Geometric Shape and Variation in Dynamic Nature of the Depositional Geomorphic Surface under Neotectonic Settings in the North Bengal Foothill of the Eastern Himalayas, India

Ramapada Sasmal

Department of Geography, Arambagh Girls' College, Arambagh, Hooghly, West Bengal, India, Pin-712 601
Email: *ramapadasasmal[at]gmail.com*

Abstract: ***High surface runoff due to monsoonal precipitation and glacier melting water of the greater Himalayas causes perennial conditions of the streams of the eastern Himalayas. The basins of the streams of the study area show highly weathered geological formations that are prone to erosion under a neo-tectonic environment and the resultant production of huge sediments that form a colony of depositional geomorphic surfaces in a triangular or almost triangular shape at the foothills. FCi analyses that the depositional geomorphic surfaces of the study area are alluvial fans. TCo & FCo analysis advocates for a higher dynamic nature of the alluvial fans in the east of the study area than west under relatively stable neo-tectonic conditions. As a result, the large alluvial fans are found in the east of the study area.***

Keywords: Co-efficient, slope, basin, fault, weathered rock.

1. Introduction

At the Himalayan foothills of North Bengal, a colony of depositional geomorphic surfaces is observed. The geometric shape of these geomorphic surfaces may be analysed vertically and horizontally. Conical, circular, oval, triangular, arrow etc. are the aerial view of these geomorphic surfaces (Amron, 2019). Analysis of long profiles is a way to study the vertical geometry of these landforms. The geometries of these surfaces are dynamic. Mainly climate and neotectonics are responsible for this dynamic nature (Bull, 1964; Hooke, 1968). Monsoon is responsible for their vastness and the Himalayan neotectonics reshape the geometry. Identification of geometric shapes and the variation in their size and dynamic nature are the central focus of this study. For this purpose, the researcher has studied the neotectonics, geology, long and cross profiles, actual fan area and ideal fan area etc. of the studied fan surfaces.

2. Location

The study area is located in the north Bengal foothills of the Himalayas and between the Chel River in the west and the Sankosh River in the east. It is extended from 88.663295° E to 90.040049° E and 26.505937° N to 27.006731° N The area passes through the districts of Kalimpong, Alipurduar and Jalpaiguri (Fig 1).

3. Methodology

To understand the nature of the alluvial fan propagation and the areal geometry of the fans, different indices and coefficients (Table 1) have been analysed based on areal morphometry. First, the conical area, ideal triangular area, ideal circular area, serve zone, no-serve zone etc. of the studied fan surfaces have been identified. For this purpose fan head, the maximum width of the fans and the outermost part of the fan side area are identified.

