Neotectonic evidences of some major rivers of North East India

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The neotectonic activity of some parts of the Assam–Arakan Basin in North East India has been studied through drainage patterns, anomalies and morphotectonics to determine the recent deformation in the area that serves as the input for any seismic hazard assessment. Various drainage anomalies like annular drainage pattern, compressed meanders, paleochannels, and knick points in the river courses reveal the presence of neotectonic activity in the area, which is also confirmed by topographic profiles and seismic sections. The present study reveals that active subsurface structures like the Rudrasagar High, Geleki Low, Geleki High and Jorhat Fault have direct influence on the development and modification of the river systems courses. The morphometric and morphotectonic studies of drainage basins flowing through the Belt of Schuppen and Dauki Fault show strong influence of tectonics. The tectonic activities of the Bomdila and Kopili Faults are studied through neotectonics and seismotectonics, supplemented by gravity data. Seismicity is fairly intense in both the areas and both faults have influences in modifying the drainage alignments of the region. Occurrence of bils/swamps and development of knicks, presence of tectonic scarps, disturbed and folding in beds on the river banks and intense seismic activity in the region reveal neotectonic activity.

Keywords: Drainage anomalies, morphotectonics, neotectonic activity, seismotectonics, seismic hazard assessment.

NORTH East India is one of the most geologically and tectonically complex regions in the world. It lies in zone V of the seismic hazard map of India[1]. The two great earthquakes (*M* 8.7) of Shillong Plateau (1897) and Assam (1950) had their origins in this region[2]. Any change in the geological activity of an area gets manifested in its drainage characteristics. Important studies on morphotectonics and neotectonics have been done elsewhere[3–5] and in NE India[6–11]. Work on neotectonism of the Himalaya and the other parts of India has also been carried out[12,13]. Studies on neotectonics in this region have also been carried out[14–19]. The present study examines the role of active subsurface geological structures in affecting the river courses and consequent drainage anomalies in some parts of the Brahmaputra Valley, Assam, NE India. Morphometric and morphotectonic parameters of some rivers flowing through the Belt of Schuppen (BoS) and Dauki Fault (DF) are studied in order to assess the influence of active tectonics on their courses. We have also examined the influence of both the Kopili and Dhansiri Faults in modifying the stream alignments of the area through study of drainage pattern and geomorphology, integrated with seismotectonics and geophysical parameters.

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Geology, structure and tectonics

Geologically and tectonically the Northeastern Region of India is divided into four major zones: the Himalayan fold belt and the Tertiary hills and mountains, the Naga–Patkai Ranges, the Shillong Plateau, including Mikir Hills and the Brahmaputra Valley in Assam. The major and minor tectonic structures of this region which are considered in this study are the E–W trending DF along the southern margin of the Shillong Plateau, the NE–SW trending BoS, Kopili Fault, Bomdila Fault, Jorhat Fault and Siang fractures[20–23].

The study area covers two geological provinces: (i) the Upper Assam and the Naga Hills, and (ii) the Surma Valley and South Shillong Plateau. Rocks of Tertiary age are well developed in Assam and South Shillong Plateau, represented by the Jaintia (shelf) and Disang (geosynclinals) group of rocks of the Eocene. These are successively overlain by Barail (Oligocene), Surma (Lower Miocene), Tipam (Upper Miocene), Dupitila (Mio-Pliocene) and Dihing (Pliocene) groups of both shelf and geosynclinal facies.

The present study includes selected drainage basins in four major geotectonic provinces (1) Upper Assam Valley area (including the Dhansiri (South) River basin) which is a ENE–WSW trending narrow valley bounded by mobile young mountain belts. The Valley consists of thick alluvium, and is the result of uplift and subsidence of the Precambrian crystalline land masses, the remnants of which are now represented by the Mikir Hills. Various important structural elements have been identified at the basement level. (2) BoS area (Naga Hills) is a narrow linear belt of imbricate thrust slices which separates the alluvial plains in the west from the ridges of the Neogene

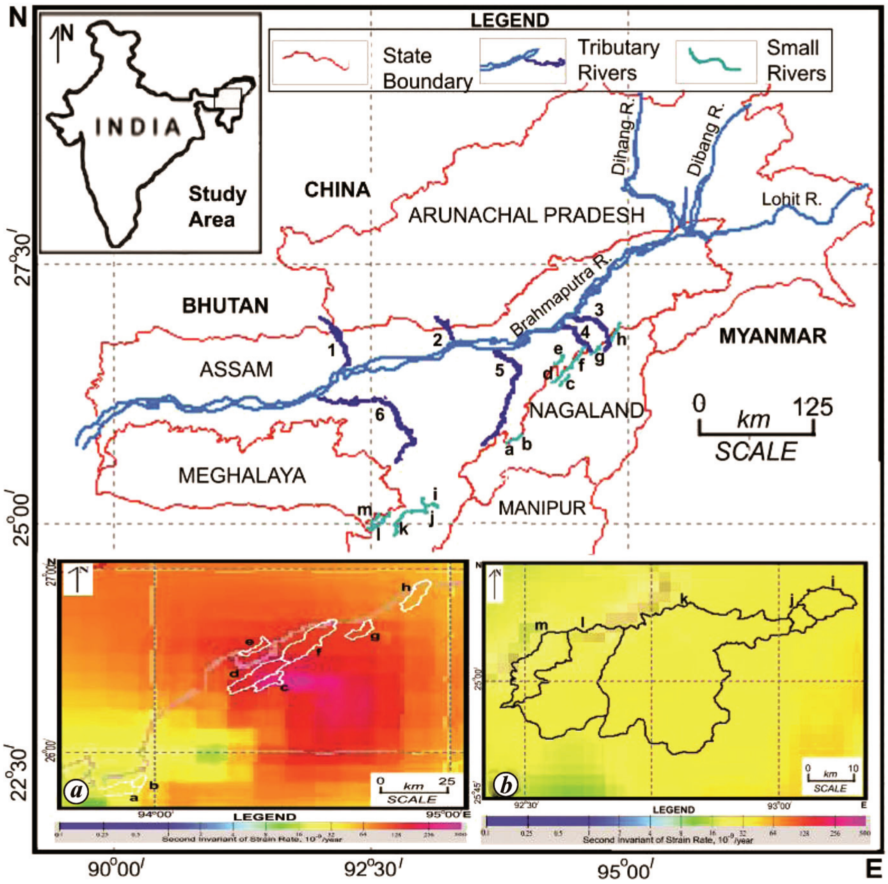

Figure 1. Location map of the study area in North East India showing the major rivers and drainage basins considered in the present study. These include: 1. Dhansiri (North), 2. Bargang, 3. Dikhou, 4. Jhanzi, 5. Dhansiri (South) and 6. Kopili. The drainage basins considered within the Belt of Schuppen belong to the rivers: a. Jharnapani, b. Zameha, c. Tsuetnala, d. Tchungnala, e. Junka, f. Tsurang, g. Tsusangyung and h. Tiru/Shishu, while the drainage basins within the Dauki Fault belong to the rivers: i. Diyung, j. Dolong, k. Jatinga, l. Larang and m. Gumra. (Insets) Strain maps (inferred from geodetic directivity) showing the basins situated within the (***a***) Belt of Schuppen area and (***b***) Dauki Fault area (modified after Kreemer *et al.*[27]).

sedimentary rocks in the east. (3) Kopili Valley area (including Dhansiri (North) River basin) and the DF area host two major structural features – Kopili Fault and DF. The former represents a rejuvenated fault (graben) system that separates the two Precambrian massifs – Shillong and the Mikir Hill blocks. (4) The DF area which defines the limits of the uplifted Archean granite gneiss of the Meghalaya Plateau, and the Neogene to Recent alluvial plains of the Surma Valley.

