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Earthquakes over Kutch: A region of 'trident' space–time geodynamics

U. Raval

National Geophysical Research Institute, P.B. No. 724, Hyderabad 500 007, India

Kutch peninsula exhibits enigmatically rapid stress accumulation/release like the New Madrid Seismic Zone. Geodynamically, it is a junction of three structural trends and three tectonothermal episodes (69–64 Ma). Combination of mobile belts and plume, evidenced here, favours lithospheric splaying, reactivation, rifting, alkaline complexes; resulting tectonic network may link Kutch with plate boundaries. The 1819 and 2001 events have occurred near the intersection, of such lineaments and accretionary belts, with its margins. Thus, Plate-boundary forces and loading (uplifts/sediments) appear to superimpose here, over relatively weakened lithosphere; and resulting litho/hydro-spheric instability would contribute to development of the Rann. The crust–mantle interactions are supported by (i) positive gravity anomalies, whose obliquity to Kutch rift indicates later reactivation, (ii) lower uppermantle velocity near Kutch, and (iii) differential uplift/subsidence. Deep geophysical probing is necessary to gain greater understanding of earthquake process.

COUNTRY-wide attention suddenly turned from Allahabad (i.e. Mahakumbh) to Allahbund (earthquakes in Kutch) following the tragic seismic event near Bhuj in the morning of 26 January 2001. It brought out, by now a familiar response from the geoscientists (after the Uttarkashi, Latur, Jabalpur and Chamoli earthquakes) that the 'culprit' is the ever ongoing compressional force following the collision of Indian subcontinent with Eurasia, along the great Himalayan belt. This implies that the Indian lithospheric plate is being pushed in the nearly NNE direction by the subterranean convection. However, this forms only a part of the story because if the continental scale compression alone is responsible then many other places in the country should also become seismically active. But the relative placidity of a large part of the Indian shield means that there have to be certain additional causes on regional as well as local scales, which when combined with continental compression complete the scenario. Figure 1 shows the various forces and plate boundaries active above Kutch.

An attempt is made here to depict the peculiar and probably unique geodynamics that puts the Kutch region in the highest seismic risk zone (zone-V), in spite of being in the intraplate (or midcontinental) region. As described below, this area appears to have undergone a 'trident' of geodynamics, both in space as well as in time.

It may be noted from Figure 2, that the epicentre of the January 26 earthquake lies in the close vicinity of the junction between three major tectonic (or mobile) belts, viz. (1) NE-SW oriented palaeo-orogenic corridor of Delhi fold belts, (2) ENE-WSW trending early Cretaceous Kutch rift, and (3) NW-SE directed late Cretaceous Cambay graben[1]. Actually, not too far from this location there is another younger tectonic structure, namely the Narmada–Tapti trend, which developed in the early Tertiary[1]. These rift structures imply doming, extension, subsidence and thermomagmatic influxing in the deep crust[2]. This is corroborated by examination of the Bouguer gravity anomaly[3], which indicates intrusion and/or under plating of high density material during the rejuvenations/formations of these aborted rifts (Figure 3). The trend of

e-mail: postmast@ngri.ren.nic.in

the Bouguer gravity field over the Kutch is quite oblique to the orientation of Kutch rift of Jurassic to early Cretaceous age. This is in striking contrast to many other rift structures like Cambay, Narmada–Son, Godavari, Mahanadi, etc. wherein the BGA patterns almost follow the trend of the rifts. The peculiar situation in Kutch implies that the underlying deep structure (i) may have been drastically modified due to later events ($T < 100$ Ma) and/or (ii) may represent, at least partly, the palaeo-syntaxis bend of the Delhi or post-Delhi accretionary belt; the first one supports asthenospheric upwelling during the break-up of Seychelles and consequent intrusive activity (including magmatic underplating) along the axis of mantle upwelling (WNW-ESE). A similar situation is evidenced in case of the New Madrid Seismic Zone (NMSZ) also. The 2001 event appears to have nucleated at the junction of Wagad uplift (WU) and Kutch mainland uplift (KMU), which obliquely cuts the eastern margin of the Kutch rift (KR) (see Figure 4). Similarly, the Allahbund lies in the vicinity of the western margin of the KR, obliquely cutting the Nagar Parkar uplift (NPU). Such intersections are noticed also at other active places like Jabalpur, Latur and Koyna.

