youngest plutonic unit in this region, we cannot conclusively establish the time for the end of granitoid magmatism and stabilization of the massif. However, if the 2429 ± 30 Ma age for the single zircon from this unit may be taken to be representative of the formation age of the leuco-granitoid, the time of stabilization of the massif is very close to the inferred stabilization age of 2.5 Ga for the Aravalli Craton[11] bordering the western side of the Bundelkhand massif.

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Seismotectonics of northeastern India

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Intraplate seismicity accounts for about 20% of the earthquake activity of northeastern India. The Shillong plateau, northern Bengal basin, Tripura fold belt and Kopili lineament zone together contribute 87% of the intraplate seismicity of the region while Upper Assam is free from earthquake activity. The high seismic activity of the Shillong plateau appears to be related to the gently northward dipping seismogenic thrust fault, rupturing of which caused the great Assam earthquake of 1897. Excessive stresses induced in the Shillong plateau, northern Bengal basin and the Kopili lineament zone due to underthrusting along the Shillong thrust fault and beneath the eastern Himalaya appear to be the root cause of the intraplate seismicity in the region. The entire intraplate area excepting Upper Assam and the Kopili lineament zone is identified as a separate stress region characterized by a mean $S_{H\max}$ orientation of N3°E. The mean $S_{H\max}$ orientation in Upper Assam is N26°E. The Kopili lineament zone forms a broad stress boundary between them. Fractures/faults associated with only the Sylhet lineament, *Eocene* limestone hinge, Kopili, Tista and Padma lineaments are favourably oriented for their reactivation in strike-slip mode. The fact that only the first three amongst them are seismically active may be attributed to the high stresses induced in the northen Bengal basin and Kopili lineament zone. It appears that the crust beneath Upper Assam is a rigid block with unfavourably oriented fractures/faults, and is being deformed at a much slower strain rate, and as a result it is seismically stable.

THE northeastern region of India is seismically one of the most active regions in the world[1]. Two among a dozen largest earthquakes (*M* 8.7) of the world occurred in this part of the country, one in 1897 in the Shillong plateau and another in 1950 in the Assam syntaxis. The region is situated at the northeastern corner of the Indian plate and comprises of plate boundary zones and intraplate area. It is bounded by the plate boundary zones of the eastern Himalaya in the north, Assam syntaxis in the northeast and northern Indoburman ranges of the Naga-Disang and Arakan-Yoma thrust fold belt in the east (Figure 1). The intraplate part of the region includes seven tectonic units namely, the Shillong plateau, Bengal basin, Tripura fold belt, Kopili lineament zone, Rajmahal-Garo gap, Brahmaputra valley and Upper Assam. Because of its critical location, the region has come under the grip of a set of complicated tectonic forces ever since the collision of India with Eurasia. It is fairly well understood that the seismicity of the plate boundary zones of the eastern Himalaya and Indoburman ranges is closely related to and controlled by the collision tectonic processes. However, intraplate seismicity of the region is not yet fully understood, and needs further study. The present paper is directed towards that goal.

A catalogue of earthquakes of northeastern India ($M \geq 4.5$) for the period 1897–1992 has been compiled by Gowd *et al.*[2] using the earthquake data base published by Gupta *et al.*[1] for the period 1897–1962 and NOAA publications for the period 1963 onwards. The catalogue indicates that 710 earthquakes of $M \geq 4.5$ including two earthquakes of *M* 8.7, 16 earthquakes having magnitude in the range of 7.0 to 7.9 and 53 earthquakes having magnitude in the range of 6.0 to 6.9 occurred in northeastern India during the last 100 years, indicating that the region is characterized by high seismic activity.

Distribution of seismic activity in different tectonic units of northeastern region of India has been determined by analysing the catalogue of earthquakes. Table 1 indicates that about 80% (568 events) of the seismic activity of the region is contributed by the plate boundary zones of the eastern Himalaya and the Indoburman ranges (subduction zone), while the remaining 20% (142 events) by the intraplate area. The Indoburman ranges are almost four times more active (451 events) than the eastern Himalaya (117 events). Amongst the seven tectonic units of the intraplate area, four units namely the Shillong plateau, Bengal basin, Tripura fold belt and Kopili lineament zone together contribute 87% of the intraplate seismicity of the region and form a zone of high intraplate seismicity (Figure 1), while Upper Assam is almost free (only four events) from earthquake activity. The other two units namely Rajmahal-Garo gap and Brahmaputra valley exhibit nominal seismicity, each contributing about 4.5% of the intraplate seismicity.

