Active fault traces along Bhuj Fault and Katrol Hill Fault, and trenching survey at Wandhay, Kachchh, Gujarat, India

Michio Morino[1,*], Javed N Malik[2,**], Prashant Mishra[2,†], Chandrashekhar Bhuiyan[2,‡] and Fumio Kaneko[1,$]

[1] *OYO International Corporation, Rokubancho Kyodo Bldg. 2F, 6 Rokubancho, Chiyoda-ku, Tokyo, Japan 102-0085.*
[2] *Department of Civil Engineering, Indian Institute of Technology Kanpur, Kanpur 208 016, India.*
[*] *e-mail: morino@oyointer.com*
[**] *e-mail: javed@iitk.ac.in*
[†] *e-mail: pram@iitk.ac.in*
[‡] *e-mail: cbhuiyan@gmail.com*
[$] *e-mail: kaneko@oyointer.com*

Several new active fault traces were identified along Katrol Hill Fault (KHF). A new fault (named as Bhuj Fault, BF) that extends into the Bhuj Plain was also identified. These fault traces were identified based on satellite photo interpretation and field survey. Trenches were excavated to identify the paleoseismic events, pattern of faulting and the nature of deformation. New active fault traces were recognized about 1 km north of the topographic boundary between the Katrol Hill and the plain area. The fault exposure along the left bank of Khari River with 10 m wide shear zone in the Mesozoic rocks and showing displacement of the overlying Quaternary deposits is indicative of continued tectonic activity along the ancient fault. The E-W trending active fault traces along the KHF in the western part changes to NE-SW or ENE-WSW near Wandhay village.

Trenching survey across a low scarp near Wandhay village reveals three major fault strands F1, F2, and F3. These fault strands displaced the older terrace deposits comprising Sand, Silt and Gravel units along with overlying younger deposits from units 1 to 5 made of gravel, sand and silt. Stratigraphic relationship indicates at least three large magnitude earthquakes along KHF during Late Holocene or recent historic past.

1. Introduction

The Kachchh region has experienced three moderate to large magnitude earthquakes since the 19th century, viz., 1819 Allah Bund earthquake (M_w 7.8), 1956 Anjar earthquake (M_w 6.0) and 2001 Bhuj earthquake (M_w 7.6) (Johnston and Kanter 1990; Chung and Gao 1995). Among these earthquakes, the 1819 event that occurred along the Allah Bund Fault (ABF), resulted in the uplift and formation of 4–6 m high fault scarp (Quittmeyer and Jacob 1979; Bilham 1998). Earthquakes with magnitude more than M_w 7.0 are generally accompanied by surface rupture. In the case of 2001 Bhuj earthquake with M_w 7.6 (left top inset of figure 1), however, no rupture appeared on the ground surface. This indicates that large earthquakes in Kachchh are generated not only by active faults, but also by blind faults, and this makes seismic hazard assessment a difficult and complex task.

Keywords. Active fault; trench investigation; Kachchh; Katrol Hill Fault.