The CSS results in this area corroborate the underplating beneath the Cambay and palaeo-orogenic Delhi belts in the form of high seismic velocity layer and/or reflector at the lower crustal depths[4,5]. The thermomagmatic crust–mantle interaction in this region is supported by the low-velocity zones in the upper part of the mantle

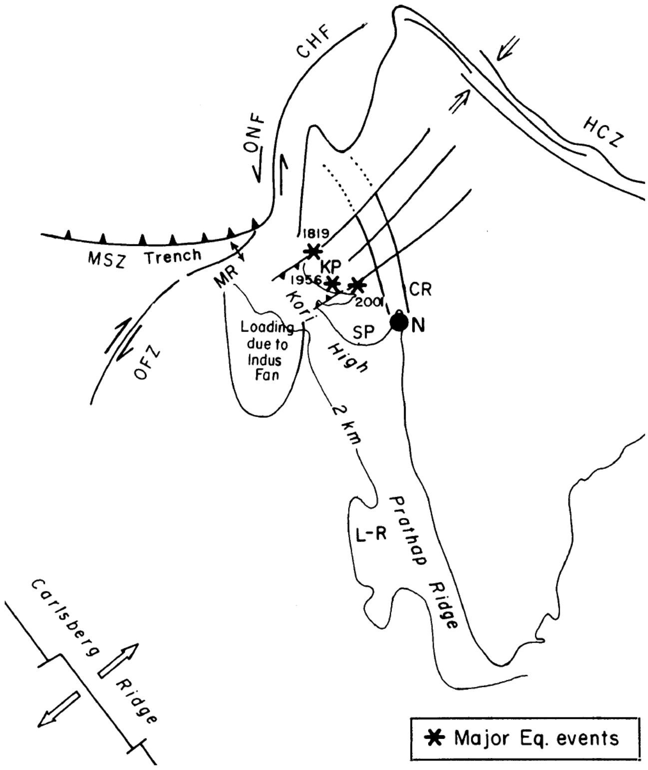

Figure 1. Active plate boundaries/forces around Kutch. CHF, Chaman fault; CR, Cambay rift; HCZ, Himalayan collision zone; KP, Kutch peninsula; LR, Laccadive ridge; MR, Murray ridge; MSZ, Makran subduction zone; N, Node of Reunion plume outburst; OFZ, Owen fracture zone; ONF, Omach Nal fault; and SP, Saurashtra peninsula.

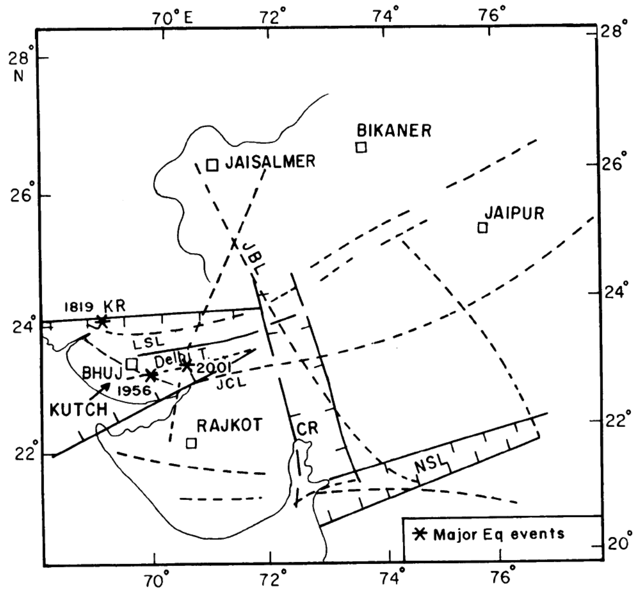

Figure 2. Spatial distribution of major tectonic trends/lineaments over and around Kutch. CR, Cambay rift; JBL, Jaisalmer Barwani lineament; JCL, Jamnagar Chambal lineament; KR, Kutch rift; LSL, Luni Sukri lineament; and NSL, Narmada–Son lineament (adapted and modified from Bakliwal and Ramasamy[57]).