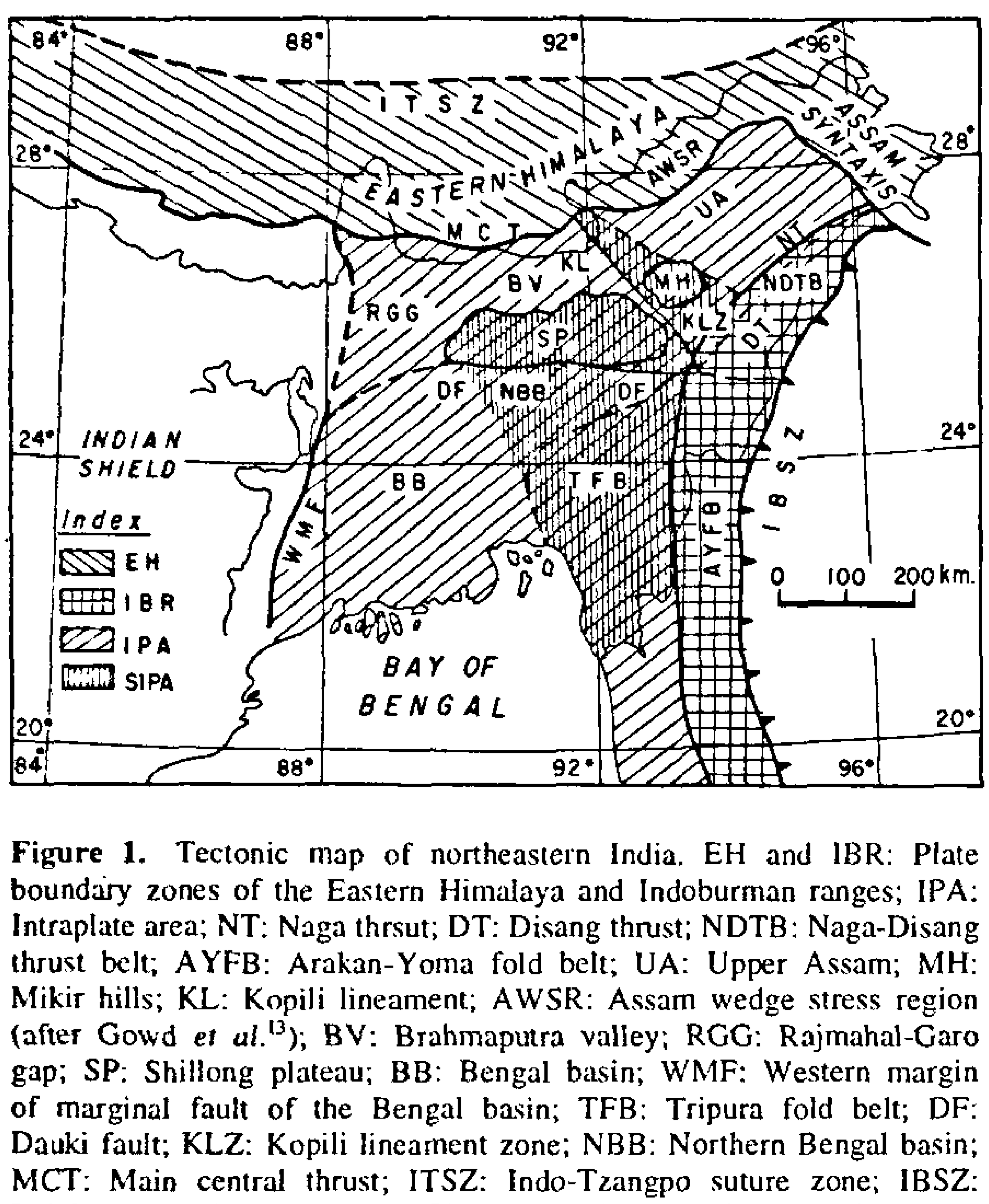

Figure 1. Tectonic map of northeastern India. EH and IBR: Plate boundary zones of the Eastern Himalaya and Indoburman ranges; IPA: Intraplate area; NT: Naga thrsut; DT: Disang thrust; NDTB: Naga-Disang thrust belt; AYFB: Arakan-Yoma fold belt; UA: Upper Assam; MH: Mikir hills; KL: Kopili lineament; AWSR: Assam wedge stress region (after Gowd *et al.*[13]); BV: Brahmaputra valley; RGG: Rajmahal-Garo gap; SP: Shillong plateau; BB: Bengal basin; WMF: Western margin of marginal fault of the Bengal basin; TFB: Tripura fold belt; DF: Dauki fault; KLZ: Kopili lineament zone; NBB: Northern Bengal basin; MCT: Main central thrust; ITSZ: Indo-Tzangpo suture zone; IBSZ: Indoburman subduction zone. SIPA: Seismically active intraplate area.