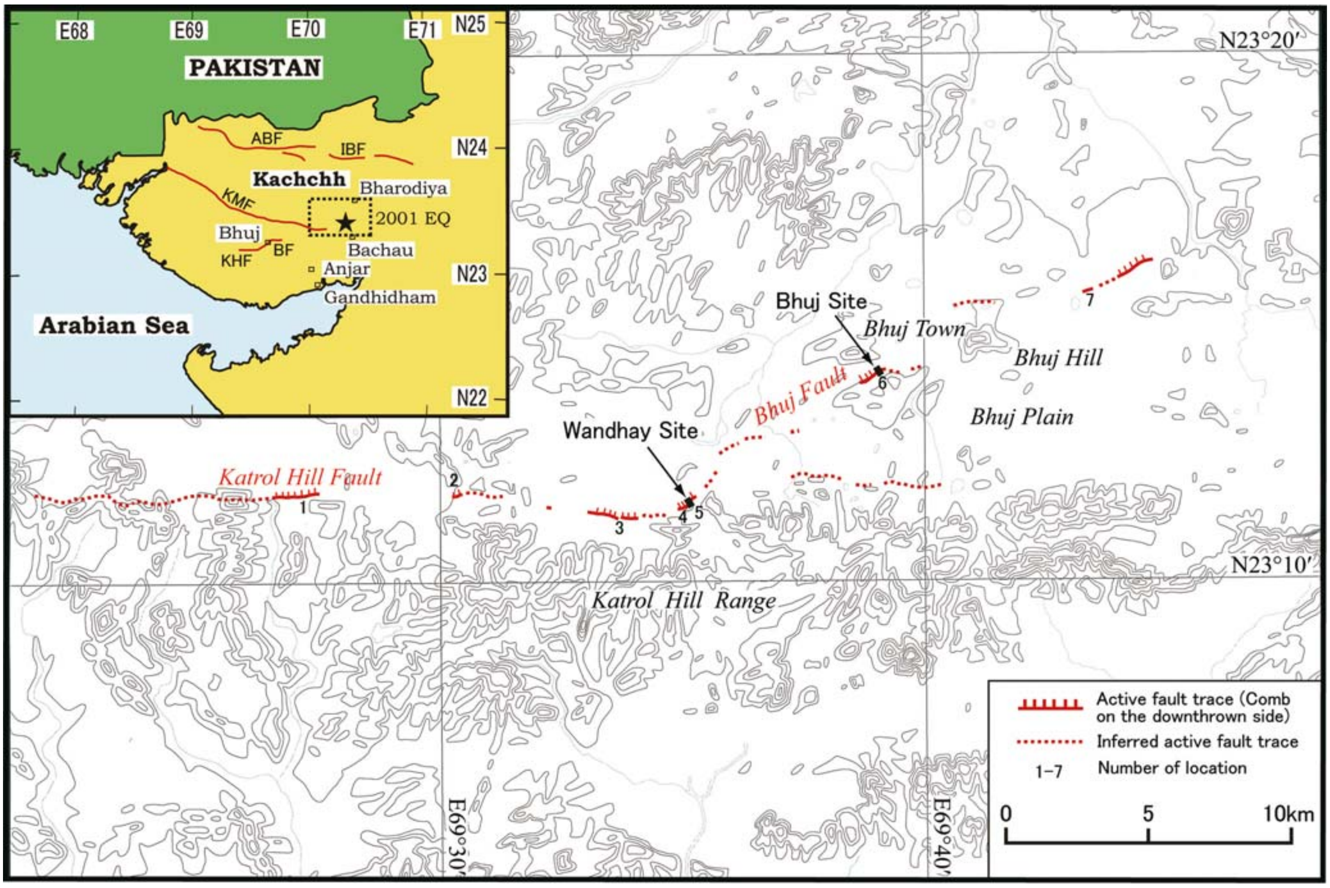

Figure 1. Active fault traces along Katrol Hill Fault and Bhuj Fault. Box in the upper left inset shows major as well as active faults in Kachchh. **ABF**: Allah Bund Fault, **IBF**: Island Belt Fault, **KMF**: Kachchh Mainland Fault, **BF**: Bhuj Fault, **KHF**: Katrol Hill Fault. Box with dashed line in the inset marks the subsurface rupture plane area of the 2001 M_w 7.6 Bhuj earthquake based on micro-earthquakes distribution (Mandal and Horton 2007). Star shows the epicenter of the 2001 earthquake.

In this paper, active fault is defined as one that ruptured repeatedly during the Late Quaternary, and is capable of rupturing and reaching the surface in future. Active faults often hold the geomorphic evidences of paleoseismicity and can therefore be recognized by the deformed geomorphic features such as fault scarp and warping scarp. The timing of paleoseismic events can be revealed by trenching survey across active faults. Our purpose in this paper is to detect active faults and reveal their faulting history.

Three narrow longitudinal E-W trending uplifts named as Island Belt, Northern Hill Range and Katrol Hill Range have been recognized, and these uplifts are bounded to their north by a major fault system the Island Belt Fault (IBF), Kachchh Mainland Fault (KMF) and Katrol Hill Fault (KHF) respectively (Biswas and Deshpande 1970; Biswas 1980). Uplifted fluvial terraces, colluvial as well as alluvial fans and younging-up of fluvial terrace along the fault led earlier researchers to suggest that these faults, particularly the KMF and KHF are active (e.g., Sohoni *et al* 1999; Malik *et al* 2001a; Mathew *et al* 2006). These faults have uplifted the Mesozoic as well as Tertiary rocks. However, displacement of Quaternary deposits due to fault movement in the Kachchh region is hitherto unreported. Based on the satellite photo interpretation, Malik *et al* (2001b) inferred several active fault traces along the KMF and KHF. But the active nature of the faults was still largely speculative as supporting field evidences were unavailable. Rajendran and Rajendran (2001) carried out paleoseismic investigation around ABF. Though identification of paleo-liquefaction features is the basic pre-requisite to understand the faulting history (e.g., McCalpin 1996), it is difficult to identify the sources of earthquakes since liquefaction may be generated even by distant large earthquakes.