Study area

The study area lies in some parts of the Assam–Arakan Basin bounded by 24°36′–27°00′N lat. and 92°00′–95°30′E long. (Figure 1). The important structures like Rudrasagar High, Nazira Low, Jorhat Fault, BoS, Kopili Fault, DF and Bomdila Fault are considered in the study. The major rivers studied include the Dikhou, Jhanzi, Dhansiri (North), Dhansiri (South), Kopili, Bargang and part of the Brahmaputra. These drainage basins lie within the Survey of India (SoI) topographic map numbers 83B/1 to 12; 83B/16; 83C/8 to 16; 83D/5, 13; 83E/4; 83F/1,5, 6, 9, 10, 14-16; 83G/4, 9, 13; 83I/8, 12, 16; 83J/3, 5-7, /9, 10 13, 14 of 1 : 50,000 scale, and degree sheet no. ng 46_7 jorhat.

Methodology

Geomorphological studies were carried out to identify the drainage patterns, drainage anomalies, lineaments, knick points, swamps/bils and paleochannels to find evidences of neotectonism using topographic maps of 1 : 50,000, 1 : 63,000 and 1 : 25,000 scales of SoI, SRTM DEM and satellite data (ETM, TM and LISS). These topographic maps and images were georeferenced and digitized using the GIS software ILWIS3.4 and ERDAS Imagine8.5 in the UTM projection system.

Fluviogeomorphological features like paleochannels, compressed meanders, cut-off channels, swampy lands, reticulate stream pattern, stream alignment and annular drainage were identified and mapped to examine the role of subsurface structures of the alluvium-covered plain areas in part of the Sivasagar district, Assam.

Eight drainage basins, viz. Kukhipani, Zameha, Tsuetnala, Tchungnala, Junka, Tsurang, Tsusangyung and Shihu/Tiru within the BoS area and five drainage basins, viz. Jatinga, Larang, Gumra, Diyung and Dolong within the DF area were considered to study the morphometric and morphotectonic parameters aiming at using drainage basins as tectonic markers in areas of active structural deformation. The parameters used for the study include: linear aspects (order, number and length of stream channels), areal aspects (basin area, basin length, basin width, basin configuration – form factor, circularity ratio, basin elongation ratio, drainage density, constant of channel maintenance, stream frequency, length of overland flow), relief aspects (basin relief, relief ratio, relative relief, ruggedness number, stream channel slope, maximum valley side slope) and morphometric indices (drainage basin asymmetry–transverse topographic symmetry factor, asymmetry factor, valley floor to valley width ratio, hypsometric curve and hypsometric integral (HI), profile concavity and steepness, longitudinal/equilibrium profiles and stream length gradient index).

Simultaneously, hypocentral and source parameters are determined using SEISAN[24], RAKE[25] and FOCMEC (http://www.iris.edu/pub/programs/focmec/) software. The gravity data were collected from the GRACE satellite mission. Field investigations were carried out at a few places to find evidences of neotectonism such as prominent scarps, paleochannels, swamps/bils, etc. Prominent features identified in the maps were cross-checked in the field by GPS.

Results

The evidences of neotectonic activity in different areas under study are as follows.

Neotectonics in the Brahmaputra Valley area

For the study of neotectonics of the Brahmaputra Valley area, the drainage of the Dikhou and Jhanzi rivers in Sivasagar district, Assam, were considered (Figure 2). The study reveals a large and prominent annular pattern formed by the Dikhou and Jhanzi, and some other smaller rivers (Figure 2(i)). This indicates the presence of a subsurface high at the central part near Changmaigaon, which can be correlated with the Rudrasagar High. The NE–SW trending courses of the Disang, Diroi and Dimou rivers in the northeast corner as well as the nearly N–S trending courses of rivers such as Teok, Mudoijan and Kakojan on the southwest corner of the study area accentuate the annular drainage pattern in the central part more prominently, as confirmed by the seismic section (Figure 2(ii)).

Development of compressed meanders in the upstream segments of the Dikhou, Namdang and Jhanzi rivers indicates the presence of upwarp in their downstream part. The paleochannels at Changmaigaon and Bihubar confirm the presence of this upwarping (Figure 2(iii)). The topographic profile across this annular drainage pattern shows a high of about +6 m between the rivers Namti and Namdang, which confirms the reason for the abandonment of the Namdang River channel (now the Mori Namdang) which was once flowing through the centre of this upwarp (Figure 2(iv)). Notably, the dissection of an almost E–W trending large paleochannel at Changmaigaon perpendicularly by the present N–S trending small streams confirms change in regional slope of the area from earlier westerly to the present northerly direction (Figure 2(iii)).

The fine-textured reticulate drainage observed around Mezenga is in a depression, correlated to the Mezenga/Nazira Low (Figure 2(i)). The topographic profile across this Low confirms a depression of about –5.0 m at the centre compared with the surroundings. The Low resulted in the deposition of fine silt and thereby gives rise to the development of fine-textured reticulate drainage (Figure 2(iii)). The semi-circular Mori Dikhou (A′) paleochannel and the circular drainage anomaly are due to influence of the Bihubar/Naginimara/Geleki High, which caused diversion of the course of River Dikhou from the Mori Dikhou paleochannel. The topographic profile drawn across the centre of the anomaly confirms the presence of a High of about +5.0 m.

The knicks of rivers Jhanzi (a, b), Namdang (c, d, e) and Disang (f) are aligned in the NE–SW direction representing lineaments *X*–*X*′. *Y*–*Y*′ and *Z*–*Z*′ showing spectacular parallelism which might be due to the influence of the Jorhat Fault (Figure 2(iv) and (vi)). Development of a large belt of swampy area just north of the above parallel lineament (*X*–*X*′) might be another evidence of recent activities of this fault resulting in sagging of ground (Figure 2(i)).

Influence of BoS and DF on the river courses

The study of eight streams with drainage basins of 4th–6th order flowing within the BoS area, and the five streams with drainage basins of 4th–7th order within the DF area reveals that the drainage patterns are mostly dendritic, parallel to subparallel and trellis. Trends of most of the streams show a strong influence of structures in their main linear courses and right-angled bends. All the streams conform to the different laws of drainage composition.