Seismotectonic map of the intraplate area of northeastern India (Figure 2) reveals that the earthquake activity in the Bengal basin is essentially confined to its northern part immediately to the south of the Shillong plateau and is related to the northeastern segments of the Sylhet lineament and the *Eocene* limestone hinge only. Amongst these, the Sylhet lineament (L-1, L-1a) is the most active one. The most devastating earthquake of 8 July 1918 (M 7.6), and several earthquakes of $M \geq 4.5$ have occurred on the northeastern segment of the Sylhet lineament while the remaining part of this lineament is devoid of seismicity. The highly destructive earthquake of 9 September 1923 with M 7.1 and a few other moderate earthquakes have occurred on the *Eocene* limestone hinge immediately to the south of the Shillong plateau.

The Kopili lineament (L9), trending NW–SE, extends through the *Pleistocene* frontal thrusts of the Himalaya to the northwest and the Arakan–Yoma to the southeast, implying that it is of recent origin[3]. This is the seismically most active intraplate lineament in northeastern India. The destructive earthquake of 23 October 1943 (M 7.2), three strong earthquakes of $6.0 \leq M < 7.0$ and several other earthquakes of $4.5 \leq M < 6.0$ occurred on this lineament. Epicentres of several moderate earthquakes are located on the Bomdilla lineament (L10) to the immediate east of the northwestern segment of the Kopili lineament. Also several epicentres are concentrated across the Assam valley, indicating a possible extension of the Bomdilla lineament up to and along the eastern margin of the Mikir hills. As in the case of the northern Bengal basin and the Kopili–Bomdilla lineament zone, it is not possible to relate the high seismic activity of the Tripura fold

Table 1. Earthquake activity in the plate boundary zones and intraplate area of northeastern India

	Number of earthquakes										
	Plate boundary zone		Intraplate area (IPA)								
M	EH	IBR	BB	TFB	RGG	SP	BV	KLZ	UA	Total	Total
≥ 7.0	2	11	2	–	–	2	–	1	–	5	18
6.0–6.9	20	23	5	1	1	–	–	3	–	10	53
4.5–5.9	95	417	21	31	4	25	7	35	4	127	639
Total	117	451	28	32	5	27	7	39	4	142	710
%Total	165	63.6	3.95	4.5	0.71	3.8	0.90	5.5	0.56	19.1	100
%IPA			19.72	22.54	3.52	19.0	4.93	27.47	2.82	100	

M: Magnitude of earthquakes; BB: Bengal basin; BV: Brahmaputra valley; EH: Eastern Himalayas; IBR: Indoburman ranges; KLZ: Kopili lineament zone; RGG: Rajmahal-Garo gap; SP: Shillong plateau; TFB: Tripura fold belt; UA: Upper Assam.

belt to the basement fractures and faults since their surface manifestation is inhibited by the thick pile of sediments in the area.

Figure 3 reveals that the western and central parts of the Shillong plateau to the west of 92°E meridian are seismically active. The great Assam earthquake of 1897 (M 8.7) and the Dhubri earthquake of 1930 (M 7.1) occurred in the central and western parts of the plateau respectively. The epicentres of 20 out of 27 earthquakes of the Shillong plateau are located to the west of 92° meridian while the remaining seven epicentres are confined to the eastern margin of the plateau, implying that its eastern part is relatively free from earthquake activity. Several workers[4–7] have investigated microearthquake activity in northeastern India. Kayal[8], Kayal and De[9], and Kharshing *et al.*[10] have studied microearthquake activity of the Shillong plateau and the results of their study also indicated that the western and central parts of the plateau are a zone of high seismic activity while the eastern part is free from such activity. When compared to the earthquakes of $M \geq 4.5$, the microearthquake activity is more uniformly distributed over the western and central parts of the plateau, suggesting that the earthquake activity in the plateau is not related to the lineaments of the area namely the Brahmaputra and the Mikir.

Molnar[11] reassessed the great Assam earthquake of 1897 and concluded that the Shillong plateau and the area just north of it were undoubtedly within the epicentral region of this earthquake. The area of the high seismic activity of the Shillong plateau covers much of the maximum intensity (XII) zone of this great earthquake which was caused due to rupturing of a gently northward dipping thrust fault, the southern margin of which coincided with the southern edge of the plateau, and the western margin was probably near western edge of the plateau[11]. It appears that continuing movements on this gently northward dipping thrust fault, termed here as the Shillong thrust fault, ever since the great Assam earthquake of 1897, leading to random rupturing of this fault at smaller scales, are responsible for the high seismic activity of the Shillong plateau.

A total of seven moderate earthquakes of $M \geq 4.5$ occurred to date in the Brahmaputra valley and all of them are confined to its southern part adjoining the Shillong plateau. Interestingly, the epicentres of these earthquakes are aligned in E–W direction about 26.5°N parallel (NN in Figure 3) and may mark the northern margin of the Shillong thrust fault. We are tempted to conclude that the Shillong thrust fault extends from beneath the southern edge of the Shillong plateau to the 26.5°N parallel. However, extension of this seismogenic thrust fault up to and beneath the eastern Himalaya cannot be ruled out, particularly in the light of the observation by Khattri[12] that the entire Brahmaputra valley up to the eastern Himalaya exhibits significant microearthquake activity.

