TECTONIC MODEL OF NW HIMALAYAN FOLD AND THRUST BELT ON THE BASIS OF FOCAL MECHANISM STUDIES

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Abstract:

NW Himalayan fold and thrust belt is considered to be seismically one of the active zone in the world. The detailed seismological study of the area indicates that seismicity (≥4.0 Mw) appears to be associated with both the surface and blind faults. At the same time, clustering of events in specific parts along the surface faults shows that some fault segments, especially in the Hinterland zone are more active. In parts of the active deformational front like Salt Range, southern Potwar and Bannu, lesser seismic activity (≥4.0 Mw) could be due to the damping effect of the thick Precambrian salt.

Majority of the earthquakes (86%) range in magnitude from 4.0 to 4.9 Mw followed by 107 events (13%) having magnitude ranging from 5.0 to 5.9 Mw. The remaining 1% range from 6.0 to 6.7 Mw. There is a predominance of shallow seismicity (<50 km focal depth). Even within this depth range, about 81% of the events have focal depths of <25km. Larger magnitudes events are more in the hinterland zone. In contrast, based on distribution of 683 (≥4.0 Mw) events from the adjoining areas, a deeper level of seismicity (50 to 200 km) prevails especially in the Hindukush Range of Afghanistan.

Focal Mechanism Solutions (FMS) of 45 earthquakes (Mw≥4), including 21 from the Hinterland zone and 24 from the Foreland zone show dominance of strike slip faulting (27 out of 45). 11 indicate thrusting, 6 reverse faulting and 1 normal faulting solution. Tectonic complexity seems to be due to interplay of a variety of factors. Thrust and reverse solutions near the northern collisional boundary have mostly NE-SW directed P-axis orientations. Imbricate thrusting, breaking and thickening of the crust is believed to be occurring due to the steep bending of the underthrusting plate at the collisional boundary. Another compressional E-W direction in the southwestern portion suggests the presence of a restraining bend in the Chaman Fault (the western plate boundary). A single normal faulting solution from this part could be similar to the one in the Central Salt Range and acting as a buttress to the south verging compression.

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Strike slip solutions from the hinterland zone are related to the ongoing uplifting in the Nanga Parbat-Haramosh massif and the Besham dome. In the Foreland zone a regional shear couple between the N-S trending sinistral Chaman Fault and the Jhelum Fault at the western and eastern margins respectively is forming the Reidel structures (synthetic shears). A few strike slip solutions represent the P shears (secondary shears). Involvement of basement in the deformation process shows that models of thin-skinned tectonics formulated by different workers may not be valid.

Introduction:

The active fold – and – thrust belt along the northwestern margin of the Indo – Pakistan plate is divisible into two parts – the Sulaiman belt and the NW Himalayan fold and thrust belt. The former is believed to be along a zone of transpression, whereas the latter is associated with the main zone of Himalayan convergence (Jadoon, 1992). Transpression is considered to be result of the 80 to 900 km long Chaman and Ornach – Nal Fault Zones (Lawrence and Yeats, 1979) and forms the western plate boundary. In the Himalayan zone of convergence (Fig.1), the Main Karakoram Thrust (MKT) also known as the Shyok Suture Zone; Main Mantle Thrust (MMT) also known as the Indus Suture Zone; Main Boundary Thrust (MBT) and the Salt Range Thrust (SRT) delineate the major subdivisions of the collision zone (Yeats and Lawrence, 1984; Tahirkheli et al., 1979).

It is believed that the Kohistan Island Arc (Tethyan tectonic domain, according to Kazmi and Abbas, 2001) situated between the MKT and MMT sutured in the north (along MKT with the Laurasian tectonic domain) about 100 Ma during the Cretaceous (Treloar et al., 1989). The collision at its southern extremity (along MMT with the Gondwanian domain) occurred about 50 Ma (Treloar and Rex, 1990). Following the cessation of movement along MMT (3 – 15 Ma according to Zeitler et al., 1980), deformation shifted southwards to MBT. Here the Lower Tertiary rocks are thrusted over Miocene molasses. In the later phases, thrusting propagated south to the SRT. In the Salt Range, deformation as young as 0.5 Ma has been documented by Yeats and Lawrence, (1984).

On a regional scale, the region south of SRT is an east-west trending ridge of Precambrian rocks, referred to as the Sargodha High, and corresponds to the forebulge of the NW Himalayan fold and thrust belt (Pennock et al., 1989) as a result of flexure of the underthrusting Indo-Pakistan plate (e.g. Duroy et al., 1989). The Kohistan Island Arc (north of MMT) is considered to be representing an orogenic wedge.

The compressional forces being experienced in the NW Himalayan fold and thrust belt are believed to be a result of the ongoing collision of the Eurasian and Indo-Pakistan plates that took place in the late Eocene to Early Oligocene. The Indo-Pakistan plate, relative to the Eurasian plate is still moving northwards at a rate of about 2 mm/yr (Patriat and Achache, 1984). In this part of Pakistan (NW Himalayan fold and thrust belt), recent work of some workers (e.g. Verma, 1991; Sercombe et al., 1998; MonaLisa et al., 2002; MonaLisa et al., 2004) as well as the present study suggests that transpression (strike slip faulting) is also operative in this compressional regime. The NW Himalayan Fold and Thrust belt is one such structure that is undergoing active deformation.

Seismicity Pattern:

Pakistan and adjoining countries experience high frequency of earthquakes, which in some cases have resulted in great loss of life and destruction. In Pakistan, besides the two active fold and thrust belts (Sulaiman Fold and Thrust Belt and NW Himalayan Fold and Thrust Belt), high zones of seismicity exist in other parts of the country also.

In the discussion to follow, an account of the historical and instrumental seismicity along with a brief account of the seismicity pattern observed within the study area is provided.

Historical Seismicity

The destructive power of earthquakes have been observed, narrated and even transferred to written accounts long before the advent of seismic instruments. This information has proved useful in not only becoming aware of earthquake prone regions of the historical past but in knowing the probable loss of life and in assessing the amount of damage that may have occurred. Quantification of this information in terms of intensity scales like the Modified Mercalli Intensity scale (MMI) have aided in assigning various magnitudes to the historic events in the area of interest. Thus the historical data is also shown in the seismicity map compiled for the area (Fig.2b).

Keeping in view the above information, a number of catalogues that have included historical seismicity are available for the study area. Some notable contributors who have provided this information are Oldham (1893, in report of Pakistan Meteorological Department); Ambraseys et al., (1975); Quittmeyer et al., (1979); catalogues of the seismic observatories of Pakistan Meteorological Department, Atomic Energy Commission, and those of Tarbela and Mangla Dams. All this information, although most likely incomplete, forms part of the Table.1.

Instrumental Seismicity

The quality of detection and location of earthquakes in the subcontinent improved in 1964 after its coverage by the World Wide Seismographic Stations Network (WWSSN) that comprised of about 120 stations in 60 countries, although instrumental recording of earthquakes had started in 1904.

Thus the recorded data for the period 1904-1964 of the region is quite limited. Present day seismicity is reported by both international and local networks like World Wide Standard Seismograph Network (WWSSN), United States Geological Survey (USGS), International Seismological Centre (ISC), British Association for the Advancement of Science (BAAS), International Seismological Summary (ISS), microseismic networks of Pakistan Atomic Energy Commission, Mangla and Tarbela seismological observatories of WAPDA and Pakistan Meteorological Department (PMD). With the help of above-mentioned sources an instrumental catalogue has been prepared listing a total of 813 events with magnitude ≥4.0 Mw.

Seismicity Pattern

Using both historical and instrumental earthquakes, a seismicity map has been prepared and is shown as Fig. 2b. These events as mentioned in the previous section are of magnitude ≥4.0 Mw. In addition, in order to give a better picture of the overall seismicity prevailing within the region, 683 earthquake events of magnitude ≥4.0 Mw that occurred in the adjacent areas during the period 1904-2002 have also been plotted. This data was obtained mostly from the ISC and USGS websites.

The maximum magnitude event that occurred within the study area is of 6.7 Mw in the Raikot-Sassi Fault Zone. It can be observed from Fig. 3.1 (a) that majority of the events (696) range in magnitude from 4.0 to 4.9 Mw. These events forming 86% of the total are followed in abundance by those with a magnitude ranging from 5.0 to 5.9 Mw. Such events numbering 107 form 13% of the total events. Only 10 events have magnitude ≥6.0. Further, the events that occurred in the adjacent areas and are shown in the seismicity map (Fig. 2) also have a similar distribution of magnitude as the study area. This can be observed from Fig. 3.1 (b).

The distribution of seismicity with respect to focal depth is shown in Fig. 3.2 (a). From this figure it can be concluded that shallow seismicity <50 km focal depth) dominates in the study area. A further subdivision of this shallow focal depth indicates that most seismicity is occurring within 25km depth ranges. In contrast to the study area, the adjacent area has deeper levels of seismicity. This can be observed from Fig. 3.2 (b) where 683 events recorded by the international networks are plotted. It shows that majority of the events in the adjacent areas have focal depths of 50 to 200 km. These deeper levels of seismicity mostly occur to the northwest of the study area in the Hindukush range of Afghanistan.

Overall picture of the seismicity showing the distribution of magnitude with respect to depth is given in Fig. 3.3. The figure contains the data of the study area as well as the data of the adjoining region that was plotted in Fig. 3.2 (b). It indicates that events having magnitude ≥ 5.0 originate at relatively shallower depths.

Epicentral distribution of the earthquakes shown in Fig. 2b indicates that all of them are not associated with surface tectonic features, but appear to be randomly distributed. This leads to the inference that besides the active surface faults, active blind faults also exist. In some cases, the epicentres occur in clusters along the local tectonic features. This clustering appears more prominent in the hinterland zone of the fold belt. In the foreland zone too, some concentration of epicentres is observable such as along the southern termination of the Jhelum Fault and in southern Kohat.

In the seismicity map (Fig. 2b) there are areas like the Salt Range, Southern Potwar near Talagang and the Bannu Basin with little or no epicentral distribution. One reason is that inspite of general agreement of Salt Range and Southern Potwar being a part of an active deformational front, only low magnitude levels (≤ 4.0 mb) have been recorded as previously observed by Seeber and Armbruster (1979), and Quittmeyer et al., (1979); where as in the seismicity map only events having magnitude ≥4 have been plotted.

Another reason may be the presence of a thick sequence of EoCambrian salt in the Salt Range and Potwar area that may be having a damping effect. The lithologies occurring in the Salt Range/Potwar are believed to be extending into the Bannu Basin also (e.g. Kemal, 1992) thereby implying the presence of salt in this part also.

Focal Mechanism Solutions (FMS):

Procedure Employed

In the present work, forty-five Focal Mechanism Solutions (FMS) of earthquakes (Mw≥4) that occurred in the North Western Himalayan Fold and Thrust Belt (NWHFTB), Pakistan during the period of 1964 to 2004 (Table.2) have been carried out using the P-wave polarity data. The standard lower half hemisphere projections on an equal area net have been used. Two programs, namely AZMTAK and PMAN of Suetsugu (1997) in FORTRAN, using a PC have been employed. The former computes the epicentral distance and azimuth for each station, and obtains the take-off angle. The latter generates the focal mechanism diagrams based on input of geographic coordinates, magnitude, focal depth and P-wave polarity for each event.

Overall, 21 events are from the hinterland zone and the remaining 24 from the foreland zone of the NW Himalayan Fold and Thrust Belt. The football diagrams of all these 45 FMS are given in Fig.4. Source and FMS parameters are given in the Tables 2 and 3 respectively.

