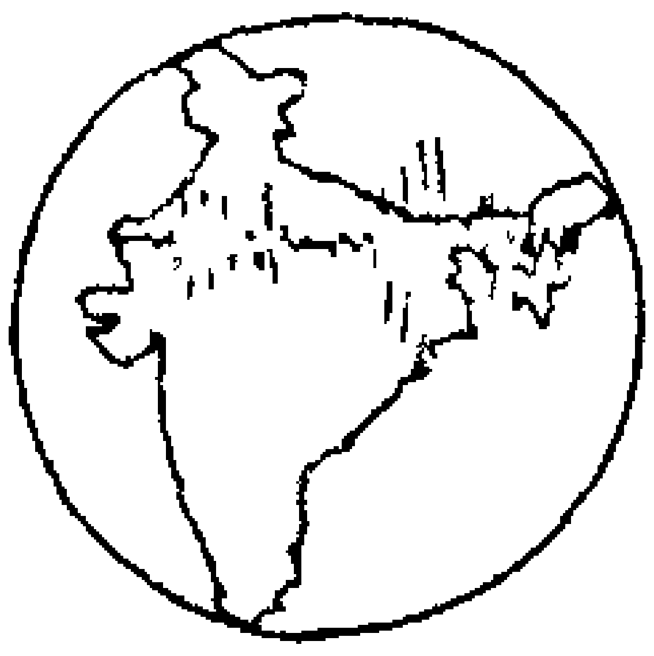

STATE OF STRESS IN THE INDIAN SUBCONTINENT: A REVIEW

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ABSTRACT–*The state of tectonic stress in the Indian subcontinent and the Burmese–Andaman–Nicobar arc regions inferred from focal mechanisms is presented in this paper. The directions of maximum and minimum horizontal compressions, S (Hmax) and S(hmin) in three major provinces – the Himalaya, Peninsular India and the Andaman–Nicobar regions–are reviewed. On the basis of changes of variations in stress orientations, several stress regimes were identified.*

In the Himalaya, these include the Quetta syntaxis and eastern Afghanistan, Hindu Kush, Frontal arc, Assam syntaxis, Shillong and Tibetan plateau. In the Andaman–Nicobar arc region, three blocks–the Andaman–Nicobar arc, Andaman Spreading Ridge and Sumatra trench–were identified. The orientation of S (Hmax) along the Himalaya varied from NNW-SSE in the Quetta and Afghanistan region to N-S and NNE-SSWalong the Himalayan frontal arc, NE-SW in Assam syntaxis and to nearly E-W in the Burmese Arakan Yoma arc. Further south, in the Andaman–Nicobar arc, S (Hmax) showed a N-S to NNE-SSW trend. In Peninsular India, however, S (Hmax) showed uniform orientation in the N-S to NNE-SSW direction. For Peninsular India, the data were too scanty to divide into stress provinces. The mean directions of maximum and minimum horizontal stresses were used to derive a generalized stress map of the Indian subcontinent and the Andaman–Nicobar arc regions.

INTRODUCTION

State of tectonic stress in interplate regions can be remarkably different from those in continental interiors. Intercontinental collision and convergence at plate boundaries generate highly heterogeneous stress fields over interplate regions whereas stresses over stable plates are expected to be fairly uniform. These arguments are consistent with well-documented data on the global stress field (Zoback *et al.*[1]). Proximity to a collision zone can however influence the stress field in the plate interiors.

State of stress in the Indian subcontinent and its vicinity provides an excellent example of the complex nature of stress field following intercontinental collision. In the Himalayan collision zone, the stress orientation reflects deformation at the plate boundary. In the shield areas the pattern of stresses generally reflect the plate motion and convergence. To understand the state of stress in the Indian subcontinent, we studied three major regions shown in figure 1. These are:

- The Himalaya
- The Peninsular India
- The Andaman-Nicobar arc region.

The broad region under the Himalaya included the arcuate trending mountain ranges bounded by Sulaiman and Kirthar ranges to the west; Hindukush ranges to the northwest and Tibetan plateau to the north. To the east, Himalaya is bordered by the Arakan Burma ranges. Peninsular India is the region south of the Ganga basin. Andaman-Nicobar ridge system forms the southward continuation of the Arakan-Burma arc and forms the boundary between the Indian and Eurasian plate in the east.

Three hundred and seventeen published focal mechanisms were used to derive the state of stress in the Indian subcontinent. One hundred and ten of these were from the Andaman-Nicobar region, presented by Rajendran and Gupta[2]. Only seven focal mechanisms were available for Peninsular India. The rest were

