First Active Fault Exposure Identified along Kachchh Mainland Fault: Evidence from Trench Excavation near Lodai Village, Gujarat, Western India

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Abstract: We report first identified active fault exposure from Kachchh region along the Kachchh Mainland Fault (KMF) other than the 1819 Allah Bund earthquake. The active fault scarps striking E-W were identified near Lodai village along KMF. North facing scarps with height from 10-15 m are the manifestation of the displaced alluvial fan surface along this fault. Occurrence of discontinuous linear mound ranging in height from 3-5 m aligned along the strike about 100 m north of the main scarp are suggestive of younger tectonic movement and progressive shift of tectonic activity towards north along new imbricating fault. Three low to high angle reverse fault strands (F1, F2 and F3) displacing young Quaternary deposits (late Pleistocene-Holocene?) classified as A to F units comprising gravel and sand-silt facies were identified in a trench excavated at the base of the linear mound along KMF. Our preliminary observations revealed occurrence of at least two large magnitude earthquakes along the F3 fault, and may be older events along the F1 and F2. Latest event (Event-I) occurred along F3 after the deposition of unit B registering the displacement of ~33 cm, penultimate event (Event-II) occurred after the deposition of unit C with ~40 cm of displacement. The maximum displacement of about 73 cm along F3 indicates cumulative displacement accommodated during more than one event. The total displacement of ~98 cm along F2 strand displacing the E and F units is the result of more than one event, and since the F2 probably displaced the unit C suggests that the movements occurred during penultimate (Event II) and during the Event III, older than penultimate. Displacement of Mesozoic succession during older events and unit B during the latest Event I along F1 suggests repetitive movement along this fault. The fragile nature of ~3-4 m wide shear zone formed in Mesozoic rocks (shale-sandstone) also point towards repetitive tectonic movement along KMF.

Keywords: Active fault, Paleoseismic investigation, Paleo-earthquakes, Kachchh Mainland Fault, Kachchh, Gujarat.

INTRODUCTION

The Kachchh region which falls under seismic zone V outside the Himalaya has experienced several large to moderate magnitude earthquakes during last 300 years. These events are 1668 Indus Delta (M7); 1819 Allah Bund (M7.7±0.2), 1956 Anjar earthquake (Ms6.1), and the recent 2001 Bhuj earthquake (Mw7.6) (Malik et al. 1999a; Bilham, 1999). Out of these earthquakes, only 1819 Allah Bund earthquake has been reported to have accompanied with 80-90 km long surface rupture and uplift resulting into formation of about 5-6 m high scarp (Quittmeyer and Jacob, 1979; Johnstan and Kanter, 1990). Whereas, other events likewise the 2001 Bhuj event showing no evidences of surface faulting, suggest movements on blind fault. Along with the modern and historic earthquake records (Malik et al. 1999a), active tectonic studies and few paleoseismic investigations emphasizing mainly on the paleo-liquefaction evidence suggest that the Kachchh region remained under the influence of active tectonic movements during recent historic and geologic past (Sohoni and Malik, 1998; Rajendran et al. 1998; Sohoni et al. 1999; Malik et al. 1999b; Malik et al. 2001a; Malik et al. 2001b; Rajendran et al. 2001; Mathew et al. 2006). Based on satellite photo-interpretation first attempt was made by Malik et al. (2000), who reported several trace of active fault scarps along Kachchh Mainland Fault (KMF) and Katrol Hill Fault (KHF), however, no field and paleoseismic investigations (trenching) were carried out. Active faults are considered to be the source for large
magnitude earthquakes in seismically active regions. Their proper identification and distribution significantly help in knowing the seismic potential and associated hazard in the region. With this background and keeping in mind the past earthquake history, we reexamined the satellite photos and carried out detailed field survey along KMF. In this paper we present the first exposure of active fault identified from the trench excavated across the active fault trace near Lodai village along KMF (Figs.1 and 2a, b).

