

# A review of structure and tectonics of Kutch basin, western India, with special reference to earthquakes

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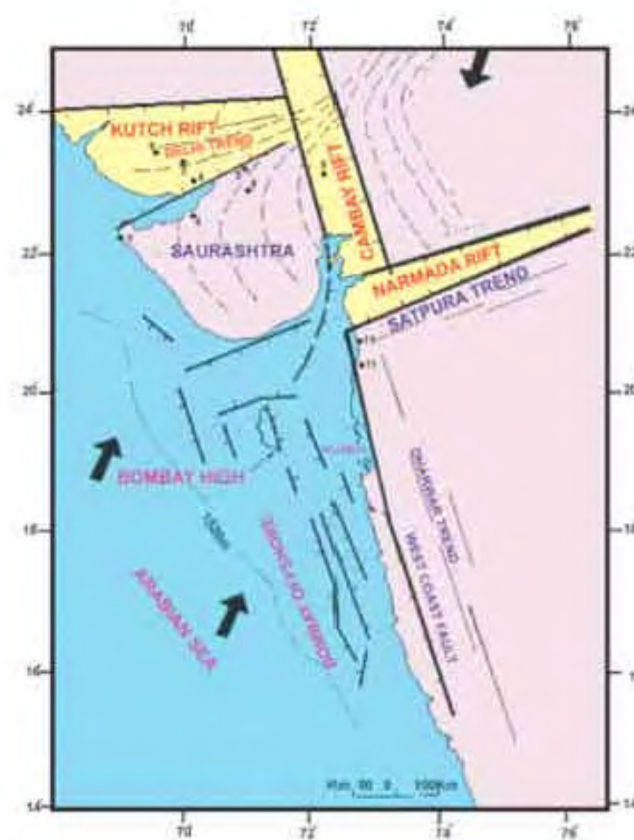
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The Kutch basin is a western margin pericratonic rift basin of India. Nagar Parkar uplift in the north and Kathiawar uplift (Saurashtra horst) in the south respectively along Nagar Parkar and North Kathiawar faults delimit the E–W rift. The Kutch rift was initiated during the Late Triassic break up of the Gondwanaland by the reactivation of primordial faults in the Precambrian Delhi fold belt. The rifting was aborted during Late Cretaceous pre-collision stage of the Indian plate. During post-collision compressive regime of the Indian plate, the Kutch rift basin became a shear zone with strike-slip movements along sub-parallel rift faults. The Kutch Mainland Fault along the rift axis became the active principal fault. Presently, this right lateral strike-slip fault is overstepped by the South Wagad Fault in the eastern part of the basin. The overstep zone between the two wrench faults is a convergent transfer zone undergoing transpressional stress in the strained eastern part of the basin. The epicenters of two big earthquakes as well as the aftershock hypocenters of Bhuj earthquake are located within this zone. The study of the intrusive rocks, rift geometry and seismic tomography indicates presence of a large ultramafic body in the lower crust. An overview of the structural and tectonic evolution of the basin is discussed in the context of earthquakes. Based on structural and detailed depth-wise analysis of aftershock data, a conceptual domino-listric model of Kutch rift is presented here. On the basis of this model, an attempt is made here to explain the dynamics of the earthquake generation in the Kutch basin.

THE sedimentary basin of Kutch occupies the entire district of Kutch in Gujarat State of Western India close to its western border with Pakistan, between lat. 22°30' and 24°30'N and long. 68° and 72°E (Figure 1). It is an east-west oriented pericratonic rift basin at the westernmost periphery of the Indian craton<sup>1,2</sup>. The basin is a fossil rift at the southern end of the Indus shelf and is bordered on the north by the fossil rifts of Thar and Southern Indus basins<sup>3</sup>. To the south occurs another parallel rift basin, the western offshore extension of Narmada rift, with the Saurashtra horst between them. The north–south trending Cambay rift crosses the two parallel rifts. Together, the three rifts