Mean bifurcation ratios (>3) indicate influence of BoS and DF on the streams (Table 1). The mean lengths of different orders of some of the streams in the BoS area do

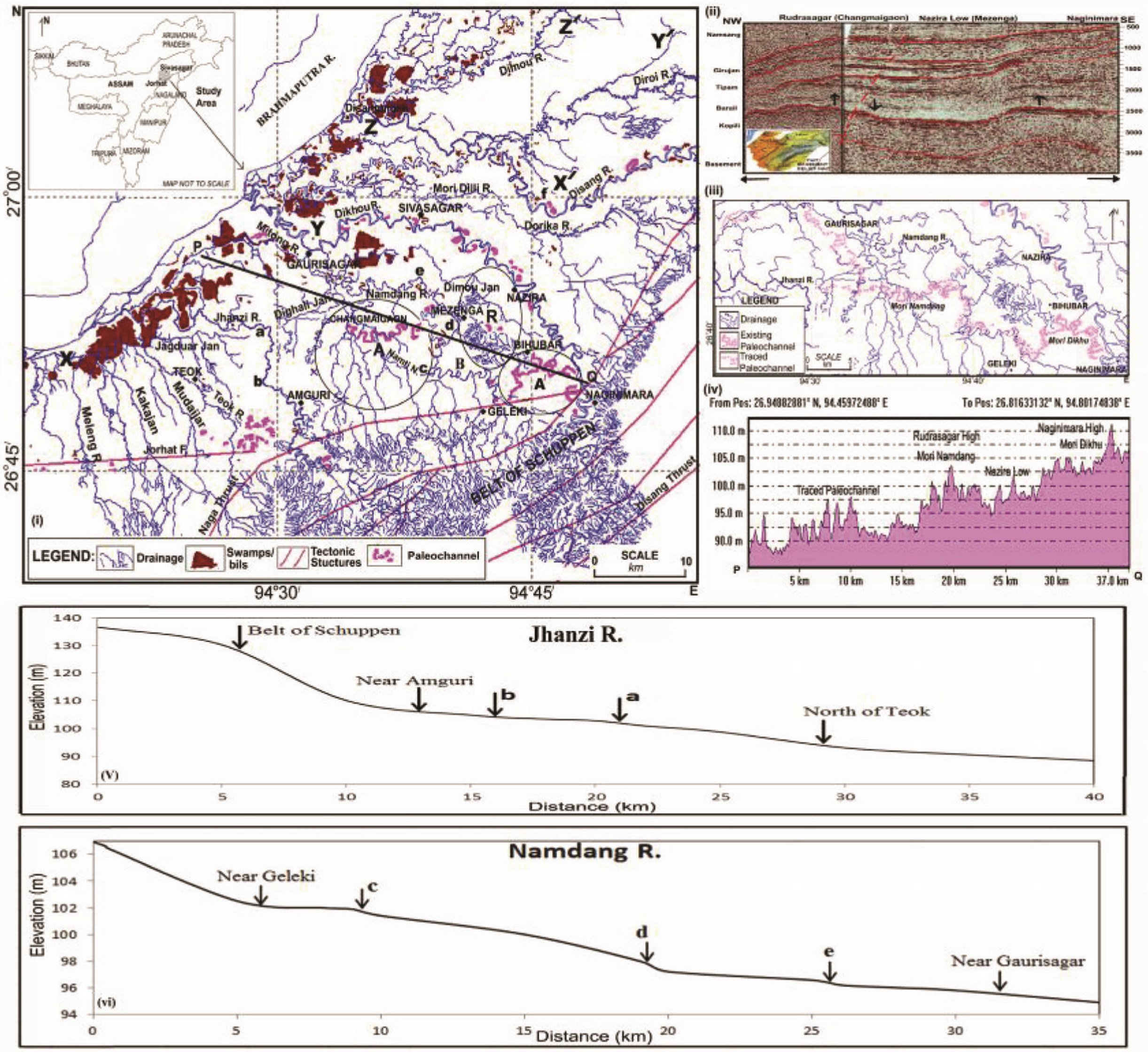

Figure 2. Location map of Dikhou and Jhanzi rivers showing (i) drainage lines along with major geological structures (modified after refs 28, 29), swamps/bils, knick points or right-angle bends (a, b, c, d, e, f) of the rivers, traced lineaments along *X–X′*, *Y–Y′* and *Z–Z′* and drainage anomalies (shown by circles) at Rudrasagar (A), Mezenga (R), Naginimara (C) anomalies; (ii) seismic section showing the Rudrasagar High, Nazira Low and Naginimara High. (Inset of (i)) Two-way time (TWT) structural map near the top of the basement of the North Assam Shelf (modified after Akhtar *et al.*[30]); (iii) Mori Dikhou and Mori Namdang paleochannels in Survey of India map (shown by continuous lines) and traced paleochannels (shown by broken lines) interpreted from ETM+7, 2001 satellite data; (iv) topographic profile *P–Q* across the Rudrasagar (A), Mezenga (R) and Naginimara (C) anomalies; (v), (vi) longitudinal profiles of Jhanzi and Namdang rivers showing the knick points (b, a) and (c, d, e) respectively.

not maintain a uniform value, indicating that the development of the stream is not uniform (Table 1), while in the DF area they maintain more or less uniform value (Table 2). Higher drainage density (3.20–4.38 km^{-1}) in most of the basins indicates weakly impermeable rocks, active incision, and larger surface run-off which also favour high stream frequency (3.20–6.35 km^{-2}). On the other hand, the rivers Jatinga, Larang and Gumra of the DF area have comparatively low drainage density (2.3–2.8 km^{-1}) with low stream frequency (2.4–3.1 km^{-2}). The constant of channel maintenance (3.3 and 4.4 km^2/km) in both areas indicates that 3–4.5 km^2 area is required to maintain 1 km of these stream channels. The lengths of the overland flow for the drainage basins are low (0.11 and 0.19 km), except for Larang (0.22 km) in the DF area, indicating short flow paths with steeper ground slopes with more run-off, less infiltration and early stage of basin development.

