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Preliminary geodetic constraints on plate boundary deformation on the western edge of the Indian plate from TriGGnet (Tri-University GPS Geodesy Network)

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Abstract

Shortly after the 2005 Kashmir earthquake, scientists from three Pakistan Universities collaborated with US, and through them, Indian scientists to monitor seismotectonic deformation and crustal velocities on the western edge of the Indian plate. Twelve GPS receivers were installed at key locations in Pakistan, with some sites monitored continuously and others for a week once each year. More than 80 points have been measured with various periods of longevity. We report here the initial results of these surveys using the Indian pate as a fixed frame of reference. Following are the main results of our study: 1) Sindh province and the southern Punjab are deforming insignificantly (linear strain rates 0.01 µstrain per year) 2) the Makran coast is moving rapidly (18 mm yr^{-1}) southward indicating a locked offshore region; 3) post-seismic effects of 2005 Kashmir earthquake are largely ceased by 2009; 4) interseismic convergence of the Karakorum ranges (>16 mm yr^{-1}) is reduced to 5-8 mm about a line from Peshawar through Islamabad to Srinagar indicating significant strain to have focused in the ranges to the north; 5) the Potwar plateau is moving at less than 3 mm SSE, a factor of four slower than to its geologically estimated rate of 13±2 mm yr^{-1}; and 6) the geodetic rupture parameters of the 2005 Kashmir, and the October 2008 Pishin Baluchistan earthquakes.

1. Introduction

Pakistan lies on the western edge of the Indian plate, bordered to the west and north by the Eurasian plate and to the southwest by the Arabian plate. All these three plates are mutually converging, although the mechanisms differ from north to southwest. In the Himalayas in the north, the collision is typically south to north head-on, translating into dip-slip faults. To the west, the collision is oblique-slip transpressional, as reflected in the Chaman Fault Zone and the western thrust-fold belt. Further to the west, the Arabia-Eurasia convergence is taking place along the north-dipping active Makran subduction zone (Jacob and Quittmeyer, 1979; McCall and Kidd, 1982).

Pakistan's northern contact with the Asian plate is characterized by a1500 km wide zone of deformation that includes the Pamir, Hindu Kush, Karakoram, Kohistan and the Himalaya. This deformation zone owes its origin to successive accretion of several microcontinents of Gondwanic affinity and Neotethyan island arcs at the southern margin of Asia between Triassic and Late Cretaceous, culminating at Early Tertiary India –Asia collision (Beck et al., 1995). As much as 2000 km of crustal shortening is attributed to post-collisional indentation of the Indian plate into Eurasia (Molnar and Tapponier, 1977), with the present-day convergence rates being 37-42 mm yr^{-1} (Chen et al., 2000; Shen et al., 2000). The southern part of this deformation zone is manifested in the

Hindu Kush, Karakoram, Kohistan and Himalayan ranges in northern Pakistan. The October 8, 2005 Kashmir earthquake (Mw 7.6) is the latest manifestation of the strain release in the foreland thrust-fold belt of northern Pakistan. Unlike the main Himalayan arc in India and Nepal, where four earthquakes of Mw>8 have occurred in the past about one century, there is no historical record of major earthquakes in the western Himalayas in Pakistan. Is this because of substantially reduced convergence rates in Pakistan Himalayas? Or is it the creep in the Eocambrian evaporates of the Salt Range Formation that extend northwards beneath the Himalayan thrusts, which inhibits major earthquakes in Pakistan Himalayas (e.g., Brodsky and Mori, 2007).

Unlike the Himalayas in the north, the collision at the western-northwesten margin of the Indian plate against the Afghan block was oblique resulting in a sinistral plate boundary manifested in Kurram, Waziristan, Sulaiman and Kirther ranges in Pakistan. The width of this sinistral plate boundary, as expressed by a deforming cover of surface fold and thrust belts, varies from 100 km in the south to 300 km in the north. The rate of sinistral shear between the Eurasian and the Indian plates throughout the length of this plate boundary is approximately 3 cm yr^{-1}. The transcurrent Chaman fault system that separates the western thrust-fold belt of western Pakistan from the Afghan block consists of a series of left lateral strands whose long-term slip velocities have been estimated from offset features (Lawrence and Yeats, 1979; Yeats et al., 1979; Lawrence et al. 1981; 1992), but whose specific velocities have not been constrained by paleoseismic investigations. The history of earthquakes on the Chaman fault is patchy and does not extend much before 1800, which does not help in constraining the slip rate (Ambraseys and Bilham, 2003). Large sections of the main segment of the Chaman fault are clearly delineated morphologically (Nakata et al., 1991), but few earthquakes have been recorded directly in the fault. Thus, it is enigmatic whether the slip on Chaman fault segments north and south of the 1892 ≈Mw=6.7 Chaman earthquake (Griesbach, 1893) is seismic or aseismic (i.e., creep). Numerous moderate earthquakes occur on the fault to the north of Chaman and these have been interpreted to be associated with slow slip events (Furuya and Satyaballa, 2008). To the south of Chaman the fault ultimately meets a series of en-echelon faults termed the Ornach-Nal fault system on which no significant seismicity has been reported. In the south, near Bela, the Ornach Nal fault is represented by a wide zone of recent mud deposits that have been extruded from the fault zone.

GPS data from Oman demonstrate that relative motion between Arabia and India is negligible close to the India/Arabia/Eurasia triple junction near Karachi. However, a smaller plate, the Ormara plate (Kukowski et al., 2000), has been identified on the southern coast of Makran, which appears to move to the NW beneath the coast. No land area exists on this plate and we are, therefore, unable to determine its velocities using GPS methods.

GPS geodesy is ideally suited to the determination of strain rates near and within a plate boundary. Following the 2001Bhuj earthquake, NCEG initiated a GPS Geodesy survey in Pakistan in collaboration with University of Colorado, Boulder (USA) by measuring three points in the Nagar Parker, in addition to establishing several new points in northern Pakistan from Salt Range to Hunza. Shortly after the 2005 Kashmir earthquake scientists from three Pakistan Universities (NCEG-University of Peshawar, NED University, Karachi and Baluchistan University, Quetta) joined together to establish a GPS geodesy network in Pakistan termed TriGGnet (the Tri-University GPS Geodesy network) to monitor seismotectonic deformation and crustal velocities in Pakistan. Twelve GPS receivers have been installed at key locations in Pakistan, with some locations monitored continuously and others for a week once each year. To date, more than 80 points have been measured with various periods of longevity (Fig. 1 and 2).

Typical accuracies in determining crustal velocities through GPS geodesy are ≈3 mm yr^{-1} for 3-7 day annual occupations at a point, and 1 mm yr^{-1} for continuous data. The procedure we adopt for annual occupations is to cement a bolt into rock, or into the parapet of a flat-roofed concrete-frame building, to which is attached an antenna, and to operate a GPS receiver continuously from solar panels for 4-7 days. We return to the site after an interval of a year and compare the former and present positions to determine a velocity. Where a bolt is impractical we install a stainless steel screw and occupy the point with a bipod, a low profile device that assures vertical offsets are uniform throughout the TriGGnet array and that centering accuracy is better than 1 mm.

