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SEISMOTECTONICS OF KUTCH RIFT BASIN AND ITS BEARING ON THE HIMALAYAN SEISMICITY

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INTRODUCTION

In the evolutionary history of the Indian Peninsula extending for about 4 billion years, several episodic changes have taken place from time to time, leaving behind their imprints on the rocks and landscape. The drifting of shield segments, opening and closing of oceans, organic movements, development of mobile belts and extensive rifting are some of the important tectonic phases associated with Precambrian times. Vast areas of the Indian Shield comprised basement of Archean Crystallines represented by granite, gneiss and schistose rocks. Faulted basins and grabens were subsequently formed in the basement due to various tectonic processes during different times and were occupied by sediments belonging to Proterozoic, Palaeozoic, Mesozoic and Cenozoic ages. Extensive parts of Western and Central Peninsula were flooded with basaltic lava flows during late Cretaceous – early Tertiary period. Major tectonic activity subsided in Tertiary-Quaternary though minor movements continue to take place even in the present times.

The breaking off of the Indian subcontinent from the Gondwana Mainland and its northward drift due to ocean floor spreading started in late Triassic period. In late Cretaceous, the subcontinent got detached from Madagascar and by early Eocene, separated from Sychelles. The free-drift of the subcontinent came to a halt during Eocene-Oligocene times with the commencement of subduction of its oceanic crust below the Tibetan plate. By about 45-40 My B.P., the neotethys ocean closed along the Indus-Tsang Posuture, and the collision of Indian and Tibetan continental crusts began thereby heralding the rise of the mighty Himalayas.

Rifting in the Indian subcontinent along certain Precambrian structural trends started right since its detachment from the Mainland. In the western margin of the Indian Shield, the faulting was controlled by NE-SW Aravalli, ENE-WSW Son-Narmada-Tapti (SONATA) and NNW-SSE Dharwar trends (Biswas, 1982). Thus, during the migrating history of the subcontinent, three rifted basins, namely Kutch, Cambay and SONATA, developed (Figure 1). The SONATA zone, traceable for a length of 1600 km, has been identified as a typical mid-continental rift, characterized by high gravity, positive isostasy, anomalous geothermal regime, shallowing of magnetic crust, elevated Curie point and moderate seismicity (Shanker, 1995). A large scale accreted igneous intrusion at the base of the crust beneath this zone has been postulated (Singh and Meissner, 1995). Relative vertical movement upto one kilometer and lateral movement to the extent of 30 km have been established in the 150-200 km wide SONATA belt during Quaternary times (Shanker, 1987).

The Cambay Graben, formed in co-linearity with the Dharwar trend during early Createaceous period, adopts a NNW-SSE trend and has length and width of 200 km and 80 km, respectively. This linear structure is occupied by a 3500 m thick pile of Tertiary and Quaternary sediments, and crosses the SONATA zone near Broach. The Cambay Graben is displaced westward by right lateral Narmada tear fault and continues southward parallel to the western coast right upto Vengurla Arch (Biswas, 1987).

The Kutch rift basin developed during Jurassic early Cretaceous till it was aborted in late Cretaceous (Biswas, 1987). The structure has length and width of about 320 km and 160 km, respectively, and adopts an E-W trend, almost parallel to the SONATA zone. Its northern limit is marked by Nagarparkar ridge and the southern by the Kathiawar uplift. In the east, it is restricted by NNW-SSE trending Radhanpur Arch, which also defines the western margin of Cambay Graben. An across-the-basin median-high structure occurring along the hinge zone corresponds with the earliest tectonic movement in late Jurassic times.

The Mesozoic-Cenozoic sequence representing margins overlap cover is well developed in the area. The structural configuration of Kutch basin is characterized by highlands and plains, which are the areas of uplifts and half grabens, respectively. The uplifted blocks are bounded by E-W trending major faults, prominent among them being Kathiawar, Katrol, Kutch Mainland (KMF) and Island Belt faults. Important lineaments of the region are "Lathi-Rajkot", "Chambal-Jamnagar", "West Coast", "Kishangarh-Chipri" and "Luni-Sukri".

