Terrain response to the 1819 Allah Bund earthquake in western Great Rann of Kachchh, Gujarat, India

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We report here the development of a drainage network following the 1819 Allah Bund earthquake in the western Great Rann of Kachchh. The juvenile nature of the drainage network, particularly along the scarp, indicates that earth surface processes have not yet attained equilibrium with the base level even after 200 years. Hence it serves as an ideal model of resurrection of topography dominantly controlled by the tectonics. Another important observation has been the identification of a submerged/subsided tax collection port around 60 km southwest of Sindri. Optical dating of pottery indicates that the subsidence is coeval with that of the Sindri fort. This would imply that during 1819 there were two subsiding areas separated by a marginally high land mass (Sunda high). In the absence of detailed structural data, a preliminary inference has been drawn based on field and satellite data. It suggests flexure folding of the footwall during the 1819 earthquake.

Keywords: Allah Bund, Basta Bunder, coseismic subsidence, drainage network, terrain resurrection.

THE Kachchh rift basin is passing through the rift reversal phase in response to the compressive stresses active on Indian plate[1]. The salt-encrusted terrain known as Ranns of Kachchh are recent depositional basins within the structural depressions resembling half graben formed during the later phase of uplift[2,3]. The Ranns existed as a shallow embayment and inlets of the sea from the Tertiary until Recent[4–6]. Nevertheless, in the last 2 ka, silting of the area, probably accompanied by elevation of the land has converted the marine embayment into dry salt-covered mud flats slightly above the tidal range of the Arabian Sea[7]. The present observations pertain to the geomorphological changes that have occurred after the 1819 earthquake in the western Great Rann (Figure 1). We have attempted to find a mechanism that could be responsible for regional topographic changes in a single earthquake of large magnitude in intra-plate settings and the response of erosion over the rejuvenated landscape.

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There are historical evidences to suggest that the Great Rann witnessed moderate to strong earthquakes. For example, earthquakes of AD 893 and AD 1668 were reported to be severe, which occurred to the north and northwest of the Great Rann in Sind area, Pakistan[8,9]. Their impact on the terrain morphology is still uncertain. Compared to this, the 1819 Allah Bund earthquake estimated to be of M_w 7.9 that occurred within the western Great Rann, uplifted the 80 km long and 16 km wide region of the Rann[8,10–12]. It has uplifted the Rann sediment to variable heights (3–6 m) and obstructed the Nara River till 1826 (refs 9 and 11). Besides causing large-scale devastation in the Kachchh region, a coseismic Sindri depression was created against the uplifted land mass which led to the submergence of the Sindri fort[9] (Figure 1). During monsoon, the depression is inundated by sea water pushed inland by the storm-induced tides of the Arabian Sea from the west and southwest. Frequent inundation and evaporation led to the formation of vast salt-encrusted land masses[10,13]. The only detailed description on the post-1819 earthquake-induced landform changes was attempted by Rajendran and Rajendran[9] with emphasis on the scarp morphology and seismically induced deformations.

In this communication, we have studied the evolution and modification of the drainage network in the vicinity of Allah Bund scarp and ascertained the regional impact of the 1819 earthquake, particularly on the less studied southwestern part, viz. the Kori Creek area (Figures 1 and 2). Carless[14] surveyed the area between Koteshwar and Lakhpat and concluded that compared to the mainland Kachchh, the Kori Creek (deltaic area) was depressed after the 1819 Allah Bund earthquake. He also mentioned two ruined forts; one proximal to Lakhpat was attributed to the 1819 earthquake, whereas the other lying at the western bank of Kori Creek called the Basta Bunder was destroyed prior to the 1819 earthquake. A systematic study is warranted in the Kori Creek that lies ~60 km southwest of the Sindri depression to understand the style of deformation and extent of the 1819 earthquake-induced landform changes (Figure 1).