As mentioned previously, time period covered is till 2004. Events have been numbered 1-45 considering their date of occurrence with number 1 being the oldest and number 45 the last event to have occurred in this time period. A brief description of FMS is provided below. The solutions of the hinterland zone are discussed first followed by those of the foreland zone.

FMS in Hinterland Zone:

A total of 21 out of 45 events are located within the Hinterland zone that comprises of the tectonic subdivisions of the crystalline nappe zones and the Khyber-Lower Hazara Metasedimentary Fold and Thrust Belt. 14 FMS are from the former and 7 from the latter (Fig.2b). Their detail description is provided below.

FMS IN THE CRYSTALLINE NAPPE ZONE:

In the crystalline nappe zone, 8 solutions indicate thrust/reverse faulting while 6 are of strike slip faulting.

FMS 44 and 45: These events are situated near the MMT (Figs.2a and b) that forms the northern boundary of the study area and is also the collisional boundary where the Indo-Pakistan plate underthrusts the Kohistan Island Arc. Another important thrust occurring in this part of the area, immediately south of the MMT is the Banna Thrust that is a part of the tectonic subdivision referred to as the Banna Nappe.

In this part of the study area, on the basis of seismicity, a wedge shaped NW trending structure has been recognized. Armbruster et al., (1978) named it as the Indus Kohistan Seismic Zone (IKSZ). Later workers (e.g. Seeber and Armbruster, 1979; Ni et al., 1991) have also confirmed the presence of this NW trending 100 km long feature between the Hazara-Kashmir Syntaxis and the MMT. This nearly 50km wide zone of seismicity has a nearly horizontal upper surface and a lower NE dipping surface.

Ni et al., (1991), on the basis of relocated hypocentres, have identified two seismic zones within the IKSZ i.e. a shallow zone extending from the surface to a depth of 8km and a more pronounced midcrustal zone lying at depths of 12 to 25km. The upper boundary at a depth of about 12 km is considered to be representing a decollement surface that decouples the sediments and metasediments from the basement.

Focal depth of these events (10 km) suggests that the cover rocks within the Banna nappe zone were affected by the earthquake activity. These rocks comprising of schists, slates, phyllites and marbles have undergone both ductile and brittle deformation and have been emplaced on the mylonites, gneisses and schists of the Precambrian Tanawal Formation. In both the solutions (Fig.4), the nodal planes trending in the NW-SE direction are considered to be the rupture planes. Their dip direction towards the NE is in agreement with the general dip direction of the area. A right lateral sense of motion is inferred in both the solutions. They are from an area located to the east of the Besham dome (Fig.2). In this domal structure, the basement uplift is still an ongoing process (Baig and Lawrence, 1987; Treloar et al., 1989) and may be the reason for generating right lateral strike slip faults in this part of the study area. The FMS in Harvard CMT Catalogue also show strike slip solutions with some thrust component.

FMS 12: This event like the previous two events is also located near the MMT (Figs.2a and b). It was the second largest earthquake to have affected the study area and it had a magnitude of 6.4 Mw (Table.2). Another important fault located near the epicentre is the left lateral Puran Fault (Baig et al., 1989). Focal depth for this event is 15km.

From the earlier description, it is known that the IKSZ occurs at depths ranging from 12 to 25km. According to Ni et al., (1991) most IKSZ events are deeper than 12 km in which the shallow events are associated with the reactivated parts of MMT, while the deeper earthquakes may be related to the underthrusting of the Indo-Pakistan plate beneath the IKSZ. The lower portion of IKSZ (12-25 km) represents a major thrust zone (Armbruster et al., 1978; Ni et al., 1991).

Various workers named this event as the Pattan earthquake of 1974, due to its location near Pattan village, and determined its FMS. Different workers (Chandra, 1975, Pennington, 1979, Khurshid et al., 1984) have inferred thrust faulting with the rupture plane trending in the NW direction and dipping towards NE except the solution of Chandra (1975) that shows dip in the NW direction.

Composite fault plane solutions obtained from the IKSZ show reverse faulting along NW striking planes dipping towards the NE or more steeply towards the SW (Armbruster et al., 1978; Ni et al., 1991), or strike slip solutions or a mixture of both (Armbruster et al., 1978). Solution obtained in the present study (Fig.4) is of reverse faulting. A similar NW trend dipping towards the NE as obtained by the above named workers is obtained. Dip is 520NE (Table.3). Like Pennington (1979), a right lateral strike slip component is inferred. Finally the solution supports the contention that a major active thrust fault zone (IKSZ) underlies the decollement.

FMS 1, 3, 7, 11, 13, 14 and 23: All of these events are situated near or along the MMT that forms the northern boundary of the study area (Figs.2a and 2b). The other important active faults in this area are the right-lateral Thakot and left-lateral Puran faults (Baig and Lawrence, 1987; Baig et al., 1989) except in the case of event number 23. This has its epicentral location on the northeastern side of HKS (Figs. 2a and b) between the MBT and Batal Thrust. The latter fault is also considered to be representing the Main Central Thrust (Chaudhry and Ghazanfar, 1992), a major thrust that separates the Lesser Himalayas from the Higher Himalayas.

Focal depth for these events varies from 47 to 68 km (Table 2) thereby indicating seismic activity below the earlier described IKSZ. Publications of Armbruster et al., (1978), and Seeber and Armbruster (1979) have documented seismic activity from these deeper levels. According to Ni et al., (1991), a zone of diffuse seismicity occurs below the IKSZ till a depth of 50km and indicates intraplate activity in the Indo-Pakistani plate. Armbruster et al., (1978) recognized seismic activity till a depth of 70km. Earthquake activity is inferred to be within the basement of the plate or in the uppermost mantle due to the steep bending of the plate. Most workers including those basing their interpretation on gravity data (e.g. Khan and Ali, 1994) agree on the presence of the Indo-Pakistan plate and it's underthrusting beneath the Himalayas.

There is general agreement that thrusting is the major deformational process operating at these levels. Focal mechanism solutions of these events support this contention as all solutions show thrusting (Fig.4). All trend in the NW-SE direction and have dips ranging from 70 to 340 in the NE direction. P-axis orientations of these events (Fig. 4) are NE-SW directed. Following Armbruster et al., (1978), it is believed that imbricate thrusting, breaking and thickening of the crust to a depth of 60 to 70 km is producing thrusts with mostly shallow dips in an overall steeply dipping seismic pattern. Thus, they are considered to be intraplate events affecting the lower crust.

In the case of event number 23, it supports the contention of Seeber et al., (1980), that a similar style of deformation prevails in this part of the area also.

FMS 40: This event is located on the nearly N-S trending, right-lateral strike slip Thakot Fault (Figs.2a and b). The fault is considered to be the surface expression of the Tarbela Seismic zone. This zone lying between depths of 8-18km (8 to 15km according to Ni et al., 1991) overlies the HLSZ and comprises of thrusts and strike slip faults with strikes in both the NW and NE directions (Armbruster et al., 1978; Seeber and Armbruster, 1979). According to Ni et al., (1991), the strike of faults is in the E-W direction and can be correlated to the surface mapped thrusts and strike slip faults.

Composite fault plane solutions of microseismic data indicate steeply dipping faults with reverse or strike slip motions (Armbruster et al., 1978). In the present case, the nodal plane trending in the NW-SE direction with nearly vertical dip is considered to be the rupture plane (Fig.4). The sense of motion indicated is of right lateral slip. Thus, the FMS although having a slightly different trend, but with similar sense of motion as the Thakot Fault is considered to be representing it. Focal depth (10km) of the event also supports the contention of Baig and Lawrence (1987) that it is a basement fault.

FMS 28: This event is located in the Mohmand-Swat crystalline nappe zone of Kazmi and Jan (1997) about 10 km west of the Puran Fault (Figs.2a and b). This is high angle, left lateral shear and marks the western boundary of the Besham nappe zone. No other mapped fault is situated at the epicentral location. Focal depth given by ISC is 33km and according to them this number should be treated with caution.

From amongst the two nodal planes in this strike slip solution (Fig.4), the one trending in the NE direction is considered to be the rupture plane. This trend is not only similar to the trend of the Puran Fault, but also gives steeper dip (880) and indicates left lateral sense of motion. It is believed that the continued uplift of the Besham antiformal structure is responsible for left lateral strike slip faulting on its western side (Baig et al., 1989). Thus the shear zone accommodating the uplift may be broader than previously envisaged and is most likely extending at least till this part of the study area.

FMS 42 and 43: Both of these events are situated in the Nanga Parbat Haramosh massif (the north-eastern most nappe zone) as shown in Figs.2a and 2b. Focal depth is 23 and 45 km respectively (Table. 2).

The fault-bounded massif has a complex geology. According to Chaudhry and Ghazanfar (1992), the tectonic history (plutonism, metamorphism and deformation) of the Indo-Pakistan plate in the massif is markedly different from other parts. On the western side of the massif, near the epicentral locations, a nearly N-S trending MMT/Raikot-Sassi fault zone occurs. Both thrusting and dextral strike slip faulting has been documented from this part with the latter more prominent in the northern portion. It is considered to be part of an ongoing phase of deformation.

FMS 42 (Fig. 4) obtained is of strike slip faulting with some normal component. From the two nodal planes, the one trending in the NNE-SSW direction is considered to be the rupture plane. This inference has been made due to the reason that it is similar to the dominant trend of faults in the area including that of the major suture (MMT). Further, a number of fault splays parallel to the MMT occur in the vicinity. Probably one of the splays was activated. The trend (NNE-SSW) of the rupture plane indicates a right lateral sense of motion that is in agreement with such type of movement in the area.

FMS 43 is for an event having magnitude of 6.7Mw (Table.2) and is the strongest of the earthquakes to have affected the area. This event occurred after about 19 days of event number 42, in the southerly part of the same fault zone. According to Kazmi and Jan (1997), the gneisses of the Indo-Pakistan plate have been thrusted on the recent alluvium in the vicinity of the epicentre and the southeast dipping thrust is named as the Liachar Thrust (Raikot Fault). The MMT is also situated nearby. A number of right lateral strike slip faults trending in the NNE-SSW direction have also been recognized in this area of thrusting. As such, in the focal mechanism solution (Fig. 4), the NNE-SSW trending nodal plane that indicates right lateral sense of motion is inferred to be the rupture plane.

Khwaja et al., (2003) have obtained similar solutions for both the events. Most likely, complex convergence of the plate, differential but rapid rates of uplift that are being accommodated along the fault zone, structural alignment of domes in an E-W direction within the massif individually or in combination may be contributing towards this type of activity. It may be mentioned that for both these events Harvard CMT Catalogue shows normal faulting and did not incorporate local data.

FMS IN THE KHYBER-LOWER HAZARA METASEDIMENTARY FOLD AND THRUST BELT:

A total of 7 FMS have been determined from this part of the hinterland zone. Majority of them are strike slip (5 events), 1 is reverse, while the solution of one event is undecided. Further description is given below.

FMS 8,10,25,33,34 and 35: are for events located in an area in which a number of faults (Figs. 2a and b) like the Panjal-Khairabad Fault and the Darband Fault (left-lateral strike slip fault) occur. At a distance of about 60 km from the earlier described IKSZ, two seismic zones overlying each other have been recognized from this part of the study area (Seeber and Armbruster, 1979). They run parallel to the IKSZ i.e. extend in the NW-SE direction.

The overlying zone, which extends from 8-18km depth is referred to as the Tarbela Seismic Zone (e.g. Kazmi and Jan, 1997). It comprises of steeply dipping faults with NW and NE trends (Armbruster et al., 1978; Seeber and Armbruster, 1979). Ni et al., (1991) infers the trend of faults (Thrusts and strike slip faults) to be in the E-W direction. Underlying the Tarbela Seismic Zone between 20 to 50km depth is the Hazara Lower Seismic Zone (HLSZ). Like in the IKSZ, a nearly horizontal decollement is considered to be separating these two zones. Steeply dipping reverse and right lateral strike slip motion in the basement is inferred (e.g. Seeber and Armbruster, 1979).