Drainage basin asymmetry factor of the basins in both areas indicates their tilting and asymmetrical nature influenced by neotectonism. Shape parameters show that basins are highly elongated/elliptical to near semi-circular/circular. Basin elongation ratio indicates that basins of the BoS area have high to moderate relief with active to

Table 1. Morphometric and morphotectonic parameters of the rivers situated in the Belt of Schuppen area

Basin name	Stream order	Number of streams	Bifurcation ratio	Total length of segments (km)	Mean length (km)	Cumulative length (km)	Length ratio
Linear aspects							
Junka	1	153		65.37	0.43	0.43	
	2	35	4.40	26.94	0.77	1.20	1.79
	3	4	8.75	8.13	2.03	3.23	2.64
	4	1	4.10	18.77	18.77	22.00	9.25
				$\sum L_k = 119.21$			
Tiru/Shishu	1	417		177.64	0.43	0.43	
	2	98	4.31	49.94	0.51	0.93	1.18
	3	26	3.73	26.12	1.00	1.93	1.96
	4	9	2.88	16.63	1.85	3.78	1.85
	5	2	4.50	40.25	20.13	23.91	10.88
	6	1	2.00	11.12	11.12	35.03	0.55
				$\sum L_k = 321.7$			
Tsusangyung	1	217		119.66	0.55	0.55	
	2	47	4.62	30.38	0.65	1.20	1.18
	3	13	3.62	14.30	1.10	2.30	1.69
	4	3	4.33	5.47	1.82	4.12	1.66
	5	1	3.00	11.54	11.54	15.66	6.34
				$\sum L_k = 181.35$			
Tsuetnala	1	237		123.11	0.52	0.52	
	2	57	4.16	37.57	0.66	1.18	1.27
	3	14	4.07	14.68	1.05	2.23	1.59
	4	4	3.50	10.64	2.66	4.89	2.53
	5	1	4.00	12.91	12.91	17.8	4.85
				$\sum L_k = 198.91$			
Zameha	1	132		62.01	0.47	0.47	
	2	24	5.50	21.59	0.90	1.37	1.91
	3	6	4.00	8.58	1.43	2.80	1.59
	4	1	6.00	6.91	6.91	9.71	4.83
				$\sum L_k = 99.09$			
Kukhipani	1	457		200.2	0.44	0.44	
	2	87	5.25	52.36	0.60	1.04	1.36
	3	22	3.95	32.99	1.50	2.54	2.50
	4	7	3.14	15.45	2.21	4.76	1.47
	5	1	7.00	14.26	14.26	19.01	6.45
				$\sum L_k = 315.26$			
Tchungnala	1	440		276.50	0.63	0.63	
	2	105	4.19	94.70	0.90	1.54	1.43
	3	27	3.89	44.44	1.65	3.19	1.83
	4	4	6.75	13.95	3.49	6.68	2.12
	5	1	4.00	20.84	20.84	27.52	5.97
				$\sum L_k = 450.43$			
Tsurang	1	789		414.1	0.53	0.53	
	2	175	4.51	126.04	0.72	1.25	1.36
	3	48	3.65	71.08	1.48	2.73	2.06
	4	9	5.33	17.54	1.95	4.68	1.32
	5	1	9.00	71.11	71.11	75.79	36.47
				$\sum L_k = 699.87$			

(*Contd*)

Table 1. (*Contd*)

Basin name	Stream order	Mean basin area (km^2)	Basin length (km)	Basin perimeter (km)	Basin width (km)	Shape parameters: Form factor	Shape parameters: Circularity ratio	Drainage density (km^{-1})	Constant of channel maintenance (km)	Stream frequency (km^{-2})	Length of overland flow (km)
Areal aspects											
Junka	1	0.086									
	2	0.497									
	3	2.540									
	4	32.88	14.95	37.55	2.37	0.15	0.29	3.63	0.28	4.65	0.14
Tiru/Shishu	1	0.079									
	2	0.395									
	3	1.360									
	4	2.840									
	5	33.88	19.85	48.87	4.27	0.20	0.42	4.06	0.25	5.26	0.12
	6	79.32									
Tsusangyung	1	0.109									
	2	0.556									
	3	1.800									
	4	4.940	14.27	36.44	3.57	0.22	0.43	4.02	0.25	4.81	0.12
	5	45.15									
Tsuetnala	1	0.106									
	2	0.555									
	3	2.269									
	4	6.930									
	5	52.02	15.05	45.67	3.53	0.23	0.31	3.82	0.26	4.56	0.13
Zameha	1	0.090									
	2	0.610									
	3	2.370	7.59	23.26	2.97	0.41	0.55	4.21	0.24	5.61	0.12
	4	23.52									
Kukhipani	1	0.080									
	2	0.470									
	3	2.110									
	4	7.970	14.25	45.43	5.1	0.35	0.44	4.38	0.23	6.35	0.11
	5	71.94									
Tchungnala	1	0.156									
	2	0.809									
	3	2.948									
	4	16.55	25.22	73.85	5.18	0.22	0.32	3.28	0.31	3.21	0.15
	5	137.3									
Tsurang	1	0.113									
	2	0.595									
	3	2.427	30.13	77.68	6.09	0.20	0.37	3.96	0.25	4.46	0.13
	4	7.720									
	5	176.9									

(*Contd*)

Table 1. (*Contd*)

Basin name	Maximum basin relief (m)	Relief ratio	Relative relief	Ruggedness number	Stream channel slope	Avg. maximum valley side slope		Steepness index (K_s)	Concavity index (θ)	HI
						Right hand	Left hand			
Relief aspects										
Junka	282	0.019	0.008	1.02	0.01	0.08	0.09	0.087	0.52	0.46
Tiru/Shishu	619	0.030	0.013	2.51	0.02	0.11	0.07	0.185	0.32	0.23
Tsusangyung	752	0.050	0.020	3.02	0.04	0.22	0.19	0.187	0.31	0.47
Tsuetnala	862	0.060	0.020	3.29	0.03	0.22	0.16	0.165	0.36	0.32
Zameha	941	0.120	0.040	3.96	0.03	0.17	0.17	0.107	0.45	0.44
Kukhipani	1170	0.080	0.030	5.13	0.02	0.17	0.09	0.133	0.39	0.30
Tchungnala	1070	0.040	0.020	3.51	0.01	0.12	0.22	0.187	0.47	0.26
Tsurang	1150	0.040	0.020	4.55	0.02	0.16	0.14	0.347	0.42	0.27

HI, Hypsometric integral.

Basin name	Basin elongation ratio	Drainage basin asymmetry		Average valley floor to valley width ratio
		Topographic symmetry factor	Asymmetry factor	
Morphotectonic parameters				
Junka	0.43 (<0.50-tectonically active)	0.31 ($T > 0$ asymmetric basin)	42.28 (tilt in basin)	1.95 (Broader valley with low incision)
Tiru/Shishu	0.50 (tectonically slightly active)	0.30 (asymmetric basin)	34.77 (tilt in basin)	0.72 (Deep, narrow valleys, active incision, high uplift rates)
Tsusangyung	0.53 (tectonically slightly active)	0.37 (asymmetric basin)	28.20 (tilt in basin)	0.79 (Deep, narrow valleys, active incision, high uplift rates)
Tsuetnala	0.54 (tectonically slightly active)	0.22 (asymmetric basin)	65.88 (tilt in basin)	0.22 (Deep, narrow valleys, active incision, high uplift rates)
Zameha	0.72 (tectonically slightly active)	0.23 (asymmetric basin)	46.09 (tilt in basin)	0.38 (Deep, narrow valleys, active incision, high uplift rates)
Kukhipani	0.67 (tectonically slightly active)	0.33 (asymmetric basin)	35.85 (tilt in basin)	0.30 (Deep, narrow valleys, active incision, high uplift rates)
Tchungnala	0.52 (tectonically slightly active)	0.29 (asymmetric basin)	33.98 (tilt in basin)	0.97 (Broader valley with low incision)
Tsurang	0.50 (tectonically slightly active)	0.21 (asymmetric basin)	61.32 (tilt in basin)	0.57 (Deep, narrow valleys, active incision, high uplift rates)

