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Impact of Natural Hazards on Water Management: Remote Sensing Identifies Evidences in Pakistan

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Abstract: Regional tectonic changes, under the influence of strong seismicity activities, had caused drastic diversion of some of the main contributory rivers and also affected their water-flows in the western Himalayan region about 4000-years before present. Eventually, those changes resulted in extinction of one of the river-systems, the Sarasvati-Hakra river system. Present study concentrates on sever earthquake activities of October 2005 comprising of over 500 high magnitude earthquakes within one month in northern Himalayan mountain region of Pakistan and Kashmir. In addition to enormous life and property damages, the geological forces also reshaped the rugged mountainous areas. Present study has correlated and integrated the landslide events based on the satellite images captured before and after earthquakes. Results of the study have identified the crustal uplifting and the massive landslides all along the rivers' courses, which blocked and forced the rivers and their contributories to modify their courses in the affected areas. It is inferred that such deformational activities might have caused adverse impact on the river-flows. Presently proposed seismo-tectonic model indicates possible distinct changes in water flow of Indus river and some of its contributory rivers. These changes show compatibility with those of the tectonic changes in geological history associated with extinct Sarasvati-Hakra river system. Newly changing tectonic conditions now need to be investigated in more details for the planning of adequate and sustainable water management of the Indus river system.

Key words: Seismic hazard • River deformation • Water management • Pakistan

INTRODUCTION

In general, the rapid growth of population, industrialization, urbanization, irrational irrigation, increased pollution of surface and groundwater, improper water management, shortcomings in designing legislation and global climatic changes have been considered to cause acute water stresses in the developing countries. But it has also observed that in addition to all these factors affecting the status of water potential, some active geological processes, associated with deep-seated crustal changes, are also responsible for shifting and modifying of the river courses affecting totally or partially the rivers ecosystems [1]. Even such changes have resulted in almost total extinction of the river-system causing consequent vanishing of wetlands and the human settlements because of reworked water starving hydrogeological environment.

An integrated research study of the aerial photogeology and the seismo-tectonic activities associated with the western Himalayan region had revealed the causative tectonic factors for the dramatic flow changes of the Sarasvati-Hakra river system during the geological recent past about 4000 years before present [1-4]. It was inferred that those changes were resulted due to the geologic structural deformation, which consequently forced to divert the Satluj river into Beas river and the Jamna river into Delhi river - now known as Yamuna river, a contributory of the Ganges river system (Figure 1). Divergence of the contributory rivers consequently resulted extinction of the Sarasvati-Hakra river system, which was comprised of its contributory rivers, namely Sutlaj, Ghaggar and Jamuna and usued to flow about 4000BP parallel to Indus river. At present, the Sutlaj flows as on of the contributory of Indus river and the Jamuna river becomes the part of

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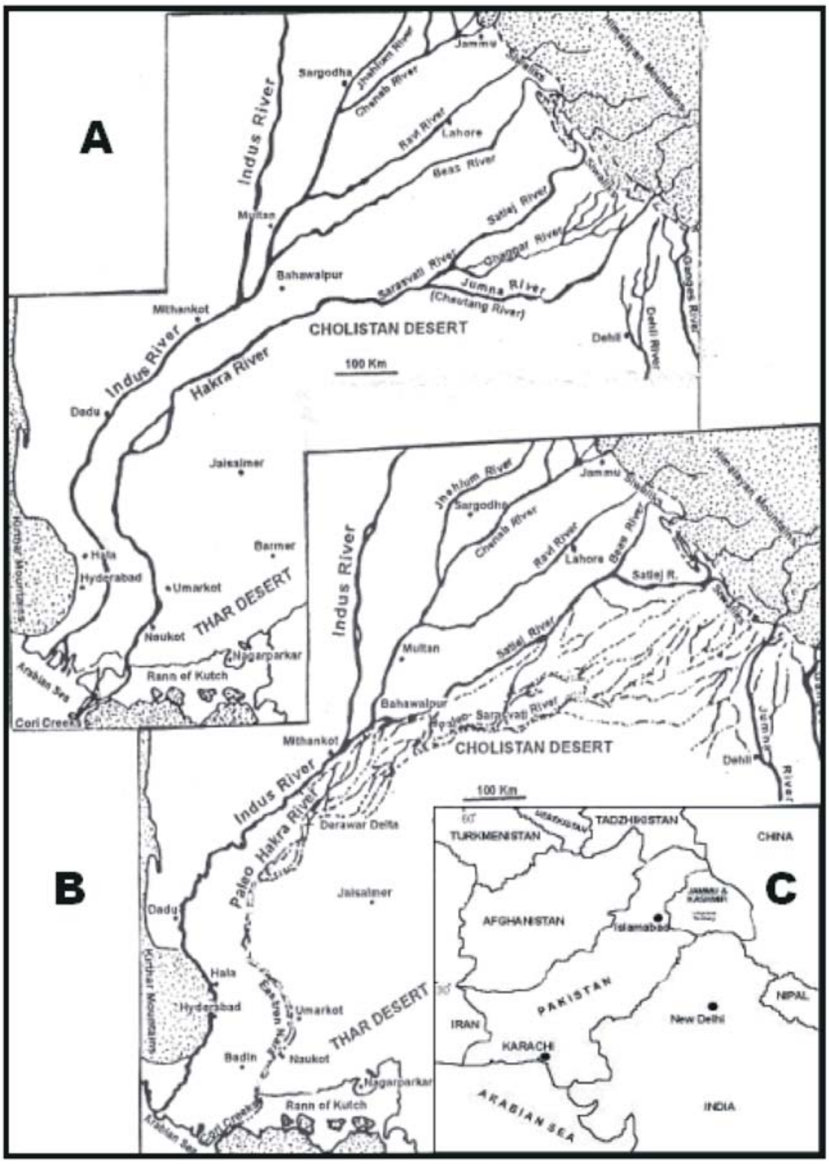