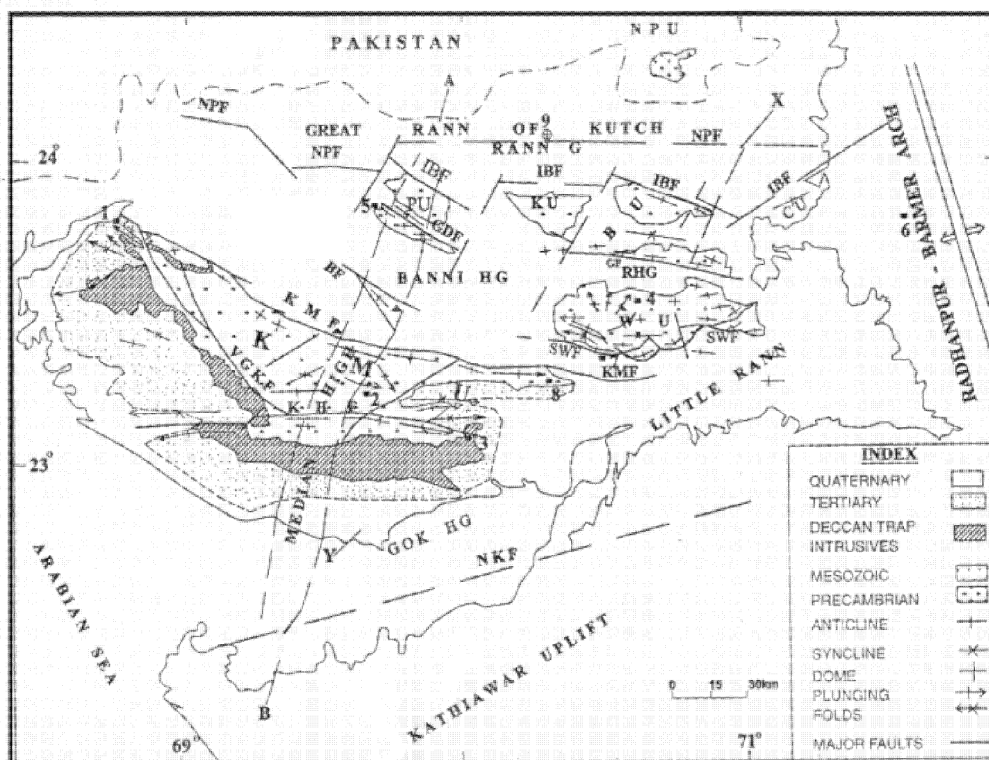
form an inter-connected rift system around the foundered cratonic block of Saurashtra at the trailing edge of the Indian continental plate (Figure 1). Mumbai offshore shelf extends south of the Narmada rift along the West Coast fault.

Mesozoic, Tertiary and Quaternary sediments fill up the Kutch basin. The sediment fill thickens from less than 500 m in the north to over 4000 m in the south and from 200 m in the east to over 2500 m in the west. To the north, Precambrian basement rocks are exposed in Meruda Takkar and Nagar Parkar (in Pakistan) hills. To the east, the Precambrian rocks, under cover of alluvium, extend over the North Gujarat plains. To the west the basin extends across the continental shelf while to the south, the uplifted Saurashtra



**Figure 1.** Rift system of Western India and major Precambrian trends (after Biswas<sup>22</sup>). 1, Bhuj; 2, Anjar; 3, Bhachau; 4, Gandhidham; 5, Maliya; 6, Jamnagar; 7, Dwarka; 8, Surendra Nagar; 9, Ahmedabad; 10, Surat; 11, Navsari. Black arrows indicate regional stress direction.

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**Figure 2.** Tectonic map of Kutch (modified after Biswas<sup>10</sup>). 1, Lakhpat; 2, Bhuj; 3, Anjar; 4, Rapar; 5, Khavda; 6, Radhanpur; 7, Adhoi; 8, Bhachau; 9, Meruda Takkar. Black triangle: Locations of drilled wells. A–B, section line of Figure 3. X–Y, section line of Figure 4.

platform covered by Late Cretaceous sediments and Deccan Trap lava delimit the basin.

The region is conspicuously featured by uplands surrounded by lowlands (Figure 2). The uplands are rugged hilly terrain exposing the Mesozoic rocks bordered by thin strips of gently dipping Cenozoic rocks which form coastal plains. The lowlands are extensive plains, alluvial or mud and salt flats (*Rann*) and grassy undulations (*Banni*). The highlands are the areas of uplifts and the plains are intervening basins. No outcrop is seen within the featureless plains and consequently subsurface information is lacking for these areas excepting for some geophysical and well data.

Geologists of the Oil and Natural Gas Corporation carried out detailed mapping for more than one and a half-decades followed by basin analysis. Based on this work Biswas<sup>4,5</sup> presented a detailed account of the structure and tectonics of the basin. A review of the same is presented here with an attempt to work out a geological model incorporating seismotectonic data<sup>6–8</sup>. The proposed conceptual model attempts to integrate the causative rupture surface of the earthquake, as interpreted from the aftershock data, with the mapped structural framework of the rift basin undergoing convergence.

