Geodynamic Implications for the 8 October 2005 North Pakistan Earthquake

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Abstract   We propose here that the 8 October 2005 North Pakistan earthquake occurred beneath the wedge-top of Balakot Formation in the Hazara-Kashmir syntaxial area. Slip occurred along the Muzaffarabad thrust, a southeast extended part of the Indus-Kohistan seismic zone. Tectonic loading of the high-density wedge/thrust sheet between the wedge-top and the descending Indian lithosphere coupled with continued flexural tectonics provoked this earthquake. The obliquely converging Indian plate along with block rotations led to development of a pinned zone around Northwestern Syntaxis of the Himalayas. Strain adjustment related to the rotational deformation processes resulted in the buckling of the more competent rock-units sandwiched between the less competent rock-units around the Hazara-Kashmir syntaxis. The western limb of the buckled unit gave rise to the development of thrusts and associated oblique slip in the inner arc of the competent rock-unit. The observations demonstrate reactivated tectonic movement along the growing fracture-tip of the buried Riasi thrust.

Keywords   Hazara-Kashmir syntaxis · High-density wedge ·
Indus-Kohistan seismic zone · Oblique convergence

1 Introduction

The 8 October 2005 North Pakistan earthquake (magnitude $M_w = 7.6$), which occurred near Balakot (Fig. 1) at 8:50 a.m. local time, caused widespread damage. This event

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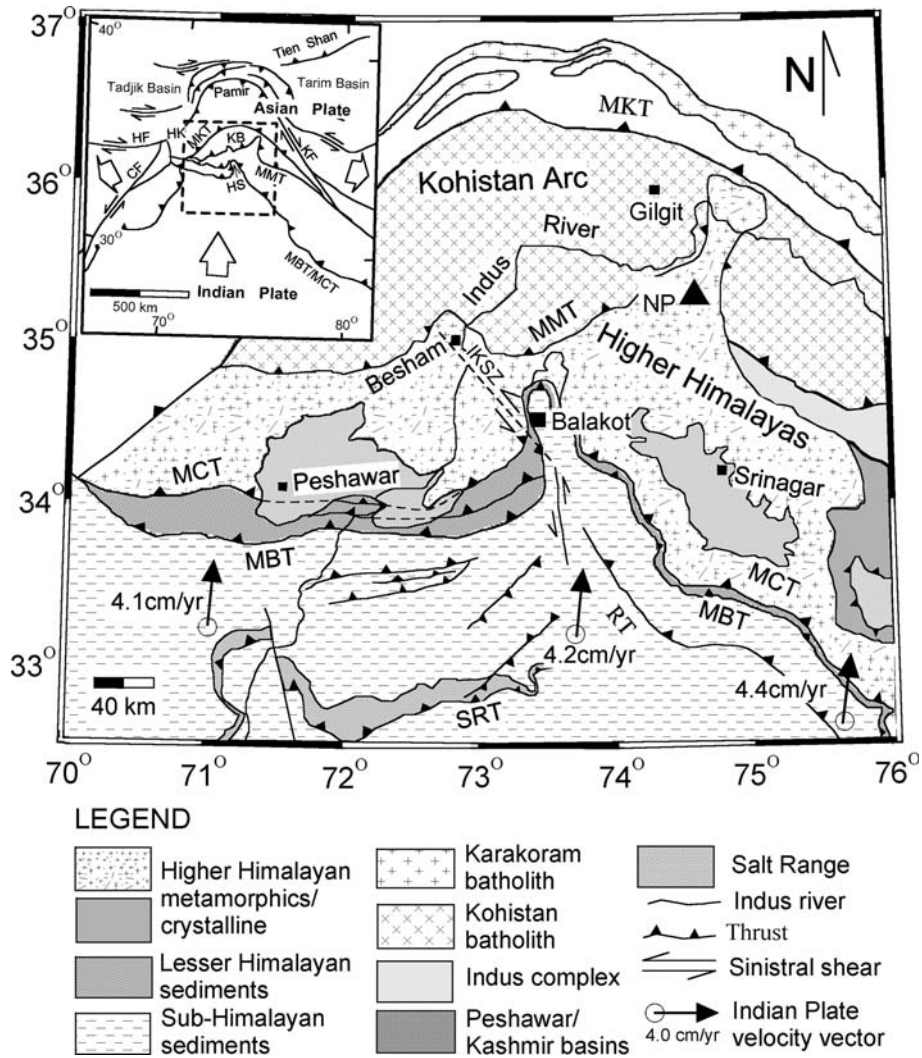
Fig. 1 Regional tectonic map of North Pakistan and adjoining areas (after Treloar et al. 1991; Searle et al. 1999; Hussain et al. 2004). *CF* Chaman Fault, *HF* Herat Fault, *HK* Hindukush, *HS* Hazara Syntaxis, *IKSZ* Indus-Kohistan Seismic Zone, *KB* Kohistan Batholith, *KF* Karakoram Fault, *MBT* Main Boundary Thrust, *MCT* Main Central Thrust, *MKT* Main Karakoram Thrust, *MMT* Main Mantle Thrust, *NP* Nanga Parbat, *RT* Riasi Thrust, *SRT* Salt Range Thrust. Indian plate motion vectors with respect to Eurasia marked in the map were calculated using NUVEL-1A (DeMets et al. 1994). *Framed area* in the *inset* shows the position of the geological map

claimed the lives of over 87,000 people, making millions more homeless. The earthquake was reportedly accompanied by rupture along a NW–SE trending fault (Muzaffarabad thrust) near the Hazara-Kashmir Syntaxis in North Pakistan (Tapponnier et al. 2006; Nakata and Kumahara 2006; Avouac et al. 2006; Parsons et al. 2006; Pathier et al. 2006; Bendick et al. 2007; Kaneda et al. 2008). This interpretation is supported by the detection of post-earthquake changes in geomorphic landscape of the mid-Jhelum valley near Muzaffarabad (Thakur et al. 2006). Analyses of ASTER images and seismic waveforms by

Avouac et al. (2006) also confirm development of a surface rupture on the southern flank of the syntaxial bend. This rupture of 75 km length, with average fault offset of 4 m, terminated against MBT, whose local name is Murree thrust. This 2005 earthquake has poor correlation with the major fault systems in this part of the Himalayas such as Main Frontal Thrust (MFT), Main Boundary Thrust (MBT) and Main Central Thrust (MCT) (Tapponnier et al. 2006; Nakata and Kumahara 2006). Several studies (Armbruster et al. 1978; Seeber et al. 1981; Nakata et al. 1991; Parsons et al. 2006) have also documented the seismically inactive nature of all these Himalayan main thrusts, adjacent to the Hazara syntaxial bend. Therefore, the 2005 earthquake that occurred in North Pakistan after more than a century (Ambraseys and Douglas 2004), has rejuvenated the interest for identification of the geological processes responsible for this rare incidence in this part of the Himalayas.

Coulomb stress distribution during the 2005 Kashmir earthquake determined by Parsons et al. (2006) shows increased stress-level to the northwest of a rupture, along the trend of Indus Kohistan Seismic Zone (IKSZ). An increase in stress-level is also observed to the southeast of the rupture zone adjacent to Kashmir basin (Fig. 1), where two large historical earthquakes were recorded in 1555 and 1885 (Bilham 2004). Parsons et al. (2006) have suggested that the southeast extension of this high-stress level zone was previously the nucleation site of the 1905 Kangra earthquake ($M = 7.8$) (Wallace et al. 2005; Avouac et al. 2006; Hussain et al. 2009). Analyses of the operative stress field around the Hazara-Kashmir syntaxis indicate the predominant direction of maximum horizontal principal stress (σ_1) to be perpendicular to the strike of the main thrusts (e.g., MCT and MBT), and decrease in the stress release towards southwest and northeast, perpendicular to the 2005 rupture-strike (Parsons et al. 2006). As fractures develop either parallel to (extension fractures) or at an angle of ~ 30–$35°$ (shear fractures) with the maximum principal stress direction, the cause for the earthquake event and the Coulomb stress release pattern of the 2005 earthquake needs suitable explanation. The present analysis was undertaken to investigate the cause for the occurrence of the 2005 Kashmir earthquake along with other damaging earthquakes around this syntaxis in the wider tectonic context. We have carried out a high-resolution study on the spatial variation of aftershocks in the backdrop of other historical earthquakes around this area. Further, the Bouguer gravity anomalies of this area were assessed in detail to identify the sub-crustal causative mechanisms, which facilitated the triggering process of the 2005 earthquake.

