Eight Days in Bhuj: Field Report Bearing on Surface Rupture and Genesis of the 26 January 2001 Earthquake in India

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INTRODUCTION

The M_w 7.6 Bhuj (Republic Day) earthquake in India occurred in the morning of 26 January 2001, resulting in nearly 20,000 deaths. The event occurred away from a plate boundary and is a possible analog to intraplate earthquakes such as those of the New Madrid and Charleston regions of the eastern United States. We visited the epicentral area for eight days between 11 and 18 February. The purpose of our visit was to characterize surface ruptures associated with the earthquake, examine the region for evidence of longer-term tectonic activity, and place the location and mechanism of the earthquake into the context of the regional geology. We report here observations and impressions arising from our brief visit, with the aim of documenting our efforts to record surface rupture as well as providing a starting point for field investigations by others that may follow. Toward that end, we also draw on published literature that came to our attention subsequent to our return.

PLATE TECTONIC, REGIONAL GEOGRAPHIC, AND GEOLOGIC SETTING

The USGS National Earthquake Information Center places the epicenter of the Bhuj earthquake in northwestern India at 23.40°N latitude and 70.32°E longitude. The epicenter sits within a zone of diffuse seismicity that extends southeastward and into the Indian Plate from the Eurasian, Arabian, and Indian Plate triple junction, which is located near the city of Karachi, Pakistan (Figure 1).

The Bhuj earthquake may reflect reactivation of older structures. Plate tectonic reconstructions show that the Indian subcontinent split from the larger supercontinent of Pangaea during Permian to Triassic (Biswas, 1982) and migrated north through equatorial latitudes until colliding with the Asian continent in the Eocene (Figure 2A). The process of rifting is of some import to understanding the setting of the Bhuj earthquake. The break-up of continents and continental drift is initiated by the formation of multilimbed rifts that ultimately coalesce into spreading centers (Dewey and Burke, 1974; Figure 2B). A number of the early rifts ceased to be active and are not incorporated into the spreading centers that ultimately separate the continents. These early failed rifts are commonly preserved at the edges of continents (Figure 2C). Today these failed rifts are filled with sediments of ages that approximately coincide with the initiation of rifting and early stages of spreading. Rocks exposed in the epicentral region of the Bhuj earthquake are generally Mesozoic (Figure 3) and have been interpreted to mark deposition in rifts that date to or to relatively soon after the break-up of India with Madagascar and Africa (Biswas, 1980; Biswas, 1982). The epicenter of the Bhuj earthquake sits structurally within the Kutch[5] rift.

The geological and structural observations of the epicentral area summarized in the map and cross-sections shown in Figures 3 and 4 are adapted from Biswas (1980, 1982, 1987), Biswas and Deshpande (1983), and Merh (1995). The epicenter is located on the Kutch mainland, which sits between the Great Rann of Kutch to the north and the Gulf of Kutch to the south. The Great and Little Ranns of Kutch are areas of playa or salt flat. During the summer monsoon the Ranns typically flood and the Kutch mainland is then an island. A number of highlands to the north also rise above the level of the Great Rann. The city of Rapar sits upon the largest of these, the Wagad highland.

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5. The name Kutch is now spelled as "Kachchh" on topographic sheets of the Survey of India. The older spelling of Kutch appears commonly in the literature and often is still used by state governments and agencies. The old spelling is used here.
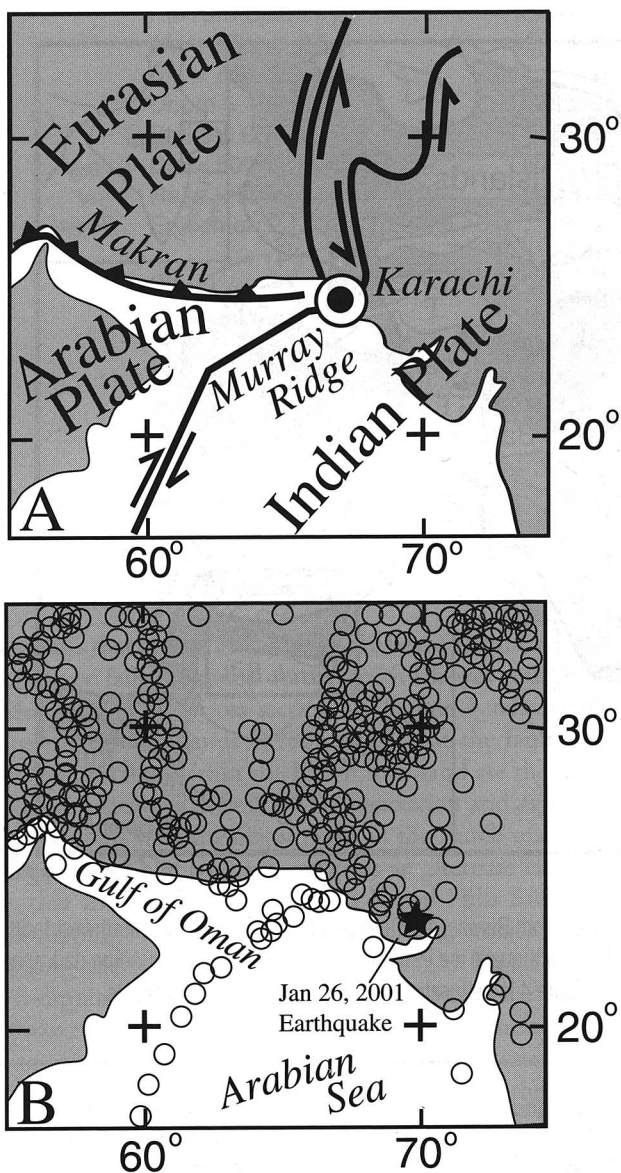
▲ **Figure 1.** (A) Plate tectonic setting and (B) epicenter (solid star) of the Bhuj earthquake in context of seismicity (circles) recorded by National Earthquake Information Center during the period of 1977 to 1997.

