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Regional plate tectonics from Himalayan earthquakes and their prediction

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ABSTRACT. Regional plate tectonics provides a broad basis for assessing the magnitude of earthquakes, besides understanding the orientation of stresses producing such earthquakes. Keeping this in view, reliable focal mechanism solutions obtained during 1972 to 1975 in the Himalayan region have been discussed. Four radial vertical sections showing the depth plot of earthquakes near the northern boundary of Indian plate were drawn based on the data during the years 1964-1974 but no clear dipping of the Indian plate could be seen. In the mechanism solutions except for Kinnaur (1975) and Assam (1950) earthquakes, thrusting was observed near the foothills. The pressures are generally acting at right angles to the mountains and the slip vectors also show a northerly trend. An earthquake located near Burma border, however, showed normal faulting and needs further explanation. However, the present movements of the Indian plate and their inferred changes show that northeast India will continue to be highly seismic.

1. Introduction

Active seismicity in Himalayas and northeast India is attributed to the collision of Indian and and Eurasian plates. The initial contact between these plates is believed to have occurred in late Palaeocene time approximately 55 m.year ago. Plate motion resumed or accelerated in a slightly different direction in early Oligocene time, approximately 35 m.year ago with India converging towards Asia in a more northerly direction. These results were mainly derived on the basis of survey of magnetic anomalies over Indian Ocean as well as geological data in and around the Himalayas (Powell and Conaghan 1973). During Oligocene and early Miocene time, however, sediments now found in the sub-Himalayan ranges consisted of Murrees derived predominantly from continental India in the south. Himalayas started forming by middle to late Miocene time. Present movement of the Indian plate is northeasterly at the rate of about 5 cm per year.

Several seismological investigations have been carried out in India and elsewhere to study the complex pattern of seismicity in this zone of continental type of collision. A critical evaluation of the fault plane solutions in the light of regional plate tectonics has raised several problems, for example, the occurrence of normal as well as thrust faulting along the Himalayan-Burmese-Andaman regions and the predominance of strike slip movements for some earthquakes (Ichikawa *et al.* 1972, Srivastava 1973, Chaudhury *et al.* 1974, Tandon and Srivastava 1975, Chaudhury and Srivastava 1976, Chaudhury and Srivastava 1977).

In this paper the vertical cross-sections of earthquakes occurring in the vicinity of the boundary of Indian and Eurasian plates have been examined and some newly determined fault plane solutions have been discussed in the light of regional plate tectonics.

2. Analysis of data

For the study, the data on earthquake foci for the period 1964-1974 as published in the Bulletins of the I.S.C. were utilised. As the Himalayan mountain chain is arcuate with its concavity northwards, four radial cross-sections across the foothills were chosen and the earthquakes occurring near these sections were projected on to them.

Fault plane solutions of earthquakes in the region have been worked out by various authors using data from different sources. Some workers have worked them out exclusively on the basis of data available in the Bulletins of the I.S.C. (Ichikawa *et al.* 1972, Rastogi *et al.* 1973). Molnar and his co-workers (1973, 1975) have worked out solutions by using *P*-wave first motion data read only from long period instruments. While reducing the inconsistencies in observations, this also reduces the quantity of data due to the smaller number of long-period seismographs. Due to this some workers have supplemented the long period seismograph data with those from short-period seismographs as well (Fitch 1970). In