Data were recorded either with Trimble NetRS, 5700 or R7 receivers using a 15 second sampling rate, and processed using an elevation cut-off angle of 10^o. Campaign data have durations of 3-7 days from each site. The daily data from these sites were processed along with data from 10 regional IGS stations using GAMIT version 10.34 (King and Bock, 2002). The regional solutions were then combined with global solutions from SOPAC (ftp://garner.ucsd.edu/pub/hfiles) using GLOBK/GLORG version 5.16 (Herring, 2002) to determine time series and velocities in the ITRF2000 reference frame. Initially these velocities were transformed into an Indian plate-fixed reference frame using pole of rotation parameters determined by Bettinelli et al. (2006). Our data are now processed in the ITRF 2004 frame and these are shown with India fixed velocities in this article.

In this paper, we discuss the initial results in five areas: Makran, Sindh, the Chaman/Quetta /Bolan region, the Salt Range and Potwar, and the Kashmir earthquake region (Fig. 2).

2. GPS Geodesy Results

2.1. *The Makran Coast (NED University Karachi)*

Our pilot study here consists of three points along the coast that have been re-measured over a period of four years, and a number of points that have yet to be re-measured (Fig. 3). The coast is moving southward at 16-18 mm yr^{-1}, a rate that is approximately half the convergence velocity between the Asian plate and the Arabian plate (White, 1982; Thenhaus and Campbell, 2002). This suggests that the creep occurs beneath the Makran sediments at rates close to the full Asian convergence velocity but is locked near the coast and offshore. If this is the case the coast is presumably rising slowly during the current interseismic period. The result is unexpected since the most detailed analysis of the Makran earthquake of 1945 (Byrne et al., 1992) quantifies the rupture zone as extending inland for ~90 km terminating near the coast and producing co-seismic uplift. Our data cannot distinguish between plastic deformation of the coastal sediments, and elastic deformation stored near the coastline in preparation for a future offshore earthquake, but we note that the area offshore (weak sediments in a 50 km N-S zone, see Fig. 3) is insufficient to sustain an earthquake much greater than Mw7.5. Hence we deduce provisionally that the Makran subduction interface may not have "healed" since the last great earthquake there. In support of this notion we note that numerous mud volcanoes were activated at the time of the 1945 earthquake and that several continue activity to the present day. The point measured at Pasni, which was near the center of the 1945 rupture, is in fact moving slower southward and it is possible that this indicates locking may be developing inland, however, we have only two measurements from Pasni spanning 2 years and its velocity may change as a result of a longer time series.

Further measurements inland are needed to define the velocity field will permit us to estimate both the loading rate at the locking-line and its depth. The locking-line is defined to represent the transition between creep at depth and a frictionally-locked décollement at shallower depths whose rupture results in great earthquakes. Of interest here is whether the locking line is a sharp transition as in the Himalaya, or a more diffuse region consistent with its shallower northward dip. These measurements have been initiated but it will take some time before precise estimates are possible.

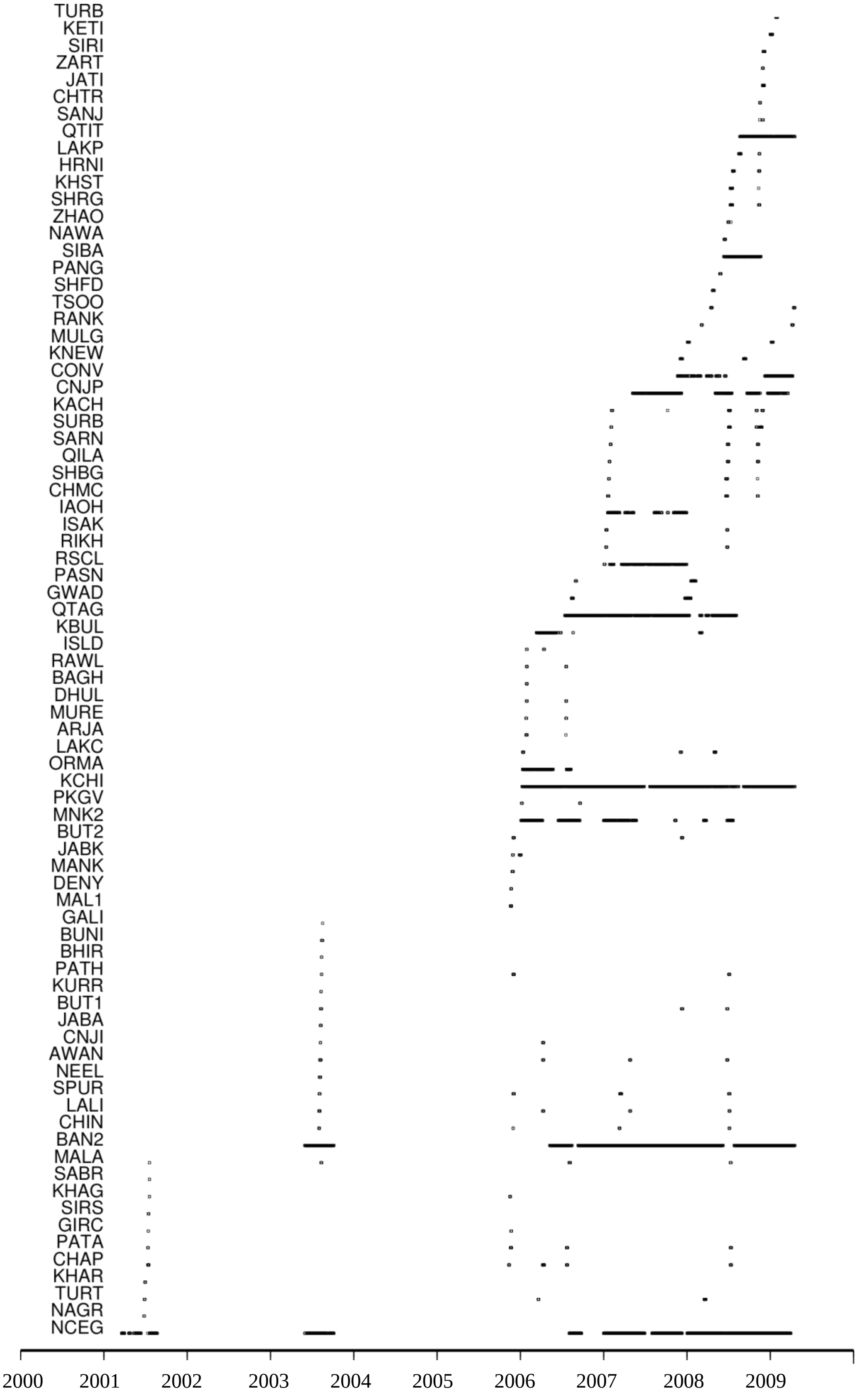

Fig. 1. The summary of TriGGnet in Pakistan showing GPS points (y-axis) and their measurement history (x-axis) between 2001 and 2009. Points with solid horizontal black line are the permanent stations while those with dots are reoccupied after every 2 to 3 years with measurements for a minimum of three days.