Table 2 shows that the focal depths of these events ranges from 21 to 50 km i.e. they occur within the HLSZ. All solutions are in agreement with the above observation of reverse or strike slip faulting prevailing in the HLSZ. Event number 10 is of reverse faulting (Fig.4). The nodal plane with steep dip and trending in the similar direction as the HLSZ i.e. in the NW direction is considered to be the rupture plane (Table.3). It may be mentioned that Verma et al., (1980); and Verma and ChandraSekhar (1986) obtained a left lateral strike slip solution based on the data of USGS only.

The other FMS (Nos. 8, 25, 33, 34 and 35) show right lateral strike slip faulting (Fig.4), if the rupture planes are considered to be having a NW trend. The trends and steep dips are in agreement with the observations of Seeber and Armbruster (1979). It may be mentioned that for FMS 8, Tandon and Srivastava (1975a) inferred normal faulting and related the event to MBT.

The advance of the Indo-Pakistan plate northwards and its deformation has created a complex geologic pattern in the study area. In this part, deformation is proceeding in both the overriding rocks as well as affecting the basement rocks of the plate. According to Ni et al., (1991) the interpretation of Seeber and Armbruster (1979) that the entire basement of the Indo-Pakistan plate has been broken up is not correct and is based on only a short period of seismicity. Further they point out that gravity data also do not indicate a major break. On the other hand, Khan and Ali (1994) basing their conclusions on gravity interpretation suggest that HLSZ comprises of a number of blocks broken up by faults. In the present case, based on midcrustal seismicity, one reverse and five strike slip solutions; the existence of HLSZ with the basement undergoing significant changes is documented.

FMS 20: This event of Mw 5.1 is located in the Peshawar Basin, a subdivision of the metasedimentary belt (Fig.2a and b). The area is underlain by alluvium. However, two E-W trending faults (Nowshera and Kund Faults) dipping towards the north and a few pressure ridges showing left lateral or reverse slip occur in the vicinity of the epicentral location. Basement is considered to be involved in faulting for all these structures. More than one type of FMS can be obtained (Fig.4). Based upon the nearby structure a strike slip solution has been selected. The only conclusion that can be drawn is about the involvement of the basement.

FMS in Foreland Zone:

24 events for which the required parameters were available have been analysed from the foreland zone of the study area. Out of these 24 FMS, 15 are strike

slip, 8 are reverse/thrust and 3 are normal. The foreland zone comprises of tectonic zones like the Hazara Kashmir Syntaxis (HKS), Kurram-Cherat-Margalla fold and thrust belt, and Salt Range and Kohat-Potwar fold belt. Majority of the FMS (20) are from the Salt Range and Kohat-Potwar fold belt followed by three solutions from the Kurram-Cherat-Margalla Fold-and-Thrust belt and one FMS only from the HKS. Details are given below.

FMS in HKS: FMS 6 is situated in the core of HKS near its eastern limb (Figs.2a and b). Structurally the area is very complex. Most of these structures are thin-skinned structures and no known deeper structure has so far been documented from or near the epicentral location. The only major subsurface structure occurring in the core, but at some distance away is the Bagh Basement Fault (BBF). According to Khan and Ali (1994), based on gravity data, a NW-SE trending steeply dipping (NE direction) basement fault extends to the Moho from a depth of about 18 km.

Focal depth of the event (43km) suggests that the crystalline basement has been affected (total thickness of crust here is about 58km). FMS obtained is of a pure thrust (Fig.4). Considering the trend and dip direction of the above described basement fault, the plane dipping towards the NE at an angle of 260 is inferred as the rupture plane (Table.3). This suggests that more than one basement fault exist in the core of the syntaxis. Probably more detailed gravity modelling would help in providing information about its existence.

FMS IN THE KURRAM-CHERAT-MARGALLA FOLD AND THRUST BELT:

Three FMS have been analysed from this part of the foreland zone i.e. FMS 2,17 and 32. Except for the FMS 2 (right-lateral strike slip), the remaining two events are reverse/thrust.

FMS 2 and 17: These two events are from an area characterized by thrust sheets. Prominent thrusts identified by different workers are the Nathiagali Thrust, Sangargali Thrust and Thandiani Thrust (Figs. 2a and b).

The earlier described HLSZ extends to this part of the study area also. It was mentioned that this seismic zone occurs at depths of 20 to 50 km. In this zone, steeply dipping reverse and right lateral strike slip motion is affecting the basement (e.g. Seeber and Armbruster, 1979). Focal depths of FMS 2 and 17 are 37 and 42 km respectively (Table.2) thereby indicating their location within the HLSZ. FMS 2 indicates right lateral strike slip motion if the nodal plane trending in the NNW-SSE direction is inferred to be the rupture plane. The trend, sense of motion and steep dip (Table.3) is in accordance with the behaviour of the HLSZ. In the case of FMS 17, reverse faulting is inferred on the NW trending nodal plane. A minor component of right lateral strike slip is also obtained on this plane. Thus, this solution is also in agreement and supports the nature of changes taking place in the HLSZ.

FMS 32: This event is from an area situated immediately north of the MBT (Figs. 2a and b). It is a major thrust of the area and has variable dips ranging from 500 to nearly vertical (Kazmi and Jan, 1997). A number of left lateral strike slip faults with minor displacement and small lateral extent occur on both sides of the MBT (e.g. Sercombe et al., 1998; Jadoon et al., 1995). These are considered to be splays of the northward dipping MBT and in the vicinity of the epicentre have a nearly NE-SW trend.

The depth of basement near the MBT is about 8km (Jaswal et al., 1997). On the basis of gravity data, it has been inferred that the MBT is a thick-skinned fault penetrating upto the depth of the upper crystalline basement (Khan and Ali, 1994).

Seeber and Jacob (1977) had suggested that MBT is directly connected to the earlier described HLSZ forming a north dipping reverse fault. According to Seeber and Armbruster (1979) this seismic structure (decoupling layer) is well recognized below a depth of 20km. The focal depth of the event of about 8km (Table 2) coincides to the depth of basement thereby indicating that the event is probably not related to this seismic structure, but occurs above it. It may be mentioned here that the TSZ that overlies the HLSZ is not known to extend in this part of the study area.

FMS obtained is of thrusting with a strike slip component (Fig.4). Considering the above information, the nodal plane trending in the NW direction is considered to be the rupture plane (Table.3). This indicates left lateral sense of motion that is in accord with the observed motion on the mapped strike slip faults occurring in the area. Thus the event indicates shallow activity on one of the many splays of the MBT. Influence of the left lateral Jhelum Fault (western boundary of HKS) or uplift of the Hazara Kashmir Syntaxis is considered to be playing an important role in the development of left lateral slip.

SALT RANGE AND KOHAT-POTWAR FOLD BELT: It covers a large part of the foreland zone between the MBT in the north, and the Salt Range Thrust, Kalabagh Fault and the Surghar/Khisor/ Marwat Thrusts in the south. Along the eastern margin, the Jhelum Fault separates it from the Hazara-Kashmir Syntaxis, while the Kurram Fault delineates its western boundary (Figs. 2a and b). A total of 20 events have been analysed from this part. Out of these, 14 are strike slip, 5 are reverse/thrust and 1 is normal solution. The FMS are discussed below.

FMS 26,31,15,16,5,24,38,21,22,39 and 41: All these eleven events occurred in the Potwar Plateau (Fig.2). Out of these eleven, ten are strike slip and one is reverse.

FMS 26 and 31: Both these events are located in an area bounded by the MBT in the north and Khair-i-Murat Fault (KMF) in the south (Figs.2a and b). The area is commonly referred to as the Northern Potwar Deformed Zone (e.g. Kazmi and Jan, 1997). E-W trending tight and complex folds characterize this area. The southern limbs of the folds are overturned and cut by steep angle faults.

According to Lillie et al., (1987) the area contains an imbricate stack of thrust faults (mostly E-W trending, but NE-SW trend in eastern part) with some being on the surface and others occurring as blind thrusts. Seismic sections indicate that several subsurface faults merge into the basement between the MBT and the KMF. They also reveal that MBT has a dip of about 650–700 and KMF has steeper dip of 800. Both dip towards the north. Further a number of left lateral strike slip faults with small displacement and lateral extent occur on both sides of the MBT (e.g. Sercombe et al., 1998; Jadoon et al., 1995). These are considered to be splays of the MBT.

The focal depths of both the events are 10 and 6.5 km respectively (Table.2). Basement (for FMS 26) and cover rocks (for FMS 31) seem to have been affected. Strike slip solutions are obtained for them (Fig.4). The E-W trending nodal plane in solution number 26 and the NE trending nodal plane for solution number 31 with left lateral slip are considered to be the rupture planes. These trends are in agreement with the observed trend of major structures. Also the nearly vertical dips of these inferred rupture planes support this view.

Probably the uplift of Hazara-Kashmir Syntaxis located to the east of these events is responsible for left lateral slip in the area. The influence of the N-S trending left lateral Jhelum Fault, a major structure of the area that also separates this area from the HKS could also be the reason for this type of displacement. In this same area i.e. eastern Potwar, Iqbal and Ali (2001) have interpreted the NE oriented thrusts to be a result of deformation along the left lateral Jhelum Fault.

FMS 15 and 38: FMS 15 of magnitude 5.5 Mw (Table.2) is one of the strongest events to have occurred in the Potwar Plateau. The hypocentral depth of the event commonly referred to as the Rawalpindi earthquake is 14.5 km (Table.2). Structurally NE-SW trending folds and faults characterize this area. Riwat thrust is one of these NE-SW trending faults and the epicentre of this event is located on the Riwat fault (Figs.2a and b).

This event has previously been studied (Seeber and Armbruster, 1979; Verma and ChandraSekhar, 1986). Strike slip solutions were obtained in both the studies. In the present case too, a strike slip solution has been obtained (Fig.4), but our interpretation is different. According to Seeber and Armbruster (1979) the decoupling layer recognized by them in the north (see the discussion for FMS 9,11,28,39,40 and 42) may be extending here and responsible for the earthquake. Similarly, Verma and ChandraSekhar (1986) believe that activity to the north in Hazara region is the cause.

In the present case, the information of Pennock et al., (1989), has been incorporated to arrive at a different conclusion than the above-mentioned workers. According to Pennock et al., (1989), another fault exists below the Riwat Fault at a depth of 2-3km and it extends into the basement. This blind fault dips towards the southeast. Considering the NE trending nodal plane as the rupture plane in the solution (Fig.4) not only indicates a left lateral sense of motion, but also show dip in the southeast direction (Table.2). Thus, it is believed that the blind fault in the basement is active and responsible for the generation of this earthquake. Like the previously described two events, the tectonics of the HKS seems to be influencing the development of left lateral slip in the area.

FMS 38: is of an event having magnitude 5.2 Mw (Table.2) and focal depth of 5km. Its epicentre is located a few km south of the Riwat Thrust in a syncline. The Chak Beli Khan and Tanwin–Bains anticlines occur to north and south of the syncline respectively. Pennock et al., (1989) consider the Tanwin-Bains anticline as a pop up structure. The two thrusts bounding the pop up have a NW and NE trend. At the northwestern terminus of the Chak Beli Khan anticline, the Riwat Thrust occurs on the surface. The basement has a low dip of 1 to 1.5 (Moghal et al., 2003). According to Pennock et al., (1989) and Moghal et al., (2003) based on seismic reflection data, a basement fault exists beneath the Chak Beli Khan anticline. In this area of structural complexity, the basement is encountered at a depth of about 5km.

