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FLOW OF THE TIBETAN PLATEAU AND TECTONICS ALONG THE BURMESE ARC

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The seismicity of northeast India and its surroundings (18 °N to 32 °N and 84 °E to 100 °E) is very complex. It includes the Himalayan thrust, the Burmese region and a small portion of the Tibetan plateau. It shows widespread distribution of earthquakes and constitutes one of the important tectonic features of the world. It has been reported that the northeast drift rate of the Indian plate and southeast flow of the Tibetan plateau are of the same order, i.e. 18±7 mm/year. Thus the effect of flow of the Tibetan plateau on seismicity distribution of the meeting zone of the Indian and Burmese plates and the Tibetan plateau would be greater than the Indian and Burmese plates because of its high crustal thickness. Normally shallow earthquakes are observed all over the region except the Burmese arc, where intermediate earthquakes occur to a depth of 200 km. The width of the arcuate seismicity is maximum around 24 °N and reduces on either sides terminating at 21 °N and 27 °N. The fault plane solutions suggest that the compressive stresses also act along the strike of the arc; extensional stresses are also observed. In the paper a model is presented to explain seismicity, focal depth, frequency and stress distribution in the arc zone taking into account the southeast flow of the Tibetan plateau.

Keywords: tectonics, seismicity, drift rate, stress distribution

1. Introduction

The northeast region of India is very complex from the geological, geophysical and seismological points of view. The tectonic features of the region comprise the Himalayan thrust, the Burmese region, and a small portion of the Tibetan plateau. The nature of the tectonic deformations has been studied by several authors: the Himalayas by FITCH [1970], VERMA et al. [1977], VERMA et al. [1980]; the Tibetan region by MOLNÁR, TAPPONIER [1978], MOLNÁR et al. [1987], VERMA, REDDY [1988]; and the Burmese region by

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RASTOGI et al. [1973], VERMA, KUMAR [1987]. The clockwise rotation of the Burmese region with the westward movement towards the Indian plate was reported by HAMILTON [1979] and CURRAY et al. [1982]. The above studies reveal drifting of the Indian plate towards the northeast, the extension of the southern Tibetan region towards the northwest, and the southeast, and the Burmese region towards the west.

The considered region shows widely distributed large earthquakes. Intermediate focal depth earthquakes are observed along the Burmese arc, which has been reported to be due to subduction of the Indian plate towards the Burmese region. However the characteristics of the seismicity distribution along the arc [TENG et al. 1987] suggest that the northeast drifting of the Indian plate would not be able to produce the existing nature of the subduction zone. MOLNÁR et al. [1987] reported the northeast drift rate of the Indian plate and southeast flow of the Tibetan plateau to be of the same order, i.e. 18±7 mm/year. Thus the effect of southeast flow of the Tibetan plateau on the seismicity distribution pattern on the region would be of the same order as the northeast drifting of the Indian plate.

The present study discusses a plausible model that would explain the distribution and concentration of earthquakes and the direction of tectonic stresses along the arc-shaped zone.

2. Seismicity data

The earthquake catalogues prepared by the National Geophysical Data Centre (NGDC), Boulder, Colorado, have been used so as to have uniformity in the data. As large earthquakes are recorded all over the world, the estimation of their hypocentres may be taken to be reliable. For the present study the data have been considered since 1912 to 1977 with magnitude $M \geq 6.0$. The seismicity distribution map prepared by TENG et al. [1987] with body wave magnitude $m_b \geq 4.0$ for the period 1961 to 1980 has also been incorporated in the present study. *P*-wave first motion data have been taken from the Bulletin of the International Seismological Centre (ISC) for the selected events of the period 1969 to 1984. The bulletin reports first motions, compressions, and dilatations for a large number of observations (short and long period records).

3. Tectonic characteristics

The considered region has complex geological formations. It includes regional folding mainly striking north-south in the Burmese region, almost east-west in the Himalayas, as well as the Siling fold belt and Kunlun faults of the Tibetan plateau. The tectonic pattern of the region is highly complex.

YANSHIN [1966] and ZHANG [1983] published a tectonic map of China and the Tibetan plateau showing the lineaments and faults (*Fig. 1*). At present this palteau is under violent tectonic movement. An arcuate structural belt convex towards the east that strikes northeast is the principal characteristic of the structure of the plateau. The Himalayan regions are associated with intensive folding and thrusting [KROPOTKIN 1969, LOMNITZ 1974].