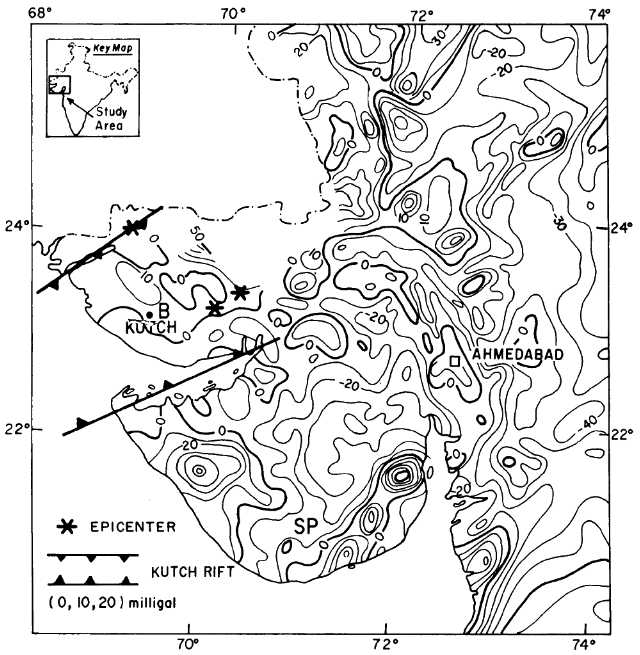

Figure 3. Unusually large positive Bouguer gravity anomalies occur over the north-western part of the subcontinent. As this region is also mostly affected by the trace and outburst of the Reunion plume and continental break-up, these gravity highs are suggestive of regional scale magmatic underplating and intrusive activity in the underlying crustal column (NGRI Bouguer Gravity Map, 1975).

(~ 90–100 km), inferred from tomographic studies[6,7,8] (see Figure 5). Higher heat flow and fluid movement are other repercussions which may give rise to electrical conductivity anomalies. This is corroborated by a recent magneto-telluric (MT) study[9], geothermal maps[10], and palaeo-drainage of Saraswathi/Sindhu[11]. In fact, the rift along continental margins and Mesozoic basin exhibits higher thermal gradient[10] as is evidenced by high heat flow (90–100 mw/m^2) and geothermal gradients (60–70°C/km) measured in closely juxtaposed Cambay and Rajasthan basins[12,13] from where a heat flow value of ~ 50–70 mw/m^2 and gradient of (25–30°C/km) have been extrapolated for the Kutch region[10]. This implies shallower brittle–ductile transition beneath Kutch[14], which matches with the focal depth of 2001 event, being in 10–23 km range[9].

Kutch seems to be a junction of 2 or 3 Precambrian trends, viz. Dharwar, Delhi and probably Satpura, since the following major tectonic trends meet here[1] (see Figure 2). (i) ESE-WSW oriented uplifts and subsidences, which are subparallel to line of break-up between Seychelles and India; and sharp westward turning of Delhi (and/or post-Delhi) fold belt (DFB). Near its southern end, the NE-SW trending Delhi–Aravalli fold belt seems to branch out[1] such that: (a) one of the branches merges with the ENE-WSW Satpura trend; (b) another enters into the Saurashtra peninsula; and (c) the third turns westward forming ESE-WNW trending uplifts over Kutch[1]. Since the crust mantle below this part of DFB has been affected by at least two thermomagmatic activities around ~ 65 Ma, the pre-existing structures might also be affected by them. (ii) NE-SW Kutch rift (KR) in line with DFB; boundary faults of KR are cut obliquely by uplifts (or ridges) like Wagad, Nagar–Parkar, etc. (Figure 4). (iii) NW-SE oriented Cambay rift and Radhanpur–Barmer arch crosses it on the northeastern side. These two seem to follow the Dharwarian trends and/or line of west coast break-up.