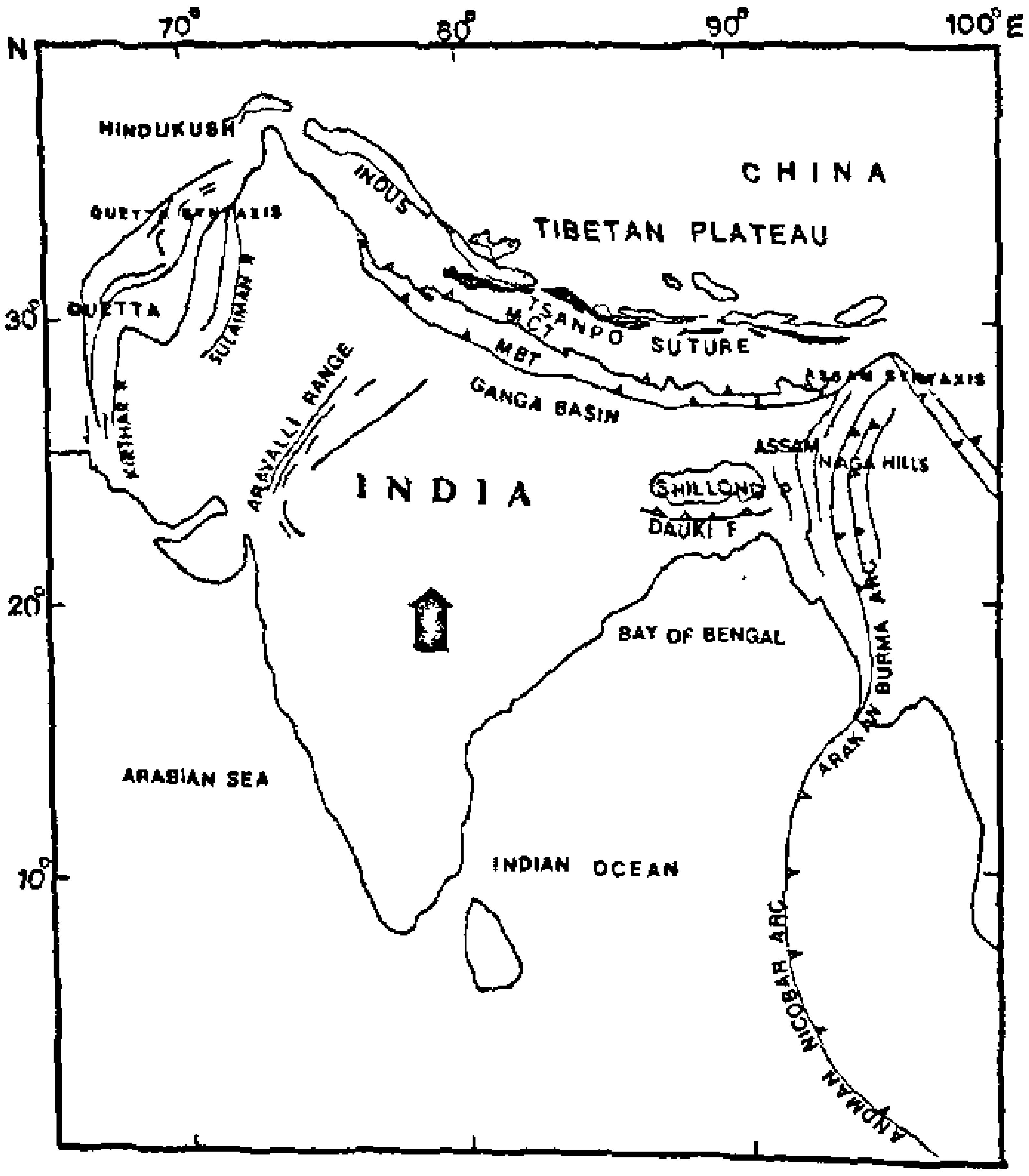

FIGURE 1. Map of the Himalaya, Peninsular India and Andaman–Nicobar arc regions showing the major tectonic features (tectonic features after Gansser; Molnar and Tapponnier[7]; Chandra[10]).

from the Himalaya. Orientations of maximum and minimum horizontal stresses S (Hman) and S (hmin) were derived from focal mechanisms giving appropriate weightage to their quality. Quality criteria followed by us and the limitations of deriving stress orientations from focal mechanisms are discussed in Rajendran and Gupta[2] and Rajendran *et al.*,[3]. Only the results are presented in this paper.

EARTHQUAKE DATA BASE FOR THE INDIAN SUBCONTINENT

The Himalaya

Seismicity and tectonics of the Himalaya have been examined by several workers (Dewey and Bird[4]; Powell and Conaghan[5]; Rastogi[6]; Molnar and Tapponnier[7]; Tandon and Srivastava[8]; Verma *et al.*[9]; Chandra[10,11]; Seeber *et al.*[12]; Khattri and Tyagi[13]; Khattri *et al.*[14], Ni and Barazangi[15]; Baranowski *et al.*[16]; Molnar[17]; Tapponnier *et al.*[18]; and Windley[19], among others. Earthquake focal mechanisms have also been published by Rastogi *et al.*[20], Tandon and Srivastava[8], Verma *et al.*[21,9] (1976, 1978) Chandra[10], Singh and Gupta [22], Gupta and Rajendran[23], Molnar and Chen[24], Valdiya[25], Ni and Barazangi[15], Verma and Kumar[26], and several publications of Dziewonski *et al.*[27]. The focal mechanism data used in this paper were compiled from various publications, some of which are listed above. The complete data base was presented by Rajendran *et al.*[3].

In this study, the focal mechanisms of earthquakes shallower than 70 km were treated separately from those that were deeper. The cut off depth of 70 km was chosen for two reasons:

- It is the average crustal thickness in the Himalaya (Gupta and Narain[28]; Hirn *et al.*[29]).
- The frontal arc is characterized by shallow earthquakes, with a maximum depth of about 50 km. Considering the possible erros in hypocentral depths and also the changes in crustal thickness, a depth of 70 km was considered to be a suitable lower boundary for the study.

Focal mechanisms for these two depth levels are presented in figures 2a and 2b.