2 Geological Set-Up and Tectonic Evolution

The region around the northwestern Himalayas, Hindukush Range and Pamir-Karakoram Range is a complex terrain comprising of components derived from different crustal blocks: the Eurasian plate in the North, the Indian plate in the South and the Kohistan block sandwiched between the two (Fig. 1). The boundary between the Eurasian plate and the Kohistan block is marked by a suture zone (Shyok suture) in the North. The Indian plate is separated from the Kohistan block by another suture on the South (the Main Mantle Thrust, MMT). The regional NW–SE structural trends in the eastern part show sharp changes through EW to NNE-SSW in the western part, defining two major syntaxial bends (Nanga Parbat syntaxis in the North East and Hazara-Besham syntaxis in the West). Coward et al. (1986) postulated that the Kohistan Island arc had two-phase evolution involving first collision with the Asian plate (prior to the Himalayan orogeny) along the Shyok suture during late Cretaceous time, and a later collision with the Indian plate along the MMT

(Tonarini et al. 1993; Smith et al. 1994; Treloar et al. 1996; Searle et al. 1999, Leech et al. 2005). Diamond shaped geometry of the leading edge of the Indian plate is considered to be responsible for the development of the syntaxial bends and oblique convergence along the two boundaries (Treloar and Coward 1991). Palaeomagnetic studies (Klootwijk et al. 1985; Bossart et al. 1990) indicate an early transport on the East of syntaxis with large clockwise rotation and late transport in the western part (Potwar Plateau and Salt Range region) associated with small anticlockwise rotation. The boundary between these two rotational domains is considered to be located towards the West of the Hazara syntaxis (Bossart et al. 1990) and the centre of rotation is located at the intersection of IKSZ and MMT near Besham syntaxis at about 70 km North West of the Hazara syntaxis (Klootwijk et al. 1985). The early transport in the East at $\sim$ 50 Ma was initially opposite to the motion of India and rotated $\sim$45° to its present position (towards $\sim$N220°). The late transport in the West was also opposite to the movement of India and rotated $\sim$20° to its present position (towards $\sim$N160°).

The Indian plate in the northwestern Himalayas comprises of three tectonic blocks: an internal metamorphic belt of the Higher Himalayas, an external unmetamorphosed to low grade metamorphic belt of the Lower Himalayas and the foreland sedimentary belt (Treloar et al. 1991). Ongoing oblique convergence with early crustal thickening in the northwestern Himalayas, including the obduction of the Kohistan microplate onto the leading edge of the Indian plate, generated a rigid block that mechanically impeded the lateral propagation of the younger Himalayan thrusts and, hence, pinning them at their western termination (Armbruster et al. 1978; Klootwijk et al. 1985; Treloar and Coward 1991), and caused increased southwest-directed shortening. This southwesterly directed shortening strain pattern is corroborated by cleavage strike of NNW-SSE in the core of the Hazara syntaxis. The coeval development of adjacent synformal intermontane-basins (viz. Kashmir and Peshawar basins) symmetrically on opposite sides of the Hazara syntaxis (Burbank and Tahirkheli 1985) suggests that orogenic processes in these areas are still active. The studies of Burbank and Johnson (1982) reveal that the Kashmir basin is presently experiencing rapid uplift along its southwestern margin. Farther to the South, the MBT separates the Tertiary foreland basin deposits from those of deformed metamorphosed rocks of the hinterland zone to the North (Kazmi and Jan 1997; Pivnik and Khan 1996).

Throughout the foreland basin, from Pakistan through India to Nepal, a major detachment surface is thought to separate rocks representing the last marine facies of Eocene time and mid-Oligocene to early Miocene continental sediments derived from the eroded metamorphic rocks of the rising Himalayan orogen (Pivnik and Wells 1996; Najman et al. 1997; DeCelles et al. 1998, 2001). To the North of the Hazara-Kashmir Syntaxis, the Balakot Formation represents a continental foreland basin sedimentary sequence (Najman et al. 2001, 2002) of more than 8 km thick sandstone, mudstone, and caliche red-bed succession of mixed metamorphic and igneous provenance, derived from the India-Eurasia suture zone and the metamorphic rocks of the Himalayas (Critelli and Garzanti 1994).

3 Study of Seismicity

Historical earthquake data of the area between latitudes 32.5° and 38.0°N and longitudes 70.0° and 76.0°E were considered for study of the broad geodynamic perspective of the North Pakistan earthquake. The historical earthquake data (of 2211 events; $m_b \geq 4.0$; shown in Fig. 2) recorded at more than 15 stations (during the period 1964–2003) were
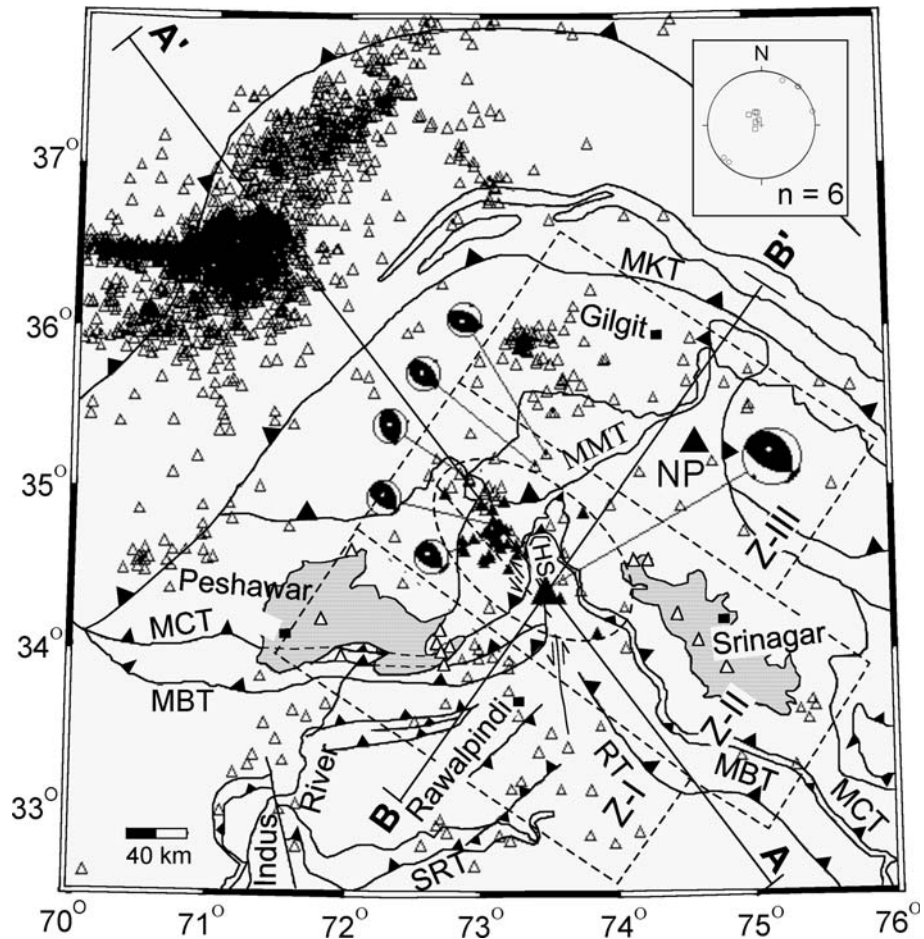
Fig. 2 Map showing the regional distribution of epicenters of historical seismicity (*open triangle*), mainshock and aftershocks of 2005 (*solid triangles*). Positions of profile lines AA' (orthogonal to Hindukush seismicity trend) and BB' (orthogonal to IKSZ) are shown by *solid lines*, and the three subdomains, with *dashed boundaries*, are marked as Z-I, Z-II and Z-III. *Inset* on *top right* shows lower hemisphere equal area projection of P (*open circle*) and T (*open square*) axes for the five historical events and the main shock of 2005. Beach balls of mainshock (*large focal sphere*) and historical events (*small focal spheres*) indicate thrust related movements with oblique slip. Confinement of the aftershocks in zone-II is demarcated by dashed lines showing elliptical shape. The trends of the major and minor axes parallel and perpendicular with the strike of Riasi thrust may be noted. Abbreviations are explained in Fig. 1