### Basin architecture

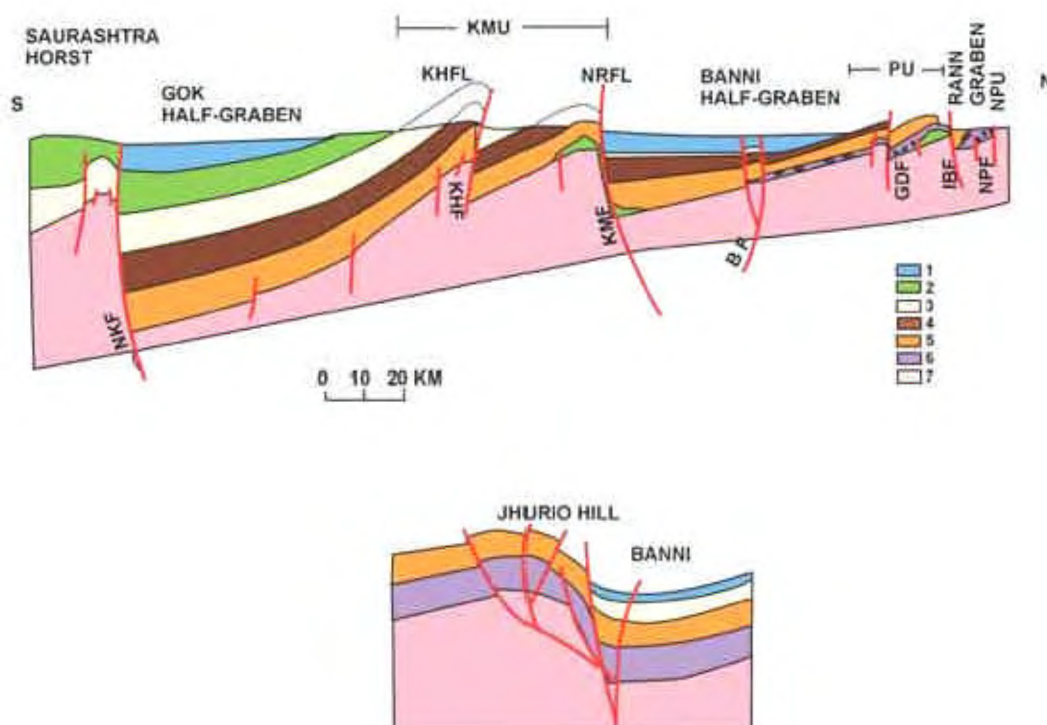
The basin has the typical geometry of an asymmetric rift basin tilted to the S (Figures 2 and 3). The Nagar Parkar

Precambrian block and Saurashtra block are respectively the northern and southern rift shoulders. The Radhanpur–Barmer basement arch is the hinterland high, which limits the rift extension to the east. To the west, the rift is open, merging with the continental shelf. The basin slopes towards the southwest. The shoulder highs and the hinterland are the source areas for sediment supply. The sediment fill has the typical synrift fill signature, e.g. development of conglomerate fan lobes along the bounding faults along with sediments of axial and hanging wall drainage.

The most striking feature of the basin is the occurrence of a first order meridional (NNE–SSW) high across the middle of the basin<sup>1</sup> (Figure 2). It passes transversely across both positive and negative elements of the basin so that the uplifts plunge bilaterally and the sub-basins have a central high or shallow region. It has a strong geomorphologic expression in the present-day landscape. The raised ground of Banni above the Rann surface is an expression of this subsurface high. The MH, which controls the sediment facies and thickness<sup>1</sup> is a tectonized zone along the hinge line of the basin.

### Stratigraphy

The stratigraphy of Kutch consists of three packages – Mesozoic, Tertiary and Quaternary. The Mesozoic package comprises Late Triassic (Rhaetic) continental, Middle to Late



**Figure 3.** Geological cross section across Kutch basin along axis of Median High in Figure 2: line A–B. Vertical scale exaggerated. KHFL, Katrol Hill Flexure. NRFL, Northern Range Flexure. Box index: 1, Quaternary and Tertiary; 2, Deccan Trap/intrusives; 3, Lower Cretaceous; 4, Upper Jurassic; 5, Mid. Jurassic; 6, Lower Jurassic–Upper Triassic; 7, Precambrian. (*Inset*) Sketch section across Jhurio dome in NRFL, suggesting flower structure (see text).

Jurassic marine and Late Jurassic to Early Cretaceous fluvio-deltaic sediments. Mesozoic sediments are the rift-fill sediments and constitute the major part of the basin fill. The Tertiary sediments, on the other hand, are mostly shallow marine shelf sediments in the peripheral and intervening structural lows bordering Mesozoic uplift areas. The Quaternary consists of a wide variety of sediments ranging from marine to fluvial, lacustrine and eolian. Maximum stratigraphic succession is exposed in Kutch Mainland situated at the depocentral region. In the northern and eastern highlands, only the Lower part of the Mesozoic sequence, bordered by Late Tertiary and Quaternary sediments outcrops. The sedimentological studies suggest that Late Triassic, Jurassic and Early Cretaceous sediments were deposited respectively in early-, syn- and post-rift stages.

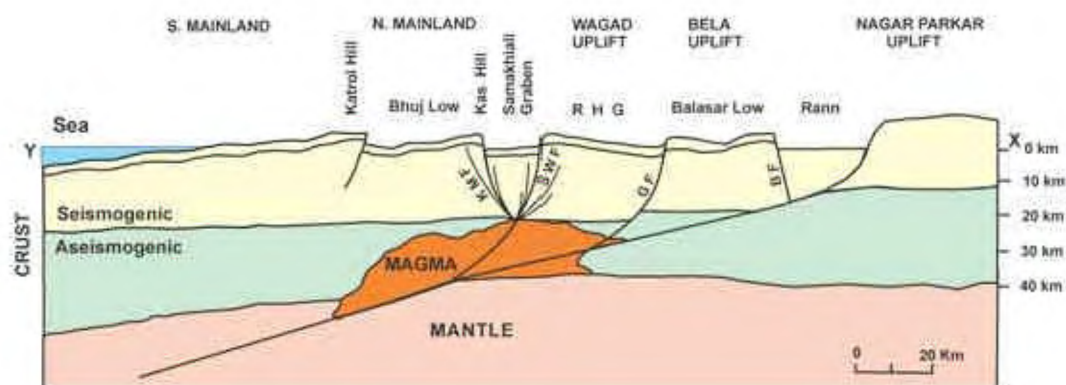
### Tectonic framework and structural style

The Kutch Rift evolved within the Mid-Proterozoic–Aravalli–Delhi fold belt by reactivation of pre-existing faults along NE–SW trend of Delhi fold belt that swings to E–W in Kutch region (Figure 1). The rift is bound on the N and S respectively by the Nagar Parkar (NPF) and the North Kathiawar (NKF) faults. The rift shoulders are uplifted Precambrian basement blocks. The graben between them is asymmetric, with a tilt to the south along NKF accommodating thicker sediments towards the Kathiawar block.

