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Structural Interpretation on the Basis of Focal Mechanism Studies in the Area of Kohat Plateau, Bannu Basin and Western Extension of Salt Range

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ABSTRACT

The identification of structural traps is the main aim in hydrocarbon exploration. A number of techniques are employed for this purpose. Analysis of seismological data through Focal Mechanism Solutions (FMS) is one of these. However this technique has not been widely used in Pakistan for hydrocarbon exploration. Combining published structural information with FMS, it is attempted to identify the surface and subsurface structural pattern. For this purpose, a seismicity map using the earthquake data from international and local seismic networks for the time span 1904-2002 has been prepared. It shows a distinct seismicity pattern in the central Kohat Plateau and along the margins of the Bannu Basin (Khisor, Marwat and Bhittani Ranges). The Bannu Basin itself seems to be aseismic. A total of 9 earthquakes have been investigated, out of which 5 are from Kohat Plateau and the rest are along the margins of the Bannu Basin. Within the Kohat area, 4 out of 5 FMS indicated left lateral strike slip and one shows reverse faulting, which infers wrench faulting in the subsurface. However the margins of Bannu Basin revealed mixed FMS i.e. thrust, reverse and normal. These findings suggest the flower structure (thick-skinned tectonics) geometry due to basement involvement for the study area.

INTRODUCTION

Focal Mechanism Solutions in active deformed belts worldwide offer significant assistance in determining structural styles, however in Pakistan in most of the structural models this technique has not used. In the present study the correlation of the seismological data with the structural information is made. That can be incorporated in the structural/seismological models of the area.

TECTONIC SETTING

The NW Himalayan fold and thrust belt is one of the active fold–and–thrust belt along the northwestern margin of the Indo–Pakistan Plate. The Main Mantle Thrust (MMT); the 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). The area between the MMT and SRT and its westward extensions i.e. Surghar, Marwat, Bhittani and Manzai ranges are referred as its boundaries (Kazmi and Jan, 1997). In the south these ranges are marked by thrusts (Gee, 1980). The tectonic domains of Hazara-Kashmir Syntaxis and the Nanga Parbat Haramosh Massif comprise its north eastern boundary. The western limit is not well defined but a number of south-east directed thrusts and strike-slip faults are prominent features.

In this nearly 250 km wide and 560 km long NW Himalayan fold and thrust belt, the Panjal-Khairabad fault (Figure 1) divides it into hinterland zone toward the north and the foreland zone into the south. The hinterland zone is also referred to as the Hazara Crystalline Zone (Bender and Raza, 1995) and Himalayan Crystalline Zone (Kazmi and Abbas, 2001), whereas the foreland zone lies between the Panjal-Khairabad Fault and the Salt Range Thrust along with its westward extension. In the foreland zone the crystalline basement is lying at a depth of 8 km overlain by thick sedimentary sequences. This foreland zone comprises of many thrust sheets with a southward translation of up to 100 Km.

Many workers (Kemal, 1992; Bender and Raza, 1995; Kazmi and Jan, 1997) have classified this part of the study area into different zones. Following the classification of Kazmi and Jan (1997), the foreland zone on the basis of deformation style is divisible into the Salt Range and Kohat-Potwar fold belt, Kurram-Cherat-Margalla fold and thrust belt and the Hazara-Kashmir Syntaxis. The study area belongs to the Salt Range and Kohat-Potwar fold belt, which is briefly described.

THE SALT RANGE AND KOHAT-POTWAR FOLD BELT

This belt covers a wide area between the MBT in the north, and the Salt Range Thrust, Kalabagh Fault and the Surghar/Khisor and Marwat Thrusts in the south and south west. Along the eastern margin, the Jhelum Fault separates it from the Hazara-Kashmir Syntaxis, while the Kurram Fault delineates its western boundary (Figure 1). Sedimentary rocks of Eocambrian to Recent occupy the area. Dominant structures are east-west trending folds and thrust faults. The intensity of deformation is more pronounced along the MBT and SRT. Generally folds are more tight, complex and faulted.

