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Structural Trends and Focal Mechanism Studies in the Potwar Area with Special Emphasis on Hydrocarbon Exploration

MonaLisa[1] and Azam Ali Khwaja[1]

ABSTRACT

In the present paper an attempt has been made, for the first time, to identify the surface/subsurface structural pattern for the area of Potwar with the help of focal mechanism studies- a technique that is widely known for interpreting structural traps at depth. For this purpose all available earthquake data (during 1964-2002) from international seismological networks and the local seismic observatories have been collected for the compilation of seismicity map of the area. Based upon this seismicity map, the area appears to be very active compared to the adjacent regions of Kohat Plateau and Salt Range with apparently very prominent patterns of seismicity along Jhelum Fault and Main Boundary Thrust (MBT). Focal mechanism solutions of thirteen events for which required parameters were available indicate left-lateral strike-slip faulting for eleven events while two events (4 and 10) represent thrust faulting. Earthquakes number 1, 6, 8 and 11 are located near Qazian anticline and all are representing basement events (as depth indicated by nearest local seismic observatory is > 6 km) except event number 11 whose depth is 5.0 km. The dominance of strike-slip faulting is in agreement with the previous workers. Majority of the interpreted focal mechanism solutions are located in the northeastern (i.e. near Jhelum Fault) and the northern portion (i.e. near MBT) of the area, which are major structures of the Potwar area. P-axes orientations (i.e. the axis of maximum compressions) are in NW-SE and NE-SW directions. Basement is found to be involved in the deformation.

INTRODUCTION

Pakistan possesses the northwestern boundary of the Indian lithospheric plate. The underthrusting of Indo-Pak Plate beneath the Eurasian Plate is producing compressional thin-skinned tectonic features since Eocene time on the northern and northwestern fringes of the Indo-Pak Plate. The continued underthrusting of the Indo-Pak Plate since Cretaceous produced the spectacular mountain ranges of the Himalaya and a chain of foreland fold-and-thrust belts as thick sheets of sediments thrust over the Indian craton (Kemal, 1991).

Foreland Fold-and-Thrust belts are conspicuous features of convergent continental plate boundaries and are very important areas for the recent tectonic movements. NW Himalayan Fold-and-Thrust belt is one of these and is characterized by a number of active faults. In northern Pakistan, thrusting in the Indo-Pak Plate is certainly the main accommodation method of shortening in the Himalayas. Focal mechanism solutions of earthquakes give evidence that these are linked to the thrusts. However, in the NW Himalayan fold-and-thrust belt, complications arise as earthquakes fault planes do not follow the thrusts, which change in orientation, suggesting that other accommodation features besides simple thrusting are occurring in the NW Himalaya (Spencer, 1992).

HYDROCARBON POTENTIAL

The Potwar sub-basin is one of the major hydrocarbon-producing province of the country. Multiple reservoirs of carbonate and clastic sediments of Cambrian through Miocene age occur. In total 11 reservoirs are known to be productive. Out of these fractured carbonates of Sakesar and Chorgali units are the major producing reservoirs (Iqbal and Ali, 2001). Numerous studies have been undertaken to highlight and understand the exploration processes for hydrocarbons in this 9000m thick sediments filled basin but no attempt has yet been made to utilize the Focal Mechanism Studies (FMS), which is a widely used technique for identification of structures at depth, supplemented by conventional techniques for exploration. It is beyond the scope of the present work to correlate FMS with all the exploration techniques, however we tried to carry out FMS with special emphasis on hydrocarbon potential in the area by concentrating the structural trends in the area.

Published literature reveals that Potwar area is characterized by NS compression and transpression related to conversance of Indian and Eurasian plates. However, in the study area presence of evaporites (Eocambrian) has led to the development of duplex type models with the basal decollement in the evaporites above the Precambrian basement. Indications are that levels deeper than the Eocambrian evaporites are also undergoing deformation. Thus, in the present study the nature of fault motions prevailing at depth in the Potwar area is described. Such type of information would lead to incorporation of seismicity data in future structural models of the area.

PHYSIOGRAPHY AND MAIN FEATURES OF THE AREA

The area of Pakistan is bounded by the alluvial covered peninsular shield of India on the east, the great Himalayan arc towards the NE, the Pamir and Hindukush mountains to the north, the central Afghan mountains to the NW, the

[1] Department of Earth Sciences, Quaid-i-Azam University, Islamabad.

Zagros folded belt on the west and the Arabian Sea on the south. All the major structures in the area, such as the Chaman Fault, Kirthar Ranges, Sulaiman Ranges, Salt Range, Potwar Plateau, Hazara Kashmir Syntaxis (HKS), Nanga Parbat Haramosh massif, the Main Boundary Thrust (MBT) and the Hazara thrusts owe their origin to the processes of collision that have taken place since Early Tertiary times.

The Potwar Plateau belongs to the Himalayan zone of convergence in which two prominent sutures are situated. The northern suture known as the Main Karakoram Thrust (MKT) formed about 100 million years ago (Treloar, 1989) and the southern suture referred to as Main Mantle Thrust (MMT) is believed to have originated about 50 million years ago (Treloar and Rex, 1990). Kohistan Island Arc lies between these two sutures. The deformation is believed to have shifted southwards with time to Main Boundary Thrust (MBT) and in the Himalayan foreland. Kohat Plateau, Potwar Plateau and Salt Range represent a zone of foreland deformation south of the MBT (Figure 1).

The Himalayan mountains, which have a general NW-SE trend, take a sharp bend near the north of Islamabad and west of Kashmir, forming the Hazara mountains with a general NE-SW trend. This sharp bend is known as Hazara Kashmir Syntaxis (HKS). Potwar Plateau lies in the west of Hazara mountains (Figure 1).