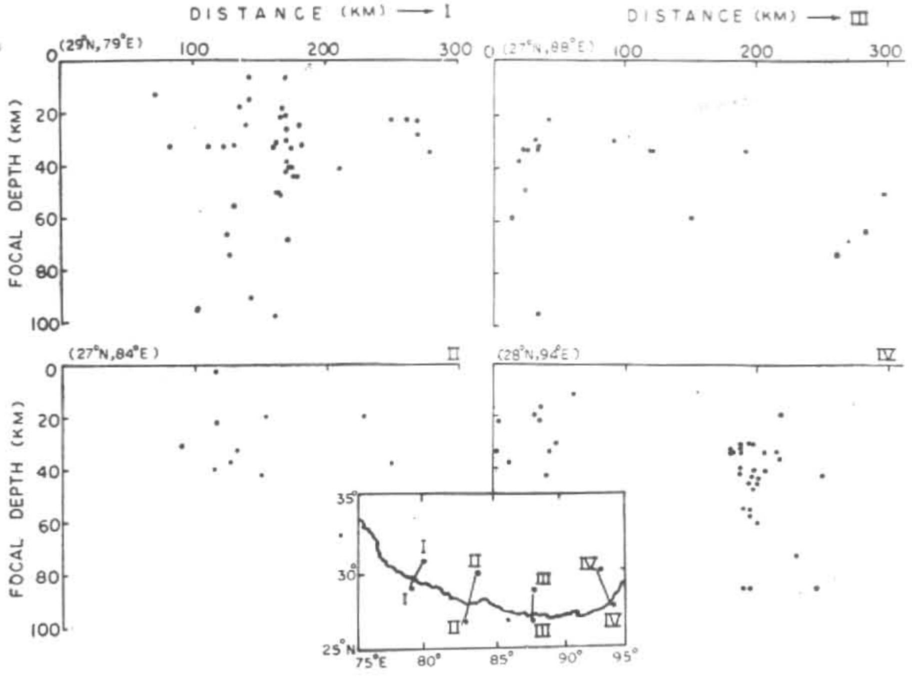

Fig. 1. Radial cross-sections along four vertical planes in the Himalayan arc. Inset shows the planes across which epicentres have been projected within ± 1°.

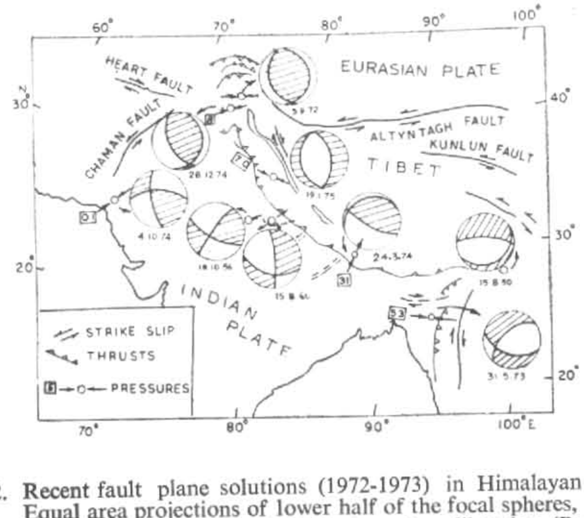

Fig. 2. Recent fault plane solutions (1972-1973) in Himalayan region. Equal area projections of lower half of the focal spheres, shaded region denotes compression, blank region dilatation (Base map by Molnar and Tapponier 1975).