Stratigraphically, the region is characterized by a ~5,000 m thick sedimentary sequence (Figure 3). The oldest rocks are Mesozoic (lower Jurassic to middle Cretaceous) sandstones of marine and fluviatile origin which reportedly sit unconformably on Precambrian basement. The Mesozoic sandstones are overlain by upper Cretaceous to Paleocene basalts of the Deccan Trap formation. The Deccan volcanics are generally capped by a laterite weathering horizon of Paleocene age, presumably formed while India migrated through equatorial latitudes (Figure 2). Younger Tertiary marine and fluviomarine beds of Eocene to Pliocene age rest unconformably on the Deccan basalts. Younger Quaternary deposits include fan gravels, aeolian deposits, and fine-grained basin-fill deposits of the Rann.
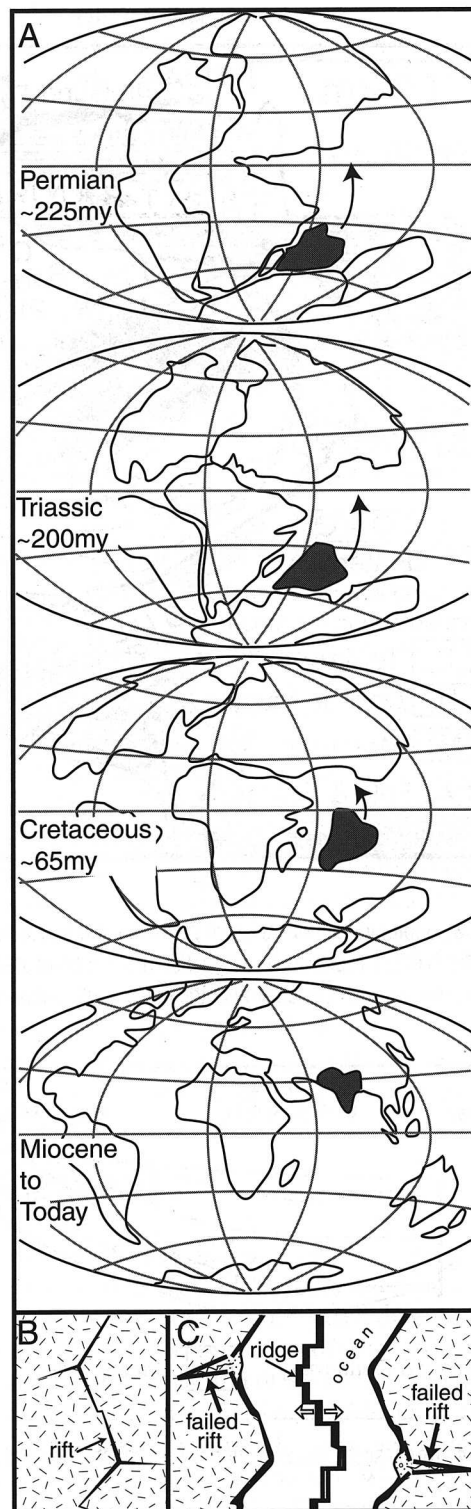
▲ **Figure 2.** (A) Schematic diagram of break-up of Pangaea in Permo-Triassic and subsequent northward migration of India until collision with Asian continent in Eocene. (B) Continental break-up and drift is initiated by the formation of multilimbed rifts that ultimately coalesce into spreading centers. (C) Failed rifts are those that cease to be active and are commonly preserved at the edges of continents. The Bhuj earthquake occurred within a rift that formed during or soon after the initiation of spreading (modified from Dewey and Burke, 1974).
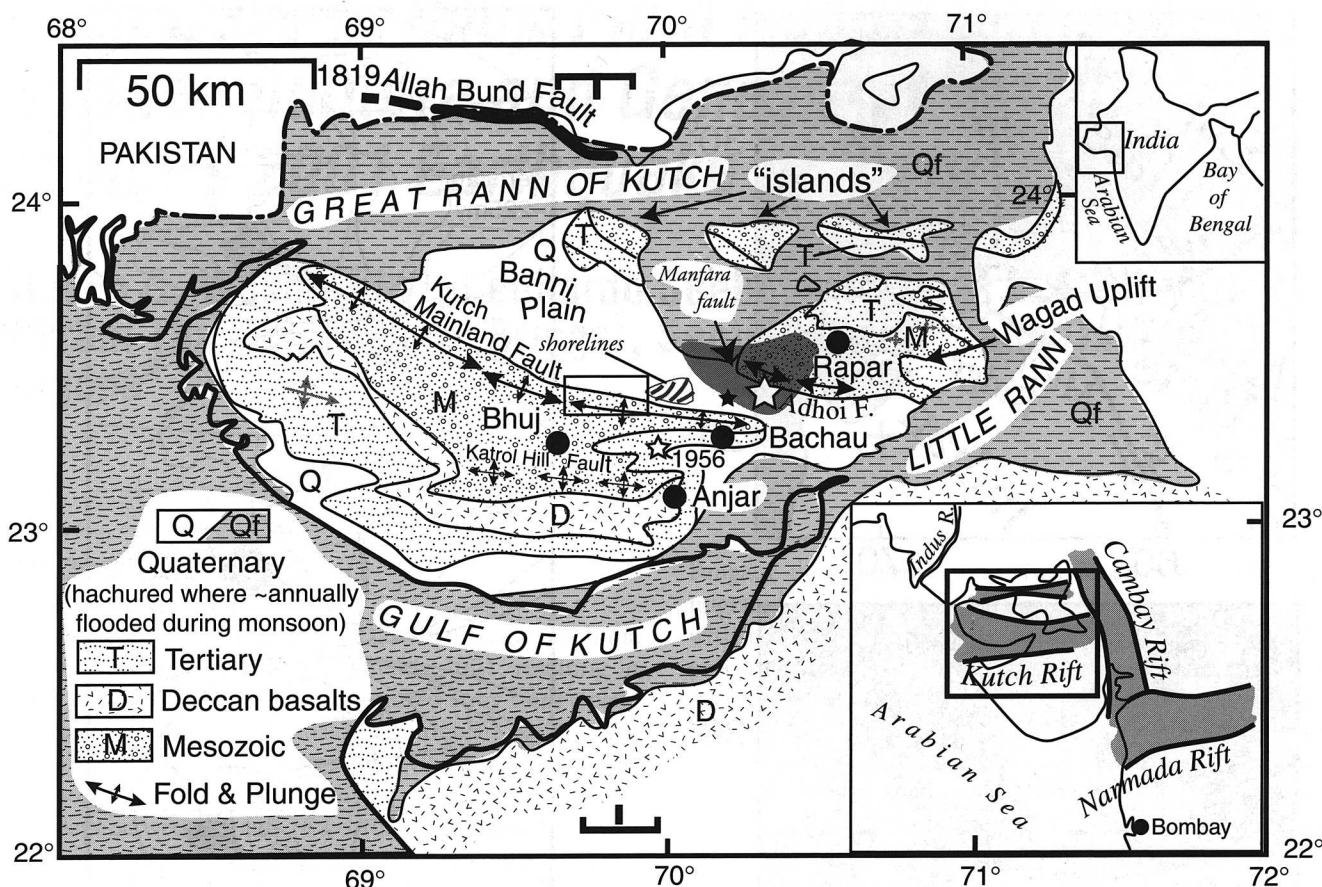
▲ **Figure 3.** Geologic map of the Kutch mainland and surrounding areas (modified from Biswas, 1980). Insets show region sits in northwest India and within the Kutch Rift. The epicenter and spatial distribution of aftershocks of the Bhuj earthquake are indicated by large star and surrounding dark shading, respectively. The approximate location of the north-south cross-section shown in Figure 4 is delineated by large opposite-facing brackets.
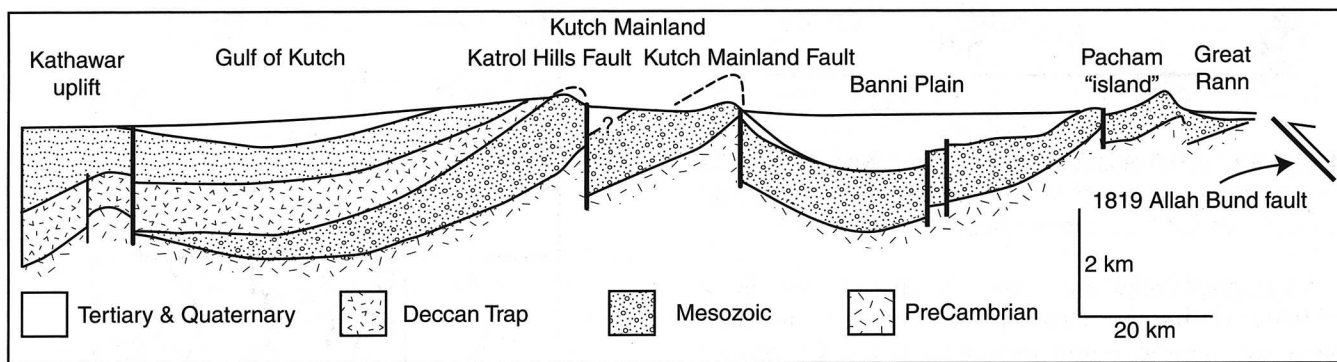
▲ **Figure 4.** North-south cross-section across Kutch mainland adapted from Biswas (1987). Approximate location shown in Figure 3.