Peninsular India

A region of low seismicity, Peninsular India was sparsely instrumented until the Koyna earthquake of 1967. Historically some large earthquakes have occurred in this region (Rao and Rao[30]), but there are only few earthquakes for which focal mechanisms are available. The seven focal mechanims used in this study are from Gupta *et al.*[31], Chandra[32], and Johnston and Metzger[33]. The focal depths were poorly constrained due to lack of local stations. The depths for two events were greater than 30 km, and for three between 10 and 20 km and the remaining were shallower than 10 km. Three of these events were associated with thrust faulting, one with strike slip faulting and the rest with a combination of both. One report from well breakout and another from hydrofracture measurements are available for Peninsular India (World Stress Map Data Base). S (Hmax) orientations derived from the focal mechanisms as well as the *in situ* stress measurements are given in figure 3.

Andaman–Nicobar Regions

Earthquake focal mechanisms for the regions have been published by several workers (Fitch[34,35]; Verma *et al.*[9]; Eguchi *et al.*[36]; Dziewonski *et al.*[27]; and Mukhopadhyay[37] among others). Rajendran and Gupta[2] used focal mechanisms of 110 earthquakes (figure 4) to identify three major tectonic blocks and the nature of their stress field. The results of their study are summarized here.

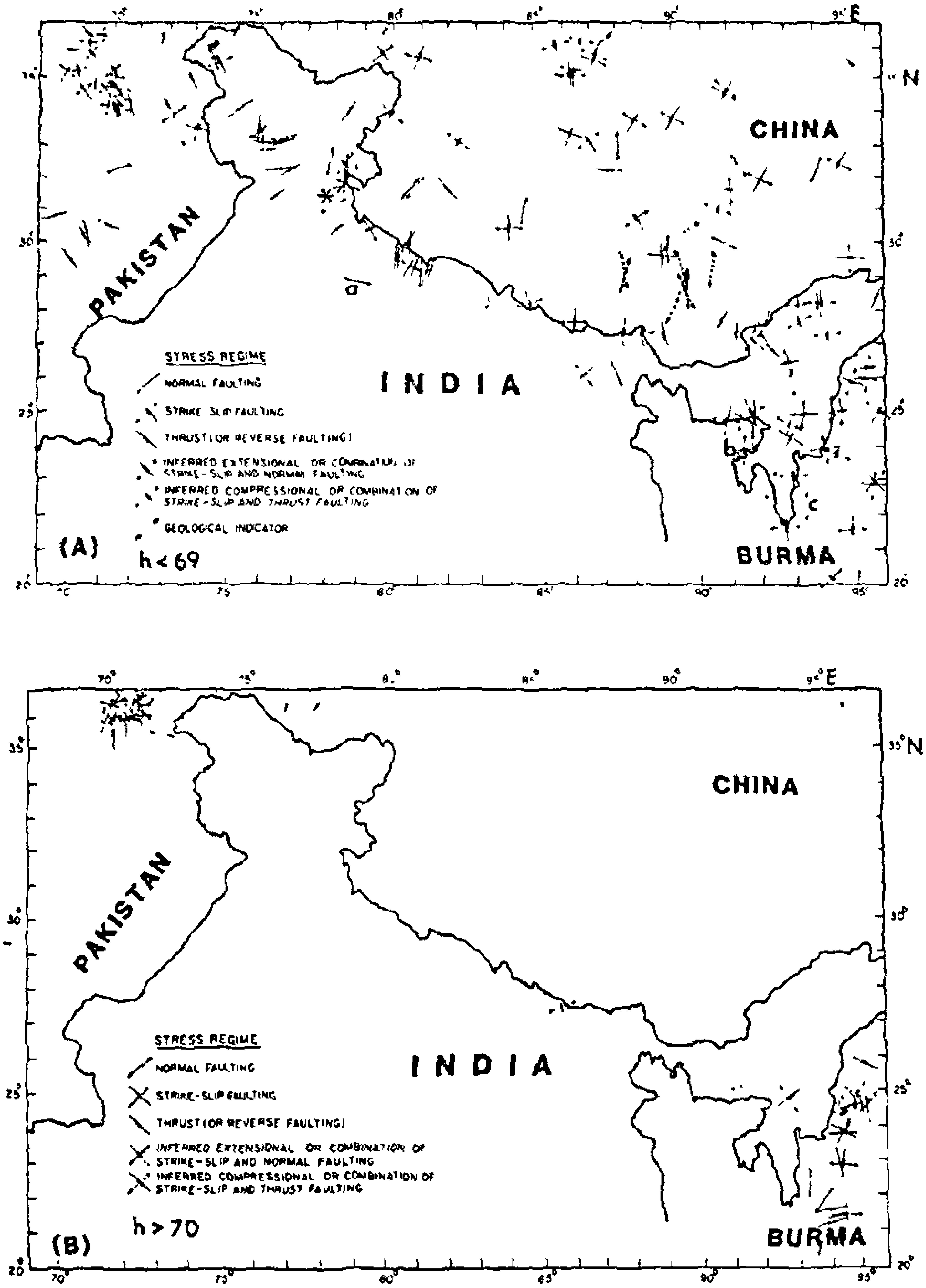

FIGURE 2. (A) Map showing directions of the P- T-axes inferred from focal mechanisms in the Himalaya and vicinity for focal depths ≤ 69 km and (B) for focal depths ≥ 70 km. Orientation of converging arrows for strike slip and thrust faulting and diverging arrows for normal faulting indicate P- and T-axes, respectively.

DISCUSSION

The mean orientations of S (Hmax) or S (hmin) derived from the focal mechanisms have been useful in understanding the broad variations in the orientation of stress field over the Himalaya, Peninsular India and the Burmese–Andaman–Nicobar arc regions.

