it valley on the old Panagarh fan to form a fanhead trench which emerges onto the fan surface near Barsul area, east of Burdwan. Rivers of the Panagarh fan delta like Damodar, Khari and Banka incised their valley deeply. Being a trunk stream Damodar river incised it valley more deeply than the distributary channels. The bed of these distributary channels now situated at the higher level than the trunk stream. Probably this incident disconnected the distributary channel from the Damodar river. Two important incidents led to flow The Ganga river through present Bhagirathi channel. One is formation of Rajmahal Garo Gap in the Pliocene and another is headward erosion of the proto Bhagirathi river during the late Pleistocene. During the post glaciation huge amount of snowmelt water came through the Saraswati River and cut the distal portion of the Panagarh fan delta and the Memari fan delta. Huge amount of sediment with snow melt water create the natural levee along the both bank of Bhagirathi-Hooghly River. Bhagirathi river system has truncated the edge of the Memari fan delta (Fig. 7d).

During the Holocene transgression marine processes only active in the distal part of the fan. Sea level finally recedes from the Bengal basin in late Holocene. Since this period to till date only subaerial fan forming processes are included for the Development of Damodar fan delta. Thick gravel deposit in the lithological column of Burdwan and Kalna and course sand deposit at Balagarh indicates the fan delta deposition (Acharyya and Shah, 2007). Behula, Gangur, Ghia, Kana, Kunti and Kana Damodar are the main river of this fan delta.

Recent Active Fan

Now the fan forming processes are active only on the western side of the Memari fan delta. The depositional area shifted from Memari fan delta (Fig. 7e) to the to the recent active fan area through some changes of river courses govern by the flood and anthropogenic activities. The rivers of Memari fan delta changes their courses in different direction from its apex near Barsul. Some historical maps and documents depict the changing courses of Damodar river in Memari fan delta. The map of Jan De Barrows (1550) shows that the Kana Damodar was a broad channel takes off at Jamalpur to meet Hooghly at Uluberia. In the same period a small channel, Kana river flowed towards the east and met the Saraswati river at Nasibpur and Hooghly river at Noaserai (Fig 8a). According to the Van den Brouke's map (1660) Damodar had two main branches in seventeenth century (Fig 8b). These two branches were separated at Chachai village near southward bent of main channel. One branch followed towards northeast along the present course of Gangur river and met the river Hooghly at Kalna. Another branch used present Moja Damodar channel to flow southward. This channel met Rupnarayan river at Bakshi. In the eighteen century the flow was confined in Kana Damodar, Amta Channel, Kana-Kunti and Ghia (Fig 8c). In the nineteenth century the main flow shifted to the Amta channel and the Mundeswari river. Mundeswari is the newest channel of the Damodar fan system started to flow in 1865. Only two channels, Mundeswari and Amta channels are active now. An embankment constructed in the mid of nineteenth century along the left bank of Damodar river (Fig 9a) and Amta channel from Silla to the mouth at Falta totally disconnecting the earlier channels (Inglis, 1909). Flood water cannot inundate the left bank for this embankment. That's why fan forming processes is active only in the western part of Memari fan delta. Channel aggradation,