The Arabian sea inlets on either side of Kutch peninsula appear to have major tectonic significance because (1) 1819 Allahbund earthquake ($M \sim 7.8$) occurred close to the junction between NE-SW trending western margin of the Kutch and its northern margin defined by Biswas[1] as fault F1 (see Figure 5). The latter also defines nearly ESE-WNW running trend of the great Rann of Kutch (GRK), which appears to reach up to the NW-SE directed Sanchor and Cambay basins. The Anjar earthquake of 21 July 1956 ($M_W - 6.1$, dip 46.5°, strike 235°, rake 85°, seismic moment 1.19×10^{25} dyne cm, focal depth 15 km and stress drop 162 bar)[15] has also taken place along Katrol Hill fault[16]. According to Chung and Gao[15], the northern boundary of the Kutch mainland appears to have been caused by reactivation of a normal fault due to inverse tectonics. The differential movement of the coexisting uplifts and subsidence in Kutch imply strong lateral heterogeneity in the underlying rheology, which is also reflected in the strong gravity gradients (Figure 3). It is pertinent to note that occurrence of the SCR earthquakes over the subcontinent is highly correlated with the topography and gravity gradients[17]. The differential uplifts may have mobilized many structures like the Katrol Hill Fault[18]. Figure 6 gives the fault plane solutions for major earthquakes (Bhuj, Anjar, Mt. Abu and Broach) in this region[9,15]. (2) The epicentre of the 26 January 2001 earthquake event (IMD: $M_s - 7.8$, M1 – 6.9, 23.6°N, 69.8°E, 15 km, 8 h 46 min IST) lies close to the zone where the northern boundary of Kutch mainland uplift, KMU (F4) and southern boundary of the Wagad uplift

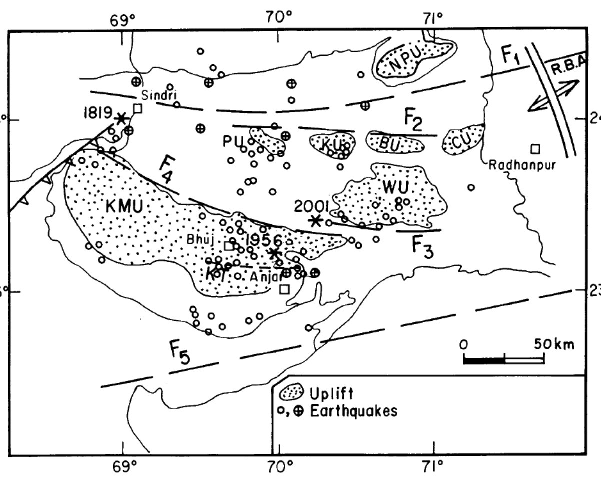

Figure 4. Trends of uplifts, faults and epicentres over the Kutch region. BU, Bela uplift; CU, Chorar uplift; KMU, Kutch mainland uplift; KU, Khadir uplift; NPU, Nagarparkar uplift and WU, Wagad uplift (modified after Biswas[1]; Malik *et al.*[16]). Earthquake locations are from Malik *et al.*[16].

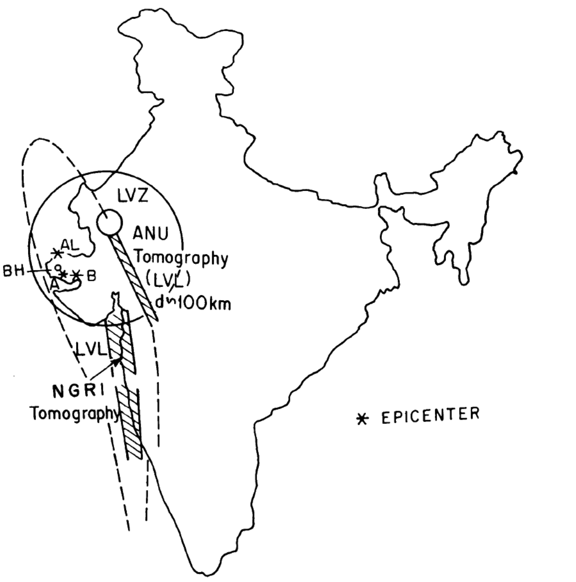

Figure 5. Areas where low-velocity zones have been inferred from the teleseismic imaging[6,7] in the depth range of 90–120 km. This implies that thermally-induced effects of Reunion plume and continental rifting probably still persist. AL, Allahband; A, Anjar; and B, Bhuj.

(F3) meet the NE-SW oriented eastern margin of the Kutch and little Rann of Kutch (Figure 4). This earthquake activity seems to be concentrated around a 'neck', formed north of Bachhau, by convergence of the two Ranns. The subsidences north of KMU, such as Banni basin, allow the sea-way connection between the two margins.