obtained from the published catalogue of the International Seismological Centre (ISC). The hypocentral parameters and earthquake focal mechanism data for mainshock and after-shocks (33 aftershock events; $m_b \geq 4.9$; shown in Fig. 3) were retrieved from the Harvard Centroid Moment Tensor (CMT) Catalog for the period October 08, 2005 to March 20, 2006. The selection of 33 aftershock events is constrained by the rupture propagation, faulting mechanisms and associated static stress changes around the epicentre of 2005 Kashmir earthquake (Avouac et al. 2006; Parsons et al. 2006; Pathier et al. 2006; Bendick et al. 2007; Kaneda et al. 2008). Focal mechanisms of five historical events ($m_b \geq 5.4$) were taken from Harvard CMT Catalog, and the work of Molnar and Lyon-Caen (1989).
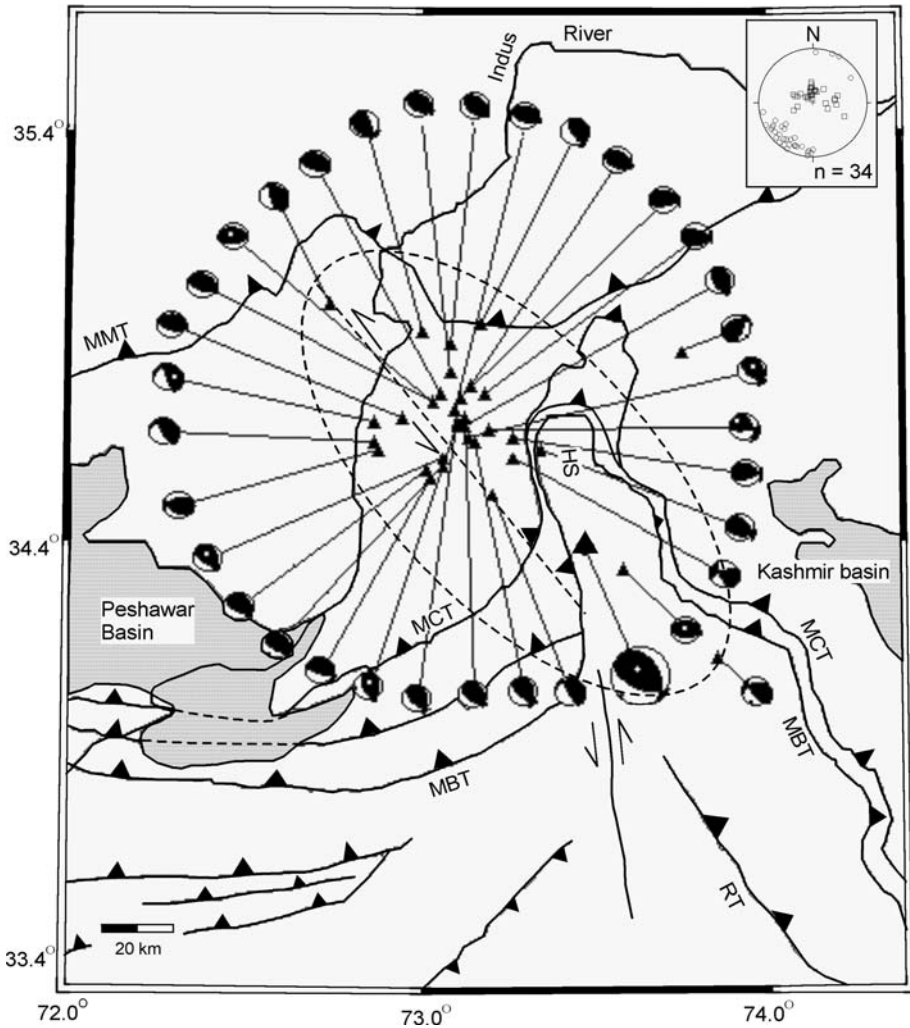
Fig. 3 Detailed map showing the focal mechanism solutions of the mainshock (*large focal sphere*) and aftershocks (*small focal spheres*). All the focal mechanisms show thrust related movements, with small oblique slip component. *Inset* on *top right* shows lower hemisphere equal area projection of P (*open circle*) and T (*open square*) axes for the aftershock events. The predominant direction of *P* axis is nearly orthogonal to the strike of the Riasi thrust. Abbreviations are explained in Fig. 1

The effects of the Earth's lateral heterogeneity on earthquake location are very important, more so in the case of high-velocity downgoing plate in the subduction margins (Engdahl et al. 2007). We appreciate the inherent uncertainty in Benioff zone reconstruction as also the possibility of hypocenters being relocated. Studies using teleseismic data for relocation (Engdahl et al. 1998, 2007; Engdahl and Villaseñor 2002) reveal that all locations are well determined only in relative sense. Hence, within the constraint of available seismic database we have reconstructed the Benioff zone (Fig. 4). The Centroid Moment Tensor (CMT) Catalog—spanning the period from 1977 to the present—is routinely updated by the Harvard Seismology Group for earthquakes distributed globally
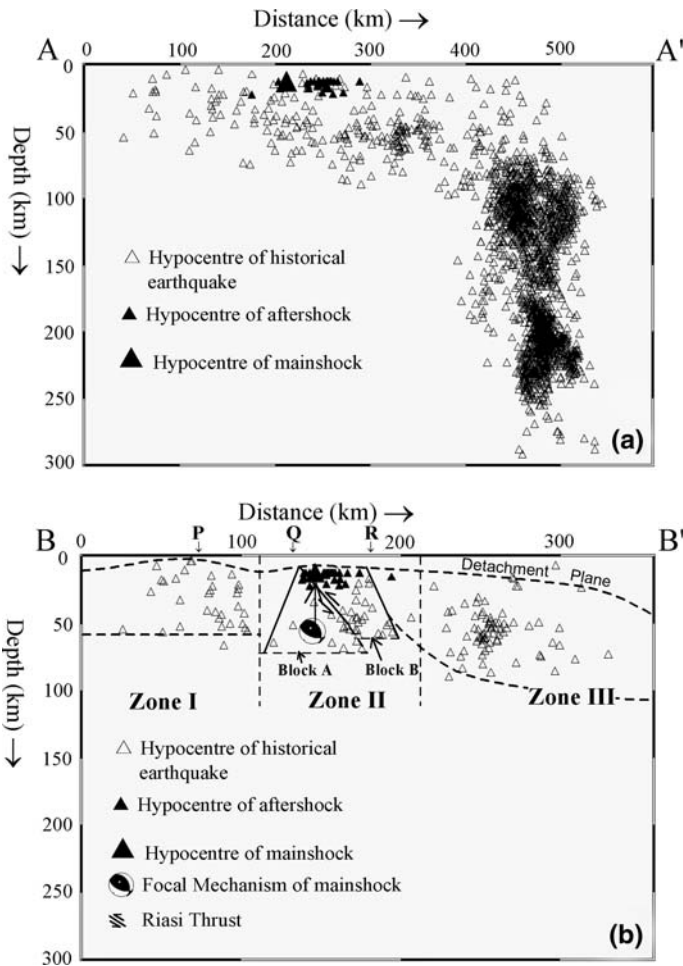
Fig. 4 Depth-section profiles along AA′ (**a**) and BB′ (**b**) for the hypocenters of historical, mainshock and aftershock events. Steepening of the lithosphere indicated by subvertical concentration of hypocentres towards northwest (A′ in **a**) is observed. *Detachment surfaces* (marked by *dashed lines* in **b**) were identified on the basis of absence of hypocentres. In the depth-section (**b**), the sub-surface Riasi thrust was marked after Armbruster et al. (1978) and Seeber et al. (1981). This thrust divides the seismicity of Zone II into two seismic domains (Blocks A and B, demarcated by *dashed lines*). Concentration of the aftershocks at the *top* of the block B may be noted

with magnitude approximately above 5.2. The uniqueness and reliability of the CMT method (Dziewonski et al. 1981; Dziewonski and Woodhouse 1983) is testified to by its wide use for tectonic studies (e.g., stress maps, global plate motion models and cumulative moment tensors studies; Pondrelli et al. 1995). Being based on long period seismograms (i.e., body waves filtered with periods greater than 45 s and, for large events, mantle waves with periods greater than 135 s), it reconstructs the average characters of the entire fracturing process of an earthquake, and the centroid of moment release. Similar parameters related the fracturing for smaller magnitude events (threshold value may reach to 4.2) are also being computed with a modified standard CMT algorithm modeling Love and

Rayleigh surface waves after low-pass filtering with a cut-off at 35–45 s (Arvidsson and Ekström 1998; Ekström et al. 1998). This surface-wave CMT methodology, which yields compatible and very similar results as in standard CMT, allows study of the complex processes of stress transfer to different fault segments that marked the unusual time evolution of the sequence (Arvidsson and Ekström 1998; Ekström et al. 1998; Morelli et al. 2000).