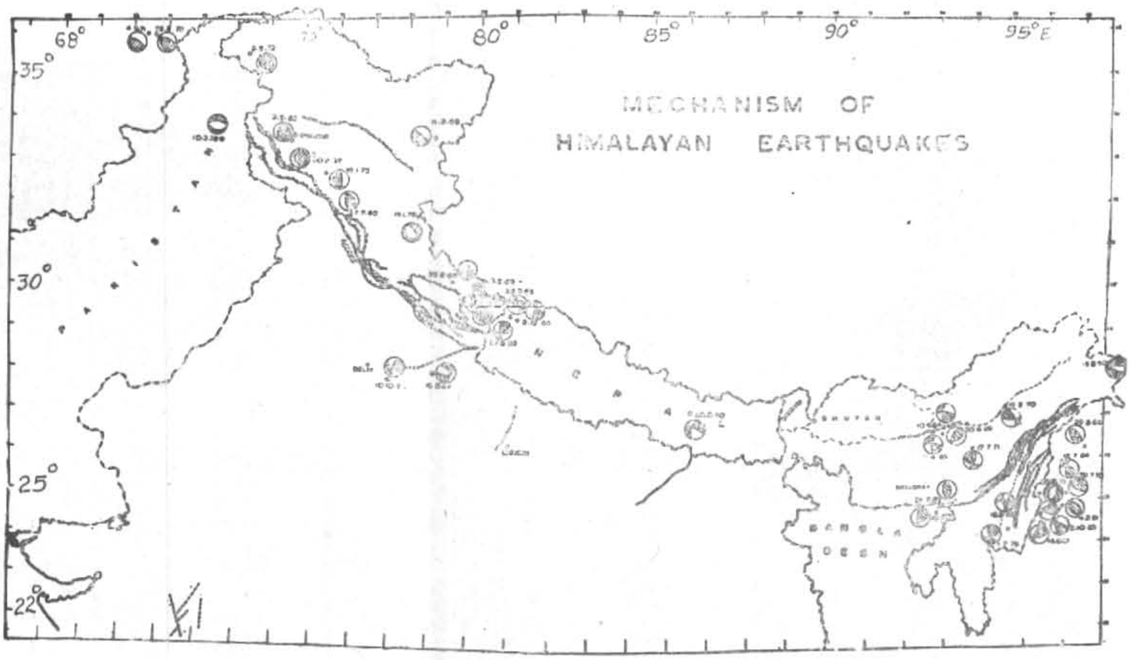

Fig. 3. Fault plane solutions determined by India Meteorological Department (1950—1972)

relation to the Himalayan foothills, near distance observations such as are provided by the Indian seismic network play an important role in the study of focal mechanism. Nonavailability of these data—many stations are for special studies and their data are not included in routine bulletins—is a handicap in the reliable determination of the fault plane soultions. In the studies by the authors, therefore, attempts have been made to use all available data from the Indian network through scrutiny of the original charts in addition to those from the bulletins of I.S.C. and data sheets from U.S.G.S. and Moscow and the data obtained through requests to individual stations. Suitable weightage was also given while working out the solutions to the quality of the reported data or records (Chaudhury *et al.* 1974, Tandon and Srivastava 1975, Chaudhury and Srivastava 1974, 1976).

3. Results and discussion

Fig. 1 shows the radial cross-section in four zones in the Himalayan arc. It may be noticed that dipping of the Indian plate is not reflected from these cross-sections (as also reported by Chaudhury *et al.* 1974 based on data during the year 1964-1969) although Kaila and Narain (1976) inferred from ten such profiles that the seismic planes in the Himalayan region dip at angles ranging from 30° to 60°. Seismicity in the zones of continental collision is generally considered diffuse (Dewey and Bird 1970).

Fig. 2 shows the fault plane solutions of some recent earthquakes (1972-1974) in the Himalayan region plotted on lower half of the focal sphere while Fig. 3 shows the fault plane solutions as determined by India Meteorological Department. The shaded region includes compressions while the blank region shows rarefactions.

The recent damaging earthquakes near Gilgit (1972), Pattan (1974) and Kinnaur (1975) provided valuable data for determining fault plane solutions. The results are given in Table 1. Fault plane solutions of the great Assam earthquake (1950) and two other earthquakes within the Indian plate near Bulandshahar and Moradabad reported by Tandon (1955,1975) have also been shown in Fig. 2. The pressures deduced at the foci are shown by arrows in the figures and dip angles are shown within squares.

It is interesting to note that the pressures are acting at right angles to the Himalayan front and are shallow dipping. The slip vectors as revealed from the earthquakes of September 1972, March 1974 and December 1974 show a northerly trend if the nodal planes dipping towards north are assumed as the fault planes. These three earthquakes show thrust faulting in the region. Earthquakes of August 1950 (Assam), January 1975 (Kinnaur) and May 1973 (Burma border) however, show normal faulting. Ichikawa *et al.* (1972), Srivastava (1973), Chaudhury *et al.* (1974) Tandon and Srivastava (1975), Chaudhury and

