Siesmotectonics of Pakistan: A Review of results from Network Data and implications for the Central Himalaya[1]

L. SEEBER, R. QUITTMEYER and J. ARMBRUSTER

Abstract: Microearthquakes detected by two telemetered seismic networks in northern Pakistan reveal a decollement style of tectonics for the Hazara and northwest Punjab region. The three-dimensional distribution of seismicity and composite fault-plane solutions delineate a nearly horizontal surface along which the decollement of sediments and metasediments is decoupled from the basement. Below the decoupling surface major faults trend northwest. These faults are recognized as basement structures that are associated with the Himalayan arc, but that extend towards the northwest beyond the Hazara-Kashmir syntaxis. During the last six years, the period of network observations, the seismicity is mostly associated with the basement faults. Seismic activity within the decollement is generally low and the decoupling surface is either aseismic or associated with very low seismicity.

The results from northern Pakistan, together with recent seismicity along the Himalayan arc and information on great Indian earthquakes, are combined to derive a general model of Himalayan tectonics. A shallow thrust of gentle dip, termed the *Detachment,* underlies the Indo-Gangetic plain and the Lower Himalaya. Rupture of this fault, which separates the low-strength sedimentary wedge from the basement, results in great earthquakes that cause devastation over a wide area, but occur only infrequently. Down-dip from the Detachment, beneath the Higher Himalaya, the thrust assumes a steeper dip and juxtaposes basement material of similar properties. Earthquakes occur more frequently on this portion of the fault, termed the *Basement Thrust,* but are smaller than the Detachment events. They can, however, be damaging locally. The model suggests that much of the Indo-Gangetic plain underlain by the Detachment has a high seismic hazard. In the Hazara arc region of northern Pakistan the Detachment is associated with a thick layer of Infracambrian salt. In this region the Detachment may slip aseismically; however, slip by large infrequent earthquakes cannot be ruled out.

Results from a seismic network centered on Quetta show that the Chaman fault, and the fault associated with the Quetta earthquake of 1935, are currently active. The segments that ruptured during the most recent large earthquakes on these faults, 1892 on the Chaman fault and 1935 on the Quetta fault, are relatively quiet at present. On both faults the current seismicity is concentrated near the ends of the ruptures associated with these earlier events, and indicates left-lateral strike-slip. In analogy with the San Andreas and Alpine fault systems, in California and New Zealand, respectively, two distinct portions of the Chaman fault system are recognized. One, north of approximately 31°N, trends obliquely to the regional slip vector and is probably characterized by infrequent great earthquakes. The other, south of 31°N, has a strike subparallel to the regional slip vector and consists of a broad zone of faults that rupture in large, but not great, earthquakes.

INTRODUCTION

The Lamont-Doherty Geological Observatory, in cooperation with various government agencies within Pakistan, has established over the past six years three telemetered seismic networks in northern and central Pakistan. The Tarbela network, covering the Hazara and Indus-Kohistan regions (Figures 1 and 3), has operated since 1973 to monitor seismicity in the region surrounding the Tarbela dam and reservoir. The Chashma network was established in 1976 to aid in the evaluation of seismic hazard for the Potwar and northwest Punjab region (Figures 1 and 3). More recently a network was set up to study the seismic activity in the area around Quetta (Figures 1 and 8).

Data recorded by these networks provide unique information about the active structures in the fold and thrust belt along the northwestern edge of the Indian subcontinent and in the underlying basement. A preliminary analysis of the recent seismicity along the entire Himalayan arc, and of the great ($M \geq 7.8$) Himalayan earthquakes during the past two centuries, suggests that the main features observed in Hazara are pertinent to a general model of continental plate convergence along the Himalayan arc.

THE HAZARA ARC

The Hazara arc in northern Pakistan (Figure 3) forms the northwestern limit of the Indian shield. It is defined by a broad belt of subparallel structures that

[1] Lamont-Doherty Geological Observatory Contribution No. 2874.

Proc. Intern. Commit. Geodynamics, Grp. 6, Mtg. Peshawar, Nov. 23-29, 1979: Spec. Issue, Geol. Bull. Univ. Peshawar, Vol. 13, 1980.

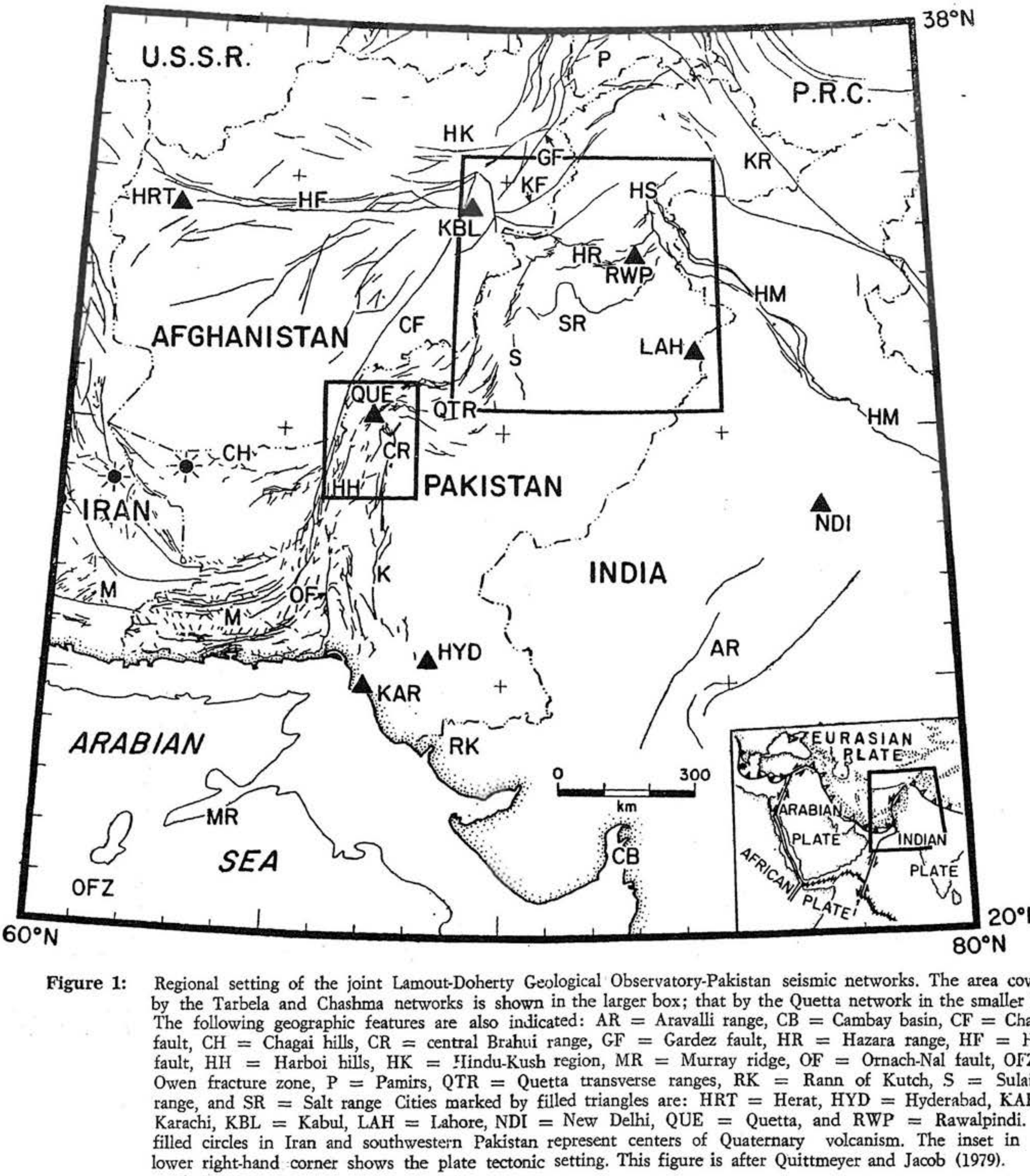


Figure 1: Regional setting of the joint Lamout-Doherty Geological Observatory-Pakistan seismic networks. The area covered by the Tarbela and Chashma networks is shown in the larger box; that by the Quetta network in the smaller box. The following geographic features are also indicated: AR = Aravalli range, CB = Cambay basin, CF = Chaman fault, CH = Chagai hills, CR = central Brahui range, GF = Gardez fault, HR = Hazara range, HF = Herat fault, HH = Harboi hills, HK = Hindu-Kush region, MR = Murray ridge, OF = Ornach-Nal fault, OFZ = Owen fracture zone, P = Pamirs, QTR = Quetta transverse ranges, RK = Rann of Kutch, S = Sulaiman range, and SR = Salt range Cities marked by filled triangles are: HRT = Herat, HYD = Hyderabad, KAR = Karachi, KBL = Kabul, LAH = Lahore, NDI = New Delhi, QUE = Quetta, and RWP = Rawalpindi. The filled circles in Iran and southwestern Pakistan represent centers of Quaternary volcanism. The inset in the lower right-hand corner shows the plate tectonic setting. This figure is after Quittmeyer and Jacob (1979).

delineate an arc convex to the south-southeast. These structures form a typical fold and thrust belt that verges radially outward toward the foreland. The deformation involves a belt of syndeformational terrigeneous sediments in the outer part of the arc near the foreland, as well as older sediments and metasediments in the inner part of the arc (Figure 5).

Deformation in the Hazara arc is characterized by a decollement style of tectonics. Microseismic data from the Tarbela and Chashma networks provide most of the information used to develop this tectonic model (Figures 4, 5 and 6), but other geophysical and geological data have also been incorporated when available (Armbruster *et al.*, 1978; Seeber and Jacob, 1977; Seeber and Armbruster, 1979). The distribution of seismicity and composite fault-plane solutions show that a wedge of sediments and metasediments (the decollement) is moving south with respect to the basement along a nearly horizontal surface of decoupling (Figure 6). Deformation within this decollement produces the belt of folds and thrusts prominent at the surface. The basement faults below the decollement, which are delineated by the seismicity, do not show any direct correlation with the surface structures, but they correlate closely with topographic steps.

The main active faults in the basement are most easily observed when only earthquakes in the lower crust are considered (Figure 5). Two parallel lineations of activity can be discerned extending for about 150 km in a northwestern direction from the Hazara-Kashmir syntaxis. These two seismic zones, the Indus-Kohistan seismic zone (IKSZ) and the Hazara lower seismic zone (HLSZ), are interpreted as northwestern extensions of the structural trends in the Kashmir Himalaya east of the syntaxis. This same extension of the basement activity is also seen for the teleseismic shocks (Quittmeyer and Jacob, 1979); however, depths for the teleseismic events are not well known (Figure 2).