Table 1 reveals that during the past 100 years 117 earthquakes of $M \geq 4.5$ occurred in the eastern Himalaya while 142 earthquakes occurred in the intraplate area of the northeastern region of India, indicating that about 16.5% and 19.9% of the seismic activity of the region

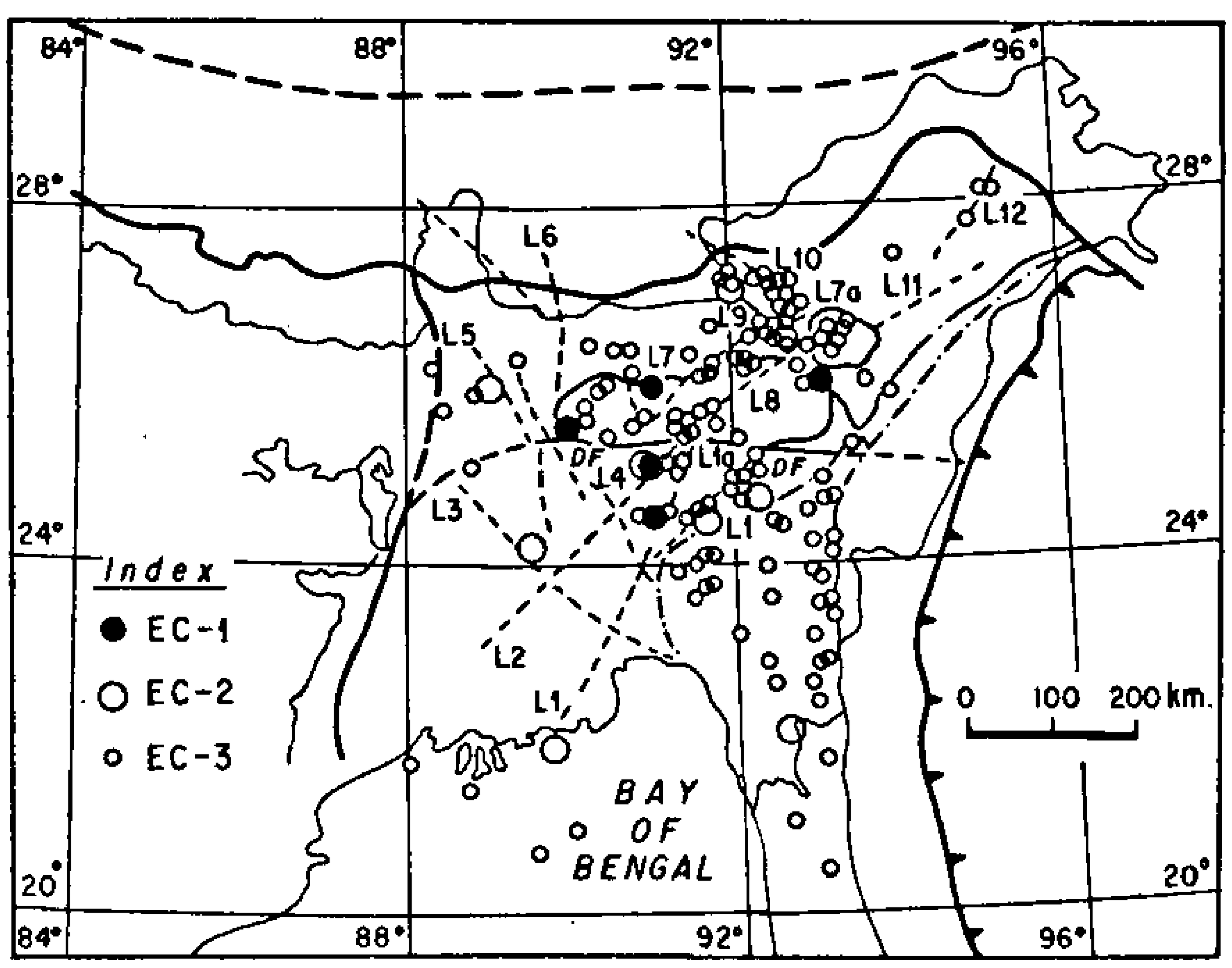

Figure 2. Seismotectonic map of the intraplate area of northeastern India. EC-1: Epicentres of $M \geq 7.0$; EC-2: Epicentres of earthquakes of magnitudes in the range of 6.0 to 6.9 ($6.0 \leq M < 7.0$); EC-3: Epicentres of earthquakes of magnitude in the range of 4.5 to 5.9 ($4.5 \leq M < 6.0$); L1, L1a: Sylhet lineament; L2: *Eocene* limestone hinge; L3: Padma lineament; L4: Madhupur lineament; L5: Tista lineament; L6: Jamuna lineament; L7: Brahmaputra lineament; L8: Mikir lineament; L9: Kopili lineament; L10: Bomdilla lineament; L11: Jorhat lineament; DF: Dauki fault.