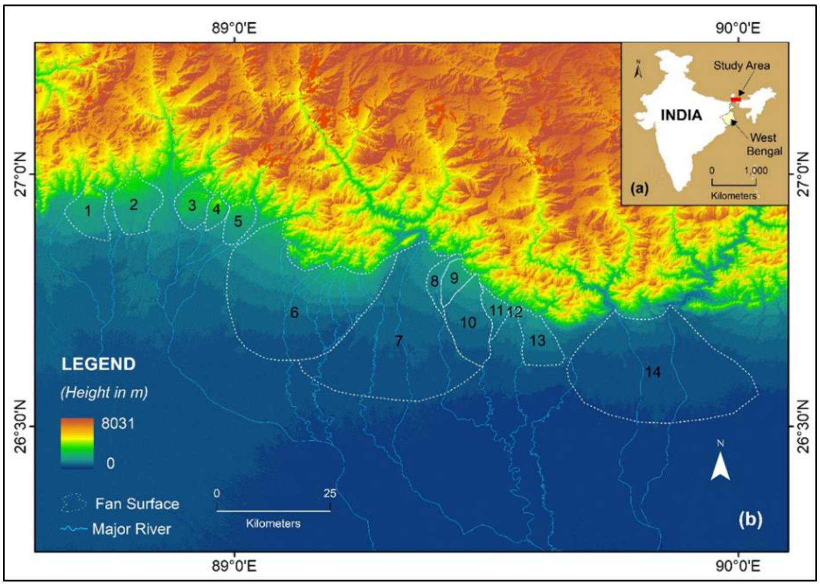

Figure 1: Location of the study area

The fan head 'H' represents both the pick of the conical area and the triangular area. Two sides of the cone touch the fan side margin and represent the radius 'r' of the arc of the cone. The arc touches the distal point 'P' of the fan. The maximum width of the fan surface represents the base 'RL' of the triangular area. A centre point 'C' of the circular area is considered in the middle of the line 'RL'. Here the radius 'r' of the circle is equal to 'CR' & 'CL'. The area above the line 'RL' is identified as a serving zone and below this line is intended as a no-serve zone (Fig 2).

Table 1: Methodology to analyse the aerial geometry

Formula	*Description*	*Source*	*Remarks*
FCi =AaFd/IaCd	FCi= Fan Conicality index. AFd= Actual area of Fluvial deposit. IaCd= Ideal area of Conical deposit	Mukharji, 1976	<1= Alluvial fan >1= Not an Alluvial fan
TCo =TaFs/ATs	TCo= Triangular Coefficient. TaFs= Total area of Fan surface. ATs=Area of Triangular surface.	Amron, 2019	1=Ideal triangular fan shape. <1=Approaching toward triangular fan shape. >1=Move from triangular to typical shape.
FCo =ASz/AHc	FCo= Fan shape Coefficient. ASz= Area of Serve zone AHc= Area of Half circle	Amron, 2019	100% =Ideal typical fan shape. <100% = Move from triangular to typical fan shape. >100% =Move from typical to triangular shape.

To study the vertical geometry the long and profiles of the alluvial fans are constructed with the help of SRTM DEMs. Details of the data sources and their methods of analysis are given here (Table 2). A methodological flow chart is constructed to understand the whole work (Fig 3).

Table 2: Data source and analysis

Subject	*Data source*	*Analysis*
Geometry	SRTM DEM Dates:11/02/2000, 11/02/2000 Sensor: SIR-C/X-SAR Extension: 88°E to 89°E, 26°N to 27°N; 89°E to 90°E 26°N to 27°N Resolution: 30 m	Software: ArcGIS 10.3, QGIS. Data analysis: MS Excel 13
Geotectonic	Map: Literature: Online journals, Libraries	
Geology	Map: Literature: Online journals, Libraries	