The Kutch mainland is characterized by a relatively linear northern margin that is bounded by the Kutch Mainland Fault (Figure 3). A long and narrow, asymmetric north-verging anticline occurs along and immediately south of the Kutch Mainland Fault and is structurally responsible for the Northern Hill ranges, which reach to several hundred meters elevation. Southward, rocks are generally characterized by shallow, southerly dips and semiarid plains and hills of 100 to 200 m average elevation dropping gradually into the Gulf of Kutch, except where disrupted by the Katrol Hill Fault and anticline which strike westward from Anjar. In contrast to the Kutch mainland, the Wagad highland is bounded on its southern edge by a fault, the Adhoi Fault. The Wagad highland is characterized by a more domal uplift and by beds that generally dip shallowly to the north over most of the region and steeply on the southern border of the anticline.

Harvard Solution
M_O = 3.6 exp 27
M_W = 7.6
Depth = 18 km
Strike = 65°
Dip = 50°
Rake = 50°
Epicenter: 23.45°N 70.34°E

Tokyo Solution
M_O = 2.9 exp 27
M_W = 7.6
Depth = 10 km
Strike = 78°
Dip = 58°
Rake = 81°

NEIC Solution
M_O = 2.3 exp 27
M_W = 7.5
Depth = 17 km
Strike = 60°
Dip = 50°
Rake = 62°
Epicenter: 23.40°N 70.32°E
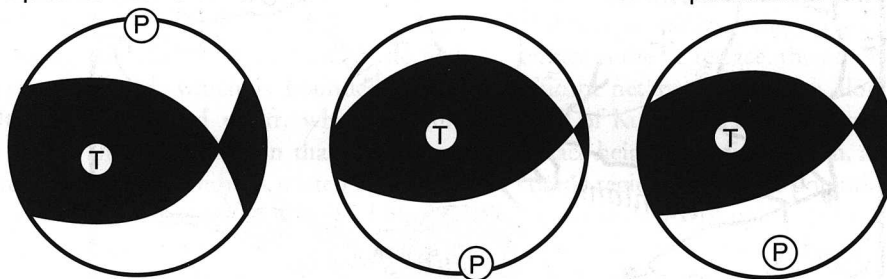
▲ **Figure 5.** Focal mechanisms and source parameters of the Bhuj earthquake reported by Harvard, the Earthquake Research Institute of Tokyo, and the USGS National Earthquake Information Center.