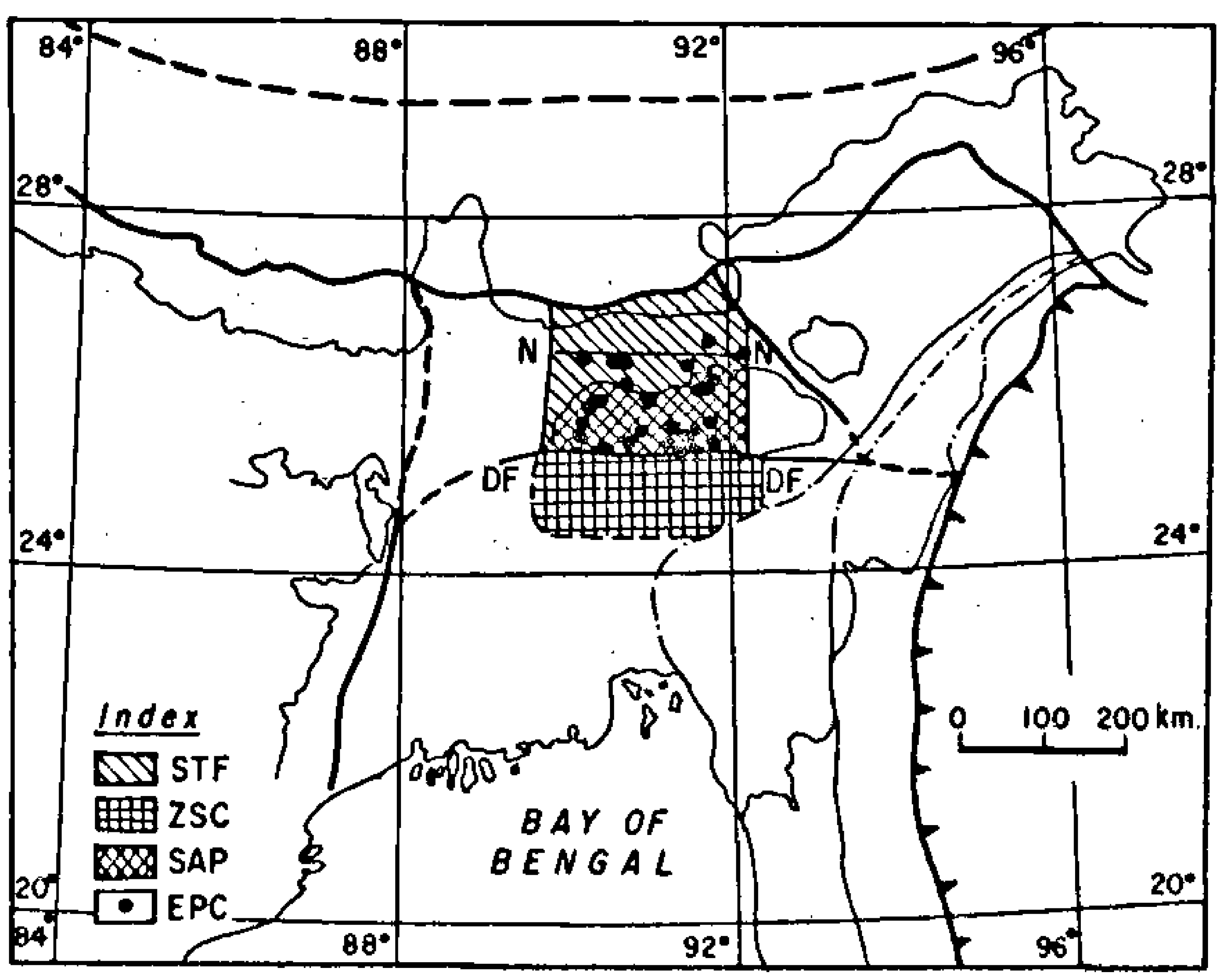

Figure 3. Seismogenic Shillong thrust fault extending beneath the Shillong plateau northward from the Dauki fault. STF: Seismogenic thrust fault; ZSC: Zone of stress concentration in northern Bengal basin; SAP: Seismically active region of the Shillong plateau; EPC: Epicentres ($M \geq 4.5$); NN: E–W alignment of epicentres in the Brahmaputra valley.