Several intra-basinal sub-parallel strike faults are responsible for the tilted block uplifts, forming a series of half grabens. Structurally, the basin contains footwall uplifts and half-grabens along intra-basinal strike faults (Figures 2 and 3). The uplifts are the outcropping areas and the grabens/half-grabens form extensive plains covered by Quaternary sediments. The plains (structural lows) around the uplifts (structural highs) form ‘residual depression’<sup>9</sup>. The graben/half-grabens are different depositional domains for rift-fill sedimentation.

E–W faults, related uplifts and drape folds design the structure (Figure 2). The marginal hill ranges of the highlands with escarpments facing the plains of the sub-basins are marginal flexures or monoclines along the master faults of the uplifts. The uplifts show typical geometry of tilted basement blocks draped over by thin sediment cover—long gently sloping back limbs and short quasi-vertical to over turned forelimbs (Figure 3). In the western part of the basin the uplifts are step faulted with southward tilt whereas in the eastern part they are differently tilted.

The uplifts are bound by five parallel faults<sup>10</sup>: from N to S, (1) Nagar Parkar fault (NPF), (2) Island Belt fault (IBF), (3) South Wagad fault (SWF), (4) Kutch Mainland fault (KMF), and (6) North Kathiawar fault (NKF). Block tilting along these faults during rift phase extension gave rise to four sub-parallel linear ridges: Nagar Parkar uplift (NPU), Island Belt uplift (IBU), Wagad uplift (WU), and



**Figure 4.** Geological section across Kutch rift along line X–Y on Figure 2 (scales approximate), and the cartoon showing conceptual model of the rift basin. See text for explanation.

Kutch Mainland uplift (KMU). The Kathiawar uplift (Saurashtra horst) along NKF is a quadrangular block bound by faults on all sides (Figure 1). The IBU is broken into four individual uplifts presumably by unexposed transverse wrench faults as evidenced by relative displacements and orientations: Pachham (PU), Khadir (KU), Bela (BU) and Chorar (CU) (Figure 2). Standing amidst the plains, these uplifts appear as a chain of *islands* and hence are collectively called *Island Belt*. Several small fault-related uplifts occur in line with the bigger ones, e.g. Kuar Bet, NW of PU and Kakindia, Karabir, Gorabir and Gangta *Bets* (small uplands), which occur between KU and WU. Fault-bounded domes and/or faulted anticlines define these small uplifts.

The positive Bouguer anomalies along the lineaments formed by these ridges indicate that these are basement highs<sup>1</sup>. The E–W trend of the positive gravity lineaments changes to NE–SW across the Cambay basin following the trend of the Delhi fold belt. This confirms the control of the Precambrian trends in rifting. The NE–SW orientation of CU is significant in this context.

From north to south, the Great Rann sub-basin is a narrow graben (GRG) between NPF and IBF, the Banni half graben (BHG) is formed by southward tilting of the IB block, similar tilting of the KM block formed the Gulf of Kutch half-graben (GOKHG). In the eastern part the WU, placed en echelon to KMU is tilted to the north along Gedi fault (GF) forming Rapar half-graben (RHG) (Figure 4). The GF bounds the Bela horst to the north (Figure 2). The comparatively thin sediment cover was apparently drape-folded over tilted basement blocks producing linear monoclinical flexures or *bruchfaltens*<sup>11</sup> along the faulted margins of the uplifts. Strings of closed structures, viz. domes, brachy-anticlines and doubly plunging elongated anticlines of varying dimensions and shapes, in turn feature the marginal monoclines. The marginal/master faults are exposed wherever the flexures are eroded (Figure 3). The southern part of WU is tilted up along a complicated pattern of faults with associated folds.

The southern parts of PU and KMU are affected by faults parallel to the master ones along their northern margins – Katrol Hill fault (KHF) in KMU and Goradongar fault (GDF) in PU. These southern fault blocks are also tilted north side up producing sharp flexures in the same style as that along the marginal faults (Figure 3). Each of these uplifts is thus styled by a pair of north-side-up step faulted blocks accompanied by flexures with chains of closed structures and intervening half-grabens forming synclinal structures: Bhuj syncline (BS) in KMU and Dhorawar syncline (DS) in PU.

Limited seismic and drill data (ONGC source) suggest homoclinal slope of the hanging wall of BHG rising to PU. Maximum sediment thickness recorded close to the fault (KMF) is 2.2 km, thinning gradually towards PU. About 350 m Tertiary sediments lie unconformably over the Mesozoic rocks below the Quaternary cover of BHG. This shows the post-Tertiary reactivation of the fault. Further, steeply upturned Tertiary beds juxtaposed with steeply folded Mesozoic beds along KMF indicating posts-Tertiary movements.