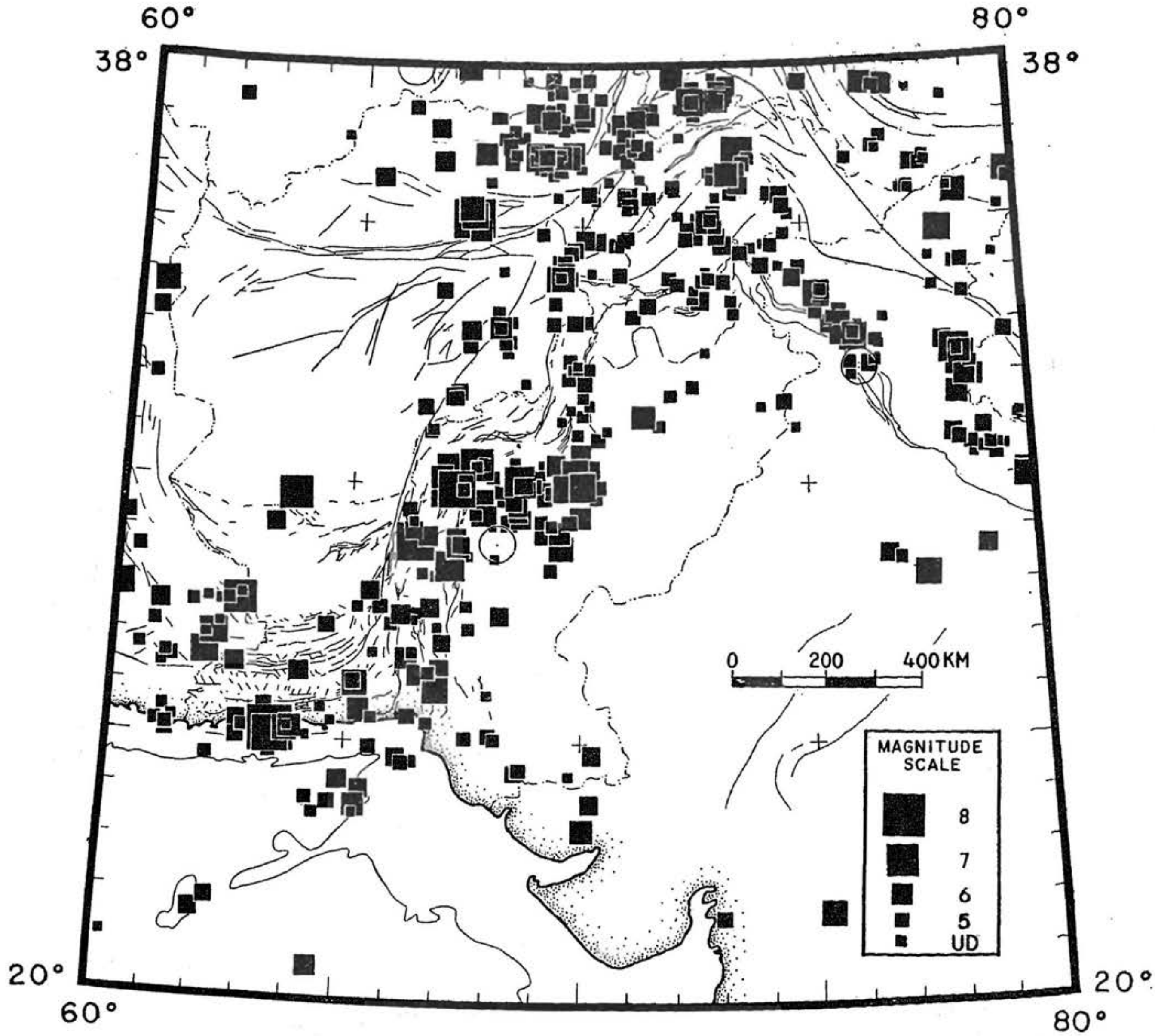


Figure 2: Teleseismic activity of south-central Asia. Earthquake occurring between January 1914 and April 1975 are shown. Four large events prior to 1914 are also indicated by large, open circles. Note the continuation of the northwest trend of Himalayan seismicity beyond the Hazara-Kashmir syntaxis. The symbol labelled UD in the magnitude scale signifies an undetermined magnitude (from Quittmeyer and Jacob, 1979).

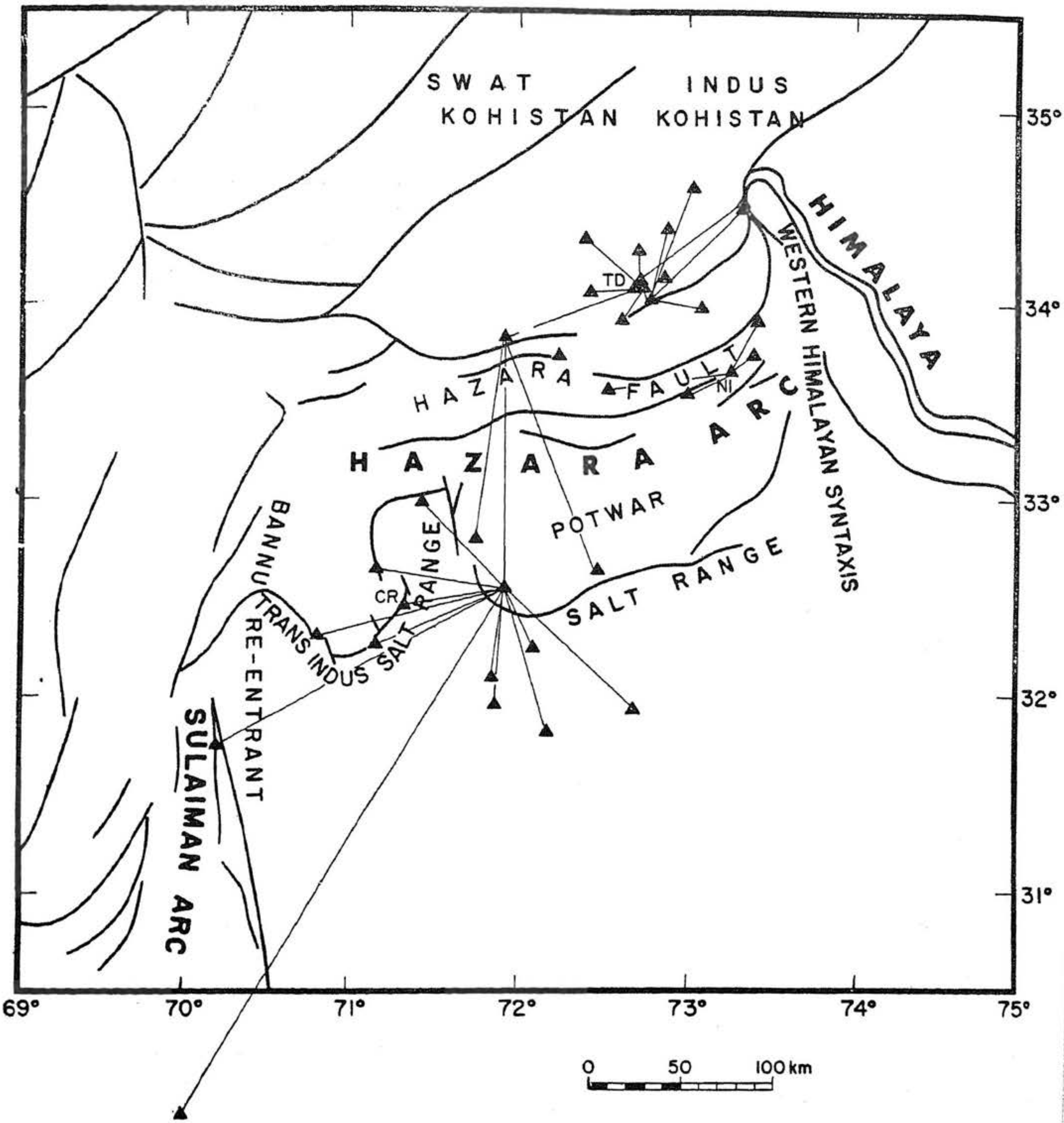


Figure 3: Station distribution and telemetry links for the Tarbela and Chashma networks. The filled triangles mark station sites; telemetry links are shown by straight lines.

Of the two seismic zones within the basement, the IKSZ is currently the more active. Fault-plane solutions indicate it as a zone of thrust faulting that dips to the northeast (Armbruster *et al.*, 1978; Pennington, 1979). The slip-direction is approximately perpendicular to the strike of the IKSZ. This is similar to observations elsewhere along the Himalayan arc (Fitch, 1970; Molnar *et al.*, 1973; Chandra, 1978).

The HLSZ, on the other hand, is a strike-slip fault with right-lateral movement. Similar strike-slip faults are not documented along the central Himalaya. The existence of such a fault in the Hazara region is probably related to the obliqueness of convergence between the Indian and Eurasian plates along this portion of their collisional boundary. Similar pairs of thrust and strike-slip faults are identified in other zones of oblique convergence (Fitch, 1972). Convergence in the Hazara arc, as determined from rigid plate assumptions, is directed approximately northward at a rate of 3.7