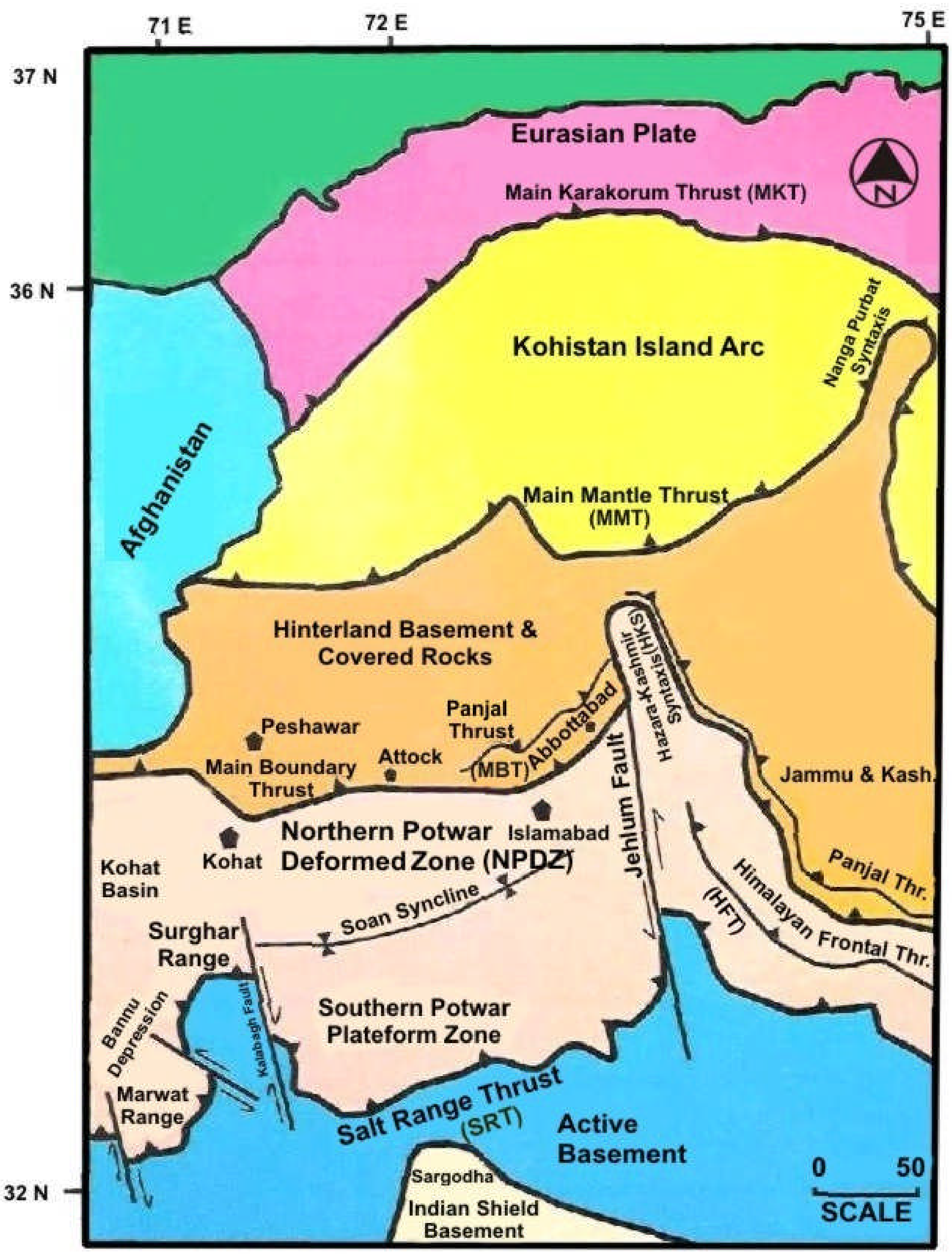

Figure 1 - Regional tectonic map of northwest Himalayas of Pakistan.

GEOLOGY OF THE AREA

Potwar Plateau has undulating topography. It is characterized by a series of parallel ridges and valleys, generally trend in the E-W direction. Geologically, it forms part of the foreland zone of the NW Himalayan Fold-and-Thrust belt. This foreland zone comprising of Salt Range, Potwar Plateau, Kohat Plateau and Hazara ranges is an area bounded by the Salt Range Thrust in the south and the Panjal-Khairabad Fault in the north (Figure 1). At its eastern end is the nearly N–S running left-lateral Jhelum Fault (Kazmi and Jan, 1997).

In this zone of convergence, intense deformation has resulted in the formation of complex structures.The northern part of Potwar Plateau, also referred to as the Northern Potwar Deformed Zone (NPDZ) lies between the Main Boundary Thrust and the Soan Syncline (Figure 2 & 3). It is more intensely deformed than the southern Potwar and the Salt Range. Mostly E-W trending tight and complex folds with their southern limbs overturned with steep angle faults occur in NPDZ.

The area contains a series of thrusts. Lillie et al., (1987) describe the northern Potwar as an imbricate stack of thrust faults on the surface and in the subsurface as blind thrusts. General trend of these thrusts changes from E-W to N-E direction in the eastern part of the NPDZ (Figure 2 and 3). A number of workers have already given the description of these faults (e.g. Lillie et al., 1987; Jadoon et al., 1995, Jadoon and Frisch, 1997 and Jaswal et al., 1997).

Soan Syncline is the major structural feature of Potwar. Its southern limb is less steep than the northern limb. In the study area, it is believed to have evolved between 3.4 to 1.9 Ma with the southern limb forming prior to the northern limb. According to Johnson et al., (1986) the development of the southern limb took place due to thrusting along the Riwat thrust (Figure 2). This thrust trends in the NE-SW direction lies about 20 km south of Rawalpindi. Jadoon et al., (1995) believe that cessation of movement along the Riwat thrust stopped at about 2.7 Ma.