The south-facing Allah Bund scarp owes its genesis to the north-dipping thrust that was activated during the 1819 earthquake[9,15,16]. The northern hanging wall is dominated by young gullies and ravines, whereas the southern footwall is frequently occupied by marine ingression during monsoon (Figure 2). Some of the streams follow the regional tilt (towards north), but majority of them tend to incise the uplifted scarp in order to meet the Nara River bed. The Nara River has attained the local base level of the Sindri depression over the last 200 years. Compared to this, the juvenile streams are still in the process of attaining the equilibrium profile of the 1819 uplifted terrain. Further, based on the headward extent of incision, we could demarcate the northern limit of coseismic uplift, which seems to vary between 3 and

Figure 1. Location and physiographic map of the study area showing a part of the western Rann of Kachchh that was affected by the 1819 Kachchh earthquake and generated large-scale coseismic features that modified the topography of the Rann and the western creek area of Kachchh. Note a channel of Indus known as Nara River abuts at the coseismic uplift of Allah Bund. Sunda is an upwarped region between two coseismic depressions of Sindri in the northeast and Basta Bunder in the southwest.

13 km (Figures 2 and 3 *b*). Our indirect estimate based on the extent of headward erosion compares well with the levelling survey data of Rajendran and Rajendran[9], but is at variance with the estimate of the 16 km wide zone[10,12]. The dominant northward tilt is also seen in the sediment strata exposed near the Nara River channel (Figure 3 *a*).

We also performed the drainage density analyses, which are used as a surrogate for terrain maturity/youthfulness. The drainage density is usually low in the arid and semi-arid regions[17]. Therefore, in principle, a terrain like the Great Rann should have low drainage density. Instead, we observed moderately high density (14 km/km^2) around the Allah Bund scarp region, implying that the terrain was rejuvenated in the recent times. We also observed few scarp-parallel drainages flowing from east to west along the scarp crest (Figure 2). Such anomalous deflection of the stream course has been attributed to the high rate of structural uplift relative to erosion rates. In such cases, transverse rivers tend to deviate the rising land mass rather than cutting across it[18,19]. Sediment incision rate is governed by the base-level change caused due to climate and tectonics[20]. Assuming that during the last 200 years rainfall has not changed from the present-day rainfall[21] of 200–380 mm, the incision would largely be governed by the tectonically induced relief changes. Since the optical and radiocarbon ages[22] of the uppermost incised Rann sediment are around 2 ka years, we assume that incipient drainage incision was largely after the 1819 earthquake around the scarp. Thus, we consider that the observed incision happened during the last 200 years, which is around 100 cm, i.e. around 0.5 cm/yr. This appears quite high as the streams are yet to attain the local base level, implying that in a tectonically active terrain, incision probably is an ongoing process like Himalaya[18].

Archaeological evidences suggest that the western Great Rann was a hospitable terrain in the past[14,22]. Sites proximal to the streams that were flowing into the Great Rann from the Indus floodplain were being meticulously selected by the historical people. Near Karim Shahi, the archaeological site dated to 3000 yrs BP and now located