Structural cross sections across the Potwar and Salt Range recognize the presence of a decollement in the Eocambrian evaporites (Jaume and Lillie, 1988; Pennock et al., 1989) thereby implying thin-skinned tectonics. Similar

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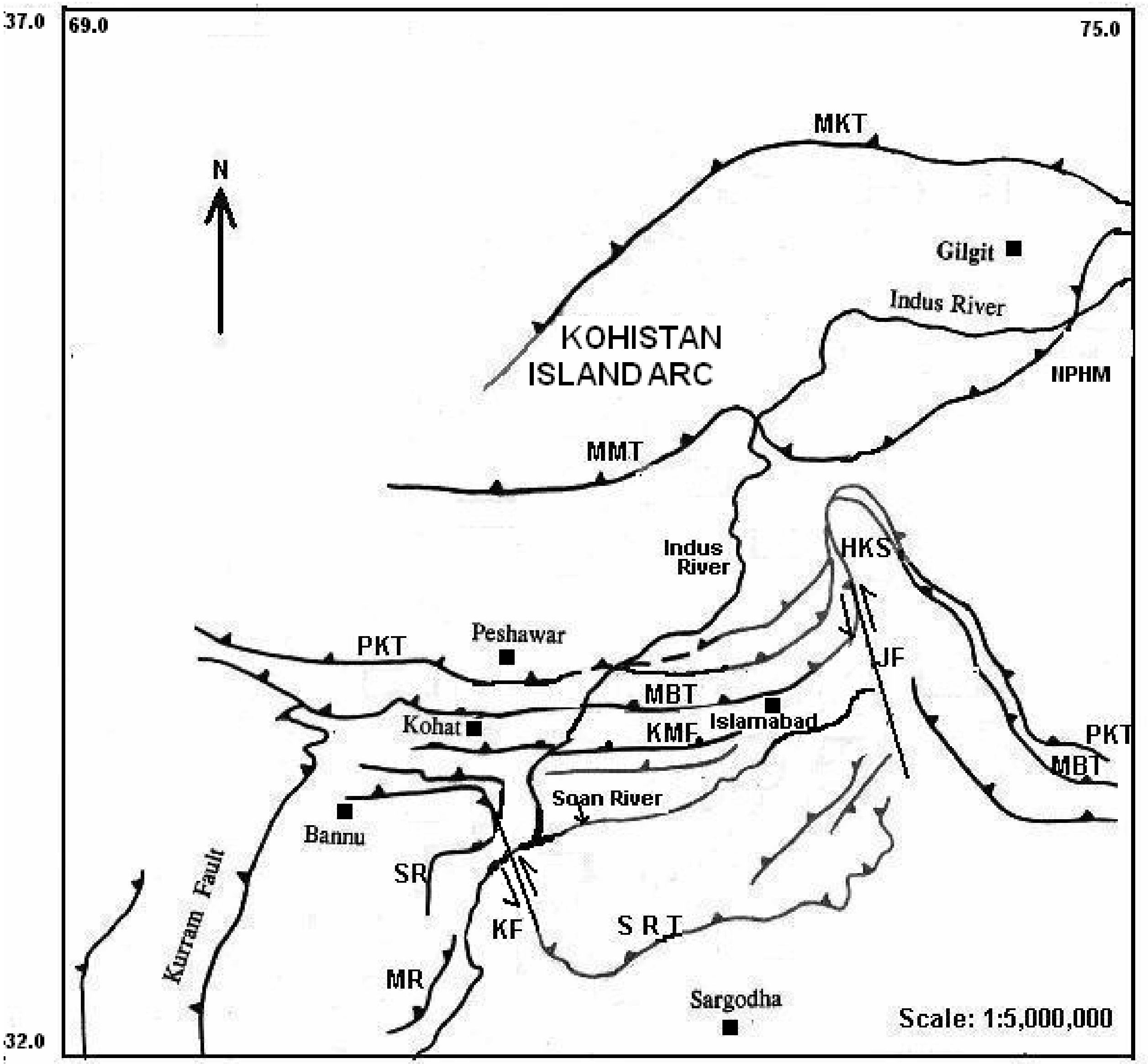

Figure 1- Tectonic map of the study area and adjoining regions.