Several workers (Menke and Jacob 1976; Armbruster et al. 1978; Chatelain et al. 1980; Seeber et al. 1981; Ni and Ibenbrahim 1991; Fan et al. 1994; Mellors et al. 1995; Lukk et al. 1995; Zhu et al. 1997; Searle et al. 2001; Khan 2003) have studied the seismicity and the geological processes of the northwestern part of the Indian plate, and have suggested that the seismicity in this region is apparently caused by the mutual interaction between the Kohistan Arc and the Indian plate (Fig. 1). The Indian plate, which was subducted below the Himalayas, Karakoram, and Hindukush with widely variable dips, partially regulates the adjustment between seismic structures as well as the crustal shortening/thickening of this area. The depth-distribution of hypocenters (i.e., up to 350 km beneath the Hindukush, 200 km beneath the Karakoram, and within the mid-crustal zone in other parts of the area) indicates a significant variation of tectonic regime along this continental plate margin.

Distribution of historical seismicity of the area and western part of the Himalayas (Fig. 2) shows maximum concentration of seismic activity in the Hindukush area. These events are observed to be associated with a near-vertical zone (Fig. 4a). The seismicity, though sparsely distributed in other parts of the region, apparently links the lower Hazara, Indus-Kohistan and Nanga-Parbat seismic zones. Based on earthquake activity, gravity anomaly trend, and geomorphic features, the area (excluding the Hindukush seismic zone) was divided into three NW–SE trending seismic zones (Zones I, II and III in Figs. 2, 4). While Zone I encompasses the Hazara lower seismic zone, Zone II includes the Indus-Kohistan seismic zone, and Zone III covers the Nanga-Parbat area. It may be noted that most of the damaging earthquakes lie in Zone II, and show thrust related movements in the mid-crustal part (IKSZ/Riasi thrust; Fig. 2; Table 1). The concentrations of both historical and recent seismic activity within the Zone II delineate a seismogenic layer (cf. Watts and Burov 2003), which is estimated to be at a depth of ∼10 to 74 km (Fig. 4b). The present analysis indicates that the predominant compressive regional stress field (direction of P-axes or σ_1 derived from focal mechanism solutions) is in the NE–SW direction (Fig. 2). The projection of the Riasi thrust (cf. Armbruster et al. 1978) through the Benioff zone (Fig. 4b) allowed for modeling the region into two well-defined seismic domains (i.e., blocks A and B in Fig. 4b). The upthrown domain (block B in the model) shows a definite control on the occurrence of large damaging earthquakes in this area. Further, the thrust related movements of the seismic domain along the Riasi thrust support the views of

Table 1 Hypocentral parameters of five historical earthquakes shown in Fig. 2

Sl. no.	Date			Latitude (°N)	Longitude (°E)	Depth (km)	Magnitude (M_b)
	Date	Month	Year				
1.	28	12	1974	35.06	72.91	12	6.0
2.	12	09	1981	35.22	73.48	10	6.1
3.	22	22	1982	35.15	73.4	15	5.4
4.	14	02	2004	34.75	73.22	12	5.4
5.	14	02	2004	34.78	73.12	19	5.4

similar activity on several parallel faults in this part of North Pakistan (Armbruster et al. 1978; Seeber et al. 1981). No such movement, however, is apparent in NW directed profile (Fig. 4a).

3.1 Mainshock Characteristics

The 8 October 2005 North Pakistan earthquake occurred at latitude 34.38°N and longitude 73.47°E, and at a depth of 12 km (HRV CMT Solution). The source region was dominated by thrust related movement (Figs. 2, 4b) on a moderate dipping (40°) plane having strike of 334°. This strike of the nodal plane was selected on the basis of local tectonics of the area. The rupture associated with this event was initiated at the southeast end of IKSZ and propagated towards northwest (Parsons et al. 2006; Pathier et al. 2006). Focal mechanisms of five historical events, interestingly, reveal thrust related movements along a fault, dipping ($\sim$48°), with an average strike of $\sim$330° (Fig. 2; Table 1). The mainshock and all the five events document dominantly thrust motion with small oblique slip components. This recorded oblique slip motion is not a mere coincidence along this part of the Himalayas, but a very common feature along oblique convergent margins (e.g., eastern margin of India, Ben Menahem et al. 1974; McCaffrey et al. 2000; Khan and Chakraborty 2005).

3.2 Aftershock Features

Aftershock events are dominantly confined at depths between 10 and 22 km (Fig. 3). Interestingly, shallower part of the crust (<10 km) does not record any activity. Based on depth distribution pattern of aftershock events, a thin seismically inactive layer was identified (Fig. 4b). The boundary between this inactive layer and the deeper high-level seismic zone is interpreted to be a decoupling surface. Similar surfaces have been identified in other areas and have been termed as basal unconformity (cf. Crampton and Allen 1995). This tectonic surface is apparently acting as a stress barrier that inhibits the transmission of stress energy at the shallower level in this area. The depth-profile (Fig. 4b) also indicates that the mainshock and all the aftershocks are restricted beneath this unconformity, and are concentrated at the shallowest part in block B. Epicenters of the aftershocks are distributed in an elliptical zone with its major axis parallel to the IKSZ, and the minor axis having same orientation as that of the maximum compressive stress direction derived from historical earthquake database and the mainshock (Figs. 2, 3). Both, moderate to maximum damage area (Thakur et al. 2006) and the Coulomb stress migration (Parsons et al. 2006), caused by the 2005 Kashmir earthquake overlap the above mentioned elliptical zone. Similar to the mainshock and the historical events, all the aftershocks are dominated by thrust related movements with small oblique slip component.

4 Assessment of Gravity Anomalies

The intermittent occurrences of the large damaging earthquakes, particularly the Pattan earthquake of 28 December 1974 ($m_b = 6.0$) and the North Pakistan earthquake of October 08, 2005, and other intermediate to several small earthquakes along the IKSZ, suggest high-stress level in the region. These can be interpreted in the backdrop of Bouguer gravity anomaly gradient through a high-resolution study (Wang 1988; Khan and Chakraborty 2007). The Bouguer gravity anomaly map (cf. Verma and Prasad 1987) was reconstructed at high-resolution (Fig. 5).
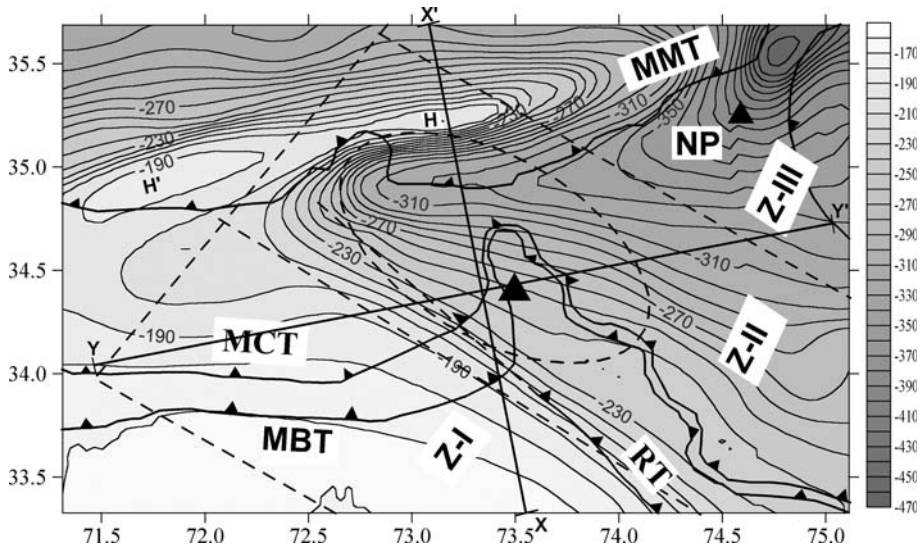
Fig. 5 Bouguer gravity anomaly contour map for the Hazara and surrounding regions (after Verma and Prasad 1987). *Solid triangle* represents the epicentre of the mainshock. Note the steep gradient of the contours along the IKSZ and sharp turn of the contours around Besham syntaxial area in North Pakistan. H and H′ are two gravity highs identified symmetrically at opposite sides of the Besham area. Note also the sharp change in contour separation from close to wide one near the Hazara area. Sections shown in Figs. 6 and 8 are marked as XX′ and YY′, respectively