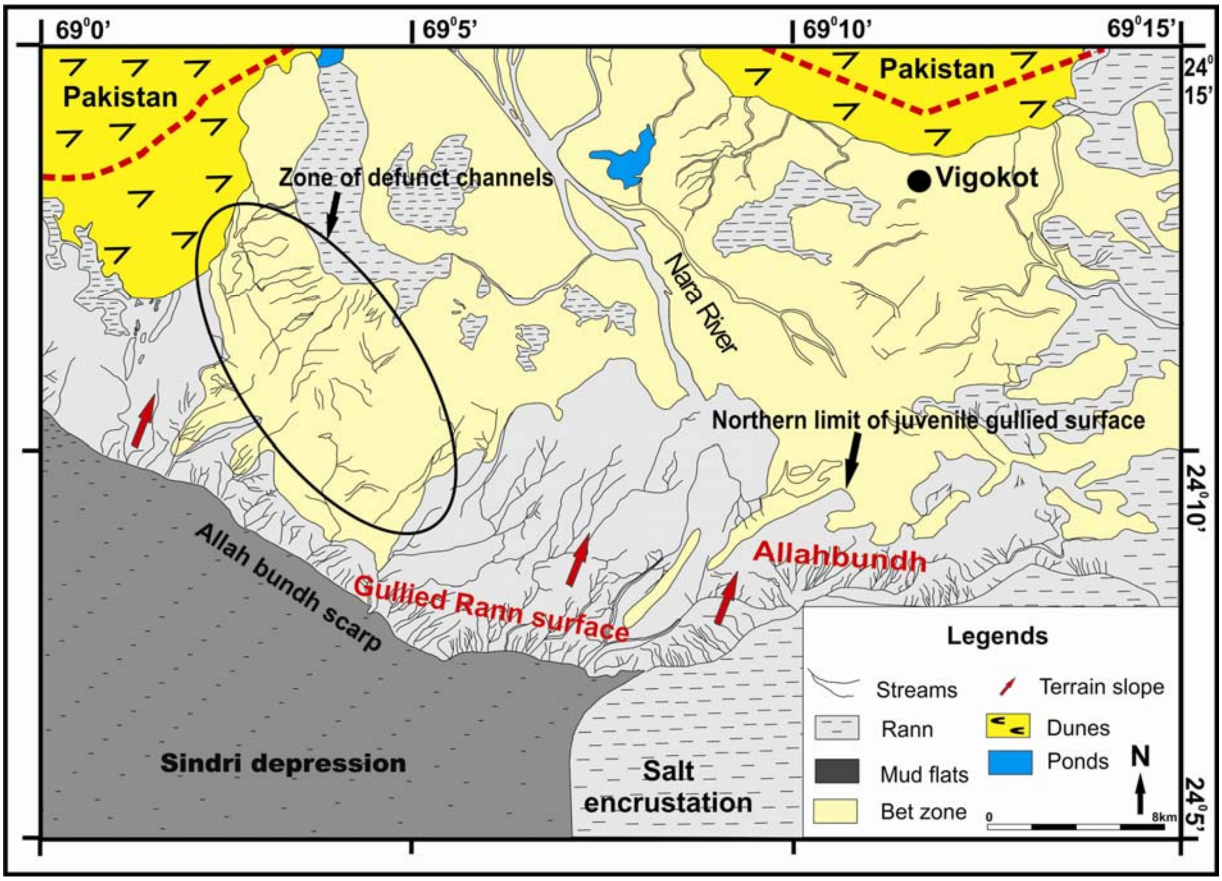

Figure 2. A close view of the topographic expression of coseismic uplift of Allah Bund illustrates juvenile streams flowing to the north from the gullied surface of the Allah Bund ridge and merging with the northern bet zone, while Nara River, a distributary of the Indus flows to the south on the pre-1819 slope. Note the zone of defunct channels in response to the 1819 coseismic uplift to the west of Nara.