The solution obtained is of strike slip faulting and is probably related to the basement fault that is present here. Left lateral motion on the NE-SW trending nodal plane is inferred (Fig.4). It seems likely that the major fault of the area referred to as the Jhelum Fault and epeiorogenic movements in the HKS are influencing the active strike slip faulting in this part of the study area. Further details about its influence are described in the last section of this chapter.

FMS 16: The epicenter of FMS 16 is located on the Jhelum fault (Figs.2a and b). The focal depth of this event having magnitude 5.1 Mw (Table.2) as given by the local network is 8.8 km. It is a nearly N-S trending left lateral strike slip fault that is playing an important role in the present deformation history of the area. Seismicity map (Fig.2b) shows a cluster of seismic events located in the vicinity of the fault.

The fault has steep dips towards the east and a left lateral offset of about 31km (Baig and Lawrence, 1987). Rocks along the fault are highly deformed. Baig and Lawrence (1987) have documented uplift and tilting of Quaternary terraces with localized active landslides. Another feature indicating the active nature of the fault is the presence of shatter zones between Kohala to near Muzaffarabad along the Jhelum River.

In the FMS (Fig.4), the nodal plane with a NW trend and indicating a left lateral sense of motion is considered as the rupture plane. This trend nearly approximates the orientation of the fault and shows a similar sense of motion. Further the steep dip suggests that the fault is nearly vertical at this location.

FMS 5 and 24: are for events located in the southern Potwar, an area located between the Soan Syncline and Salt Range (Figs. 2a and b). The area is mostly characterized by large anticlines and synclines. A decollement at the base of Eocambrian evaporates is believed to be present (e.g. Kazmi and Jan, 1997). In addition, at least one more decollement is recognized in younger rocks (Moghal et al., 2003). The basement in the Salt Range and Potwar plateau is interpreted to be having a gentle dip of 10 to 40 towards the north (Lillie et al., 1987). Near the location of the two events, the basement is encountered at a depth of about 4km (Pennock et al., 1989).

Surface structure occurring near these two epicentral locations is called the Qazian anticline. It like other surface structures of this area has a NE-SW trend. It is considered to be a pop up structure bounded by two thrust faults (Pennock et al., 1989; Moghal et al., 2003). Balanced cross section of Pennock et al., (1989), which incorporated seismic data also indicates that these thrusts extend till the basement that lies at a depth of about 4km. They further interpret the presence of a normal or reverse fault in the basement, based on seismic data. A major fault (Jhelum Fault) is located about 10 km east of the epicentre.

FMS 24 is of an event located along the axis of the Qazian anticline. Hypocentral depth is 13 km (Table.2). Solution obtained is of strike slip faulting (Fig.4). Considering the active nature of the left lateral Jhelum Fault and the influence of the probable uplift taking place in the HKS, the nodal plane trending in the NE-SW with a dip of 760 NW is inferred to be the rupture plane. Thus a left lateral blind fault in the basement is inferred.

In the case of FMS 5 that is for an earthquake occurring a few km south of FMS 24 (Fig. 2b), reverse faulting with a component of strike slip is obtained (Fig.4). Like the previous event, the NE trending plane indicating left lateral sense of motion is preferred. Exact hypocentral depth is not known, but probably the basement has been affected. If basement was affected then reverse fault recognized by Pennock et al., (1989) in the basement below the Qazian anticline (described previously) could be the cause of the earthquake. This part of the study area is also most likely being influenced by the major active fault i.e. the Jhelum Fault. Its role in forming NW trending structures is described in the last section of the chapter.

FMS 41: It is for a magnitude 5.7 Mw (Table.2) earthquake that occurred near the southeastern margin of the Potwar plateau (Fig.2b). In this part also, the surface structures have a NE-SW trend (Fig.2a). A major structure occurring a few km southeast of the epicentral location is the Domeli Fault. Pennock et al., (1989) consider it to be an emergent thrust comprising of a northeastern segment (Domeli Fault) and a southwestern segment (Dil Jabba backthrust). Sercombe et al., (1998), refer to both the segments as the left lateral strike slip Domeli Fault. NESPAK reports suggest that the fault is linked to the left lateral Jhelum Fault. Balanced cross-section of Pennock et al., (1989) show the fault to be dying out before reaching the basement.

Focal depth of the event is 32 km (Table.2) thereby indicating deformation in the basement. FMS obtained is of strike slip faulting (Fig.4). Harvard CMT also obtained a strike slip solution with a small thrust component. In the present case, the negative values of rake for both the planes indicate a very small normal component. The NW trending plane indicating a left lateral sense of motion is most likely the rupture plane. Khan et al., (2002) had also obtained a strike slip solution, but with a right lateral sense of motion on a blind fault. As will be further discussed at the end of the chapter, in a shear couple with the active left lateral Domeli or Jhelum Faults on one side, their influence are more likely to generate left lateral motion rather than right lateral motion as inferred by Khan et al., (2002). Thus, the present interpretation seems more reasonable.

FMS 39: It is for an event having magnitude of 4.3 Mw (Table.2). Epicentre is located a few km north of the earlier mentioned Domeli Fault (Figs.2a and b). Another surface fault believed by some workers to be present in the immediate vicinity is the WNW trending Kallar Kahar Fault (Figs. 2a and b). According to Kazmi (1979), the fault shows right lateral movement. Seismic section of Moghal et al., (2003) for this area shows that basement is at a depth of about 4km and offsets are present in it. Similarly small emergent and blind faults are shown in the cover rocks. They do not recognize the Kallar Kahar Fault in their time section.

Previously Khan et al., (2002) obtained a right lateral strike slip solution for this event. They infer the presence of another fault a few km north of the

Kallar Kahar Fault and parallel to it. In the present case, a thrust with a strike slip solution has been obtained (Fig.4). If stratigraphic thickness of the different units is considered than indications are that the event occurred in the Cambrian-Eocene sequence.

It seems unlikely that the NW dipping Domeli Fault could be the cause. This is based on the observation that if it were assumed to be present here then it would be encountered at a much deeper level than the focal depth of the event. Thus if the influence of the left lateral Domeli Fault is ignored which seems to be the case, then the Kallar Kahar Fault could be the reason of this activity. It may be mentioned that the orientation of both the nodal planes are different from the orientation of the fault. Geological map of Gee (1980) shows the presence of a number of small faults in the area. Probably the event is related to one of them. As mentioned in the earlier discussions, left lateral slip seems to be quite prevalent in this part of the study area. Thus, most likely the NE trending nodal plane indicating left lateral sense of motion may be the rupture plane in the case of this very shallow event.

FMS 21 and 22: Two very shallow earthquakes of magnitudes 5.1Mw (Table.2) occurred on 20th and 27th December 1984 in southern Potwar (Figs.2a and b). Geology of the area is very complex with both NW and NE trending surface folds and faults being present (e.g. Moghal et al., 2003; Shami and Baig, 2002). Epicentral location of both the events can be marked on the seismic section of Moghal et al., (2003). It indicates the presence of a NW trending, southwest dipping backthrust at the focal depths of these events in the cover rocks. Nearly similar directions of nodal planes are obtained in both the FMS. They were combined together to obtain a composite FMS. In the composite FMS (Fig.4), the nodal plane having similar trend and dip as the backthrust is inferred to be the rupture plane. Further the solution indicates a left lateral strike slip component.

FMS 19,9, 30, 29 and 4: These five earthquakes are located in the Kohat Plateau. Out of these five events, 4 are strike slip and one is reverse.

FMS 19: The epicentre of FMS 19 is located a few km south of the MBT (Figs.2a and b). Structural map of Pivnik and Sercombe (1993) shows the presence of a small NE-SW trending thrust fault named as the Bazid Khel Fault (BZF) at this location. They include it as part of the relict Mir Khweli Sar thrust belt (MKSTB) that contains at least 12 thrust faults that sole into a decollement. According to Pivnik and Sercombe (1993), the initial low angle thrust regime is now characterized by tight folding related to left lateral strike slip and high angle reverse faults in the basement. Like the Potwar area, previous workers have inferred the structures to be thick skinned. Two detachment levels were recognized with the lower one marked between the

Eocambrian salt and Paleozoic-Mesozoic sediments at the depth of 6-7km (Abbasi and McElroy, 1991). The focal depth of this earthquake is 15 km (Table. 2) thereby indicating involvement of the basement. Solution indicates reverse faulting with a strike slip component (Fig.4). Considering the information provided by Pivnik and Sercombe (1993), the nodal plane with a NE-SW trend is inferred to be the rupture plane as it indicates a left lateral sense of motion. As will be discussed in the last section of this paper, this and other subsequent 5 solutions are most likely a result of transpressional tectonics.

FMS 9: It is for an earthquake that occurred in an area marked by NE-SW trending tight folds (Pivnik and Sercombe, 1993). Overall they infer the presence of wrench faulting in the subsurface of Kohat plateau. No surface fault is known to be present here by these workers. The dominant trend of the folds is in the NE-SW direction (Figs.2a and b).

According to Sercombe et al., (1998), seismic and aeromagnetic data shows that the major subsurface trend is in the NW-SE direction. At the same time, they observed a less dominant NE-SW trend in the area of epicentral location. As such in the wrench fault solution obtained for this event (Fig.4), if the nodal plane having similar direction (i.e. NE-SW) as the less dominant trend of the subsurface structures is inferred to be the rupture plane it indicates a right lateral sense of motion. This inferred slip is difficult to reconcile with the shear couple being formulated for the region (see discussion at the end). Alternatively, if the NW directed plane (similar to regional subsurface trend) is considered then the correct left lateral motion compatible with the shear model is obtained. Thus, the solution is interpreted to be of a steeply dipping left lateral strike slip fault (wrench fault). Focal depth (Table.2) suggests the involvement of basement.

FMS 4, 29 and 30: These events occur close together in an area where the surface geology shows the presence of tight anticlines and synclines (Figs. 2a and b). Pivnik and Sercombe (1993) consider these NE stepping folds to be the surface expression of small displacement strike slip deformation. In addition, a number of north dipping thrusts (Banda Daud Shah Fault, Bozda Fault and Hukni Fault) occur in the immediate vicinity of the epicentral locations (Pivnik and Sercombe, 1993).

FMS obtained for these three events show strike slip faulting (Fig.4). In the case of FMS 30, a reverse component is also present. For this solution, Harvard CMT is of thrusting and incorporates less number of stations. Recent detailed work of Sercombe et al., (1998) and Pivnik and Sercombe (1993) has inferred the Hukni Fault (located close the epicentres) and other faults of the area as wrench faults. Ahmad et al., (2004) also believe that thick-skinned structures occur in parts of Kohat. The initial N-S Himalayan collision followed by the prevailing underthrusting of the area along the sinistral Kurram Fault/Chaman Fault in the west is believed to be forming transpressional related structures in the area.

Steep dips obtained in the solutions (Table.3) and influence of the above named faults (Kurram/Chaman Fault) leads to the inference that the NW-SE trending nodal planes that indicate a left lateral sense of motion are the rupture planes. Most likely they represent the Reidel shears. It may be pointed out that in this area Sercombe et al., (1998) on the basis of magnetic and seismic data, have inferred the presence of similar trending faults in the basement.

FMS 27,37,36 and 18: All these events are from southeast portion of the study area. This area consists of the Bannu Basin and the ranges (Surghar, Marwat, Khisor and Bhittani Ranges) that form the margins of the basin (Figs.2a and b).