The KU is a south-tilted block, northern fault and flexure being eroded and covered by Rann sediments. In PU parts of the northern flexure are exposed. The BU is a horst bound by E–W faults forming marginal flexures with a central syncline. Most parts of CU flexure have also been eroded away and covered by the sediments excepting in the westernmost part.

The MH stretches NNE–SSW across GOK HG, KMU, BHG, PU and beyond. It divides the KMU and BHG almost symmetrically. No uplift is seen NW of this orthogonal high. West of the high is the featureless *residual depression* of the Great Rann (Figure 2).

The E–W striking master faults (Figure 2) are the primary faults, which controlled the structural evolution. The fault pattern as mapped and seen on the outcrops show common features, characteristic of strike-slip faults<sup>5</sup>. The en echelon arrangement of the faults in map view suggests



dextral slip. Uplifts themselves are extensively affected by secondary faults of different generations, both normal and strike-slip ones as also a few reverse ones. These faults appear to be cogenetic with the primary faults. There are different generations of faults developed during episodic movements along the PDZ. Some of the NE–SW striking faults are extensive wrench faults and dislocate the primary faults.

A 4 km-wide-zone of no reflection in BHG, close to the faulted escarpment of KMU, is seen in the seismic data (ONGC source). This zone of no reflection suggests near vertical attitude of the fault at depth. A well drilled north of Nirona close to exposed KMF (Figure 2), reached basement at a depth of 2.2 km (ONGC). From this it is concluded that KMF is a planar domino fault bounding a large basement block.

Eastward KMF side steps to the north as SWF. The two faults overlap north of Dudhai–Bhachau segment (Figure 2). The relative position of KMU and WU blocks suggests right lateral strike-slip. Thus, SWF is the eastward continuation of KMF after its left side stepping, with shift of uplift from south to the north. SWF is a fault zone consisting of two curved, semi-concentric marginal faults, which converge and diverge bounding folds of varying dimensions along restraining bends. Such complex deformation zone with converging/diverging-curved fault traces and folds in restraining bends suggest convergent wrench movement<sup>12</sup>.

The overlapping tips of both KMF and SWF dip steeply (80°–85°) towards each other. Thus the overlapped step over zone is a convergent transfer zone<sup>13</sup>. The KMF fades out and SWF continues eastward as the PDZ. It is likely that at depth KMF could be either antithetic or a down dip step over<sup>14</sup> with relation to SWF (Figure 4). Left-stepping of right lateral fault indicates that the overlap zone is transpressional. Strike-slip faults tend to detach within middle or upper crust<sup>15</sup>. Further, steep faults are expected to flatten at depth towards the aseismic semi-brittle zone below the seismogenic layer<sup>16</sup>. In the present case it is most likely that SWF may flatten in mid-crust region (Figure 4).

### Igneous activity

Igneous intrusions are fairly common in all the uplift areas. All known forms of intrusive bodies are present and are mainly concentrated in the narrow deformation zones accompanying the master faults<sup>4,10</sup>. The maximum intensity of igneous activity is seen in the northwestern part of KMU west of MH and in the northern part of PU (Kala-dongar Hill) close to the marginal faults, i.e. KMF and IBF. A series of igneous plugs occur along a belt in the central region of KMU. These plugs are the main feeders of Deccan Trap flows now exposed by erosion. These plugs consist of alkaline basalts with xenoliths of spinel lherzolite<sup>17</sup> and olivine<sup>18</sup> indicating that they are derived from upper Sub-Crustal Lithospheric Mantle (SCLM). The intrusive bodies

associated with marginal deformation zone in the western KMU are composed of ultramafic rocks<sup>19</sup>. The associations of different groups of basic and ultramafic rocks are suggestive of different phases of igneous activity, viz. synrift stage, post-rift thermotectonic stage and inversion stage. During the earlier rift stage, mantle-derived ultramafic rocks might have intruded as the upper lithosphere was sheared by discontinuous stretching. During the later stage the plume (Reunion) related Deccan Trap igneous activity took place.

The various forms of intrusive bodies exposed at the surface are the manifestations of rift-related magmatism. These intrusives only represent a fraction of the large volume of melt that was generated during rifting. Stress-induced lithospheric stretching may cause decompression of the lower lithosphere and asthenosphere and their consequent partial melting during rifting. This results in diapiric rise of melts into the zone of thinned lithosphere causing a pillow-like structure below the rift zone. In the present case, similar structure is evident from seismic tomographic data<sup>6,7</sup>. Diapirically rising melts ponding at the crust/mantle boundary creates additional stress for thermal doming of the mantle<sup>20</sup>. Permeation of the lower crust by mantle-derived melt may be related to the process of magmatic underplating. Raval<sup>21</sup> discussed the role of thermomagmatic influx in deep crust during rifting. Bouguer gravity anomaly data, which corroborate with the rift structures, indicate underplating of high-density material in Kutch–Saurashtra–Cambay region. These occurrences suggest the presence of large magmatic body in the deeper crust close to the mantle formed by lithosphere melting and injection in the lower crust during rifting.