Table 2. Morphometric and morphotectonic parameters of the rivers situated in the Dauki Fault area

Basin name	Stream order	Number of streams	Bifurcation ratio	Total length of segments (km)	Mean length (km)	Cumulative length (km)	Length ratio
Linear aspects							
Diyung	1	298		139.37	0.47	0.47	
	2	66	4.52	41.70	0.63	1.10	1.34
	3	13	5.08	17.47	1.34	2.44	2.13
	4	3	4.33	12.42	4.14	6.58	3.09
	5	1	3	4.53	4.53	11.11	1.09
				$\sum L_k = 215.49$			
Dolong	1	113		54.71	0.48	0.48	
	2	19	5.95	15.34	0.81	1.29	1.69
	3	4	4.75	8.45	2.11	3.40	2.60
	4	1	4.00	3.39	3.39	6.79	1.61
				$\sum L_k = 81.80$			
Jatinga	1	2139		1128.70	0.53	0.53	
	2	470	4.55	374.40	0.80	1.33	1.51
	3	122	3.85	185.85	1.52	2.85	1.90
	4	27	4.52	100.93	3.74	6.59	2.46
	5	7	3.86	73.76	10.54	17.13	2.82
	6	3	2.33	74.64	24.88	42.01	2.36
	7	1	3.00	5.95	5.95	47.96	0.24
				$\sum L_k = 1944.23$			
Larang	1	691		347.60	0.50	0.50	
	2	154	4.49	127.57	0.83	1.33	1.66
	3	33	4.67	90.18	2.73	4.06	3.29
	4	8	4.13	41.77	5.22	9.28	1.91
	5	2	4.00	28.08	14.04	23.32	2.69
	6	1	2.00	16.90	16.90	40.22	1.20
				$\sum L_k = 652.10$			
Gumra	1	311		149.80	0.48	0.48	
	2	74	4.20	49.63	0.67	1.15	1.40
	3	16	4.63	26.95	1.68	2.83	2.51
	4	4	4.00	16.32	4.08	6.91	2.43
	5	1	4.00	24.83	24.83	31.74	6.09
				$\sum L_k = 267.53$			

(*Contd*)

Table 2. (*Contd*)

Basin name	Stream order	Mean basin area (km^2)	Basin length (km)	Basin perimeter (km)	Basin width (km)	Shape parameters: Form factor	Shape parameters: Circularity ratio	Drainage density (km^{-1})	Constant of channel maintenance (km)	Stream frequency (km^{-2})	Length of overland flow (km)
Areal aspects											
Diyung	1	0.03									
	2	0.38									
	3	2.30									
	4	15.57									
	5	53.37	13.24	27.14	4.67	0.31	0.91	4.04	0.25	5.58	0.12
Dolong	1	0.11									
	2	0.74									
	3	4.44									
	4	21.77	7.23	21.44	3.26	0.42	0.60	3.76	0.27	5.19	0.13
Jatinga	1	0.11									
	2	0.72									
	3	3.07									
	4	13.07									
	5	64.51									
	6	205.77									
	7	687.40	46.73	161.03	16.62	0.32	0.33	2.83	0.35	3.11	0.18
Larang	1	0.11									
	2	0.73									
	3	5.06									
	4	25.58									
	5	125.10									
	6	289.30	27.66	92.12	10.09	0.38	0.43	2.25	0.44	2.39	0.22
Gumra	1	0.13									
	2	0.67									
	3	2.83									
	4	14.73									
	5	99.25	20.92	63.29	4.84	0.23	0.31	2.69	0.37	3.13	0.19

(*Contd*)

Table 2. (*Contd*)

Basin name	Maximum basin relief (m)	Relief ratio	Relative relief	Ruggedness number	Stream channel slope	Avg. maximum valley side slope		Steepness index (K_s)	Concavity index (θ)	HI
						Right hand	Left hand			
Relief aspects										
Diyung	1150	0.09	0.04	4.65	0.06	0.17	0.24	0.27	0.29	0.39
Dolong	1366	0.19	0.06	5.14	0.17	0.26	0.25	0.53	0.27	0.54
Jatinga	1645	0.04	0.01	4.66	0.01	0.14	0.09	0.29	0.42	0.15
Larang	1480	0.05	0.02	3.34	0.03	0.11	0.08	0.44	0.12	0.16
Gumra	1190	0.06	0.02	3.20	0.04	0.13	0.13	0.37	0.41	0.31

HI, Hypsometric integral.

Basin name	Basin elongation ratio	Drainage basin asymmetry		Average valley floor to valley width ratio
		Topographic symmetry factor	Asymmetry factor	
Morphotectonic parameters				
Diyung	0.62 (Tectonically slightly active)	0.60 (Asymmetric Basin)	22.11 (Tilt in basin)	0.33 (Deep, narrow valleys, active incision, high uplift rates)
Dolong	0.73 (Tectonically slightly active)	0.45 (Asymmetric Basin)	72.94 (Tilt in basin)	0.26 (Deep, narrow valleys, active incision, high uplift rates)
Jatinga	0.63 (Tectonically slightly active)	0.13 (Asymmetric Basin)	49.33 (Steady setting)	0.48 (Deep, narrow valleys, active incision, high uplift rates)
Larang	0.70 (Tectonically slightly active)	0.48 (Asymmetric Basin)	39.34 (Tilt in basin)	0.62 (Deep, narrow valleys, active incision, high uplift rates)
Gumra	0.54 (Tectonically slightly active)	0.45 (Asymmetric Basin)	66.83 (Tilt in basin)	0.35 (Deep, narrow valleys, active incision, high uplift rates)

slightly active tectonic activity, but in the DF area the relief is moderate to low with slight tectonic activity. The maximum basin relief, relief ratio, relative relief and ruggedness number show that all the basins are situated in high elevation and highly rugged areas with steep to gradual slope and strong relief, while Junka and Tiru/Shihu of the BoS area are relatively less rugged streams with gradual slope. The stream channel slope indicates steep slopes, except for Junka and Tchungnala of the BoS area. HI values (0.23–0.54) show that the rivers lie in young topographic terrain indicating high topography, where the river basins lie in consolidated rocks which can resist erosion; while Jatinga and Larang in the DF area lie in low topography and stable landform. Steepness index indicates that all the drainage basins have high rate of both uplift and incision and are in unstable condition, except for Junka, Zameha and Kukhipani of the BoS area. Low concavity index of the basins Tiru/Shihu, Tsusangyung, Tsuetnala in the BoS area and Diyung, Dolong and Larang in the DF area suggests steep drainage with increase in incision rate, commonly associated with knick points in the river profiles. The high concavity index of Junka, Zameha, Kukhipani, Tchungnala and Tsurang in the BoS area and Jatinga and Gumra in the DF area suggests actively uplifting channels experiencing close to uniform tectonic uplift rates. Stream length gradient index reveals that most of the streams in the BoS area indicate high tectonic activity, while all streams in the DF areas indicate relatively low tectonic activity. It was observed that the knick points have distinct anomalous stream length (SL) values (Figure 3). The average valley floor to valley width ratio indicates high uplift rates, deep valleys, active incision and narrow valleys, except for Junka (1.95) and Tchungnala (0.97) in the BoS area (Figure 3 *a–m*).