FMS 27: This earthquake is located where the Surghar Range trends in the E-W direction (Figs.2a and b). It is not known whether this part of the range like the N-S trending portion forms the boundary of the Bannu Basin or not.

The emergent north dipping Surghar Range Thrust occurs here. Balanced cross section of McDougall and Hussain (1991) indicates that the thrust penetrates the Cambrian rocks. Precambrian basement is encountered at depth of about 6 km beneath the thrust.

Solution obtained is of thrusting and is based on polarity data of only 8 stations (Fig.4). Focal depth of about 4km (Table.2) suggests that the deformation took place in the Cambrian rocks overlying the basement, where the Surghar Range Thrust is also present according to McDougall and Hussain (1991). Thus this solution is related to it and the plane dipping towards the NW considered its representative.

FMS 37: The epicentre is located in the southern part of the Bannu Basin where the NE trending Marwat Thrust, NW trending Bhittani Thrust, and the right lateral strike slip Pezu Fault occur (Figs. 2a and b). Searle and Khan (1996) consider the Bhittani Thrust to be a right lateral strike slip fault.

The solution obtained for this event is of a thrust with a minor strike slip component (Fig.4). Presence of two faults with a right lateral component in the vicinity leads to the inference that the north trending nodal plane similar to trend of these two faults and dipping towards the west could be the rupture plane. Thus either of these two faults, which seem to be linked together, are believed to be responsible for the earthquake. It may be mentioned that Kemal (1992) consider the Pezu Fault to have played an active role in the deformation process due to NE-SW compression and in the solution a similar direction is obtained for the P-axis.

FMS 36: Epicentre is located near the NE-SW trending Manzai range (near the south western boundary of the Bannu Basin). A northwest dipping thrust fault runs along the length of the range and is called the Manzai Thrust (Figs. 2a and b) by Kazmi and Jan (1997).

FMS obtained is of normal faulting (Fig.4). Focal depth (~15km) indicates that the fault occurs in the basement. Subsurface geology of the area is not well known. Deformation style here is nearly similar to that of Southern Potwar and the Eocambrian salt has also served as the basal decollement (Kemal, 1992). Thus he postulates that occurrence of basement normal faults (as in parts of Salt Range) are a possibility in the Khisor and Marwat Ranges. These may be acting as a buttress to the south verging compression and also resulting in the ramping of up along the thrust. In such a situation, the nearly E-W trending nodal plane indicating down-to-north normal fault may be the rupture plane.

FMS 18: FMS 18 is located a few km west (2.5km) of the Manzai Thrust, the southwestern boundary of the Bannu Basin (Figs.2a and b). Solution obtained for this shallow earthquake having focal depth of 9 km is of thrust/reverse faulting (Fig.4). Details about the thrust are lacking. If its extension is postulated in the subsurface till the focal depth of the event, then a dip of about 750 is obtained. This steep dip is not much different from the nearly vertical dip obtained for the nodal plane having a nearly similar trend as the Manzai fault in the solution. If such is the case then reverse faulting is indicated. It may be mentioned that in the foreland zone, a number of workers based on seismic data have recognized thrusts with shallow dips at or near the surface that become nearly vertical at depths. In fact at the eastern boundary of the Bannu Basin, in the Surghar Range, a combination of thrusting and sinistral wrenching is believed to have formed a flower structure (Kemal, 1992).

Compressional and Transpressional Tectonics:

The distribution of seismicity has already been described in section3. Inspite of a large number of events occurring in the study area, focal mechanism studies of only 45 events could be carried out. This number, as mentioned previously, is limited because the relevant parameters essential for undertaking such a study were not available for all the events. However, a reasonable distribution of the solutions (Fig. 2b) has been obtained to make it possible for an assessment of the regional deformation/tectonics of the area.

Looking at the study area in the regional perspective, a number of interpretations by different workers are available to explain the collisional tectonics between the northward moving Indo-Pakistan and the Eurasian plates. It is beyond the scope of this study to describe them. Earlier contributions are summarized in Molnar and

Tapponnier (1975), Molnar et al., (1977), Tapponnier and Molnar (1976, 1977), Farah and DeJong (1979), whereas later contributions are available in Kazmi and Jan (1997). All agree that the Indo-Pakistan plate is being underthrusted at the suture referred to in this study as the MMT.

Regional shortening due to convergence is probably absorbed by thickening of the crust, folding and accommodation along strike slip faults both to the north and south of the Himalayas (e.g. Royden and Burchfiel, 1997). One of these faults along the western boundary of the study area is nearly 1000 km long, sinistral Chaman Fault. This fault is also the western plate boundary of the Indo-Pakistan plate.

In the present work, prevalence of a compressional regime is reflected by the thrust (7 out of the 9 FMS) and the two reverse solutions from the hinterland zone. Except one i.e. FMS 10, all of these events (focal depths ranging from 47 to 68 km) are located near this convergent boundary (maximum epicentral distance is about 40 km away from the MMT) and have their P-axis orientations in the NE direction (Fig. 4). In the earlier discussion they have been interpreted as indicative of intraplate activity due to steep bending of the Indo-Pakistan plate. Thus, following Armbruster et al., (1978), it is believed that imbricate thrusting, breaking and thickening of the crust i.e. regional shortening of the crust is taking place.

Besides the compressional regime prevailing at the northern boundary, there is evidence to suggest that an E-W directed compression also prevails in the western portion of the study area, but to a lesser extent. The N-S directed thrusts having dips towards the southeast or northwest mapped by different workers from the area (some are shown in Fig. 2) support this contention. Further, 4 FMS from the SW of the study area (FMS 19, a reverse solution from Kohat plateau; FMS 27, a pure thrust solution from Surghar Range; FMS 18 and 37, two thrusts with minor strike slip component) indicate crustal shortening in this part. It may be mentioned that the sinistral nearly N-S trending Chaman Fault that is the western plate boundary passes to the west. Most likely a restraining bend in this fault is producing thrusting in this part.

Another type of deformation (transpression and transtensile) occurs in a wide range of geodynamical settings like at oceanic and continental transforms, convergent plate boundaries such as orogenic belts, and regions of continental extension undergoing rifting (e.g. Allen and Allen, 1993). Transpressional features have been recognized from parts of the study area (e.g. Sercombe et al., 1998). Some focal mechanism studies (e.g. Verma et al., 1980; Verma, 1991; Khan et al., 2002 and MonaLisa et al., 1997, 2002) undertaken in parts of the study area indicate the strike slip solutions. Majority of the FMS obtained in this study (26 out of 45) show the dominance of strike slip deformation.

It has already been mentioned that the sinistral Chaman Fault is responsible for the convergent (transpressive) strike slip deformation in the area. Recent work of Iqbal and Ali (2001) in the Potwar area includes a stress model to explain the formation of structures between the Jhelum and Kalabagh Faults. Earlier Sercombe et al., (1998) in their work on the Kohat area emphasized the importance of Chaman Fault and Domeli Tear (in Potwar area) to explain strike slip deformation.

Kohat and Potwar, the two areas mentioned above form part of the foreland zone. Most of the solutions indicate a left lateral sense of motion. The model shown in Fig. 5 is for the foreland zone in which the left lateral Chaman and Jhelum Faults are considered to be forming the regional shear couple. Considering the P-axis orientations in the FMS that are dominantly in the NE direction, it is envisaged that most of them are Synthetic shears (Riedel shears) with a few being Secondary synthetic shear (P shears).

The importance of the Hazara Kashmir Syntaxis and the Jhelum Fault (western margin of the syntaxis) in the present shear model (Fig. 5) seems to be quite prominent. Uplift rates within the syntaxis are not known, but Baig and Lawrence (1987) have observed uplifted and tilted Quaternary terraces in the area. Stresses being generated here could explain the left lateral slip inferred for 7 FMS from the eastern Potwar (part of study area on the western side of the syntaxis). Considering the orientation of the inferred rupture plane and sense of motion, 5 solutions (FMS 24,26,31,38,5) may be representing synthetic shears and 2 having NW orientations (FMS 15,16) the secondary shears.

Similarly two tectonic features, namely the Nanga Parbat-Haramosh massif and the Besham dome are believed to be influencing the development of strike slip faulting in the hinterland zone. As mentioned in the interpretation of some FMS, some of the worlds most rapid rates of uplift have been recorded from this fault bounded massif. This uplifting could explain the formation of right lateral and left lateral strike slip faulting on its eastern and western sides respectively. Thus, FMS 42 and 43 (Figs. 2a and b) have been related to the stresses being generated by the massif. Similarly the uplift documented in the Besham dome (e.g. Baig et al., 1989; Kazmi and Jan, 1997) is most likely generating left (FMS 28) and right lateral (FMS 40, 44, 45) strike slip on its western and eastern sides respectively.

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Table 1: Historical Earthquakes

S.No.	Date	Lat (N)	Lon (E)	Magnitude	Max. Intensity
1.	25 AD	33.73	72.87	7.0	IX-X
2.	03.01.1519	34.80	71.90	5.0	VI-VII
3.	04.06.1669	33.37	73.23	6.5	VI-IX
4.	06.06.1828	34.08	74.82	7.0	IX-X
5.	25.03.1869	32.92	73.72	5.0	VI-VII
6.	20.12.1869	33.77	72.33	5.5	VII-VIII
7.	22.04.1871	33.62	73.07	5.2	VI-VIII
8.	15.01.1885	34.00	74.82	6.0	VII-VIII
9.	30.05.1885	34.28	73.47	6.5	VIII
10.	06.06.1885	34.17	75.00	7.0	IX-X
11.	05.11.1893	34.00	71.55	5.0	VI-VII
12.	20.01.1902	34.00	74.82	5.5	VI

Table 2: Source parameters of forty five earthquakes whose FMS has been determined in the present study

FMS Nos.	Date D/M/Y	Time H: M: S	Lat (N)	Lon (E)	Depth (Km)	Magnitude (M_w)
1	8/11/65	21:23:09	34.6	73.3	65	5.1
2	2/2/66	9:13:00	33.89	73.2	37	5.6
3	6/4/66	1:51:53	34.91	73.06	54	5.6
4	18/11/68	5:05:05	33.24	71.2	17	5.5
5	30/4/70	3:24:54	33.3	73.4	33	5.3
6	28/4/71	15:12:42	34.44	73.6	43	5.3
7	27/12/71	20:59:39	34.98	73.02	55	5.7
8	10/3/72	14:36:16	33.91	72.72	40	5.4
9	7/5/72	10:05:04	33.45	71.5	17	5.5
10	27/09/72	2:03:39	33.99	72.7	41	5.6
11	27/09/72	20:24:56	35.07	72.91	49	5.3
12	28/12/74	12:11:46	35.06	72.91	15	6.4
13	28/12/74	22:38:53	34.99	73.1	68	5.3
14	7/4/75	6:41:02	34.91	72.97	53	5.5
15	14/02/77	22:37.0	33.6	73.27	14.5	5.5
16	7/5/78	10:32:25	33.53	73.58	8.8	5.5
17	4/3/79	2:51:47	33.89	72.98	42	5.2
18	28/05/82	0:58:48	32.36	70.09	9	5.1
19	11/2/84	8:37:06	33.6	71.6	15	5.3
20	18/02/84	7:04:59	34.09	71.82	52	5.1