Fig. 1: Map shows paleo- and present status of Indus river and Hakra-Saraswati river systems (modified after Wilhelmy, H., [2,3]). A: Paleo-Indus and Hakra river systems, when Sutlaj river was not a contributory of Indus and Hakra river used to flow parallel to Indus river draining via Cori creek into Arabian Sea. B: Present active Indus river system with Sutlaj as its one of contributories. Jamuna joined Delhi river and became part of Gangage river system flowing eastward. Hakra-Saraswati system has now extinct and there is no flow. C: Index map of Pakistan

the Ganges river system. Present-day eastern Nara canal is considered the paleochannel of Hakra river, which used to drain its discharge via Cori creek into the Arabian Sea.

The geoidal contours (Figure 2) reflect the basement structural relief, which controls the drainage in the region. The Indus and its tributaries are gathered into the low separated from the Ganges low by the geoidal high marked as “Great Divide”. The Great Divide is the location of the drainage divide to the west of which waters flow into the Arabian Sea and to its east, into the Bay of Bengal. The river’s changes in the upper reaches were taking place where the historical seismicity attested the occurrence of the sever earthquake activities beneath the Great Divide.

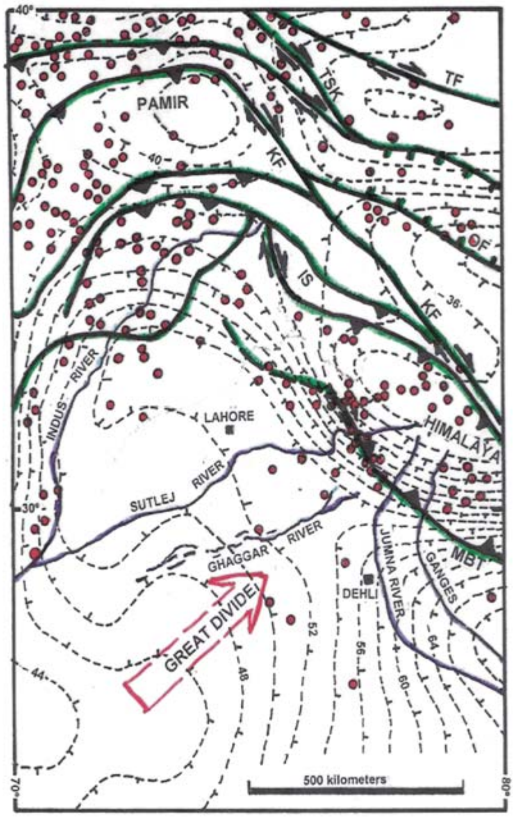

Fig. 2: Map shows Structural elements of the west Himalayan syntaxis, the contours of 2-meter geoid and the earthquake epicenters of less than 70 km. TF: Talass Fault, TSK: Tien Shan-Kunlun Fault, KF: Karakoram Fault, IS: Indus Suture, MBT: Main Boundary Fault

Modern seismicity also demonstrates the similar tectonic deformational activities in the northern part of Pakistan. On October 8, 2005, a high magnitude earthquake of 7.6 M_w struck the Himalayan region of northern Pakistan and Kashmir. The crust-rupturing, warping, uplifting and the massive landslide-phenomenon were the particular features of the seismic event in addition to huge life and property losses.