The uplifts that appear as islands in the Great Rann are interpreted to be fault-bounded on the north (Biswas and Deshpande, 1983). The cross-section in Figure 4 reflects the interpretations of Biswas (1980, 1987) that the faults and observed structure within the Kutch mainland are the result of slip on quasivertical faults. The association and asymmetry of the folds with the major faults in the Kutch mainland and the Wagad highland suggest to us an alternate explanation, that the Kutch Mainland and Katrol Hills Faults are south-dipping thrusts and, similarly, that major faults bounding the southern edge of the Wagad highland are north-dipping thrusts. The Allah Bund Fault sits at the northern edge of the Great Rann and produced surface rupture or warping during an earthquake in 1819. Recent analyses of the surface deformations produced by the 1819 earthquake imply the causative fault is a north-dipping thrust (Bilham, 1998; Rajendran and Rajendran, 2001). In summary, the orientation of east- to southeasterly-striking thrust faults and fold axes indicates that a northerly contraction of the region occurred post-Mesozoic. We are aware of no explanations that explicitly address the timing and processes responsible for initiation of the northward contraction of Kutch Rift sediments. A major question remains as to whether or not the contractional features observed in the bedrock are remnants from an earlier deformation event or reflect a process that continues today.

EARTHQUAKE HISTORY AND PARAMETERS

Focal mechanisms for the Bhuj earthquake consistently indicate thrust motion on easterly-striking nodal planes, and seismic moment estimates for the event are about 3×10^{27} dyne-cm (Figure 5). Rapid postearthquake aftershock studies by the Center for Earthquake Research and Information delineate an aftershock zone that dips southward between depths of about 10 and 25 km (http://www.ceri.memphis.edu/~withers/Gujarat/). The surface projection of the aftershock distribution is shaded in Figure 3.

Two large historical events have occurred in the immediate vicinity of the Bhuj earthquake. The largest is the M_w 7.8 Kutch event of 1819, which produced a large scarp or flexure along the northern boundary of the Great Rann (Figures 3 and 4). Bilham's (1998) recent analysis of historical accounts and survey lines across the Allah Bund suggests the causative thrust fault is north-dipping. The focal mechanism of the 1956 M_w 6.0 Anjar event, which occurred within the epicentral area of the Bhuj earthquake (Figure 3), showed similarly directed thrust motion (Chung and Gao, 1995). Both earthquakes produced deadly damage to structures in the vicinity of Bhuj (Bendick et al., 2001; Bilham, 1998). In sum, the focal mechanisms of all events indicate a north-south contraction of the region.

SURFACE FAULTING

Our search for surface faulting encompassed driving the roads shown in Figure 6, conducting a number of traverses by foot, and asking the local inhabitants if they were aware of ground deformations in the vicinity of their villages. There is a large region within the Rann of Kutch that we were logistically unable to reach. We are quite confident that within the vicinity of the roads we traveled there was no primary surface faulting reflecting large reverse motion. We did observe one tectonic rupture showing strike-slip motion. The location of the strike-slip fault is above the aftershock zone of the event and along the western boundary of the Wagad uplift (Figure 3).