MBT=Main Boundary Thrust; MKT=Main Karakoram Thrust; MMT= Main Mantle Thrust; PKT= Panjal Khairabad Thrust; KMF= Khair-I-Murat Fault; SR= Surghar Range; SRT= Salt Range Thrust; JF= Jhelum Fault; HKS= Hazara Kashmir Syntaxis; NPHM=Nanga Parbat Haramosh Massif.

models have been proposed for the Kohat area (Baker et al., 1988; Abbasi and McElroy, 1991). Recently, Moghal et al., (2003) have proposed the presence of at least two decollement levels. The basal one of these detachment level occurs in Eocambrian evaporite as proposed by previous workers and the upper levels at the interface between Eocene and younger rocks. On the other hand, Sercombe et al., (1998); MonaLisa and Khwaja (2004) have suggested that basement involved tectonics is instrumental in the structural deformation.

The Bannu Basin (about 8000 km^2) has similar structural deformation to southern Potwar (Kemal, 1992).The Quaternary sediment fill of about 400m thickness is underlain by southeast verging imbricate thrust sheets. Kemal (1992) believes that Eocambrian salt has served as the basal decollement here. At the same time, Kemal (1992) interprets the Surghar Range to be a flower structure. Thus, more work is needed to decipher the subsurface structure in the Bannu Basin. This study shows that the Bannu Basin is aseismic, with one normal fault. FMS solutions for the southern margin, and thrust/reverse obtained for the eastern and northern margins of this basin.

HYDROCARBON POTENTIAL

The sedimentary basins are supposed to be the natural habitat for occurrence of oil and gas, and thus are significant for petroleum exploration. The area under investigation is characterized by complex structural styles. A number of oilfields occur in this zone. The Dhurnal oilfield was the largest and has reserves of about 52 million barrels of oil and 0.13 TCF of gas. Geothermal gradients in this zone vary from 1 to 2^0c/100m. The oil window occurs at depth of 2750-5200m (Khan et al., 1986, Raza et al., 1989) and this is reflected in the occurrence of oil at depths greater than 2750m.

SEISMICITY

Pakistan experience high frequency earthquakes, which have resulted 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.

Available information indicates that the Makran coastal earthquake of 1945 and the Quetta earthquake of 1935 were the severest earthquakes those affected Pakistan. In the vicinity of the study area, the 1905 Kangra earthquake (in India) of m_b 8.4 activated the MBT. More recently, Pattan (1974), Rawalpindi (1977), Bunji (2002) and Batgram (2004) and Muzaffarabad (2005) earthquakes badly affected the study area.

Using the earthquake data for the period of 1964-2002 obtained from the United States Geological Survey (USGS), International Seismological Centre (ISC), International Seismological Summary (ISS) and local seismic networks a seismicity map has been prepared (Figure 2). The seismicity pattern in terms of magnitude of earthquakes shows concentration in the central Kohat and along the margins of the Bannu Basin, whereas the Bannu Basin seems to be inactive as there is no epicentral distribution in the basin. Khwaja and MonaLisa (2005) have noted that the Salt Range, Southern Potwar near Talagang 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 m_b) have been recorded (Seeber and Armbruster 1979; Quittmeyer et al., 1979; whereas in the seismicity map only events having magnitude ≥4 have been plotted. Another