21	20/12/84	7:32:07	32.95	72.7	0.1	5.1
22	27/12/84	20:22:05	32.96	72.64	1.2	5.1
23	28/12/84	16:28:01	34.61	73.61	47	5
24	12/7/87	12:19:18	33.4	73.4	13	4.9
25	7/12/88	21:13:54	34.03	72.98	50	4.7
26	7/4/89	43:24.0	33.75	73.2	10	5.1
27	17/02/91	7:00	33.06	71.39	4.1	5
28	16/3/91	3:57:42	34.52	72.66	33	5
29	20/5/92	12:20:32	33.25	71.3	10	6.5
30	5/6/92	12:23:19	33.27	71.34	0.6	5.5
31	17/2/93	16:06:07	33.55	72.5	6.5	5.4
32	8/6/93	14:30:37	33.68	72.62	7.6	5.3
33	20/2/96	2:55:52	34.04	72.67	46	5.2
34	8/8/96	14:58:19	34.06	72.82	21	5.3
35	12/7/98	5:54:00	34.11	72.63	27.4	5.5
36	23/01/99	9:53:00	32.27	70.2	14.6	6
37	16/4/99	22:11:00	32.49	70.8	10	5.3
38	28/4/99	13:00:00	33.33	73.12	5	5.2
39	15/7/99	4:29:00	32.76	72.82	0.3	4.3
40	17/7/2000	5:26:00	34.59	72.89	10	5.5
41	16/07/2001	16:07:06	32.93	73.06	31.9	5.7
42	1/11/02	22:09:29	35.62	74.66	23	5.8
43	20/11/2002	21:32:00	35.51	74.68	45	6.7
44	14/02/2004	11:56:58	34.81	73.19	10	5.4
45	14/02/2004	10:30:22	34.828	73.255	10	5.5

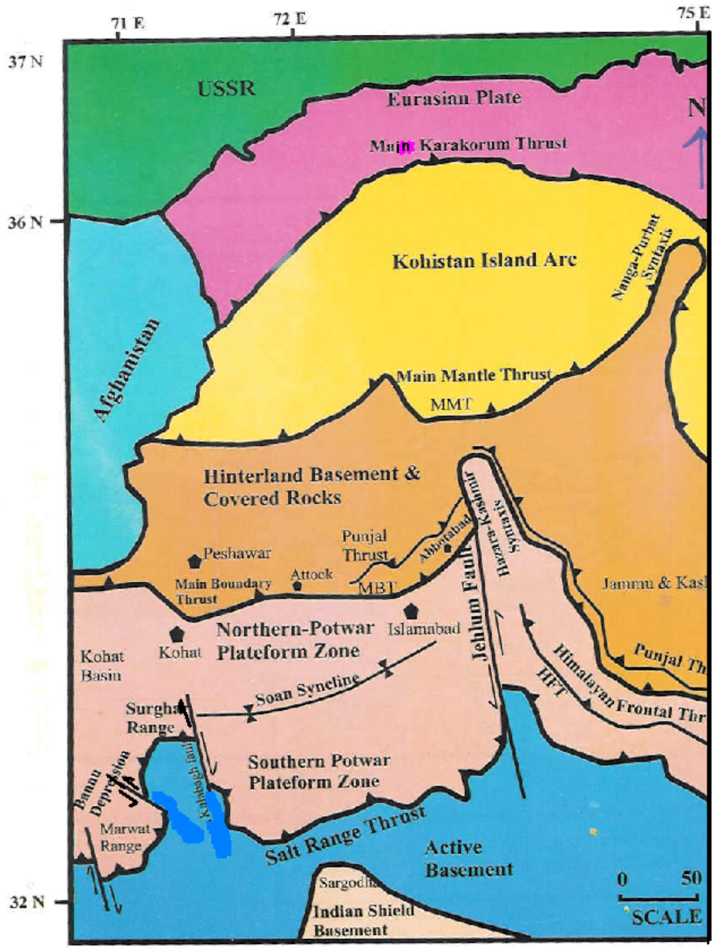
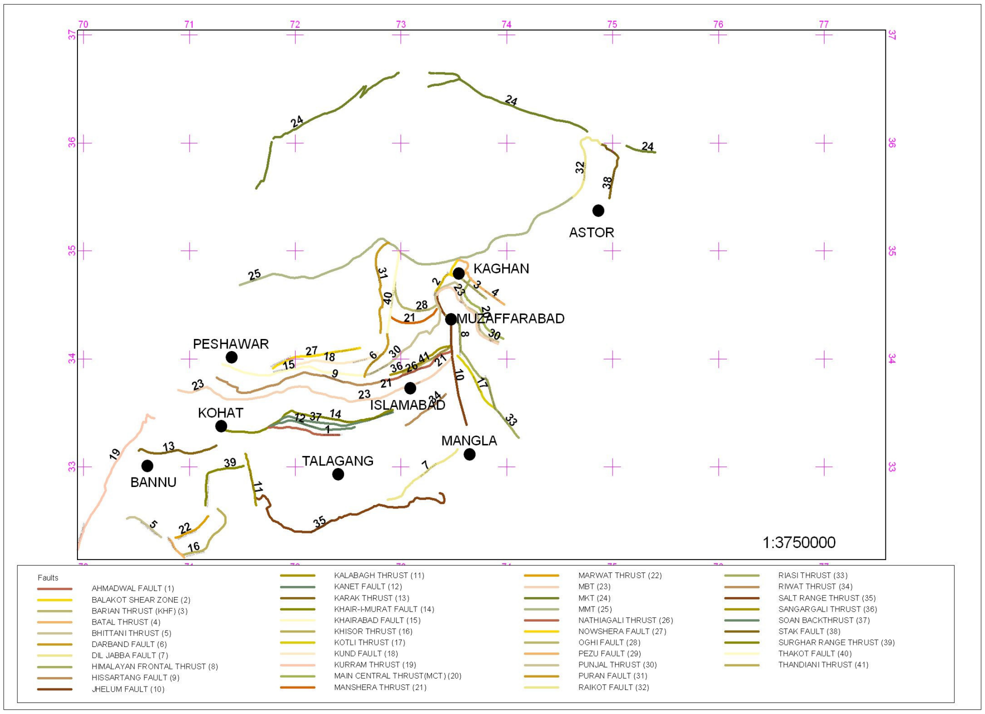


Figure 1: Regional Tectonic Map of Northwest Himalayas of Pakistan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Faults
AHMADWAL FAULT (1)
BALAKOT SHEAR ZONE (2)
BARIAN THRUST (KHF) (3)
BATAL THRUST (4)
BHITTANI THRUST (5)
DARBAND FAULT (6)
DIL JABBA FAULT (7)
HIMALAYAN FRONTAL THRUST (8)
HISSARTANG FAULT (9)
JHELUM FAULT (10)
KALABAGH THRUST (11)
KANET FAULT (12)
KARAK THRUST (13)
KHAIR-I-MURAT FAULT (14)
KHAIRABAD FAULT (15)
KHISOR THRUST (16)
KOTLI THRUST (17)
KUND FAULT (18)
KURRAM THRUST (19)
MAIN CENTRAL THRUST(MCT) (20)
MANSHERA THRUST (21)
MARWAT THRUST (22)
MBT (23)
MKT (24)
MMT (25)
NATHIAGALI THRUST (26)
NOWSHERA FAULT (27)
OGHI FAULT (28)
PEZU FAULT (29)
PUNJAL THRUST (30)
PURAN FAULT (31)
RAIKOT FAULT (32)
RIASI THRUST (33)
RIWAT THRUST (34)
SALT RANGE THRUST (35)
SANGARGALI THRUST (36)
SOAN BACKTHRUST (37)
STAK FAULT (38)
SURGHAR RANGE THRUST (39)
THAKOT FAULT (40)
THANDIANI THRUST (41)

Figure 2

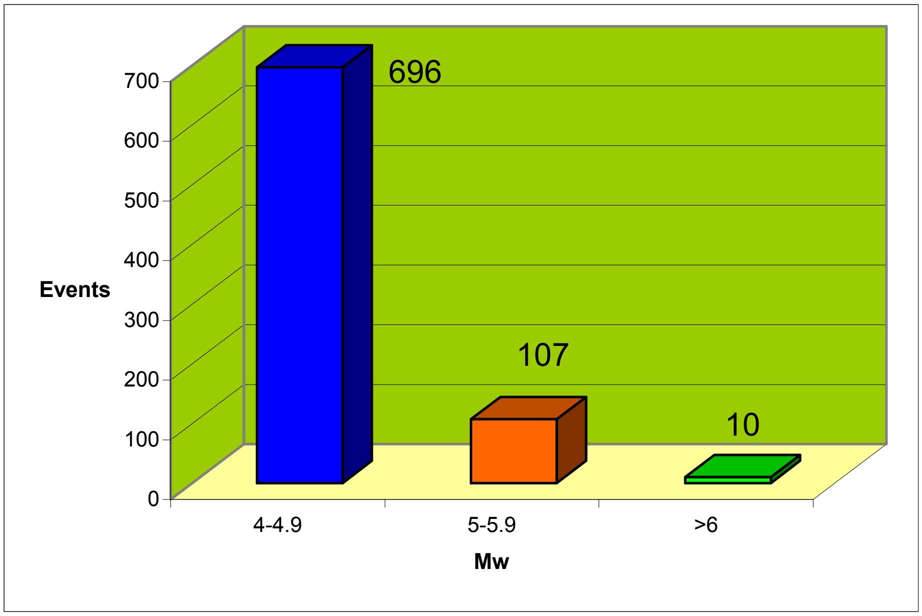


Figure 3.1 a: Number of events versus Magnitude (study area)

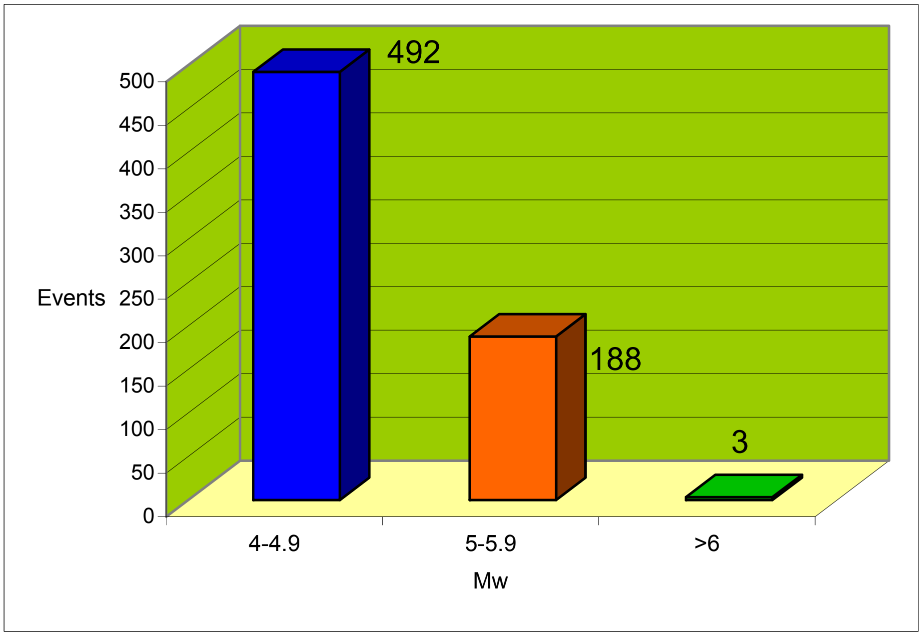


Figure 3.1 b: Number of events versus Magnitude (adjacent areas)