Soan (Dhurnal) backthrust is a distinctive feature of the Northern Potwar Deformed Zone, occurs in the northeastern portion of the NPDZ (Figure 2). The dips along the backthrust are nearly vertical in contrast to near horizontal along axis of the Soan Syncline. The top of Kamlial Formation marks its location. North of the backthrust, highly deformed rocks of Murree Formation with steep to vertical dips occur, where as further north till the Khair-i-Murat Fault steeply dipping Siwalik Group rocks are exposed.

According to Pennock et al., (1989) the basement along the Soan Syncline is at a depth of about 6 km. It increases towards the north and near the MBT is about 8 km (Jaswal et al., 1997). The MBT itself is represented by many high

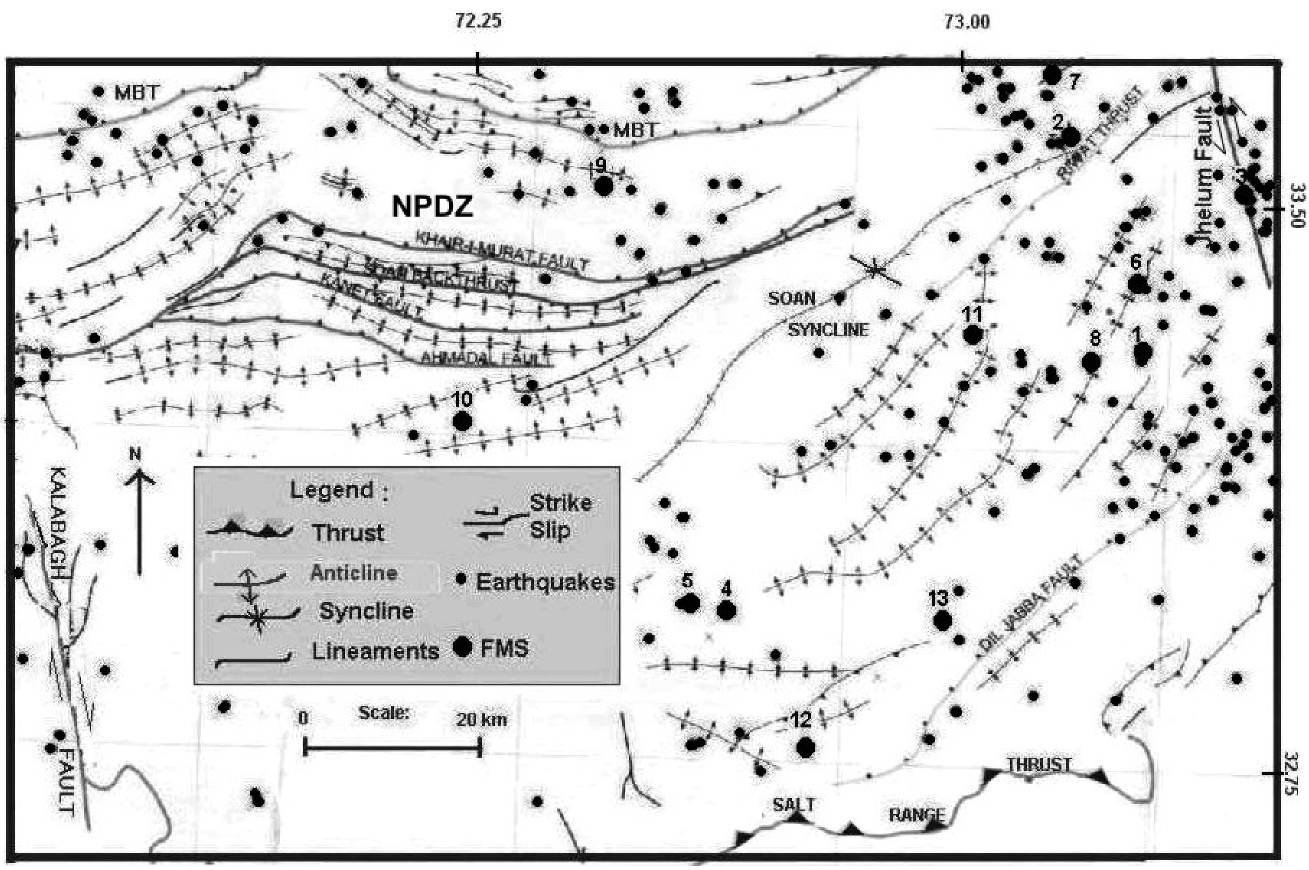

Figure 2- Seismicity and structural map of the study area where 1-13 represents the locations of the earthquakes whose Focal Mechanism Solution (FMS) has been mentioned in the text.

angle thrusts along which Eocene and older rocks have been thrusted over the molasses of the NPDZ. The NPDZ is considered to be a thin-skinned tectonic feature by most workers in which the basal decollement is in the Eocambrian Salt Range Formation. In this interpretation the Soan (Dhurnal) backthrust is a passive backthrust and the area bounded by it and the Khair-i-Murat Fault is a triangle zone of complex geology (e.g. Jadoon et al., 1999).

The models invoking duplex structure have been questioned by Pivnik and Sercombe, (1993); Sercombe et al., (1998). These workers recognize the presence of strike-slip faults at the surface and even in the basement. They relate the structures (high angle strike-slip faults and associated flower structures) to transpressional deformation.

SEISMICITY

Before discussing the focal mechanism solutions, a brief introduction to the seismicity of the area is presented.

Pakistan lies in a high seismicity area with a history of large earthquakes causing a great loss of life and property. Two major destructive earthquakes in the recent past, which killed thousands of inhabitants, are the Quetta earthquake of 1935, claiming about 30,000 lives: and the Pattan earthquake of 1974, with a death toll of about 6,000. Other large earthquake that caused major destruction is the 1981 Darel Valley earthquake.