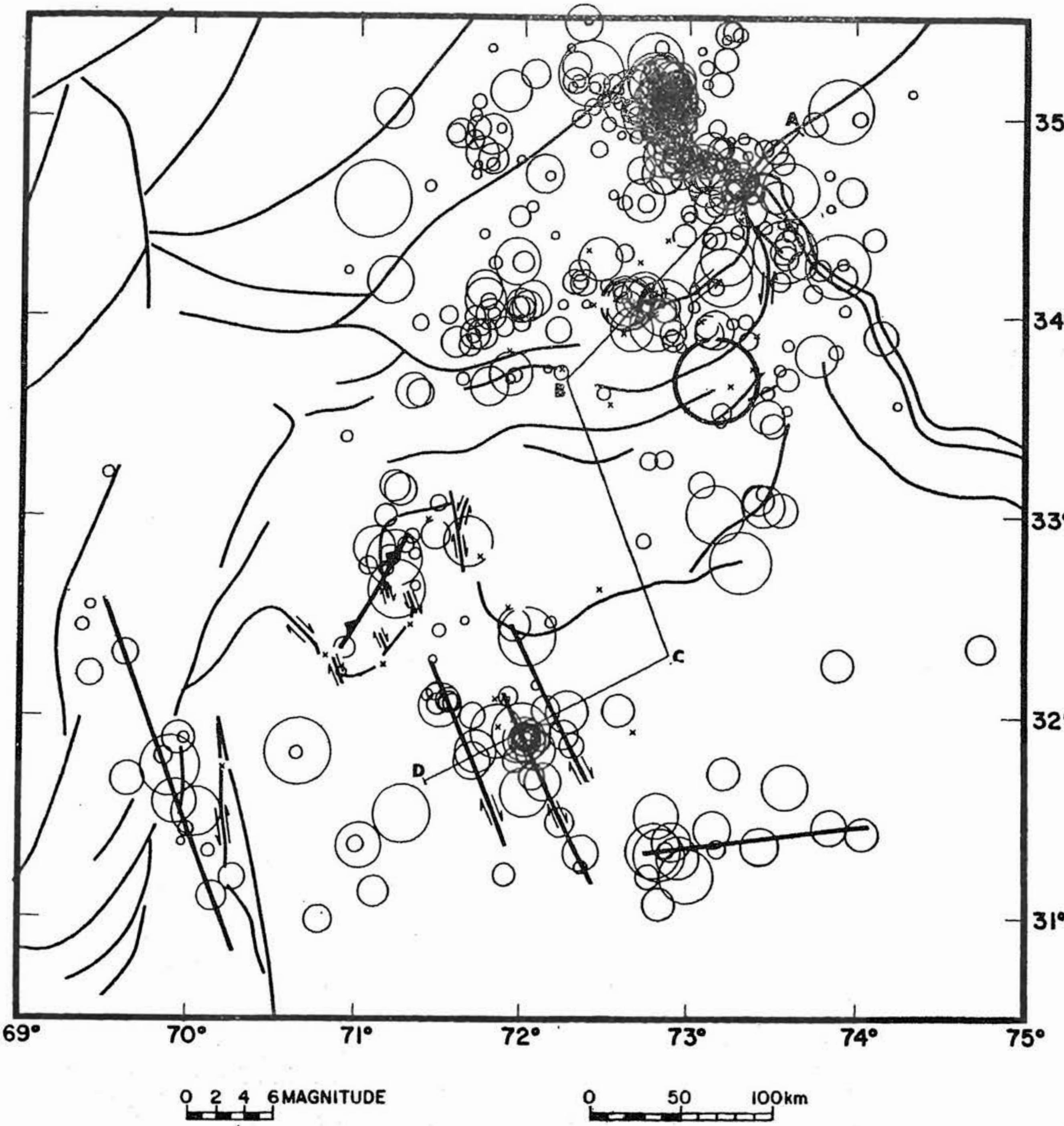


Figure 4: Six months of epicentral data from the Tarbela and the Chashma networks (from May to November 1976 for the Chashma network; from February to August 1976 for the Tarbela network). All depths compare to Figure 5. Compare to Figure 3 for location names. The epicenter of the February 14, 1977 Rawalpindi earthquake is also shown (larger circle in the figure). Only earthquakes of magnitude 0.5 or greater are plotted to obtain a picture of the seismicity within the area of the network unbiased by station sensitivity. This short sample is comparable to the longer term seismicity (see Seeber and Jacob, 1977; Figure 2). The main structural features known from geologic work are shown in thinner lines; major fault zones inferred from the seismicity in the southern part of the Hazara arc are indicated in thicker lines. (From Seeber and Armbruster, 1979).

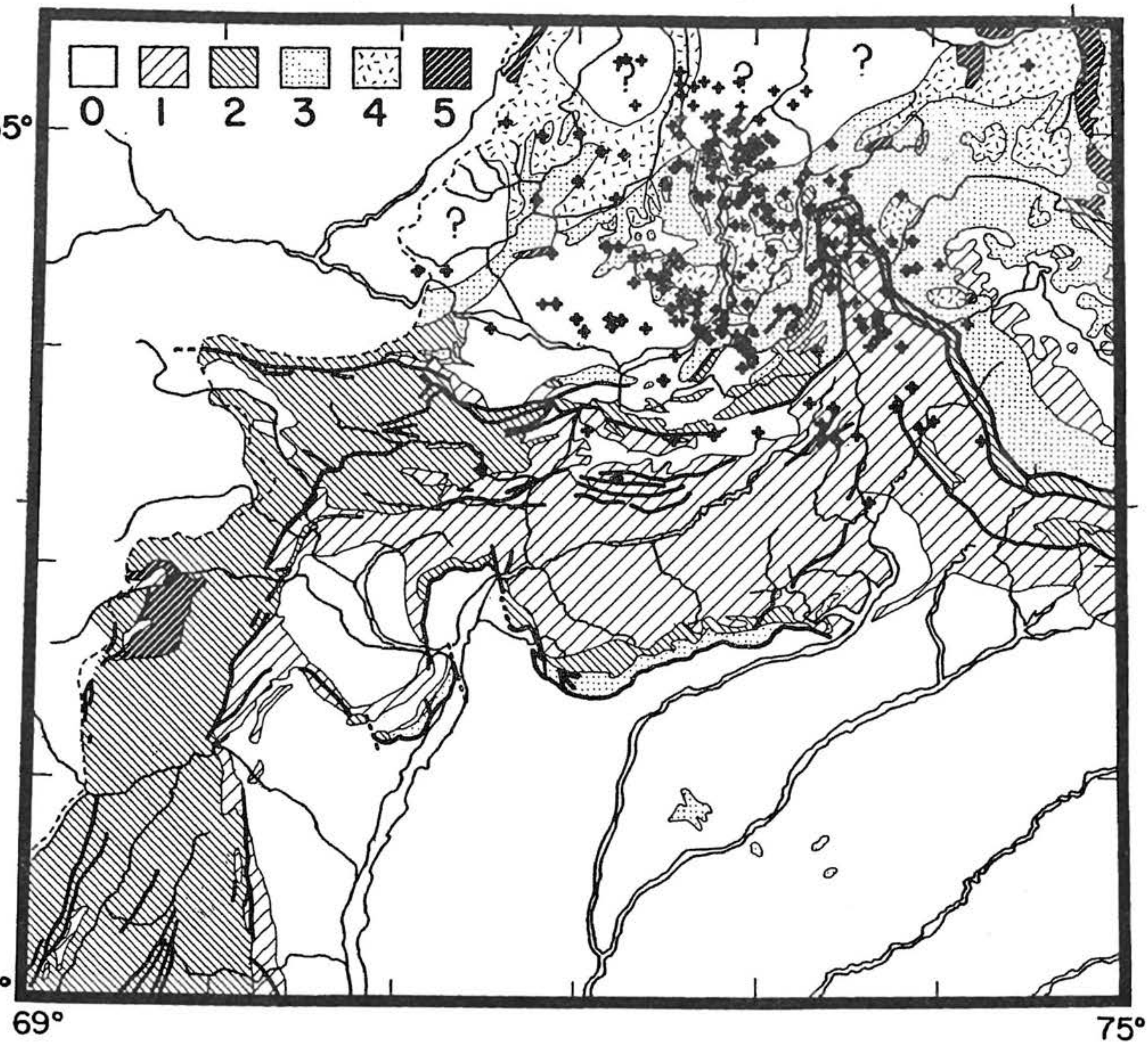


Figure 5: Geological sketch map of the Hazara region and surrounding areas showing epicenters for earthquakes (1973-1976) with depths greater than 40 km. The geological information is after Bakr and Jackson (1964): 0) post-Siwalik basins; 1) Siwalik and Murree (post-collisional); 2) lower Tertiary (pre-collisional) and Mesozoic; 3) Paleozoic and Precambrian; 4) granites (Tertiary?); 5) ophiolites. Note the two parallel zones of seismicity extending the main Himalayan trends beyond the Hazara-Kashmir syntaxis. The southwestern zone is the Hazara lower seismic zone (HLSZ); the northeastern one is the Indus-Kohistan seismic zone (IKSZ) (from Seeber and Jacob, 1977).

cm/year. Slip to the northeast on the IKSZ and slip to the northwest along the HLSZ, when combined, may account for the rigid plate convergence. However, an unknown amount of convergence may be taken up north of the Himalaya (Molnar and Tapponnier, 1975).

Generally, little seismicity is observed within the sedimentary wedge above the basement. A sharply delimited zone of seismicity is, however, located at shallow depths in the sedimentary wedge beneath the Tarbela dam region (Figure 6). This localized zone of activity is referred to as the Tarbela seismic zone (TSZ). Composite fault-plane solutions for linear trends of activity within the TSZ, indicate the seismicity is the result of slip on steeply dipping faults that trend both northeast and northwest (Armbruster *et al.*, 1978). These faults are abruptly truncated at a depth of about 17 km along the horizontal zone of decoupling.

The cause of this anomalous concentration of activity is not known. As a working hypothesis the TSZ is associated with a block of basement trapped in the