None of the faults except ABF are reported to have generated large magnitude earthquakes in the Kachchh region. If these faults were indeed active during the Late Quaternary, one can expect large earthquakes along these faults in future. Therefore, it is of paramount importance to undertake detailed field investigations to understand the faulting history along these faults for proper seismic hazard assessment of the Kachchh region. We had the opportunity to investigate the foreland region of Katrol Hill Fault (KHF) as part of the project on *"Seismic Microzonation of Gandhidham, Kachchh, Gujarat"*, sponsored by Gujarat State Disaster Management Authority (GSDMA), Government of Gujarat. In this paper, we document several new active fault traces along KHF as well as associated geomorphic features, fault exposure along newly identified *Bhuj Fault* (Morino *et al* communicated) and trench investigation at Wandhay site (figure 1).

2. Geomorphology and fault exposures along Katrol Hill Fault and Bhuj Fault

We re-examined the satellite photo interpretations made by Malik *et al* (2001b), and conducted field surveys along KHF. Several active fault traces along KHF and Bhuj Fault were identified (figure 1). We were able to trace the active fault for about 45 km between location 1 and 7 (figure 1). At location 1, the E-W striking north facing low scarp with height of about 1–2 m extends laterally for about 1km. The southern elevated side of the scarp marks the lower terrace. The terrace is back-tilted towards the south. On the basis of field investigation that a small stream has developed along the scarp, we suggest that this scarp represents an erosional scarp. The manifestation of deformation was well observed on satellite photo towards east as E-W trending gently warped surface, passing through the alluvial-colluvial fan at location 2. The gentle warping of the surface was completely modified because of severe cultivation practice. Therefore, it was difficult to confirm it in field. To the south of the gentle warping the sharp topographic boundary between Katrol Hills and plain represents an erosional scarp. Another E-W striking scarp was observed on the satellite photo as well as in the field at location 3. Two parallel low-angle reverse faults with strike N29°W and dip 22°SW developed in the bedrock were observed on the left bank of a stream cutting the terrace. Faulting is well revealed by 10–30 cm thick gouge. Lack of any corroborating evidence showing displacement of Quaternary deposits makes it difficult to decipher the active nature of the fault. However, the probability cannot be ruled-out. In the outlet of the small valley at location 4 composed of the colluvial fan, a low scarp with height of about 1–2 m was observed in the satellite photo. Although the southeastern part of the scarp is comparatively more elevated, most of the scarp has been modified by present day farming. At location 5 near Wandhay village, an active fault trace is demarcated by a prominent sharp boundary between the Katrol Hill and the fluvial terrace. The fault, displacing Quaternary fluvial terrace deposits, is exposed along the left bank of Khari River near Wandhay Dam (figures 2A and 2B). Here the NE-SW striking active fault is aligned with the Kartol Hill on the northern side and further it cuts through the fluvial terrace along the Khari River (figure 1). Figure 2(A) shows an exposure of the fault (lat. 23°11′36″N, lon. 69°35′22″E). On the hanging wall, the exposed succession is marked by inclined Jurassic shale and sandstone sequence overlain by terrace deposits (figure 2A). The shale and sandstone on the hanging wall are highly sheared, and a width of the sheared zone extends for more than 10 m. About 20 m north of the fault exposure in the downstream of Khari River, a massive sandstone succession is exposed. The sheared shale and sandstone on the hanging wall and the sandstone on the footwall correspond with Upper Jurassic Jhuran Formation and Lower Cretaceous Bhuj Formation respectively (S K Biswas, personal communication). The strike and dip of the fault between the sheared bedrock and terrace deposits are N44°E, 62°SE respectively. The inclination of the terrace surface to the northern and southern sides of the projected fault trace (marked by a person in figure 2A) are different. The southern side is inclined by about 5°, whereas, the northern side is almost horizontal. This warping is a manifestation of the deformation related to the most recent event. The close-view of the fault along the river bank is shown in figure 2(B). Three to four low-to-steeply inclined reverse faults were observed. These faults have displaced the terrace deposits comprising sand and gravel units. The uppermost layer covering the terrace deposits marks the unconformity. It was assumed that these faults have also displaced the uppermost layers. However, the upward termination of the faults is ambiguous, because the cliff was steep and high, making detailed investigation impossible. The occurrence of Upper Jurassic rocks on the hanging wall and Lower Cretaceous rocks on the footwall and the displacement of younger Quaternary deposits along the fault possibly suggest reactivation and continued tectonic activity along the old KHF.

A small hill composed of bedrock was located further north at the southern edge of Bhuj Town (figure 3A). Along the northern fringe of the hill a sharp curved topographic boundary between the hill and the Bhuj Plain was observed at location 6. Two parallel faults, the southern fault and the northern fault, were found near Bhuj Town (figures 1, 3A and 3B). The southern fault was observed along the road cutting (figure 3A).