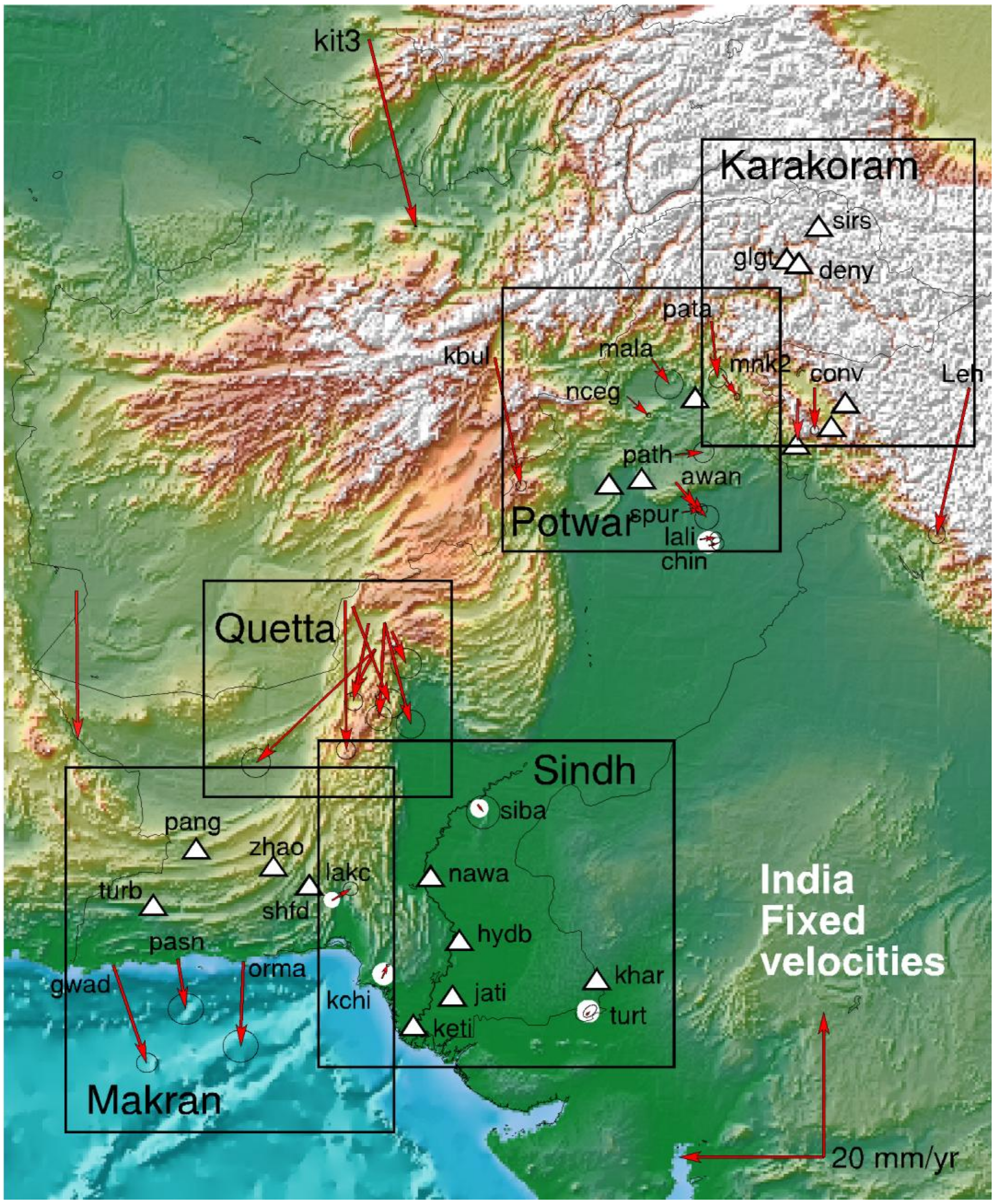

Fig. 2. Summary map of TriGGnet activity in Pakistan, showing outlines of the five regions discussed in this paper. Red arrows indicate GPS velocities 2006-2009 in Pakistan relative to the Indian plate. White triangles indicate points that have been measured but not remeasured. The five white circles indicate sites where velocities are less than 3 mm yr^{-1}. Squares indicate areas that are discussed in more detail in the text. Early post seismic relaxation velocities have been removed from the Kashmir 2005 earthquake region and from the Pishin October 2008 earthquakes region of Baluchistan. Note, the absence of post seismic (or any nearby deformation) of the point Turt, on the Nagar Parkar granite north of the Rann of Kachchh. Strain rates between Karachi, Sukkur and the Indian Plate are less than 0.01 µstrain yr^{-1}.

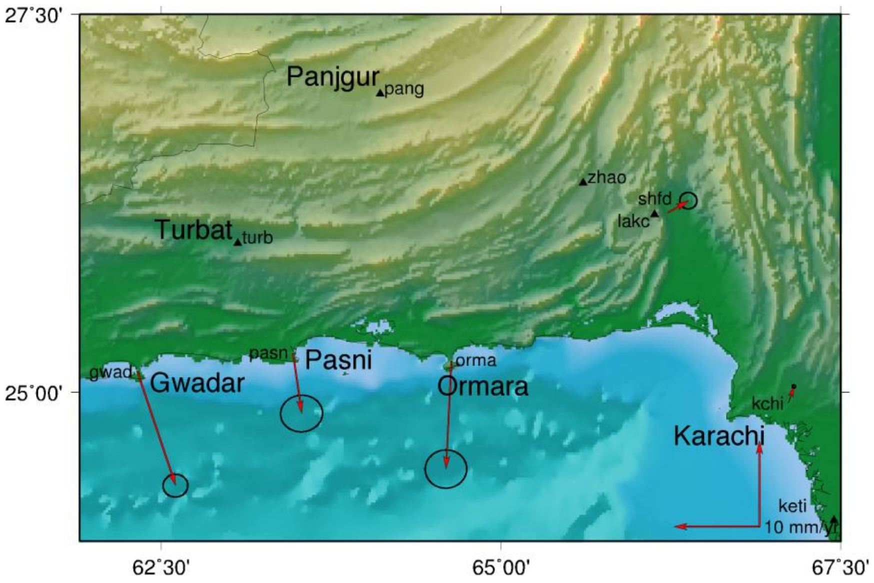

Fig. 3. Relief map showing the location of GPS measurements within the Makran accretionary prism. Coastal points at Gwadar, Pasni and Ormara have been re-measured several times, and a continuous site operates at Karachi, but inland points at Panjgur, Turbat, ZHAO and SHFD have been measured only once.

2.2. Sindh Province (NED University, Karachi and NCEG, University of Peshawar)

Within the region of Sindh, we include the offshore Arabia/India/Eurasia triple junction, the Rann of Kachchh (also spelled as Kutch) region of historical and recent Mw>7.5 earthquakes, the Ornach/Nal segment of the Chaman transform boundary, and the eastward verging fold-and-thrust belt of the southernmost Siestan hills surrounding Karachi. Our data here show that Bela, Karachi and Sukkur are all moving very slowly relative to each other suggesting them being part of the same plate (Fig. 4). Linear strain rates are less than 0.01 µstrain per year indicating that seismic productivity is much lower than has hitherto been inferred from activity in the Rann of Kachchh (Bilham et al., 2007). Evidence for seismicity is absent in the recent instrumental record, but we have made some progress on investigating historical earthquakes in Sindh province, which abounds in anecdotal traditions of earthquake damage. These studies have equated the destruction and abandonment of Mansurah and Samawani, two ancient cities to earthquakes c. 980AD and 1668 (Oldham and Oldham, 1883; Bilham and Lodi, 2009) although the magnitude of these earthquakes is currently unknown. Speculation about earthquake damage to Bhanbore based on inscriptions at the time of reconstruction of the city in the 8th century (Kovach et al., 2008) has superseded earlier errors in conflating an Armenian earthquake with one in Sindh province (Ambraseys and Jackson, 2003), although the evidence for earthquake damage is as yet unconvincing.