The rupture cuts through the small town of Manfara and, for convenience, we refer to the rupture as the Manfara fault. A detailed map showing the location, geometry, and offset along the fault is shown in Figure 7. The fault strikes northwest for a distance of about 8 km, shows primarily
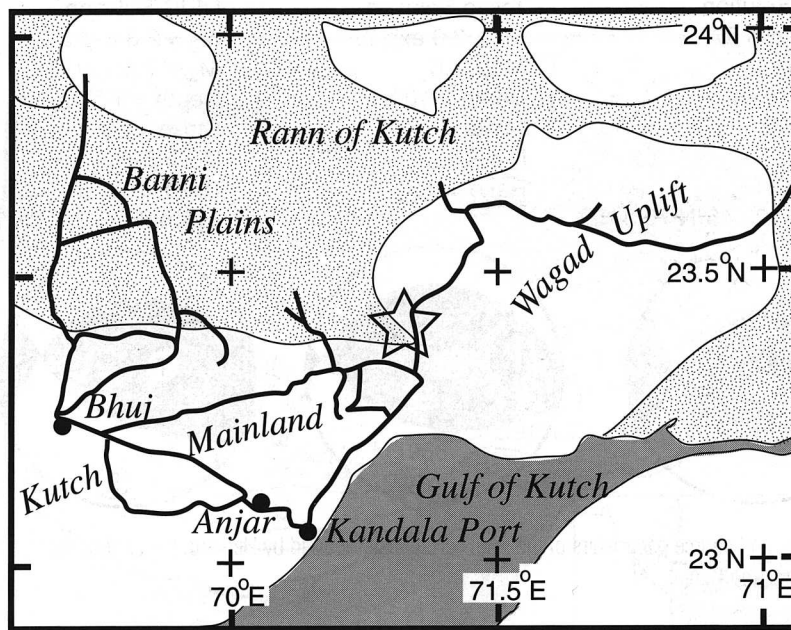
▲ **Figure 6.** The main roads traveled in search of surface rupture. Ocean and low-lying regions of playa and salt flat are shaded. Epicenter of the Bhuj earthquake denoted by open star. See Figure 3 for geologic context.
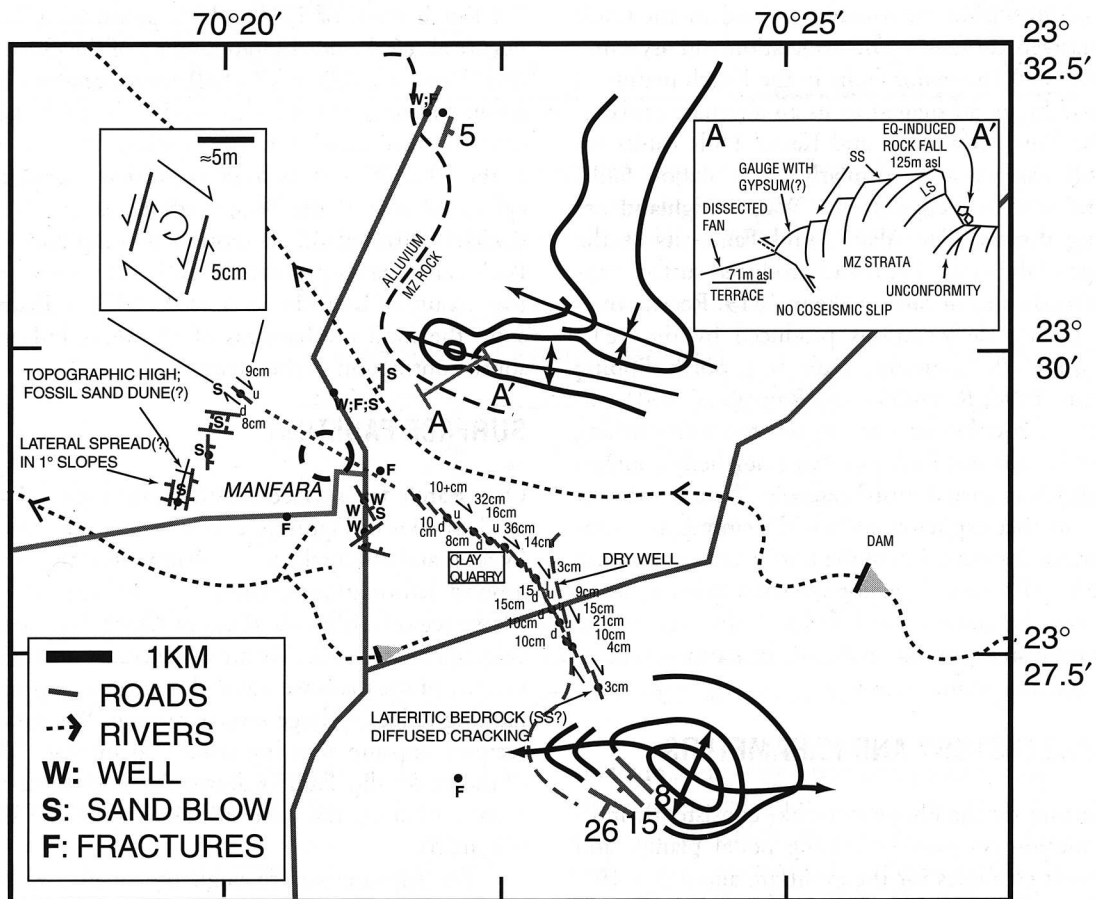
▲ **Figure 7.** Map showing location, geometry, and amounts of offset measured along the Manfara Fault. Adjacent fold and dome structures in Mesozoic bedrock denoted by thick curvilinear lines with strike, dip, and fold symbols.

right-lateral motion with up to 32 cm of slip, and locally is characterized by a zone of distributed faulting reaching 10 to 20 m in width. The fault displays geomorphology typically associated with right-lateral strike-slip faults (Figure 8). The Manfara fault appears to be reflecting coseismic deformation of the hanging wall above the main causative fault plane. The rupture is close to the boundary between bedrock exposure on the northeast and alluvium on the southwest. We observed no conclusive evidence indicating prior Quaternary movements along the fault. The location of the fault between the Kutch mainland, which is bounded on the north by a fault, and the Wagad uplift, which is fault-bounded on the south, allows speculation that the rupture occurred on a pre-existing fault, perhaps related to a structural discontinuity or tear between the two uplifted blocks.

Additionally, we encountered numerous occurrences of liquefaction and ground cracking due to liquefaction. It was beyond the scope of our effort to provide a systematic account of all such features throughout the epicentral area. One particular liquefaction feature warrants documentation because the potential exists to attribute the feature incorrectly to primary surface faulting. Within the epicentral region and above the aftershock zone, we observed a scarp about 50 cm high that strikes east-west over several hundred meters or more along strike. The scarp occurs in farm fields which have a very gentle slope of 1 to 2 degrees to the north and manifests as an asymmetric mound (Figure 9A). Vertical separation decreases rapidly southward from the scarp to virtually zero on the hanging wall. About 100 m south of the scarp, the ground is pervasively fractured by extensional faults, resulting in a miniature Basin and Range structure over tens of meters of ground surface (Figure 9B). The lack of vertical uplift between the thrust scarp and the zone of extensional faulting, the shallow level of the ground water table, and the observation that the amount of noticeable extension is qualitatively comparable to the amount of shortening reflected in the reverse scarp led us to conclude that this feature is a lateral spread. A schematic illustration of the observations and interpretation is given in Figure 9C.