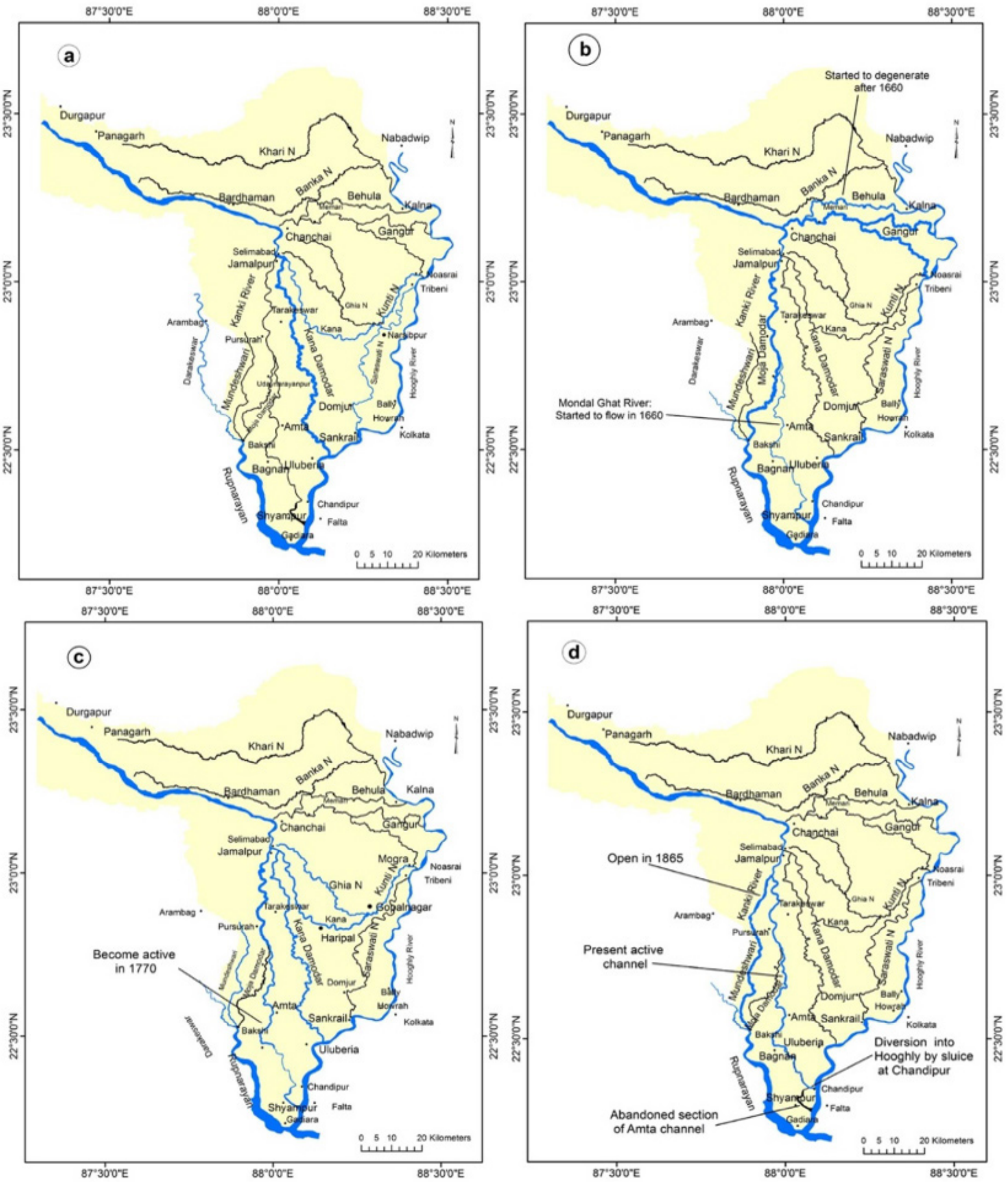

Fig.8. Changing Cources of Damodar River in last five centuries (**a** – active channels of Damodar Fan in sixteenth century; **b** – active channels of Damodar Fan in seventeenth century; **c** – active channels of Damodar Fan in eighteenth century, **d** – active channels of Damodar Fan nineteenth and twentieth century. (The maps have been produced based on the data from Bhattacharyya, 2011; Rudra, 2010; Bandyopadhyay, 2007; Bhattacharjjya, 1959 and some historical maps)

overtopping, embankment breaching and sheet flow, these mechanisms are active at the present depositional lobe of Damodar Fan Delta (Fig 9).