The second surprise in this region is the discovery that the Las Bela region shows low velocities similar to the points in the Indian Plate (e.g., Sukhar, Karachi, Nagar Parkar). Being part of the Kirthar-Sulaiman thrust-fold belt at the plate boundary, this region is expected to have velocities close to 15 mm yr^{-1}.

2.3. The Chaman/Pishin/Mach/Kachi Shear Zone (University of Baluchistan, Quetta)

The ancient trade route from Chaman through the Bolan Pass to Sibi represents the narrowest route between the highland plateau of Kandahar and the plains of the Indus. Geologically it defines a transition in geological structure from the partitioned thrust/wrench fault system of the Northern Kirthar ranges to its south, and the lobate thin skinned tectonics in the Quetta transverse zone to its north (Quittmeyer and Jacob, 1979; Quittmeyer et al., 1979). The transition zone, which for convenience, we term the Pishin-Mach shear zone, occurs near a 15° restraining bend in the Chaman fault near Chaman. The kinematics of this restraining bend suggests that basement subsurface dextral shear beneath a 5-15 km cover of surface geology occurs at a rate of ≈8 mm yr^{-1} (Fig. 5).

The cumulative seismic moment release (1.1 x 10^{28} dyne-cm) from about three dozen damaging 6<Mw<7.7 earthquakes that have occurred within about 100 km of this transition zone in the past century (1892-2009) is equivalent to that released by a single Mw=8.0 earthquake, rivaling the moment release in Pakistan's northern provinces in the same period of time (Ambraseys and Bilham, 2003; Szeliga et al., 2009). The cumulative death-toll from these earthquakes in this sparsely populated region exceeds 38,000, most of whom were killed in the 1935 Mw=7.7 earthquake.

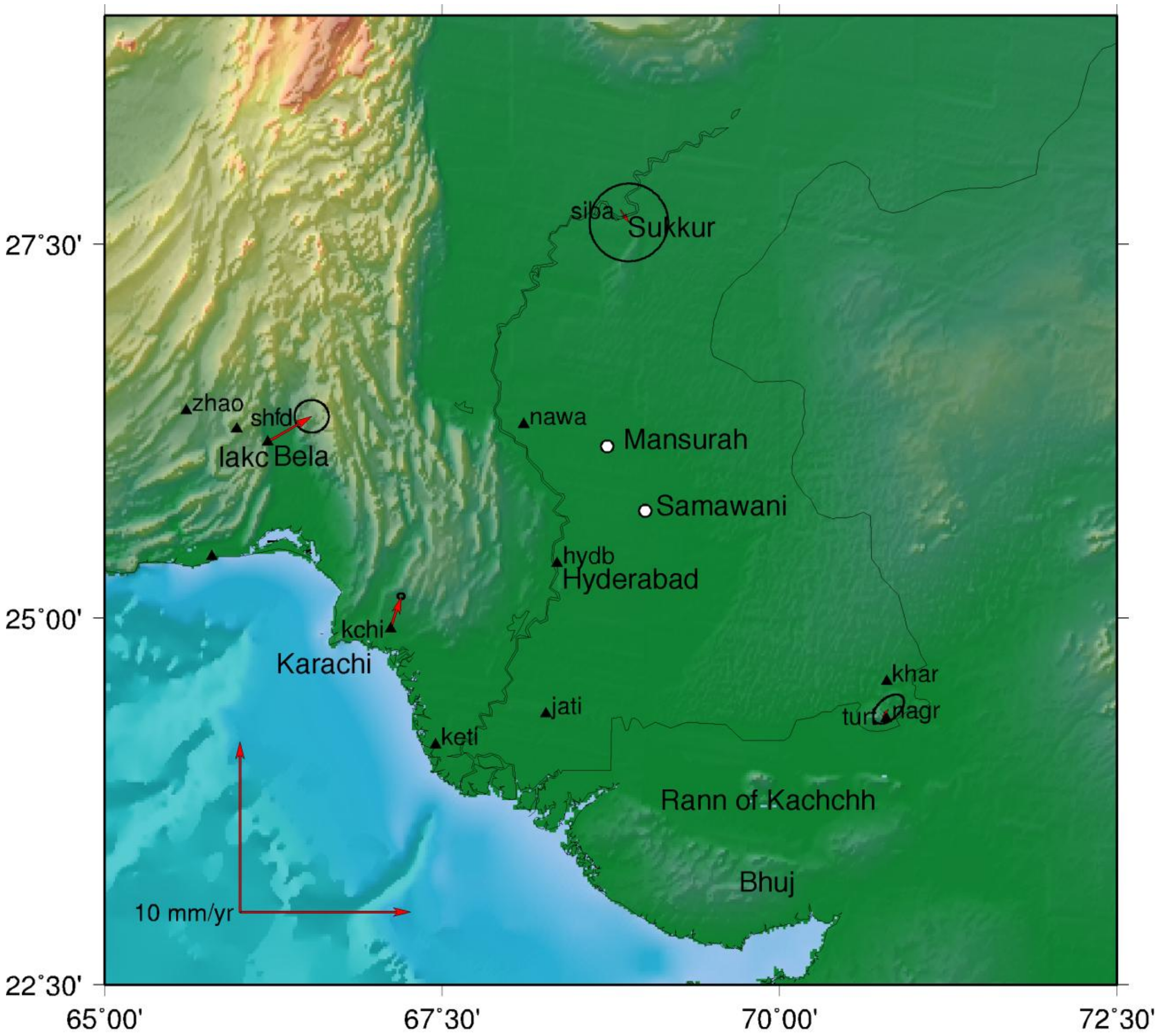

Fig. 4. Relief map of the Sindh region showing continuous tracking sites at Karachi (Kchi) and Sukkur (Siba) with campaign sites at Lakc (near Bela), Keti, Jati Hyderabad, Nawabshah (Nawa) and two locations north of the Rann of Kachchh (Khar and Turt). We show also the locations of two towns that we infer to have been destroyed by earthquakes in 980 AD (Mansurah) and 1668 (Samawani).

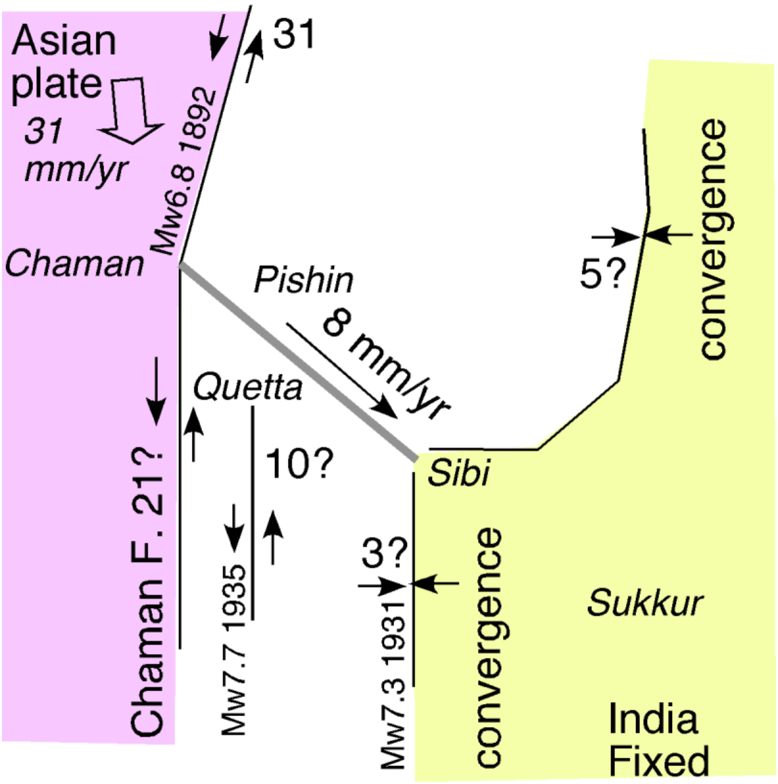

Fig. 5. A schematic representation of the study area illustrating approximate kinematic block motions and strain partitioning present near the Chaman restraining bend. Speculative velocities are indicated in mm yr^{-1}. Continuous GPS instruments operate at Sukkur (NED University, Karachi) and Quetta (University of Baluchistan).