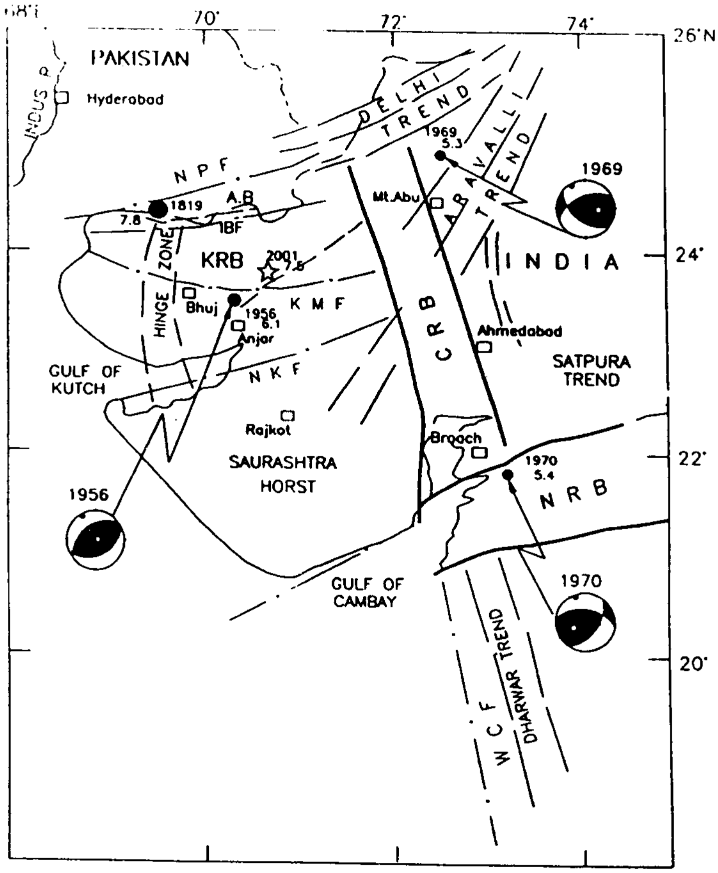

Fig. 1 Map showing major tectonic features of the study region (compiled from Biswas, 1987); KRB: Kutch rift basin, CRB: Cambay rift basin, NRB: Narmada rift basin, NPF: Nagar Parkar fault, IBF: island belt fault, KMF: Kutch mainland fault, NKF: north Kathiawar fault, WCF: west coast fault, AB: 'Allah Bund' (see text) (epicentres and fault-plane solutions of the significant earthquakes are shown)

SEISMICITY OF KUTCH REGION

Kutch has been a tectonic domain of known high seismicity, included in Zone V of the Seismic Zoning Map of India. Here, the seismic energy release has been of the order of 7.31 x 10^{20} ergs/year, which is comparable with certain active blocks of the Himalayas. The major seismic events of the region include 1819-Cutch, 1956-Anjar and 2001-Kutch (Bhuj) earthquake. A brief account of the earthquakes is as follows.

1. Cutch Earthquake of 16 June 1819

Of the intraplate earthquakes of the world, the 1819 event occupies a special place in the annals of seismology because of its great destructive power and intense ground deformation capability. Oldham (1926) estimated the epicentral intensity as XI where 1543 people were reported to be killed. Based on the reported intensity, Gutenberg and Richter (1954) assigned $M_L \cong 8.4$, whereas Johnston and

Kanter (1990) assigned $M_W = 7.8$. Chandra (1977) estimated the epicentre at 23.6^{0}N and 69.6^{0}E while Quittmeyer and Jacob (1979) estimated at 24.0^{0}N and 69.0^{0}E. Sir A. Burnes in his account of the catastrophe mentions that by the severe shock of the earthquake, hundreds of the inhabitants of Cutch perished and every fortified strong hold was shaken to its foundation (in Oldham, 1926). Innumerable wells and rivulets were changed from fresh to salt water. The brick fort at Sindri was overwhelmed at once with a tremendous inundation of water from the ocean, converting the area into a 25 km long lake. The inhabitants of the fort saved their lives by ascending its walls and sailing to the land the following day by boats. The account states that the inhabitants noticed the presence of a mound of earth 8 km northward of the fort. It had a length of nearly 25 km and stretched in an E-W direction across a channel of Indus river (Pharran or Puran river). The natives called this feature as 'Allah bund' or the bund of God, in allusion to its not being like the other dams in the Indus, which extend for about 80 km and showed a maximum vertical displacement of 6 m. The faulting has been inferred to be of reverse type since the uplift exceeded subsidence and the fault dip estimated as 65^0 towards north (Bilham et al., 1998). However, Wynne (1872) doubted the elevation of the Allah bund and considered the appearance of uplift as deceptive, but accepted the subsidence of the land south of the natural feature.