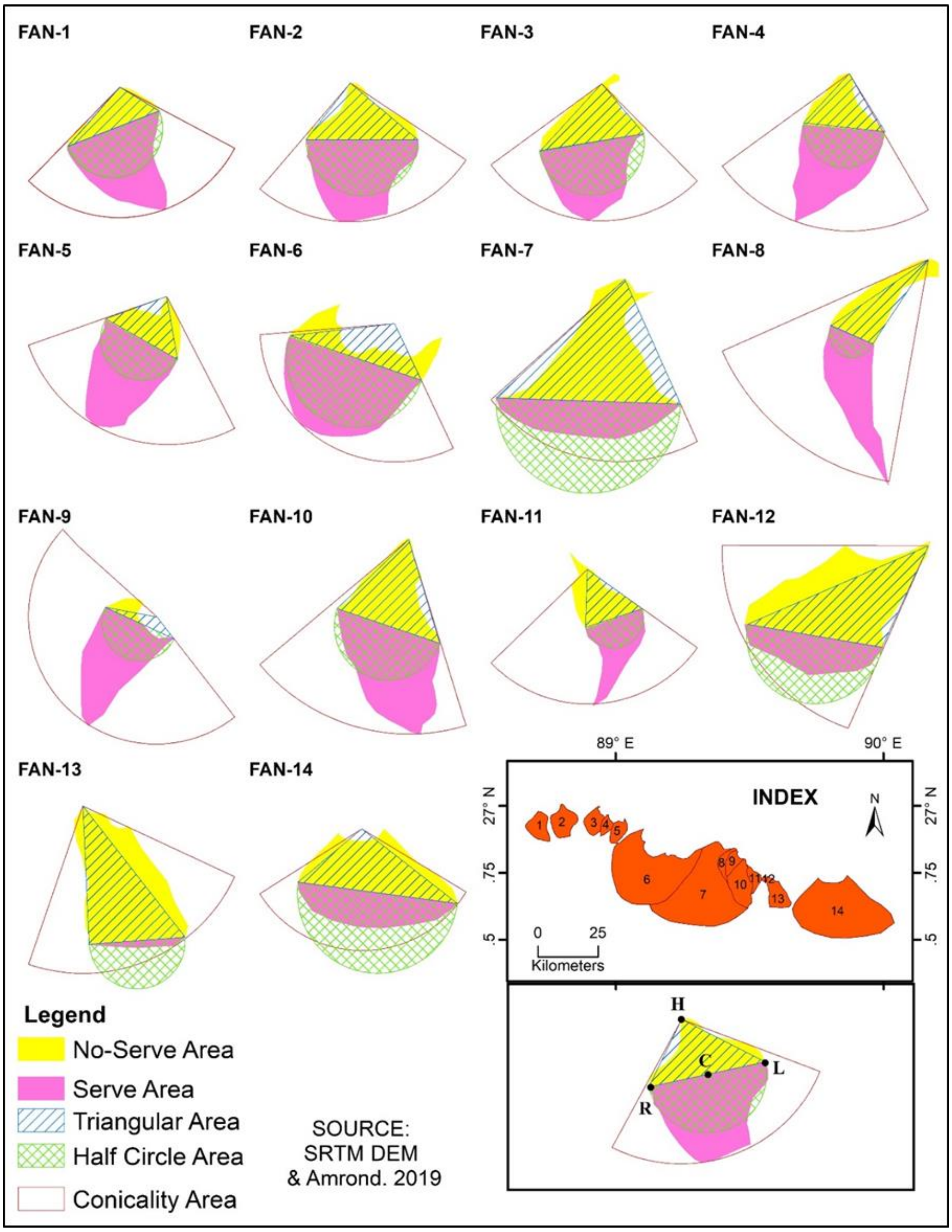

Figure 2: Fan shape geometry

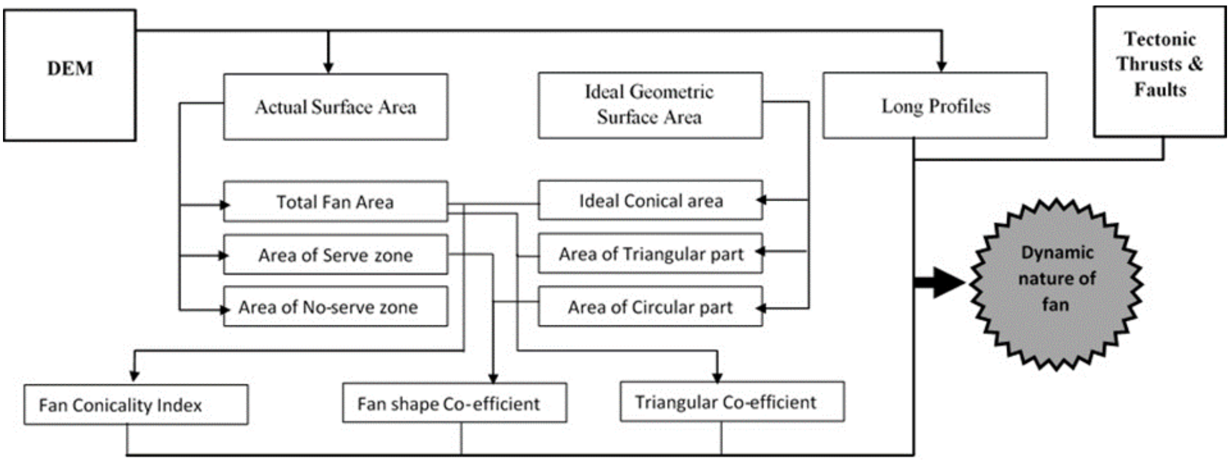

Figure 3: Methodological flow chart

4. Observation and Interpretation

Neo-tectonics rupture the geological formations and reshape the surface slope. On the other hand, climate controls the nature of weathering and erosion of the geological surface of the basin area, and sediment transport to the fan area. The slope is a factor of sediment deposit. So, the slope, climate, drainage, geology and neo-tectonics have been studied to understand the geometric shape and dynamic nature of the studied geomorphic surfaces.