The direction of S (Hmax) varied from NNW- SSE in eastern Afghanistan to NNE-SSW to N-S in the Himalayan frontal arc and E-W in Burmese Arakan arc (figure 5a). Over the frontal arc, the S (Hmax) orientations were fairly uniform. The changes in S

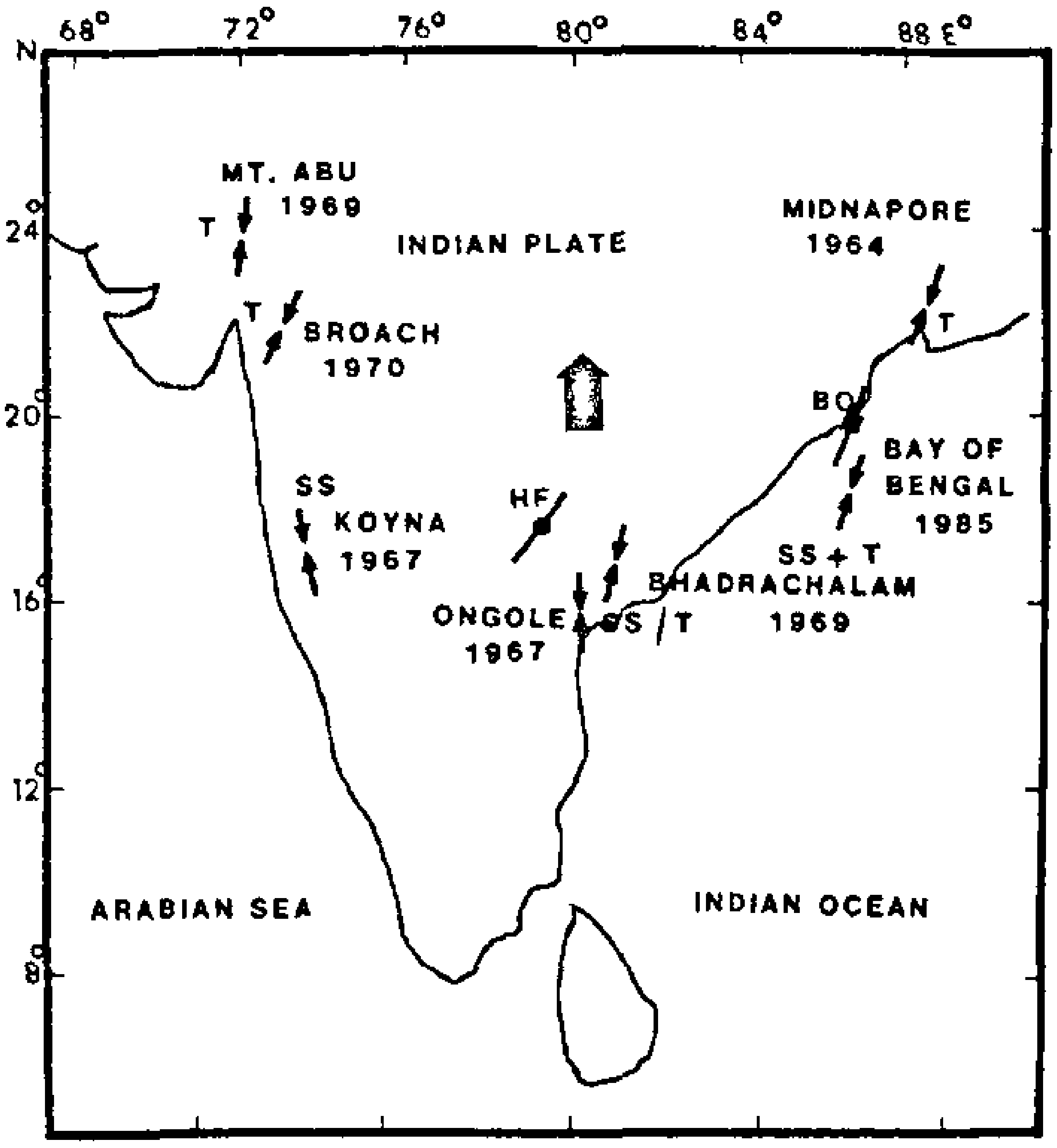

FIGURE 3. Map of Peninsular India showing focal mechanisms, *in situ* stress and well break out data. Converging arrows indicate the direction of P-axes for earthquake focal mechanisms. SS and T indicate strike slip and thrust mechanisms, respectively. Bo and HF indicate locations of well break out and hydrofracture measurements, respectively.

(Hmax) orientations occurred at the western and eastern syntaxis where the deformation is very complex. Variations in S (Hmax) orientations are largely restricted to shallow crustal depths, suggesting crustal deformation following the collision.

At intermediate depths, the inferred S (Hmax) orientations are fairly consistent. On the basis of changes in S (Hmax), some stress provinces in the Himalaya were identified. These are shown in figures 5a and 5b and are discussed in the following sections.

Quetta Syntaxis (QS) and Eastern Afghanistan (EA) Region

The available focal mechanisms in this region suggest thrust faulting along EW or NE striking nodal planes (Quittmeyer and Jacob[38]; Chandra[10]). Isolated occurrences of earthquakes with normal faulting were observed in this region. With T-axes generally perpendicular to the direction of convergence, they suggest zones of possible stretching of the upper crust.