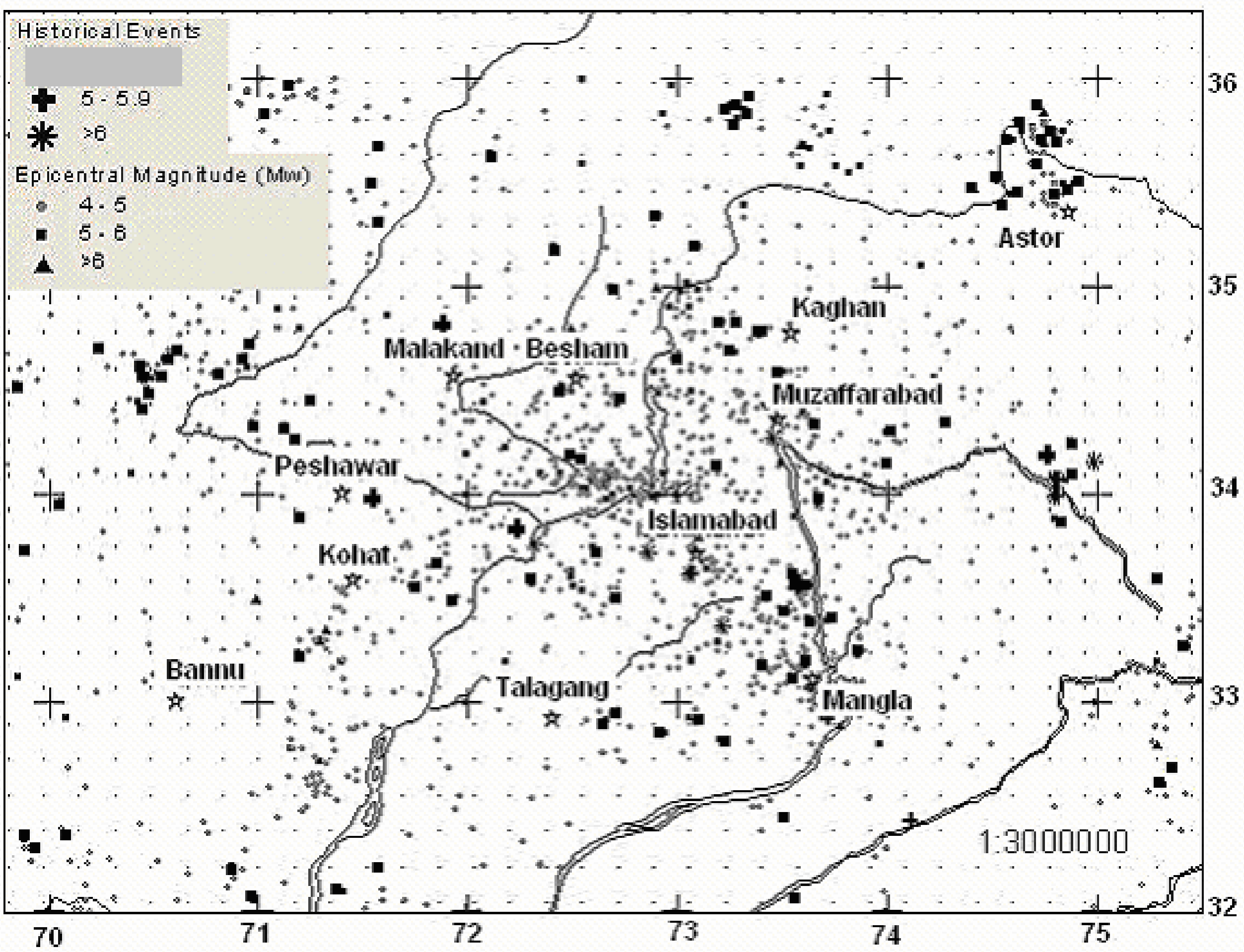

Figure 2- Seismicity map of the NW Himalayas, Pakistan.

reason may be the presence of a thick sequence of Eocambrian salt in the Salt Range and Potwar area that damps the seismic waves. Further, the lithologies occurring in the Salt Range/Potwar are believed to be extending into the Bannu Basin (Kemal, 1992) thereby implying the presence of salt in this part also.

FOCAL MECHANISM STUDIES-BRIEF PROCEDURE

To understand the earthquake phenomenon different approaches are being carried out. One such approach is the Focal Mechanism Solution (FMS) or Fault Plane Solution (FPS) that helps in identifying seismic faults and their rupture processes. Further, the FMS in combination with the tectonic history and structural features provide an improved understanding of the earthquake occurrence of an area.

In the present work, 9 Focal Mechanism Solutions (FMS) of earthquakes ($M_w \geq 4$) that occurred in the North Western Himalayan Fold and Thrust Belt, Pakistan during the period of 1964 to 2004 (Table 1) 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. From the large number of events shown in the seismicity map prepared for the area (Figure 2), only FMS of 9 events could be carried out. This limitation is due to insufficient coverage of the area in terms of less number of stations and non-availability of relevant parameters such as polarity data and azimuthal angles.