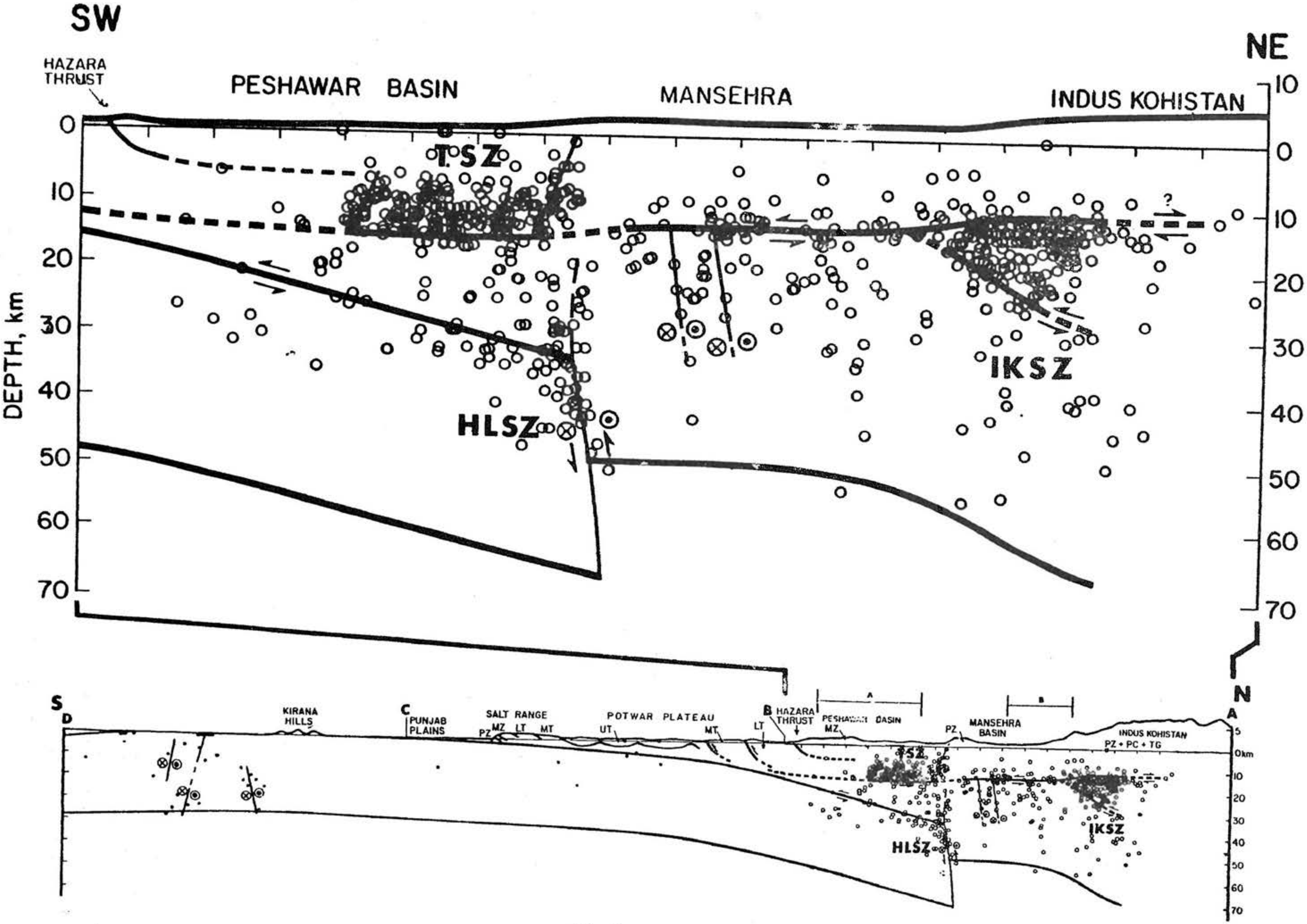

SW
NE
HAZARA THRUST
PESHAWAR BASIN
MANSEHRA
INDUS KOHISTAN
DEPTH, km
TSZ
HLSZ
IKSZ
S
D
KIRANA HILLS
C
PUNJAB PLAINS
SALT RANGE
PZ
MZ
LT
MT
POTWAR PLATEAU
UT
B
HAZARA THRUST
MANSEHRA BASIN
INDUS KOHISTAN
PZ + PC + TG
N
A
0km

Fig. 6

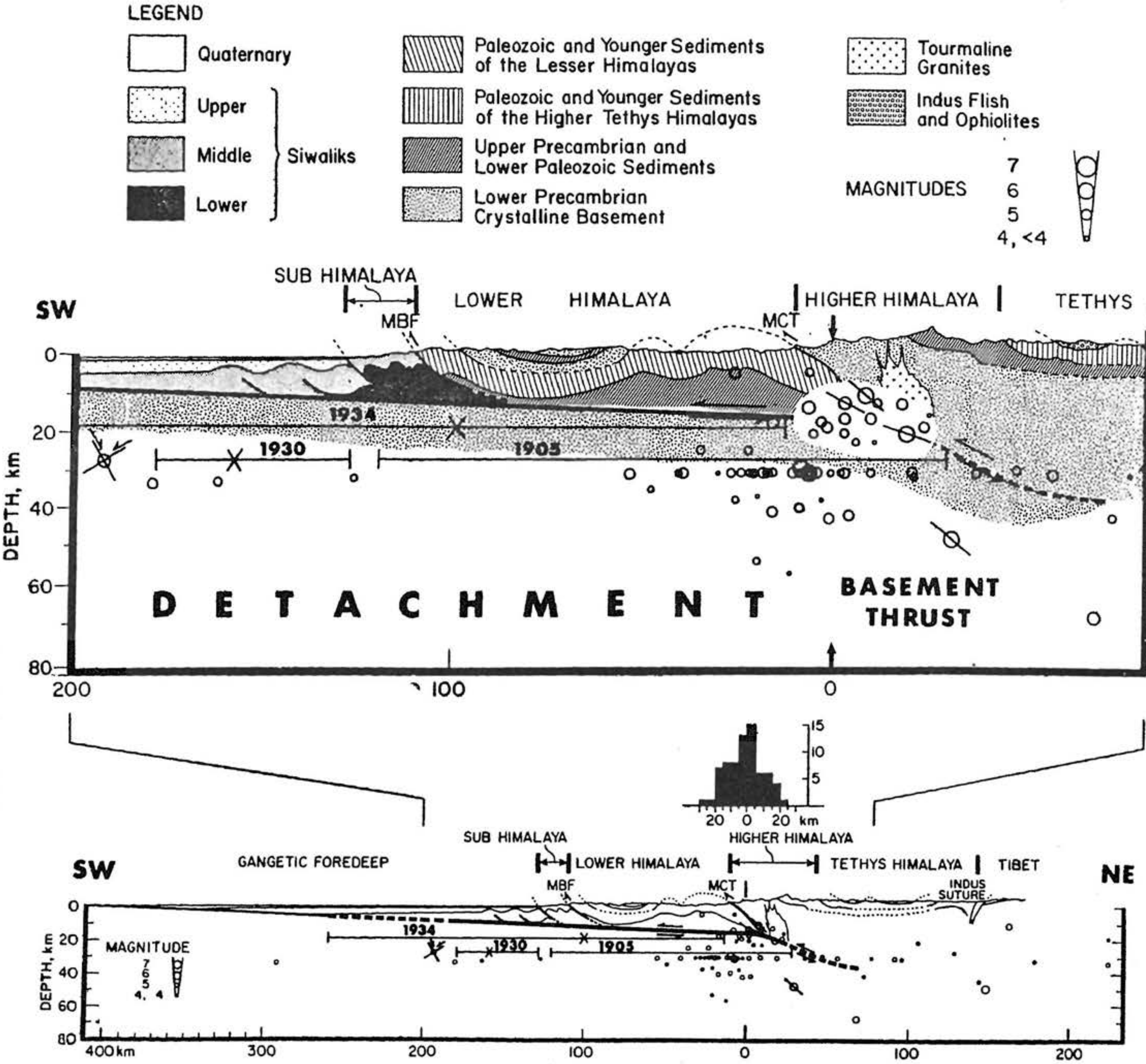

LEGEND
Quaternary
Upper
Middle
Lower
Siwaliks
Paleozoic and Younger Sediments of the Lesser Himalayas
Paleozoic and Younger Sediments of the Higher Tethys Himalayas
Upper Precambrian and Lower Paleozoic Sediments
Lower Precambrian Crystalline Basement
Tourmaline Granites
Indus Flish and Ophiolites
MAGNITUDES
7
6
5
4, <4
SUB HIMALAYA
LOWER HIMALAYA
HIGHER HIMALAYA
TETHYS
SW
NE
MBF
MCT
1934
1930
1905
DEPTH, km
DETACHMENT
BASEMENT THRUST
GANGETIC FOREDEEP
TETHYS HIMALAYA
TIBET
INDUS SUTURE
MAGNITUDE
400 km

Fig. 7

decollement. The basement material is more brittle than the surrounding sedimentary rocks. It thus deforms seismically in contrast to the surrounding sedimentary rocks which tend to deform aseismically.

The decoupling surface between the sedimentary wedge and the basement appears to be generally aseismic. This surface is recognized primarily as a subhorizontal boundary to seismic zones: the lower boundary to the TSZ and the upper boundary of the IKSZ (Figure 6). However, a few earthquakes in the Mansehra basin, where the seismicity above and below the decoupling layer is low, can be associated by fault-plane solutions directly with the southward slip of the decollement on the decoupling layer. The ongoing southward movement of the decollement is also documented by the structures presently developing along the southern front of the fold and thrust belt at the Salt range (Johnson *et al.*, 1979). The evidence of tectonic activity, coupled with the lack of seismic activity during the period of observation (since 1973), implies either that the network is operating during an interseismic period between major earthquakes when slip on the decoupling layer is temporarily halted, or that slip on this fault occurs aseismically.

The decollement model is summarized in Figure 6. In the Hazara region the decoupling surface extends from south of the Salt Range to north of the IKSZ. The decoupling layer dips gently northward in the Potwar and it is associated with a thick layer of Infracambrian salt that outcrops at the Salt range (Exploration data, M. Hussain, personal communication; Gansser, 1974, p. 26). North of the Hazara thrust the model is based entirely on seismic data and the association of the salt with the decoupling layer is somewhat speculative (Seeber and Jacob, 1977). Salt (halite) deforms ductilely even under the moderate temperature conditions found at shallow depths (1-3 km; Borchert and Muir, 1964, p. 279). Thus, the presence of salt along the decoupling layer suggests that the lack of seismicity on this active shear zone is the result of aseismic slip rather than an interseismic period of elastic strain accumulation.

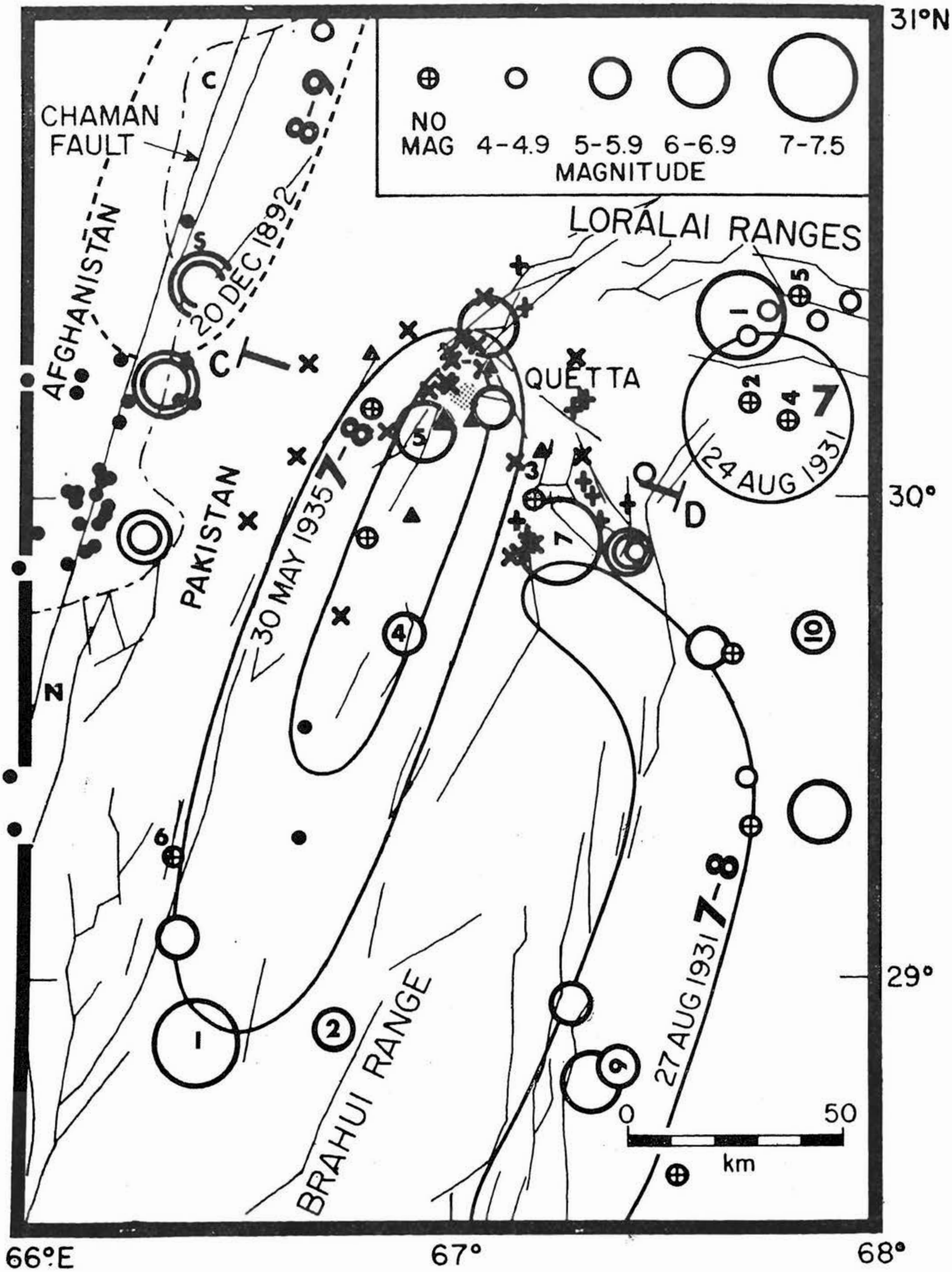
On the other hand, movement during large earthquakes at infrequent time intervals can explain equally well the current aseismic character of this surface. The historical record (Quittmeyer and Jacob, 1979) includes a number of damaging earthquakes in the Hazara region. Only one of these events, however, could possibly be associated with fault rupture over a wide area (Taxila earthquake, ~ 25 A.D.; Ambraseys *et al.*, 1975), and even for this event the evidence is not very convincing. Thus, none of the damaging earthquakes in the Hazara region appear to be similar to the great Indian earthquakes that occurred on the decoupling surface or Detachment along the central Himalaya (Seeber *et al.*, 1979; see the next section) and caused severe damage over several tens of thousands square kilometers. The occurrence of great earthquakes ($M > 7.8$) associated with slip of the decollement surface is less likely in the Hazara arc than in any other portion of the Himalayan front, but it cannot be ruled out from the available data.