Neotectonic and seismotectonic study of the Kopili and Bomdila Faults

The neotectonic activities of the Kopili region are characterized by different trends in the regional drainage pattern (Figure 4 *a*), disturbed and folding in beds on the river banks (Figure 4 *b*(i) and (ii)), straightness of river courses along the faults (Figure 4 *b*(iii)), parallel and arcuate drainage pattern, presence of tectonic scarps (Figure 4 *b*(A)), abandoned channels (Figure 4 *b*(B)), occurrence of bils/swamps, development of knicks on major regional structures like MCT and BoS, and intense seismic activity in the region (Figure 5).

The trend of the Kopili river is in a SW–NE direction from its origin up to Diyungmukh, where it takes an abrupt turn in the NW–SE up to Raha; thereafter it again takes a completely E–W turn (Figure 4 *a*). The rivers to the west of the Kopili (from Diyungmukh to Raha) all show a NNW–SSE trend, whereas some parts of the rivers on the east and north show nearly a E–W trend. The rivers in the North Dhansiri area flow in a nearly N–S direction, whereas the course of the Dhansiri (N) from the foothills up to Balisia is trending anomalously NW–SE contrary to the regional drainage trend.

Several abandoned channels on the right bank of river Kopili from Diyungmukh to Jamunamukh, Raha to Tetelia and those of the Dhansiri (N) near Kharupetia confirm that the Kopili, Kalang and Dhansiri (N) have shifted their courses to their west, south and east respectively. The region near Raha, Tetelia and west of Chataribari along the Kalang has extensive swamps and low-lying areas, inferring subsidence of the same (Figure 4 *a*).

The anomalous right-angled turn of the Dhansiri (S) River from NNE–SSW to NW–SE near Golaghat which lies along the Bomdila Fault, is evidence of structural control of this active fault (Figure 4 *b*). Migration and abandonment of the rivers Gelabil, Dhansiri (S) and Mora Dhansiri infer subsidence and formation of the scarp near Numaligarh due to neotectonic activity (Figure 4 *b*(A)). Presence of numerous ox-bow lakes in the area signifies their origin from cut-off of the river meandering. These meanderings may be due to migration of river due to tilting of the area. Longitudinal profiles of the Kopili and the Dhansiri (S) rivers show knick points and right-angle bends (Figure 4 *c* and *d* respectively).

The region where the Kopili and Bomdila Faults intersects main boundary thrust (MBT) and MCT reveals active tectonic activity (Figure 5 *a*). The focal mechanism solutions show that both the Kopili and Bomdila Faults are characterized by strike–slip nature[26]. The Kopili Fault dips towards the NE direction with an average dip angle of about 75°, whereas the Bomdila Fault dips towards the NNE direction with an average dip angle of about 50°–55°. The bottom of the seismogenic zone is within 45 ± 2 km for the Kopili Fault (Figure 5 *b*) and 50 ± 2 km for the Bomdila Fault (Figure 5 *c*). The topographical profiles indicate that the faults occupy places where there are breaks in the slopes (Figure 5 *d*(i) and (ii)). The high gravity values from north to south of the Kopili Fault indicate shallow basement as we approach the BOS area (Figure 5 *e*(i)). Moreover, low gravity values around Golaghat indicate the presence of thick alluvial deposits (Figure 5 *e*(ii)). All these indicate that both faults/lineaments are neotectonically active and this activity is responsible for the existing regional landforms and drainage.

Discussion

The present study identifies that the drainage anomalies within Sivasagar district lying entirely within the plains of Assam are influenced by subsurface structures. The annular drainage anomaly of Dikhou–Jhanzi is correlated with the Rudrasagar High, the fine reticulate drainage around Mezenga with Mezenga or Nazira Low, the Mori Dihkou anomaly with Bihubar/Naginimara/Geleki High