is contributed by these tectonic units respectively. Out of a total of 18 earthquakes of $M \geq 7.0$, 53 earthquakes of M 6.0–6.9 and 639 earthquakes of M 4.5–5.9 pertaining to the entire northeastern region, as many as 5, 10 and 127 events respectively originated in the intraplate area of the region. Against these, two earthquakes of $M \geq 7.0$, 20 earthquakes of M 6.0–6.9 and 95 earthquakes of M 4.5–5.9 occurred in the eastern Himalaya. The table indicates that the frequency of occurrence of earthquakes of $M \geq 7.0$ in the intraplate area is 2.5 times more than in the eastern Hiamalya while that of M 6.0–6.9 in the former is 50% less than in the latter. This demonstrates that the intraplate area of northeastern India is as much, if not slightly more, seismically active as the eastern Himalaya, suggesting that the convergence of India with the Himalaya is perhaps equally accommodated by underthrusting beneath the Himalaya and along the Shillong thrust fault extending from beneath the Shillong plateau up to the eastern Himalaya. Due to the movement along this thrust fault, excessive stresses are induced not only in the Shillong plateau but also in the northern Bengal basin because of its proximity to the southern active end of this thrust fault. Also high stresses are induced in the Kopili lineament zone because of its closeness to both the zones of underthrusting beneath the eastern Himalaya and Shillong plateau. This appears to be the root cause of the high intraplate seismicity of northeastern India.

Gowd *et al.*[13] evaluated tectonic stress field in the region using two types of stress indicators, namely wellbore breakouts and focal mechanisms, and identified the Bengal basin as a separate stress province, and the Assam wedge as a separate stress region. The stress data has been updated by Gowd *et al.*[2]. The updated data includes P-axis orientations of 16 well-constrained earthquake focal mechanisms[14–20]. A map of maximum horizontal compressive stress ($S_{H\max}$) orientations in the intraplate area of northeastern India (Figure 4) has been prepared using these P-axis orientations. The map reveals that P-axes in the eastern Himalaya, Shillong plateau, basement and crust of the Bengal basin, Tripura fold belt and Brahmaputra valley are consistently oriented in approximately N–S direction and therefore all these tectonic units together with Rajmahal-Garo gap are grouped into a separate stress region namely the Shillong stress region within the midcontinent stress province. P-axis orientations in this stress region have a mean of N3°E and a majority of them vary from N8°W to N12°E. In view of this, the Bengal basin stress province originally identified by Gowd *et al.*[13], may be treated as a stress province restricted to the sedimentary pile only.

The mean $S_{H\max}$ orientation of the Shillong stress region (N3°E) is markedly different from that of the midcontinent stress province (N23°E), indicating that the stress field in the Shillong stress region is rotated anticlockwise by 20°. This perturbance must have been caused by the deformation processes relating to underthrusting along the northward dipping seismogenic Shillong thrust fault and apppears to be a good piece of evidence in support of the hypothesis, proposed by us in the present study and earlier by Molnar[11], that the convergence of India with the Himalaya is partitioned between underthrusting beneath the eastern Himalaya and Shillong plateau. Seismic activity in the Shillong plateau and its neighbourhood is certainly higher than that of the linear seismic belts of the Indian shield, implying that the magnitude of $S_{H\max}$ and $S_{H\min}$ in this intraplate area of the northeastern region should be at least equal to those estimated by Gowd *et al.*[21] for the latter (linear seismic belts of the Indian shield).

Fault plane solutions are available for only one earthquake[22] out of the four earthquakes of Upper Assam. In order to have a larger data set, fault plane solutions of the earthquakes of the neighbouring areas have been examined. Well-constrained P-axis orientations for two sites, one in Mikir hills[16] and the other in the Assam syntaxis[23,24], have been identified and the same are shown in the stress map. This data set, though limited, indicates that the P-axis orientations are consistent with a mean of N26°E, indicating that the stress field in Upper Assam is similar to that of the midcontinent stress province. According to Gowd *et al.*[13], the Assam wedge stress region is characterized by inconsistent $S_{H\max}$ orientations. However, it may be understood from the present study that the inconsistency is true in the case of the plate boundary zones only. The NW–SE trending Kopili