GEOMORPHIC CHARACTERISTICS OF DAMODAR FAN DELTA

The geomorphic characteristic of a fan delta is the resultant form of fan forming processes and its evolutionary history. Long evolutionary history, fan forming factors like tectonic, Climate and base level gives the distinct geomorphic characteristics to the different division of the Damodar fan delta. The neotectonics activities influence the present day drainage network of Damodar Fan Delta. Abrupt changes of Damodar river from east to southward direction at Palla, about 15 km east of Burdwan and north eastward flowing of the Kunti against the regional slope from Singur to Kuntighat indicates the influence of active tectonics on the river courses of Damodar fan delta. The shape of the Damodar fan delta is diverged from the ideal fan shape due to long evolutionary history. The extensive erosion of two adjacent river Darakeswar and Ajoy give the concave shape of the northern and southern boundary of the fan. The perfect convex shape of the distal part of Damodar fan delta was truncated by the Saraswati and Hooghly river (Fig 7e). The longitudinal profile of the fan surface is slightly concave where transvers profile of Memari fan delta and Recent active fan (Fig. 10b) shows the perfect convex shape. Fig 7e shows the different elements of the present day Damodar fan delta. It has a sediment source region in the upper catchment area. It has a very long feeder channel from sediment source region to the secondary apex at Barsul (SA). Progradation of this fan to the down fan area gives the characteristics of the long feeder channel. The topographic apex is at the east of the Chhotanagpur foothill fault. The intersection point is moves to the south of Jamalpur which indicates the low input of water into the fan. Implementation of four dam in the upper catchment area moderate the peak flood. That's why the intersection point shifted to the down fan area. At the time of the