The most recent damaging earthquakes in the region occurred in 2008 in the Pishin/Mach (Ziarat) region, NE of Quetta. The University of Baluchistan mounted a special survey of this earthquake sequence in the days and months following the earthquakes using five borrowed GPS receivers (two from the NCEG, University of Peshawar) (Fig. 6). Fortunately, the measurements were initiated two years previously at six points near the epicentral region, and it was possible to not only measure the coseismic displacements that occurred in the earthquake, but also the post-seismic deformation that is still ongoing (Fig. 7).

The mode of formation of the lobate features of the Sulaiman and Kirthar ranges have been demonstrated in sand-box experiments (Haq and Davis, 1997) and as mathematical models using thin-skinned kinematics (Bernard et al., 2000). A common feature of these models is the need to invoke an underlying Katawaz block that is believed to slide along the boundary between India and Asia, rigidly attached to neither plate, and which according to paleo-magnetic data has rotated 50° clockwise since the Palaeozoic (Klootwijk et al., 1981). It is possible that the Katawaz block continues to rotate or that it is bounded by a shear zone to its south as suggested by the recent Pishin earthquake sequence. Our data (Fig. 2) are presently unable to detect rotation.

The pre-seismic and post seismic velocity field near Quetta suggests that shear is distributed eastward far from the Chaman fault accompanied by distributed convergence of less than 5 mm yr^{-1} associated with the transpressive bend in the Chaman system. The closeness in time of our measurements to the Pishin earthquake sequence suggest that these numerical estimates may change as additional GPS measurements are acquired in the next decade.

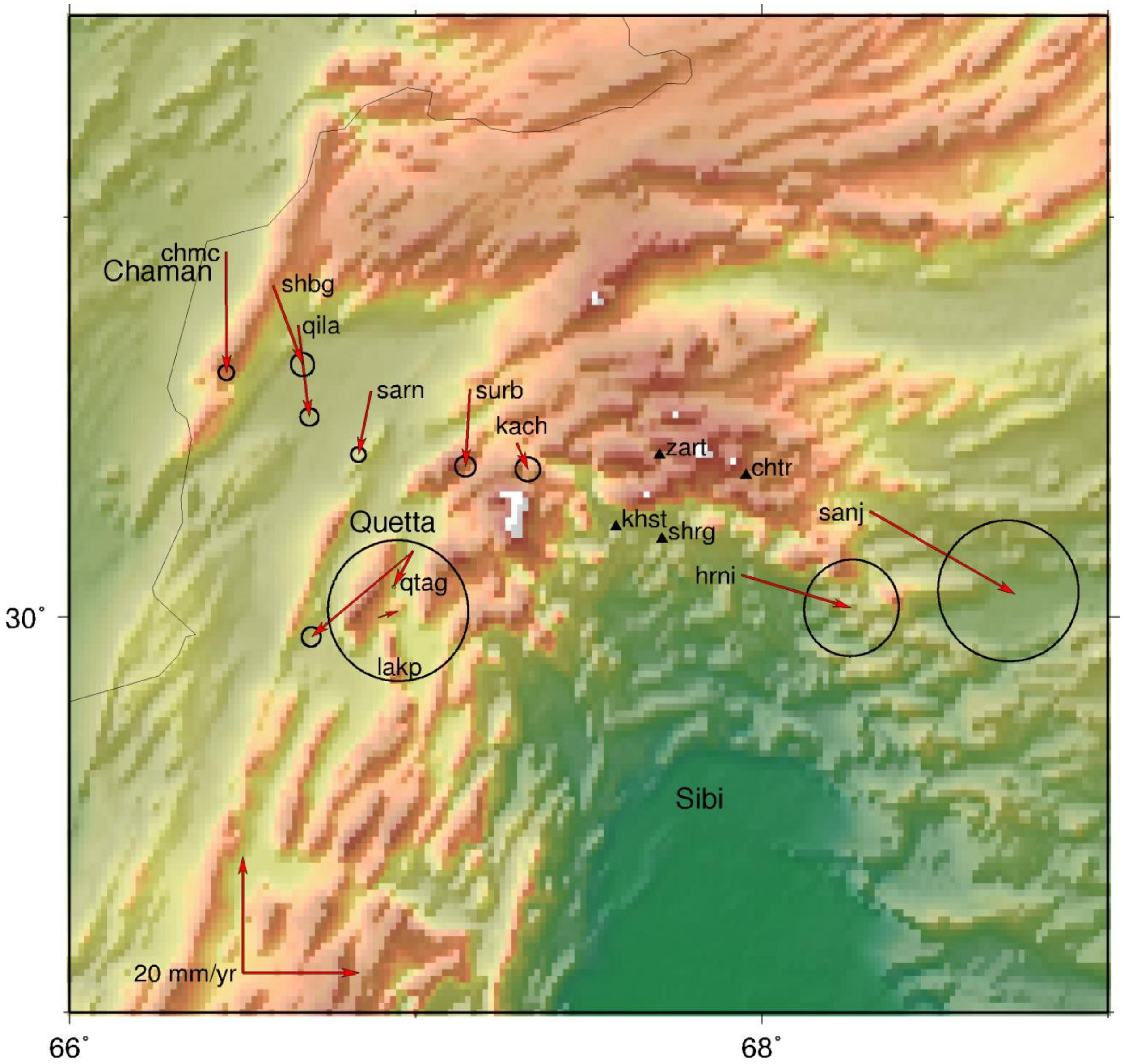

Fig. 6. Relief image showing fourteen GPS points measured in the past three years by the University of Baluchistan, Quetta. Continuous measurements at Quetta reveal subsidence exceeding 10 cm yr^{-1}. Coseismic displacements occurred at our two closest GPS points to the Pishin October 2008 sequence (3 cm at Surb) and 8.6 cm at Kach), consistent with ≈0.6 m of dextral strike-slip faulting near the base of the cover rocks (Fig. 7). No surface rupture was detected suggesting decoupling beneath surface and subsurface geology. All surface structures trend orthogonal to the inferred basement shear zone, which we infer may extend from the Chaman fault system SE towards Sukkur. The most southern expression of faulting on this zone may be the Kachi earthquake of 1909 (Heron, 1911).