North of Quetta, in eastern Afghanistan, the style of faulting changes from thrust to a combination of strike slip and thrust faulting (figure 5a). Thrusting occurred on NE-SW trending nodal planes by NNW-SSE compression at shallow and intermediate depths. A change in the orientation of S(Hmax) from NNE-SSE to NNE-SSW in the Eastern Afghanistan (figures 5a and 5b) was noticed. In general, the direction of S(Hmax) in the Quetta syntaxis region was oriented NNW-SSE. In the eastern Afghanistan, the same trend was observed at shallow depths but a change to NNE-SSW direction occurred at intermediate depths.

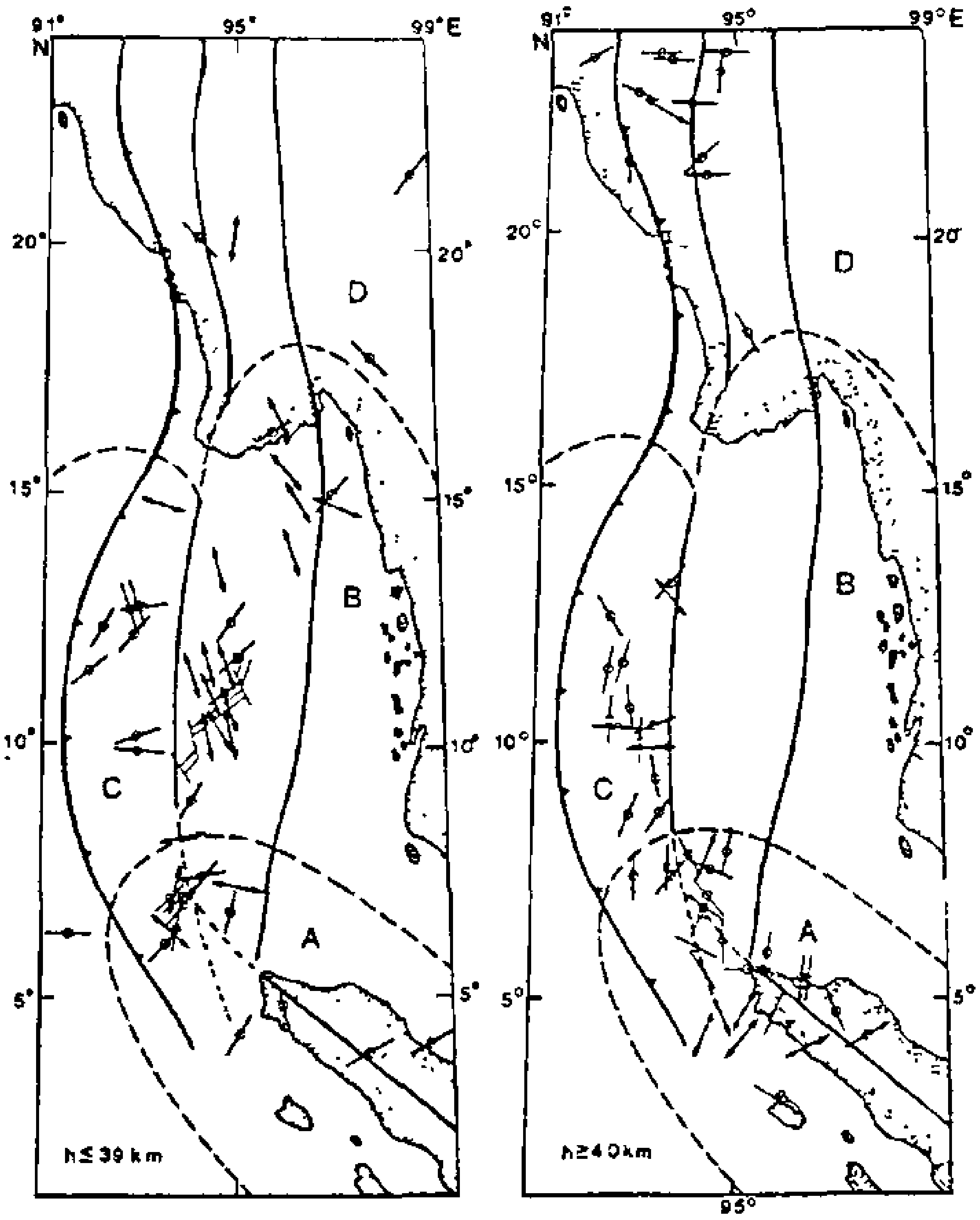

FIGURE 4. Directions of P- and T-axes and type of faulting derived from focal mechanisms with focal depths (a) 39 km and (b) 40 km (From Rajendran and Gupta[2]). Lines with open circle in the centre represent P-axes orientations derived from strike slip of thrust faulting. Lines with capped arrows represent T-axes orientations derived from normal faulting.

Hindu Kush (HK) Region

Several authors have discussed the seismotectonics of the Hindu-Kush region (Nowroozi[39]; Chatelain *et al.*[40]; Chandra[11]; Kaila[41]; Ram and Yadav[42], and others). Most of the activity related to the Hindu Kush region lies further north of the study area and is not discussed here. From the focal mechanisms used in this study, strike slip and thrust faulting were observed to be the dominent style of faulting at shallow as well as intermediate depths (figures 5a and b). The southern part of the Hindu Kush region covered in this study is