The Bouguer anomaly map shows northwesterly trend of gravity contours in the southeastern part and a sharp turn around the central part. The turning area coincides with the Besham syntaxis (Treloar and Rex 1990). Another sharp turn of gravity contours is found towards northeast of the Besham Syntaxis (near the MMT). These two turning points define a 'Z-shaped' regional pattern in the area. The northern part of this Z-shaped bend has ∼EW regional trend of gravity contours. Two gravity highs (H and H′, Fig. 5), with ∼EW alignment, are located on the northern fringe of the short limb of the 'Z-shaped' pattern of gravity anomaly near the Besham Syntaxis and MMT. Two gravity anomaly profiles (whose positions are marked as XX′ and YY′ in Fig. 5) were prepared to understand subsurface structural controls. The average elevation of the area (Fig. 6a; after Verma and Prasad 1987), observed gravity anomaly (Fig. 6b) and Airy's (1855) scheme of compensation for different density contrasts (Fig. 6b) were used to develop the model shown in Fig. 6c. A normal crustal thickness of ∼30 km was considered near the sea level. We have used the method described by Talwani et al. (1959) to compute the gravitational attractions of polygonal, two-dimensional bodies and we have assumed that the Bouguer gravity anomalies of interest are caused by density contrasts between the crust and upper mantle as determined from Deep Seismic Sounding Studies of the Northwestern Himalayas (cf. Kaila et al. 1984). Figure 6b indicates that the computed Bouguer anomaly is approximately 45 mgal less in magnitude than the observed value. This leads us to suggest that the actual Moho is located at a greater depth than that shown in Fig. 6c. Therefore, another model (Fig. 7) following the general relationship between the Moho, thrusting of a high-density wedge-shaped body, and average elevation was reconstructed. The computed Bouguer anomaly for this model matches with the observed Bouguer anomaly (Fig. 7a). The inner gravity anomaly high (cf. Fig. 7a) is thus due to the presence of high-density wedge with
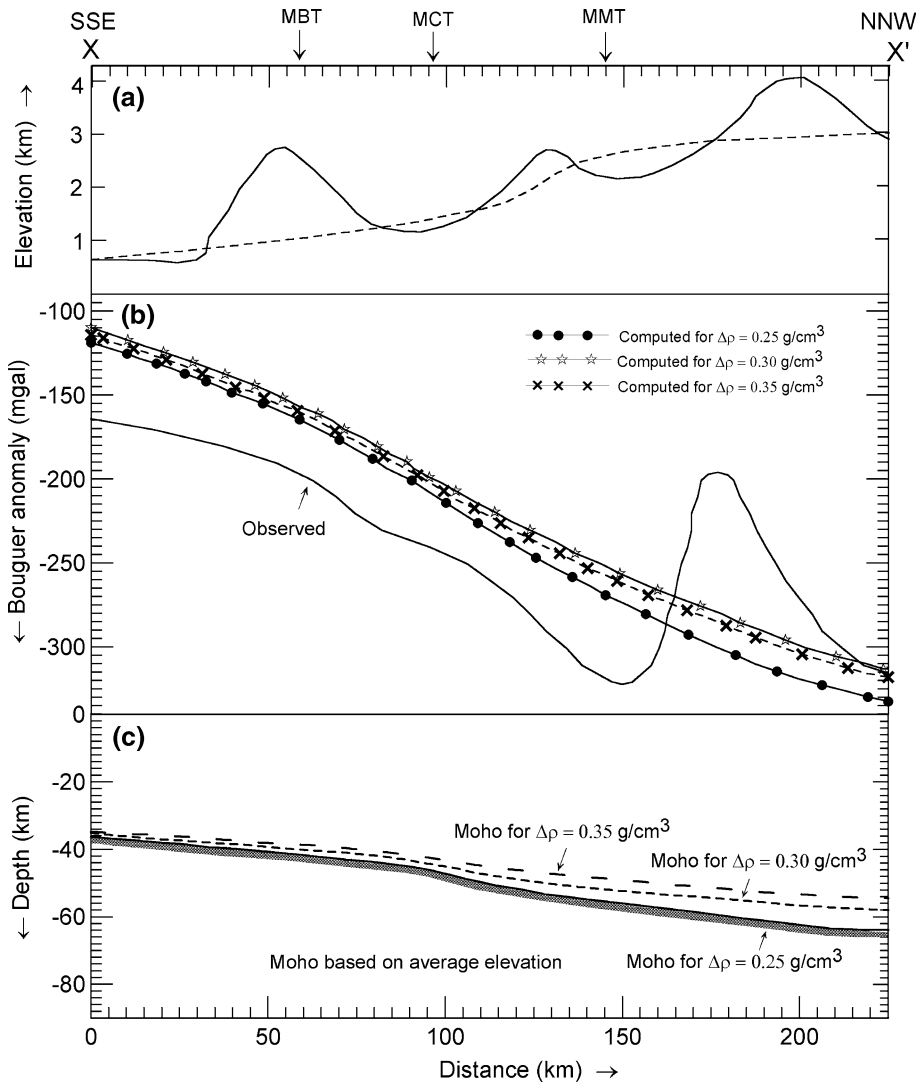
Fig. 6 Cross-section along XX′ showing **a** topographic variation with average elevation (*dashed line*), **b** observed Bouguer anomaly and computed Bouguer anomalies for different density contrasts between crust and upper mantle, and **c** the depth of Moho based on average elevation (after Verma and Prasad 1987) and Airy's model of compensation

density contrast of 0.4 g/cm^3 between this wedge and the crust. The two gravity highs (H and H′) near the Besham region (discussed earlier) possibly account for high-density wedge, perhaps thrusted either from lower crust or upper mantle along the MMT (Fig. 7b). This mantle wedge (Fig. 7b) must have acted as a rigid block and caused deformation of the footwall block towards SSE during neotectonic movements. In a similar manner, the crustal model shown in Fig. 8 was constructed on the basis of the relation between average elevation and Moho depth (after Verma and Prasad 1987). In section YY′, two opposite dipping thrust planes (MBT) in the central part of the area indicate that the central footwall block
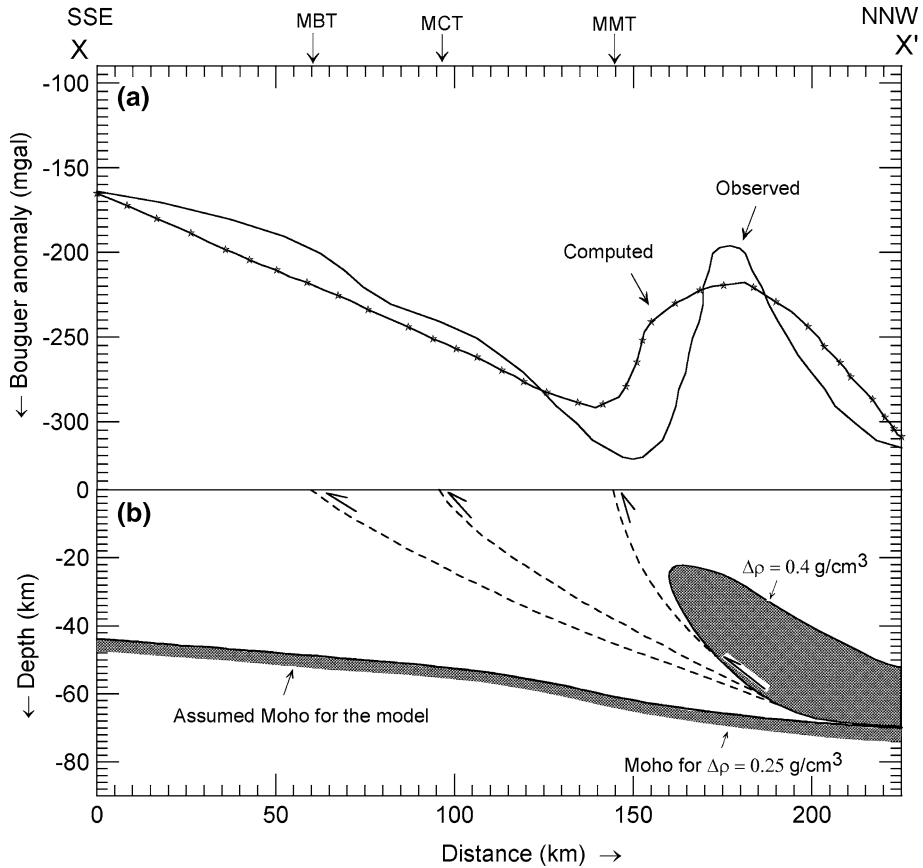
Fig. 7 Cross-section along XX′ showing **a** observed Bouguer anomaly and computed Bouguer anomaly for the model shown in (**b**), and **b** the proposed model based on the relationship of average elevation and depth of Moho. The nature of gravity anomaly on the NNW can be explained by a high-density wedge. The thrusts are marked on the basis of map pattern of the area

(coincident with the Hazara syntaxis) is getting shortened because of opposite directed compressive motion (arrows in Fig. 8c) of the thrust units (see also Fig. 4b).