A seismicity map of the area, prepared from 1964-2002 using the data obtained from the United States Geological Survey (USGS), International Seismological Centre (ISC), International Seismological Summary (ISS) and local seismic networks is shown on structural map (Figure 2). Historical earthquakes from Oldham (1893) and Quittmeyer and Jacob (1979) are also included. Although the entire region of Pakistan is considered to be seismically active, however, the Potwar Plateau appears to be relatively more active as compared to the adjacent areas of the Kohat Plateau and the Salt Range. The seismicity appears to be scattered in most of the area. Only distinct patterns are seen along the Jhelum Fault i.e. in the northeastern part and along the MBT i.e. in the northern portion. The epicentral distribution appears to be concenterated in nearly NE-SW and NW-SE directions along the MBT.

FOCAL MECHANISM STUDIES

The destruction caused by earthquakes is a matter of great concern for the scientific community and different approaches are being implemented to understand the earthquake phenomena. One such approach, whereby an understanding of earthquake is obtained is the focal mechanism solution. The main purpose of a focal mechanism study is to identify seismic faults from seismological observation. If we can directly observe surface faulting due to an earthquake we need not rely on seismological methods to identify the seismic fault. For oceanic earthquakes also, it is difficult to see the fault traces at the sea bottom, even when the fault rupture appears. Thus seismological approaches such as focal mechanism study are indispensable for studying seismic faults and their rupture processes.

Focal mechanism solutions undertaken by earlier workers (Verma et al., 1980; Verma and ChandraSekhar, 1986; MonaLisa et al., 1997; Khwaja et al., 2003) from immediately adjacent regions have shown the dominance of strike-slip faulting with some thrust faulting in this area of collisional tectonics. In the present case, for the determination of focal mechanism solutions, the earthquakes reported by USGS, ISC and the local networks with magnitudes near 4.0 and above occurring in the area during the period of 1964-2002 were considered. Thirteen focal mechanism solutions (Figure 2 and Table 1 and 2) were determined from the P-wave first motion directions. The parameters for the epicenters and the focal mechanism solutions of all the thirteen earthquakes are listed in tables. 1& 2. One of these (event No.2) had previously been analyzed by Seeber and Armbruster, (1979) and Verma and ChandraSekhar, (1986).

PROCEDURE EMPLOYED IN THE PRESENT STUDY

In this study, thirteen focal mechanism solutions of earthquake events (Mb > 4) that occurred in the Potwar area during the period of 1964 to 2002 have been carried out. The standard lower half hemisphere projections on an equal area net have been used. Visual interpretation of these focal mechanism diagrams generated with the help of a computer program PMAN (Suetsugu, 1996) that required input of geographic coordinates, magnitude, focal depth and P wave polarity was carried out for each event. The other two parameters azimuthal angle and take-off angle are determined by the software AZMTAK (Suetsugu, 1996). From the large number of events shown in figure 2, the above-mentioned parameters were available only for the thirteen events discussed in this study.

FOCAL MECHANISM SOLUTIONS

Event No.1

Event No.1 of magnitude 5.1 Mw is one of the few strongest events (Mw>5.0) to have occurred in the area during the study period and for which the required parameters were available (Table 1). The hypocentral depth of this event as given by local network is 33 km. Prominent structural trend of the area where the event occurred is in the NE-SW direction. Qazian anticline (Figure 3) is one of these NE-SW trending anticline and the epicenter of the event is located along the axis of the Qazian anticline. Another important structural feature located about 20-25 km east of the epicentral location is the NW-SE trending Jhelum Fault.

Different workers suggest that the folded structures in the eastern Salt Range (SR) and Potwar Plateau (PP) are cored by blind thrusts. Qazian anticline is also a pop up bounded by two thrusts. Recent workers (Pennock et al., 1989: Moghal et al., 2003) on the basis of seismic data have also confirmed the presence of a pop up structure. Seismic data shows that these two thrusts originate at a depth of about 1.5 km and extend up to the depth of 4 km in the subsurface. In addition, Pennock et al., (1989) also identified a normal fault in the basement.

Table 1. Source parameters of the earthquakes used in the present study.

S. No.	Date			Origin Time			Location						Depth (Km)	Magnitude (Mw)
							Latitude (N)			Longitude (E)				
	Year	Month	Day	Hrs	Min	Sec	Deg	Min	Sec	Deg	Min	Sec		
1.	1970	04	30	03	24	54.0	33	18	00	73	24	00	33.0	5.1
2.	1977	02	14	00	22	37.0	33	36	00	73	16	12	14.5	5.5
3.	1978	05	07	10	32	26.0	33	31	48	73	34	48	8.8	5.1
4.	1984	12	20	07	32	7.00	32	57	00	72	42	00	0.1	4.9
5.	1984	12	27	20	22	8.59	32	57	36	72	38	24	1.20	4.9
6.	1987	07	12	12	19	18.0	33	24	00	73	24	00	13.0	4.6
7.	1989	04	07	05	43	24.0	33	45	00	73	12	00	10	4.6
8.	1990	04	30	18	18	35.0	33	17	24	73	19	12	7.30	4.9
9.	1993	02	17	16	06	7.00	33	33	00	72	30	36	6.5	5.4
10.	1996	03	25	06	31	14.0	33	13	12	73	29	24	10.0	4.9
11.	1999	04	28	13	00	00	33	19	48	73	7	12	5.0	4.7
12.	1999	07	15	04	29	00	32	45	36	72	49	12	0.3	3.8
13.	2001	07	16	16	07	20.1	32	55	48	73	03	36	31.9	5.2

Table 2. Parameters obtained from Focal Mechanism Studies.