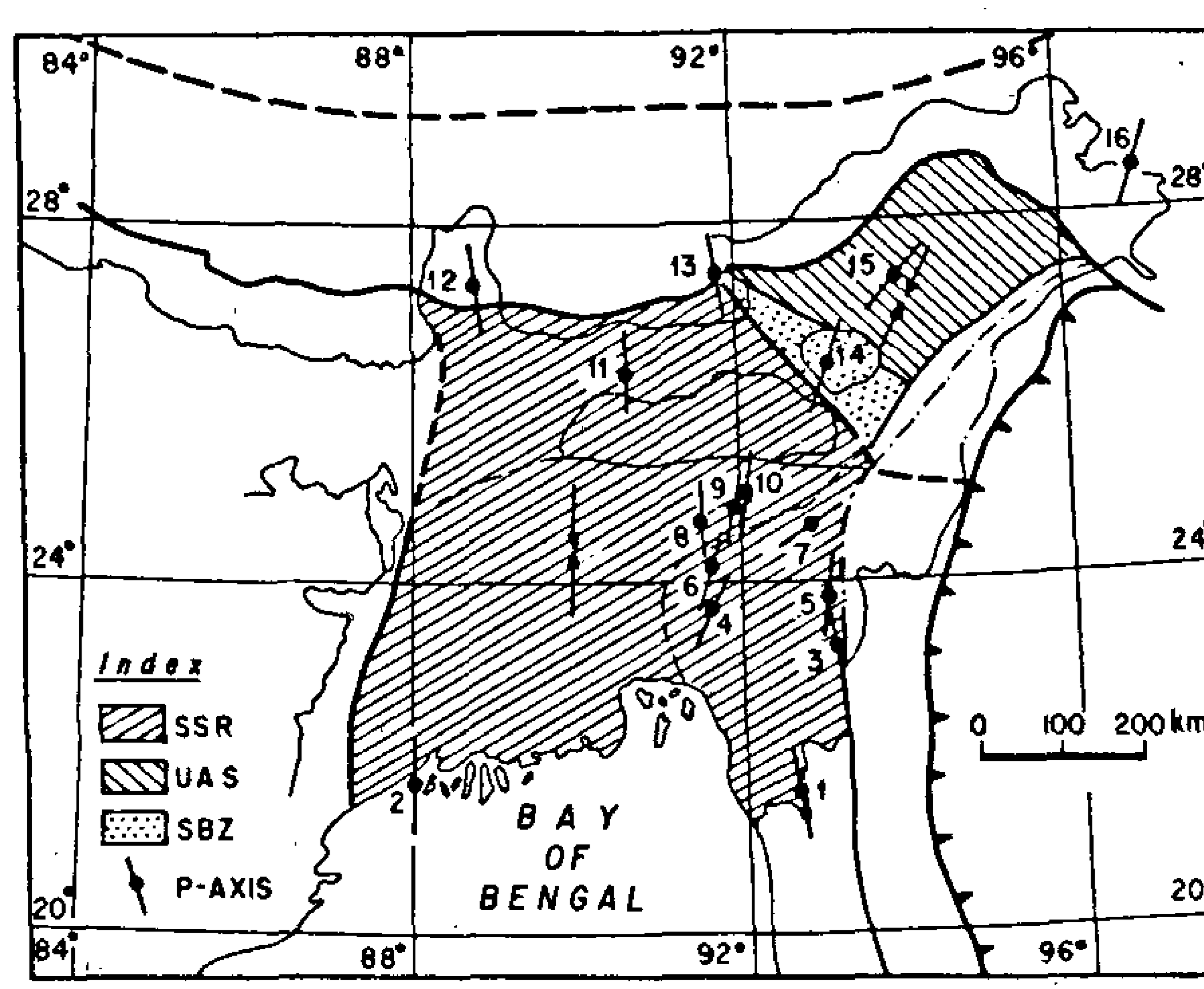

Figure 4. Stress map of the intraplate areas of northeastern India. 1–16: Sites of P-axis orientations; SSR: Shillong stress region; UAS: Upper Assam stress zone; SBZ: Stress boundary zone (Kopili lineament zone) in between SSR and UAS; Thick inward pointing arrows indicate the mean $S_{H\max}$ orientations in the respective stress regions.

lineament zone, bounded by the Kopili and Bomdilla lineaments, forms a broad stress boundary between the Shillong and Assam wedge stress regions.

The mechanisms responsible for the reactivation of various lineaments/faults of the intraplate area of north-eastrern India have been analysed using the criteria established by Gowd *et al.*[21]. The analysis was done taking into consideration strike and dip of the fractures/faults of which the lineaments are a surface manifestation, local $S_{H\max}$ orientation, reactivation angle (the angle between the fault plane and the local $S_{H\max}$ orientation), and pore pressure. The results reveal that none of the 12 major lineaments and the Dauki fault of the intraplate area, which are understood to be steeply dipping, can be reactivated in thrust faulting mode because supra-lithostatic pore pressures are needed for their reactivation, attainment of which is impossible. The four major lineaments/faults associated with the Shillong plateau, namely the Dauki fault, Jamuna, Brahmaputra and Mikir lineaments cannot be reactivated in strike-slip mode also, because pore pressures almost as high as or even higher than $S_{H\min}$ are required for their reactivation, attainment of which is not possible. The non-seismogenic character of these lineaments is in agreement with this observation. Though the Sylhet lineament, *Eocene* limestone hinge and the Tista lineament are favourably oriented, only the first two are seismically active. This discrepancy is attributed to the high stresses induced in the northern Bengal basin immediately south of the southern active margin of the seismogenic Shillong thrust fault. However, such excessive stress concentrations cannot be caused in the Rajmahal-Garo gap and in the central and southern Bengal basin as the former area adjoins the passive western margin of the fault and the latter areas are away from the active southern margin of the fault. As a result, the Tista and Padma lineaments extending through these areas can exhibit nominal intraplate seismicity only. This is in agreement with the seismicity patterns in the Rajmahal-Garo gap and Bengal basin.