The NW–SE trending Bouguer gravity anomalies have closer spacing towards the Besham area. This is indicative of steepening of the subducting Indian plate. Through inversion of P-waves and S-waves travel time data of the area between Besham and Hazara syntaxis, Ni and Ibenbrahim (1991) identified a high-density mid-crustal wedge, which was interpreted as the leading edge of a slab detached from the basement of the descending Indian plate. They further concluded that along the NW trending IKSZ the Indian plate bends more steeply towards the North East beneath a seismically active southwest-directed mid-crustal wedge. In addition, Seeber et al. (1981) proposed of a prominent topographic step along IKSZ, with northeast block more elevated compared to the southwest. It is thus clear that the northeast part of the IKSZ/Riasi thrust invariably records presence of high-density masses with occasional upward movement. Another interesting feature of the Bouguer anomaly trend is the presence of a widely spaced zone of gravity contours lying between closely spaced contours near the Hazara syntaxis. This is indicative of a steepened Moho changing to a flat one below the epicentre of the 2005 earthquake near Balakot (Fig. 5).
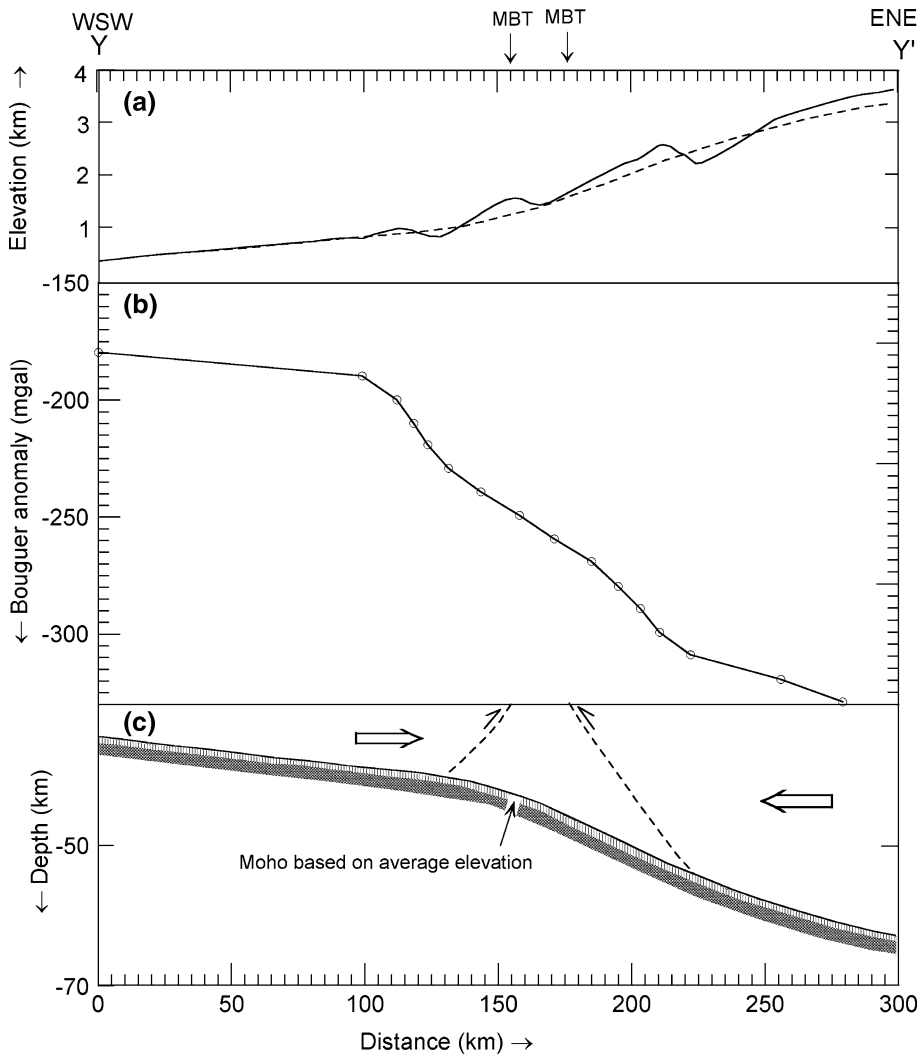
Fig. 8 Cross-section along YY′ showing **a** topographic variation with average elevation (*dashed line*), **b** observed Bouguer anomaly pattern, and **c** the Moho based on the relation between average elevation and Moho depth. The thrusts are marked on the basis of map pattern of the area. The movement directions of thrusts (compression axes) are shown by *open arrows*

The emplacement of the high-density geological mass (mentioned earlier) in a collisional settings can be explained through buoyancy analysis of either a heavy lower-crustal or an upper mantle orogenic wedge (Moore et al. 2005). The heavy mass is generally raised from deeper to shallower parts of the lithosphere due to an increase of the positive buoyancy force induced by enhanced potential energy that subsequently thickens the crust over a wide deformation belt. It is also well established in the literature (Wadia 1931; Butler et al. 1989; Ni and Ibenbrahim 1991) that activation/reactivation of faults is predominant along the northwest continuation of the Riasi thrust. This region also records lateral transport/escape of the rotated thrust sheets away from the growing Besham anticline (Coward et al. 1988;

Treloar and Rex 1990), and the motion is contiguous with the IKSZ toward Hazara-Kashmir syntaxis (Treloar and Coward 1991). These whole geodynamic processes may be explained through oblique convergence of the Indian plate as observed elsewhere (Diament et al. 1992; McCaffrey et al. 2000; Khan and Chakraborty 2005).

5 Proposed Geodynamic Model

The convergence between the Indian and Eurasian plates in the northwestern Himalayas was accommodated dominantly by subduction and crustal thickening, and partly by movements along two major strike-slip faults (Chaman fault and Karakoram fault). The studies of different workers (Beloussov et al. 1980; Kaila et al. 1984; Verma and Prasad 1987) indicate a wide variation of crustal thickness ($\sim$35 to 75 km) in this region, and complex tectonic adjustments on the descending Indian plate. The change in strike-direction (i.e., from NNW to NE, Fig. 1) of the two crustal windows of the Indian plate (i.e., Hazara syntaxis in the lower Himalayas and Nanga Parbat syntaxis in the higher Himalayas) as well as of the causative stress fields (viz. from NE–SW around Hazara to E–W around Nanga Parbat) also records widely varying operative tectonics. Thus, the geodynamic aspects behind the occurrence of 2005 Kashmir earthquake lie in the geo-dynamic evolution of the Himalayas, and its coeval tectonic adjustments, mainly controlled by the varying tectonic trends around the syntaxial bends giving rise to widely variable convergence obliquity.