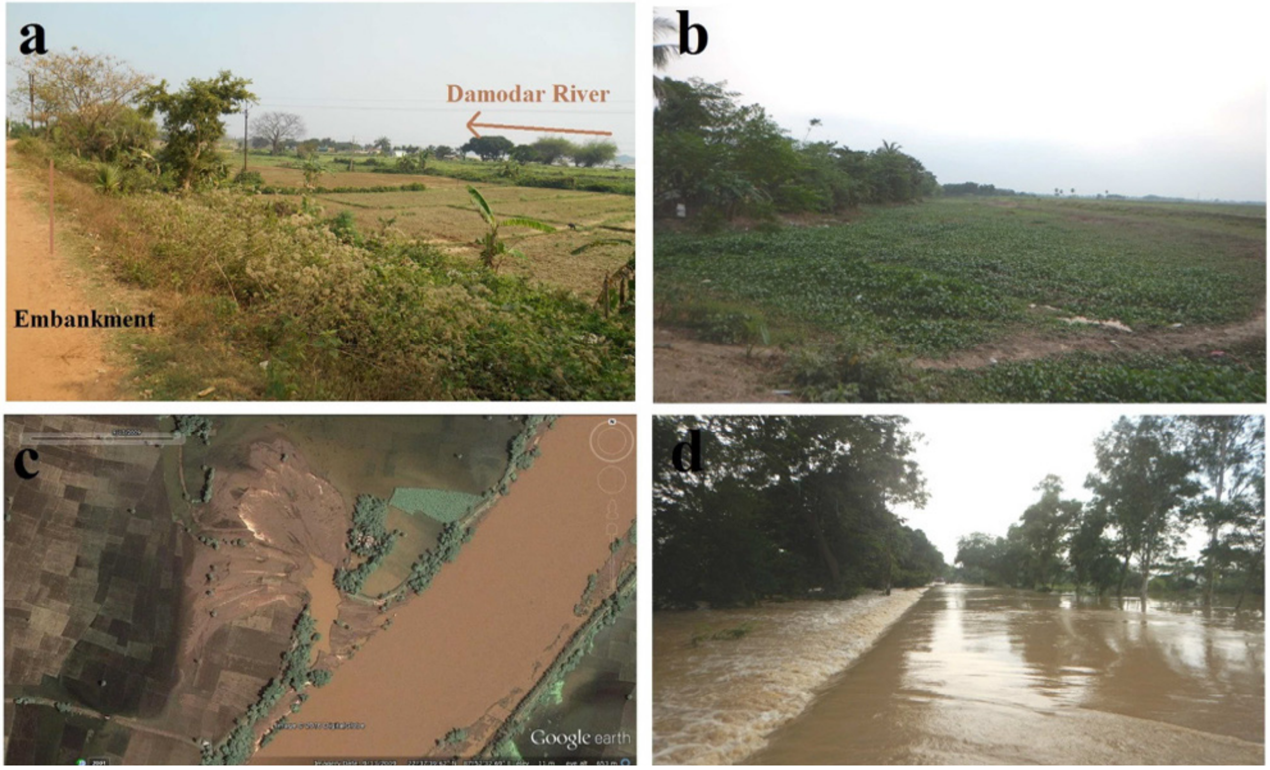

Fig.9. (a) Embankment in the left bank of Damodar river; **(b)** Dry river bed of a disconnected channels; **(c)** crevasse splay formation at right bank of Mundeswari River; **(d)** Sheet flow on the active fan area.