Oldham (1926) has described that at Bhuj, the shock was very severe destroying a large part of the town and fortifications and killing 1140 people. At Anjar also, the damage was proportionately as great. The other places where damage was severe were Thera, Kotheree, Mothara, Nulliah, Venjan, Jodiya, etc. Of those, which suffered less include Mandvi, Mundra, Sandham, Poonree, Bhachau and Adohi. There is some indication of a northerly extension of the epicentral area, as the damage reported from Baliari, Umarkot and Jaisalmer was quite high. To the east, the shock was severe at Ahmedabad where the minerets of a 450 year old Great Mosque were thrown down and many private houses reduced to ruins, though no loss of life was reported. Shocks were perceived felt as far as at Kolkata, Bombay and Chennai where some had a feeling of giddiness. To the west of Kutch, the extension of the shock was very much less and caused no damage in the towns of Sind (Pakistan).

Landslips and sand vents (liquefaction) were frequent and widespread through out Kutch wherever favorable conditions existed. The aftershock activity was most profound for the first ten days and continued with much diminished frequency till November (6 months).

2. Anjar Earthquake of 21 July 1956

Although the Anjar earthquake occurred much before the establishment of the World Wide Standardised Seismograph Network (WWSSN), Chung and Gao (1995) well studied the source mechanism of this event using the teleseismic long period P- and SH- wave-forms. The magnitude (Ms) was assigned as 6.1 and epicentre located at 23.3^{0}N and 70.0^{0}E. The maximum intensity was reported to be IX (MM scale). The major axis of the elliptical isoseismals was in the NE-SW direction, similar to that of the present Bhuj 2001 earthquake. By wave-form modelling, Chung and Gao (1995) determined a reverse-fault mechanism for the 1956 Anjar earthquake (Figure 1). Both the nodal planes of the solution strike NE, sub-parallel to the trend of the Kutch rift and very close to the trend of the isoseismals.

3. Kutch (Bhuj) Earthquake of 26 January 2001

After a gap of 45 years, another major earthquake occurred in the Kutch basin which proved to be the most destructive of the Indian seismic events recorded so far, in terms of socio-economic losses. A total of 20,072 people got killed and nearly 10.8 lakh houses were damaged in 7904 villages of Gujarat state.

The seismological parameters of the main shock of 26th January, 2001 are estimated by different agencies; some of these are as follows:

IMD	M_W 7.7	23.4^0 N, 70.28^0 E	25 km	8 h 46 m 42.9 s. (IST)
USGS	M_W 7.5	23.399^0 N, 70.316^0 E	17 km	8 h 46 m 41 s (IST)
ERI (Tokyo)	M_W 7.6	23.4^0 N, 70.3^0 E	10 km	

The magnitude (M_W = 7.5) estimated by the USGS and ERI is consistent. The IMD (India Meteorological Department) has well estimated the depth at 25 km using the 'converted phases' recorded by the national broad band network, and it is fairly consistent with the NGRI (National Geophysical

Research Institute) - estimated depth (22 km) based on the national and global data. The USGS and the ERI estimated the centroid depth at 17 km and 10 km, respectively.