TABLE 1

New fault plane solutions

Date	Epicentre Lat. (°N)	Epicentre Long. (°E)	Origin time (GMT) h	m	s	Focal depth (km)	Nodal planes Dip. I Direction	Dip. I Angle	Dip II Direction	Dip II Angle	Pressure Az.	Pressure Dip. angle	T Az.	T Dip angle	Remarks
3 Sep 72	36·0	73·4	16	51	03	45	069	56	230	35	252	08	020	70	Dip slip, thrust
31 May 73	24·3	93·5	23	39	52	1	196	48	313	66	087	53	336	10	Normal
24 Mar 74	27·7	86·0	14	16	01	20	336	19	203	77	182	31	032	58	Thrust, strike slip
4 Oct 74	26·4	66·7	22	24	33	32	240	68	342	63	203	0	110	37	Thrust, strike slip
28 Dec 74	35·1	72·9	12	11	47	45	218	56	077	30	338	08	037	43	Thrust, strike slip
19 Jan 74	32·4	78·5	08	01	58	1	240	36	073	55	090	89	070	10	Normal

Srivastava (1976) and Banghar (1974) and others have also found normal as well as thrust faulting within the Indian plate, along the plate boundary as well as in the wide zone of deformation. The event of May 1973 near the Burma border is interesting. If the northeasterly oriented nodal plane is chosen as the fault plane, the dip is found to be opposite to that postulated by the geologists for the faults in the Manipur-Burma region, but the motion is right lateral strike slip as anticipated along this plate boundary. The pressures are acting generally at right angles to the mountain ranges and rather steeply dipping.

In the event of October 1974 in Pakistan neither of the nodal plane appears to agree with the trend of the mountain ranges. However, if the one dipping towards the north is taken as the fault plane, the resulting motion would be left-lateral strike-slip with some thrusting. The slip vector also comes out to be northeasterly. These fit well with the observed features along the faults in this region (Nowroozi 1972).

Event of August 1950 in Assam showed normal faulting on an east-west striking plane dipping to the north at an angle of 75° (Tandon 1955). Using Rayleigh to love wave amplitude ratios, Ben Menahem *et al.* (1974) concluded that a fault striking N 26° W and dipping 60° E with nearly pure strike-slip motion is compatible with all the above observations, as well as with first motion of P waves reported in the ISS, the aftershock distribution, and macroseismic effects. This new solution was attributed to the reporting of New Delhi, Pune and Helwan as compressions in the ISS instead of dilatations used by Tandon who examined the Indian seismograms very carefully. The large spread of aftershocks as determined by Tandon (1955) implied that multiple faults were associated wih the event. This was also the reason why its aftershocks were not included in the magnitude-aftershock relationships as given by Tandon and Srivastava (1975). Cheng and Molnar (1977) redetermined these aftershocks which lay in a zone approximately 250 km long and 100 km wide. Cheng and Molnar have fitted a low angle north dipping thrust to Ben Menaham *et al.*'s data. This solution of theirs agrees with the general plate tectonic movements accepted for the Indian plate. They, therefore, conclude that the Assam earthquake was a complex one comprising of movments on faults of thrust type as well as strike slip motion. In an earlier paper by Molnar *et al.* (1973), Tandon's solution (normal fault) for this earthquake was explained as resulting from a stretching of the region northeast of the corner of the plate. The different and somewhat conflicting interpretations only show that the process is not well understood. According to Tatham *et al.* (1976), the complexity of the area is reflected in the fault plane solutions which do not show consistent pattern of orientation of slip vectors or stress axes. One of the possible explanations of this is the existence of very small plates or blocks along large scale plate boundaries which may have large components of rotational as well as translational motion and hence, the pattern of focal mechanism of earthquakes occurring at the boundaries may be quite complex, varying drastically over short distances.