ONGOING AND QUATERNARY RATES OF DEFORMATION

When considering the proximity of the Bhuj earthquake to a plate boundary and the spatial association of the zone of seismicity in which the Bhuj earthquake occurred to a nearby triple junction, the event is perhaps best described as a plate-boundary-related intraplate event. Regardless of the classification of the event, the important question that remains is whether Quaternary deposits and related geomorphic observations can be used to place quantitative limits on the rate and style of deformation in the region.

The northern shore of the Gulf of Kutch varies from quite linear in the central reach to a more irregular and embayed character to the northwest (Figure 3). Embayed and linear shorelines are often attributed to submergence or uplift of coastlines with respect to sea level. Kar (1993) suggests the changes in shoreline morphology cited here are due to Quaternary tectonism. We observed during a brief visit to the coastline west (N23.22° E68.67°) and south (N21.16° E73.22°) of Bhuj the presence of a single prominent marine terrace at an elevation of 5 to 6 m above current sea level. The formational elevation of the oxygen isotope substage 5e terrace, generally placed at about 120 ka (e.g., Muhs et al., 1994), is generally on that same order. If indeed the observed terrace is the 5e terrace, the observation would preclude significant net vertical motion along the west and southwest coast of Kutch in 120 ka. A systematic examination of the terrace height and distribution, and age of terraces along the coastal regions, holds the potential to place quantitative limits on the degree of uplift along coastal areas of the region.

We focused some attention along the Kutch Mainland Fault in our search for surface rupture. We constructed from field observation and Landsat imagery a map and schematic cross-section of a portion of the region we visited (Figure 10). The Haro and Kas Hills are part of the Northern Hill Range and reach a maximum elevation of about 300 m, dropping to about 9 m or less northward into the Banni plains. To the south, they average about 100 to 200 m elevation. The northern topographic fronts of the Haro and Kas Hills are abrupt. Along the Kas Hills, we observed an emergent fault thrusting sandstone over shale at the rangefront, although we could find no exposures involving Quaternary alluvium. We did not observe the fault to be reactivated by the Bhuj earthquake.