Most of the late- and mid-Proterozoic sutures constitute inherently weak corridors, as is the case with the crustal column beneath Kutch, because of it being part of a palaeo-orogenic belt (DFB) and probably another accretionary zone at the time of formation of the Rodinia supercontinent. Extension during Rodinia break-up[19], Malani volcanism[20] and Pan-African activity[21] would further weaken it. Since DFB takes a sharp turn over Kutch, it may represent a palaeosyntaxis in analogy with the eastern syntaxes of the Himalaya near the epicentre of the great Assam earthquake of 1950. Another evidence of substantial tectonics in the Kutch region follows from the fact that the later contains nearly complete sequence of the Mesozoics and this activity appears to be coeval with the Karoo volcanisms of South Africa. It is strongly supported by: (i) the pre-Mesozoic igneous rocks found at Lodhika, situated close to the eastern margin of Kutch graben[1] or Kathiawar fault (F-5), and (ii) the trend of Kutch rift is aligned almost parallel to the Mozambique belt and Madagascar; both of which have been remobilized during the Pan African activity; and a Pan-African age has been recently reported[21] north of Kutch also. Presence of DFB in Kutch implies a plume (Reunion: RU) – mobile belt (DFB) combination, which is generally fatal for the stability of a continental collage and leads to rifting; and Kutch along with Seychelles might have also broken apart from India.

Substantial similarity has been noted between Kutch (1819) and NMSZ (1811, 1812), as both exhibit rifting, arch/basement ridges, gravity highs, triple junctions and hotspot activity. Johnston and Schweig[22] expressed this link between Kutch and NMSZ as 'within the second decade of the 19th Century, a unique and common bond was established between a little town on the Missisipi River and little fort on a Indian salt flat – a bond that none could have imagined beforehand'.

Figure 7 shows that:

(1) the Kutch region has experienced a bolide impact at Anjar near KTB (i.e. ~ 66–65 m.y. ago) as evidenced by the Ir anomalies[23,24], fossils[21] and natural fullerenes[25].
(2) In the time interval 67–64 Ma, this area traversed over a hotspot formed by the Reunion plume, which led to enormous outpouring of the Deccan flood basalts over the western and central parts of the subcontinent, including Kutch and Saurashtra. It seems that this volcanism occurred in two phases; the first was an early pulse[26,27], while the second coincided with the outburst of the Reunion plume-head[3].

It may be noted that all the intraplate (or mid continental) earthquakes of $M > 6$ during the past ~ 200 years, have occurred in the Deccan Trap (or Reunion plume-affected) region. This implies a major rheological change in the crust mantle structure due to interaction between the large plume-head (diameter ~ 1000–2000 km) centred around Cambay–Kutch region and the overlying continental lithosphere. Erosion of original cover of Deccan trap could be another cause of variation in strain and differential uplift. This will make the boundary between uplifts and basement structures (Figure 4) more vulnerable. The present-day seismicity[2,28] over the plume outburst region and along the plume trace is shown in Figure 8. There would have been large-scale doming in this whole area due to the central part of the hot Reunion

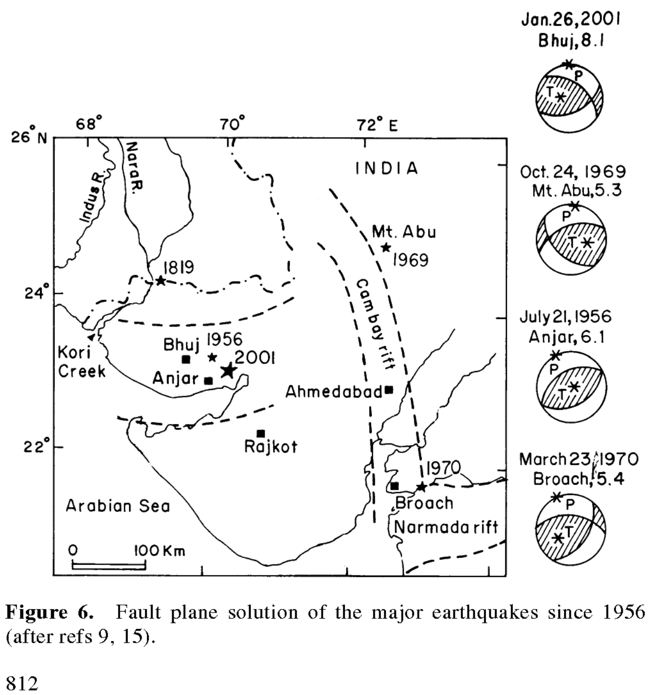

Figure 6. Fault plane solution of the major earthquakes since 1956 (after refs 9, 15).