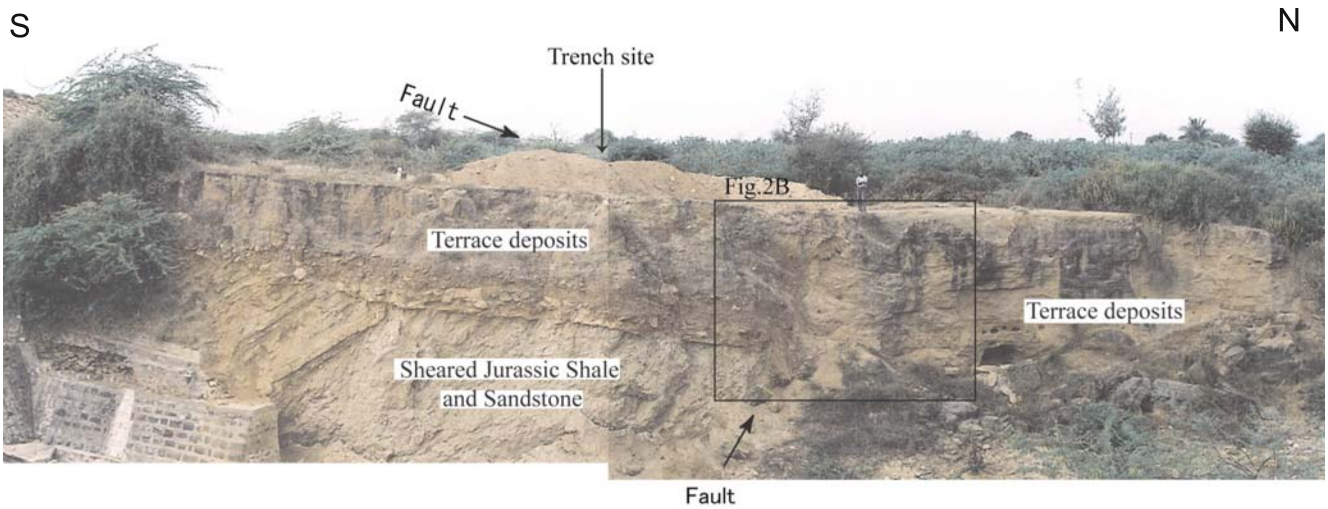

Figure 2(A). Fault exposure on the left bank of Khari River near Wandhay Dam. Arrows show the fault trace displacing the terrace deposits. The sheared Mesozoic succession comprising shale and sandstone sequence with a width of more than 10 m was observed on the hanging wall on the southern side of the cliff. Note the change in the inclination of terrace surface to the north and to the south of fault trace (projected by arrow) at the base (person standing on top of the surface for scale). See text for details.

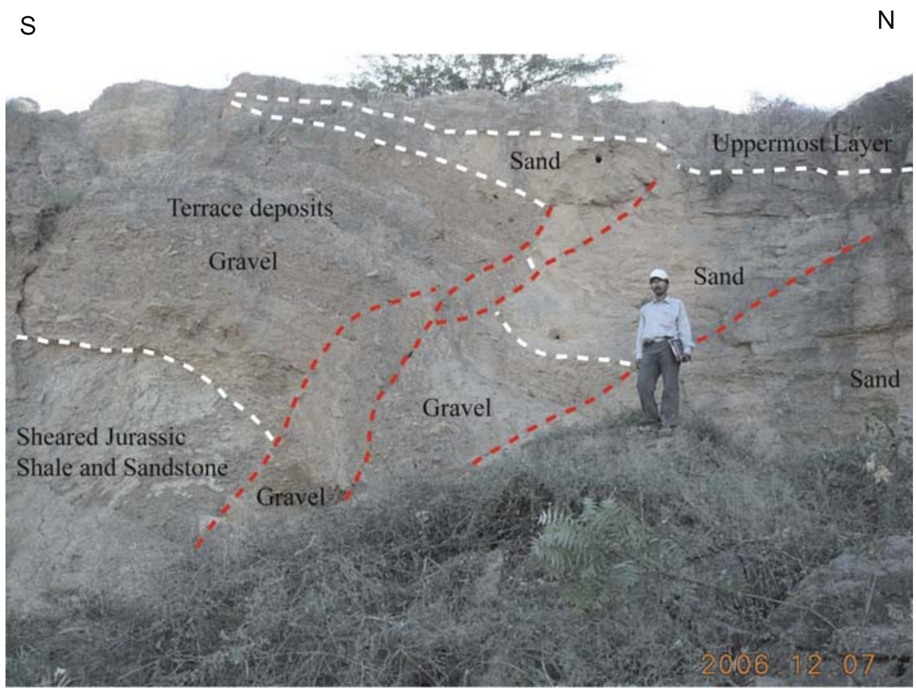

Figure 2(B). Close-view of the fault showing displacement of the terrace deposit. The terrace deposit is composed of sand and gravel. See text for details.