This paper describes the expected seismo-tectonic impact on the present-day river-flow dynamics correlating the modern seismicity and its deformational activities with the historical seismic events and crustal up-lifting in the northern Pakistan and Kashmir region.

Modern Seismicity in Northern Pakistan: On 8th October 2005, a large magnitude earthquake of 7.6 M_w struck the Himalayan region of northern Pakistan and Kashmir. It was followed by about 573 moderately high magnitude aftershocks and/or earthquakes within a period of three weeks from 8th to 31st October 2005. The death toll as of November 2005 was 87,350; approximately 38,000 were injured; over 3.5 million rendered homeless; about 250,000 farm animals died; more than 780,000 buildings were either destroyed or damaged beyond repair [5]. The tectonic forces, which triggered the powerful earthquakes in the vast area, also reshaped the rugged mountainous region as revealed from the studies of the post-earthquake satellite images.

In general, the geology in northern Pakistan and surrounding areas is controlled by the northward drifting and consequent collision of the Indo-Pakistan subcontinent against the Eurasian plate. As the continents collided, several active mega crustal thrust & fold zones were developed giving birth to the highest mountain ranges and plateaus of the Himalaya, Hindu Kush, Karakoram and Pamir on the planet. Eventually, the faults slip, releasing their compressional forces are the main source for high seismicity associated with the main boundary thrust fault zones.

For the present study, the earthquake epicenters were overlaid on the geological map in view to correlate the interrelationship between the earthquakes and the exposed geological structures and also to assess the lateral extent of the seismicity activities (Figure 3). It was observed that the main 7.6 M_w and 6.2 M_w earthquakes of 8-Oct-2005 seismically invoked and reactivated the tectonic processes and as such about 573 earthquakes occurred spreading over an area of about 35,000 km^2 between Main Boundary Thrust (MBT) and the Main Mantle Thrust (MMT) of the western Himalayan within a short period of about 3 weeks (Figure 3).

Geomorphologically, the massive landsliding phenomenon was a particular feature of this event. Wide spread landslides were observed along the trace of the main fault-rupture(s) in the affected areas. In addition to great lose of life, property, communication services and other basic but vital utilities, the landslides severely blocked the river courses completely and/or partially causing changes in the water-flow dynamics. Moreover, the post-earthquake investigations revealed the fault rupturing, up-warping and up-lifting at places within the Himalayan mountain ranges of the northern part of Pakistan and the Kashmir.

Landslides along River Channels: Acquired satellite images, relevant to the pre- and post-earthquake activities, demonstrated the extent and the intensity of