The occurrence of large damaging earthquake events in an oblique convergent margin can be explained by partitioning of convergence into trench-parallel shear component and trench perpendicular subduction component (Fitch 1972; Ben Menahem et al. 1974; Ishii et al. 2005; Lay et al. 2005). The perpendicular component has a definite control on the occurrence of large event while the tangential component accommodates the subsequent shearing motion through generation of aftershocks in the area paralleling the trench-axis (Ben Menahem et al. 1974; Lay et al. 2005). In a similar manner, the enhanced causative force in the northwestern syntaxial area can be interpreted by mutual interaction between the subducting Indian plate and oroclinal bending of the southern edge of the Asian plate (Klootwijk et al. 1985; Treloar and Coward 1991). Studies (cf. Bossart et al. 1990; Burtman and Molnar 1993; Thomas et al. 1993; Ratschbacher et al. 1994; Peltzer and Saucier 1996; Searle 1996; England and Molnar 1997; Larson et al. 1999; Reigber et al. 2001; Meade 2007; Thatcher 2007) involving palaeomagnetism, geological and GPS (Global Positioning System) reveal clockwise rotation of the western Tibetan plateau and anticlockwise rotation of the western Pamir region (Tadjik and Fergana basins) with respect to the Indian plate, and pinning of the lithosphere near the syntaxis (Figs. 1a, 9, 10). These opposite directed rotations around the western syntaxial bend is thought to result in maximum pressure (σ_1) directed towards the syntaxial bend (Fig. 9a, b), giving rise to block rotation with pinning (which is equivalent to buckling; cf. Fig. 9) in the region. Therefore, the deformation of the region can be visualized using the theory of the buckling of layers of different competence (cf. Biot 1959; Ramberg 1962; Ramsay and Huber 1987). In the case of buckled competent layers sandwiched between incompetent layers, the outer arc undergoes stretching (extension), whereas the inner arc is shortened (Fig. 9b). The latter often gives rise to the development of reverse faults at an angle of $\sim$30° with the layer boundary (F_1 and F_2 in Fig. 9c). The sense of slip, in the case of oblique slip motion, differs in the opposite limbs of the fold (Fig. 9d). The crystalline rocks of the area around the syntaxial bend have higher competence than the foreland basin
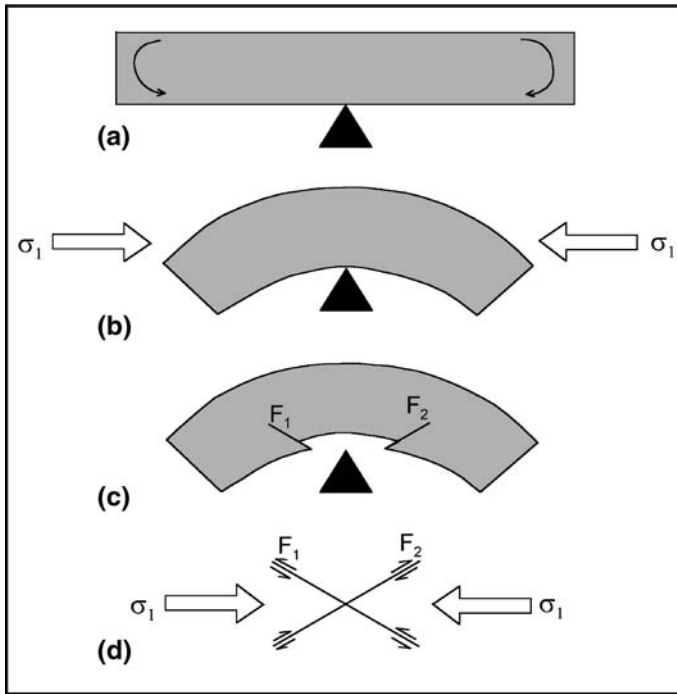
Fig. 9 Models of deformation for the Northwestern Himalayas. **a** Opposite rotations of the Karakoram (*dextral*) and Chaman (*sinistral*) blocks causing pinning of the crustal block at the syntaxial bend. **b** Buckling of the crustal blocks from opposite directed principal stresses. **c** Extension of the outer arc and compression of the inner arc resulting in development of thrusts (F_1 and F_2) in the inner arc. **d** Relationship between fracture orientation and slip patterns with respect to the principal stress axis

sediments in the inner part of the Himalayan arc and also greater than a thin sedimentary belt on the Higher Himalayan region (Fig. 10a). The relationship between the regional stress patterns, as derived from focal mechanism solution diagrams (Figs. 2, 3), and gravity modeling (Fig. 8c), with respect to the geometry of the map scale features around the syntaxial bend (Fig. 10b) satisfies the requirements of buckling. Therefore, we have interpreted the seismic events in the IKSZ to be related to presently active fracturing and thrusting of the western limb of the syntaxial bend (Fig. 10c, also compare Fig. 9c, d). The absence of such transpressive zones on the eastern limb is thought to be dominated by orthogonal compression. On the other hand the western limb is involved in greater amount of rotational deformation in the transpressive deformation.

The relationship between regional shortening and different zones of the strain ellipse is illustrated in Fig. 10d. The maximum shortening axis oriented at $\sim$N050° is expected to have the major axis of the strain ellipse oriented at $\sim$N320°, with the zone of extension lying between N290° and N350°. The principal axis divides the zone of extension into two sectors. The deformation gives rise to a thrust associated with a minor dextral slip in sector I and thrust with minor sinistral slip in sector II. In the focal mechanism solution diagrams of the earthquake events of the region, we find thrust as the dominant slip mechanism with minor amounts of both dextral and sinistral oblique slips. As discussed above, these differences in slip patterns can be explained on the basis of the relation between the fracture orientation and the major axis of the principal strain ellipse.

Fig. 10 Models illustrating relationships of crustal movement patterns, regional stress/strain and geology of ▶ the area in the Northwestern Himalayas. **a** Relationship between the obliquity of the Indian plate margin and opposite rotations of the western Tibet (*dextral*) and western Pamir (*sinistral*) blocks around the syntaxial bend. **b** Orientation of the principal stress axis with respect to the axial trace of the buckled crustal blocks of different competence around syntaxial bend. **c** Development of thrust and associated oblique slip on the western limb of the buckled units. Absence of failure in the eastern limb is considered to be accommodated by orthogonal thrust movements in the Himalayas. **d** Pattern of strain ellipse showing zones of compressional (*open area*) and extensional (*shaded area*) strains, with respect to the principal stress axis. The long axis of the strain ellipse divides the extensional strain into two zones (I and II). Along the principal axis the failure planes will have pure thrust motion, along zone I thrust motions will be associated with dextral slip and along zone II thrusts will have associated sinistral slip. Patterns of slip shown in Figs. 9d and 10c may be compared. It may be noted that the mainshock was located in zone I

The hairpin turn of the MCT and MBT around the Hazara area has low-level seismicity in the lower crustal part towards Himalayan foothills. Furthermore, the historical seismicity indicates its poor correlation with strain accommodation along northwest-extended part of the Hazara syntaxis (Armbruster et al. 1978; Seeber et al. 1981; Ni and Ibenbrahim 1991; Treloar and Coward 1991). The more pronounced activity of this area is presumed to be the extension of the Riasi thrust (termed as Indus-Kohistan seismic zone or IKSZ) striking NW, past the Hazara antiform (Armbruster et al. 1978; Seeber and Armbruster 1979). The IKSZ, though apparently trending to the central part of the Hindukush seismic zone, sharply terminates around the Besham syntaxial area. This high-level activity is interpreted to be associated with a buried structure (confined between 12 and 25 km depths), which separates the upper seismic zone from a ∼4 km thick aseismic layer. The northwest striking buried structure, involved in thrust movements, dips at an angle of ∼30° toward the North East (Ni and Ibenbrahim 1991). In contrast, the deeper activity of this area is continued to a depth of ∼70 km, with a steeper dip of the thrust plane. Another poorly defined deep-crustal fault delineated ∼100 km southwest of the IKSZ is termed as the Hazara lower seismic zone (HLSZ). Both these zones are parallel to each other and have steep dips with oblique slip reverse motion (Seeber et al. 1981; Ni and Ibenbrahim 1991). Besides these sub-crustal features, numerous faults were also delineated in the region to the West of Hazara syntaxis, parallel to IKSZ or HLSZ. The attitudes of these regional faults (NW–SE strike) are exactly similar to the model suggested above (compare Figs. 1, 10) and match with the attitude of nodal plane of 2005 event.