4.1. Slope

A break in slope that suddenly reduces stream competency and deposits sediments to form a colony of depositional landform at the Himalayan foothill is observed in North Bengal (Nakata, 1972). The long profiles of the studied geomorphic surfaces change their nature from west to east. In the west, the geomorphic surfaces of the Gorubathan recesses show short and unsmooth long profiles with breaks in slope whereas in the east the long profiles are smooth and elongated (Fig 4).

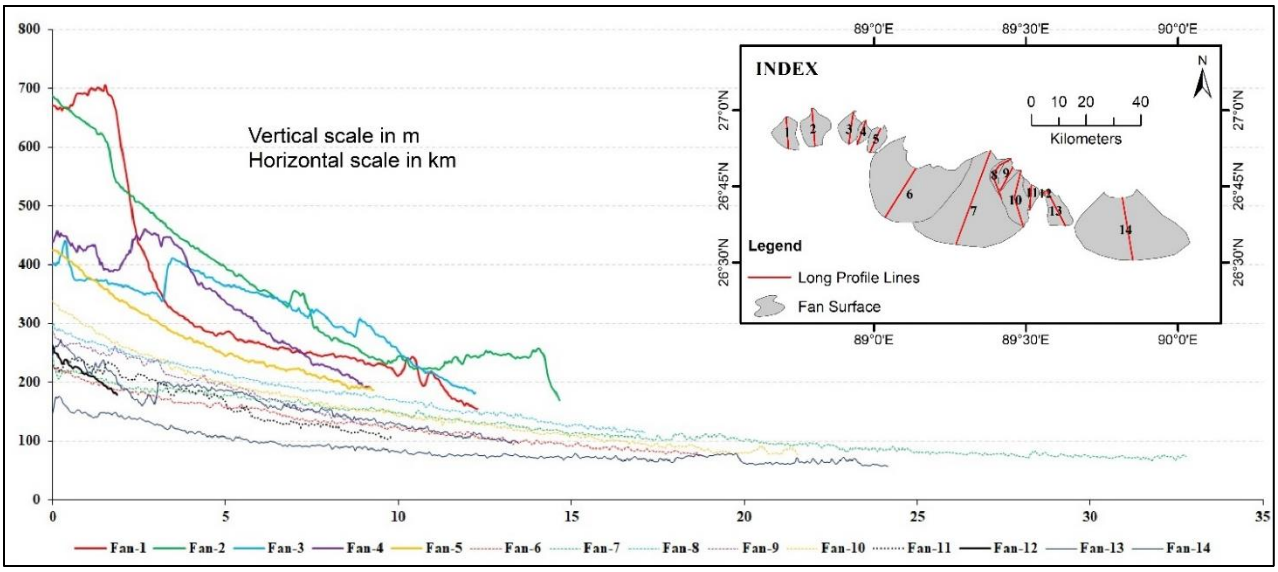

Figure 4: Long profiles of the studied geomorphic surfaces

4.2 Climate

The monsoon climate dominates the area. In the river basin area extreme cold (2°C) is observed in the north due to the height and presence of mountain glaciers and the middle part is experiencing 19°C annual average temperature and receives about 1000 mm average monsoonal rainfall (Sam et al, 2019). In the geomorphic area under study, the annual average temperature is 27°C and the annual average rainfall is 3000 mm (West Bengal District Gazetteers 1981; Sam, et al, 2019). About 1800 mm of total rainfall is received in the monsoon period (Jana, 2002).

4.3 Drainage

It is a dominant controlling factor in developing a geomorphic surface at the foothills of the study area. With the variation of the size and shape of the drainage basin, the nature of channel flow is changed which controls the sediment supply to the depositional land surface under study and thus controls the geometry of the geomorphic surface. The river basins 14, 20 & 21 are very large and the remaining basins are relatively very small in size (Fig 5). The stream orders also reveal the degree of transportation and sediment supply in the study area. The maximum order of streams is 5th, 4th, 3rd and 2nd for different geomorphic surfaces in the study area (Fig 5).