Event No.	Fault Plane		Nature	Auxiliary Plane		P-Axis		T-Axis	
	Strike	Dip		Strike	Dip	Plunge	Azimuth	Plunge	Azimuth
1	N238^{0}E	35^{0}NW	LLSS	N146^{0}W	89^{0}SW	34^0	207^0	37^0	86^0
2	N27^{0}E	53^{0}SE	LLSS	N285^{0}E	74^{0}SE	14^0	-20^0	38^0	239^0
3	N121^{0}W	88^{0}NE	LLSS	N31^{0}E	86^{0}SE	2^0	-104^0	4^0	346^0
4	N215^{0}E	73^{0}NW	Thrust	N38^{0}E	17^{0}SE	28^0	-54^0	62^0	123^0
5	N9^0 E	53^{0}SE	LLSS	N119^{0}E	65^{0}SE	7^0	-119^0	46^0	339^0
6	N16^{0}E	76^{0}SE	LLSS	N145^{0}W	62^{0}SW	31^0	3^0	8^0	98^0
7	N261^{0}E	82^{0}NW	LLSS	N171^{0}W	87^{0}SW	02^0	-144^0	5^0	128^0
8	N240^{0}E	65^{0}NW	LLSS	N117^{0}W	41^{0}SW	14^0	354^0	57^0	105^0
9	N64^{0}E	82^{0}SE	LLSS	N332^{0}W	75^{0}NE	5^0	-162^0	16^0	289^0
10	N216^{0}E	62^{0}NW	Thrust	N35^{0}E	28^{0}SE	17^0	-54^0	73^0	126^0
11	N231^{0}E	70^{0}NW	LLSS	N141^{0}W	90^0	14^0	-173^0	14^0	94^0
12	N50^{0}E	86^{0}NW	LLSS	N306^{0}W	32^{0}NE	30^0	165^0	45^0	-289^0
13	N39^{0}E	86^{0}NW	LLSS	N306^{0}W	52^{0}NE	23^0	166^0	29^0	270^0

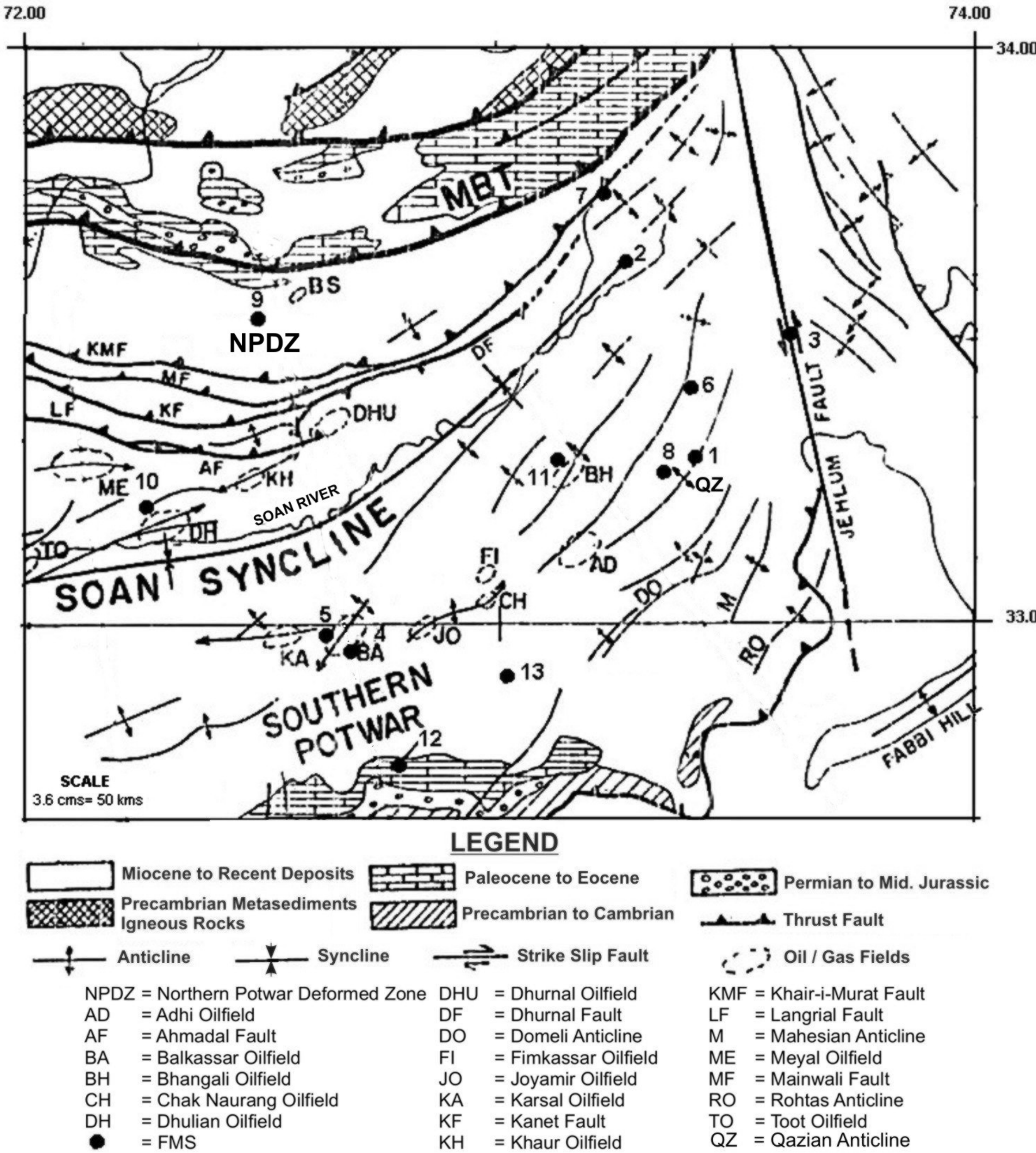

Figure 3- Generalized map of the upper Indus sub-basin showing prominent geological and tectonic features and location of Focal Mechanism Solutions (FMS 1-13) in the Potwar area.

Focal mechanism solution is of thrusting with a strike-slip component (Figure 4). Out of the two nodal planes, the one trending in the NE-SW direction is considered to be the rupture plane as according to Iqbal and Ali, (2001), thrusts with similar orientation are being produced due to movement along the major Jhelum Fault. The indication of a left-lateral sense of motion along the rupture plane is also in agreement with their model.