This low angle reverse fault (with strike and dip N26°E and 21°SE respectively) is demarcated by 1–1.5 m thick friable gouge. The NE-SW striking northern fault, associated with low fault scarp with height ranging from 1–1.5 m, was observed about 100 m north of the southern fault (figure 3B). Another low angle reverse fault was identified at location 7 (figure 1). The fault scarp with height of 1–3 m extends to east from location 7.

3. Trench investigation at Wandhay site

We have traced the faults displacing the terrace deposits but whether the overlying channel

Figure 3(A). Fault exposure along the road cutting, south of Bhuj Town. This fault has been named as Bhuj Fault marked by low-angle reverse fault with the strike N26°E and dip 21°SE. The thickness of the gouge is about 1–1.5 m. The background is Bhuj Town.

Figure 3(B). Low scarp identified about 100 m north of the fault exposure shown in figure 3(A). The height of the scarp is about 1–1.5 m. The scattered blocks of rocks are the collapsed blocks from the free face of the fault scarp.

deposits were affected by faulting during the latest seismic event was ambiguous. A 14 m long, 3.5 m wide and 2–2.5 m deep N-S trench was therefore excavated across the undisturbed low warping scarp on the terrace surface to understand the relationship of the terrace deposits and the overlying succession, and the faulting sequence-pattern of deformation (figures 2A, 4A and 4B).

Figure 4 shows the mosaic photo (A) and the logging (B) of east wall of the 14 m long trench. The exposed sedimentary succession in the trench was classified as the terrace deposits marked by horizontal stratification comprising Sand, Gravel-1, Silt, and Gravel-2 layers. These deposits are weakly consolidated. The younger sequence capping the terrace deposits marks the unconformity. The sequence is classified as unit (1) poorly stratified fine gravel with angular to sub-angular pebbles with sandy matrix; unit (2) coarse sand with sub-rounded pebbles; unit (3) poorly sorted medium sand and silt; unit (4) poorly stratified gravel with sub-angular pebbles-cobbles with sand-silt matrix; and unit (5) medium to coarse sand. Finally, the succession is capped by soil. These unconsolidated and poorly stratified sediments were deposited by small shallow channels after the uplift of the terrace and the formation of warping scarp.

Three major fault strands F1, F2, and F3 were identified in the trench (figure 4A and B). The F1 fault strand cuts the Sand layer of terrace deposits along with overlying units 1 to 4 and is covered by the ground surface soil (figures 4 and 5). The faulting along F1 is well revealed by the undisturbed horizontally stratified Sand layer along with the overlying units 1 to 4 on the footwall, and by inclined stratified Sand layer along with units 2 to 5 with inclination of about 20° towards north on the hanging wall. The displacement along F1 strand is less than 10 cm. The faulting along F1 strand represents the youngest event. It is suggested that only one seismic event has occurred after the deposition of unit 1, and before the deposition of the surface soil. The F2 strand cuts the terrace deposits (Gravel-2, Silt, Gravel-1, and Sand) along with overlying units 4 and 5 (figures 4 and 6). The displacement of the Gravel-2 and Silt of the terrace deposits is 42–50 cm. The inclination of the stratification of the terrace deposits on the hanging wall of F2 strand is about 40°. However, the Sand layer near the surface at the tip of the fault (F2) has undergone slight folding marked by high dip of about 60° (figure 6). Considering the inclination of the deposits on the footwall which is about 20° and that of the hanging wall deposits which is about 40°, it can be inferred that the terrace deposits on the hanging wall are two times steeper than that observed along F1 strand. This, in turn, possibly indicates that the terrace deposits along F2 strand was displaced twice giving rise to a much higher angle of inclination (40°) as compared to that on the footwall (20°). It is suggested that the penultimate event occurred along the F2 strand, and some amount of displacement might also have occurred along F2 strand during the latest event on F1 strand. The penultimate event occurred after the deposition of the Sand layer and before the deposition of unit 5. The F3 strand, exposed in the southern part of the trench, displaces the Gravel-2, Silt,