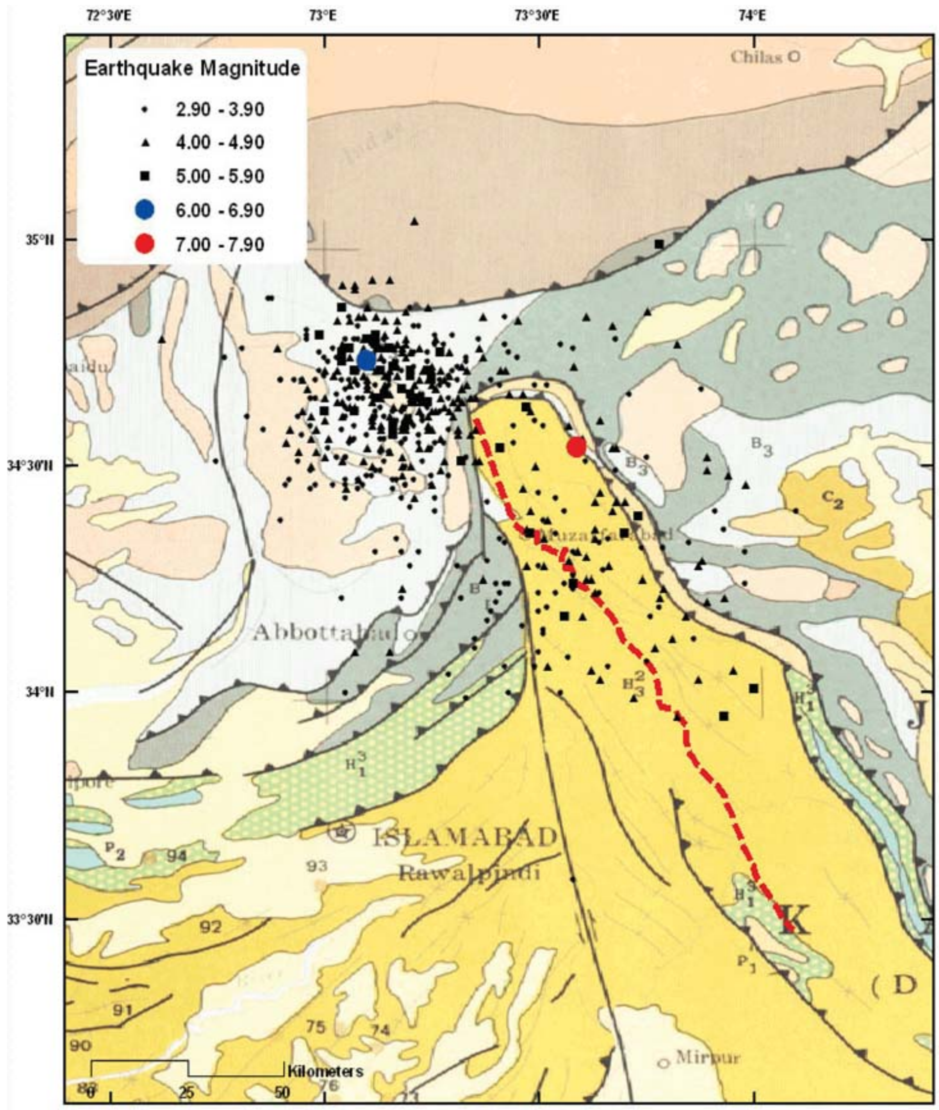

Fig. 3: Map shows the plot of epicenters of earthquakes occurred from 8th to 31st October 2005 and the rupture consequently caused by earthquakes overlaying on the tectonic map of the northern part of Pakistan. Source of base map: GSP [6] and earthquakes data: USGS/NEIC [7]

the landslides and their deformational impact on the rivers' morphology and water-flow dynamics. In fact, the earthquake activities of October-2005 triggered landslides throughout the Kashmir and the surrounding areas lying in the northern part of Pakistan. A few salient landslide instances are here being discussed in context with the degradation of the river courses in the earthquake-affected area. The satellite images were acquired from NASA [8] and other sources.

Comparison of 27-October-2005 ASTER-image with another one taken on 14-November-2000 revealed the widespread exposures of the fresh landslides generated during the seismic activities (Figure 4). In both images, vegetated land is red, water is blue, the city is dark grey and the exposed earth and/or rock are tan and white. In image of 2000, the mountains were entirely covered by the vegetation with only a few sections of grey-white rock defining mountain ridges.

In image of October-2005, nearly all of the mountains that flank the city have collapsed at several places. In some cases, wide sections of the mountain, more than a kilometer in width, were slide into the valley. The landslide area extended far beyond the region shown here in northwest from Muzaffarabad.

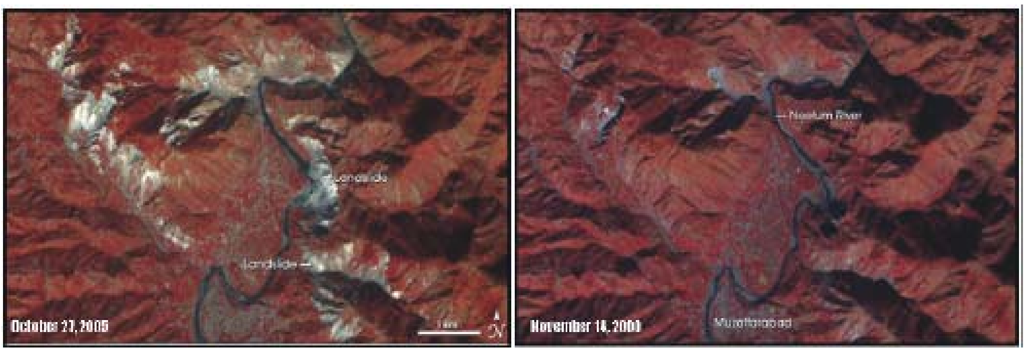

Fig. 4: ASTER image, taken on 27th October 2005 (left), shows fresh landslides as white patches in the mountains around Muzaffarabad due to October 2005 earthquakes. The satellite image, taken on 14-November-2000 (right), does not show the presence of such landslide features. Source of Images: NASA [8]

Fig. 5: 9-October-2005 Ikonos satellite image (left) shows landslide in Makhri village on northern outskirts of Muzzaffarabad illustrating collapse of western face of the mountain into the Neelum river as cascade of white-grey rock. Blue water seen on 15-September-2002 image (right), has turned brown with the dirt of landslides upstream and the landslide blocked the river's normal course forcing it to abandon the "U-shaped" bend seen in the center of the image (right) for a more straight course. Source of images: NASA [9].