South of the Salt range a number of basement faults are seismically delineated (Figure 4). The composite fault-plane solutions for these events indicate strike-slip movement in a right-lateral sense. These solutions agree in orientation and slip direction with active faults mapped by Gee and Danilchik (in Hemphill and Kidwai, 1973) across the Trans-Indus Salt range and they are interpreted as transverse faults simi-

Fig. 6. The active tectonic structure in the Hazara arc region as tentatively deduced from the seismicity detected by the Tarbela network. The hypocentral data from a strip along this section is also plotted; the section is located in Figure 4. The sense of movement on the faults in the portion A-B of the section is known from composite fault-plane solutions; X = motion away from viewer; Θ = motion towards viewer; UT, MT, LT = upper, middle, lower Tertiary; MZ = Mesozoic; PZ = Paleozoic; PC = Precambrian; TG = Tertiary granite; HLSZ = Hazara Lower seismic zone; IKSZ = Indus-Kohistan seismic zone; TSZ = Tarbela seismic zone. The Detachment, the quasi-horizontal fault that extends from the base of the Salt range to the IKSZ and beyond, is active even where seismicity is presently absent. On these portions of the Detachment slip may occur either aseismically or by rare large earthquakes (compare with Figure 7). The distribution o seismicity in the Salt Range and the Potwar Plateau is somewhat distorted by the linear projection along a curved structure; most of the seismicity occurs along the Salt Range and not in the Potwar Plateau (see Figure 4). (From Seeber *et al.*, 1979).

Figure 7: Tectonic model for the Himalayas (from Seeber *et al.*, 1979). The Detachment and Basement Thrust are shown with respect to regional geology. NOAA hypocenters (1963-1975) from 78°E to 83°E (approximately) are projected olng the Himalayas are onto the section (open circles). The preferred nodal planes for some fault-plane solutions are shown as line segments drawn across the hypocenter symbol. The concentration of earthquakes at 33 km is not real: this depth is arbitrarily assigned to events for which an independent depth determination is not available. The epicenter and extent of intensity VIII (Mercalli I to X scale) associated with the 1905 Kangra ($M = 8$), 1930 Dhubri ($M = 7.1$), and 1934 Bihar ($M = 8.3$) earthquakes are indicated by crosses and horizontal lines, respectively. Note that the largest earthquakes seem to be associated with th Detachment, while moderate-sized earthquakes in the last decade occur near the transition from the Detachment to the Basement Thrust. Surface geology is from Gansser (1964, plate II, section A), but below see-level structures are somewhat modified to fit the model obtained from seismicity.

Fig. 8



31°N
30°
29°
66°E
67°
68°
NO MAG
4-4.9
5-5.9
6-6.9
7-7.5
MAGNITUDE
CHAMAN FAULT
AFGHANISTAN
PAKISTAN
20 DEC 1892
8-9
LORALAI RANGES
QUETTA
24 AUG 1931
30 MAY 1935
7-8
27 AUG 1931
BRAHUI RANGE
0
50
km

lar to those observed elsewhere along the Himalaya (Seeber and Armbruster, 1979; Valdyia, 1976). The seismicity of the Salt range is part of the Punjab seismic zone, a broad seismic zone that coincides with the foredeep and extends from the Indus re-entrant southeastward to the Delhi-Hardwar ridge and possibly beyond (Menke and Jacob, 1976; Quittmeyer and Jacob, 1979; Figure 2).

IMPLICATION FOR THE CENTRAL HIMALAYA

A preliminary examination of recent seismicity along the Himalayan arc, and of the great Indian earthquakes that are documented historically, suggest that a tectonic model based on the decollement style of deformation observed in the extreme northwestern portion of the Himalaya in Hazara, is also applicable to the rest of the Himalaya. The convergence between the Indian and Eurasian plates is partially accommodated at the Himalayan front where extensive thrusting has produced a zone of thickened crust (Gansser, 1964, plate II; Gupta and Narain, 1967; LeFort, 1975; Molnar *et al.*, 1977). In the model proposed here (also Seeber *et al.*, 1979), the Himalayan thrust is composed of two distinct segments (Figure 7): a shallow portion dipping gently northward and labelled the *Detachment,* and a more steeply dipping portion situated down-dip from the Detachment and labelled the *Basement Thrust.* The Detachment separates the basement of the Indian shield from the overlying sedimentary wedge which is comprised of the Siwaliks and other sediments of the lesser Himalayas. The Basement Thrust, on the other hand, juxtaposes basement rocks of the Indian shield in the footwall with similar rocks in the hanging wall. The transition from the Detachment to the Basement fault marks the zone that separates crust of normal thickness overlain by the sedimentary wedge in the south from crust of double thickness in the north. The Detachment and the Basement Thrust along the central Himalaya are correlated with the decoupling surface and the IKSZ in the Hazara arc, respectively (compare Figures 6 and 7). In our model the Main Central Thrust (MCT), Main Boundary Fault (MBF) (Figure 7) and the Hazara thrust (Figure 6) are imbricate faults that splay off from the master fault. Although probably active, their tectonic significance is secondary.

Styles of seismicity along the two components of the Himalayan thrust differ dramatically. Extensive portions of the Detachment rupture in individual great ($M > 7.8$) earthquakes that are characterized by long recurrence intervals. During interseismic periods the Detachment is quiet at least at a teleseismic detection level. On the other hand, the Basement Thrust is associated with relatively continuous seismic activity. However, the maximum magnitude associated with rupture of the Basement Thrust is considerably smaller than the magnitudes of the great earthquakes on the Detachment.

Aseismic slip may play an important role on discrete portions of both the Detachment and the Basement Thrust. The possibility that the Detachment slips aseismically in Hazara was mentioned above. Seismicity on the Basement Thrust is limited to its shallowest portion, near the transition to the Detachment (Figure 7). It is possible that deeper portions of the Basement Thrust are shear heated and slip aseismically (LeFort, 1975).

The extent of rupture for large earthquakes associated with the Detachment may be approximately estimated from intensity data (Kelleher, 1972; Figure 7). The distribution of intensities mapped by the Officers of the Geological Survey of India (1939) for the 1934 Bihar earthquake ($M_s = 8.3$) clearly shows that rupture during that earthquake extended south of the MBF. This earthquake cannot, therefore, be associated with movement along the MBF. The distribution of intensity for the 1905 Kangra earthquake ($M_s = 8$), however, may not be inconsistent with a rupture of the MBF. In this case, though, levelling data obtained following the Kangra earthquake (Middlemiss, 1910) do not support reverse slip on the MBF (Seeber *et al.*, 1979). These data suggest the rupture extended south of the MBF on a thrust fault of shallow dip. The lack of any appreciable amount of documented offset during any of the great Himalayan earthquakes along either the MBF or any other of the imbricate thrusts in the

Figure 8: Seismicity of the Quetta region. Modified Mercalli intensities are shown (dotted where inferred) for the four largest earthquakes documented in this region. Open circles indicate teleseismic epicenters for events occurring between January 1914 and July 1975. The numbered events are the main shocks and aftershocks associated with the large earthquakes in 1931 and 1935: earthquakes associated with the Sharigh and Mach main shocks face left (some fall off map); those associated with the Quetta main shock face up. Three teleseismic events occurring after July 1975 are also shown by double circles: 3 October 1975 ($M_s = 6.4$) west of Quetta near the Chaman fault; 13 July 1977 ($M_s = 5.5$) southeast of Quetta near Kolpur; and 16 March 1978 ($M_s = 5.9$) southwest of Quetta along the Chaman fault north of Nushki. Stations of the Quetta network are shown by filled triangles. Preliminary epicenters determined from network data are indicated as follows: x, depths from 0 to 15 km, +, depths from 15 to 30 km; filled circles, depth fixed at 15 km. Note the relation of activity along the Chaman fault after 1975 to the 1892 meisoseismal area. C = Chaman, S = Spin Tezha, N = Nushki. (From Armbruster *et al.*, 1979).