The Kopili lineament, which forms the southwestern margin of the stress boundary zone between the Shillong and Assam wedge stress regions, is oriented favourably with respect to the local stress field pertaining to the Shillong stress region, and can be reactivated in strike-slip mode at moderate pore pressures. Whereas the Bomdilla lineament and its possible extension across Upper Assam, forming the northeastern boundary of the stress boundary zone, is not favourably oriented with respect to the local stress field pertaining to the Assam wedge stress region and its reactivation in strike-slip mode is not possible. However, this lineament can be reactivated in thrust faulting mode if its dip is less than 50°. Moreover high stresses are expected to be induced in this stress boundary zone because of its proximity to the zones of convergence beneath the eastern Himalaya and Shillong plateau. This explains the high seismicity of the Kopili lineament zone.

P-axis orientations are available at only three sites for Upper Assam and therefore it is difficult to choose a reliable value for the local $S_{H\max}$ orientation in respect of the two major lineaments in the area. *P*-axis orientation at the nearby site (site No. 15, Figure 4) has been considered as the local $S_{H\max}$ orientation in respect of the lineament L12 (Figure 2). *P*-axis orientation at site 14 in the nearby Mikir hills has been taken as the local $S_{H\max}$ orientation in respect of the Jorhat lineament. Although the former seems to be well constrained, there could be uncertainty in the latter ($S_{H\max}$ orientation in respect of the Jorhat lineament). The reactivation angle of the Jorhat lineament is almost 50°, implying that pore pressures as high as $S_{H\min}$ are needed for its reactivation in strike-slip mode. This result does not differ significantly if the mean $S_{H\max}$ orientation of Upper Assam (N26°E) is considered for the purpose. The results show that the northeastern segment of the lineament L12 can be reactivated in strike-slip mode at moderate pore pressures. Whereas its southwestern segment is parallel to the local $S_{H\max}$ orientation, and hence cannot undergo any shear deformation. Only three moderate earthquakes occurred on the northeastern segment till date (Figure 2), though it is as much favourably oriented as the seismically active Sylhet lineament. From all this it appears that the basement and crust of Upper Assam is a rigid block with unfavourably oriented fractures/faults and is being deformed at much slower strain rate, rendering it (Upper Assam) seismically inactive and stable.

It was brought out above that the great Assam earthquake of 1897 was caused due to rupturing of the gently northward-dipping Shillong thrust fault and that the convergence of India with the Himalaya is accommodated partly by underthrusting along the Shillong thrust fault and partly by underthrusting beneath the Himalaya. It was inferred above that the Shillong thrust extends in E–W direction from 90°E to 92°E longitudes, and in N–S direction from the southern edge of the Shillong plateau to 26.5°N parallel much to the south of the Himalaya, suggesting that this thrust is an intraplate fault but not a part of the Indian plate boundary. Whereas the great Assam earthquake of 1950 was caused due to rupturing of a NNE–SSW striking fault[23], which is an extension of the MCT into the Assam syntaxis. This indicates that the rupture zones of these two earthquakes belong to two independent fault systems, and that a fault connecting these two rupture zones may or may not exist beneath Upper Assam.

The Assam seismic gap proposed by Khattri and Wyss[25] and Khattri *et al.*[5] is completely devoid of earthquake activity. Only four earthquakes M 4.5–5.5 have occurred till now in Upper Assam (Table 1) and three of them have been caused due to the reactivation of the lineament L12. Also, Upper Assam has neither experienced a great earthquake of M 7.0 or more in the recent past nor has it historic record of ever being affected by a great earthquake. All these facts suggest that no major seismogenic thrust fault extends across Upper Assam.

The hypothesis of seismic gap advanced by Fedotov[26], Mogi[27] and Sykes[28] states that major earthquakes are likely to occur along sections of plate boundaries which have ruptured in the past, but have not experienced great earthquakes atleast in the past 30 years. According to McCann *et al.*[29], seismic gaps often appear to be regions of reduced activity for moderate and small shocks as well as regions of relative quiescence for large shocks. In the light of what has been discussed above, it is obvious that Upper Assam does not satisfy any of these conditions for being identified as a seismic gap. Hence, we consider that the Assam seismic gap proposed by Khattri and Wyss[25] does not exist and we are therefore, of the opinion that there is no danger to Upper Assam being affected by a large earthquake in the near future.

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