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Focal mechanism study of north Potwar deformed zone, Pakistan*

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Abstract

Northern Potwar Deformed Zone (NPDZ) is a part of the foreland zone of NW Himalayan folds and thrust belt. Seismicity map has been prepared for this region, which appears to be less active as compared with adjacent regions with apparently no distinct pattern or relationship with surface structures. Focal mechanism solutions of 4 events, for which required parameters are available, indicate left-lateral strike- slip faulting for 3 events and thrusting for one event. *P*-axes orientations are in NW-SE and NE-SW. Basement is most likely involved in the ongoing deformation.

Key words: focal mechanism; seismicity; northern Pakistan

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Introduction

Northern Pakistan is one of the seismically active regions in the world. Numerous studies have been undertaken to highlight and understand the ongoing collisional process of the Indo-Pakistan plate with the Kohistan island arc. Besides the N-S compression, as a result of the convergence, transpressional features have also been recognized. However, in the studied 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.

There are indications that the layers deeper than the Eocambrian evaporites are also undergoing deformation. Thus, in the present study the nature of fault motions prevailing at depth within a small tectonic subdivision referred to as the Northern Potwar deformed zone (NPDZ) are described. Such type of information, it is hoped, would lead to incorporation of seismicity data in future models.

1 Location and main features of the studied area

The area is bounded by latitudes 33°15′~33°37′N and longitudes 72°~73°17′E, and is the northern part of Potwar Plateau in Pakistan (Figure 1). It 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, *et al*, 1989), and the southern suture referred to as main mantle thrust (MMT) is believed to have originated about 50 million years ago (Treloar, Rex, 1990). Kohistan island arc lies between these two sutures. The

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deformation is believed to have shifted southwards with time to the main boundary thrust (MBT) in the Himalayan foreland. Kohat plateau and Potwar plateau along with the Salt Range represent a zone of foreland deformation south of the MBT (Figure 1). The studied area shows many distinct structural features that are described below. Besides the capital city of Islamabad, many other densely populated towns/cities and industrial sites are located in the studied area.

2 Geology of the area

The studied area is a part of the Potwar plateau where the topography is undulating and characterized by a series of parallel ridges and valleys. Generally they trend in 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, Jan, 1997).

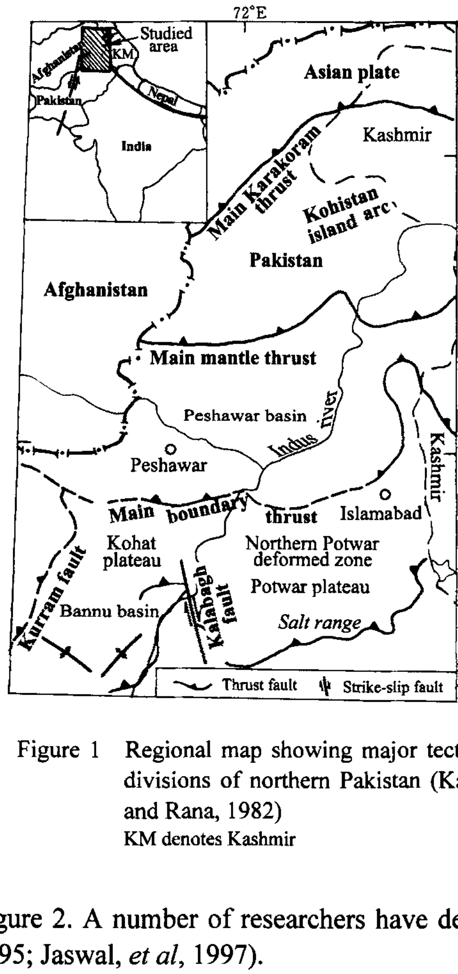

Figure 1 Regional map showing major tectonic divisions of northern Pakistan (Kazmi and Rana, 1982)
KM denotes Kashmir

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). It is more intensely deformed than the southern Potwar and the Salt range. Mostly E-W trending tight and complex folds are seen with their southern limbs overturned with steep angle faults.

The area contains a series of thrusts. Lillie, *et al* (1987) described the northern Potwar as an imbricate stack of thrust faults with some being on the surface and the others occurring at depths as blind thrusts. General trend of these thrusts changes from E-W to NE-SW direction in the eastern part of the NPDZ. Some of these thrusts are shown in Figure 2. A number of researchers have described these faults (Lillie, *et al*, 1987; Jadoon, *et al*, 1995; Jaswal, *et al*, 1997).

Important structures, which are considered to have played significant role in the development of the tectonic style that appears in the northern Potwar and described by various researchers, from south to north are the Soan Syncline, Soan (Dhurnal) back thrust and the Khair-i-Murat imbricate zone.