Event No.2

Event No.2 of magnitude 5.5 Mw (Table 1) is the strongest of all the events to have occurred in the area. The hypocentral depth of this event given by local network is 14.5 km and is commonly referred to as the Rawalpindi earthquake of Feb 14, 1977. Structurally NE-SW trending folds and faults characterize this area. Riwat thrust is one of these NE-SW trending faults and the epicenter of this event is located about 4 km NW of the Riwat fault (Figure 2).

Seeber and Armbruster, (1979) and Verma and ChandraSekhar, (1986) have also carried out focal mechanism solution of this event and obtained a strike-slip solution. Seeber and Armbruster, (1979) tried to correlate it with MBT. In the present case, a strike-slip solution has also been obtained for this event (Figure 4) but as the following discussion will show it is not considered to be a result of activation of the MBT.

The nodal planes (Figure 4) trend in the NE-SW and NW-SE directions and the one having NE-SW trend with a dip of 53^o (Table 2) is considered as the rupture plane. This inference is based on the information provided by Pennock et al., (1989) in their cross section of the area. In their section they have shown the presence of another fault beneath the Riwat Thrust at a depth of about 2-3 km. This fault extends into the basement and is a SE dipping fault. The plane selected as the rupture plane in the focal mechanism solution matches with the trend and dip of this fault and thus believed to be responsible for it.

Event No.3

The epicenter of this event is located on the Jhelum Fault. The hypocentral depth of this event (having magnitude 5.1 Mw) as given by the local network is 8.8 km. Structurally NE-SW trending folds and faults are present to the west of Jhelum Fault (Figure 2). Jhelum Fault is a NW-SE trending left-lateral strike-slip fault that is believed to be playing an important role in the present deformation of the area, especially the Potwar region. This is also substantiated from the seismicity map (Figure 2) of the Jhelum Fault where cluster of seismic events are located.

Focal mechanism solution is shown in the diagram (Figure 4). The nodal planes are trending in the NW-SE and NE-SW directions. The nodal plane in NW-SE direction with a left-lateral sense of motion is considered as the rupture plane as both the orientation and sense of motion of this rupture plane are similar to the Jhelum Fault. According to Baig and Lawrence, (1987) the fault dips steeply towards the east. However, in the present case, the dip obtained for the rupture plane is vertical 88^o (Table 2). Thus it is probable that it is nearly vertical at the epicentral location.

Event No.4

This event of magnitude 4.9 Mw (Table 1) has its epicentral location near Balkassar anticline (Figure 3). Hypocentral depth given by local network is 0.1 km. Structurally NE-SW and E-W trending folds and faults are present in the area (Figure 2 & 3). Moghal et al., (2003) have identified a number of blind faults in the area. In their cross-section based on seismic data, two faults trending in the NE-SW direction are shown to be extending into the basement also.

Focal mechanism solution as shown in figure 4, is of thrusting. The nodal planes trend in the NE-SW direction, and as mentioned above is also the orientation of the two blind faults that dip towards the NW. Therefore the nodal plane having a similar direction of dip as these faults i.e. in the NW direction is considered to be the rupture plane. Thus deeper levels of the basement seem to be involved in the deformation process either through the extension of the blind faults mentioned above or other fault may be present.

Event No.5

Epicentral location of this 4.9 Mw magnitude event (Table 1) is a few kilometers west of the location of event number 4 near the Balkassar anticline (Figure 3). This earthquake was recorded after 7 days of event number 4. Hypocentral depth given by the local network is 1.2 km. In the discussion of the preceding event, it has been mentioned that Moghal et al., (2003) have inferred the presence of a number of subsurface faults beneath the Balkassar anticline. According to them, at a very shallow depth, two faults trending in the NE direction are present.

Focal mechanism solution shown in figure 4 indicates thrusting with a strike-slip component. Considering the NE trend of the subsurface faults and their dip towards the SE, the nodal plane having a similar trend and direction of dip is considered to be the rupture plane.

Event No.6

Epicenter of this 4.6 Mw magnitude (Table 1) event is located near the axis of Qazian anticline (Figure 3). Hypocentral depth as given by the local network is 13 km. NE-SW trending folds and faults are present in the area.

Focal mechanism diagram (Figure 4) represents a strike-slip solution. The nodal planes trend in the NE-SW and NW-SE directions. The geology of the area has already been discussed in the description of event number 1. As previously mentioned, two faults exist in the subsurface beneath the Qazian anticline. The nodal plane trending in NE-SW direction with a dip of 76^o (Table 2) SE is inferred to be the rupture plane as it has the same trend i.e. NE-SW, same dip direction i.e. SW as one of the above two faults. Thus it seems likely that this fault dipping towards SE direction has been activated.

Event No.7

This 4.6 Mw magnitude (Table 1) event has its epicenter located about 1-2 km southeast of the Khair-i-Murat fault (KMF). Hypocentral depth of this event as given by the local network is 10 km. The general trend of the structures