In the following section first the FMS of Kohat Plateau (Figure 3a) is discussed, followed by the FMS interpreted for the area along the margins of Bannu Basin (Figure 3b). It may be noted that events have been numbered 1-9 considering their date of occurrence with number 1 being the oldest and number 9 the last event occurred in the studied time period. Further, these events are discussed from N to S according to their position of occurrence.

Focal Mechanism Solutions in Kohat Area

FMS 4, 2, 7, 6 and 1: These five earthquakes are located in the Kohat Plateau. Out of these five events, 4 are strike slip and one is reverse.

FMS 4: The epicentre is located a few km south of the MBT (Figure 3a). 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 Mir Khweli Sar Thrust Belt (MKSTB) that is an assemblage of at least 12 thrust faults which 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, these workers have inferred the structures to be thick skinned. Abbasi and McElroy, 1991 have identified two detachment levels with the lower one in the Eocambrian evaporite at the depth of 6-7 km and the upper one at the interface between Eocene and younger rocks.

The focal depth of this event is 15 km (Table 1) thereby indicating involvement of the basement as already mentioned that basement occurs nearly at 6-7 km depth in this area. Solution indicates reverse faulting with a strike slip component (Figure 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 (Table 2).

Table 1. Source parameters of 9 earthquakes whose FMS have been determined and referred in the present study.

FMS Nos.	Date D/M/Y	Time H: M: S	Latitude (N)	Longitude (E)	Depth (Km)	Magnitude (m_b)
1	18/11/68	5:05:05	33.24	71.2	17	5.0
2	7/5/72	10:05:04	33.45	71.5	17	5.0
3	28/05/82	0:58:48	32.36	70.09	9	4.6
4	11/2/84	8:37:06	33.6	71.6	15	4.8
5	17/02/91	7:00	33.06	71.39	4.1	4.5
6	20/5/92	12:20:32	33.25	71.3	10	6.0
7	5/6/92	12:23:19	33.27	71.34	0.6	5.0
8	23/01/99	9:53:00	32.27	70.2	14.6	5.5
9	16/4/99	22:11:00	32.49	70.8	10	4.8

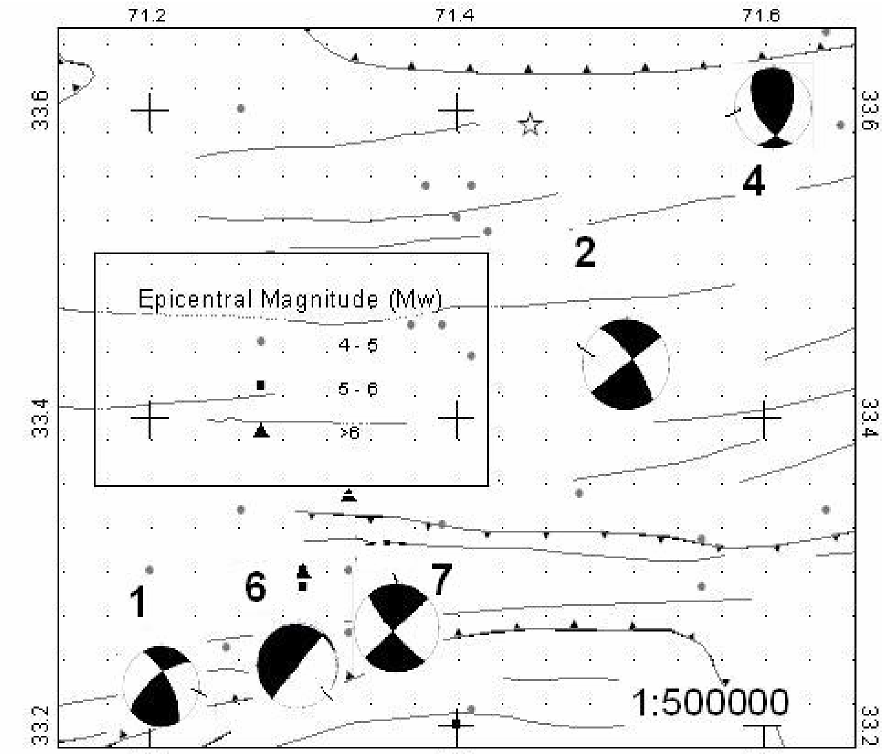

Figure 3a. Focal Mechanism Solution (FMS) map of Kohat. 1, 2, 4, 6 and 7represent the locations of the earthquakes whose FMS have been carried out.