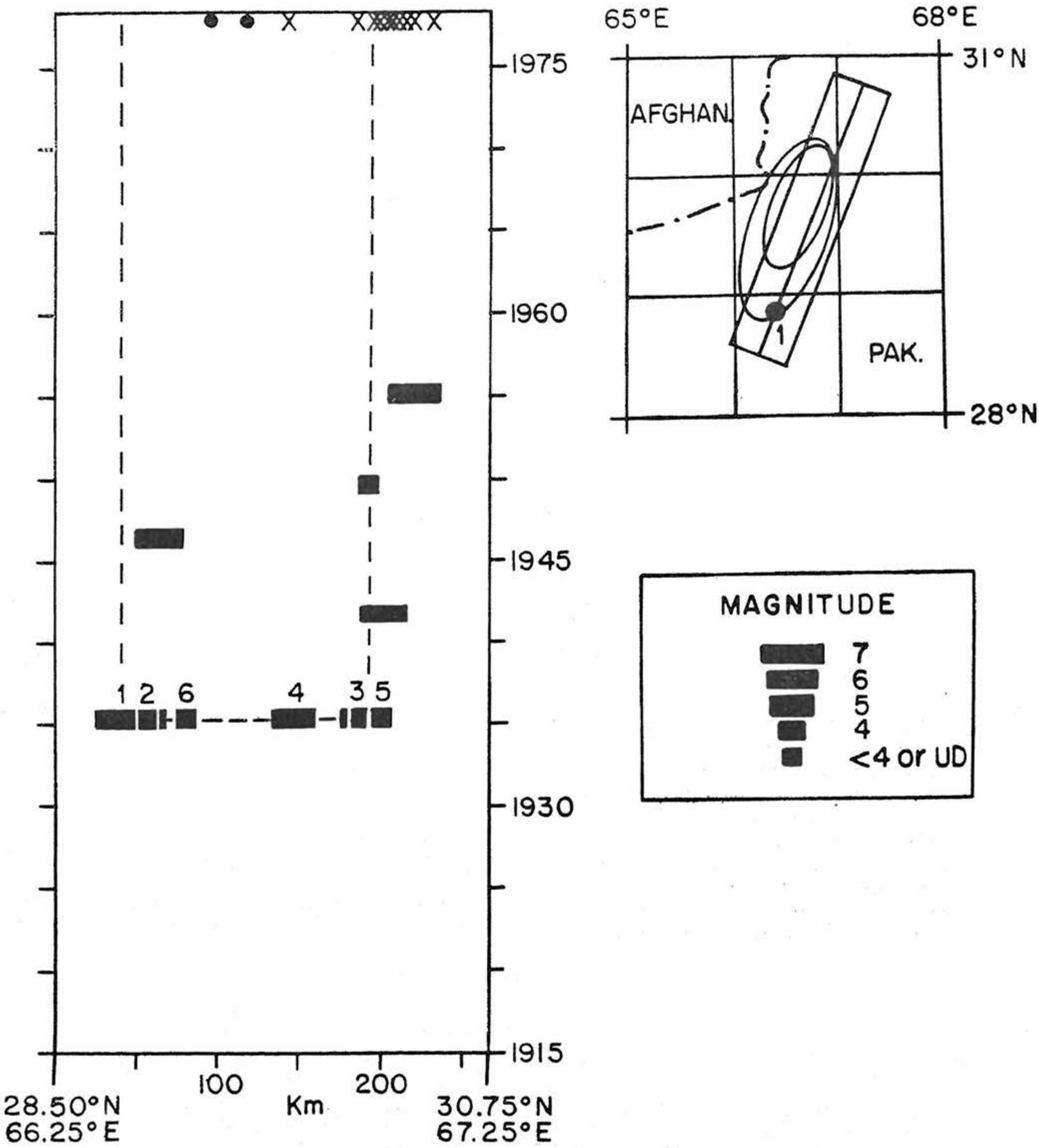


Figure 9: Distribution in space and time of activity along the Quetta fault. Within the map at the upper right, the box shows the area sampled. Isoseismals and the epicenter associated with the Quetta earthquake of 1935 are shown for reference (see Figure 8). Crosses and dots in 1978 are epicenters from network data. Note that acivity after 1935 is located near the ends of the 1935 rupture zone. (From Armbruster *et al.*, 1979).

Sub-Himalayas, is further evidence that the master fault along the Himalayan front is a buried Detachment and not the MBF.

Recent seismicity along the Himalayan arc is projected onto the cross-section in Figure 7. Although depths are not well constrained, the earthquakes appear to result primarily from movement on the Basement Thrust. The dip of this thrust in Figure 7 in constrained by several fault-plane solutions (Molnar *et al.,* 1973; Molnar *et al.,* 1977). No earthquakes with magnitudes greater than $M_s = 7$ are known to have occurred along the Basement Thrust. The relocated epicenter of the great 1934 Bihar earthquake (Seeber *et al.,* 1979b) is about 100 km south of the seismic zone along the Basement Thrust and cannot be associated with this fault. The epicenters of great Himalayan earthquakes before 1934 are not sufficiently reliable to warrant consideration in this discussion.

THE QUETTA SYNTAXIS

The northward motion of the Indian plate relative to the Afghan block of the Eurasian plate is manifested by the broad belt of seismicity associated with the Pakistani fold-belt and the Chaman fault system (Figures 1 and 2). The Pakistani fold-belt is characterized by a festoon-like series of arcs and re-entrants. The arcs are convex and verge towards the Indian craton, while the re-entrants separate consecutive arcs and are associated with syntaxis that have relatively small radii of curvature. The Quetta syntaxis defines the Sibi re-entrant, the most prominent of these reentrants.

The fold-belt is an expression of convergence normal to the plate boundary, at least within the sedimentary layers. Current plate motions, derived with the assumptions of rigid plates, indicate that motion along this boundary is now predominantly strike-slip in a left-lateral sense with only a small component of convergence. The Chaman fault, subparallel to and westward of the fold-belt is usually considered the most prominent expression of the left-lateral motion.

Locations for 62 small earthquakes, obtained from an analysis of two months of data for the Quetta seismic network (Figure 8), provide new insight into the complicated tectonics of the broad region surrounding the Quetta syntaxis. The network records events associated with both the Chaman fault and the fault responsible for the Quetta earthquake of 1935. Other seismic zones are also identified and indicate that several distinct fault systems are active in the area of the Quetta syntaxis.

The Chaman fault is the most active feature detected by the Quetta network (Armbruster *et al.,* 1979). A large earthquake in 1892 ruptured a segment of this fault northwest of Quetta. Heuckroth and Karim (1970) infer from intensity data that this rupture extends north-northeastwards from about 30.25°N, 66.25°E (Figure 8). The extent of this rupture zone, however, is not well known. Strike-slip movement in a left-lateral sense on the Chaman fault, as predicted by plate tectonics, is confirmed both by observed offsets during the 1892 shock (Griesbach, 1893) and by the fault-plane solution for an earthquake on 3 October 1975 (Quittmeyer *et al.,* 1979).

Prior to 1975 no teleseismic earthquakes were located along the segment of the Chaman fault south of that ruptured in 1892. (Events with surface-wave magnitudes greater than 6.0 to 6.5 occurring after 1920 would probably have been located from teleseismic data). On the other hand, after 1975, two moderate-sized earthquakes ($M_s = 6.4$ on 3 October 1975 and $M_s = 5.9$ on 16 March 1978) are associated with this previously quiet fault segment. The microseismic events detected along the Chaman fault by the Quetta network are also located along this same portion of the fault. Current activity south of the 1892 earthquake contrasts sharply with the current quiescence in the 1892 rupture zone itself (Figure 8). It is possible that the recent increase in teleseismic activity is the premonitory signal of a future large earthquake (Armbruster *et al.,* 1979).

In 1935 a large earthquake ($M_s = 7.5$) destroyed Quetta and killed 30,000 people. The distribution of intensities (West, 1935) and aftershocks (Quittmeyer and Jacob, 1979) suggests this earthquake ruptured a north-northeastward trending fault segment extending about 150 km from south of Kalat to Quetta (Figure 8). Teleseismic activity since 1935 is concentrated near the northeastern end of the inferred rupture zone, whereas the rupture zone itself has been relatively quiet in this period (Figure 9). Microearthquakes detected by the Quetta network (Armbruster *et al.,* 1979) also define the 1935 Quetta fault with most of the epicenters concentrated near the northeastern end of the rupture (Figures 8 and 9). Thus, the present spatial distribution of microearthquakes is similar to the distribution of teleseismic epicenters since 1935. A composite fault-plane solution for the microearthquakes along the Quetta fault indicates strike-slip motion along a steeply dipping plane striking north-northeast (Figure 10). The sense of movement is left-lateral, similar to that for the Chaman fault.

Along the Quetta fault hypocentral depths are within the upper 15 kilometers. East of the Quetta fault, hypocenters are as deep as 43 km (Figure 10). This deeper seismicity is associated with at least two distinct sources (Figure 8). One is a cluster of events

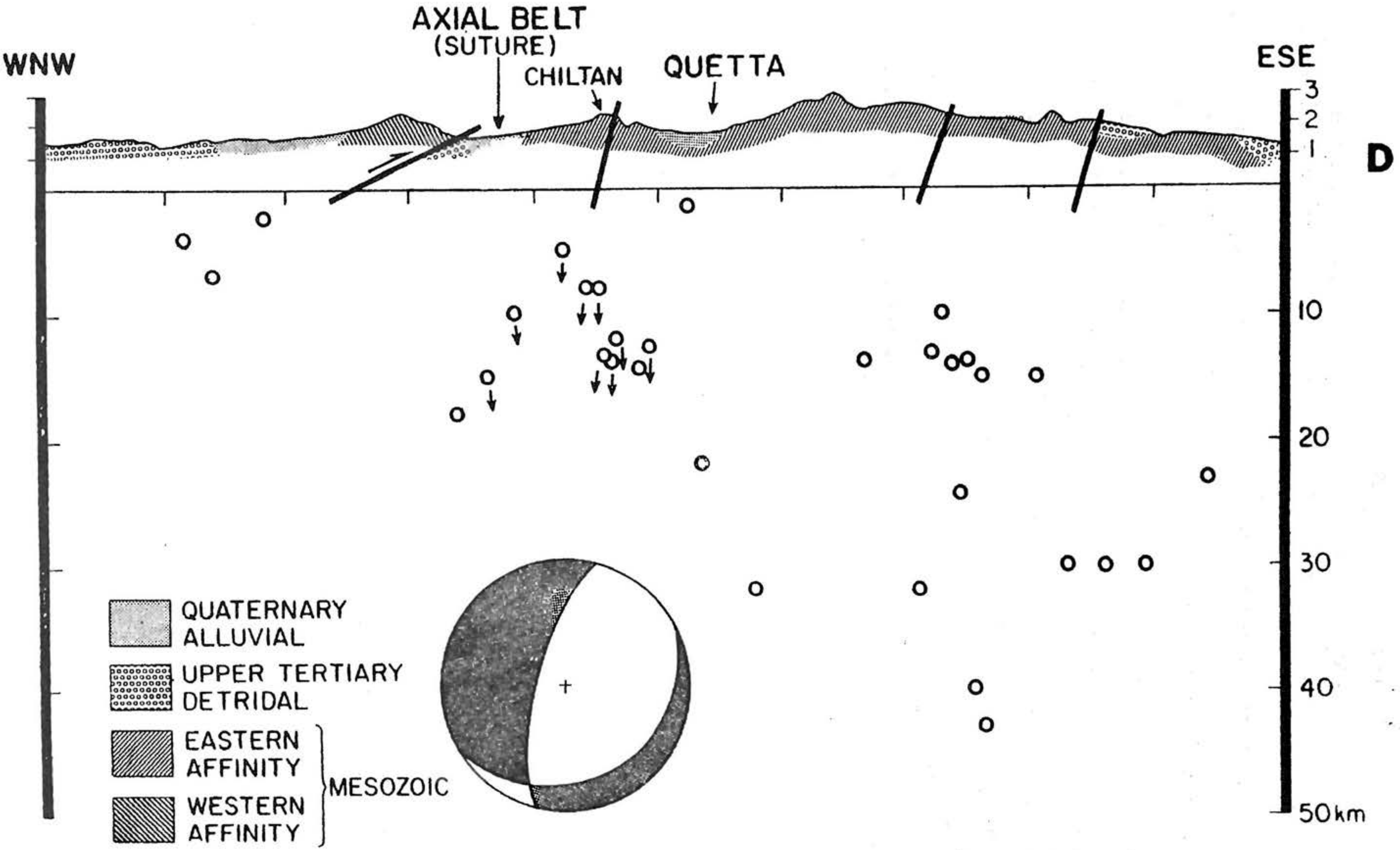


Figure 10: Vertical cross-section across the Quetta region. The projection is along line C-D in Figure 8. Small circles indicate hypocenters determined from Quetta network data. The focal mechanism for events along the Quetta fault is also shown (convex towards the viewer, compresional quadrants darkened). Note the deepening of activity east of the Quetta fault. Geology is from Hunting Survey Corporation (1961). (From Armbruster *et al.*, 1979).