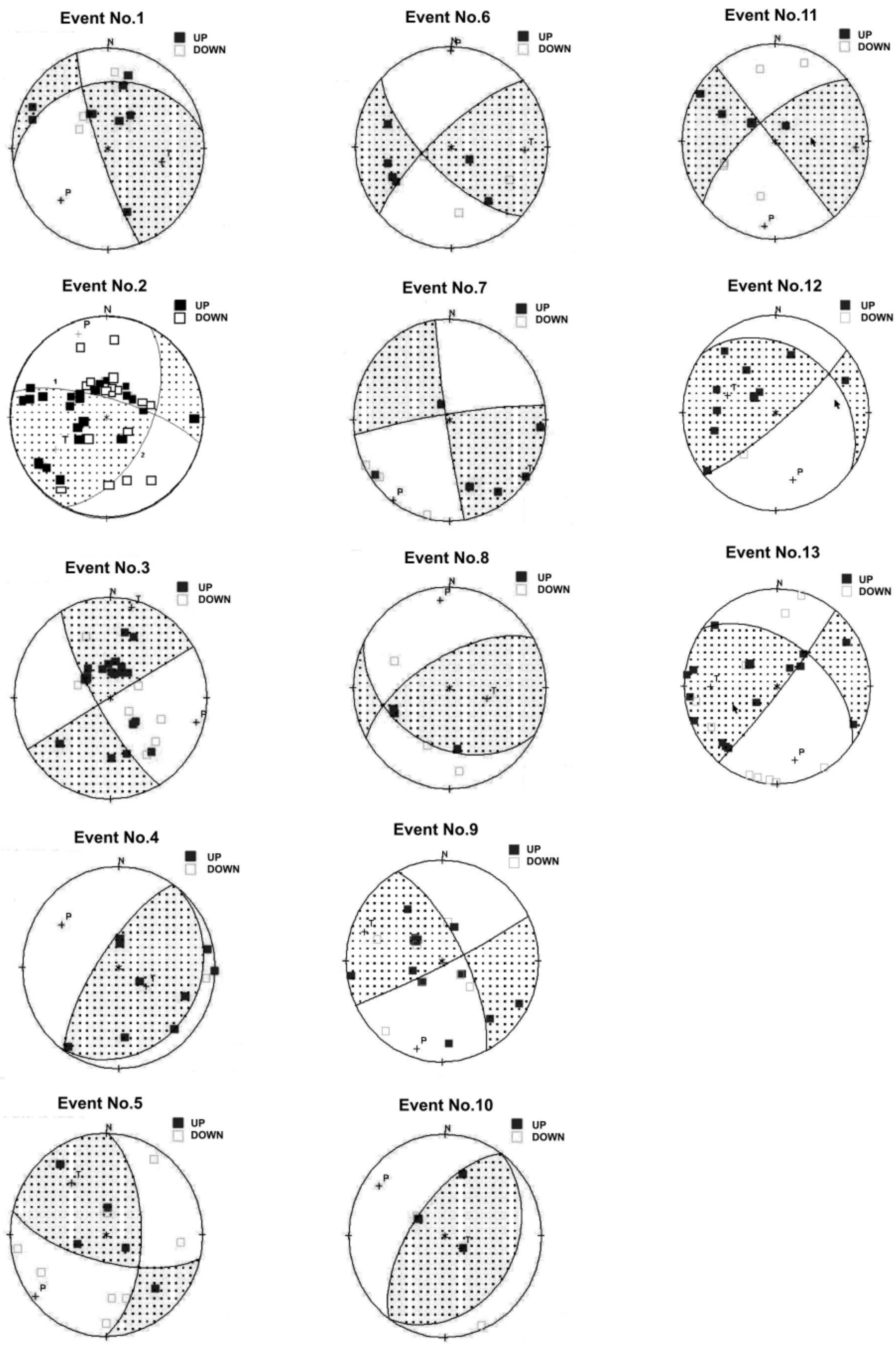

Figure 4- Focal Mechanism Solutions of all thirteen events. Here 'up' means compressions and 'down' means dilatations.

(anticlines, thrusts and back thrusts) in this part of the study area is in the NE-SW direction (Figure 3). According to Jaswal et al., (1997), the dip of KMF is 80^o NW and it extends up to a depth of 7 km. Jadoon et al., (1999) also extend till a depth of more than 8 km into the basement. Probably the Soan (Dhurnal) backthrust with a dip of 42^o SE also extends immediately south of the epicentral location (Figure 2).

Focal mechanism solution indicates pure strike-slip faulting (Figure 4). The nodal plane trending in almost NS direction is taken as the rupture plane.

Event No.8

This event of magnitude 4.9 Mw has its epicenter, like event numbers 1 and 6, located near the Qazian anticline (Figure 3). Hypocentral depth as given by the local network is 7.3 km (Table 1). Majority of the surface structures in this part of Potwar trend in the NE-SW direction.

The focal mechanism solution indicates the presence of a thrust with a strike-slip component (Figure 4). From the earlier description of geology, it is known that blind faults are present underneath the Qazian anticline and one of them even extends into the basement. According to the stress model of Iqbal and Ali (2001) for the Potwar region, one of the major controlling features in the development of structures is the left-lateral Jhelum Fault. Movement along it also results in the formation of NE-SW oriented thrust faults and associated left-lateral folds. Following these workers the nodal plane having NE trend with a left-lateral sense of motion is believed to be the rupture plane.

Event No.9

Epicenter of this event having magnitude 5.4 Mw (Table 1) is between the Main Boundary Thrust (MBT) and the Khair-i-Murat Fault (KMF) in the Northern Potwar Deformed Zone. Hypocentral depth of this event as given by the local network is 6.5 km.

The general structural trend of the area is in the EW direction (Figure 2). Moderate to high dips are present in the exposed rocks of the Murree Formation (Jaswal et al., 1997). Seismic cross sections published in the literature indicate that several subsurface faults merging into basement exist between the MBT and the KMF. The same cross-sections reveal that MBT has a dip of about 65^o –70^o and KMF has steeper dip of 80^o.

Focal mechanism solution indicates thrusting with strike-slip solution (Figure 4). According to Iqbal and Ali, (2001), northeast oriented thrusts in the Potwar region are developing due to deformation along the left-lateral Jhelum Fault. Thus the nodal plane trending in the NE-SW direction is considered to be the rupture plane. It indicates left-lateral sense of motion. Steeper dip 82^o (Table 2) obtained for the rupture plane is similar to steeper dips of the faults in the area. However, the direction of dip i.e. towards the southeast is different from the general northwards dip of the thrusts. Thus probably a blind backthrust may be responsible for the event.

Event No.10

This event of magnitude 4.9Mw (Table 1) has its epicentral location about 6 km south of Ahmadal Fault. Ahmadal Fault is a north dipping, emergent thrust in the western part of Northern Potwar Deformed Zone (NPDZ) while in the eastern part of NPDZ this fault is underthrusted beneath the Soan (Dhurnal) backthrust. Hypocentral depth of this event as given by the local network is 10 km. NE-SW direction is the prominent structural trend of the area (Figure 2). A NE-SW trending lineament is located about 6 km NE of the epicentral location.