**Geomorphology and Active Fault around Lodai Village**

The landscape around the study area shows two prominent geomorphic zones, the Northern Hill Range—representing the northern fringe of rocky Mainland Kachchh and the Banni Plain—low-lying area marked by raised mud flats (Fig. 1). These zones are separated from one another by the major E-W striking KMF, which bounds the Northern Hill Range to its north (Biswa, 1980). The KMF marks the sharp geomorphic boundary between the Northern Hill Range and Banni Plain. It has also been suggested that this KMF did not experience any movement during 2001 Bhuj earthquake (Malik et al. 2001).

Most prominent north facing fault scarp striking E-W was identified northwest of Lodai (Figs. 2a, b). The active fault extends laterally for about 2-3 km, has displaced vertically the alluvial fan surface comprising debris flow deposits resulting in development of north facing fault scarp ranging in height from 10-15 m (Fig. 2a). The uplifted fan surface is marked by comparatively flat topography, which shows abrupt termination with the Banni Plain sediments (Fig. 2a). Along with this main tall scarp at places linearly mound aligned along the strike in E-W were observed about 100 m north of the main scarp (Figs. 2a, b). These linear mounds varying in height from 3-5 m are

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**Fig.1.** Generalized structural map of Kachchh region (after Biswas and Deshpande, 1970). Inset at the left top shows DEM of India highlight the location of Kachchh peninsula. Inset at the lower right shows major geomorphic zones of Kachchh. Box marks the study area along Kachchh Mainland Fault near Lodai village. NHR- Northern Hill Range, KHR- Katrol Hill Range, KMF- Kachchh Mainland Fault and KHF- Katrol Hill Fault.
discontinuous in nature, developed due to movements along the active fault during recent times. The occurrence of mounds linearly aligned along the strike north of the main scarp also indicates progressive shift of tectonic activity towards north along newer imbricated fault.

**Paleoseismic Investigation**

To confirm the pattern of deformation a 15 m long, 3.5 m wide and 1.5-2 m deep trench was excavated at the base of about 3-4 m high fault scarp along the mound near Lodai village (Figs. 2a, b and 3). The exposed succession in the trench shows eight major stratigraphic units from A to G. The oldest unit G is highly sheared package of Mesozoic succession (Upper-Middle Jurassic) made of alternate beds of sandstone and shale representing Jhuran and Jamura Formations (Biswas and Deshpande, 1970). Unit G is marked by vertically stacked beds with slight folding at the tip of the fault near the surface; this is revealed by bending of the beds. The fragile nature of ~3-4 m wide shear zone is suggestive of repetitive tectonic movement. The Unit F comprises angular to sub-angular pebbly clasts of nodular limestone, this can well be observed by typical white powdery appearance. Unit F is medium-fine gravelly unit sandwiched between the branching faults. This is overlain by fine-medium platy gravel clasts (unit E) along with sand-silt matrix. Unit D is a debris flow deposit, poorly sorted pebbles-cobbles with shape varying from tabular-cuboidal-discoidal, angular to sub-angular with occasional rounded to sub-rounded pebbles-cobbles, fine gravel to sand supported matrix. This debris flow unit caps the unit E, indicates deposition during single phase of alluvial fan aggradation. Unit C overlying unit D is made up of yellowish-brown colour medium sand with greater content of caliche nodules along with scattered occurrence of pebbles, suggest overbank deposition during channelized flow after the alluvial fan aggradation. Unit B capping unit C is marked by fining upward sequence, fine gravel with silty-clay matrix at the base and brown colour medium sand-silt in upper portion, and few caliche nodules, suggesting channel-fill to overbank deposition. Finally the succession is capped by thin layer of brownish colour fine sand (unit A), which marks distinct boundary with the underlying units. Most likely this unit represents aeolian deposit.