Fault plane solutions of two earthquakes near Moradabad (1966) and Bulandshahar (1956) are also of special significance. The earthquake near Moradabad is of normal, strike slip type, striking N 343° E and dipping towards N 83° E at an angle of 70° which agrees with the direction of Moradabad fault as given by the Oil and Natural Gas Commission (Tandon 1975). On the other hand, the Bulandshahar earthquake shows thrust faulting with strike slip movement striking N 20° E and dipping N 290° E at an angle of 79°. This agrees with the trend of the Aravali below the alluvium in the Gangetic plains. Molnar *et al.* (1973), however, interpreted the solution of Moradabad earthquake as representing the bending of the Indian plate from this place. This is an interesting observation and the bending is expected to extend to other regions south of the Himalayan foothills. There have, however, been no significant earthquakes to give confirmation to this; the Bulandshahar earthquake being explained as due to movements across the Aravalis (Tandon 1975).

4. Intraplate tectonics

Seismicitiy within the Indian plate assumed more importance after the occurrence of recent earthquakes in the Peninsula (Koyna 1967, 1973.; Bhadrachalam 1969, Broach 1970; Bay of Bengal 1972, 1973). It may be remarkable to note that the tear faults in the foothills of Himalayas namely Moradabad, Lucknow, Patna and Dhubri faults are oriented roughly along the direction of movement of the Indian plate (as given in ONGC/GSI tectonic maps). Valdiya (1973) has also found a number of transverse lineaments in the Himalayan foothills. In order to understand the mechanism of formation of such tear faults near the continent type of plate boundaries, it may be significant to conduct a few model experiments. This is suggested so that future developments of such faults near the foothills may be anticipated.

On the basis of focal mechanism solutions of two recent Bay of Bengal earthquakes, Chaudhury and Srivastava (1974) have found evidence of a new thrust fault oriented along the direction of motion of the plate with left lateral strike slip movement. The focal mechanism of Koyna (1968) and Bhadrachalam (1970) earthquakes, and the Bay of Bengal earthquakes, show that the motions within the plate are generally oriented along the direction of the movement of the plate. Subsequently, a similar suggestion was made by Chandra (1977) that the orientation of the zones of weakness with respect to the ambient stress field may be an important factor in determining the faults along which earthquakes are likely to occur.

5. Plausible motion of the Indian plate in future

During late cretaceous time, approximately 75 million years (m.y.) ago, direction of sea floor spreading changed to become approximately north-south, parallel to the present Ninety East Ridge. This northerly movement of the Indian plate changed to northeasterly about 35 m.y. ago. The present tectonics in the Andaman Islands suggests compression in easterly direction. The epicentral distribution in this region is suggestive of the dipping of the Indian plate in the same direction. the dip angle increasing with the decrease of the latitude towards Nicobar Islands (Srivastava and Chaudhury 1978). A few fault plane solutions in the region do indicate right lateral strike slip motion from Andaman Islands to the Burmese region. On the other hand, the northern boundary of the Indian plate across the foothills of Himalayas generally indicates thrusting with varying amounts of strike slip movements.

North of the Himalayan Tibet region major eastwest trending left lateral strike slip faults have been recognised by Tapponnier and Molnar(1976). Movement on these faults appears to displace much of the converging Indian and Eurasian subcontinents. It is thus possible that the resistance to the Indian plate in Himalayas coupled with relative easier subduction in the Andaman Islands region as revealed by the depth-distance epicentre cross-sections (Srivastava and Chaudhruy 1978) may eventually allow a more easterly movement of the Indian plate than what is existing at present, resulting in increased strike slip movements near the northern boundary of the Indian plate. And because of the present northeasterly trend of the Indian plate movements coupled with the thrusting in the Himalayan-Burmese sector, the northeastern region will continue to be the source of damaging earthquakes.

6. Conclusions

The above study brings out the following:

(1) From the radial cross-sections based on the data during the year 1964-1974, the dipping of the Indian plate is not clearly brought out.

(2) Except for Kinnaur (1975) and Assam (1950) earthquakes, focal mechanism of recent earthquakes near Himalayan foothills has shown thrusting. The earthquake near Burmese border (1973) has shown normal faulting which needs further explanation. The pressures are generally acting at right angles to the faults and slip vectors show a northerly trend.

(3) The present movements of the Indian plate and their inferred changes show that northeast India will continue to be highly seismic.

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