A more detailed view could be seen in the image captured by Ikonos satellite on 9-October-2005. The image shows a landslide in Makhri, a village on the northern outskirts of Muzaffarabad city (Figure 5). Western face of the mountain was collapsed sending a cascade of white-grey rock into the Neelum river. The landslide was only one of many to occur along the river. The blue water seen on 15-September-2002, was turned brown with the dirt of landslides. The landslide shown here blocked the river's normal course, forcing the Neelum to abandon the "u"-shaped bend seen in the center of the 15-September-2002 image for a more direct course over its former brown and white banks to its northern reaches.

Terra satellite ASTER image, taken on 11-October-2005, illustrated a large landslide wedge of tan soil stretching more than 2 kilometers in length and over 1 kilometer in width along the side of the mountain in the center of the image (Figure 6). All vegetation, red in this image, was washed in the landslide region.

A number of smaller landslides are also visible, mostly along the main river and other valleys. The large landslide was southeast of the earthquake's epicenter between Muzaffarabad, Pakistan and Uri, India in the Pir Punjal range of Kashmir. Not only was the landslide itself a hazard, but it covered the convergence between two small rivers, which could trigger future floods as the water found new paths around the earthen dam made by the landslide. Before the landslide, the rivers used to flow together near the center of the scene and then flow northward into the large river at the top of the image. Three days after the earthquake occurred, small aquamarine pools of water were formed along the edge of the rubble. Two months after the magnitude-7.6

Fig. 6: ASTER image taken on 11-October-2005 shows a large landslide wedge of tan soil stretching more than 2 km in length and over 1 km in width in SE of the earthquake's epicenter between Muzaffarabad and Uri in the Pir Punjal range of Kashmir. Source of image: NASA [10]

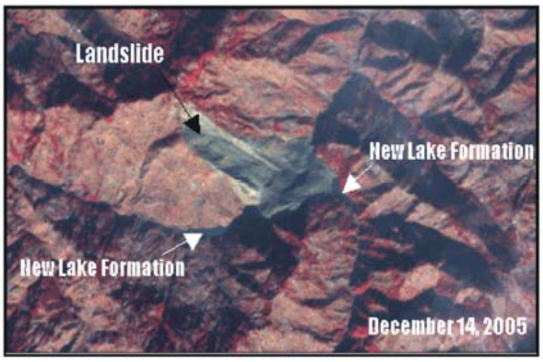

Fig. 7: Two months after 7.6 M_w-earthquake, Terra satellite ASTER image taken on 14 December 2005 shows water pooled into lakes beyond the slide. They have grown significantly since the image was taken on 11 October 2005 (Figure 6) about three days after the quake. Source of Image: NASA [11]

earthquake, the water continued to accumulate behind a natural dam, which pooled into lakes in the valleys beyond the slide as seem in the Terra satellite ASTER image taken on 14th December 2005 (Figure 7). Lakes were dark blue pools of water at the base of the tan slick of bare soil and rock that the landslide exposed. They grew significantly since the image was taken on October 11, three days after the quake.

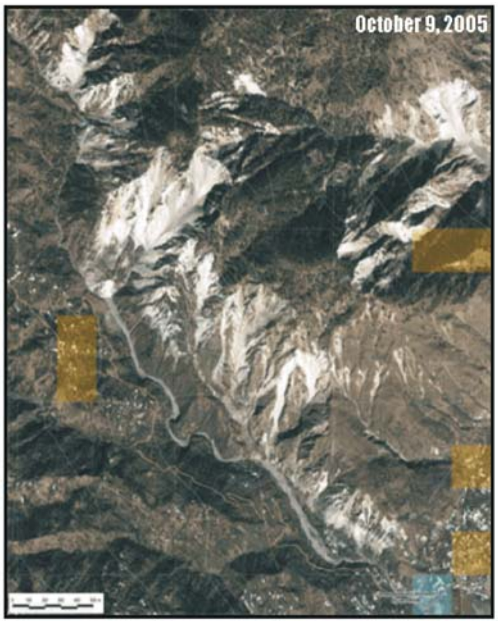

Fig. 8: IKONOS satellite image, acquired on 9 October 2005, displays generation of landslides in the west of the Muzaffarabad city. The landslides have blocked courses of the contributory streams of Neelum River. Water-flow of even smaller rivulets and gullies has also been affected in the landslide damaged area as seen in the image. Source of image: DLR, [12]

IKONOS satellite image, acquired on 9the October 2005, displays the impact of the landslides on the contributory stream of the Neelum river in west of the Muzaffarabad city (Figure 8). Water-flow of even smaller streams and gullies was affected in the damaged area. It was inferred that the water contribution from these streams and gullies was reduced to the Neelum river affecting the quantum of flowing-water.