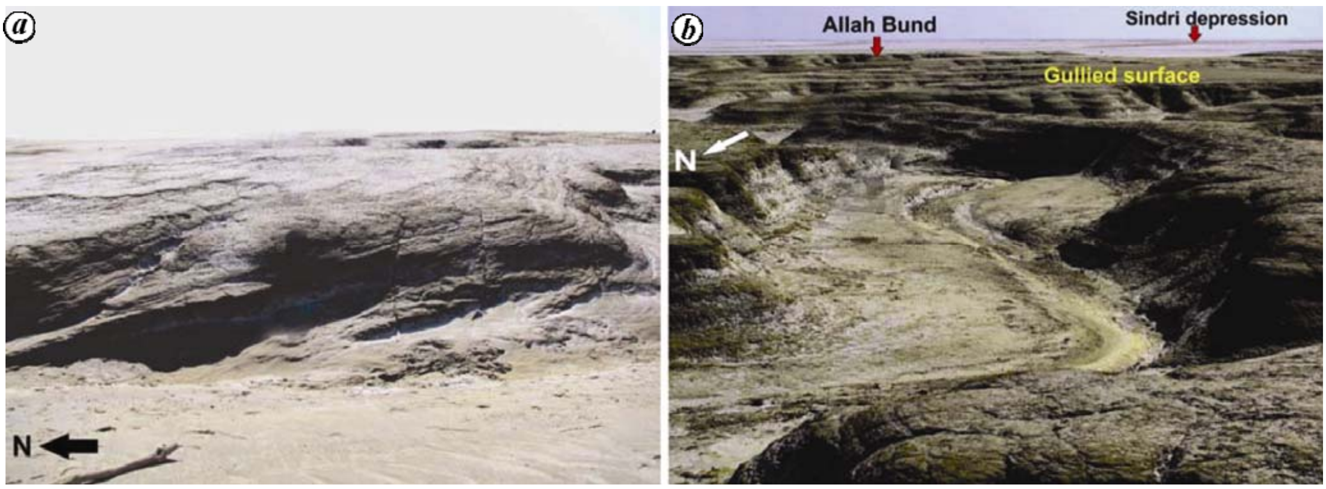

Figure 3. ***a***, North-dipping uplifted Rann sediments near the northern margin of the Allah Bund uplift axis. This is a major channel of Nara that incises the Allah Bund surface intermittently during major flooding in the north. ***b***, Southwest-facing view of juvenile Rann surface marked in Figure 2, showing distinct embryonic gullies against the Sindri depression.

proximal to the line of present-day tidal inundation[22] is not a favourable location for human habitation. That is because historical evidence suggests that prior to the 1819 Allah Bund earthquake, large tracts of land NE of Kori Creek were above high tide level. After the 1819 earthquake, the terrain north of Kori Creek seems to have subsided by about 1–5 m, leading to the creation of the Sindri basin[23]. The archaeological site is located towards the northern margin of the subsided Sindri basin. Hence, we attribute its present elevation to the coseismic subsidence caused during the 1819 earthquake.

Another major observation was the identification of the ruined fort first reported by Carless[14], called the Basta Bunder, located ~25 km northwest of Koteshwar across the Kori Creek (23°51′44.44″N, 68°30′16.36″E; Figures 1 and 4 *a*). The ruins of the fort are preserved in the form of pentagonal walls protruding 20–40 cm above the tidal mud flat of Padala Creek (Figure 4 *a*). The ruins get flooded during spring tide. The preserved wall structure indicates that the fort was made up of polygonal, five-walled structure consisting of six bastions and one gate 5 m wide in the western wall. The northern wall was longest (96 m) with kiln-like structure in the middle; the eastern wall was 76 m long with a bastion of 10 m diameter; the southeastern wall was 33 m long with two bastions of 10 and 12 m diameter at each end. The southern wall is completely collapsed, however a linear (92 m long) stone foundation with cut bricks can be seen, joining the SW bastion that is 20 m in diameter (Figure 4 *b*). The dimensions of the bastions and gate, thickness of the walls suggest that it was a robust structure comparable to its modern counterpart at Lakhpat. Carless[14] attributed its destruction to a pre-1819 earthquake event whereas Lylle[13] suggested that it was destroyed during the 1819 coseismic subsidence that lowered it to the range of high tide (Figure 4). The optical date obtained on the potsherd collected from Basta Bundar gave an age of 214 ± 20 yrs. Within error, the age broadly correlates with the 1819 earthquake and supports the suggestion of Lylle[13]. We attribute its destruction to the coseismic subsidence along with the Sindri fort after the 1819 earthquake. In view of this finding, we hypothesize that there was a complex subsidence mechanism involved during the 1819 earthquake. There were two major subsidences (Sindri in the NE and Basta Bunder in the SW) separated by a marginal uplift around Sunda (Figure 1). The above deformation can be explained by invoking a SW to NE (oblique) compression (along two points A and B in Figure 1).