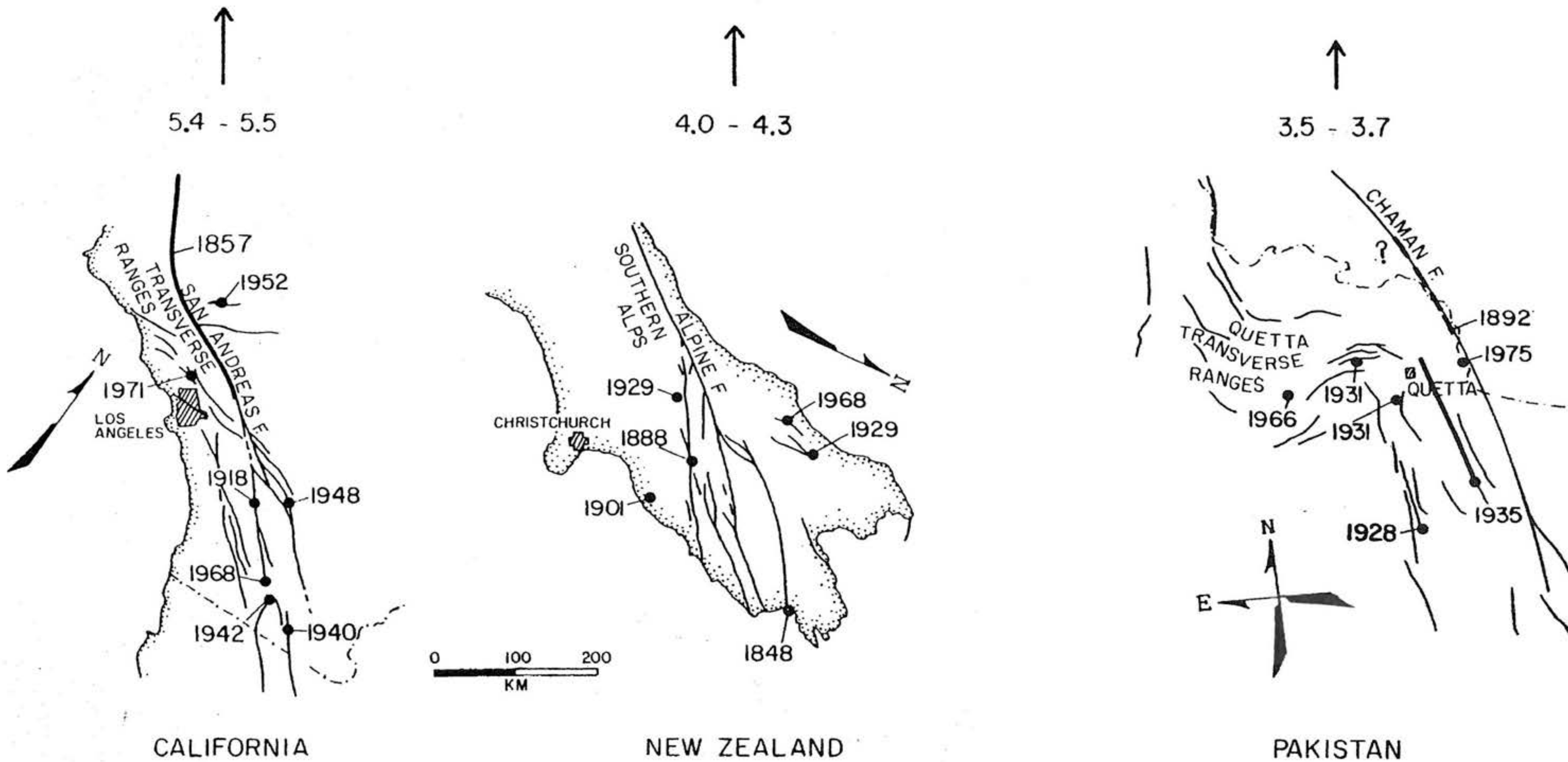


Figure 11: Major seismicity and faults of southern California and South Island, New Zealand (after Scholz, 1977), and the Quetta area, Pakistan. The maps are rotated such that the regional slip vectors (indicated by arrows) are all parallel. Note east and west are reversed in Pakistan to give apparent right-lateral strike-slip in all cases. The length of the slip vectors are proportional to the approximate rate of relative motion between major plates (rate given in cm/yr). Dates of earthquake and zones of rupture mentioned in the text are indicated.

closely associated with the July 1977 Kolpur earthquake. The spatial distribution of hypocenters and the first-motion data are consistent with left-lateral strike-slip on a fault subparallel with the Quetta fault. A second active fault zone strikes NNW, approximately along the axis of the Quetta syntaxis. First motions from this seismicity are consistent with reverse slip on such a fault, NE side up, but a large component of left-lateral strike-slip is also possible.

In analogy with the tectonic framework in northern Pakistan, Armbruster *et al.* (1979) suggest that the deeper seismicity east of Quetta corresponds to a deepening of the Moho and with a normal crust overlain by a thick and decoupled sedimentary wedge. Decollement tectonics in the area of the Quetta syntaxis would explain the lack of correlation between some of the features defines by the seismicity and surface structures (Seeber and Armbruster, 1979; Quittmeyer *et al.*, 1979). Extensive decollement slip can also account for the large anticlockwise rotations of paleomagnetic poles determined for sediments on the eastern limb of the syntaxis (Klootwijk, personal communication). Thus, even in the zone between the Indian and Eurasian plates, where sinistral strike-slip is expected to predominante, the minor components of convergence may result in compressive features within the sedimentary wedge, and a decollement style of tectonics.

THE CHAMAN COMPARED TO THE SAN ANDREAS AND THE ALPINE CONTINENTAL TRANSFORM FAULT SYSTEMS

The Chaman fault system is similar in several ways to two other transform fault systems that pass through continental lithosphere: the San Andreas fault in California and the Alpine fault in New Zealand (Quittmeyer, 1978; Armbruster *et al.*, 1979). Scholz (1977) compared these latter two fault systems and found that distinctive styles of seismicity were associated with similar tectonic features. By extending this comparison to the Chaman fault system, it is possible to make some general statements about the seismic hazard related to this fault system.

Two distinct portions are recognized in all three fault systems. These portions can be classified with regard to their orientation relative to the regional slip vector: one portion of the master fault strikes obliquely (in a convergent sense), while the other is subparallel to the slip vector (Figure 11). Rupture during great earthquakes (M > 7.8), which are characterized by relatively long recurrence intervals, is believed to be the mode of slip on the oblique portions of the faults (Scholz, 1977). The southern California earthquake of 1857 is, however, the only well documented shock of this type within the areas shown in Figure 11. Similar events, with an average recurrence time of about 200 years (Sieh, 1978A and B), have occurred in the past on the same portion of the San Andreas fault.

It is unclear whether the oblique portion of the Chaman fault has experienced a great earthquake in historical times. The 1892 earthquake may have been such an event, but the full extent of rupture during this earthquake is unknown. After the earthquake, the zone of rupture was studied over only a limited region near Chaman where a railroad was offset about 0.75 meters (Griesbach, 1893). If the 1892 shock ruptured to the northeast far beyond the region studied, producing displacements of the order of 10 meters, it may be classified as a great earthquake similar to the 1857 event in southern California. In this case the observed offset near Chaman would have to be unrepresentative of the displacement elsewhere along the fault. On the other hand, if the 1892 earthquake ruptured the Chaman fault for only tens of kilometers near the town of Chaman (31°N), then the oblique portion of this fault has not ruptured for at least a century.

In the second portion of these three fault systems, where the strike of the master fault is almost parallel to the regional slip vector, the fault systems widen to include a number of subparallel faults (Figure 11). Rupture on these faults typically produces large earthquakes (M > 7). However, these events are smaller than the great earthquakes associated with the oblique segment of the master fault. The Quetta earthquake in 1935 (M = 7.5), which ruptured 150 km of a fault east of and subparallel to the Chaman fault (Quittmeyer and Jacob, 1979), is probably typical of the larger earthquakes occurring in this second tectonic province.

The similarity between the Chaman and the San Andreas fault systems suggests that a comparison between the Quetta transverse ranges and the California transverse range is also appropriate. In both transform systems the transverse ranges are zones of convergence that probably are related to the component of plate convergence along the oblique portion of the master fault (Figure 11). In these thrust zones the level of seismicity is quite high (Figure 2; Allen *et al.*, 1965), but large earthquakes (M > 7) are not known. The 1971 earthquake near San Fernando, California is probably typical of the larger earthquakes that characterize the transverse ranges in California and Pakistan.

CONCLUSIONS REGARDING SEISMIC HAZARD

The model presented here for the tectonic processes currently at work in the Himalayas (see also Seeber *et al.*, 1979) provides a new framework for estimating the seismic hazard in that region. The largest and most destructive earthquakes will result from rupture of the Detachment. These events have the potential to seriously effect vast areas in the Indo-Gangetic plain and the Lower Himalaya. Characteristic seismic moments will probably be in the ranges 5 x 10^{27} to 10^{29} dyne-cm (Chen and Molnar, 1977; Quittmeyer and Jacob, 1979). As a comparison, the largest computed moment is 2 x 10^{30} dyne-cm for the 1960 Chile earthquake.

The time period between subsequent large earthquakes rupturing a given portion of the Detachment appears to be typified by a low level of teleseismic activity on that portion of the Detachment. Whether this aseismic character persists at lower magnitudes is not yet clear. In the Aleutian subduction zone, where a similar spatial and temporal distribution of seismicity is observed (Davies and House, 1979; Seeber and Armbruster, 1979b), the quiescence during the interseismic period extends even to the low magnitudes detected by local networks.