Satellite image of 18-October-2005 also revealed a unique phenomenon of the underwater landslide-process in the reservoir of the Terbela Dam. Turbidity caused by the dislocated sediments was visible at places along the eastern margins of the reservoir in the image (Figure 9). This deformational activity showed sediment infilling of the Tarbela reservoir on significant scale. Similar activities were also expected to occur in the reservoirs of other dams built in the northern Pakistan and Kashmir region. Since such studies or the studies in more details were not carried out for other reservoirs just after the October-2005 earthquakes, the intensity level of the degradation conditions were therefore not known. These were a few cases of the landsliding discussed in the present study. In fact, there were many more cases

Fig. 9: Part of the satellite image of 18-October-2005 reveals the under water landslide-process in the Terbela Dam reservoir. Turbidity caused by the dislocated sediments is visible along eastern margins of the reservoir. Source of image: Sertit [16]

to be accounted for the development of the complete picture of the land-sliding impact on the river courses and consequent assessment of the total variations in the quantum of river-flows.

Tectonic Warping and Uplifting During Earthquake Generation Phenomena: The Harvard CMT solution of 8-October-2005 earthquake (Figure 10), determined from the modeling of the long-period surface waves, yielded a northeast-dipping fault plane striking N133°E, with a rake of 123° and a dip angle of 40° [13].

A study, using sub-pixel correlation of ASTER images to measure ground deformation [14], revealed that the surface rupture was continuous over a distance of about 75 km and cut across the Hazara syntaxis reactivating the Tanda and the Muzaffarabad faults. The fault offset was 4m on average and peaked to 7m northwest of Muzaffarabad. The surface rupture sharply truncated against the MBT on the southwestern flank of the syntaxis in the north of Muzaffarabad. Along the upper Jhelum river valley, the fault trace was remarkably linear and followed the northeastern flank of the valley for about 30 km north of Muzaffarabad (Figure 10) along the previously mapped Tanda fault [15]. The fault trace curved and become more irregular where it joined the Muzaffarabad fault and cut across the Kunhar valley. From this geometry, the near surface dip angle was inferred to be about 10°. The fault's complexity across the Neelum river valley probably corresponded to a tear fault connecting the Muzaffarabad and the Tanda faults. However, more detailed research studies are further needed to come to a definite conclusion.

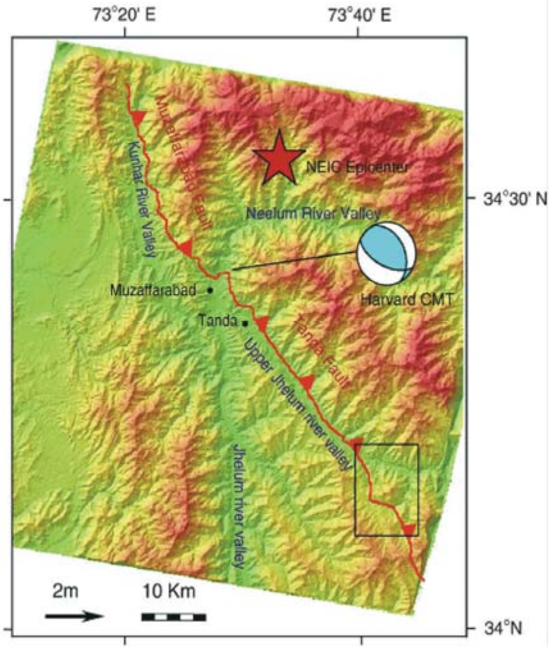

Fig. 10: Surface fault trace mapped from the discontinuity of the offset field. The rupture geometry across the Neelum River and south of the Jhelum River valley (box) indicates a shallow, ~10°, dip angle near the surface (After Jean-Philippe *et al.* [14]).