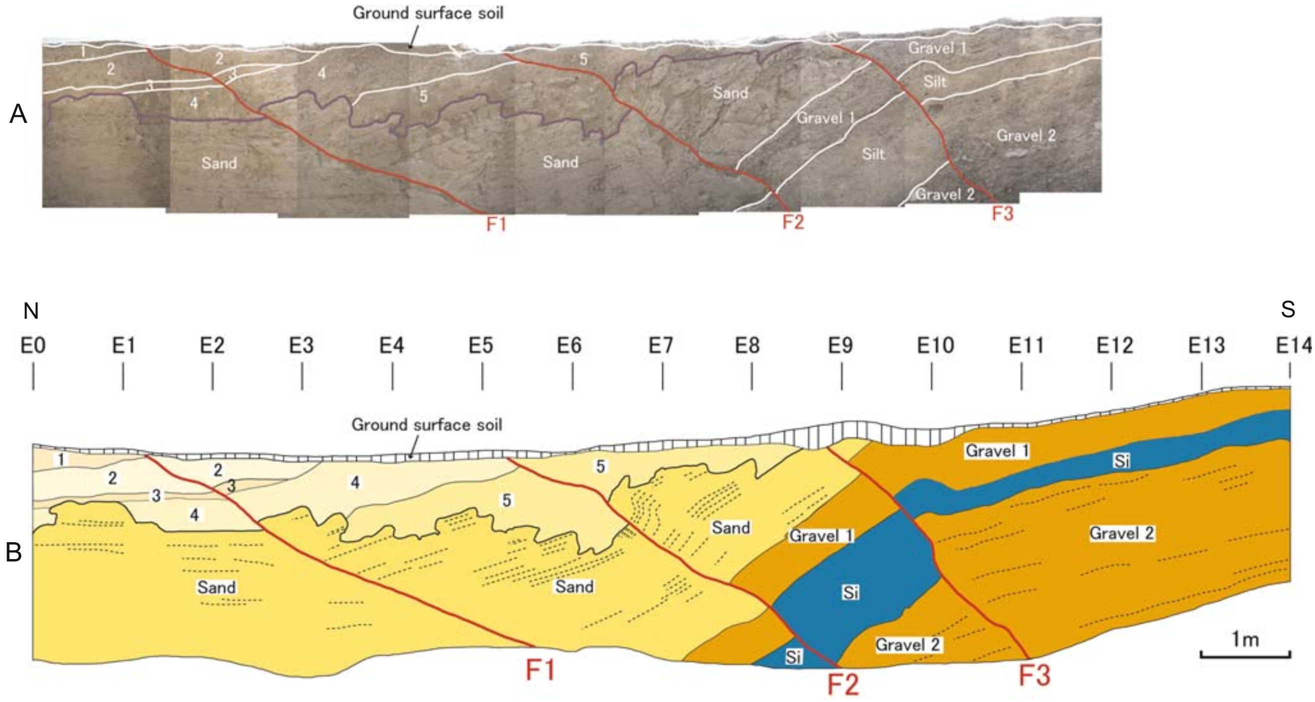

Figure 4. **(A)** Mosaic photo and **(B)** logging of eastern wall of the trench excavated across a low scarp on the terrace surface at Wandhay site (see figures 1 and 2A for location). Terrace deposits are composed of Sand, Gravel-1, Silt, and Gravel-2 layers. These terrace deposits are covered by younger Quaternary deposits. See text for details.

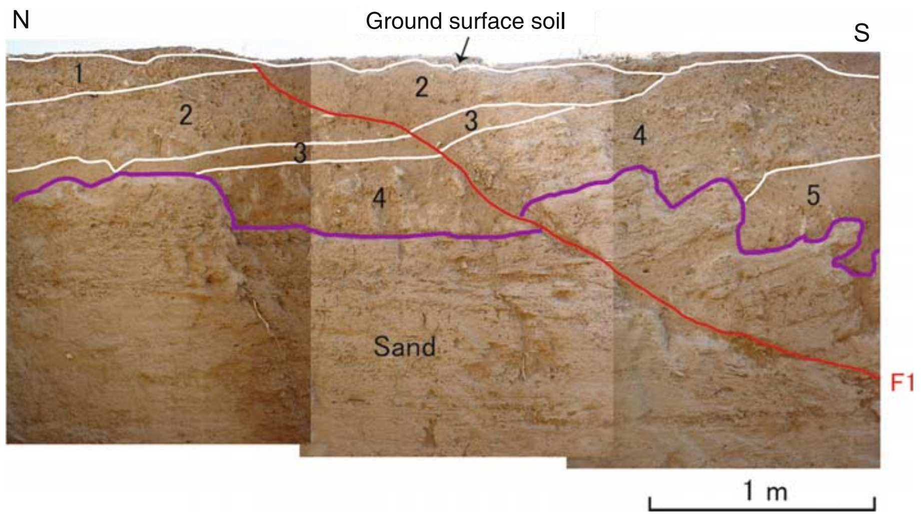

Figure 5. Close-view of F1 strand cutting the Sand layer of the terrace deposits along with the younger deposits units 1 to 4, and is covered by the ground surface soil. Sand layer and units 1 to 4 on the footwall are marked by undisturbed horizontal stratification. On the other hand, Sand layer and units 2 to 5 on the hanging wall are inclined towards north with inclination of 20°.