The Detachment may slip aseismically in some cases, and, thus, in these cases the aseismic nature of this fault can be permanent. As mentioned above, the Detachment in the Hazara arc region is associated with a thick layer of Infracambrian salt. The lack of seismicity on this portion of the Detachment, which is monitored by the sensitive Tarbela network, may be associated with aseismic slip on the salt layer rather than interseismic strain accumulation.

In regions where large Detachment earthquakes do occur, the generally low level of interseismic activity can bias some methods of seismic hazard evaluation. Studies based on a statistical analysis of seismicity (e.g., Norwegian Geotechnical Institute, 1976) can produce misleading estimates of seismic hazard when the duration of the sampling period is short compared with the recurrence interval of major Detachment earthquakes.

Large earthquakes along the Basement Thrust will also be locally destructive. However, the extent of damage associated with these events will be much less than for Detachment earthquakes. Damage will be limited to the area marked by the zone of relatively continuous activity along the Himalayan arc. The Pattan earthquake (M_s = 6.2; Ambraseys *et al.*, 1975), which occurred on 28 December 1974 in northern Pakistan, may be typical of the largest shocks to be expected from the Basement Thrust.

Three distinct seismic sources are recognized along the transform boundary between the Indian plate and the Afghan block of the Eurasian plate:

1) In the portion of the Chaman fault north of and perhaps including the 1892 rupture (i.e., north of about 31°N), left-lateral motion is concentrated on a narrow fault zone. Slip along this portion is probably accomplished by great earthquakes (M > 7.8) that are separated by periods of quiescence and long duration.

2) In the portion of the Chaman fault system south of 31°N, left-lateral slip is taken up on a set of subparallel faults that form a broad zone. Earthquakes that are large (M > 7), but not great, characterize this portion of the fault system. The interseismic period between events of this type is probably shorter than for the great earthquakes. The major rupture zones remain remarkably quiet during the interseismic period, with intermediate and microearthquake activity concentrated at their extremities.

3) In the Quetta transverse ranges the level of seismic activity has been very high during this century (Figure 2). This high seismicity may be a permanent feature of this structure, but the larger magnitude events associated with this zone are probably lower than either portion of the Chaman fault system. An inferred detachment or decoupling layer below the Quetta transverse ranges (see discussion in previous section) may not be the source of any of the known activity. However, the possibility of rare great earthquakes on this detachment, similar to the great earthquakes associated with the Himalayan Detachment, cannot be ruled out.

Acknowledgements: K.H. Jacob and C. Keith reviewed the manuscript and offered helpful suggestions. We are grateful to the Water and Power Development Authority (Pakistan), the Pakistan Atomic Energy Commission, the Geological Survey of Pakistan and TAMS Engineers (New York) for financial and logistic support in the field operations. This work was supported by USGS grant 14-08-0001-16749 and NSF grant EAR 77-15187.

REFERENCES

Allen, C.R., P. St. Amand, C.F. Richter, and J.M. Nordquist (1965). Relationship between seismicity and geologic structure in the southern California region, *Bull. Seis. Soc. Am.*, 55, 753-797.

Amraseys, N., G. Lensen, and A. Moinfar (1975). The Pattan earthquake of 28 December 1974, UNESCO, Paris, (Serial No. FMR/SC/GEO/75/134), 41 pp.

Armbruster, J., L. Seeber, and K.H. Jacob (1978). The north western termination of the Himalayan mountain front: Active tectonics from microearthquakes, *J. Geophys. Res.*, 83, 269-282.

Armbruster, J., L Seeber, R. Quittmeyer, and A. Farah (1979). Seismic network data from Quetta, Pakistan: The Chaman fault and the fault related to the 30 May 1935 earthquake, submitted to *Memoirs of the Geol. Surv. Pakistan.*

Bakr, M.A., and R O. Jackson (1964). Geological Map of Pakistan, 1:2,000,000, Geological Survey of Pakistan, Karachi.

Borchert, H., and R.O. Muir (1964). *Salt Deposits,* D. Van Nostrand Co., London.

Chandra, U. (1978). Seismicity, earthquake mechanisms and tectonics along the Himalayan mountain range and vicinity, *Phys, Earth Planet. Interiors,* 16, 109-131.

Chen, W-P, and P. Molnar (1977). Seismic moments of major earthquakes and the average rate of slip in Central Asia, *Jour. Geophys. Res.,* 82, 2945-2969.

Davies, J., and L. House (1979). Aleutian subduction zone seismicity, volcanotrench separation and their relation to great thrust-type earhtquakes, *J. Geophys. Res.,* in press.

Fitch, T. (1970). Earthquake mechanisms in the Himalayan Burmese, and Andaman region and continental techtonics in central Asia, *J. Geophys. Res.,* 75. 2699-2709.

Fitch, T. (1972). Plate convergence, transcurrent faults, and internal deformation adjacent to Southeast Asia and the western Pacific, *J. Geophys. Res.,* 77, 4432 4460.

Gansser, A. (1964). *Geology of the Himalayas.* Interscience Publishers, Now York, 289 p.

Griesbach, C.L. (1893). Notes on the earthquake in Baluchistan on the 20th December 1892, *Rec. Geol. Sur. India,* 26, part 2, 57-61.

Gupta, H.K., and H. Narain (1967). Crustal structure in the Himalayan and Tibetan plateau region from surface-wave dispersion, *BSSA,* 57, 235-248.

Hemphill, W.R , and A.H. Kidwai (1973). Stratigraphy of the Bannu and Dera Ismail Khan areas, Pakistan, *Geol. Sur. Prof. Paper* 716-B, 36 p.

Heuckroth, L.E , and R.A. Karim (1970). Earthquake history, seismicity, and tectonics of the regions of Afghanistan, Kabul University.

Hunting Survey Corporation (1961). *Reconnaissance Geology of Part of West Pakistan,* Maracle Press, Oshawa, Ontario, 550 p.

Johnson, G.D., N M. Johnson, N.D. Opdyke, and R.A.K. Taherkheli (1979). Magnetic reversal stratigraphy and sedimentary tectonic history of the upper Siwalik group, eastern Salt Range and southwestern Kashmir, in *Geodynamics of Pakistan,* (A. Farah and K. DeJong, ed.), Geological Survey of Pakistan, Quetta, p. 149-165.

Kelleher, J. (1972). Rupture zones of large South American earthquakes and some predictions, *J. Geophys. Res.,* 77, 2087-2103.

LeFort, P. (1975). Himalayas: The collided range. Present knowledge of the continental arc, *Am. Jour, Sci., 275-A,* 1-44.

Menke, W., and K.H. Jacob (1976). Seismicity patterns in Pakistan and north-western Indian asociated with continental collision, *B.S.S.A.,* 66, 1695-1711.

Middlemiss, C.S. (1910). The Kangra earthquake of 4th April 1905, *Mem. Geol. Sur. India,* 38, 409 p.

Molnar, P., T.J. Fitch, and F.T. Wu (1973). Fault-plane solutions of shallow earthquakes and contemporary tectonics in Asia, *Earth Planet. Sci. Letters,* 19, 101-112.

Molnar, P., and P. Tapponnier (1975). Cenozoic tectonics of Asia: Effects of a continental collision, *Science,* 189, 419-426.

Molnar, P., W-P Chen, T.J. Fitch, P. Tapponnier, W.E.K. Warsi, and F.T. Wu (1977). Structure and tectonics of the Himalaya: a brief summary of relevant geophysical observations, in: Proc. CNRS Symp. Geology and Ecology Himalaya, Paris, December, 1976.

Norwegian Geotechnical Institute (1976). Feasibility study of the Chisapani hydroelectric project on the Karnali River, Nepal — Seismicity (work done under the auspices of Norconsult A.S.), United Nations Development Programme Report NEP/73/014.

Officers of the Geological Survey of India (1939). The Bihar-Nepal earthquake of 1936, *Memoirs of the Geological Surv. of India,* 73, 391 p.

Pennington, W. (1979). A summary of field and seismic observations of the Pattan earthquake, 28 December 1974, in: *Geodynamics of Pakistan,* (A. Farah and K. DeJong, editors) Geoogical Survey of Pakistan, Quetta, 143-147.

Quittmeyer, R.C. (1978). The Quetta-Sibi (Pakistan) syntaxis: Evidence for its origin from seismicity and plate tectonics, *EOS, Trans. AGU,* 59, 323, (abstract).

Quittmeyer, R.C., A. Farah, and K.H. Jacob (1979). The seismicity of Pakistan and its relation to surface faults, In: Geodynamics in Pakistan (A. Farah and K. DeJong eds), Geol. Survey Pakistan, Quetta, 271-284.

Quittmeyer, R.C., and K.H. Jacob (1979). Historical and modern seismicity of Pakistan, Afghanistan, northwestern India and southwestern Iran, *Bull. Seis. Soc. Am.,* 69(3), 773-823.

Scholz, C.H. (1977). Transform fault systems of California and New Zealand: Similarly in their techtonic and seismic styles, *J. Geol. Soc. London,* 133, 215-219.

Seeber, L., and K.H. Jacob (1977). Microearthquake survey of northern Pakistan: Preliminary results and tectonic implications, in: *Proc. CNRS Coloquium on the Geology and Ecology of the Himalayas,* Paris, December, 1976, 347-360.

Seeber, L., and J. Armbruster (1979A). Seismicity of the Hazara Arc in northern Pakistan: Decollement vs. Basement Faulting, in: *Geodynamics of Pakistan,* (A Farah and K. DeJong, eds.) Geol. Survey Pakistan, Quetta, 131-142.

Seeber, L., and J. Armbruster (1979B). The Himalayan and the Alaska-Aleutian convergence zones: A similar pattern of active crustal tectonics and seismicity, *EOS, Trans. Am. Geophysical Union,* 60, p. 390 (abstract).

Seeber, L., J. Armbruster, and R. Quittmeyer (1979). Seismic network data from the Western Syntaxial area: Implications about the Himalayan arc. to be submitted to Geodynamics Project, Volume for Working Group 6.

Sieh, K.E. (1978A). Pre-historic large earthquake produced by slip on the San Andreas fault at Pallett Creek, California, *J. Geophys. Res.,* 83, 3907-3939.

Sieh, K.E. (1978B). Slip along the San Andreas fault associated with the great 1857 earthquake, *Bull. Seis. Soc. Am.,* 68, 1421-1448.

Valdiya, K S. (1976). Himalayan transverse faults and folds and their parallelism with subsurface structures of north Indian plains, *Tectonophysics,* 32, 353-386.

West, W.D. (1935). Preliminary geological report on the Baluchistan (Quetta) earthquake of May 31st, 1935, *Records Geol. Surv. India,* 69, 203-240.