### Tectonic evolution

The left-stepping KMF/SWF seems to be the principal strike slip-fault and main architect of the structural style. It divides the basin into two main domains of sedimentation, the BHG and GOK HG. WU block is apparently shifted dextrally with respect to KMU block. In fact, all the uplift blocks are located in the eastern part of the basin east of MH and their occurrence in the map view (Figure 2) shows an echelon arrangement with respect to KMU and right lateral shift along respective faults. The change of upthrow side in case of right lateral KMF left stepping as SWF suggest convergent wrenching with transpression in the step over zone. The horsting of BU against downtilted WU (RHG) along GF also suggests convergent wrench movement. Further, breaking up of the marginal flexures into faulted closed anticlines and domes, appear to be caused by transpressional tectonics which modified the original flexures during late stage compressive episode. Some of these folds which are highly faulted, e.g. Jhurio Dome at the northern edge of KMU, could be flower structures formed during this stage (see inset of Figure 3).

The rifting was initiated during Late Triassic as evident from the occurrence of Rhaetian early rift stage deposit. The rift expanded from north to south by extensional activation of E–W striking primordial faults. The GRG formed first and remained shallow with initial fan conglomerate and continental sediments of Rhaetian age. Successive southward younging half grabens formed with increasing thickness of sediments towards the master fault, NKF. This is evident from outcropping of the oldest sediments (Late Triassic/Early Mid Jurassic) in the northernmost IBU and successive younger rocks in WU and KMU. GOK HG subsided most along the master fault and accommodated the thickest sediment fill (Figure 3).

Evidently, the basin evolved in two stages: (1) an extensional rift phase, when Mesozoic sedimentation took place, and (2) a compressive inversion stage when the present structural style evolved. Due to near-vertical fault planes, strike-slip/oblique-slip movements dominated the inversion stage. The same set of primordial faults was first reactivated as normal fault during rift phase and later as strike slip faults during inversion stage. During the transitional phase between the two, vertical stress was dominating. The rifting was aborted during this phase when footwall uplifts were enhanced by upthrusts producing marginal flexures. Later, horizontal stress developed and strike-slip movements took place along the steep faults. As indicated by block orientation and geometry, the movement was mainly oblique slip with vertical component predominating in the initial stages of divergent wrenching followed by dominant horizontal stress during later stages of convergent wrenching.

The tectonic phases are well correlatable with the major movements of the Indian plate<sup>22</sup>. During break up of Gondwanaland the Kutch basin originated as pericratonic rift within Precambrian mobile belt<sup>23</sup>. Normal faulting formed a series of half-grabens successively from north to south. Rift fill sedimentation continued during the drifting of the plate till Early Cretaceous. In Late Cretaceous, the trailing edge of the Indian plate was uplifted as the leading edge was dragged down towards the Tethyan trench<sup>22</sup>. The rifting at the trailing edge of the plate was aborted at this time and the region was uplifted. Reversed movement of blocks along steep faults (normal faults during rifting) took place. The uplifts came into existence by upthrust of the footwall blocks. The KMF and GDF were activated during this time. During the drifting of the Indian plate, the horizontal stresses increased and wrench-related structures developed. This tectonic episode reached its acme in Late Cretaceous when the plate motion was accelerated considerably prior to its collision with the Tibetan plate. At this stage divergent wrench movements set up the framework of the present structural style. Post-collision stage was the period of compression and wrench movements were mainly convergent as evidenced by the positive flower structures. This tectonic movement continued episodically since Early Tertiary till present day, causing neotectonic