Focal mechanism diagram (Figure 4) shows a thrust solution. Moghal et al., (2003) have identified a number of blind faults in the area. In their cross-section based on seismic data, two faults trending in the NE-SW direction are shown to be extending into the basement also. The nodal planes trend in the NE-SW directions and as mentioned above is also the orientation of the two blind faults that dip towards the NW. Therefore the nodal plane having a similar direction of dip as these faults i.e. in the NW direction is considered to be the rupture plane. Thus deeper levels of the basement seem to be involved in the deformation process either through the extension of the blind faults mentioned above or other fault may be present.

Event No.11

This event of magnitude 4.7 Mw (Table 1) has its epicenter, like event numbers 1,6 and 8 and is also located in the eastern part of Potwar (Figure 2 & 3). Hypocentral depth as given by the local network is 5.0 km. Majority of the surface structures in this part of Potwar trend in the NE-SW direction.

The focal mechanism solution indicates the presence of strike-slip fault (Figure 4). From the earlier description of geology, it is known that blind faults are present underneath the Qazian anticline and one of them even extends into the basement. According to the stress model of Iqbal and Ali, (2001), one of the major controlling features in the development of structures is the left-lateral Jhelum Fault. Movement along it also results in the formation of NE-SW oriented thrust faults and associated left-lateral folds. Following these workers the nodal plane having NE trend with a left-lateral sense of motion is believed to be the rupture plane.

Event No.12

This comparatively low magnitude earthquake i.e. of 3.8 Mw (Table 1) has its epicenter located about 6 km NW of the Dil Jabba Fault and 9 km north of Salt Range (Figure 2). Hypocentral depth of this event as given by the local network is 0.3 km. The general trend of the structures (anticlines, thrusts and backthrusts) in this part of the study area is in the NE-SW direction. Focal mechanism solution indicates strike-slip faulting (Figure 4). The nodal plane trending in almost NE-SW direction is taken as the rupture plane. This event can be related with the Dil Jabba thrust.

Event No.13

Epicenter of this strong earthquake i.e. 5.2 Mw (Table 1) is located about 3-5 km north of Dil Jabba thrust (Figure 2). Hypocentral depth given by the local network is 31.9 km. Structural trend is NE-SW direction is quite prominent in this area.

Focal mechanism diagram (Figure 4) shows left-lateral strike-slip faulting. The nodal planes trend is in the NE-SW directions (Table 2) and is inferred to be the rupture plane as it has similar trend i.e. NE-SW as that of DilJabba thrust which is the only structure surrounding the event. So like event number 12, this event can also be related to the DilJabba thrust.

CONCLUSIONS

1. Based upon the seismicity data, the Potwar Plateau is found to be seismically active. Seismicity is mainly concenterated along Jhelum Fault in the east and MBT in the north. The earthquakes occurred in the area are shallow focused (i.e. depth < 50 km) and majority of them lie in the magnitude (Mw) range of 4-5.5.
2. Data of thirteen earthquakes have been used for focal mechanism solutions in the present study. Out of these eleven events are showing left-lateral strike-slip solutions, whereas, only two events i.e. 4 and 10 are of thrusting.
3. Qazian pop up structure exhibits strike-slip movements in the subsurface as all the events (1,6,8 and 11) occurring on Qazian anticline show strike-slip solutions.
4. Jhelum Fault is playing an important role in the deformational style of Potwar Plateau as majority of the structures are EW and NE oriented thrust faults and associated left-lateral en echelon faults.
5. In most of the cases, a direct relationship has been found between the structures and the seismicity, which confirms the hypothesis of Merin and Moore, (1986) that there exist a direct relationship between the hydrocarbon occurrence and lineaments.
6. Our Focal Mechanism studies confirm the structural model of Iqbal and Ali, (2001) in which they interpreted that the present structural pattern in the Potwar plateau is the response of left and right-lateral strike-slip movements initiated during Late Tertiary time along Jhelum and Kalabagh faults system in the east and west respectively and in our case this is quite evident as all left-lateral strike-slip focal mechanism solutions have their fault planes oriented in the northeast direction which is due to the movement along left-lateral Jhelum Fault. It is therefore suggested that, to have a clearer picture of fold-and-thrust belt, a detailed seismological work is required in the adjacent areas of Kohat Plateau and the Salt Range.
7. P-axes and T-axes, however, show mixed trend i.e. both NE-SW and NW-SE directions. This shows that energy is accumulated and released from these directions.
8. Since most of the depth data for the FMS have been taken from the local seismological networks therefore the depth estimations for the events is reliable. Based upon this depth data and final selected fault planes, it is interpreted that basement faulting is most probably involved in the deformation. Thus instead of thin-skinned deformation our results suggest the thick-skinned deformational model, however more detailed seismological work is required to confirm this hypothesis.
9. Based upon our seismological studies, it is recommended that exploration may be carried out along the strike of the northeast-directed structures.
10. In order to conventional thrust tectonics to occur in the area, certain other accommodations are also taking place in the area as can be seen from the predominance of strike-slip solutions. The orientation of structures present in the area shows that the region between left-lateral Jhelum and right-lateral Kalabagh fault is under anticlockwise rotation.
11. In the adjacent area of the Kohat Plateau, Pivnik and Sercombe (1993) and Sercombe et al. (1998) have shown that duplex structures interpreted by some workers are not present. Instead, wrench faulting and flower structures occur. According to Pivnik and Sercombe, (1993) the first episode of deformation included south verging, compression related thrusting followed by transpression related wrench faulting. The strike-slip faults inferred in the present study are believed to be a result of such overprinting of transpressional features. Thus the thin-skinned tectonic models proposed by different workers for Potwar may not be valid without considering the deformation that is affecting the basement in the area. Further work is needed to confirm the presence of a decoupling layer in the basement.

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