An epicentral intensity of X on MSK-64 scale has been recorded in an area of 780 sq. km, 60 km ENE of Bhuj town (Shanker and Pande, 2001). The maximum damage was recorded at places like Bhachau, Adhoi, Chobari and Manfera. The towns of Bhuj, Anjar, Gandhidham, Kandla and Rapar were enclosed by isoseismal IX. The isoseismals are elongated in N60^{0}E-S60^{0}W direction with attenuation of intensity in the south-west quadrant. In Ahmedabad city, though located in intensity VII, many high-rise buildings suffered heavily resulting in 718 human casualties. The tremors were felt at even distant places like Delhi, Kolkata and Chennai (Figure 2).

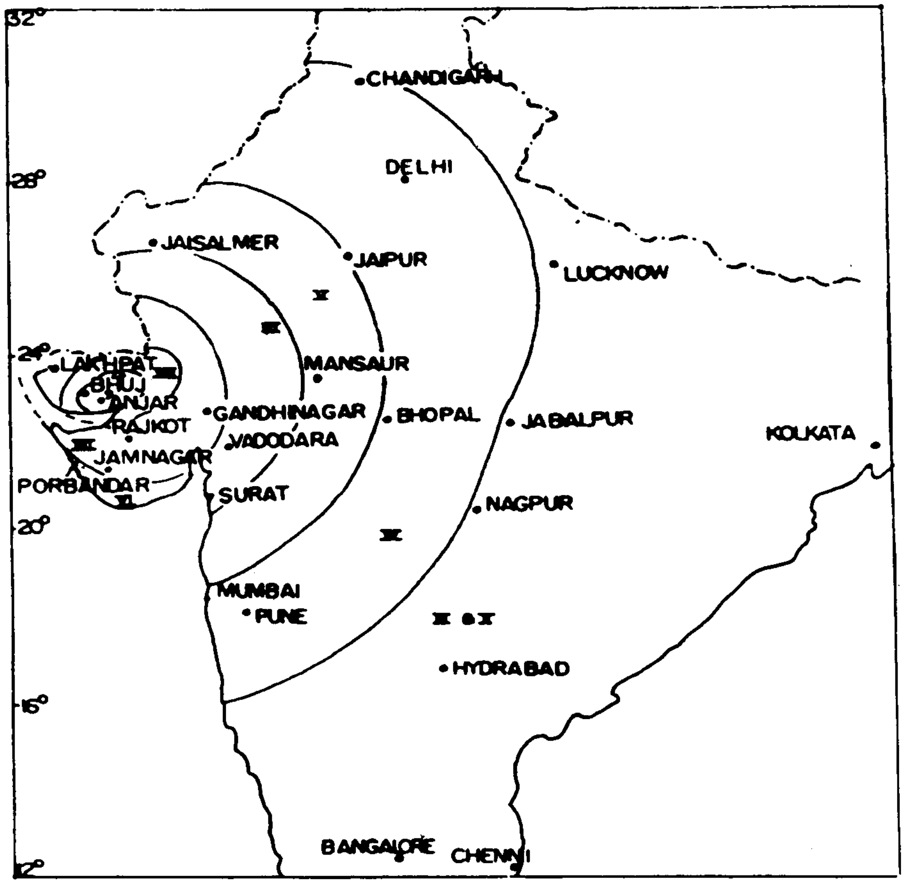

Fig. 2 Isoseismal map of Kutch (Bhuj) earthquake of 26th January, 2001

The earthquake induced profuse liquefaction in an area of 50,000 sq. km (Pande et al., 2001). Its manifestations were in the form of sand blows, craters, ground fissures-subsidence, lateral spreads and slumps. Co-seismic ground deformations were observed along the Kutch Mainland Fault and certain transverse lineaments in the meizoseist.