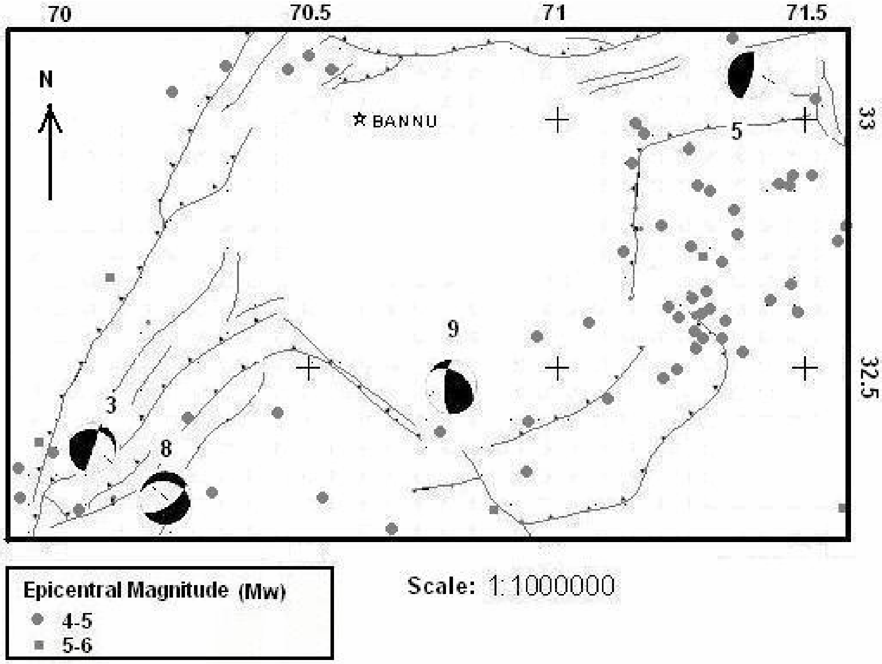

Figure 3b. Focal Mechanism Solution (FMS) map of the area along the margins of Bannu Basin. 3, 5, 8 and 9 represent the locations of the earthquakes whose FMS have been carried out.