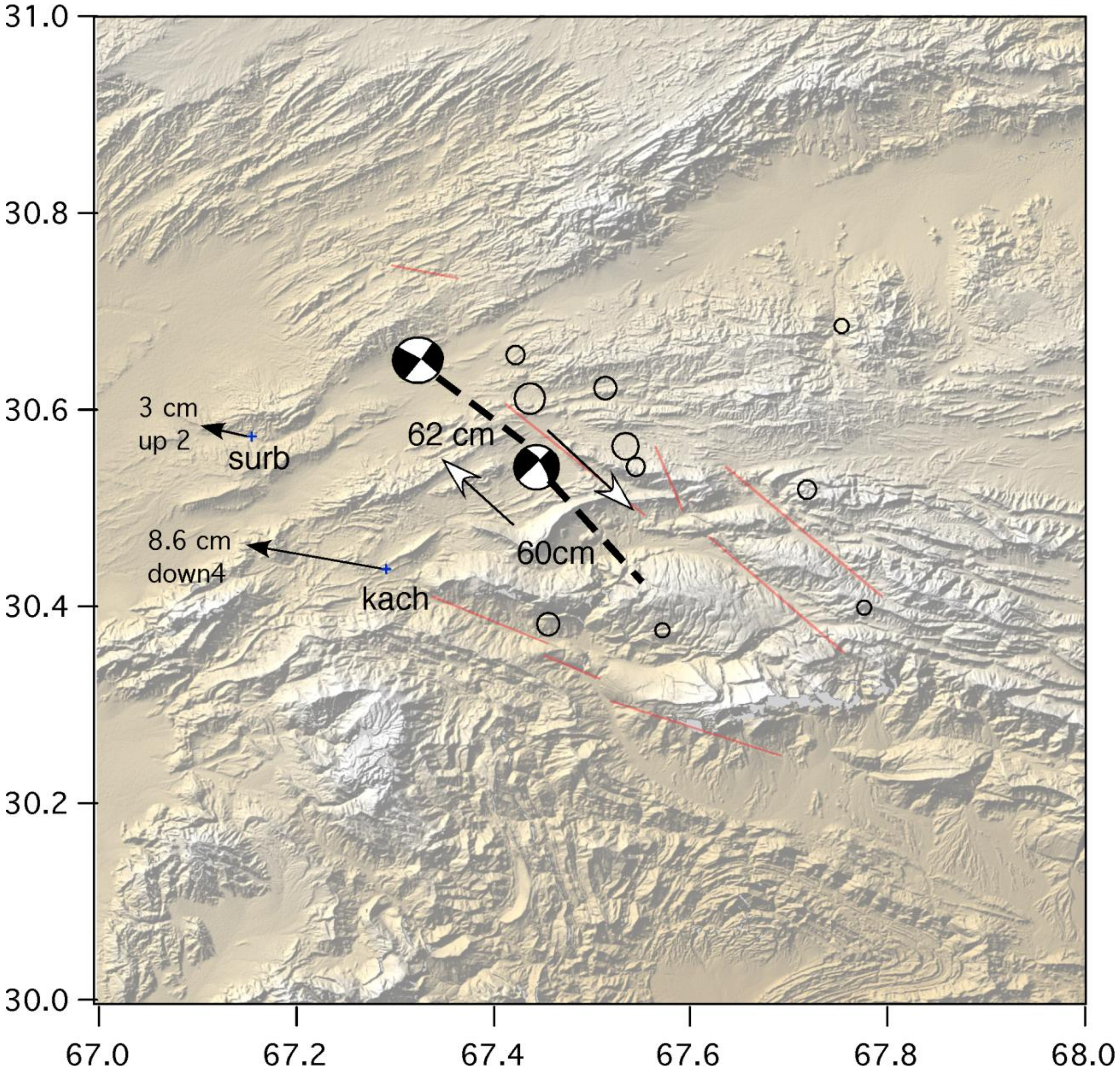

Fig. 7. Coseismic slip and inferred basement faulting in the Pishin/Mach earthquake sequence in October 2008. No surface rupture was found.

2.4. *Potwar-Salt Ranges and Kashmir Region (NCEG, University of Peshawar)*

The region includes both the Kashmir earthquake in the thrust belts in the northern provinces of Pakistan and the Potwar plateau south of Islamabad (Fig. 8). A sparse network that existed in the region prior to the Kashmir 2005 earthquake (Mw=7.6) was sufficient to obtain an estimate of coseismic slip in 2005 (Bendick et al., 2007). Since then we measured approximately 3 years of post seismic activity near the earthquake epicenter that we believe to now be approaching interseismic rates. Of interest in this earthquake was the probable identification of the role of a salt detachment at approximately 10 km depth (Seeber and Armbruster, 1979) in which decoupled surface slip moderated the location and geometry of stress adjustment following the earthquake.