Three major fault strands F1, F2 and F3 identified in a trench shows low to high angle reverse faulting with variable dips ranging from 10°-55° towards south (Fig. 3). The fault dip is higher along F1 and lower along F3. The F1, a high angle reverse fault with dip of about 55°, has placed the older Mesozoic rocks (Shale+Sandstone succession) over the younger Quaternary deposits. Looking to the compactness of the sediments, it is quite possible that the exposed fluvial succession in trench is of late Pleistocene to Holocene age. The older succession is marked by vertically stacked beds with slight folding near the tip of the fault, resulting in bending of the beds towards south (Fig. 3). The fault gouge ~5 cm thick formed between the sheared rocks and the unit F (Fig. 3), and unit F vertically squeezed between the main F1 fault and its branching fault is suggestive of repeated tectonic movements along the F1 strand. F1 displacing unit B indicates latest movement during recent times. The fault strand F2 with dip ranging from 30°-40° has displaced the unit F along with the overlying unit E by about 98 cm. From the stratigraphic cross-cutting relationship it may be suggested that the faulting activity along F2 strand might have stopped before the deposition of unit C and after the deposition of unit D, because F2 strand cuts unit D and not unit C, finally capped by unit B (Fig. 3). On the other hand, an alternative interpretation may be that the F2 fault also displaced unit C, but was eroded during the deposition phase of overlying unit B. The strand F3 marked by low-angle fault plane provides a concise picture of the tectonic movements along the KMF (Fig. 3). The F3 fault has displaced all units from F to B, based on the amount of displacement along various units we interpret that at least two events have occurred along the F3 strand (Fig.3).

The Event-II representing the penultimate event along F3 occurred after the deposition of unit C and before the deposition of unit B. Later was the phase of deposition of unit B, which eroded the displaced unit C on the hanging wall. Latest Event-I along F3 occurred after the deposition of unit B and before the deposition of unit A. This suggests that the units C and D were displaced twice and unit B once. To resolve two events we performed retro-deformation of the succession by restoring the stratigraphic contacts along F3 taking into consideration the unit C (Fig.4a). After cutting the succession along F3 and matching the upper bounding surface of unit C (Fig.4b), still some deficit in terms of displacement remained with respect to the lower bounding surface. This revealed that a displacement of about 33 cm occurred during the latest event (Fig.4b). The displacement was measured considering the lower bounding surface of unit B and the upper bounding surface of the underlying unit C. Similarly, matching the lower bounding surface of unit C on either sides of the fault plane revealed the displacement of about 40 cm and deficit of about 33 cm on the upper side of the fault (Fig. 4c). This suggests occurrence of two events. The displacement of 73 cm measured between the lower bounding surface of units C
Fig. 2. (a) An aerial view of E-W striking active fault scarp along Kachchh Mainland Fault (KMF) near Lodai village (view looking south). The tectonic movement along this fault has displaced alluvial fan succession resulting in formation of north facing prominent scarp ranging in height from 10-15 m. The displaced fan surface is marked by flat uplifted topography showing abrupt contact with Banni Plain seen in the foreground. Along the strike towards west the occurrence of linearly aligned mounds ~3-5 m in height are the manifestation of younger tectonic movement and progressive shift of activity towards north. These mounds are discontinuous in nature and are located about 100 m towards north of the main taller scarp. Active fault trace is marked by red arrows. White box indicates location of ground photo of the scarp and (b) Younger fault scarp near Lodai village. The manifestation of young deformation is in form of mounds running along the strike. Refer figure 2a for the location of photo. Height of the scarp is about 3-4 m. View of the photo looking south.
Fig. 3. East wall view of trench excavated across active fault scarp near Lodai village along Kachchh Mainland Fault (KMF). Three main fault strands F1, F2 and F3 shows reverse faulting with variable dip ranging from 10°-55° towards south. The fault dip is low along the F3 strand. The F1 is high-angle reverse fault with dip of about 55°, displaced the older Mesozoic rocks (Shale+Sandstone succession) over the younger Quaternary deposits. Total eight stratigraphic units A-G have been identified. Where units A-F are the late Pleistocene-Holocene (?) deposits and unit G is sheared Mesozoic rock (Shale+Sandstone). From the stratigraphic relationship and pattern of displacement it is suggested that at least two large magnitude events have occurred along F3 fault. Where the penultimate event with displacement of 33 cm occurred along the F3 fault after the deposition of unit C and before the deposition of unit B, and the latest event occurred after the deposition of unit B and before the deposition of unit A. Total amount of displacement of about 73 cm, measured along F3 fault taking into account the lower bounding surface of unit C with respect to the underlying unit D represent cumulative movement occurred during more than one earthquake. F2 fault has displaced the units F and E by 98 cm also indicates occurrence of more than one event along it. Quite possible penultimate event was the latest event on F3 fault. Thick shear zone and fault gauge along F1 also suggests repeated tectonic movements. White thread mark grid of 1m x 1m.Box with black dashed line marks the location of Fig.4a.
Fig. 4. (a) Close-up of the East wall view of the trench. The units B, C and D are displaced along the F3 strand, (b) after retro-deformation of the unit C. The restoration of the stratigraphic units taking into consideration the upper bounding surface of unit C with respect to the lower bounding surface of overlying unit B suggests that after restoring (~33 cm), some deficit in terms of displacement (~40 cm) remained with respect to the lower bounding surface. It is suggested that the 33 cm of displacement occurred during the latest event (Event I) and 40 cm reminder represents the penultimate event (Event II), (c) restoration of unit C with respect the lower bounding surface clearly suggest the total cumulative displacement of about 73 cm along F3 strand. After the restoration, about 33 cm of displacement remained along the upper part of the fault plane, suggestive of displacement during the latest event (Event I).
and the upper bounding surface of the underlying unit D represents the cumulative displacement during Event I and II (Fig.4c). This maximum displacement of 73 cm suggests that units C and D have been displaced twice, during the Events I and II, where about ~40 cm of displacement probably occurred during Event-II along F3 strand. Also, the total amount of displacement of units E and F along the F2 by about 98 cm could be the result of at least two events. As mentioned earlier, if the F2 had displaced unit C, then some amount of displacement was also registered along F2 during the penultimate event (Event II). And the next deposition/erosion phase of unit B eroded the evidence. This means that we are looking at penultimate event or an event older than the penultimate event along F2. It is suggested that penultimate event (Event II) along F2 occurred before the deposition of unit B and after the deposition of unit C, and an older event (Event III) occurred before the deposition of unit C and after the deposition of unit D. Thus the displacement of 98 cm is the cumulative displacement registered during Events II and III. The vertical squeezing of the sediments of unit F1 between the branching faults of F1 strand suggest repetitive movements, and also the unit B getting displaced along F1 is suggestive of repetitive events. Therefore, it is suggested that the displacements recorded along F1, F2 and F3 strands are coeval during some of the events. Likewise, penultimate event (Event II) was registered along F3 and F2 faults, and latest event (Event I) was registered along F1 as well as F3 faults.