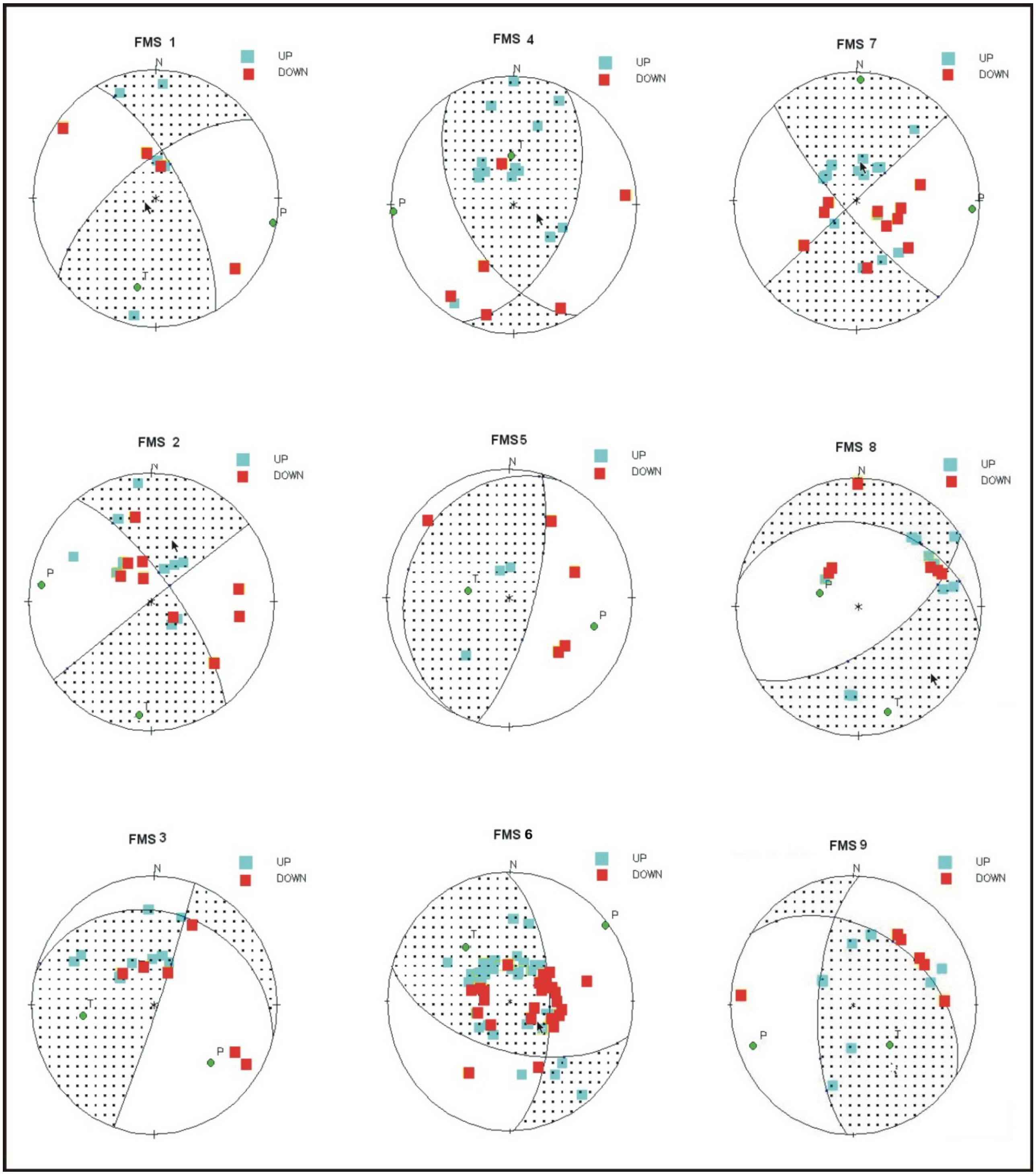

Figure 4. Focal Mechanism Solutions of all 9 events. FMS in the Kohat Plateau = 1, 2, 4, 6 & 7; FMS in the Western Extension of Salt Range = 3, 5, 8 & 9.

Table 2. Parameters obtained from the 9 FMS.

FMS No.	Nature of FMS	Fault Plane (FP)		Auxiliary Plane (AP)		P-Axis		T-Axis	
		Strike	Dip	Strike	Dip	Strike	Plunge	Strike	Plunge
1	LLSS	331^0	71^0 E	232^0	67^0NW	101^0	2^0	192^0	31^0
2	LLSS	323^0	75^0 NE	233^0	89^0 NW	279^0	10^0	187^0	11^0
3	REVERSE	019^0	88^0 SE	285^0	28^0N	134^0	36^0	263^0	41^0
4	REVERSE	025^0	51^0 SE	149^0	55^0 SW	-94^0	2^0	359^0	58^0
5	THRUST	205^0	016^0NW	015^0	74^0 SE	107^0	29^0	281^0	61^0
6	LLSS	358^0	64^0SW	106^0	59^0E	053^0	3^0	320^0	43^0
7	LLSS	138^0	81^0SW	228^0	89^0 SE	094^0	7^0	003^0	6^0
8	NORMAL	281^0	35^0 N	056^0	64^0 SE	286^0	63^0	163^0	15^0
9	THRUST	183^0	67^0 W	303^0	41^0NE	248^0	15^0	137^0	55^0

FMS 2: This 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 (Figure 3a).