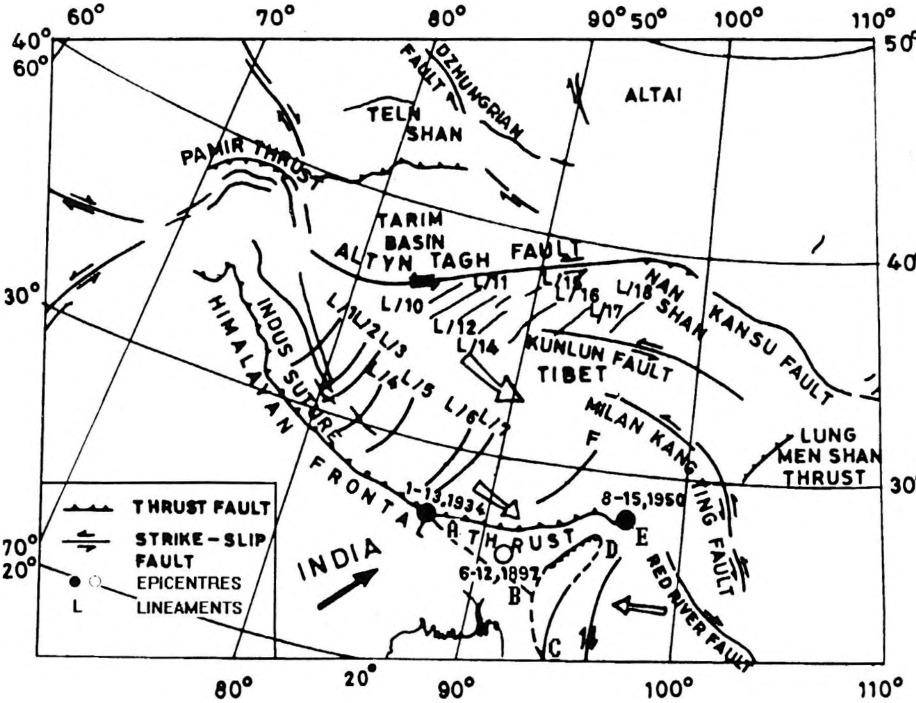

Fig. 1. Map showing recent tectonic features of Asia. Lineaments, faults and epicentres of the three major earthquakes of 1897, 1934, and 1950 are indicated. The demarcated area (A-B-C-D-E) is under the influence of southeast flow of the Tibetan plateau

1. ábra. Ázsia jelenlegi tektonikai jellegzetességeinek térképe. Az 1897, 1934 és 1950-es három fő földrengés lineamenseit, vetőit és epicentrumait jelöltük be. A körülhatárolt terület (A-B-C-D-E) a Tibeti-fennsík délkelet irányú eltolódásának hatása alatt áll

4. Focal mechanisms and orientation of stress

Tectonic motions have been inferred through fault plane solutions. Eleven focal mechanisms of earthquakes of the Burmese arc zone have been considered. Of these, six are new mechanisms whereas five have previously been reported. The focal mechanism solutions of the considered six events show different patterns along the strike of the arc zone. Mechanisms 1 and 4 show normal; 3, 5 and 6 indicate thrust; and 2 demonstrate strike slip faultings. The locations of epicentres of the considered earthquakes for the focal mechanism solutions and their ISC parameters are given in *Fig. 2* and *Table I.* respectively. *Table II* shows the orientation of the poles, and B, P, and T axes.

Event	Date	Time of origin (h:min:s)	Epicentre Lat [°N]	Long [°E]	Focal depth [km]	Magnitude (M)	Remark
1	28 Apr. 1969	12:50:15.2	25.9	95.3	50	5.2	*
2	14 Oct. 1971	12:55:23.3	23.1	95.8	63	5.2	*
3	29 Dec. 1971	22:27:02.0	25.1	94.6	33	5.5	*
4	13 Dec. 1975	22:35:44.2	23.6	94.3	63	5.2	*
5	13 Oct. 1977	11:32:09.3	23.5	95.4	61	5.2	*
6	05 Marc. 1984	21:26:42.5	24.5	94.6	69	5.2	*
A	17 Oct. 1969	01:25:12.4	23.1	94.7	124	6.0	**
B	29 July 1970	10:16:19.3	26.0	95.4	59	6.5	**
C	08 July 1975	03:03:11.6	26.5	96.4	33	5.2	**
D	22 Jan . 1964	15:18:46.4	22.3	93.6	60	6.3	***
E	15 Dec. 1965	04:43:45.9	22.0	94.5	109	5.2	***

Table I. Parameters of earthquakes of arc-shaped zone of northeast India. * denotes the present study, ** by LE DAIN et al. [1984] and *** by MUKHOPADHYAY, DASGUPTA [1988]

I. táblázat. Észak India ív-szerkezetű zónájában előfordult földrengések paraméterei. Jelölések: * — jelen tanulmány, ** — LE DAIN et al. [1984] és *** — MUKHOPADHYAY, DASGUPTA [1988] nyomán