Soan syncline is the major structural feature of Potwar. Its southern limb is less steep than the northern limb. In the studied area, it is believed to have evolved between 3.4 Ma and 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. This NE-SW thrust lies about 20 km south of Rawalpindi. Jadoon, *et al* (1995) believed that cessation of movement along the Riwat thrust stopped at about 2.7 Ma BP.

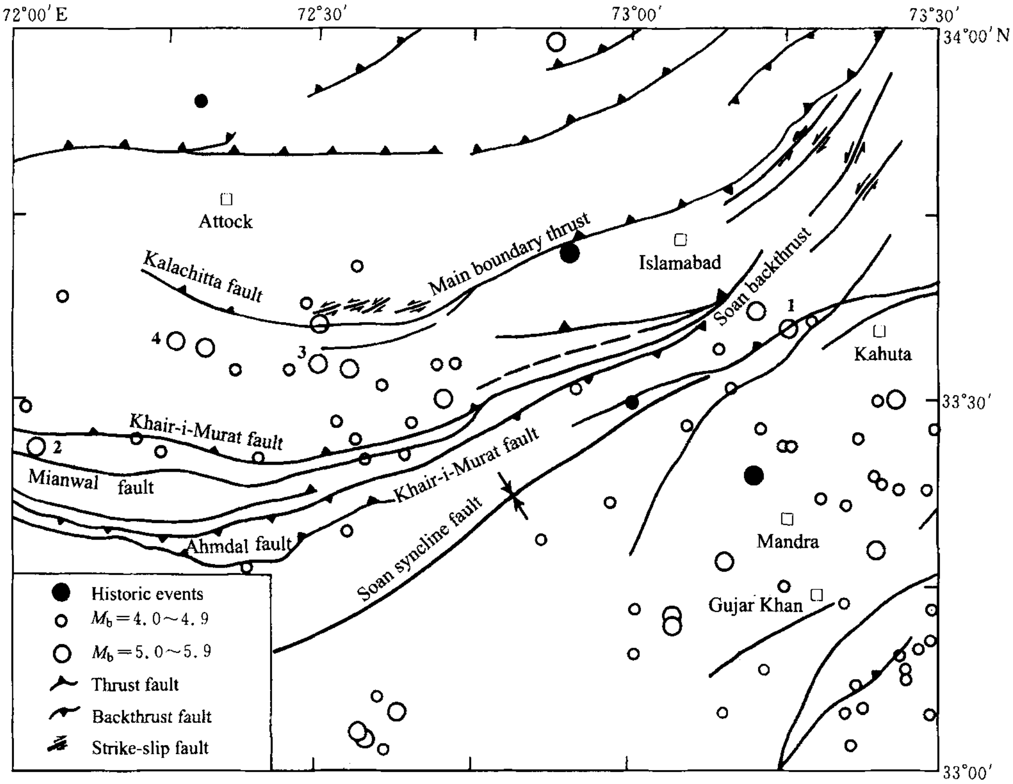

Figure 2 Map of seismicity and structures of the studied area (compiled from many sources)
The locations of events whose focal mechanism solutions have been determined are numbered 1~4

Soan (Dhurnal) backthrust is a distinctive feature of the eastern northern Potwar deformed zone. It is on the northern limb of the Soan syncline immediately south of Rawalpindi (Figure 2). The dip of the back thrust is nearly vertical in contrast to being nearly horizontal along axis of the Soan syncline. The top of Kamlial formation marks its location. To the north of the back thrust till the high angle Mianwala fault, highly deformed Murree formation rocks with steep to vertical dips appear, where, as further north till the Khair-i-Murat fault, steeply dipping Siwalik group lithologies are representative.

Khair-i-Murat and Golra imbricate zone is an area between the Soan syncline and the main boundary thrust (MBT). The Khair-i-Murat thrust named after the range of this name lies to the southwest of Rawalpindi. It is about 22 km long and 2 km wide. Golra is a name of village, now part of Islamabad. Eocene rocks are exposed along these two thrusts and have moderate to vertical dips. Overturning also exists. In the Khair-i-Murat range, the moderatly to steeply dipping Murree formation with small bedding parallel slip and related splay is imbricated. Golra fault merges eastwards in the MBT. This and other minor faults like the Shah Allah Ditta fault that lies north of the Golra fault, are probably splaying branches of the MBT. The MBT itself is represented by many high angle thrusts along which Eocene and older rocks have been thrusted over the molasses of the NPDZ.

According to Pennock, *et al* (1989) the basement along the Soan syncline is at a depth of about 6 km. It increases towards north and is at about 8 km near the MBT (Jaswal, *et al*, 1997). Most researchers consider the NPDZ to be a thin-skinned tectonic feature, in which the basal decollement is in the Eocambrian Salt range formation. In this interpretation the Dhurnal fault is a passive back thrust and the area bounded by it and the Khair-i-Murat fault (Figure 2) is a triangle zone of complex geology (Jadoon, *et al*, 1999).