The fault plane solution of the main event gives a predominantly reverse fault type mechanism with the nodal planes having strike, dip and rake of 292^0, 45^{0}NE and 132^0, and 60^0, 58^{0}SE and 56^0. The USGS solution also gives the same values for the strike of the nodal planes. Yagi and Kikuchi (2001) estimated the fault dimension of the order of 90 km x 30 km, and the maximum static displacement 6.2 m at the hypocentre. Based on wave-form modelling, they gave a fault-plane solution which depicts a thrust-fault movement on a nearly E-W trending fault plane. Fourteen seismographs were deployed by the Geological Survey of India for aftershock monitoring of the earthquake. About 2000 aftershocks $(M \geq 1.0)$ were recorded during the period from January 29 to February 28, 2001. The epicentre map of 308 well constrained aftershocks shows clustering in a 60 km x 30 km area, between 70.0^0-70.6^{0}E and 23.3^0–23.6^{0}N, which reflects the source area of the main shock and aftershocks at depth (Figure 3). The epicentres show an E-W as well as a NE-SW trend. Depth-sections of the aftershocks indicate that the events are mostly generated at two depth ranges; shallower aftershocks at a depth 0-15 km and the deeper aftershocks at 20-40 km. Composite fault-plane solution of the deeper aftershocks shows a reverse faulting with a large left-lateral strike-slip component, which is comparable with the main-shock solution. The shallower aftershocks, on the other hand, show a pure lift-lateral strike-slip mechanism (Kayal et al., 2001).

The aftershock data, fault plane solutions and isoseismal geometry suggest that the causative plane along which the initial rupture occurred in a compressional stress field, was a tectonic discontinuity following the Aravalli trend. The strain locking is inferred to have occurred at the intersection of this discontinuity, probably southerly dipping, with a transverse plane at a depth of 20-25 km (Shanker and Pande, 2001).

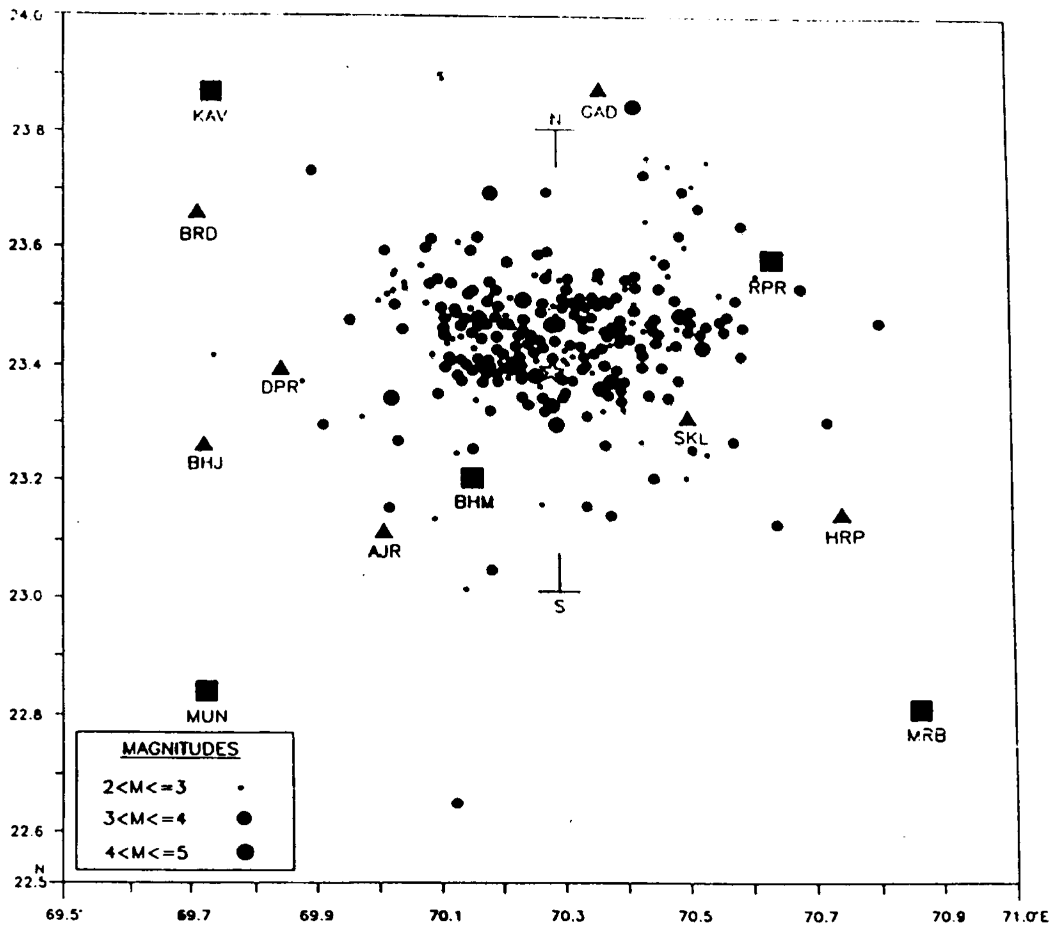

Fig. 3 Epicentre map of the well located 308 aftershocks recorded during January 29-February 28