4.4 Geology and Neotectonics

The Geology of river basins that supply sediments to the Himalayan foothill area is very important to understanding the geometric shape and dynamic nature of the geomorphic surface under study. The river basins comprise five major types of geological sequences ie. Quaternary sequence (Qs), Sub Himalayan sequence (SHs), Lesser Himalayan sequence (LHs), Greater Himalayan sequence (GHs) and Tethyan Himalayan sequence (THs) (Table 6). Four major tectonic thrusts separate all these geological sequences (Fig 6). STD separates the THs & GHs; MCT is located between GHs & LHs. MBT separates the LHs & SHs, and MFT separates the SHs and Qs. The Garubathan recess is located in the west of the study area and its western margin is demarcated with the Ghis Transverse Zone (GTZ) (Fig 6).

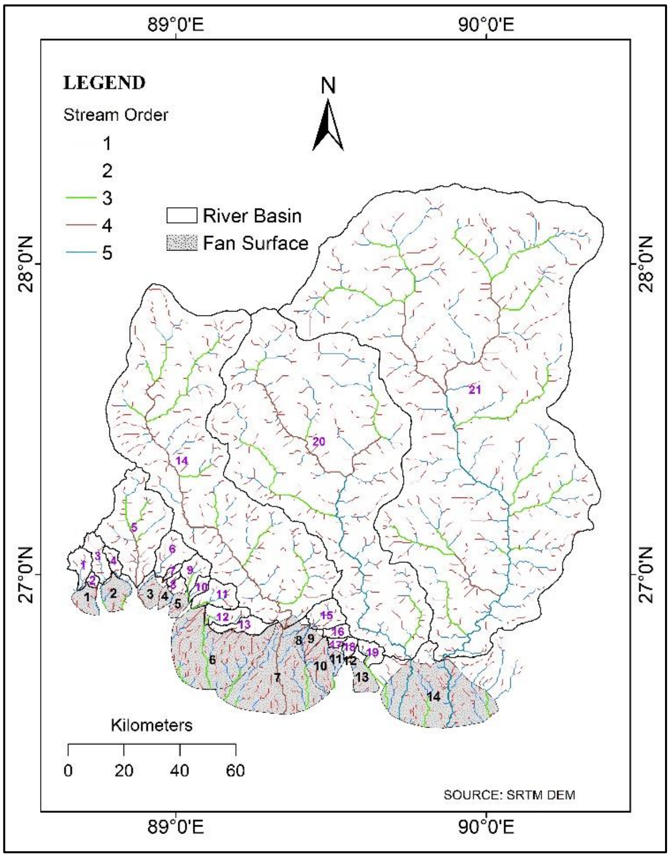

Figure 5: Drainage of the study area

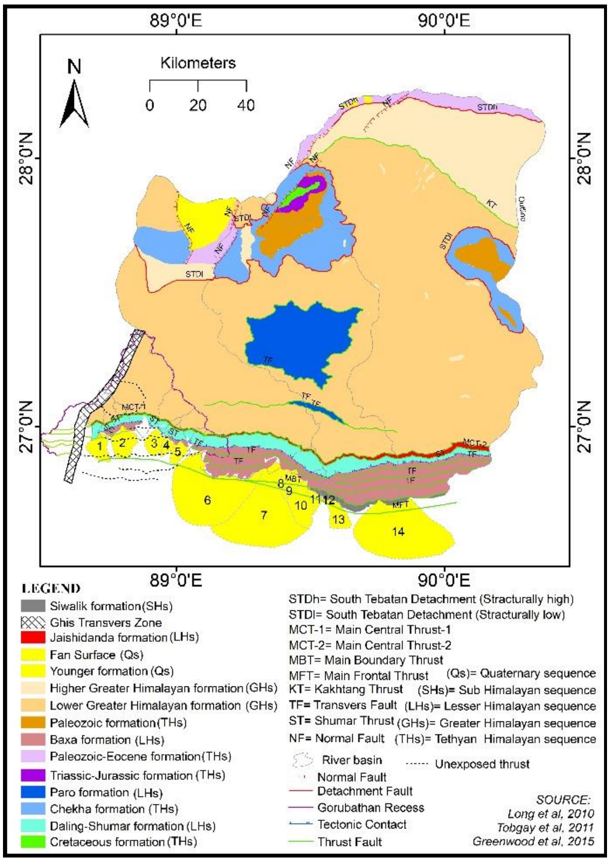

Figure 6: Geology and neotectonics of the study area

4.5 Depositional surface

The field study observes that the geomorphic surfaces are fluvial deposits and conical in shape. The surfaces having IDs 6, 7 & 14 show their area between 550 km and 660 km and are identified as very large surfaces; on the other hand, the remaining surfaces (ID 1, 2, 3, 4, 5, 8, 9, 10, 11, 12 & 13) are <120 km and identified as very small surface (Table 4). All the geomorphic surfaces have two parts i.e. no-serve area and serve area (Fig 2). Except for the surface having IDs 7, 12 and 17, all other geomorphic surfaces show the difference between the no-serve areas and the triangular areas is very low (<4.2 sq. km). On the other hand, the geomorphic surfaces show that the difference between the half-circle and the serving area is very high (between 170 sq. km and 620 sq. km for the geomorphic surface having IDs 6, 7, 11, 13 & 14; and between 3 sq. km and 45 sq. km for rest of the geomorphic surface).

5. Results and Discussion

FCi analysis reveals that all the geomorphic surfaces are alluvial fans (Table 5). Very low variation (0 to 4 sq. km; except fan having IDs 7, 13 & 14) between the area of the ideal conical surface and the no-serve zone indicates an optimum condition of this part of the fan area, which means that throughout the study area, the upper parts of the fan surfaces are stable. Very high variation (18 to 616 sq. km; except fan having IDs 4 & 8) between the area of the ideal half-circular surface and serve zone indicates rejuvenation of this part of the fan area, which means that throughout the study area, the lower parts of the fan surfaces are in unstable condition (Table 4). Overall all the fan surfaces in the study area are dynamic. Their degree of dynamic conditions varies with the variation of the controlling factors like neotectonics, climate, drainage (basin area) and geology of the basin surface that determine the shape and size of the alluvial fans of the study area.