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

3 Seismicity

Pakistan is considered a seismically active region. However, the NPDZ and other parts of Potwar appear to be relatively less active as compared to adjacent areas. Epicentral distribution of $M>4$ events that occurred during the period 1970 to 1996 are shown in Figure 2. These data are from United States Geological Survey (USGS), International Seismological Center (ISC), International Seismological Summary (ISS) and local seismic networks. As reported focal depths are generally unreliable, the depth data have been obtained from the (local) Nilore (Rawalpindi) Observatory. Also included are historical earthquakes from Oldham (1882) and Quittmeyer, *et al* (1979). No distinct pattern is observed and the seismicity is scattered.

Focal mechanism solutions of earthquakes in closely adjacent regions obtained by earlier researchers (Verma, *et al*, 1980; Verma, ChandraSekhar, 1986) have shown dominance of strike-slip faulting with some thrust faulting in this area of collisional tectonics. In the present case, four solutions have been determined (Figure 2). One of these (event No. 1) was previously analyzed by Verma and ChandraSekhar (1986), and also by Seeber and Armbruster (1979).

4 Focal mechanism

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

The destruction caused by earthquakes is a matter of great concern for the scientific community and different approaches are implemented to understand the earthquake phenomena. One such approach, whereby an understanding of earthquake is obtained, is the focal mechanism solution (FMS). The main purpose of focal mechanism analysis is to identify seismic fault from seismological observation. If we can directly observe surface faulting caused by an earthquake we need not rely on seismological methods to identify the seismic fault. For oceanic earthquakes 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 investigating seismic faults and their rupture processes.

4.1 Procedure employed in the present study

In this study, four focal mechanism solutions of earthquakes (M_b>4) that occurred in the north Potwar deformed zone (NPDZ) during the period of 1970 to 1996 have been carried out. Standard equal area projection of lower half hemisphere has been used. Visual interpretation of these focal mechanism diagrams, which were generated with the help of a computer program PMAN that requires input of geographic coordinates, magnitude, focal depth and P wave polarities, were carried out for each event. The other two parameters azimuthal angle and take-off angle are determined by the software. From the large number of events shown in Figure 2, the above mentioned parameters were available only for the four events discussed in this study.

4.2 Focal mechanism solutions

Event No. 1, commonly referred to as the Rawalpindi earthquake occurred at a shallow depth of 14.5 km. Its FMS obtained is of left-lateral strike-slip faulting (Figure 3a). Seeber and Armbruster (1979), and Verma and ChandraSekhar (1986), earlier obtained similar solutions for this event. The relevant solution parameters are listed in Tables 1 and 2.

According to Seeber and Armbruster (1979), based on hypocentral distribution of aftershocks, the rupture plane has a strike of N60°E and dip of 45° toward southeast. They discounted its relationship with the surface trace of the Hazara fault (Main boundary thrust) and proposed the existence of a decoupling layer at a depth of about 10 km, along which the strike-slip movement occurred.

Our observation shows that the epicenter is located close to the surface trace of the Riwat thrust in an area where another E-W trending thrust intersects it (Figure 2). Also shown in the figure to the north of the epicenter are the left-lateral strike slip faults that were plotted after Sercombe, *et al* (1998). According to Jadoon and Frisch (1997) the Riwat thrust dies out at a depth of 4 km, where it merges into a hinterland vergent blind thrust. This blind thrust extends upwards from the Eocambrian evaporites that cover the basement at depth of about 6 km. Earlier Johnson, *et al* (1986) interpreted the Riwat thrust as an emergent thrust propagating up section from the basement.

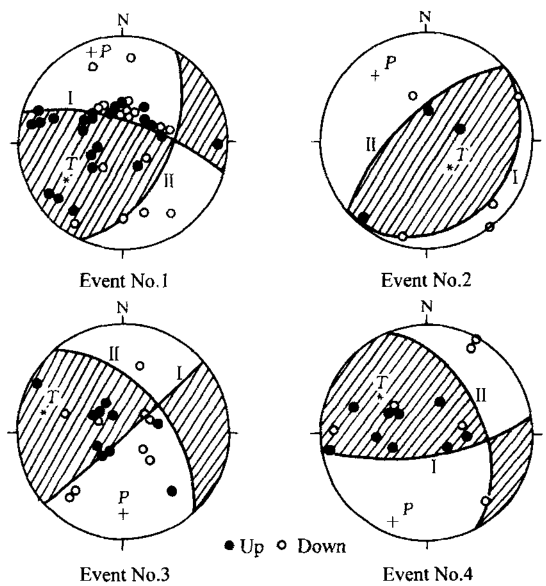

Figure 3 Focal mechanism solutions of NPDZ earthquakes using P wave polarities, lower hemisphere projections