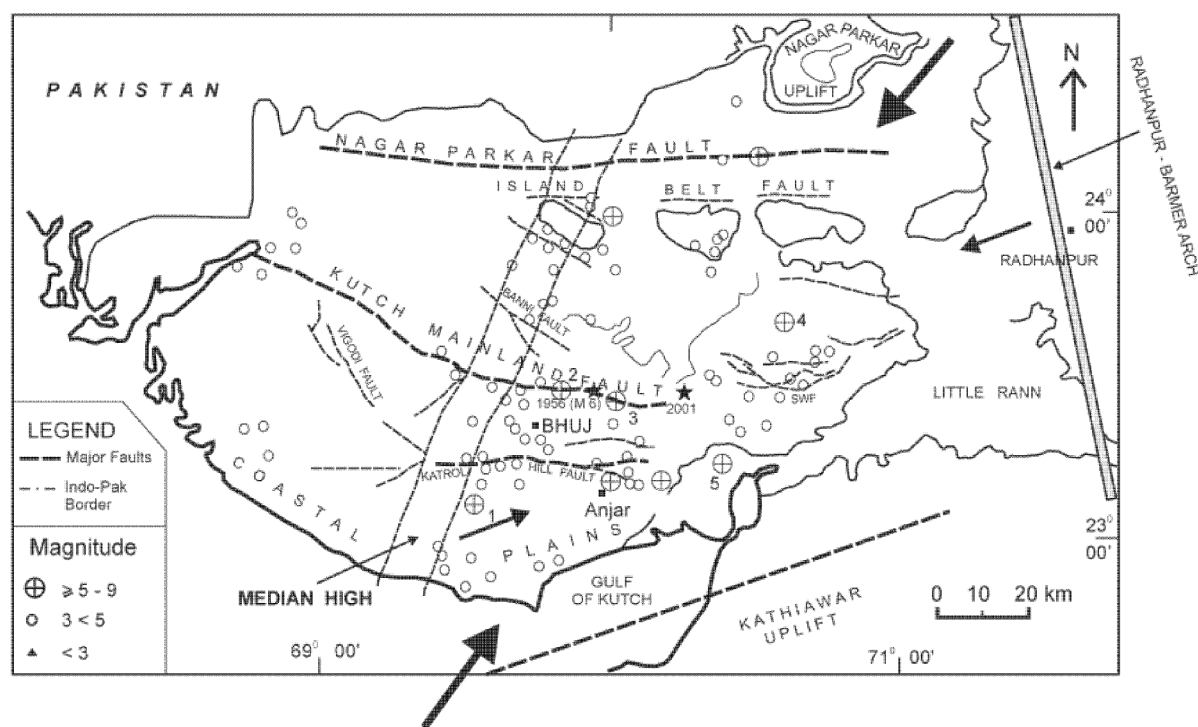
movements. First order topography, local thrusts on the back limbs of uplifts, local occurrences of fault-propagated folds, overturned limbs of the flexures<sup>24</sup> are some of the evidences of neotectonic activities.

Radhanpur Arch acting as a ramp constrains the right lateral movements along faults north of KMF (Figure 2). This is causing additional compressive stress between it and the MH, which is acting as a transfer zone. Consequently the eastern Kutch east of MH (East Banni-Wagad region), is under increasing stress which adds to the overall NNE–SSW compression of the Indian plate. This is evident from the concentration of seismic events as recorded for past several years<sup>25</sup> in this part of the basin (Figure 5). In this part, the KMF–SWF overlap zone (Samakhiali graben<sup>10</sup>) is a zone of transpression as discussed earlier. In the current tectonic cycle, this zone is further strained by the regional compressive stress and the local intra-basinal stress mentioned above. It is thus the most favoured site for earthquake generation.

The tectonic episodes were accompanied by deep crustal magmatic activity. At least two phases of magmatic activity are evident. The first activity took place during extensional stage when ultramafic rocks intruded into the older Jurassic sediments. Presumably at this time the deep-seated magmatic body was emplaced at the site of the mantle rupture close to the basin center. The other activity took place during Late Cretaceous post-rift uplift stage when plume related alkali and tholeiitic basalts were intruded into the younger Early Cretaceous sediments and extruded as the Deccan Trap flows.

### Rift model

The aftershock data indicate depth-wise stress variation and deformation pattern. 11% shock occurred in 10–20 km depth zone, 47% in 20–30 km, 25% in 30–40 km depth zone and 5.5% below 40 km<sup>7</sup> (Figure 6). Displacement pattern is uniformly north-directed thrust, on a 47° south dipping plane<sup>7</sup> with mostly left lateral shear in deeper crust and right lateral in the upper crust above 10 km<sup>6</sup>. Kayal *et al.*<sup>6</sup> reported an aseismic layer at around 10-km depth, which seems to be the boundary of the lower crust. A depth-wise discontinuous stretching model of simple or combined shear rifting<sup>20,26,27</sup> is expected in such crustal set up. Blocks of basement rocks bound by planar faults form domino blocks of the rift system in the upper brittle crust. Presumably, the planar faults would flatten at depth towards the semi-brittle lower crust and merge with a listric link fault that cuts into the mantle. The upper mantle melts would flow into the deep lower crust causing partial melt and a large magma chamber. Ziegler<sup>20</sup> pointed out that wrench-induced pull-apart basin and oblique slip rift zones often display high level of volcanic activity. This may indicate that major wrench faults transect the entire lithosphere, thus providing conduits for magma migration to the surface.



**Figure 5.** Tectonic map of Kutch showing seismic events over last 300 years and epicenters of recent earthquakes<sup>24</sup>. Numbered large circles with cross, epicenters of aftershocks related to 2001 earthquake. Long black arrows, regional stress direction. Smaller arrows indicate intra-basinal stress.

From seismic tomography Mandal *et al.*<sup>7</sup> inferred the presence of a 60 km long (N–S) and 40 km wide (E–W) ultramafic pluton/rift pillow at the hypocentral depth of 40 km resting on the base of the lower crust. This confirms the presence of a magma chamber at the crust/lithosphere boundary as discussed above. The indication of a large conductive body close to the Median High (B. R. Arora, personal communication) could be suggestive of such a large magmatic body at depth. The Median High might be a manifestation of this. Surface occurrences and tectonic analysis, discussed earlier, suggest that there is more than one episode of synrift igneous activity followed by another phase of hot-spot related post-rift igneous activity towards the close of the rifting stage around ~65 Ma. The intrusions at the surface are derived from this magma chamber through different generations of faults developed during different tectonic pulses. The convergence/side stepping of SWF and KMF with accompanying intrusives is thus significant.