CONCLUSION

Trench investigation suggests occurrence of at least two large magnitude earthquakes along the F3 fault, and may be older events along the F1 and F2. Based on the stratigraphic cross-cutting relationship and amount of displacement of various units along F3 fault it is inferred that latest event (Event-I) occurred after the deposition of unit B registering the displacement of ~33 cm, penultimate event (Event-II) occurred after the deposition of unit C registering about ~40 cm of displacement. The maximum displacement of about 73 cm along F3 and 98 cm along F2 indicates cumulative displacement accommodated during more than one event. If F2 moved during the penultimate event (Event-II) displacing unit C with similar amount (~40 cm as inferred along F3) then the total displacement 98 cm is suggestive of one more event older (Event-III) than penultimate.

Our preliminary observations suggest that the KMF is active in nature, had produced more than two large magnitude earthquakes during recent historic past, and is capable to trigger similar earthquake in future too. This information will play a key role towards evaluating the seismic hazard of this region in a better way. Because, so far no such information particularly on active faulting was available from Kachchh region other than few reports highlighting the evidence of paleo-liquefaction from Great Rann/Allah Bund region. Thus, we believe that this information will be significant in understanding the complex active tectonic pattern, and will provide a pathway to understand that not all earthquakes those struck Kachchh during historic past occurred along blind fault. But there were many such events that accompanied with prominent surface ruptures, similarly like Allah Bund fault and the one we identified along KMF.

Acknowledgement: We are grateful to the referee for providing valuable comments and suggestions which helped us in bringing more clarity to our paper. This work is a part of a project sponsored by GSDMA (Gujarat State Disaster Management Authority, Government of Gujarat) to carryout the Seismic Microzonation of Gandhidham area, Kachchh, Gujarat. The authors are thankful to Dr. S.K. Biswas for his valuable suggestion and discussion in the field and at the trenching site.

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