Discussion of Seismicity Impact on Major Rivers: The most active thrust fault under the Himalaya was generally thought to be the Main Frontal Thrust (MFT) which marked the emergence at the surface of the Main Boundary thrust (MBT). This fault was also considered the basal decollement beneath the Himalayan orogenic wedge. Between the Hazara syntaxis and about 76°E, the MBT was mostly blind as slip tapered below fault-tip

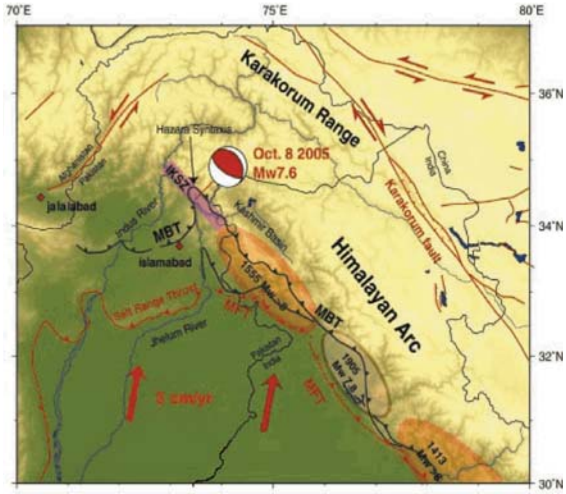

Fig. 11: Tectonic setting of northern part of Pakistan in relevance to the 8-October 2005 earthquake. Rupture areas of major Himalayan earthquakes documented from historical studies [19] and paleoseismic investigations [20]. Shaded ellipses show estimated locations of ruptures in 1413, 1555 and 1905. Major active faults, modified from Sarwar & DeJong [21] and Yeats *et al.* [18], shown in red. Velocity of peninsular India is relative to stable Eurasia [22]. MFT: main frontal thrust. MBT: main boundary thrust. IKSZ: Indus-Kohistan Seismic Zone of Seeber *et al.* [17]. Modified after Jean-Philippe *et al.* [14]

folds [17, 18]. The MBT has produced very large recurrent earthquakes with magnitudes possibly as high as Mw 8.8, as documented from paleoseismic investigations (Figure 11).

It was interesting to note that after the main 7.6 M_w event of 8-October-2005, the second largest earthquake of 6.4 M_w occurred at more than 50 km distance in northwest close to Main Mantle Thrust (MMT) out of any significant trend of the exposed geologic structures associated with the Himalayan-Karakorum-Hindukush Thrust Zone. About 573 aftershocks or the earthquakes ranging between 3.4 and 5.9 M_w from 8th to 31st October 2005 were occurred spreading over a significantly large area of about 35,000 km^2 at depths from 7 to 100 km. More than 80% earthquakes occurred at depth of 10 km. Such lateral extent and the frequency of the earthquake occurrences illustrated an exotic reactivation of dormant fault features associated with the basement mainly at shallow as well as occasionally at moderate depths over the larger extents both laterally and vertically. Moreover, the aftershock seismic activity did not correlate well with the extent of the surface ruptures and was particularly intense beyond the abrupt northern termination of main rupture extending further northwestward for a linear distance of more than 70 km along the presumed IKSZ, i.e., Indus-Kohistan Seismic Zone (Figure 11). The seismicity trend associated with the October-2005 earthquake events corresponded with the inference drawn and discussed earlier that the deep-seated northwest-trending Himalayan basement structures extend beyond the syntaxis and that the change in the strike of the MBT is a relatively shallow feature.

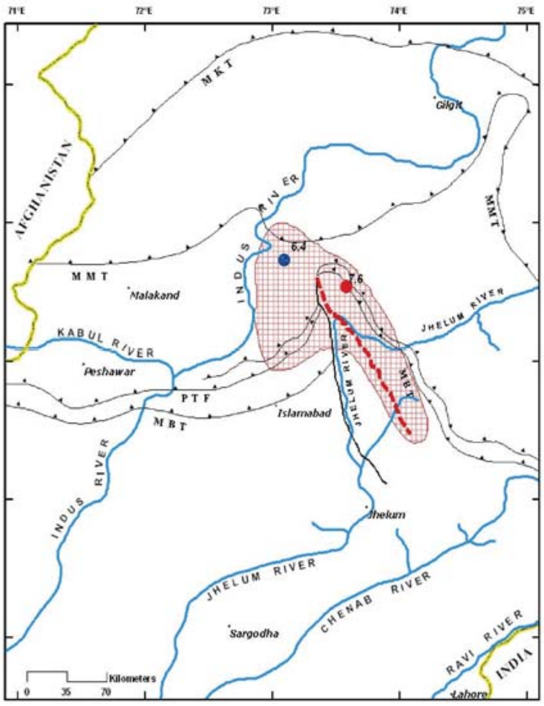

Fig. 12: Seismotectonic model shows the October-2005 seismicity trend verses major rivers and tectonic features. Main earthquakes are shown in solid circles, trace of the rupture with red thick dashed-line, seismicity distribution with pink hatched area, rivers with blue lines and tectonic trends with black teethed-lines