Along the topographic rangefront of the Haro Hills, the rangefront corresponds to steeply dipping and resistant sandstone beds which form flatirons. Conformable and dipping beds of the same formation were observed outboard of the rangefront beneath alluvium for distances on the order of a kilometer (Figure 10) in the vicinity of the cross-section. The dips of the underlying beds gradually steepen as one progresses northward from the topographic rangefront, reaching an observed maximum of 90° where we observed in one streamcut exposure that they sit in unconformable contact with a gently dipping lithified conglomerate. The exposure was insufficient to determine conclusively whether the contact represented onlap or faulting. However, at the approximate location of the contact, we observed tensional cracking on the surface. The cracks were locally impressive and laterally discontinuous over a distance of about 10 km along the trend of the contact. Locally, the cracks appeared to be associated with a scarp in alluvium of less than about 1 m height, more than could be attributed to any observed displacements, which were generally tensional. It was our impression that this band of cracks was the most likely candidate for recent expression of the Kutch Mainland Fault and that the abruptness of the rangefront cannot be explained solely by faulting but probably reflects in large part the effects of differential erosion on steeply dipping sandstone beds.
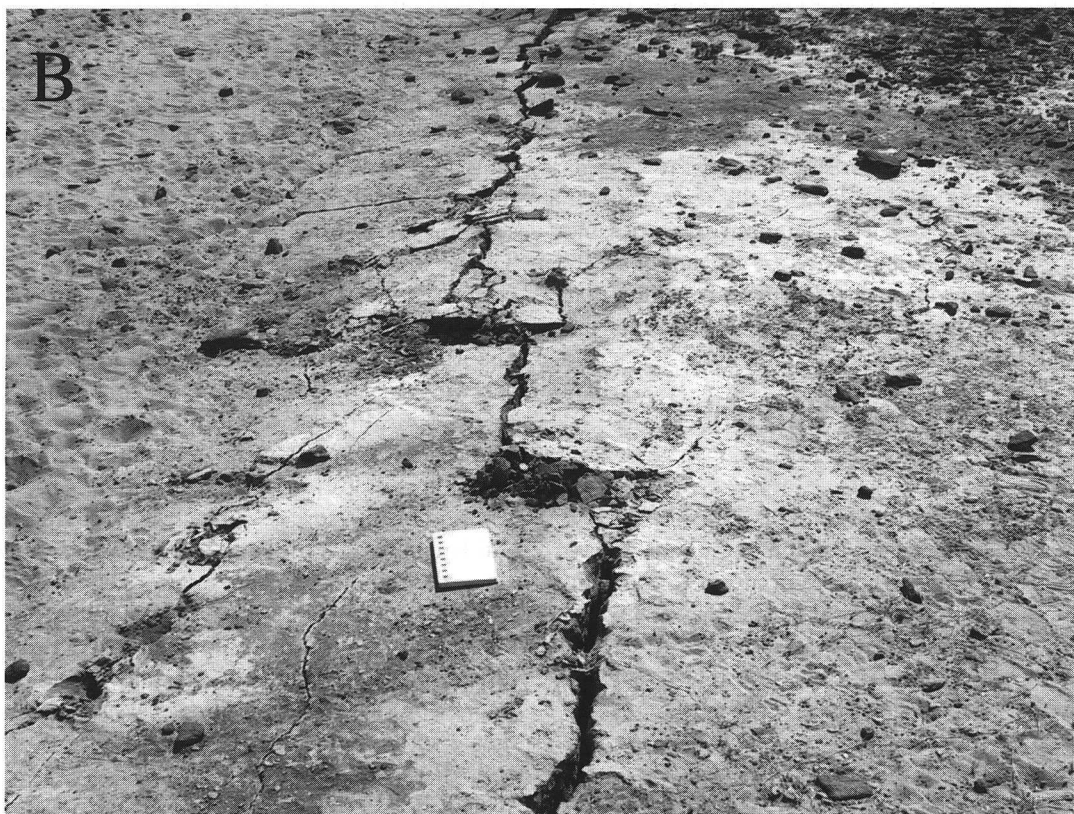
▲ **Figure 8.** Representative examples of offset along the Manfara fault. Right and left steps along the trace of the right-lateral fault exhibit (A) small extensional grabens and (B) compressional mounds, respectively.
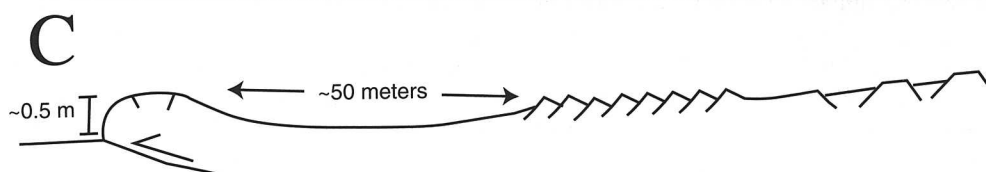
▲ **Figure 9.** (A) Scarp at toe of lateral spread observed at N23°20.58′ E70°11.63′. (B) Character of extensional cracking at head of lateral spread. Views are to the east. (C) Sketch of main features of the lateral spread (north is left).
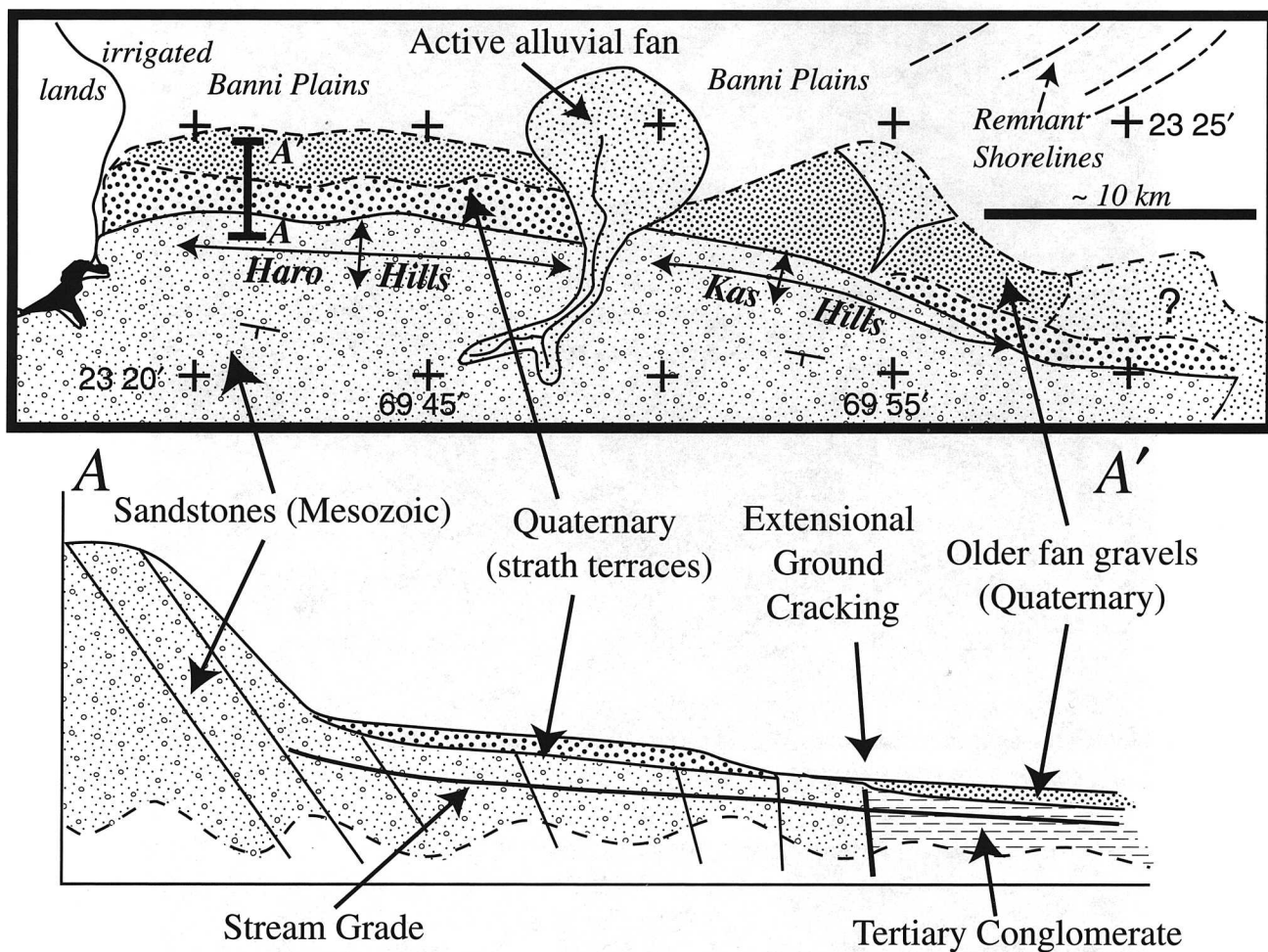
▲ **Figure 10.** (upper) Sketch geologic map of region along the northern flank of the Haro and Kas Hills which form a portion of the Northern Hill Range. Location shown by rectangle along Kutch Mainland Fault in Figure 3. (lower) Schematic cross-section between A and A'. Stippling patterns correspond to same geologic units in map and cross-section and are labeled in cross-section.