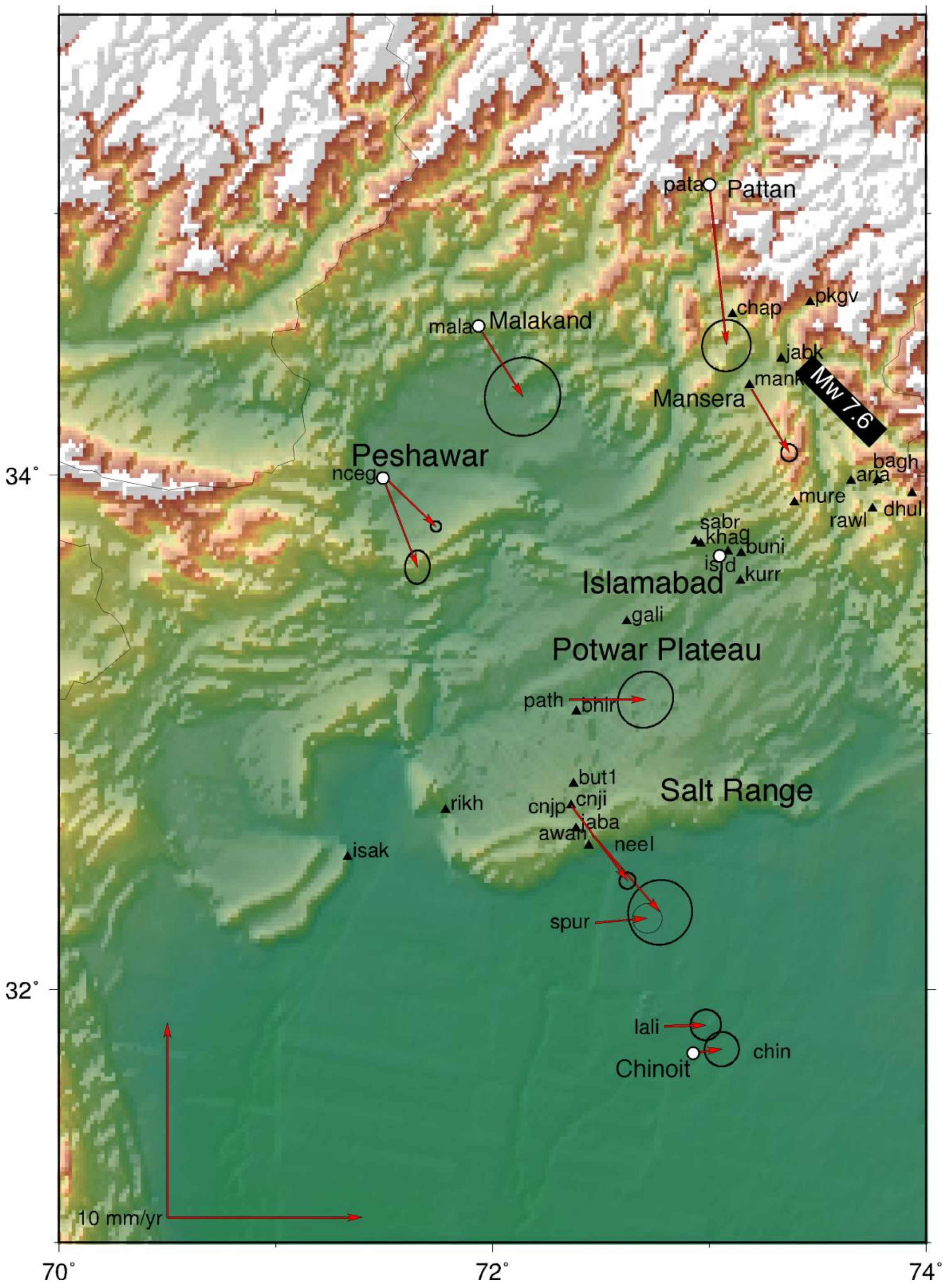

Fig. 8. GPS Measurements on and near the Potwar plateau 2001-2008. Included are SE post-seismic and SSE preseismic velocities for Peshawar (nceg), and data for several sites with somewhat brief measurement intervals (isak and rikh). Note the rotation of velocity vectors from SSE to S to SSW in this syntaxial region of the collision zone. Omitted from the figure are several post 2005 seismic measurements sites. Continuous measurements are being recorded at Peshawar, Mansehra (Mnk2) and Chinji (cnjp in the Salt Range).

The salt décollement beneath the Potwar plateau also apparently played a role in moderating post seismic adjustments there, and in the Salt Range. Although our data are presently being reviewed, it is probable that coseismic strain changes were relaxed in the plateau but not in the basement subsequent to the earthquake, with the result being that the plateau has been able to move southward slightly. The mechanism suggests an alternative to the edge-push model that is unable to translate plateau where friction is significant on the underlying decollment. GPS measurements on the Potwar plateau show that the plateau is now moving southward at rates far lower than the 10-15 mm yr^{-1} that has been inferred from geological evidence (Baker et al., 1988; Jadoon et al., 1997). Insar scenes near the Kalabagh fault show the fault to be presently locked with an uncertainty of approximately 1.5 mm yr^{-1}. The central plateau appears to be moving SSE relative to the Indian plate at ≈3 mm yr^{-1}.

The data from the plateau and to its south are suggestive of a slow clockwise rotation of a block with a pole of rotation near 31°N south of Peshawar. The existence of a crustal block is consistent with weak seismicity beneath the Punjab plain, however, we recognize that our preliminary velocity vectors appear to demonstrate the resolved stress directions of Afghanistan/Hindu Kush SE convergence and Ladakh SW convergence. The resolution of these stresses give rise to the orthogonal fold belts of the northern Potward deformed zone and the Pir Panjal/Zanskar mountains. The most puzzling result thus far concerns the velocity vectors SE of the 2005 Kashmir mainshock. Here the trend of the Pir Panjal indicates that slip on the underlying frontal thrusts is presumably SW directed, yet the velocity vectors are clearly at 45° requiring either oblique slip or a shear zone of slip decoupling. There is no obvious place to locate this zone of dextral decoupling. The Murree/Jhelum region has the correct strike for this decoupling but there is no evidence for surface slip here. The Karakorum fault is too far to the north and is currently slipping at very low rates. Further measurements are essential to resolve the details of these complex stress interactions.

2.5. Kashmir and Karakoram (NCEG, University of Peshawar)

The final area under investigation concerns the mountains in the northern provinces of Pakistan and the western edge of the Tibetan Plateau. We note that convergence with India resulting from convergent Eurasian velocities from the north (Indian plate fixed frame of reference) occurs at rates of up to 20 mm yr^{-1} (Mohadjer et al., 2009). These convergence rates have slowed to less than 5 mm yr^{-1} near Malakand and Srinagar, and hence the principle convergence must lie in the mountains north of the Peshawar and Kashmir basins. Here we seek to address the important question whether elastic locking exists beneath the mountains. There is no evidence for great earthquakes in this part of the Himalaya (north or NW of the 2005 Kashmir mainshock), but it is possible that the historical record here is sufficiently fragmentary for these to have escaped detection. We have yet to re-measure most of the northern sites shown in Fig. (9).

3. Discussions

Our GPS measurements indicate a number of surprising results. A low strain rate is determined for most of the Sindh province extending westward to the southernmost end of the Chaman fault system. This raises new challenges in the interpretation of the seismicity of Kachchh and speculation of its continuation towards Karachi.

Two possible reasons for the low strain rates observed in Sindh that are consistent with historical and recent seismicity are the presence of block rotations beneath the cover of recent sediments, and the possible existence of flexural stresses that would be essentially invisible to horizontal observations. The existence of crustal blocks has been invoked by Stein et al. (2002) as local stress responsible for the seismicity of Kachchh (Bilham et al., 2007). The notion of high strain rates near Kachchh, however must be now abandoned in the face of clear evidence for convergence of less than ≈2 mm yr^{-1} between Nagar Parkar and other GPS points located in the Indian plate. It is possible that block rotation may occur, and the data from near Bela and Karachi are suggestive of clockwise rotation at a slow rate. Slow block rotation may in fact be capable of focusing high stresses at its corners, but would be unable to renew these stresses without long intervals between earthquakes. However, this sense of rotation is opposite to that which we would anticipate at a sinistral plate boundary. The alternative method to focus stresses in the Rann of Kachchh is to invoke flexure of the crust with a neutral fiber stress at between 3 and 9 km depth, and compression below this depth, consistent with the Bhuj main shock (cf: Bilham et al., 2003). We are examining vertical motions of GPS sites to test for this possibility.