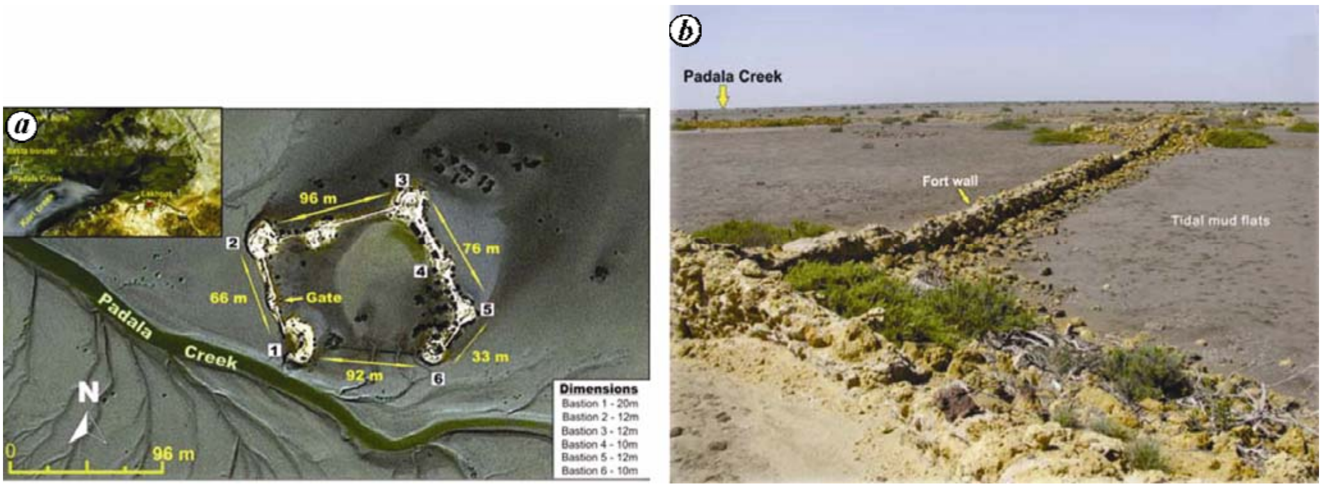

Figure 4. ***a***, Satellite photograph of the location of Basta Bunder within the tidal mud flats of the western Kachchh Creek zone (inset). The dimensions of six bastions and lengths of pentagon-shaped geometry of the fort walls at the bank of the Padala Creek are also shown. ***b***, Remains of fort wall elevated only a metre from the tidal mud flats. Note the wall is mostly made up of yellow-coloured Tertiary limestone locally available near Lakhpat.

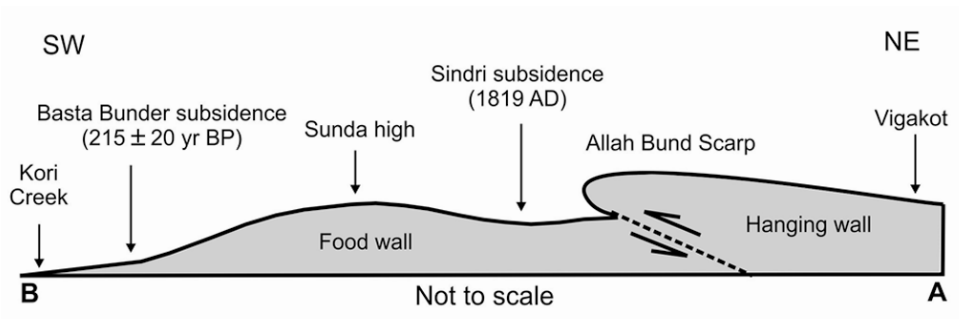

Figure 5. Schematic diagram of a cross-section from Allah Bund to Kori Creek (points A to B in Figure 1) showing a major coseismic uplift of Allah Bund accompanied by subsidiary buckling of Sindri depression and Basta Bundar subsidence separated by the Sunda uplift.

This would have caused flexure buckling near the thrust plane (Sindri fort subsidence), while upwarping southwest of Sindri caused the Sunda high and downwarping towards the southwest caused the Basta Bunder subsidence (Figure 5). This is only a preliminary interpretation; a detailed structural analysis is in progress.

Our preliminary observations in the western Great Rann indicate that the earth surface processes are in the embryonic stage. We have not mapped the lateral variability of the 1819 scarp, but field observations indicate that it was not more than 4 m. Considering the work of Rajendran and Rajendran[9], we have no estimate of how much scarp height was inherited from the older event. The study suggests that even in arid and semi-arid areas one can have high juvenile stream concentration provided the terrain is tectonically active. Assuming that majority of the streams emerged after the 1819 earthquake (a reasonable assumption considering the stream morphology and location), significant incision was observed, which we attribute to the relief factor. Our study shows that there was coseismic subsidence concurrent with the Sindri fort in the areas around the Kori Creek that led to the submergence/subsidence of Basta Bunder. We suggest a flexure buckling of silty clay-dominated Rann sediment – a hypothesis that needs to be verified. The study provides a renewed stimulus for carrying out detailed morphotectonic study in the western Great Rann for a better understanding of one of the major earthquakes and its impact on the earth surface processes.

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