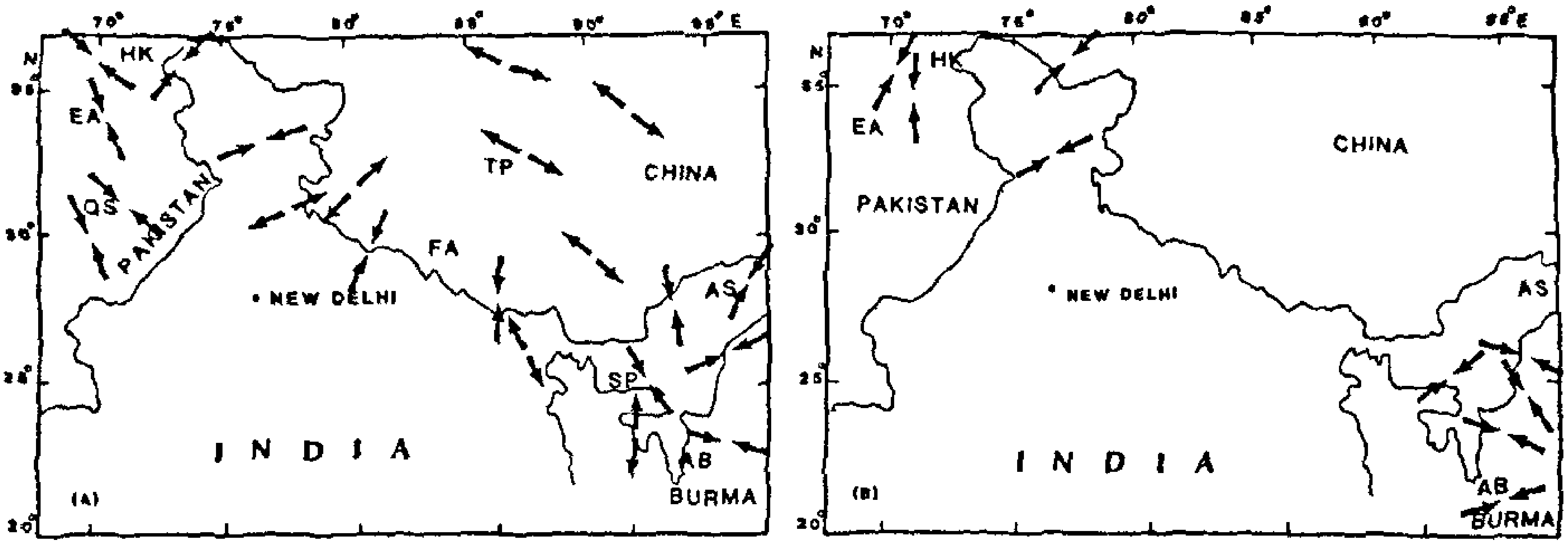

FIGURE 5. S(Hmax orientations and corresponding stress provinces in the Himalaya and vicinity for (A) $h < 69$ km and (B) $h \geq 70$ km. The provinces are discussed in the text and abbreviated as: QS–Quetta Syntaxis; EA–Eastern Afghanistan; HK–Hindu Kush; FA–Frontal Arc; TP–Tibetan Plateau; AB–Arakan Burma Ranges; AS–Assam Syntaxis and SP–Shillong Plateau.

characterized by thrust faulting at shallow depths. There appears to be a progressive deepening of seismicity to the north of 35° N (Chatelain *et al.*[40]). S(Hmax) in this region is oriented in NNE-SSW direction at shallow depths and N-S at intermediate depths (figures 5a and b).

The Frontal Arc (FA)

Focal mechanisms of most of the earthquakes in the frontal arc region reviewed in this paper suggested thrust faulting along it. Few solutions suggesting strike slip faulting were also observed (figure 5a).

Ni and Barazangi[15] reviewed fault plane solutions for this region and suggested that all large earthquakes with thrust faulting mechanisms occurred between the Main Boundary Thrust (MBT) and the Main Central Thrust (MCT). Both nodal planes were parallel to the trend of the arc and the gentler dipping plane was considered as the fault plane. Our results also suggest that along the frontal arc, compression is in the N-S to NNE-SSW direction. A change in this general orientation is noted in the Assam syntaxis region where a few earthquake focal mechanisms suggest NNW-SSE orientation of S(Hmax) (figure 5a).

To the northwest of the frontal arc, a cluster of earthquakes showing normal faulting occur (the region shown by an asterisk in figure 2a). Restricted to shallow depths, generally less than 20 km, the focal mechanisms of these earthquakes suggest T-axes oriented perpendicular to the trend of Himalaya. On the basis of two events and their NE striking nodal planes, Chandra[10] related this extensional feature to the underthrusting of Aravalli ranges (figure 1). More earthquakes showing similar styles of faulting have been reported since then and they are included in this study. A general NE-SW extension is inferred from the S(hmin) orientations (figure 5a). At this point, we have no further evidence to prove the subduction of Aravalli ranges, as suggested by Chandra[10].

Northeastern Himalaya

Tectonics and stress distribution in the northeastern part of the Himalaya are complicated because of the north-south convergence of the Himalaya and the east-west convergence of the Indo-Burman ranges (Baranowski *et al.*[16]; Ni and Barazangi[15]). The stress orientation in this part is highly heterogenous and is difficult to be strictly associated with any structure. Three provinces have been identified, with minor changes in S(Hmax) orientation.

Assam Syntaxis

Result of the convergence of the Himalayan frontal arc and the Burmese arc, the Assam syntaxis is a tectonically complex region. There have been several large earthquakes in this region, including one of magnitude 8.7 in 1950 (Chandra[10]). Focal mechanisms in this region generally show strike slip and thrust faulting (figure 2a). At shallow depths, the direction of S(Hmax) changes from N-S to NNE-SSW and NE-SE (figure 5a). As expected in a structurally complex region, no consistent pattern of S(Hmax) orientation was observed in this region. In general, the direction of convergence is in roughly E-W direction, and is more consistent at intermediate depths.