The results of present study indicated the seismically active deep-seated basement trends more or less regionally perpendicular to the courses of the Indus river and its main contributory rivers (Figure 12). Thus, any crustal change would directly affect the courses of rivers in the study region similar to the facts as discussed in the case of seismicity development that diverted the courses of Jamuna and Sutlaj rivers about 4000 years BP.

The 8-October-2005 earthquake and the associated seismic activities appeared to be a complex crustal event with significant slip distribution and a sub-shear rupture cutting across the Hazara syntaxis and passing sub-obliquely across the Jhelum river and its contributory smaller rivers and streams. The up-dip propagation of the rupture together with its steep dip angle and shallow distribution of slip might have contributed to the heavy damages in the near field. Figure 12 shows significantly northwestward hair-pin shifting or the stretching of the course of Jhelum river following more or less parallel trend of the MBT within the Hazara syntaxis probably under the dynamic slipping influence of the modern fault rupture. It is also inferred that the repeated historical reactivation of older Tanda and Muzafferabad faults, which coincided with the surface appearance of the modern fault zone, have continuously being pushed the Jhelum river northwestward since geologic time. The presence of high magnitude historical earthquakes witnessed the historical reactivation along the eastern flank of the Hazara syntaxis (Figure 11). In the same alignment as that of northwestward course shifting of Jhelum river, the Chenab and the Indus rivers also show northwestward shifting trends at relatively lesser magnitude (Figure 12).

The October-2005 events also indicated that the seismic hazard related to out-of-sequence thrusting in the Himalaya could be devastating and should not be overlooked, although major events along the MBT seem much more probable. The 2005-earthquake increased the probability of rupture along the MBT or possible out-of-sequence thrust faults with the possible repetition of events such the 1555 AD earthquake. The up-rising and/or the counter subsided crustal lows in such an event would probably be even larger than in 2005. The research-cum-applied study should be a major concern for the identification of crustal up-risings and/or counter subsided crustal lows in the whole region where the seismicity, caused by the October 2005, has widely distributed.

If the deep-seated crustal warping would have found to be started during the modern seismicity activities like it was developed in the case of Hakra-Saraswati River system about 4000-years BP creating the regional “great divide” and ultimately causing the total collapse of the river system, then the Indus river and its contributory rivers & streams, i.e. Chenab, Jhelum etc. and associated smaller rivers, like Neelum river would also be forces to change their water-flow dynamics.

CONCLUSION AND RECOMMENDATION

- The inferences, drawn from the analyses of the satellite images, seismicity data and geoidal anomalies revealed that the ongoing seismo-tectonic processes were deforming the surface geological setup under the influence of the deep-seated lithospheric features.
- Detailed integrated studies, related to 8-October-2005 earthquake and the following seismicity activities, identified the complex rupturing extending over a distance of 75 km, which cuts across the Hazara syntaxis reactivating the Tanda, Muzaffarabad and other faults.
- Lateral extent and the frequency of the earthquake occurrences illustrate exotic reactivation of the dormant fault features associated with the basement mainly at shallow depths over the larger region both laterally and vertically.
- The rupture terminates abruptly at the hairpin-turn of the MBT, but the current seismicity trends extend farther northwestward, which indicates that the deeper basement tectonic structural trends are entirely different from the exposed tectonic structural setup.
- The deep-seated basement trend is seismically active more or less perpendicular to the courses of the Indus river and its main contributory rivers at the surface. Thus, the present crustal change must have directly affected the courses of rivers in the study region. If the deep-seated crustal warping is found during the modern seismic activities like it was developed in the case of Hakra-Saraswati river system about 4000-years BP creating the regional “great divide” and ultimately causing the total collapse of the river system, then the national policy for the rational management of the Indus river system needs to be reviewed in accordance with the changed water-flow dynamics of the Indus river system.
- The research-cum-applied study should be a major concern for the identification of crustal warping, i.e. up-risings and/or counter subsided crustal lows in whole of the seismicity affected region spreading over an area of 35,000 km^2 by the earthquakes associated with the major seismic events of 8th October 2005.

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