Event	Plane 'a'			Plane 'b'			B-axis		P-axis		T-axis		Remarks
	Dip direction [°]	Dip [°]	Strike [°]	Dip direction [°]	Dip [°]	Strike [°]	Trend [°]	Plunge [°]	Trend [°]	Plunge [°]	Trend [°]	Plunge [°]	
1	326	03	N56E	146	86	N56E	056	00	326	54	146	48	*
2	102	60	N14E	358	68	EW	062	52	228	25	138	04	*
3	210	70	N60W	030	18	N60W	302	00	210	26	030	64	*
4	270	16	NS	090	74	NS	000	00	270	62	090	29	*
5	352	56	N82E	214	43	N52W	280	24	013	06	116	64	*
6	356	62	N86E	176	28	N86E	086	00	355	16	175	72	*
A	000	72	EW	180	14	EW	090	00	000	30	180	60	**
B	356	52	N86E	088	76	NS	015	57	226	26	129	16	**
C	318	38	N52E	208	60	N62W	280	37	178	16	070	48	**
D	104	74	N14E	344	30	N74E	022	24	254	54	123	25	***
E	064	68	N26W	234	22	N34W	152	03	254	66	060	23	***

Table II. Focal mechanism solutions of the considered events of the Burmese arc. * denotes the present study, ** and *** by LE DAIN et al. [1984] and MUKHOPADHYAY, DASGUPTA [1988], respectively

II. táblázat. A Burmai-ív vizsgált jelenségeinek fókuszmechanizmus megoldásai. Jelölések: * — jelen tanulmány, ** — LE DAIN et al. [1984] és *** — MUKHOPADHYAY, DASGUPTA [1988] nyomán

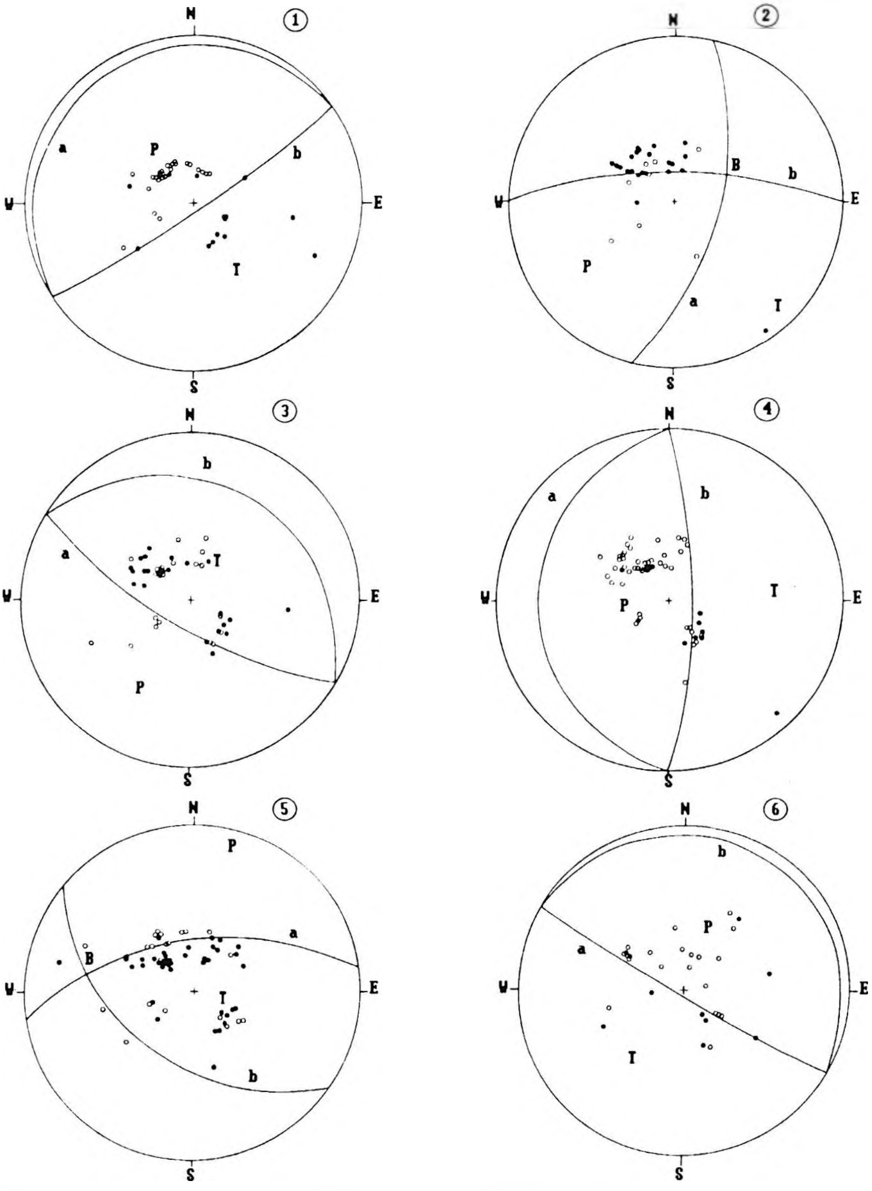

Fig. 2. Lower hemisphere equal area projection of fault plane solutions; open and solid circles indicate *P*-wave dilatations and compressions, respectively, 'a' and 'b' are fault and auxilary planes, P and T correspond to the axis of compression and tension, B is the null point