Shillong Plateau

Shillong Plateau is described as the only topographic expression of the collision, in the shield area, further south of the Himalaya (Chen and Molnar[43]). There is considerable debate about the origin and tectonic history of the Shillong Plateau, some of which are discussed in Chen and Molnar[43]. From the examination of six events, Chen and Molnar[43] suggested a NNE-SSW orientation of the P-axis. Our study however suggested an orientation, almost orthogonal, to that in NW-SE direction. This was also the orientation obtained by Kayal[44] based on composite focal mechanisms. One source of discrepancy could be the geographic selection of the events. For example, two events considered by Chen and Molnar[43] were to the north of the plateau, whereas four others were to the south and very close to the Dauki fault. Inclusion of events from the Indo Burman arc will result in more easterly average trend. Thus, it is not possible to attribute definite orientations in this area, particularly when the focal mechanisms are of questionable quality. The direction suggested by us are very preliminary and they need to be revised as new data are acquired.

Arakan-Burman Ranges (AB)

The Indo-Burman ranges mark the northward continuation of the Andaman–Nicobar arc, where the Indian ocean floor is subducted beneath the southeastern Asian continent. The N-S to NNE-SSW orientation of S(Hmax) in the frontal arc changes to almost E-W in the Arakan Burma region. The focal mechanisms of earthquakes in this area are predominantly thrust or strike slip type, with few normal solutions at intermediate depths.

The direction of thrusting in this region changes to E-W as reported by several workers (Santo[45]; Gupta and Bhatia[46]). The S(Hmax) orientations in this region are fairly uniform, and have a E-W trend.

Tibetan Plateau

Most of the seismicity in the Tibetan plateau is confined to the shallow crust (5–10 km) although isolated events as deep as 85 km have been reported for this region (Molnar and Chen[24]). The plateau is in a general state of extension, with the minimum horizontal compressive stress S(hmin) oriented almost oblique to the trend of the Himalaya. Strike slip and normal faulting were commonly observed in northern Tibet (figure 3a) and the T-axes are generally oriented WNW-ESE. This trend of extension is also evidenced by numerous N-S striking faults mapped in different parts of Tibetan plateau by Tapponnier *et al.*[18]. They reported quaternary extension at the rate of ~1 cm/yr occurring in southern Tibet.

Most of the focal mechanisms considered in this study were for earthquakes confined to the shallow crust, within 10 km. Extensional stress regimes inferred from focal mechanisms and geological indicators are shown in figures 3a and 5a. Differences in orientations of extensional stresses in sourthern and northern Tibet have been observed by various workers (Chang *et al.*[47]; Armijo *et al.*[48]; Mercier *et al.*[49]). Localized N-S extensions evidenced by shallow E-W trending normal faults have been observed in some parts, particularly in the southern flanks of the plateau (Burg *et al.*[50]; Burchfield and Royden[51]; Mercier et *al.*[49]). In general, the focal mechanisms analyzed in this paper support occurrence of WNW-ESE extension in Tibet as reported by previous workers (Chen and Molnar[43]; Tapponnier[18]; for example).

Peninsular India

The focal mechanisms used in this study are scattered over the western and eastern margins of Peninsular India (figure 3). Mechanisms of three earthquakes show strike slip faulting. Three others show predominantly thrust faulting and one in the Bay of Bengal region shows a combination of strike slip and thrust faulting (Gupta *et al.*[31]; Chandra[32]; Johnston and Metzger[33]). Some of these events were spatially correlated to regional faults (e.g. the March 1970 event can be correlated to the E-W trending Narmada-Son fault; the April 1979, event can be correlated to the NW-SE trending Godavari Graben). One of them, Koyna 1967, is related to the impoundment of an artificial reservoir. Based on focal mechanism solutions, Chandra[52] suggested that Peninsular India may be under a state of left lateral shear along NNE trending vertical planes. He also observed the general N-S orientation of p-axes, gently dipping at 10-30. Additionally, the data also include the directions of S(Hmax) orientations obtained from well breakouts in NE India and *in situ* stress measurements in Pensinsular India (figure 3). The directions of S(Hmax) obtained from these data compared well with those derived from focal mechanisms (~30° E). S(Hmax) obtained at different locations in Peninsular India are generally consistent and show N-S to NNE-SSE orientations

Weissel *et al*[53] observed the existence of N-S, NW-SE and E-W oriented compressive stresses throughout the Indo-Australian plate. They suggested that the pattern of S(Hmax) in the plate interiors is strongly influenced by collision of the Indian plate with the Eurasian plate. Thrust faulting at shallow depths observed in Indian and Australian continental regions suggests existence of large horizontal stresses (Cloetingh and Wortel[54]).

Talwani and Rajendran[53] studied seismicity at various intraplate settings and concluded that in regions closer to a collision boundary, there are large horizontal stresses and the style of faulting is generally by thrusting. Seismicity in the Indian and Australian plate was considered to be influenced by stresses transmitted from the plate boundary.

Andaman–Nicobar Arc Region

The state of stress in the Andaman–Nicobar region has recently been discussed by Rajendran and Gupta[2]. The results of their study are briefly repeated here. They identified three tectonic units based on the orientation and nature of stress fields. These were the Andaman-Nicobar, Andaman spreading ridge, and the Sumatra Trench regions shown as ANR, ASR and ST in figure 5a and b.