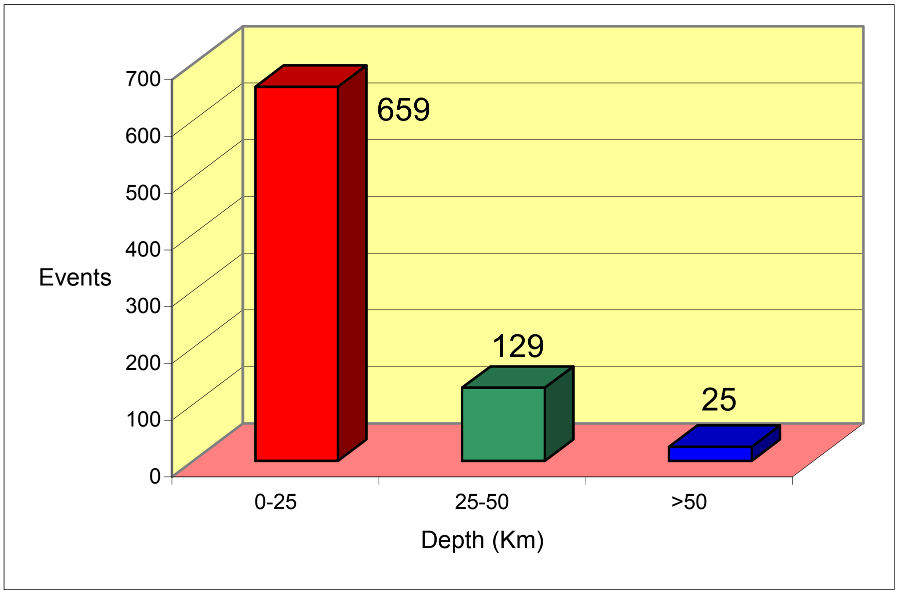


Figure 3.2 a: Number of events versus Depth (study area)

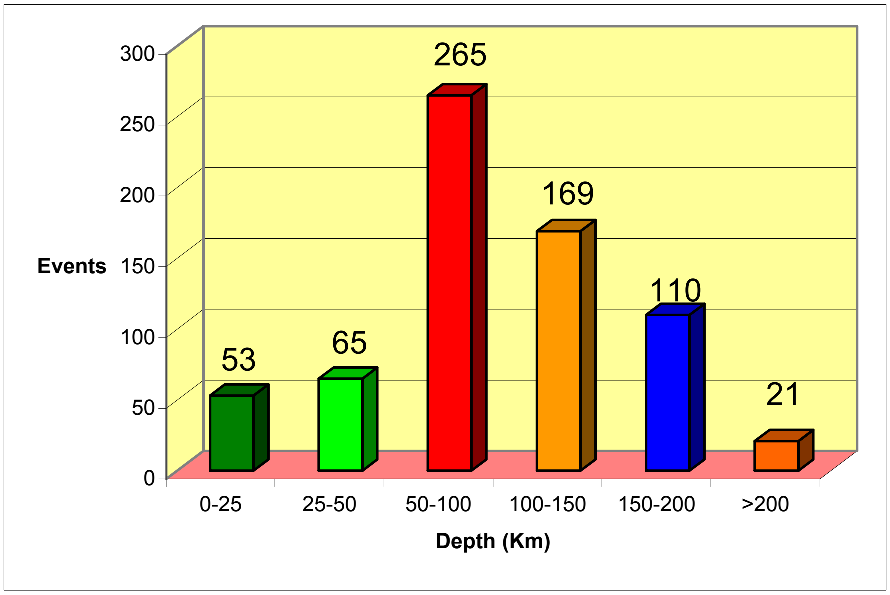


Figure 3.2 b: Number of events versus Depth (study area)

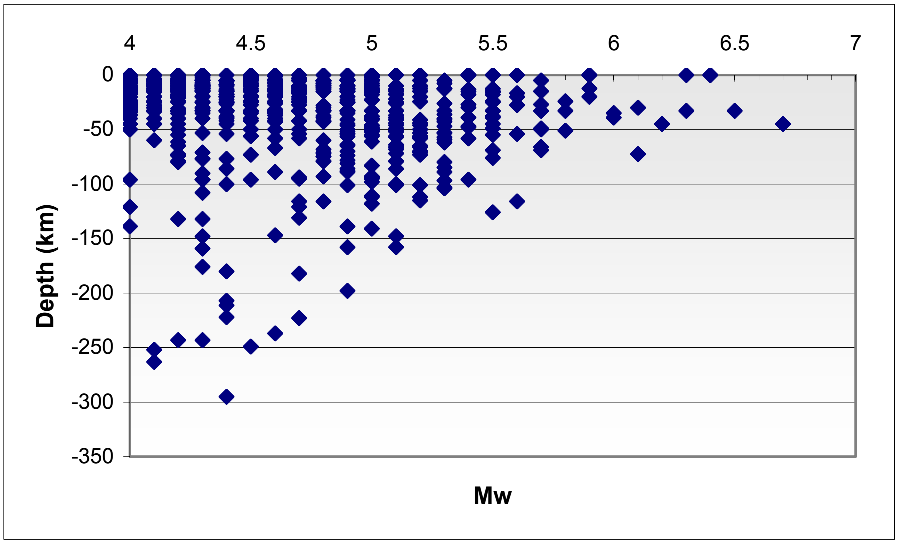


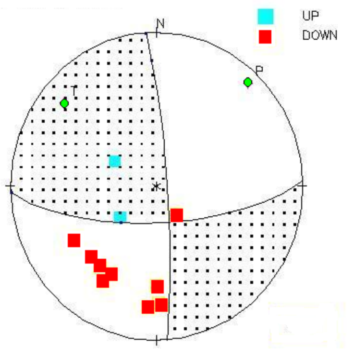
Figure 3.3: Depth versus Magnitude (overall area)

APPENDIX-C

(FAULT PLANE SOLUTIONS ANALYSED IN THE PRESENT WORK)

HINTERLAND ZONE- (1) CRYSTALLINE NAPPE ZONE

FMS 44



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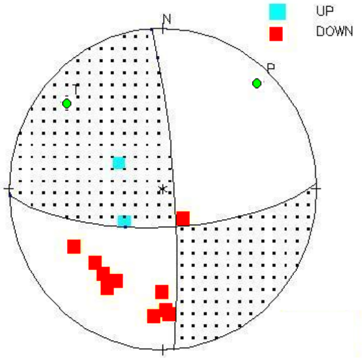

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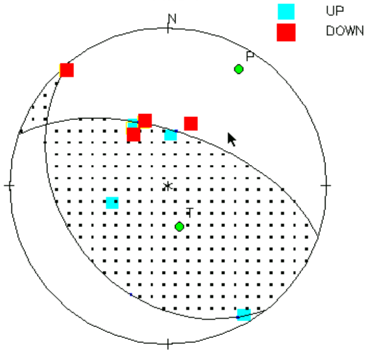
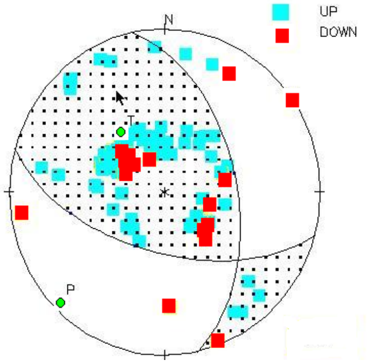
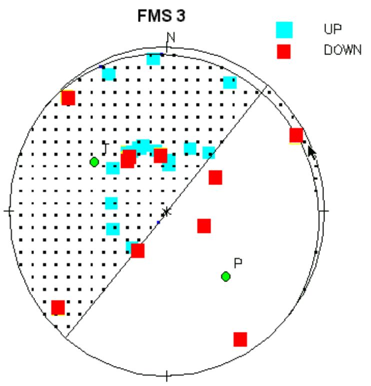


FMS 12

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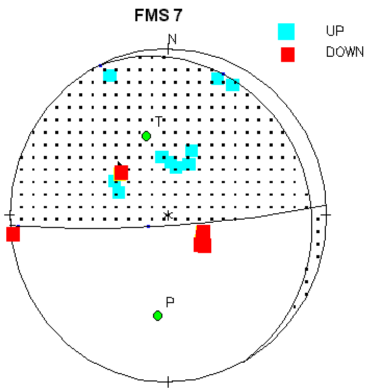
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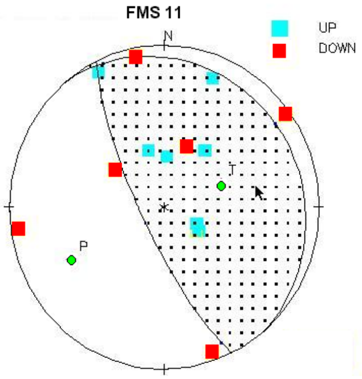
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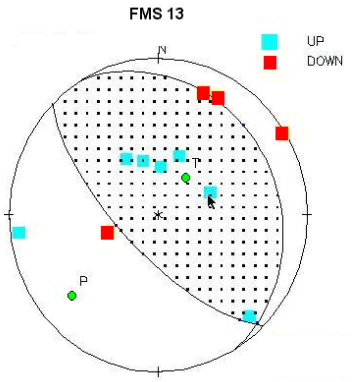
FMS 13
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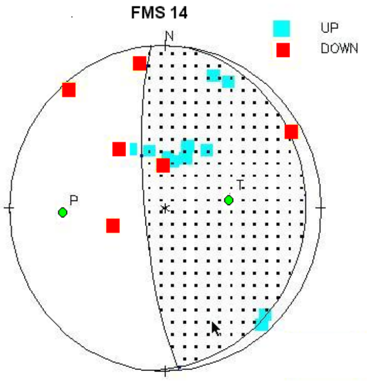
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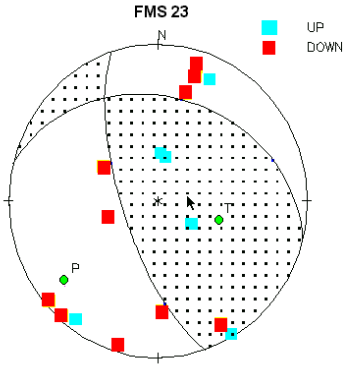
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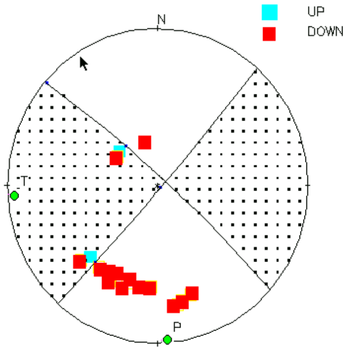
FMS 40



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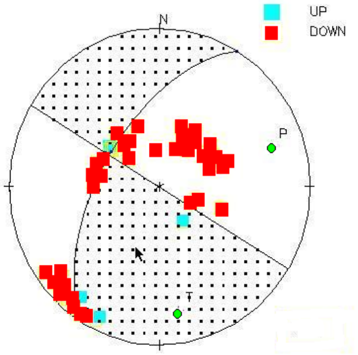

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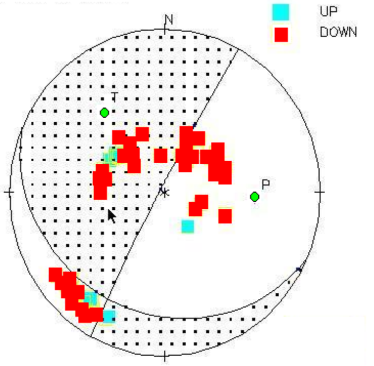
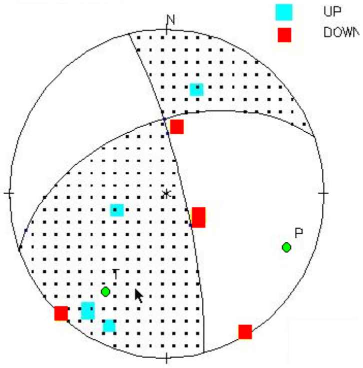
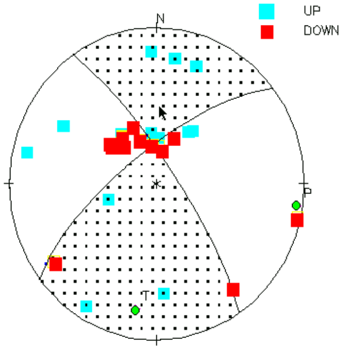