Gravel-1, and Sand layer and represents the older event (figures 4 and 7). The total displacement of Gravel-2 layer along F3 fault is about 60–70 cm. This displacement is more than two times compared to the displacement of Gravel-1 layer, which is about 30 cm. The thickness of Silt layer is about 60–70 cm on the footwall, whose thickness is almost twice that of Silt layer on the hanging wall which is about 20–30 cm (figures 4 and 7). This means that another older event took place after the deposition of Gravel-2 layer, and before the deposition of Silt layer. The Silt layer has covered the fault scarp formed as a consequence of the older event. Further it is suggested that the F3 strand moved after the deposition of the Silt and Gravel-1 layers. This suggests that movement may have occurred along

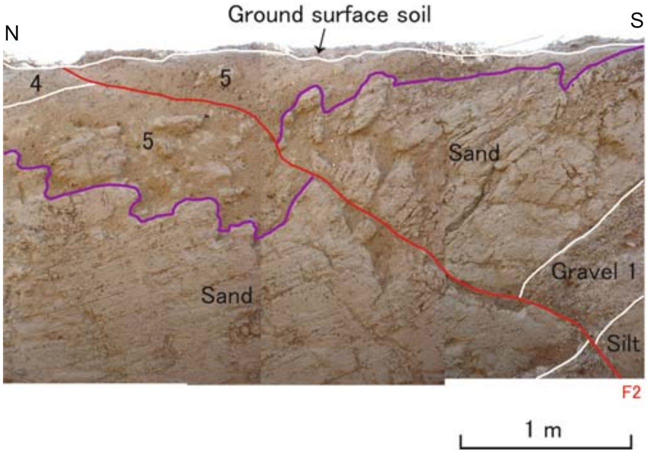

Figure 6. Close-view of F2 fault strand cutting Silt, Gravel-1 and Sand layers of the terrace deposits along with the younger deposits units 4 and 5, and is covered by the ground surface soil. The terrace deposits are highly deformed and rotated. See text for details.

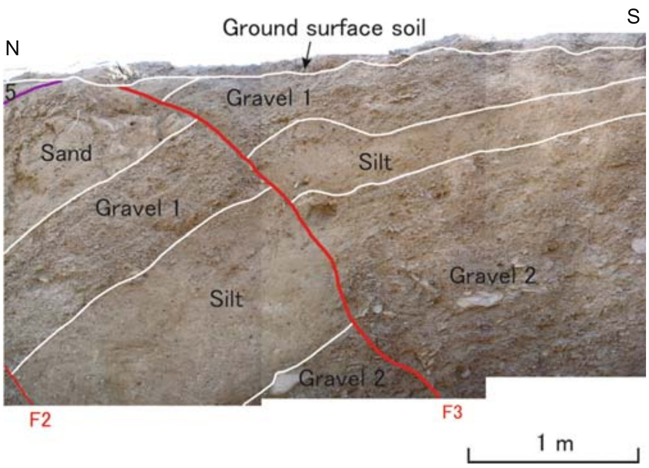

Figure 7. Close-view of F3 fault strand displacing Gravel-2, Silt, Gravel-1, and Sand layers of the terrace deposits. Note that the displacement of the Gravel-2 layer is almost double than that of the Gravel-1 layer. See text for details.

F3 strand during the penultimate event along F2 strand.

The inferred deformation pattern along the faults (F1, F2 and F3) coupled with their stratigraphic and time relationship indicates at least 3 major seismic events.