Primary observation shows that the fans of the study area are either triangular or typical (a combination of triangular and circular shapes). To understand the dynamic nature of the fan shape the TCo (Triangular Co-efficient) & FCo (Fan-shape coefficient) are analyzed (Table 5). TCo informs the triangularity of a fan more appropriately, whereas, FCo informs the typicality of a fan more accurately (Amron, 2019). TCo shows that all the alluvial fans of the study area are moving towards typical fan shapes. In contrast, the FCo shows that most of the fans (fan IDs 1 to 10) are moving from typical to triangular fan shapes and few fans (fan IDs 11 to 14) are moving from triangular to typical fan shapes (Table 5).

Table 3: Geological composition

Geological Formations	*Composition*
Tethyan-Himalayan Sequence	
Paleozoic-Eocene formation	Limestone, sandstone, shale, quartzite, slate, and phyllite
Cretaceous formation	Weathered shale, sandstone.
Triassic-Jurassic formation	Weathered shale, sandstone.
Palaeozoic formation	Silt, shale, limestone, pebble-clast, quartz sandstone and Quartzite
Chekha formation	Phyllite, phyllitic quartzite, micaceous quartzite, biotite-muscovite-garnet schist, marble
Greater-Himalayan Sequence	
Higher Greater Himalayan formation	Foliated leucogranite, Amphibolite, granulite, migmatitic orthogneiss, metasedimentary rocks, schist, paragneiss, quartzite, marble, paragneiss, quartzite and marble
Lower Greater Himalayan formation	Paragneiss, biotite-muscovite-garnet schist, greenschist, weathered granite, feldspar,Paragneiss, schist, and quartzite, amphibolite, kyanite, sillimanite
Lesser-Himalayan Sequence	
Paro formation	Biotite-rich quartzite, Micaceous quartzite, kyanite quartz veins, quartzite, biotite-muscovite-garnet schist, muscovite-biotite-garnet-staurolite schist, sillimanite-bearing schist, marble, crystalline marble, foliated leucogranite, granitic orthogneiss bodies, deformed granite, kyanite.
Daling-Shumar formation	Schist and phyllite, quartzite and limestone, mylonitized, deformed granitic, weathered quartzite, muscovite-biotite schist and phyllite, quartz vein
Baxa formation	Slate, greenschist, phyllite, limestone, marble, quartzite, conglomeratic quartzite, dolostone
Jaishidanda formation	Schist, biotite, quartzite, amphibolite facies
Sub-Himalayan Sequence	
Siwalik formation	Baded sandstone and conglomerate sandstone
Quaternary	
Alluvial Fan surfaces	Older alluvial deposits
Younger Quaternary formation	Unconsolidated sediment