The Andaman-Nicobar region is characterized by a NE-SW compression which changes to N-S at intermediate depths. A prominent feature deciphered form the S(hmin), orientation is the Andaman spreading ridge where the NNW-SSE extension is confined to shallow depths. In the Sumatra trench region S(Hmax) is oriented in a NE-SW to N-S direction at both shallow and intermediate depths.

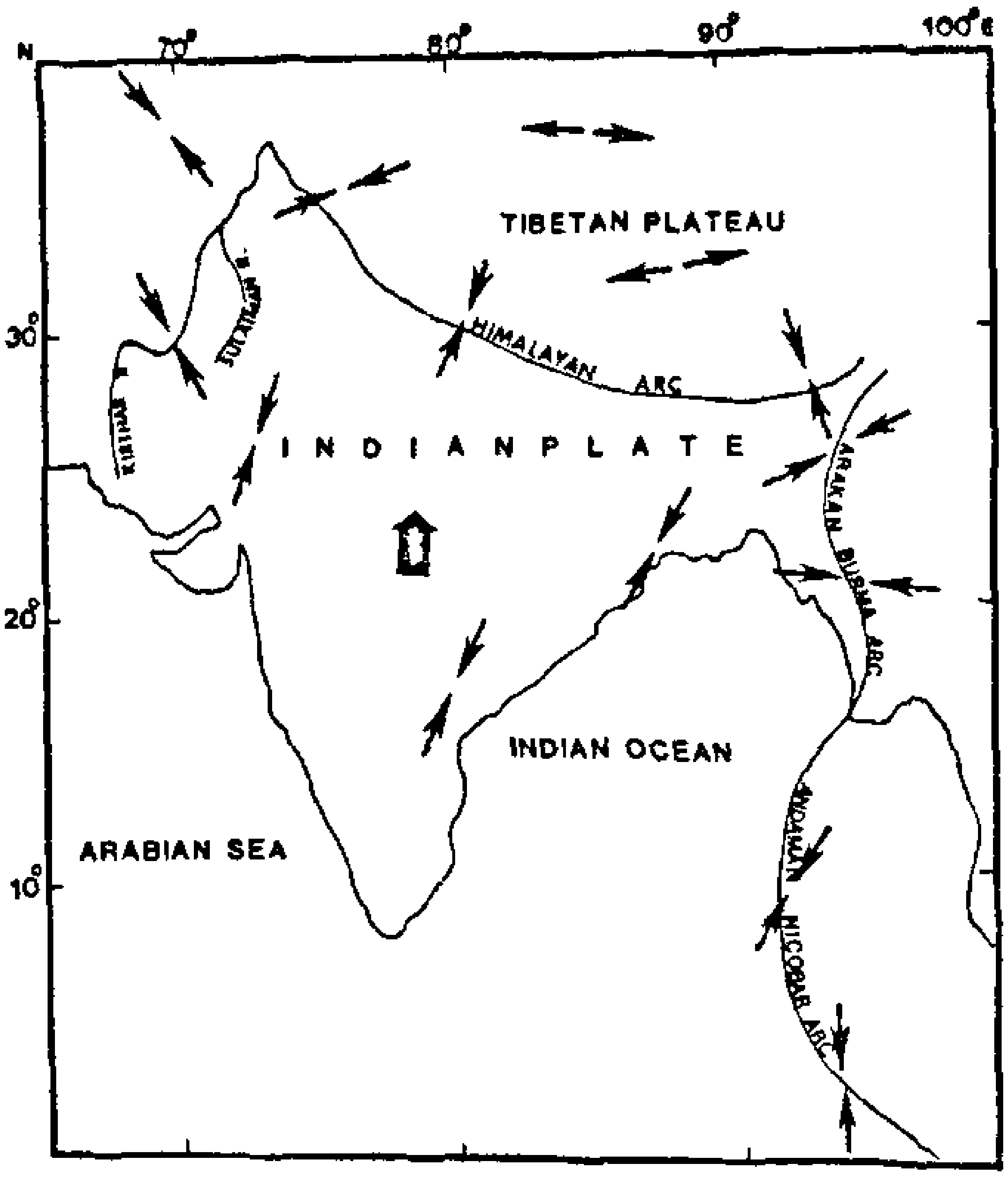

FIGURE 6. Generalized stress map of the Himalaya and Peninsular India. Arrows indicate direction of maximum horizontal compression. Bold arrow indicates direction of absolute plate motion.

CONCLUSIONS

The state of stress in the intraplate Peninsular India, interplate regions of the Himalaya and the Andaman–Nicobar arc regions, was reviewed to study the nature of stress orientations in the Indian subcontinent. The orientation S(Hmax) S(hmin) lead to the broad conclusions which are presented below:

- Orientations of S(Hmax) in Peninsular India and Andaman–Nicobar regions are generally uniform and varies from N-S to NNE-SSW.
- The uniform stress direction observed over the Peninsular India changes along the Himalaya. The significant changes are from NNW-SSE in the western syntaxis region to NNE-SSW and N-S over the frontal arc and almost E-W in the Arakan Burma arc.
- Perturbations in stress occur mostly in the syntaxes regions, particularly at shallow depths.
- Based on the average directions of S(Hmax) generalized stress map of the region was prepared (figure 6).

The boundaries of various stress provinces identified in this study were constructed by the number and quality of the solutions available. Due to such limitations, we have not attempted to explicitly demarcate the boundaries. As more data become available, we hope to define these boundaries with better precision.

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