2. *ábra.* A vetősík megoldásával azonos területű vetületek az alsó féltekén; üres és telített körök jelzik a P-hullám megnyúlásokat illetve kompressziókat, 'a' és 'b' a vető és segédsíkok; P és T megfelelnek a kompressziós és tenziós tengelyeknek; B a nulla pont

5. Seismic characteristics of the region

The seismicity data for the region (15 °N to 35 °N and 80 °E to 100 °E) for the period 1961 to 1980 are shown in *Fig 3*. It includes all the events of $m_b \geq 4.0$. The seismicity distribution of large earthquakes ($M \geq 6.0$) for the

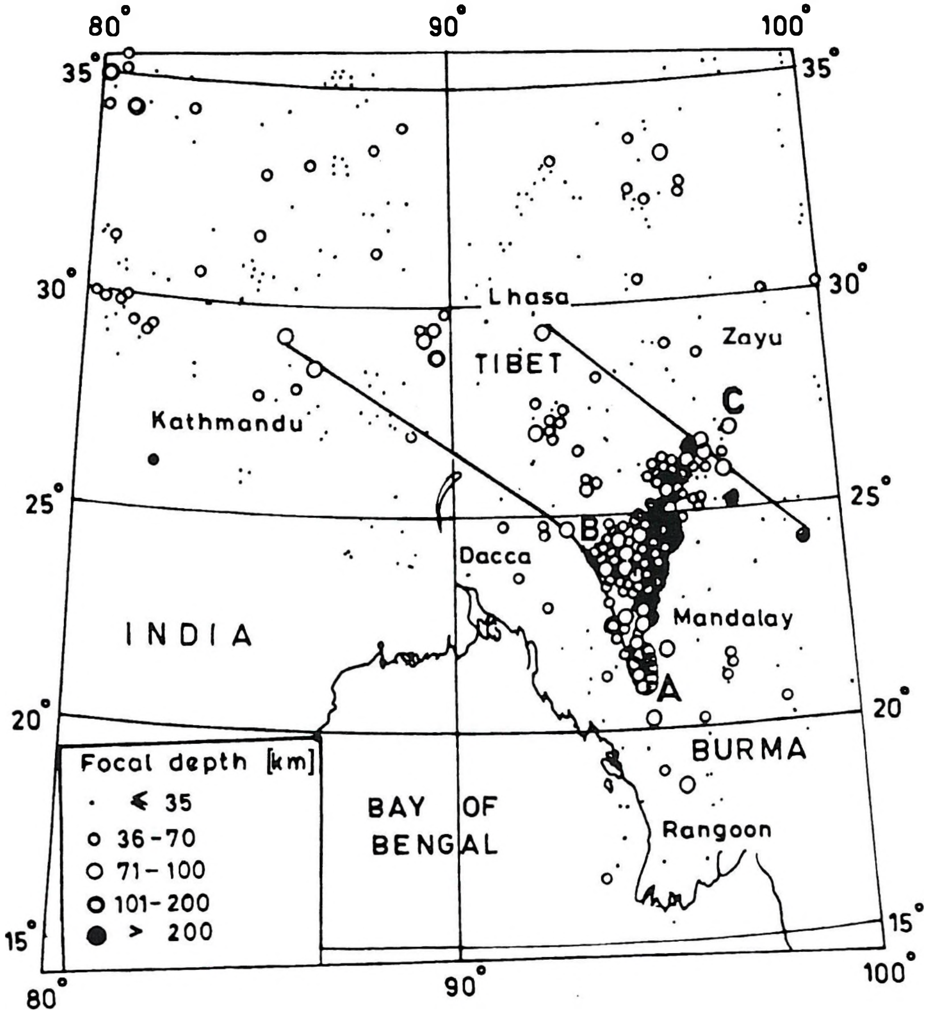

Fig. 3. Seismicity distribution of northeast India and its surroundings for the period 1961-1980 [TENG et al. 1987]. Intermediate focal depth earthquake zone is also demarcated by the two NW-SE trending lines

3. ábra. Északkelet India és környékének szeizmicitás elolszlása az 1961-1980-as időszakra [TENG et al. 1987]. A közepes fókuszmélységű földrengészónát is bejelöltük két ÉNY-DK irányú vonallal period 1912 to 1977 is shown in *Fig. 4*. Intermediate focal depth earthquakes are also shown. The above figures reveal the seismic activity to be very high along the Burmese arc. The southern portion of the plateau is affected by widely distributed large earthquakes. Both the above figures reveal a seismically active arc-shaped zone showing the width of seismicity to be about 100 km at 24 °N. The width of seismicity decreases on either side terminating at 21 °N and 27 °N. The seismic belts AB and BC strike, respectively, north-south and northeast-southwest. The high seismic activity around 24 °N may be realized due to the fact that out of thirteen intermediate earthquakes, six have been occurred in a very limited area around 24 °N. The deepest earthquake to the east of Arakan-Yoma mountain is 250 km [VERMA et al. 1978]. Three intermediate earthquakes of magnitude $M \geq 6.0$ have occurred outside the Burmese arc. TENG et al. [1987] and KAYAL [1987] reported a number of intermediate focal depth earthquakes of smaller magnitude in the southern Tibetan plateau and Assam region. The demarcation of these earthquakes is shown is Fig. 3 striking northwest-southeast. Of the considered earthquakes three show thrust, two normal faulting, and one strike-slip faulting.