BEARING OF KUTCH EARTHQUAKES ON HIMALAYAN SEISMICITY

The Kutch rift basin is located at least a thousand kilometers away from the Himalayas. Whereas the former has developed in an extensional stress regime, the latter is a product of compressional tectonics. The earthquakes of Kutch region belong to the intraplate class and those of the Himalaya are of plate margin. The recurrence interval of earthquakes in case of the former is comparatively large whereas in the Himalayas it is much shorter. There is as such no direct or indirect relation in the seismicity patterns of the two regions.

Thatcher (2001) in his assessment of the recent Kutch earthquake states that the event occurred on one of a series of E-W hidden faults. He concludes that the location of the causative fault, several hundred kilometers south of Himalaya and 200 km north of fan sediments of Indus delta, brings it to a similar stress environment which is prevailing in the Shillong plateau. In other words, the seismotectonics of Kutch and Shillong plateau region are, to some extent, comparable.

In the Himalayan region, the intensity of the 2001 Kutch earthquake was III or lower on MSK-64 scale. The strong motion recorder at Roorkee picked up its ground vibration and gave a peak ground acceleration of 0.008 g.

DISCUSSION

A comparative study of the effects of the 1819 and 2001 Kutch earthquakes reveals certain remarkable similarities. In both cases, the attenuation of intensity was towards the western side and pronounced accentuation on the eastern part. The median-high structure located to the west of Bhuj could be responsible for the attenuation. The epicentral tract in both cases showed some northerly elongation, which could have been brought about by the transverse asperity surfaces. High damage was recorded at Ahmedabad, located 240 km east of Kutch region in both cases. The two earthquakes caused profuse liquefaction in a very vast area. The meizoseist of 1819 earthquake appears to be to the southwest of 2001 earthquake epicentral tract. The co-seismic ground deformation in case of the former occurred about 100 km northwest of Bhuj. Oldham (1926) has concluded that the character and condition of strain of the outer crust of the earth is an important factor and this may lead to abrupt fractures being produced at some distance from the true epicentre. The 2001 earthquake induced ground deformations along the Kutch Mainland Fault and certain transverse lineaments in the meizoseist. These could be the manifestations of near-surface crustal adjustments along certain predefined structural discontinuities consequent to the main rupture at deeper levels, perhaps along a hidden basement fracture of Aravalli trend.

The Kutch, SONATA and other rift basins were formed during the detachment and free drift stages of the Indian subcontinent in an extensional stress field. With the jamming of the drift consequent to the collision of Indian and Tibetan continental crusts, a compressional stress regime became operative. This is how the present earthquakes occurring in the rift belts as well as relatively stable cratons in the Indian Peninsula give a predominantly thrust type mechanism of rupture.

The Heat Flow Map of India and adjoining region reflecting the operating infra and intra-crustal geodynamic processes shows that in the Peninsular part, high heat flow zone II, corresponding to values of 100 to 180 milli-Watt per sq. m occurs in stretches along the axial portions of SONATA, Godavari, Mahanadi and Cambay rift zones apart from segments of Saurashtra, Sahyadri and Tanjore regions (Shanker, 1988). These are coincidentally zones of relatively higher seismicity. However, the Kutch basin, though displaying high order of seismicity, is enclosed by the low to moderate Heat Flow Zone IV, corresponding to values between 40 and 70 milli-Watt per sq. m. This anomaly could be because of paucity of heat flow data in the Kutch region.

The seismicity of Kutch rift zone and that of Himalayas can not be compared since the two belong to totally different seismotectonic environments. It can therefore be said that the seismic safety aspects of high dams in the Himalayas need no revision in the light of earthquakes of Kutch rift basin.

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