The seismic and aeromagnetic data published by Sercombe et al., (1998) showed 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 (Figure 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 (Sercombe et al., 1998). 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 (Table 2) left lateral strike slip fault (wrench fault). Focal depth (Table 1) suggests the involvement of basement.

FMS 1, 6 and 7: These events occurred in an area where the surface geology shows the presence of tight anticlines and synclines (Figure 3a). Pivnik and Sercombe (1993) considered 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 (Figure 4). In the case of FMS 7, a reverse component is also present. For this solution, Harvard CMT is of thrusting and incorporates less number of stations. Detailed work of Sercombe et al., (1998) and Pivnik and Sercombe (1993) has inferred the Hukni Fault (located close to 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 2) and influence of the above mentioned faults (Kurram/Chaman Fault) lead 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. Sercombe et al., (1998) on the basis of magnetic and seismic data, have also deciphered similar trending faults in the basement.

Focal Mechanism Solutions Along The Margins Of Bannu Basin

FMS 5, 9, 8 and 3: All these events are from the Bannu Basin and the adjoining ranges (Surghar, Marwat, Khisor and Bhittani Ranges) that form the margins of the basin.

FMS 5: This earthquake is located where the Surghar Range trends in the E-W direction (Figure 3b). 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 (1990) indicates that the thrust extends 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 (Figure 4). Focal depth of about 4km (Table 1) 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 9: The epicentre is located in the southern part of the Bannu Basin (Figure 3b) where the NE trending Marwat Thrust, NW trending Bhittani Thrust, and the right lateral strike slip Pezu Fault occur. 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 (Figure 4). Presence of two faults with a right lateral component in the vicinity lead 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 8: 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 (Figure 3b) by Kazmi and Jan (1997).

FMS obtained is of normal faulting (Figure 4). Focal depth (~15km) indicates that the fault occurs in the basement (Table 1). Subsurface geology of the area is not well known. Deformation style 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 3: FMS 3 is located a few km west (2.5km) of the Manzai Thrust (Figure 3b), the south western boundary of the Bannu Basin. Solution obtained for this shallow earthquake having focal depth of 9 km is of thrust/reverse faulting (Figure 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 75^0 is obtained. This steep dip (Table 2) 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).

CONCLUSION

The seismological study with the special emphasis on the structural interpretation of the Kohat Plateau and the area along the margins of the Bannu Basin has been carried out. This led to draw the following conclusion.

1. The seismicity map prepared (Figure 2) shows that the study area is less active as compared to the adjoining parts of the Potwar. However there exists some epicentral concentration in the central Kohat and along the margins of the Bannu Basin i.e. Khisor, Marwat and Bhittani ranges.
2. The Bannu Basin seems to be inactive as there is no epicentral distribution. We believe that lithologies occurring in the Salt Range and Potwar area that may be having a damping effect are also extending into Bannu Basin (Kemal, 1992), which may be the cause of this low seismicity.
3. Focal Mechanism Studies of 9 earthquakes have been determined. Out of which 5 are from Kohat Plateau and 4 are along the margins of the Bannu Basin.
4. In the area of Kohat, 4 out of 5 FMS are related to left lateral strike slip whereas only one shows reverse faulting, which infers the presence of wrench faulting in the subsurface.
5. The margins of Bannu Basin indicate mixed FMS i.e. thrust, reverse and normal faulting.
6. The axes of maximum compressive stress i.e. P-axes and axes of maximum tensile stress i.e. T-axes show mixed trend i.e. both NE-SW and NW-SE directions, which show that energy is accumulated and released from these directions.
7. Duplex structures (Pivnic and Sercombe et al., 1993; Sercombe et al. 1998) for the area under investigation could not be confirmed through this study. Instead, wrench faulting and flower-structure dominate the structural.
8. Based upon the reliable depth data (from the local observatories), it is believed that the basement faulting is most probably involved in the deformation. We therefore interpret that instead of thin skinned deformation, the thick skinned model is more reasonable for the area in order to understand the deformational processes. This observation however can further be confirmed by the detailed seismological work incorporating micro earthquake data as well.

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