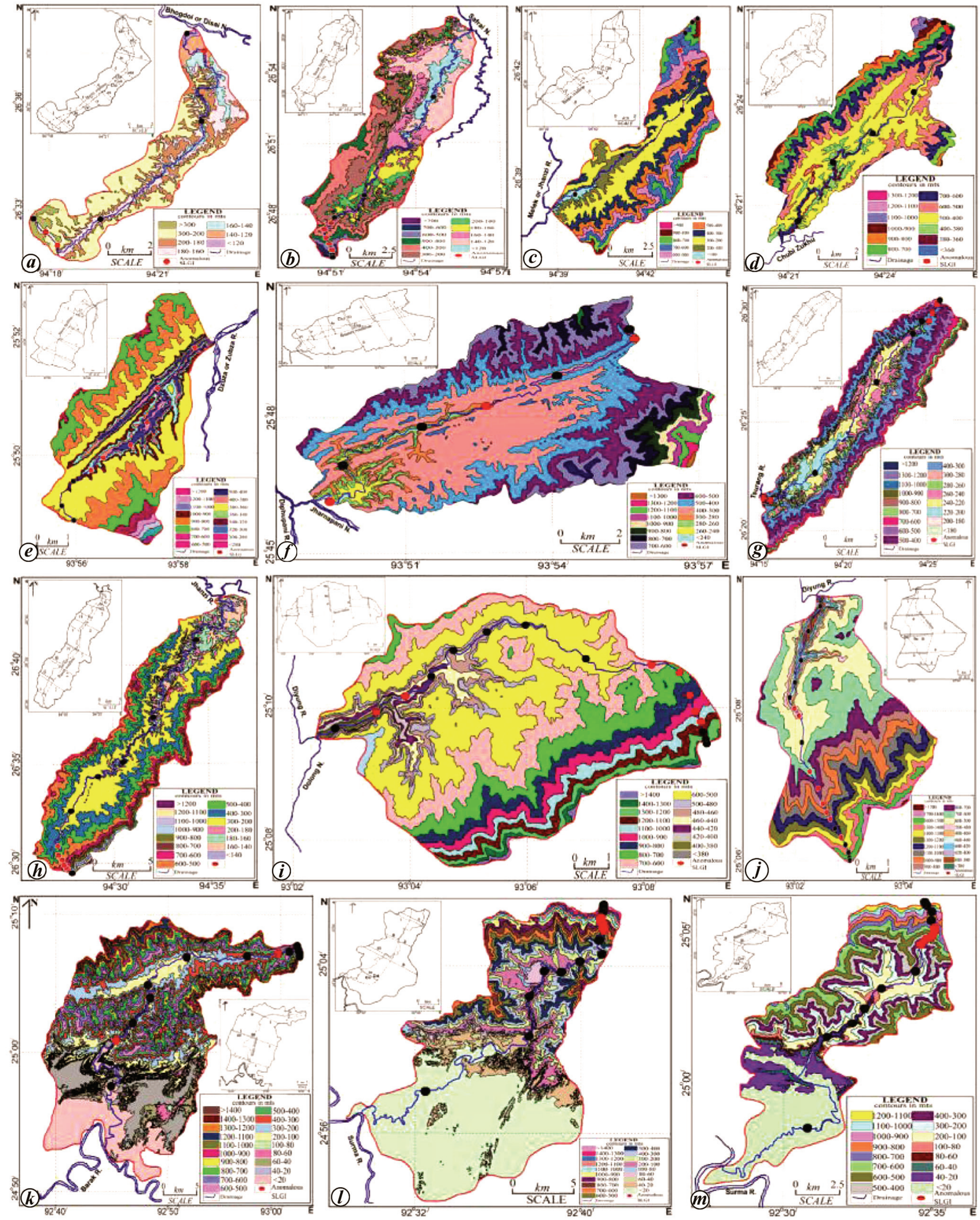

Figure 3. Calculation of stream length gradient index (black and red dots) with contours of rivers (***a***) Junka, (***b***) Tiru/Sishu, (***c***) Tsusangyung, (***d***) Tsuetnala, (***e***) Zameha, (***f***) Kukhipani, (***g***) Tchungnala, (***h***) Tsurang, (***i***) Diyung, (***j***) Dolong, (***k***) Jatinga, (***l***) Larang, (***m***) Gumra. (Insets) Segments showing calculations of topographic symmetry factor (T) (i, ii, iii, iv, …) and valley floor to valley width ratio (V_f) (1, 2, 3, …).

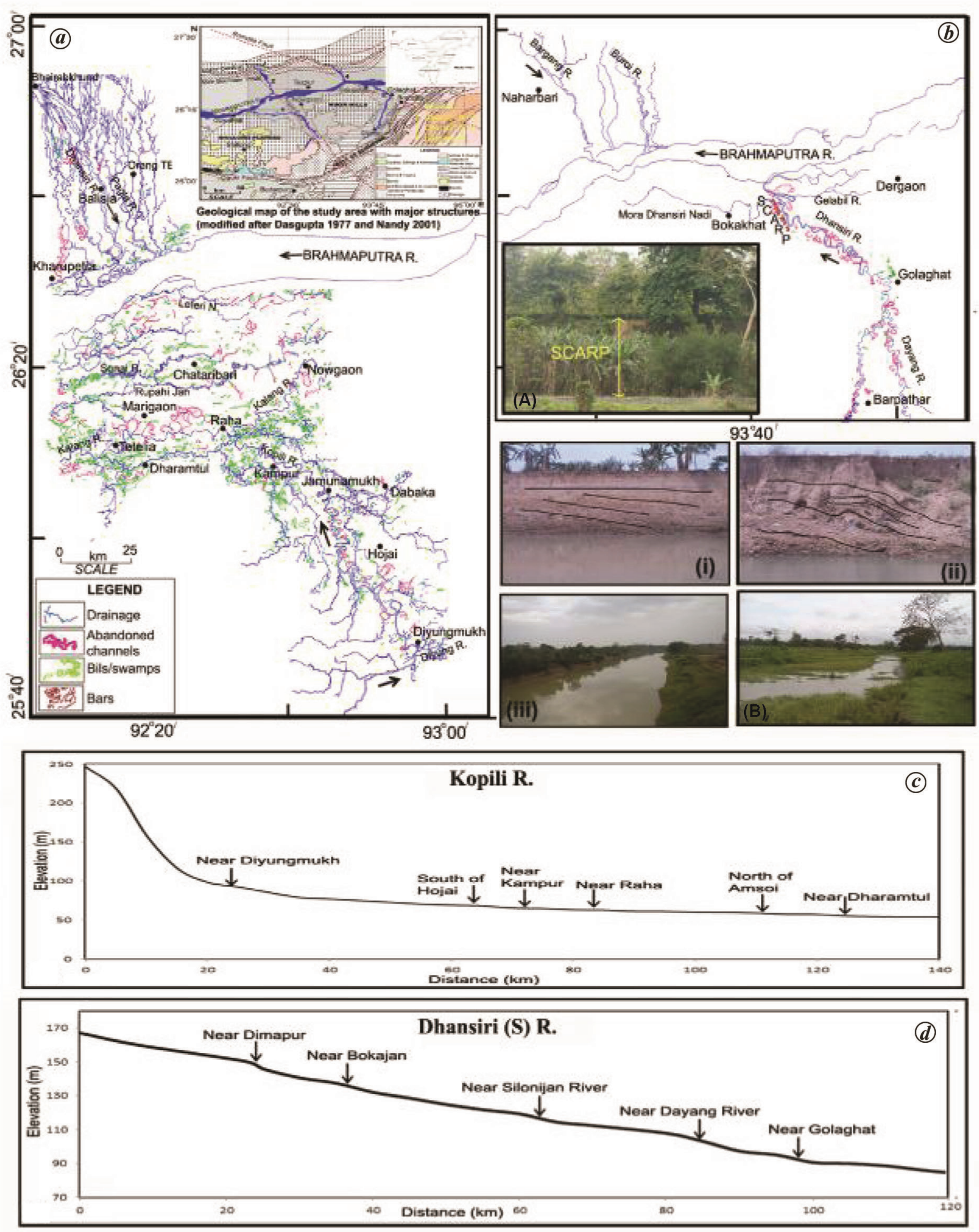

Figure 4. Drainage map showing the major rivers: (***a***) Kopili–North Dhansiri and (***b***) South Dhansiri–Bargang. The black arrows show the anomalous trend of the Kopili–North Dhansiri and South Dhansiri–Bargang rivers. (***b***) – (i) Exposure of the tilting beds in the high bank of Kopili River near Kampur (location: 26°11′49.4″N and 92°30′56.1″E). (ii) Inclination of beds near Doboka (location: 26°06′36.5″N and 92°51′55.9″E). (iii) E–W linear course of Kopili River near Dharamtul (location: 26°09′55.4″N and 92°21′13.5″E). (A) A 15 m high scarp near Numaligarh Tea Garden on the left bank of Dhansiri (S) River (location: 26°37′50.8″N and 93°43′47.1″E). (B) The present Mora Dhansiri (S) nadi near Bokakhat which was abandoned due to the formation of the scarp (location: 26°38′56.5″N and 93°36′24.5″E), (***c***, ***d***) longitudinal profiles of Kopili and Dhansiri (S) rivers showing the knick points.