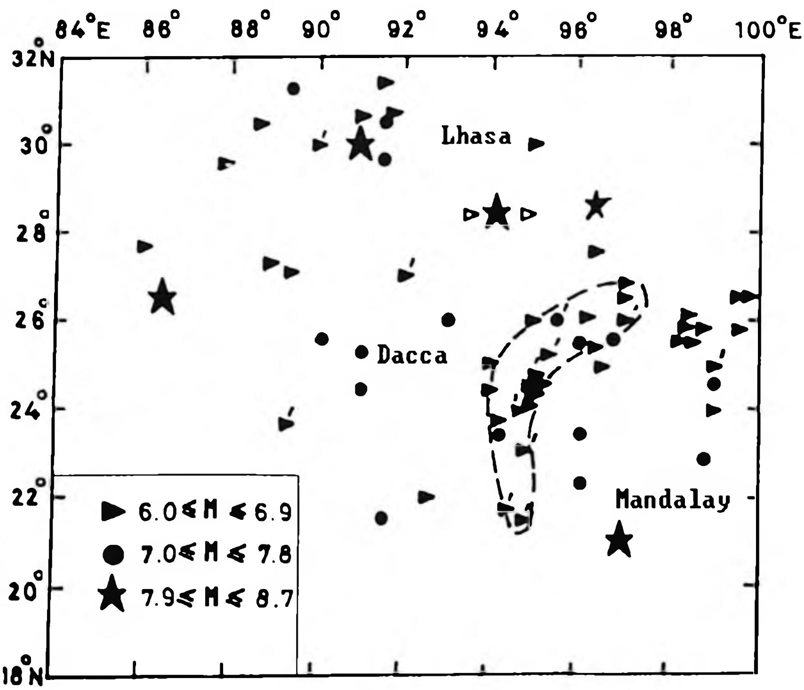

Fig. 4. The spatial distribution of large earthquakes $M \geq 6.0$ for the period 1912–1977. Dashed symbol shows the earthquakes with focal depth $\geq$ 70 km. Note that intermediate earthquakes are observed maximum around 24 °N which reduced in space and time on either side along the arc

4. ábra. Az $M \geq 6.0$ nagy földrengések térbeli eloszlása az 1912–1977-es periódusra. A szaggatott jelölés a 70 km-nél nagyobb fókuszmélységű földrengéseket mutatja. Megjegyezzük, hogy a közepes méretű földrengéseket maximum 24 °E körül észlelték, melyek mérete térben és időben csökkent az ív mindkét oldalán

Mechanisms 1 and 4, which are shallow events, show an extensional character of crustal movement. The nature of mechanisms for three shallow shocks (events 3, 5 and 6) of arc-shaped zone shows the peculiar nature of thrust faulting. The stresses are shallow dipping and oriented perpendicular to the strike of the seismic belt. Mechanism 2 shows strike-slip faulting. The directions of forces for these cases are shown in *Fig. 5*.