SOURCE: Gansser, 1983; Swapp and Hollister, 1991; Bhargava, 1995; Dasgupta, 1995; Tangri and Pande, 1995; Tangri, 1995a; Davidson et al., 1997; Wu et al., 1998; Edwards et al., 1999; Grujic et al., 2002; Daniel et al., 2003; McQuarrie et al., 2008; Hughes et al., 2010; Long and McQuarrie, 2010; Tobgay et al., 2010; Long et al., 2011A; Long et al., 2011B; Warren et al..2011

Variations in the sizes of the alluvial fans signify the difference in impacts of their aforesaid controlling factors upon them. Based on neotectonics the study area is divided into two zones i.e. the Garubathan recess area in the west and outside the Garubathan recess area in the east (Fig 6). The GTZ neotectonics rejuvenate the rivers that erode the Baxa formation of LHs & SHs, and the resultant development of the Garubathan recess in the western part of the study area (Srivastava et al, 2017; Sasmal et al, 2021, 2022, 2023).

It has been observed that the MCT tectonically is more active than MBT and the MBT tectonically is more active than MFT (Mukul et. al. 2014; Sasmal, 2021, 2023). The GTZ, MCT & MBT neotectonics cause the development of small-size maximum 3rd-order river basins (basin IDs: 1 to 10) that produce relatively low amounts of sediments (Fig 5) and rejuvenate the rivers that transport its eroded sediments to a long distance from the recessed area. The low amount of sediment supply due to small-size river basins and high stream competency under an active neotectonics causes the development of small-size (small surface area) alluvial fans (fan IDs:1 to 5) between tectonically active MCT and MBT in the recessed area. The continuous neotectonics form a local thrust fault of GT (Garubathan thrust) or RT (Ramgarh thrust) (Fig 6) along the alluvial fans and result in the upliftment of the northern triangular segments of the fans. The long profiles bear evidence of fan upliftment in this area (Fig 4). This upliftment again reduces the area of the small-size alluvial fans due to 2nd-time stream rejuvenation that increases stream erosion and stream competency and the resultant reduction of sediment supply to the fan areas.

Table 4: Area of fan segments

Fan Id	Total Fan Area (km2)	Remarks	Ideal Conical Area (km2)	No- Serve Area (km2)	Triangular Area (km2)	Difference (no-serve and triangular)	Serve Area (km2)	Half Circle Area (km2)	Difference (serve and half-circle)
1	70.76	Very small	144.28	17.89	16.38	1.51	52.86	34.63	18.23
2	89.32	Very small	149.33	29.3	29.05	0.25	59.99	27.52	32.47
3	55.08	Very small	80.22	22.57	18.44	4.13	32.5	8.31	24.19
4	24.78	Very small	57.59	7.01	6.95	0.06	17.77	14.1	3.67
5	42.56	Very small	98.84	11.19	10.81	0.38	31.37	3.11	28.26
6	595.18	Very large	930.84	147.68	159.02	11.34	447.5	14	433.5
7	607.15	Very large	901.38	389	492.39	103.39	218.15	45.42	172.73
8	29.88	Very small	95.8	12.25	8.69	3.56	17.64	8.67	8.97
9	36.27	Very small	151.93	2.96	3.03	0.07	33.31	1.57	31.74