Table 1 Source parameters of the 4 earthquakes

No. of event	Date a-mo-d	Time h:min:s	Epicentral location $\varphi_N/(°)$	Epicentral location $\lambda_E/(°)$	Depth /km	M_W
1	1977-02-14	00:22:37	33.60	73.27	14.46	5.5
2	1991-02-17	07:00:35	33.45	72.20	14	4.8
3	1993-02-17	15:06:05	33.55	72.50	13.4	5.4
4	1993-06-08	14:30:37	33.58	72.26	33	5.1

Table 2 List of earthquake focal mechanism parameters

No. of event	Nodal plane I		Nodal plane II		*P* axis		*T* axis		Fault type
	Strike/(°)	Dip/(°)	Strike/(°)	Dip/(°)	Pl/(°)	Az/(°)	Pl/(°)	Az/(°)	
1	285	74	27	53	14	−20	38	239	Left lateral strike slip
2	51	20	229	70	25	320	65	138	Thrust
3	50	83	319	56	22	179	25	280	Left lateral strike slip
4	81	72	334	46	16	−158	45	308	Left lateral strike slip

Sercombe, *et al* (1998) pointed out the fact that earthquake focal mechanism solutions (mostly strike-slip) have so far not been integrated into the models proposed by different researchers. The basement related strike slip solution of this event indicates that, at least in this area of the foreland, compressional tectonics is not the only factor prevailing. By studying more events scientists may be able to unravel the complexity.

Event No. 2 is located between the Khair-i-Murat and the Mianwala fault (Figure 2). The area between the northward dipping Khair-i-Murat thrust and the southward dipping Dhurnal fault (back thrust) is interpreted as a triangle zone underlaid by evaporates that act as a decollement (Jadoon, *et al*, 1999). They interpreted the basement to be lying at a depth of 6~7 km. At this depth, they inferred the presence of a basement normal fault with the hanging wall moving down to the north and having a throw of about 600 m. Alternatively they considered it to be a basement warp.

FMS obtained for this event is of thrusting (Figure 3b). Thrusting could be either in the NW or SE direction. As most of the surface thrusts mapped in the area dip northward, the plane with strike of N51°E and dip of 20°NW is considered to be the thrust plane. Hypocenter of this event is at a depth of 14 km. It is believed that the basement warp mentioned by Jadoon, *et al* (1999) probably extends to this depth.

Event No. 3 is located about 14 km west of Fatehjang in an area between the Khair-i-Murat fault and the MBT (Figure 2). Jaswal, *et al* (1997) in their map showed the presence of an E-W trending syncline (Seri syncline) without surface fault trace and the epicenter is located on the axis of the syncline.

A left-lateral strike slip solution is obtained for this event. The nodal plane with strike of N50°E is considered to be the fault plane (Figure 3). The near vertical dip indicates that it is a wrench fault. The focus is at a depth of 13.4 km thereby indicating involvement of the basement. According to Pivnik and Sercombe (1993), the Potwar plateau is a hybrid terrain with thrust faults, a series of short lateral-displacement and high-pressure ridges associated with vertical offsets in the basement. Thus, the inferred strike-slip fault may be a part of one such pressure ridge.

Event No. 4 is located in the same area as the previous one, but further west of it (Figure 2). The focal mechanism solution obtained is of strike-slip faulting. The nodal plane trending in E-W direction and with steeper dip (Figure 3) is considered to be the rupture plane.

Like the event No. 3, this left-lateral strike slip solution may be a part of the same or different pressure ridge that may exist in the area. Depth control is not reliable for this event. However, keeping in mind the basement offsets proposed by Pivnik and Sercombe (1993) and inferred in the other two solutions, it seems likely that it also represents basement deformation.

5 Summary and conclusion

As mentioned above, the focal mechanism solutions (Verma, *et al*, 1980; Verma, ChandraSekhar, 1986) for NPDZ and adjacent regions have shown a dominance of strike-slip faulting with some thrust faulting in this area of collisional tectonics. *P* and *T* axis orientations are shown in Table 2. A mixed *P* axis trend of NW and NE orientation is obtained. Earlier researchers also showed a similar mixed axis trend and related it to an oblique convergence.

In the adjacent area of the Kohat plateau, Pivnik and Sercombe (1993) and Sercombe, *et al* (1998) have shown that the duplex structures interpreted by some researchers are not presented. Insteadly, wrench faulting and flower structures are seen. 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 overprinting of transpressional features. Thus the thin-skinned tectonic models proposed by different researchers 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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