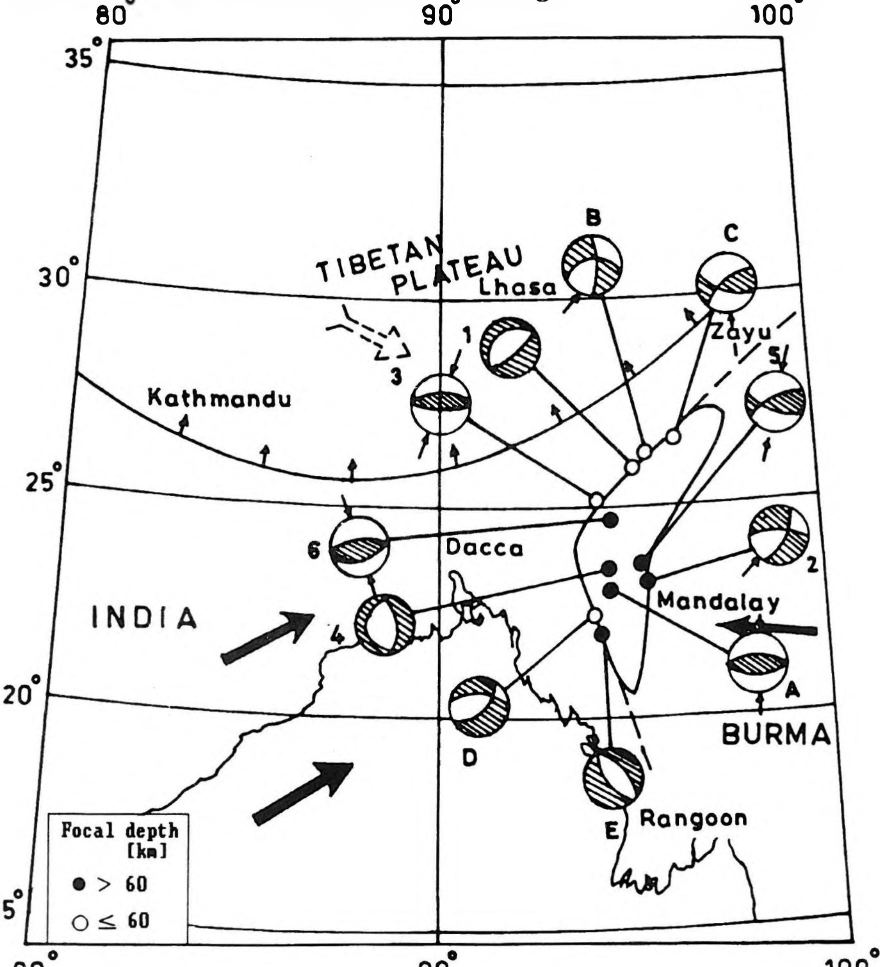

Fig. 5. A simplified map showing the direction of compressive forces. Big arrows indicate the direction of flow/drift of the surroundings. Direction of compressive stresses derived from fault plane solution and focal mechanisms for the considered earthquakes are also shown

5. ábra. A kompressziós erők irányát mutató egyszerűsített térkép. A nagy nyilak jelölik a környezet eltolódás/elfordulás irányait. A kompressziós feszültségek irányát a vető sík megoldásokból vezettük le. A vizsgált földrengések fókuszmechanizmusait is bemutatjuk

The general nature of seismicity and stresses in northeast India does not show a systematic pattern because of the converging nature of the surroundings. The northeastern Indian region experienced three large earthquakes of $M \geq 8.4$ as shown in Fig. 1. The generation of a large earthquake requires high strain rate accumulation. SINGH, SINGH [1987] studied the strain rate in the Himalayas and the nearby region. These authors reported the strain rate deformation to be maximum for the region. This suggests that the flow of the Tibetan plateau might have developed significant strain for the occurrences of such big earthquakes of northeast India, i.e. Shillong earthquake of 1897, Bihar earthquake of 1934, and Assam earthquake of 1950. The epicentre of the Shillong earthquake is not at the northern trench of the Indian plate.

TENG et al. [1987] have pointed out that an arcuate structure is formed only in the crustal layer. However, sixty-six years of seismicity data of large earthquakes indicate the arcuate structure to extend to about 150 km. The distribution of seismicity along the Burmese arc shows maximum width at 24 °N. The seismicity along AB and BC strikes north-south and northeast-southwest, respectively. The northeast drifting of the Indian plate cannot be the cause of the subduction of zone BC towards the southeast.

The fault plane solution of intermediate focal depth micro-earthquake studies for the Shillong plateau shows a northeast-southwest sriking fault dipping towards the southeast [KAYAL 1987]. This cannot be explained by northeast drifting of the Indian plate and hence supports the seismic activity as being due to the southeast flow of the Tibetan plateau.

6. Earthquakes and tectonics of the arc

The earthquake distribution of the arc is of peculiar nature. The frequency and average focal depth distribution for the earthquakes of the zone are shown in *Fig. 6a–b*. Similar observations are also taken for the average focal depth of the region. The tectonic nature of the zone shows peculiar character [VERMA, KUMAR 1987]. The nature of the faults and direction of stresses show different orientations. For shallow earthquakes, the compressive stresses are characterized by shallow dipping and are directed towards the Burmese region [FITCH 1970, RASTOGI et al. 1973]. Here fault plane solutions for eleven events have been considered, including six new mechanisms. Fault plane solutions for five events have been taken from MUKHOPADHYAY, DASGUPTA [1988] and LE DAIN et al. [1984]. Of the eleven solutions four show normal, four thrust, and three strike-slip faulting. The above solution reveal both extensional and compressive forces, focal mechanisms 1, 4, D and E reveal normal faulting which may be interpreted as bending of the lithosphere into the upper mantle due to the southeast flow of the Tibetan plateau. This also reflects that the sinking of the dipping lithosphere in the arc is still continuing. Events 3, 5, 6 and A show thrust faulting. In these cases the faultings are almost perpendicular