Sitting outboard and north of the main topographic front are active alluvial fan deposits that issue from confined drainages along the rangefront (Figure 10). Also, there are alluvial strath terraces that sit well above active stream grade (Figure 11). These terraces were recently interpreted by Malik *et al.* (2001) to suggest ongoing tectonic uplift. Although most are certainly incised and raised above active stream grade, we observed no clear fault truncation of the uplifted surfaces. The surfaces appeared to have very well formed soils, implying substantial age. Abandoned shorelines are visible on Landsat imagery on the Banni plains (Figure 3). The Banni plains rise up to 9 m in elevation above the Great Rann to the north (Kar, 1995). The possibility exists that both the shorelines and the alluvial terraces are the result of some broader tectonic uplift. Alternatively, they may simply relate to a higher stand of sea level about 125,000 bp (*e.g.*, Muhs *et al.*, 1994), in which case no tectonic uplift is involved. Our time was insufficient to address these problems in detail. We departed with the impression that any tectonic rates averaged over the Quaternary are quite low and that events similar to the 2001 earthquake are on average rare.

Fluvial drainage patterns and incision of alluvial fan deposits have also led to the suggestion that much of the morphology of the Kutch mainland is youthful and tectonically controlled (Malik *et al.*, 2000, 2001; Sohoni *et al.*, 1999). The Katrol Hill Fault, which strikes northwestward from near Anjar and bounds hills reaching 150 to 350 m immediately to the south, is the major drainage divide across the Kutch mainland. Malik *et al.* (2000) imply the drainage divide reflects recent tectonism. We did not address this hypothesis while in the field.

OLDER STRUCTURE

It appears well accepted that a north-south contraction of the Mesozoic bedrock in the region occurred in the Tertiary. The folding associated with the contraction is perhaps the most obvious geologic feature when viewed on the surface or through satellite imagery. We are unaware of any explanations concerning when or why this northward contraction of rift sediments commenced. It is natural to suggest from the north-directed *P* axis of the event focal mechanism that the
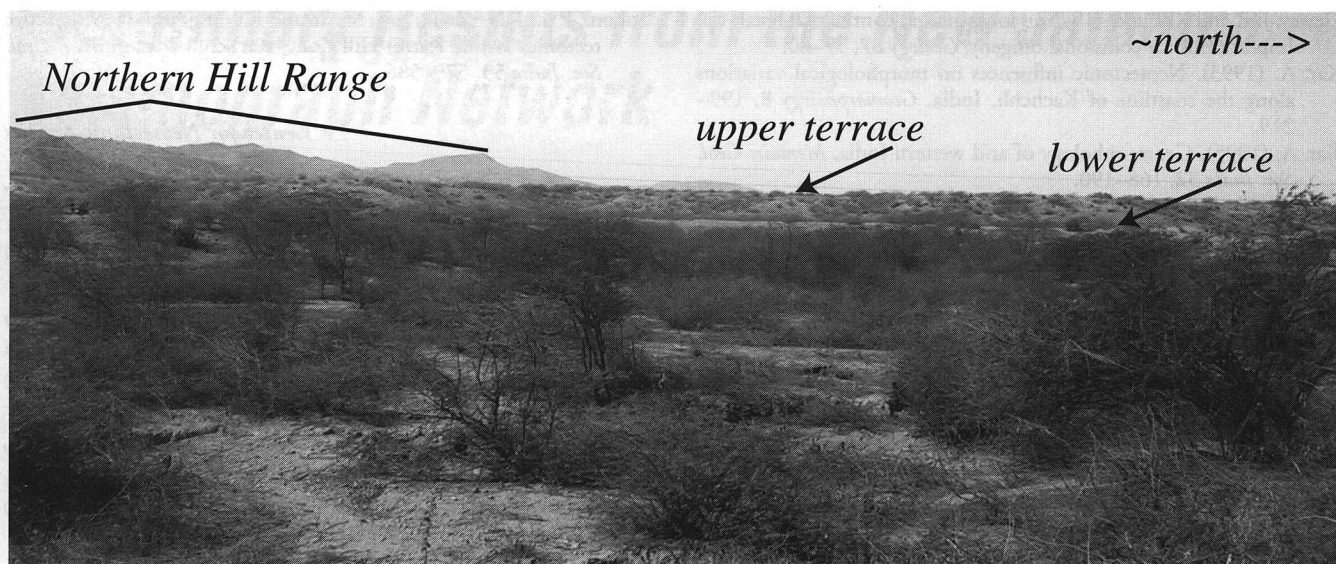
▲ Figure 11. A pair of alluvial terraces rests above active stream grade along the northern front of the Northern Hill Range. View is westward from about N23°23′ E69°54′.

contraction observed in the bedrock is continuing today. It is possible that the compressive structures are relatively ancient, reflecting a past geologic event, and that current activity may be reactivating these structures. Our search was certainly not comprehensive, but we observed no clear indication that the folds observed in bedrock are associated with deformation of younger deposits as well. An understanding of the earthquake will ultimately require an understanding of the genesis of the bedrock fold and fault structure.

SUMMARY

Our visit to the field area did not reveal any evidence of a major surface rupture related to the main thrust, perhaps not so surprising in light of subsequently reported aftershock studies that show the main and aftershocks of the event were generally limited to depths below 10 km. Our search did document a tectonic, though secondary, rupture in the hanging wall of the rupture. The northwest-striking right-lateral strike-slip fault showed maximum offsets of 32 cm and reflects a pure shear or a tear in the hanging wall. There is a consistent indication of northward contraction in the bedrock structure and the focal mechanism of the event. Quaternary strath terrace deposits in the area that locally sit above active stream grade may reflect tectonic uplift in the region, but we did not observe a clear relationship of the deposits to fold or fault structures in the bedrock. We left the epicentral area with the impression that a concerted effort to document the distribution and age of Quaternary deposits and the signature of past sea-level changes is needed to quantify tectonic rates of motion in this intraplate region. ◿

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