FMS 28

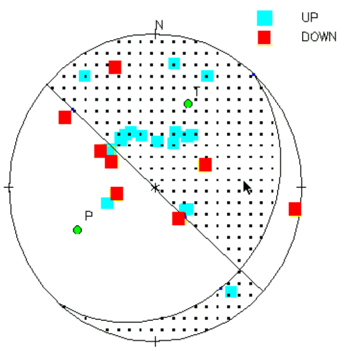


(2) KHYBER LOWER HAZARA METASEDIMENTARY FOLD AND THRUST BELT

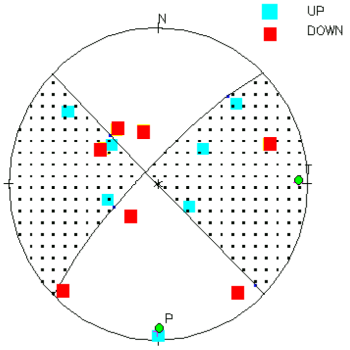
FMS 8



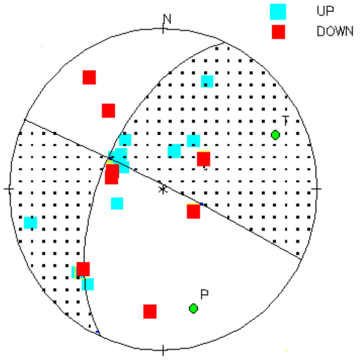
FMS 10



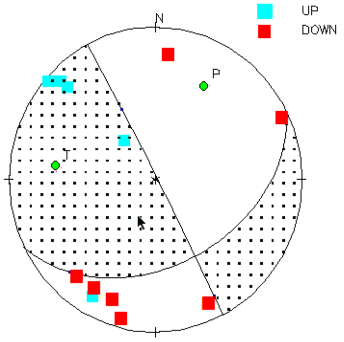
FMS 33



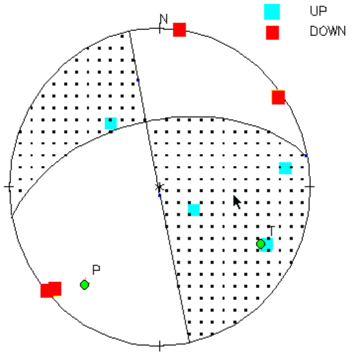
FMS 34



FMS 35

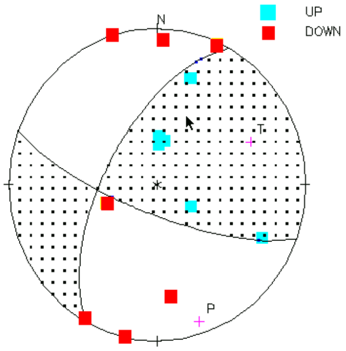


FMS 25

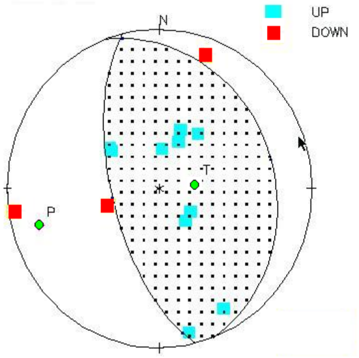


FORELAND ZONE – (1) FMS IN HKS

FMS 20

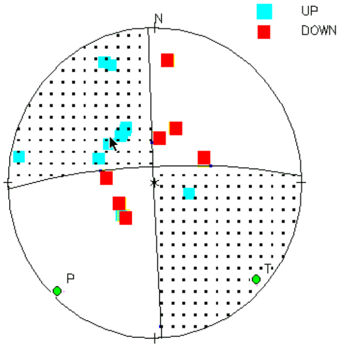


FMS 6

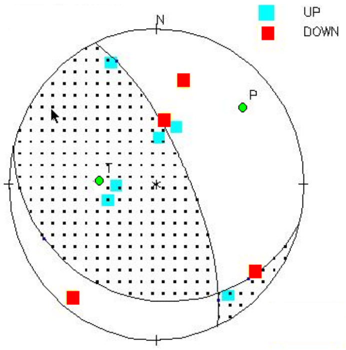


(2) FMS IN KURRAM CHERAT MARGALLA FOLD AND THRUST BELT

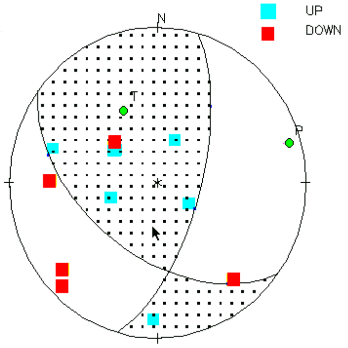
FMS 2



FMS 17

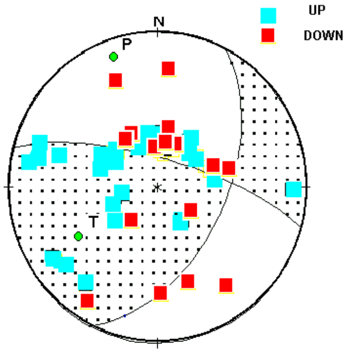


FMS 32

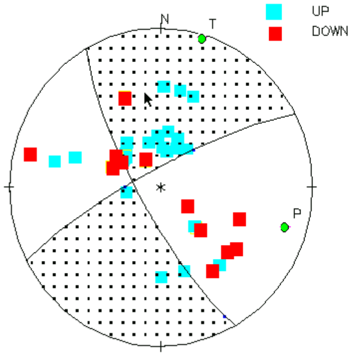


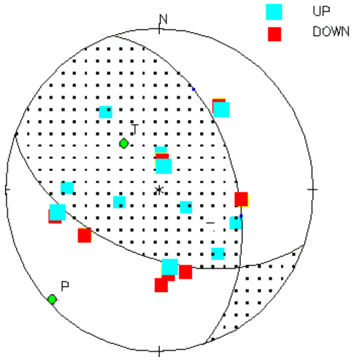
(3) FMS IN THE POTWAR

FMS 15

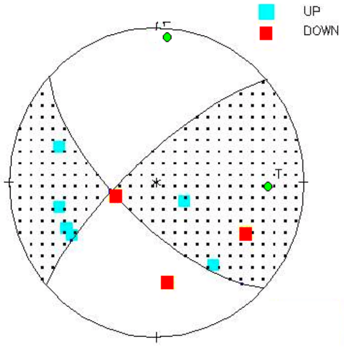


FMS 16

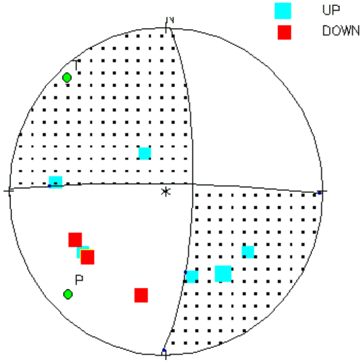




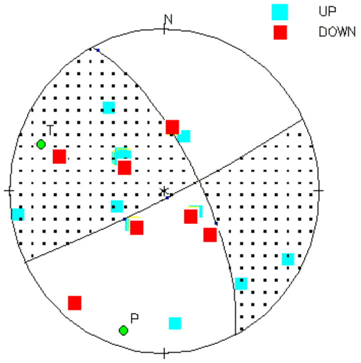
FMS 21 and 22 composite



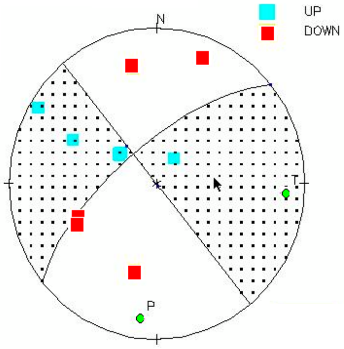
FMS 24



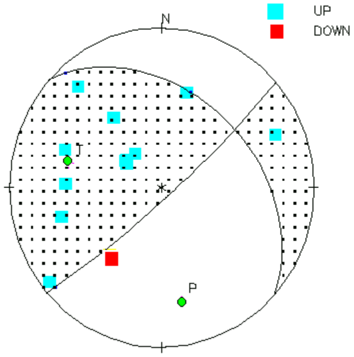
FMS 26



FMS 31

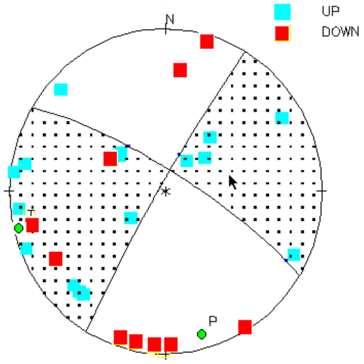


FMS 38

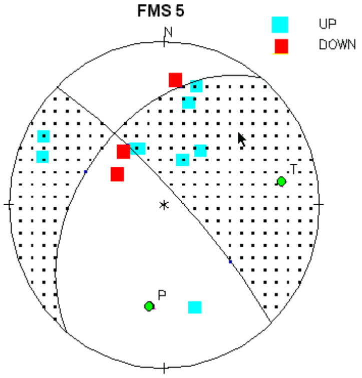


FMS 39

FMS 41

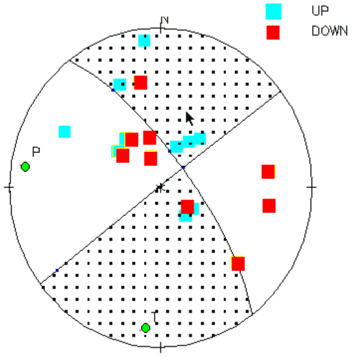


FMS 5

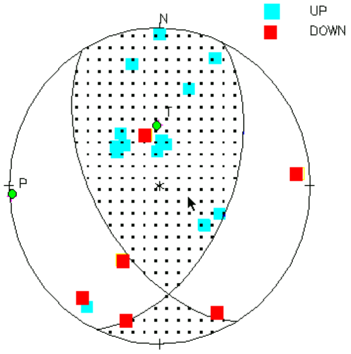


(4) FMS IN THE KOHAT

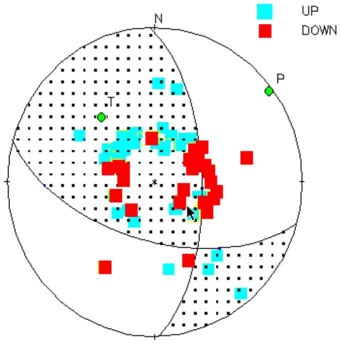
FMS 9



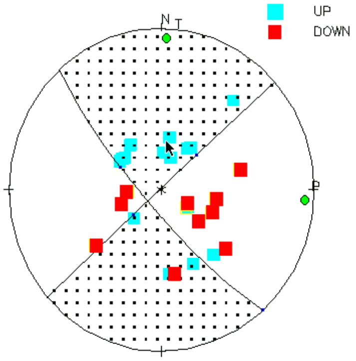
FMS 19

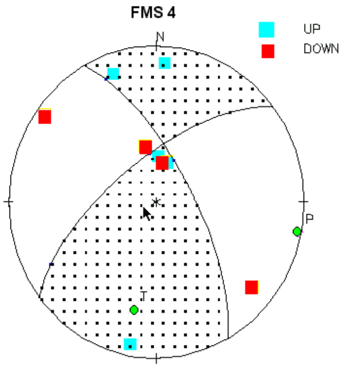


FMS 29



FMS 30





(5) FMS IN THE WESTERN EXTENSION OF SALT RANGE