10	120.64	Very small	218.7	45.05	47.23	2.18	75.58	26.97	48.61
11	30.23	Very small	98.37	13.83	10.05	3.78	16.4	632.72	616.32
12	3.1	Very small	5.26	2.27	1.59	0.68	0.83	44.91	44.08
13	73.99	Very small	152.29	70.46	49.32	21.14	3.53	384.89	381.36
14	652.58	Very large	934.05	383.53	306.49	77.04	269.05	583.07	314.02

In the east of the study area both the large (fan IDs: 6, 7 & 14) and small (fan IDs: 8 to 13) size alluvial fans are observed. Like Goruba recesses the alluvial fans in the eastern part of the study area are not developed between the tectonic structures. The large fans are developed in the south of the tectonic structures (MCT, MBT, MFT & TF) (Fig 6). As a result, the large fans are relatively more stable than the fans of the Gorubathan recesses area. On the other hand, the unstable tectonic structures produce huge sediments in the fan head area of the large fans. Active neotectonics develop the small size 2^{nd} & 3^{rd} order river basins (basin IDs: 11 to 13) that produce a low amount of sediments, but their cumulative supply of sediments and relative tectonic stability in the fan surface area form the large alluvial fan having the ID 6.

Table 5: Coefficients of alluvial fans

Fan Id	Fan Conicality Index	Remarks	Triangular Co-efficient	Remarks	Fan-shape coefficient	Geometric Shape
1	0.49	Alluvial fan	4.32	Toward typical	152.65	Typical to triangular
2	0.60	Alluvial fan	3.07	Toward typical	217.93	Typical to triangular
3	0.69	Alluvial fan	2.99	Toward typical	391.26	Typical to triangular
4	0.43	Alluvial fan	3.57	Toward typical	126.02	Typical to triangular
5	0.43	Alluvial fan	3.94	Toward typical	1008.97	Typical to triangular
6	0.64	Alluvial fan	3.74	Toward typical	3196.61	Typical to triangular
7	0.67	Alluvial fan	1.23	Toward typical	480.28	Typical to triangular
8	0.31	Alluvial fan	3.44	Toward typical	203.55	Typical to triangular
9	0.24	Alluvial fan	11.96	Toward typical	2118.19	Typical to triangular
10	0.55	Alluvial fan	2.55	Toward typical	280.26	Typical to triangular
11	0.31	Alluvial fan	3.01	Toward typical	2.59	Triangular to typical
12	0.59	Alluvial fan	1.95	Toward typical	1.85	Triangular to typical
13	0.49	Alluvial fan	1.50	Toward typical	0.92	Triangular to typical
14	0.70	Alluvial fan	2.13	Toward typical	46.14	Triangular to typical

The large size, 4^{th} & 5^{th} order and erosion-prone foliated geological surface (Table 3) of the river basins (basin IDs: 14, 20 & 21) causes the production of huge sediments. The relative tectonic stability in the fan surface area and huge sediments of the large basins (basin IDs: 14, 20 & 21) causes the development of the large alluvial fans having IDs 7 & 14. The small alluvial fans (fan IDs: 8 to 13) are the result of structural control of MBT & MFT neotectonics in the east of the study area.

6. Findings and Concluding Remarks

- The high surface runoff due to monsoonal precipitation and erosion-prone foliated geology supplies huge sediments which developed an alluvial fan colony along the North Bengal foothills.
- Small size alluvial fans are developed in the Garubathan recess area under an unstable tectonic environment and relatively large size alluvial fans are developed under a relatively stable tectonic environment at the outside of the Garubathan recess.
- Most of the fans are typical in shape but they vary in their dynamic nature. The large fans are more dynamic than the small fans due to tectonic stability in the fan area.
- The alluvial fans bearing ID 1 to 10 are moving from triangular to typical fan shape and the alluvial fans bearing ID 11 to 14 are moving from triangular to typical (Table 5).

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Author Profile

Ramapada Sasmal, the author, passed the Madhyamik and Higher Secondary from the West Bengal Board of Secondary and Higher Secondary Education and he completed his Graduation and Post-graduation from the University of Calcutta, West Bengal, India. He published two books, five chapters in a book in different national publications. He published six papers regarding Geography and Earth Science in different national and international journals like IJBAR, OIIRJ, IRJET, and JGSI (Springer).