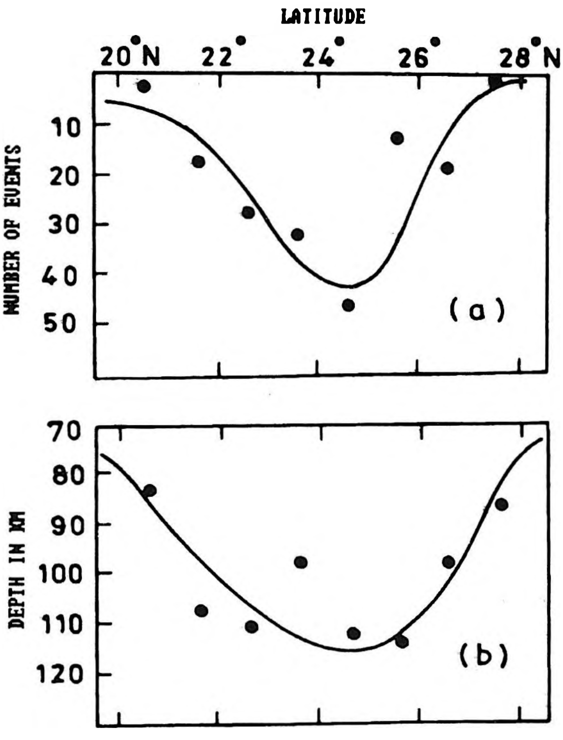

Fig. 6. a—Variation of frequency with latitude for the region 20 °N to 28 °N and 92 °E to 97 °E, based on 25-years (1960-1984) seismicity data as reported by the National Geophysical Data Centre. The considered region includes an arc-shaped zone; b—Average focal depth variation with latitude for the considered zone

6. ábra. a — A gyakoriság változásai a földrajzi szélességgel a 20 °É - 28 °É és a 92 °K és 97 ° K tartományban, a 25 éves (1960-1994) szeizmicitás adatok alapján, a Nemzeti Geofizikai adatközpont jelentéseiből. A vizsgált terület egy ív-alakú zónát is tartalmaz; b — Átlagos fókuszmélység változás a földrajzi szélességgel a vizsgált zónában

to the strike of the seismically active zone. The direction of stresses acting in thrust and strike-slip faultings (2, B and C) is along the strike of the arc.

7. Discussion

Several scientists have studied the seismicity of the Burmese arc and its adjoining areas [SANTO 1969, LE DAIN et al. 1984, MUKHOPADHYAY, DASGUPTA 1988]. The Benioff zone showing intermediate earthquakes along the Burmese region has been reported to strike north-south (from 21 °N to 24 °N) and northeast-southwest (from 24 °N to 27 °N). The tectonics and seismicity of the Burmese arc have been explained by northeast drifting of the Indian plate. The present nature of the arc-shaped zone cannot be explained by northeast drifting of the Indian plate as it cannot explain arcuate subduction. At the same time the distribution of intermediate earthquakes, the 100 km width of seismicity around 24 °N which reduces on either side, the earthquake frequency, the focal depth distribution, and the nature of forces acting along the arc cannot be explained by collision of the Indian and Burmese plates. The above observations may be explained in the light of bending of the eastern plate margin due to the southeast flow of the Tibetan plateau.

MOLNÁR et al. [1981] and MOLNÁR, CHEN [1983] revealed the extensional tectonics of the Tibetan plateau. MOLNÁR, TAPPONNIER [1975] showed the southeast-south flow of the block along the Kang-Ting fault. MOLNÁR et al. [1987] reported the drift rate of the Indian plate and the slip rate of the plateau to be of the same order. The crustal thickness of the Tibetan plateau, and the Indian and Burmese plates are, respectively, 60-70 km, 35-45 km and 30-35 km [SHIH et al. 1979]. The Tibetan plateau is very large in comparison to northeast India (Fig. 3), therefore its southeast extension with the rate of 18±7 mm/year [MOLNÁR et al. 1987] would produce considerable effect in the seismicity pattern of the region. As the subduction is not observed along the plateau-Himalayas boundary, it would push northaest India (e.g. events EDB) and would make it rotate clockwise causing the bending of the eastern margin at B down to the upper mantle. The lateral movement of the Shillong plateau along the Dauki fault was reported by EVANS [1964] to form a gap — known as the Garo-Raj Mahal gap.

A schematic diagram explaining the distribution of seismic activity and the stressess in the arc zone is shown in *Fig. 7a–c*. Figure 7a shows the northern and eastern boundaries of the zone, the direction of movement of the Indian plate, and the southeast flow of the Tibetan plateau. Owing to the southeast flow of the 70 km thick Tibetan plateau, boundary E-D would become concave towards the Indian plate. It would push the E-D-B zone (rotating clockwise) giving rise to the arc-shape at the eastern boundary (Fig. 7b). In doing so the zone of the eastern boundary, i.e. A-B-C-A, would be compressed and buckle down to the upper mantle showing strike of zone B-C along northeast-southwest. Bending would cause the maximum width of seismicity to take place at B with decreasing trend on either sides. Zone A-B is virtually undisturbed whereas C has shifted from southeast to the present position changing the strike of B-C from north-south to northeast-southwest. Since the drifting of the Indian plate and extension of the plateau have been continuing throughout the geologic past, the subduction of zone A-C would take place showing maximum frequency and average focal depth around B. Bending would generate compressive stress along the strike of the seismicity zone A-B and B-C. The stresses thus developed may be responsible for thrust faulting perpendicular to the strike of the seismic zone and strike-slip faultings causing right-lateral motion (solutions 2, 3, 5, 6, A, B and C; VERMA, KUMAR [1987]). The drifting of the Burma plate towards the west has also played a role in the development of the folded mountain chain of the arc zone. Though the tectonic nature and seismicity distribution are very complex and are the results of the converging pattern of the surrounding plates, the nature of orientation of subduction, frequency and average focal depth distribution and stress acting in the arc are due to the extension of the Tibetan plateau towards the southeast. The present study thus offers a new means of understanding the nature of seismicity and the tectonic pattern in the arc zone.