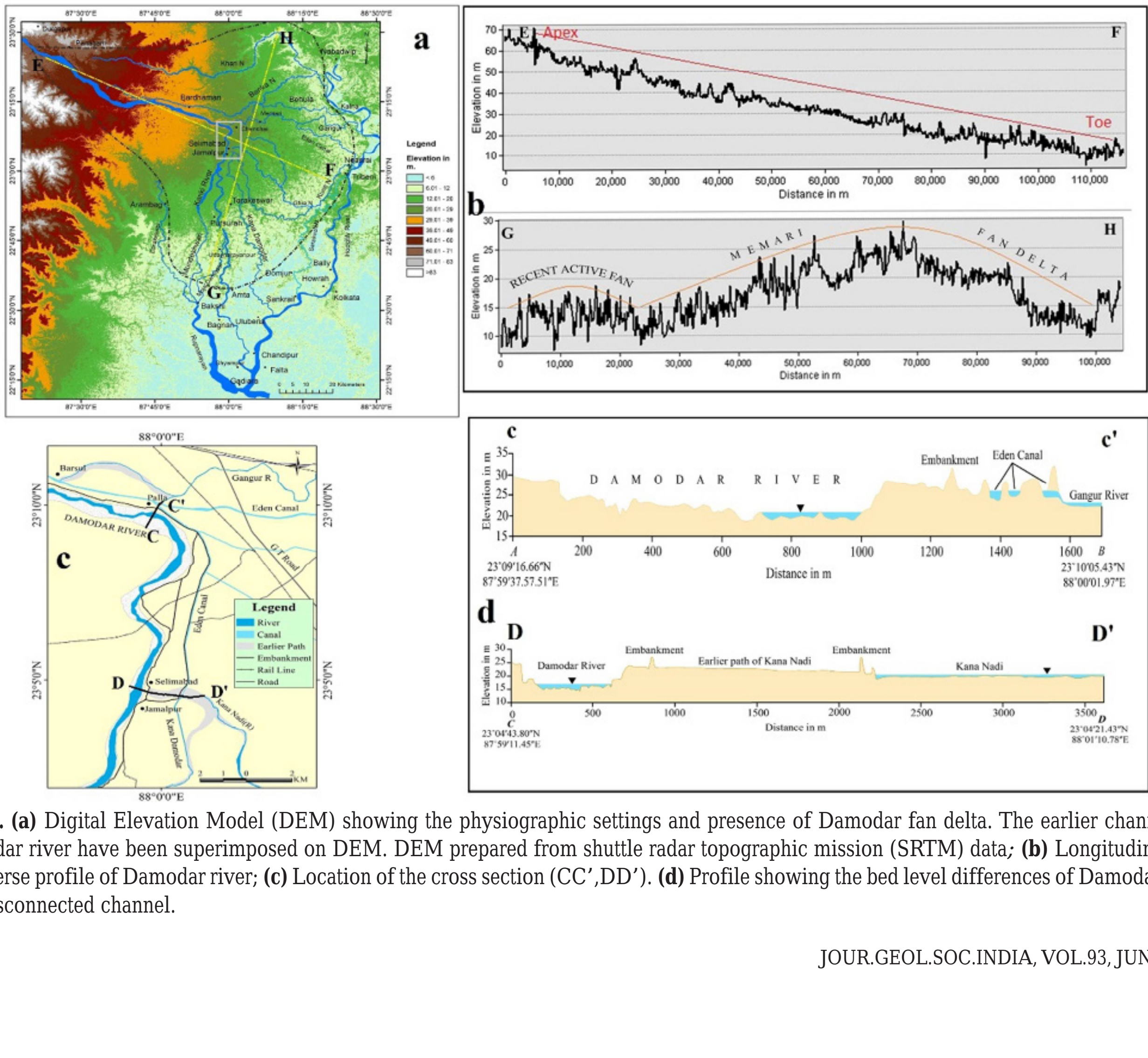

Fig.10. (a) Digital Elevation Model (DEM) showing the physiographic settings and presence of Damodar fan delta. The earlier channels of Damodar river have been superimposed on DEM. DEM prepared from shuttle radar topographic mission (SRTM) data; **(b)** Longitudinal and transverse profile of Damodar river; **(c)** Location of the cross section (CC′,DD′). **(d)** Profile showing the bed level differences of Damodar river and disconnected channel.

evolution of the Damodar fan delta it was near the Panagarh area. Figure 7e shows the three distinctive depositional lobe of the fan delta. The geomorphic characteristics of the differents division of the Damodar fan delta has different geomorphic charactics. The Panagarh fan delta is characterised by the highly meander river channel, oxbow lake, incised meander, incised channel, disconnected channels, neakpoint, paleochannels. These geomorphic characteristics reveals that the Damodar fan delta is polycyclic landform. The main geomorphic features of the Memari fan delta are Paleochannels, meander scar, alluvial ridge, yazoo stream, back swamp. The transition zone of the Damodar fan delta and the Hooghly river formed low swampy land. The Behula and Gangur flows parallel to the levee of Hooghly river before entering to the river. The Recent active fan has the geomorphic feature of point bar, crevasse splay (Fig.9c), natural levee. The cross profile along Damodar river and long profile along the disconnected channel shows that the bed level of Damodar river is situated in lower elevation than the disconnected channels which indicate that Damodar river as a incised channel (Fig. 10d).

CONCLUSION

Formation of new channels through channel avulsion and degeneration of the old channels through siltation is the genetic characteristics of an alluvial fan or a delta. These processes have been still occurring since the Tertiary period in Damodar fan delta. That's why Damodar river shifted its course from northeast direction to southwest direction. Human activities started to hamper this natural system since thousands of years ago. Construction of embankment along the left bank of the main channel has disconnected the left bank branches. Due to this incident, only western side of Damodar fan delta is active now. Besides this, after the construction of Dams in upper catchment area the amount of discharge during the flood is reduced. That's why the occurrence of overspilling in the upper reach (upstream from Jamalpur) is fewer than the lower reach (south of Jamalpur) because the carrying capacity of the upper reach is more than the amount of food discharge. Thus the flood-prone area is shifted towards the southwestern portion of Damodar fan delta i.e. the Recent active fan. Generally, the highest depth of channel in an alluvial fan located in the apex and it progressively decrease in the down fan area (Lecce, 1990). In an alluvial fan, also the slope is reduced in the down fan area. In the case of Damodar river for the first 241 km the slope is 1.86 m/km, for the next 167km it is 0.57 m/km and in the lower reach, it is 0.16m/km. Due to the reduction of depth and slope, the carrying capacity of the channel is gradually reduced towards the edge of the fan. As a result, the river is divided into many branches to sustain the drainage network. This is the natural floodwater distribution system of a river. Every year, Mundeswari and Amta both breach embankment to open new channel but the people prevent to open a permanent channel by repairing immediately. That's why every year flood is occurring through over spilling, embankment breaching, and sheet flow. So the present study reveals that genetic characteristic of this region and present-day human interference on the natural system is responsible for the floods.

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