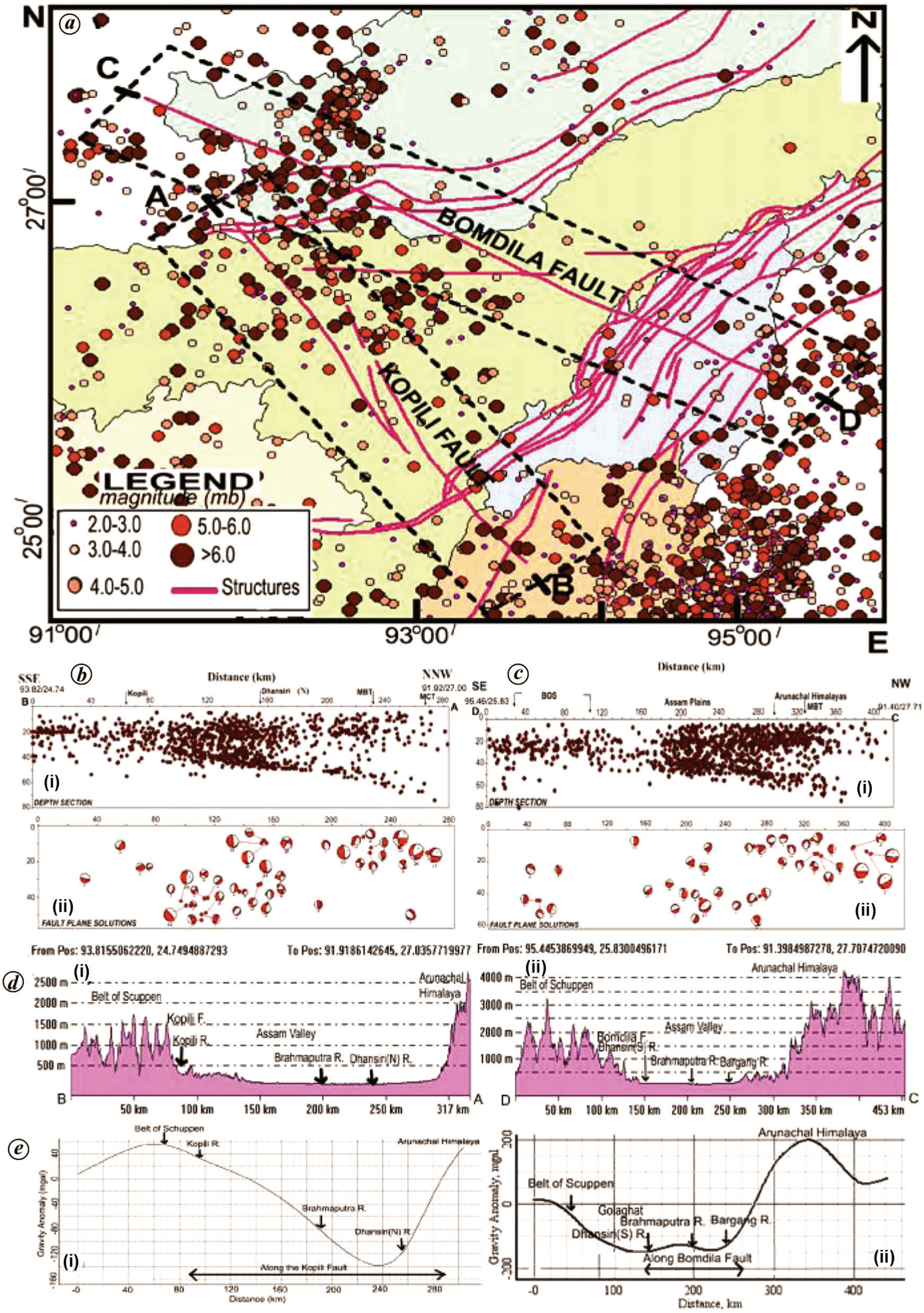

Figure 5. ***a***, Seismicity map of Kopili–Dhansiri (N) and Dhansiri (S)–Bargang valleys showing sections BA along the Kopili Fault and DC along the Bomdila Fault. The bounding lines indicate a distance of 40 km on either side of the section lines. ***b***, ***c***, (i) Depth distribution and (ii) projected depth view of focal mechanism solutions of events along the Kopili Fault (section BA) and Bomdila Fault (section DC) respectively. ***d***, Topographical profiles BA and BC along (i) Kopili and (ii) Bomdila rivers. ***e***, Gravity profiles along (i) Kopili and (ii) Bomdila Faults.

and the nearly NE–SW trending stream alignments with the Jorhat Fault. These are substantiated with the two-way time structure map and seismic sections.

Morphotectonic parameters indicate that the BoS area is 67.25% active, whereas the DF area is 20% active. Thus, tectonic activity of the BoS area is relatively higher than in the DF area, which is also substantiated by the strain map, indicating that the BoS area has higher strain rate ($256–500 \times 10^{-9}$ nanostrain/yr) compared to the DF area ($16–32 \times 10^{-9}$ nanostrain/yr) (Figure 1 *a* and *b*).

Inter-relationship of Kopili and Bomdila Faults with the geomorphological evidences of Kopili–Dhansiri (N) and Dhansiri (S)–Brahmaputra–Bargang rivers indicates evidences of neotectonism. Most of the streams show anomalous, abrupt, right-angle bends, linear, parallel, rectangular and trellis pattern indicating direct influence of the structures. The overall change in drainage pattern in the Kopili–Dhansiri (N) areas reveals that the Dhansiri (N) area, i.e. northern part of the Kopili Fault is tectonically more active at different times. During active stage, rivers in the area are aligned along the Kopili Fault in the NW–SE trend, whereas in the inactive stage they take the regional trend. Moreover, abandonment of the westerly course of the earlier Dhansiri (S) river (Mora Dhansiri river of Kaziranga) towards the present WNW direction by avulsion (Figure 4 *b*(B)) and the presence of a linear 15 m high topographic scarp near Numaligarh indicate the influence of tectonic activity along the Bomdila Fault (Figure 4 *b*(A)).

Seismicity is prominent towards the northern side of the Kopili and Bomdila Faults, whereas it is less in the southern part. Source characteristics distinguish the faults by strike–slip nature and it is considered that the fault zone transgresses below the Himalaya to the north and the BoS to the south. Topographic Highs and Lows in the profiles confirm the ongoing changes in the river channel. Study of gravity data indicates huge, thick sediments in both these valleys and also the influence of these faults up to the basement.

Conclusion

The important facts revealed in the present study are as follows:

(1) The courses of the hilly streams/rivers have been controlled by the underlying geological structures.
(2) Active subsurface structures have direct influence on the development and modification on the courses of some major rivers and have resulted in the development of several characteristic geomorphological features in the Brahmaputra Valley.
(3) The BoS is tectonically more active than the DF.
(4) The Kopili and the Bomdila Faults are both active in recent times. This is evident from the earthquake (*M* 6.4) on 28 April 2021, with its epicentre at Dhekiajuli, Assam, which lies right on the Kopili Fault line which caused ground fissures and damage to buildings.

The holistic study of some faults/lineaments of the North-eastern Region of India through a multidisciplinary approach helps us in understanding the tectonic behaviour of these structures and their influence on geomorphology. Such studies might lead to an understanding of the probable occurrence of any seismic event in the vicinity of these structures in the near future. This in turn will help to prevent loss of lives and property by adopting adequate methods of earthquake preparedness and mitigation.

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