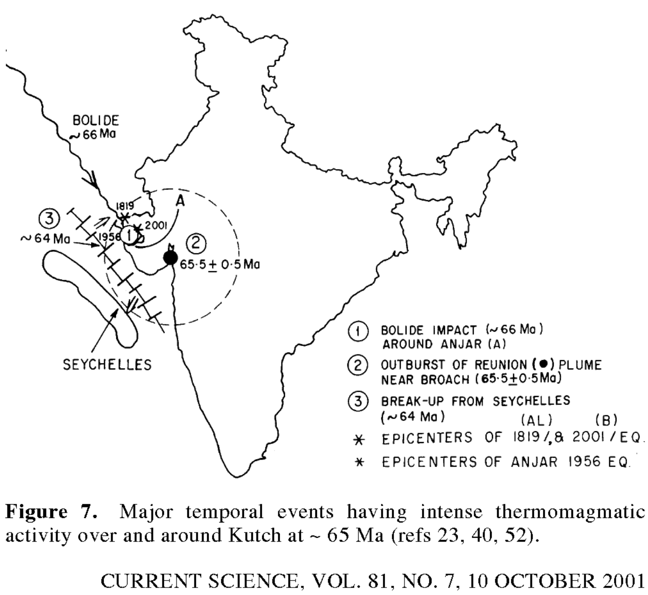

Figure 7. Major temporal events having intense thermomagmatic activity over and around Kutch at ~ 65 Ma (refs 23, 40, 52).

plume-head upwelling up to the base of the continental lithosphere beneath this region at ~ 66 Ma. (Figures 3 and 4 show that conspicuously high BGA over the Kutch region coincides with the uplifted blocks.) Actually, the NW part of the subcontinent has the maximum number of very large positive gravity anomalies[3,29]. These gravity highs and associated uplifts may be due to intrusive activity and magmatic underplating following the plume activity (Reunion and Malani) and lithospheric thinning. The ridges and highlands in Kutch and western Rajasthan are then relics of this doming due to cooling of highly heterogeneous crust, which leads to differential uplifts. On the other hand, subsidence follows from (i) cooling after the deep-seated thermal source has either moved away or dissipated, and/or (ii) foundering of the crust due to probable gabbro–eclogite transition near the Moho depths[3]. Since DT cover will be thicker along subsided corridors, erosion will give rise to inverse tectonics, greater strain changes along their boundary faults and uplifts.

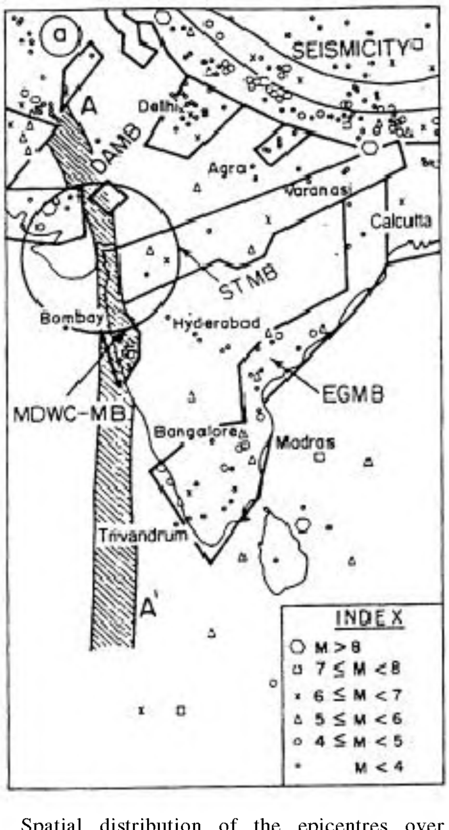

Figure 8. Spatial distribution of the epicentres over the subcontinent[2,28,29,32] clearly show high seismicity over the trace and outburst of Reunion plume (shown by a circle around Cambay). Almost all these intraplate earthquakes of magnitude $M > 6$ during the past ~ 200 years, have occurred over the plume (Reunion/Kerguelen)-affected and Deccan-Sylhet/Rajmahal traps covered regions. Note the negligible seismicity along the middle part of Delhi–Aravalli mobile belt (DAMB). However, near its southern end where it meets Cambay/Kutch rifts, significant activity occurs again, as shown by a square at the junction of DAMB and Cambay/Kutch rifts.