6 Discussion

Oroclinal bending of the Himalayan arc and continued pinning of the main thrusts coupled with continued thickening through southwest transportation of the crust at the northwestern Himalayas (Seeber et al. 1981; Klootwijk et al. 1985; Treloar and Coward 1991) possibly triggered the 2005 North Pakistan earthquake at the base of antiformal Hazara structure i.e., beneath the Balakot Foreland Formation (Bossart and Ottiger 1989; Critelli and Garzanti 1994; Najman et al. 2001, 2002). Increasing rotation of the thrust sheets and subsequent thickening of the crust (to the North East of the Riasi thrust) induced by oroclinal bending of the Himalayan arc apparently documents higher potential vis-à-vis stress-level directed towards the South West. These rising thrust sheets by positive buoyancy possibly reactivated the thrust movement on a pre-existing thrust plane, and the reactivation process was enhanced through oroclinal bending of the Himalayas and the simultaneous anticlockwise rotation of the Indian plate. Following failure through this process, the remaining strain is released by simple shear due to oblique convergence of the
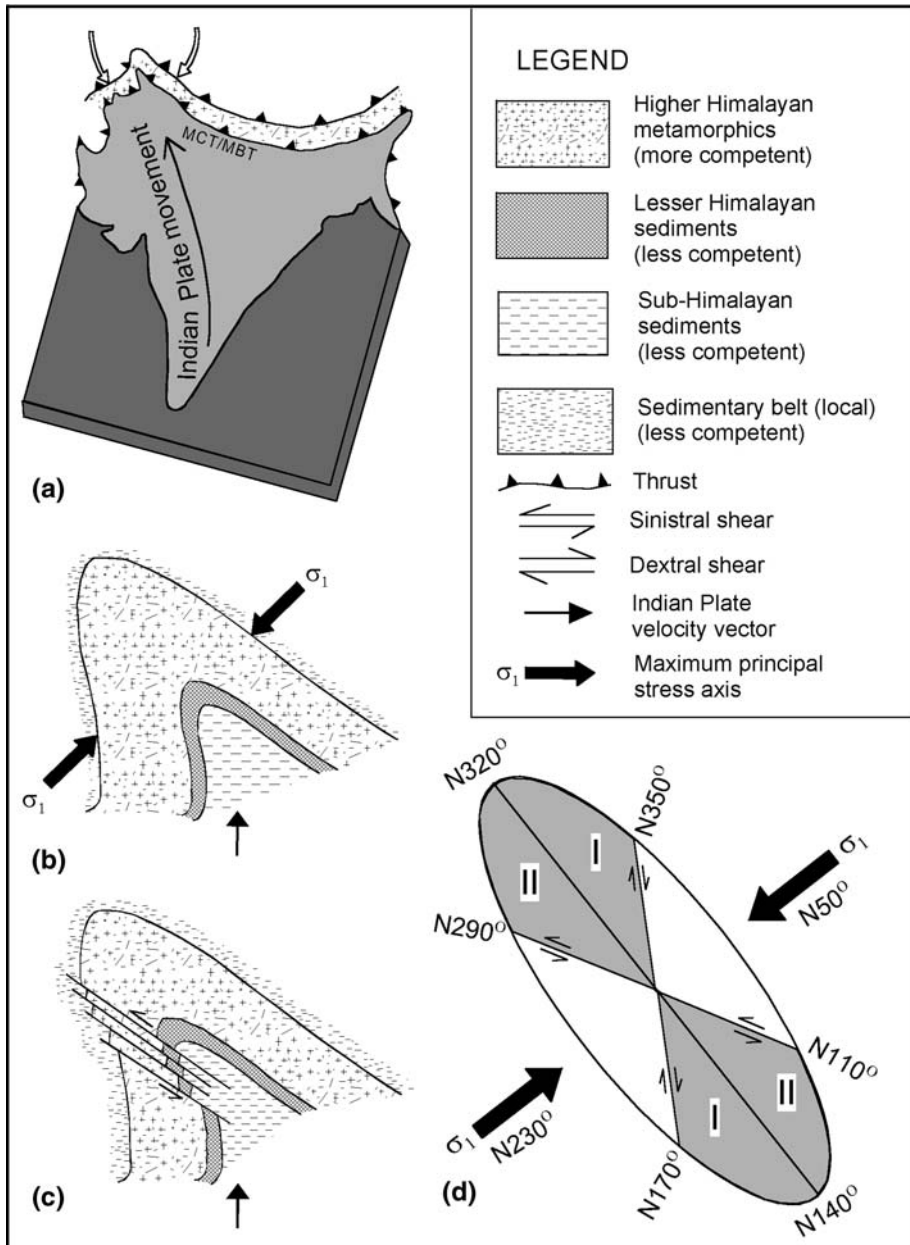
Indian plate along the IKSZ (cf. Figs. 9, 10). The state of causative stress, strike and dip of the fault planes derived using the earthquake database also support this contention.

Geological incidences like landslides and ground upheaval occurred following this earthquake were concentrated on the topographic step (Armbruster et al. 1978; Seeber et al. 1981) along the hanging wall of the Riasi thrust. The present study also shows that all the damaging thrust earthquakes were concentrated within the upthrown side (i.e., block B of Fig. 4b) of the Riasi thrust, and possibly constrained by a basal detachment surface

generally formed in foreland system (Crampton and Allen 1995). In the model (Fig. 4b), sharp undulation of the basal detachment may be interpreted through flexural response of the descending Indian plate behind the occurrence of 2005 North Pakistan earthquake in the Balakot foreland basin. We propose here that the surface zone between Q and R (Fig. 4b), below which this 2005 earthquake struck, is correlated with the wedge-top while the zone between P and Q is associated with foredeep along the foreland systems (Fig. 1 of DeCelles and Giles 1996), and the North Pakistan earthquake was triggered due to the upward movement of the high-density wedge along the thrust sheet (in blind thrust zone, Armbruster et al. 1978; Ori et al. 1986) beneath the wedge-top. The interplay between the descending Indian lithosphere and the base of the wedge-top during tectonic loading of higher potential mass possibly enhanced the thrust related movement. Forward modeling of foreland basins that are formed by flexural response also record similar geodynamic processes like migration of thrust sheets or fold loads along the fronts of the thrust belts (Watts and Burov 2003).

Structural and geochronological studies show at least three distinct phases of motion occurred on the MCT and MBT between 25 and 15 Ma, between 9 and 7 Ma, and at ∼2.3 Ma (Hodges et al. 1988; Macfarlane 1993). The first phase of motion coincides with a time when the MCT acted as the basal decollement (Hodges et al. 1988; Burchfiel et al. 1992), whereas the later two episodes occurred when the base of the MBT was the decollement. This coeval motion on these two fundamental structures suggests that the underthrusting of the Indian plate involved the gradual decrease of displacement rates on the MCT as a major shortening shifted to a new, structurally lower one, the MBT. The IKSZ, which was presumed to be an extension of the shallow dipping, buried Riasi thrust, to the North West of the Hazara syntaxis, possibly evolving as a new shear-plane on the surface. The deformation of a rigid high-density domain on a sub-horizontal surface may be composed of rigid translation, rigid rotation, and internal deformation (Laubscher 1996); those are all common in this part of the Himalaya. This also is supported by the occurrence of the large thrust earthquake events in North Pakistan (Armbruster et al. 1978; Seeber et al. 1981; Butler et al. 1989; Ambraseys and Douglas 2004). This relative temporal continuity of these geological processes also complies with the maintenance of orogenic topography, short-term sediment fluxes, and uplifting of the areas around the pinning point in the North West Himalayas (Treloar and Coward 1991).

7 Conclusions

We propose that the 8 October 2005 North Pakistan earthquake occurred beneath the wedge-top (i.e., Balakot Formation) in the foreland basin around the Hazara-Kashmir syntaxis. The growing high-density orogenic wedge (detached from the lower crust or upper mantle) due to its higher potential underwent thrust related movement in the hanging-wall side along the frontal thrust zones beneath a basal detachment surface, and provoked the occurrence of this large damaging earthquake. The basal detachment surface, which was delineated under the present study, is acting as a stress barrier, and alternatively inhibits the occurrence of seismic activity at the shallower part around this syntaxial belt. Another interesting feature noted here is the confinement of both the mainshock and aftershock hypocenters just beneath the basal layer, and may be interpreted through zipper-type opening of the Riasi thrust towards the surface during intermittent generation of several intermediate to large earthquake events in this part of the North Pakistan and apparently widening the Himalaya main thrust zone (e.g., MBT) towards the North West.

The geodynamic processes related to oroclinal bending of the Himalayas and its counterclockwise rotation apparently was responsible for the thickening and southwestward transportation of the crust and thrust wedges. The causative stress field behind the operative flexural tectonics occasionally reactivates the thrust movements along the Riasi thrust and triggers the unprecedented earthquake events in these areas. The dynamic slab load between the subducting slab, overlying mantle-wedge material and the base of the overriding Indian plate along the frontal part of the thrust belts caused by flexural response possibly initiates the reactivation process. The tangential/shear component of the oblique convergence of the Indian plate against the Asian plate might have controlled the rupture propagation and corresponding stress release along the Indus-Kohistan seismic zone, presumably terminated at the Besham syntaxis towards the North West, while the orthogonal component of the Indian plate convergence was possibly regulating the basement tectonics, and apparently responsible for provoking this earthquake.

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