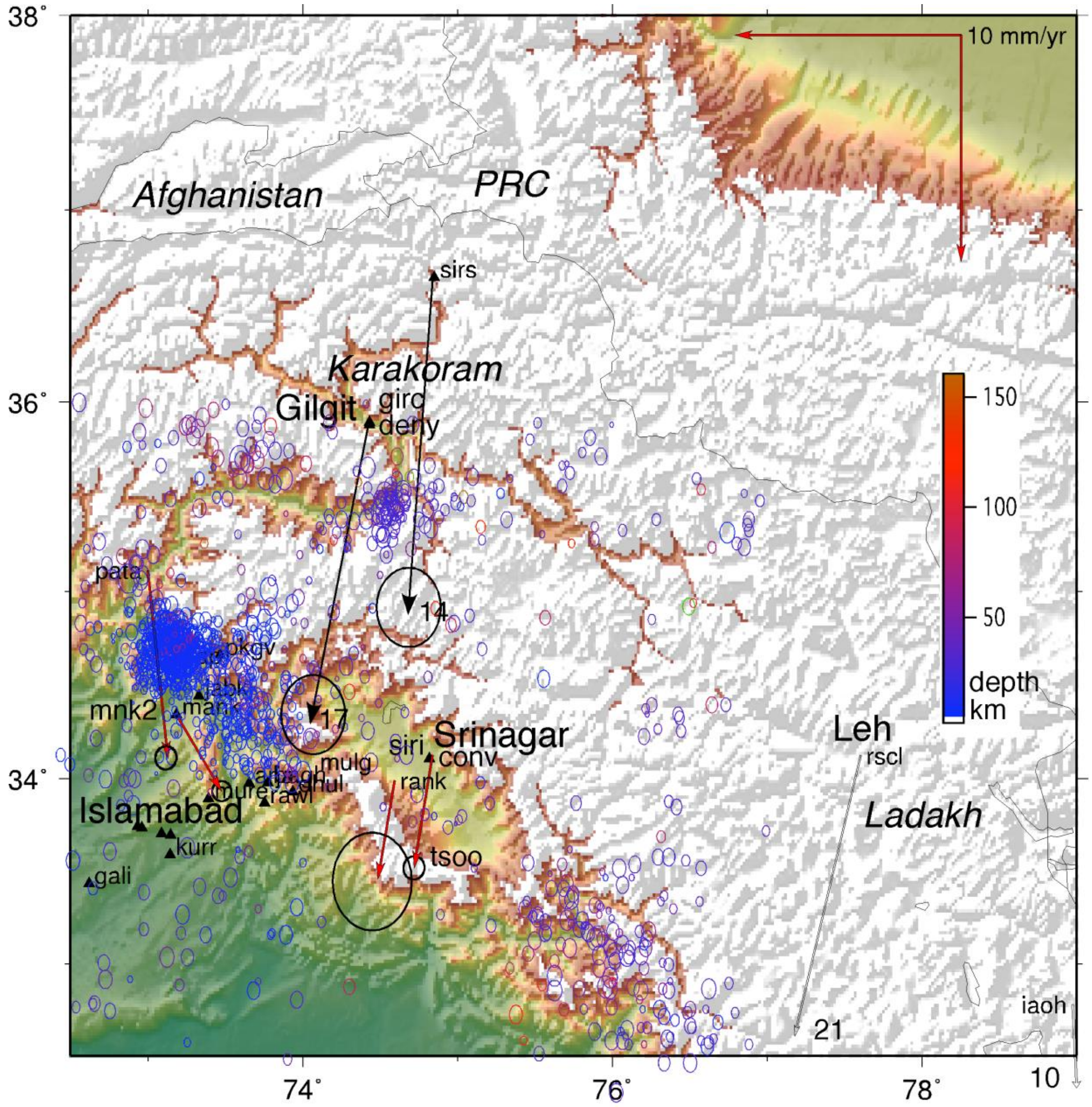

Fig. 9. Relief map of the Karakoram, Kashmir and the northern areas of Pakistan. A continuous receiver (CONV) is operated at Srinigar by the Univerity of Kashmir, and at Manshera (SW of the 2005 Kashmir rupture) by the University of Peshawar. Note the large velocities at Gilgit and Leh compared to the subdued velocities measured at Malakand and Srinagar (CONV) indicating long recurrence intervals for earthquakes in the Pir Panjal and the possibility of significant events in the Zanskar region.

The Las Bela region shows no evidence for the shear velocity field one might expect near a major plate boundary. If the prominent active fault (the southernmost Ornach/Nal system) west of Bela is indeed the Eurasian /Indian plate boundary we should expect to find velocities close to 15 mm yr^{-1} at Bela. Their absence may be interpreted as evidence for complete decoupling by the recent mud extruded in the fault zone, and the dominance of aseismic slip of the fault, or a very much wider plate boundary extending into the Makran accretionary prism, involving the down dip extension of the Ormara or Arabian plates. The en-echelon segmentation of the Ornach-Nal system, the presence of the Gulf of Somniani, the proximity of the Arabia/India/Eurasia Triple Junction and the arcuate form of fold belts eastwards towards Karachi suggests that additional studies will be needed to unravel the complexities of the region. Additional measurements have been initiated to clarify the seismotectonics here.

We find that the Makran subduction zone may not have locked following the 1945 Mw=8.1 earthquake, and that there is no evidence for contiguous locked patches inferred by Byrne et al., (1992). These two findings reduce the seismic hazard potential to Karachi. However, we note that, as in the case of the recent Chengdu earthquake, a slow strain rate is clearly insufficient to switch off seismicity, it merely extends the time between earthquakes.

In the Quetta region we infer a shear zone beneath the fold and thrust belt responsible to the seismicity between Chaman and the Bolan Pass region. The shear zone acts as the transition zone between the fold belts of the Kirthar Ranges to the south and west and the much broader fold belts of the Suleiman lobe to its north and east.

We find the Potwar plateau to be much less mobile than previously expected with rates less than a quarter of those determined geologically. The mobility of the plateau is apparently increased at the time of nearby earthquakes as a result of decoupling between basement and cover rocks. We may have missed an important opportunity to quantify this bimodal behaviour by not having a denser array re-measured before the 2005 Kashmir earthquake.

Our measurements are sparse in northern Pakistan where we know that convergence of 15 mm yr^{-1} occurs north of where most of our measurements are located. The slow southward displacement of the Kashmir Valley and the region north and west of the 2005 Kashmir earthquake rupture towards the Indian plate raises additional questions concerning the recurrence interval of damaging earthquakes in the Kashmir Valley that have damaged Medieval and earlier temples (Bilham et al., 2009), and have shaken Lahore and Amritsar in historical times. It has hitherto been assumed that damaging earthquakes have occurred beneath the Pir Panjal Range, and this inference is reasonable given the similarity in structures to those along the main Himalayan range. The difference is that the convergence rate across the Pir Panjal Range is apparently 1/3 to 1/4 of the convergence rate of the Himalaya eastward, with 10-15 mm yr^{-1} of convergence north of Srinagar. The possibility that large earthquakes can occur in the Zanskar range is neither proven nor refuted by the historical record. As in the region north of Malakand, additional measurements are essential to distinguish between a locked, potentially seismic zone, and alternative forms of absorbing convergence, for example, in the form of subsurface creep.

We envisage that a tenfold increase in the number of GPS measurement sites can be justified to clarify details where our measurements are currently insufficient. For example, we envisage that a quite modest effort can clarify the mode of slip and locking depth on the Chaman fault system between Chaman and the Makran coast, and the details of strain development in the Makran accretionary prism. Measurements in the north promise to reveal the details of strain partitioning from the Karakorum southwards.

Measurements between Potwar and Multan, Sukkur and Karachi may be able to identify the presence of block rotation and rift faulting beneath the Indus sediments, but these will need engineered monuments if they are to reliably detect the slow relative movements (1-2 mm yr^{-1}) identified by our preliminary measurements.

4. Conclusions

GPS measurements in Pakistan and western India in the past few years provide new insights into the seismotectonics of the western and NW edge of the Indian plate and its interaction with the Eurasian plate. Despite the evidence of historical as well as instrumental seismicity in the Sindh region, the velocities measured over past about eight years are negligible. Likewise, the measured velocities in the Potwar region at ~3mm yr^{-1} are three to five times lower than those deduced from geological evidence (e.g., balanced cross sections). The displacement rate on the Chaman/Ornach Nal system is approximately 3 cm yr^{-1}, and convergence to the north in the Himalayas and Karakoram is of the order of 2 cm yr^{-1}. These rates are responsible for historical and future seismicity in Pakistan and Kashmir. These data, despite being in preliminary stages, provide a strikingly different view of the seismotectonics of the western edge of the Indian plate than those based on historical seismicity alone, and even in their preliminary state suggest that regional seismic hazard maps may well need to be revised.

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