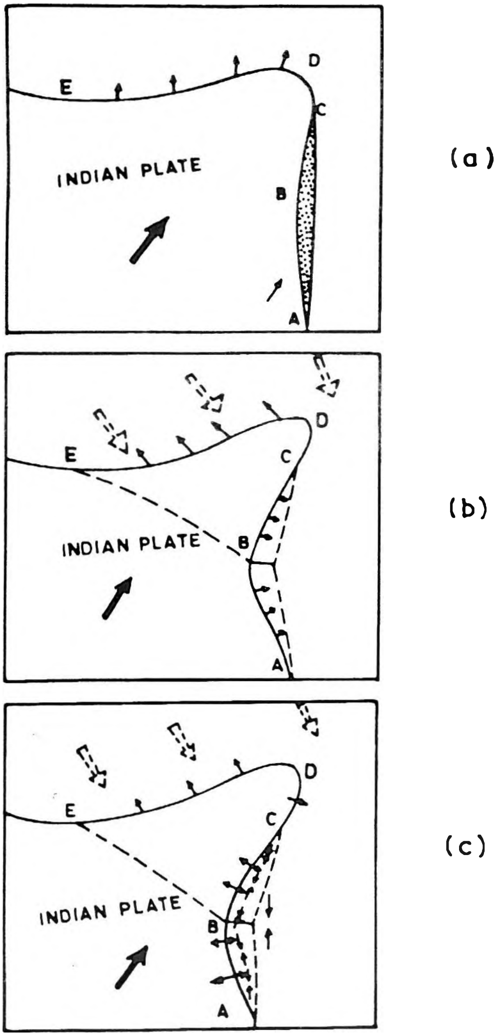

Fig. 7. Proposed model for the development of the Burmese arc zone. (a) demonstrates the stresses acting at the northern boundary of the Indian plate; (b) exhibits the southeast flow of the Tibetan plateau and its effect on the eastern boundary of the Indian plate; (c) illustrates the direction of stress, distribution of seismicity in the arc zone

7. ábra. A Burmai-ív kialakulására javasolt modell (a) bemutatja az Indiai-lemez északi határán működő feszültségeket; (b) a Tibeti-fennsík délkeleti áramlását, és annak hatását az Indiai-lemez keleti határára; (c) a feszültség irányait és a szeizmicitás eloszlását az ívelt zónában

8. Conclusions

The following conclusions have been drawn:

1. The compressive stresses acting along the strike of the Burmese arc are the result of the pushing of the northest India region by the southeast flow of the Tibetan plateau.
2. Normal faultings are also observed in the arcuate zone, which suggests that subduction of the lithosphere is still continuing.

3. The intermediate focal depth earthquakes and the present shape of the seismically active arc zone are the result of the southeast flow of the Tibetan plateau. This flow is also responsible for the frequency and focal depth distribution of the events.

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A TIBETI-FENNSÍK ELTOLÓDÁSA ÉS TEKTONIKÁJA A BURMAI-ÍV MENTÉN

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Északkelet-India és környékének (18°É és 84°K-tól 100°K-ig) szeizmicitása nagyon összetett. Magában foglalja a himalájai áttolódást, a Burmai-régiót és a Tibeti-fennsík kisebb hányadát. A földrengések nagymértékű szóródását mutatja és a föld egyik legfontosabb tektonikai jellegzetességét alkotja. Beszámoltak arról, hogy az Indiai-lemez északkeleti eltolódási sebessége és a Tibeti-fennsík délkeleti irányú eltolódása azonos nagyságrendű, azaz 18±7 mm/év. Így a Tibeti-fennsík eltolódásának hatása a szeizmicitás eloszlására — a lényegesen nagyobb kéregvastagság miatt — az Indiai- és Burmai-lemezek, valamint a Tibeti-fennsík találkozási zónájában nagyobb lenne, mint magukon az Indiai- és Burmai-lemezeken. Általában az egész területen sekély földrengéseket észlelnek, kivéve a Burmai-ívet, ahol közepes földrengések jelennek meg 200 km mélységig. Az ívszerű szeizmicitás szélessége maximum 24°É körüli, és mindkét oldalán csökken, befejeződik 21°É és 27°É-nál. A vető sík megoldások azt sugallják, hogy a kompresszív feszültségek az ív csapása mentén is hatnak; extenzionális feszültségeket is megfigyeltek. A cikkben egy modellt mutatunk be, hogy megmagyarázzuk a szeizmicitást, a fókuszmélységet, a frekvencia és feszültség eloszlást az ív zónájában, figyelembe véve a Tibeti-fennsík délkelet irányú eltolódását is.