4. Discussion and conclusion

- The fault traces identified by us in the western part of KHF is broadly consistent with those predicted by the previous workers. However, new active fault traces were recognized about 1 km north of the topographic boundary between Katrol Hill and the plain area (figure 1). The topographic boundary probably represents the eroded scarp. The fault exposure along the left bank of the Khari River near Wandhay Dam suggests that the old fault was reactivated. This is well revealed by 10 m wide highly sheared zone made up of Upper Jurassic and Lower Cretaceous rocks, and also the older Quaternary succession riding over the young Quaternary terrace and channel fill deposits.
- The newly identified Bhuj Fault, a branched-out fault of KHF, bends at Wandhay village changing its strike from E-W to NE-SW or ENE-WSW. This fault extends laterally in the ENE-WSE for about 20 km and passes through Bhuj Town till the northern fringe of Bhuj Hill, located 5–6 km north of Katrol Hill. This is indicative of the active foreland migration of KHF. Since the Bhuj Fault shows left stepping pattern, it may be a reverse fault with a right-lateral slip component. Bhuj Fault further extends towards NE or ENE direction.
- Trench investigation carried for the first time across the KHF revealed occurrence of at least three large magnitude seismic events during geologic past. These events occurred along 3 major fault strands: F1, F2 and F3 representing the latest, penultimate and the older than penultimate events respectively. The pattern of deformation was clearly revealed by the displaced terrace units as well as the overlying younger channel-fill deposits. The loose unconsolidated sediments and fault scarps developed on the alluvial-colluvial fan surfaces possibly suggest that these faulting events had occurred during late Holocene or recent historic past. Dating of these horizons will be of immense help to establish the time relationship between the major seismic events in the KHF. The samples for Optically Stimulated Luminescence (OSL) dating have been collected and are in process.

We confirm for the first time the occurrence of active faults along KHF system. Our data will form the basis of further detail paleoseismic investigations and seismic hazard evaluation in the Kachchh region.

Acknowledgments

The authors are thankful to Rajesh Kishore, Chief Executive Officer, GSDMA, for his permission to publish this work. The authors are grateful to Dr. B K Rastogi, Institute of Seismological Research, and Dr. Alpa Sheth, VMS Consultants Private Limited, for the discussion on this study. The authors appreciate valuable suggestions and discussion by Dr. S K Biswas in the field at Wandhay trench site.

References

Bilham R 1998 Slip parameters for the Rann of Kachchh, India, 16 June 1819 earthquake quantified from contemporary accounts; In: *Coastal Tectonics* (eds) Stewart I S and Vita-Finzi C, *Geol. Soc. London Spec. Publ.* **146** 295–319.

Biswas S K 1980 Structure of Kutch-Kathiawar Region, Western India; *Proc. 3rd Ind. Geol. Congr. Pune* 255–272.

Biswas S K and Deshpande S V 1970 Geological and tectonic maps of Kutch; *Bull. Oil Nat. Gas Comm.* **7** 115–123.

Chung W-Y and Gao H 1995 Source parameters of the Anjar earthquake of July 21, 1956, India, and its seismotectonic implications for the Kutch rift basin; *Tectonophys.* **242** 281–295.

Johnston A C and Kanter L R 1990 Earthquakes in stable continental crust; *Scientific American* **262** 69–75.

Malik J N, Sohoni P S, Merh S S and Karanth R V 2001a Active Tectonic control on Alluvial fan Architecture along the Kachchh Mainland Hill Range, Western India; *Zeithschrift für Geomorphologie* **45(1)** 81–100.

Malik J N, Nakata T, Sato H, Imaizumi T, Yoshioka T, Philip G, Mahajan A K and Karanth R V 2001b January 26, 2001, the Republic Day (Bhuj) earthquake of Kachchh and active faults, Gujarat, western India; *Active Fault Research* **20** 112–126.

Mandal P and Horton S 2007 Relocation of aftershocks, focal mechanisms and stress inversion: Implications toward the seismo-tectonics of the causative fault zone of M_w 7.6 2001 Bhuj earthquake (India); *Tectonophys.* **429** 61–78.

Mathew G, Singhvi A K and Karanth R V 2006 Luminescence chronometry and geomorphic evidence of active fold growth along the Kachchh Mainland Fault (KMF), Kachchh, India: Seismotectonic implications; *Tectonophys.* **422** 71–87.

McCalpin J P (ed) 1996 *Paleoseismology*; (New York: Academic Press) p. 588.

Morino M, Malik J N, Mishra P, Bhuiyan C and Kaneko F New active fault in and around Bhuj town, Kachchh, Gujarat, India; *EOS Trans. Am. Geophys. Union* (communicated).

Quittmeyer R C and Jacob K H 1979 Historical and modern seismicity of Pakistan, Afghanistan, North-western India and South-eastern Iran; *Bull. Seismol. Soc. Am.* **69** 773–823.

Rajendran C P and Rajendran K 2001 Characteristics of deformation and past seismicity associated with the 1819. Kutch earthquake, northwestern India; *Bull. Seismol. Soc. Am.* **91** 407–426.

Sohoni P S, Malik J N, Merh S S and Karanth R V 1999 Active tectonics astride Katrol Hill Zone, Kachchh, Western India; *J. Geol. Soc. India* **53** 579–586.

MS received 25 September 2007; revised 6 January 2008; accepted 14 January 2008