The plume activity often leads to alkaline complexes along the shoulders of rift structures. In case of the Reunion plume, this is evidenced along the western margin, over the Kutch/Saurashtra regions and the western part of the Narmada–Son graben[30]. Older alkaline complexes are seen along the Eastern Ghat mobile belt[31]. From the spatial distribution of seismicity over the subcontinent[28,32,33], it is seen that earthquake activity over India correlates with alkaline magmatism (e.g. Tirupattur, Ongole, Bhuj, Meghalaya, etc.).

(3) Up to 64 Ma, Seychelles was a part of the Indian continental lithosphere, lying close to its present-day NW margin. It got separated due to a mid-oceanic ridge (MOR) upwelling developing in the underlying region. This MOR was the early manifestation of the Carlesberg ridge, now active in the north-western part of the Indian Ocean (see Figure 9). The mantle upwelling and its (northward) lateral spread result in approximately WNW-ESE lineaments and/or interact with the pre-existing weak zones (e.g. Kutch and Cambay). The MORs are often accompanied or dissected by a number of fractures (Fs) and/or transform faults (TFs), which run almost transverse to the ridge axis. For example, the Owen fracture which runs up to thousands of kilometres from Carlsberg ridge to the western boundary between the Indian and Arabian plates (Figure 9). This scenario could be tested by a suitably designed, deep geophysical probing of the region, e.g. deep seismic studies (including 2-D and 3-D reflection seismics), seismic tomography, magnetotellurics, heat flow measurement in the deep bore wells and xenoliths.

The temporal geodynamical events in Kutch and closely adjoining regions are given in Table 1.

Another area which seems to resemble Kutch is the Meghalaya plateau, due to large seismicity and similar trident geodynamics, as it has also experienced (i) plume

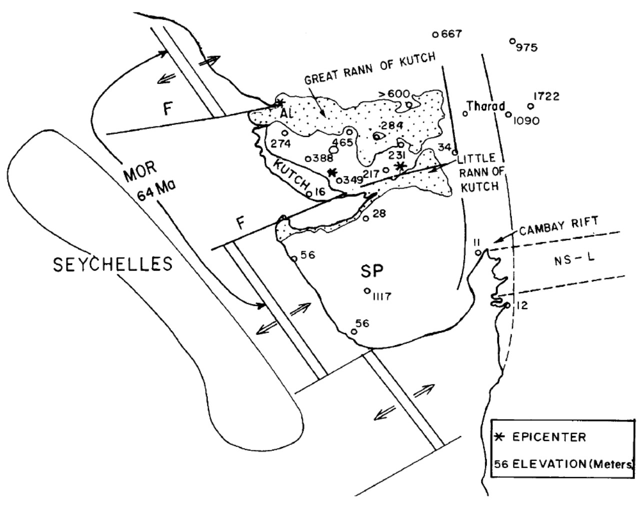

Figure 9. Possible development of mid-oceanic ridges (MOR) between India and Seychelles (at ~ 64 Ma). This clearly suggests the possibility of mantle upwelling beneath Kutch. Numbers show the elevations over and around Kutch, indicative of crustal loading by uplifts (high land) surrounding it.

activity (Kerguelen/Crozet hotspots) and flood basalts (Sylhet/RajMahal traps) at ~ 117 Ma[34] alkaline magmatism and carbonatites[35], (ii) bolide impact as indicated by the Ir anomaly[36], and (iii) continental break-up of India from Antarctica and Australia at ~ 130 Ma. In addition, there are also horst-like uplifts and lithospheric flexure due to loading of Himalayas to its north and Ganga from sediments to its south[37,38].

Even though Kutch, along with the Himalaya, has been categorized as zone-V after the 1819 Allahbund (M ~ 7.8) and 1956 Anjar (M ~ 7.0) earthquakes, because of the low seismicity during the past 50 years, this region did not get much attention. The large seismic energy release in Kutch remains enigmatic due to it being an intraplate region and due to the low near-surface strain rate. This apparent 'quiescence' or low seismicity in Kutch since 1956, has proved deceptive. An important and pertinent question is by what mechanism does the stress gets accumulated and released to such large levels in this intraplate region? Such a relatively rapid occurrence of large magnitude events implies that strain might be accumulating here at rates similar to those at near-plate boundaries, i.e. 10^{-5}–10^{-6}. This figure is in contrast with strain rate in the intraplate cratonized regions (10^{-7}–10^{-10})[39]. Hence, as in the NMSZ study, for causes of the additional strain, the underlying crustal structure and geodynamics need to be looked into.

From more detailed and quantitative characterization of the seismogenic parameters, insights should be gained about the active fault(s) and the spatio-temporal characteristics and their mechanism. They may decipher why and how the compression due to plate movement is getting partitioned within the deeper parts of the crust below this region. An important beginning has been made very recently[40] to delineate the palaeoseismological characterization of the Allahbund region (1819 earthquake of M nearly 7.8) in western Kutch.

The large release of seismic energy over relatively short time successions, in the intraplate Kutch region is indeed enigmatic. To gain insight into this phenomenon, it is necessary to know if the near-surface strain accumulation due to (i) docking of the Indian plate on the NW corner, (ii) ongoing compression, and/or (iii) anti-clockwise rotation, is sufficient. Or, an additional (or extra) contribution from underlying structural heterogeneities is also required for the observed concentration/relaxation of stress.

The tectonics and geodynamical history of the Kutch discussed above, indicate the possibility of many faults under this region. Their reactivation under the ambient thermomechanical conditions depends also on the weaker sectors (for example, due to serpentinite gauge-fillings) and strain localization along these hidden faults[41]. The latter are caused by hydrothermal influxing in response to

Table 1. Temporal geodynamical events in and around Kutch

Events/forces	Time	Effect	Ref.
Uplift of Delhi–Aravalli, Kirtihar and Himalaya (North and West of Kutch).	Quaternary and Neogene	Loading and flexure	43–45
Accumulation of sediments in the Indus Fan and Kori high (south of Kutch)	Quaternary and Neogene	Loading and flexure	37, 46
Docking of the Indian lithospheric plate in NW corner of the subcontinent	~ 50–60 Ma	Compression and mechanism back-reaction to the collisional bang	47
Break-up from Seychelles	~ 64 Ma	Transform faults, lithospheric thinning and modification of lower crust	48
Bolide impact near Anjar	~ 65 Ma	Faults, mass extinction	23, 49
Trace and outburst of the Reunion plume	~ 68–65 Ma	Alkaline/intrusive magmatism, flood basalts and mass extinction, magmatic underplating and gravity high anomalies	50–52
Karoo volcanism and its consequences along Transcontinental MBs like Trans-Antarctica, Tasmania, Mozambique Madagascar, etc.	~ 180 Ma	Magmatism and rift formation (e.g. Kutch graben). Presence of igneous rocks between Mesozoic sediments and basement.	Lodhika Well report (ONGC)
Pan-African event found in western Rajasthan to its north, Seychelles/ Madagascar to its south.	~ 550 Ma	Deep-seated change in the lower parts of the crust	21
Granite, magmatic, Seychelles	~ 630–700 Ma	Formation of basement of the continental part of Seychelles	53, 54
Malani igneous activity	~ 750 Ma	Magmatic underplating, rhyolites	20
Erinpura plutonic belt	~ 850 Ma	Emergence of granitic belt along the accretionary boundary (or weak zone)	55
Ambaji Deri belt of accretion (post-Delhi accretionary wedge)	~ 1000 Ma	Post-Delhi weak zone	56

plume activity and rifting in this region. Further, this region is a part of the mobile (or palaeoorogenic) belt and hence may consist of palaeothrusts analogous to MCT and MBT of the Himalayan collision zone. There may also exist the deformation-induced preferred structural orientations (especially of the olivine mineral grain), often evidenced in deep-seated seismic anisotropy. In such a case, the later thermal fluxing or plume activity may give rise to anisotropic heating of the crust–lithospheric column, which in turn reactivates and splays the frozen structures having preferred orientations[42].

To delineate and constrain the above factors, investigations of deep geophysical structure(s) of the underlying crust and uppermost mantle (particularly the seismic velocity, seismic reflectors and electric conductivity) are necessary, as they form an essential complement to the ongoing earthquake studies in the region.

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