As explained by Gibbs<sup>27</sup>, the slip along the listric link fault under extensional and/shear stress was adjusted by rotation of the domino blocks and the covering sedimentary layer adjusted by flexural deformation that determined the structural style of the rift.

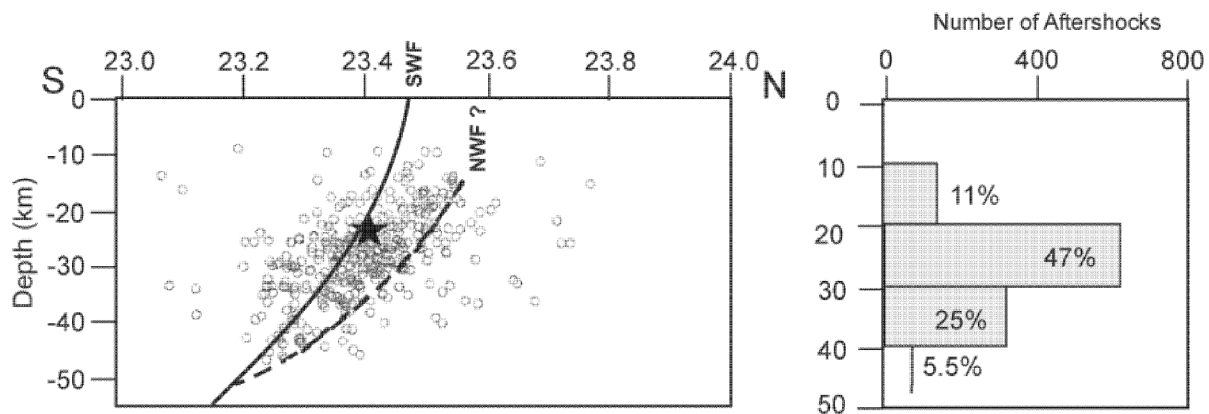
During the following rift inversion stage, contractional forces reversed movement along the faults and induced thrust motion modifying the existing structures. Under present NNE-directed compression, the Kutch rift zone is undergoing active convergence. Integrating the available

geological and geophysical data as discussed above, a conceptual model of Kutch Rift basin is presented in Figure 4. The model is depth-wise projection of the surface geology as seen in the transects across KMU–WU and KMF/SWF overlap zone (Figures 3 and 4). The faults are projected at depth following the standard geometry of fault propagation across crustal layers<sup>20,27</sup>. This model needs validation/refinement or modification by acquiring detailed 2D deep reflection seismic data.

### Dynamics of earthquakes

As discussed, the eastern segment of KMF is the most strained and active part of the fault where SWF oversteps it. Epicenters of two earthquakes, 1956 and 2001, are located in this critical zone. One of them, the Bhuj 2001 earthquake is a major one in SCR. The overlapping zone is stressed as explained above. The aftershocks of Bhuj earthquake are concentrated in this zone. SWF continues at depth with flattening dip (Figure 4). Seismic data indicate that focus of Bhuj (2001) earthquake is located at depth of 25 km on a south dipping thrust plane<sup>6–8</sup>. At that depth the quasi-vertical SWF should be passing through the lower crust with gradual flattening of dip towards the detachment surface along the listric link fault close to the magmatic body.

The distribution pattern of the aftershock hypocenters conforms to the geometry of SWF hypocenter described



**Figure 6.** Aftershock hypocentres along N-S profile through the epicentre of 2001 Bhuj earthquake (modified after Mandal *et al.*<sup>7</sup>).

above<sup>28</sup>. The distribution pattern of aftershock hypocentres<sup>6-8</sup> show a south dipping ( $47^\circ$ ) thrust plane (Figure 6). This plane matches with the lower crust segment of SWF as projected on geological considerations (Figure 4). It is to be noted that the aftershock hypocenters scatter behind the thrust where earthquake nucleates as subsidiary fractures develop at the back of the main thrust during strain adjustment (Figure 4). The 'blind' thrust, North Wagad Fault (NWF), as postulated by Mandal *et al.*<sup>7</sup> appears to be one such subsidiary fault branching off from SWF at depth within the same fault zone. The KMF/SWF are actually zones of complex faulting consisting of several intricate fracture planes related to multiple movements along these faults. The strain of thrusting along such fault zones is released either by movement along the existing fractures or by generation of new rupture plane branching off from the main thrust. Thus, it could be concluded that SWF zone is the main fault where thrusting occurred and NWF is the resultant rupture responsible for the Bhuj earthquake. The SWF seems to be the causative fault of the Anjar earthquake also since its epicentre is located in the same region. The focus of Bhuj earthquake is located close to the mafic body discussed above, where the accumulating stress due to current episode of structural inversion, is released periodically by thrusting. The trapezoidal rupture surface interpreted by Bodin and Horton<sup>8</sup> from the aftershock data could also be explained within the established geological framework. The eastern and western boundaries of the trapeze appears respectively the extension of NE-SW wrench fault inferred between KU and BU (Figure 2) and the eastern flank of the deep magmatic body manifested as MH. The Banni-Rann boundary approximately delineates the eastern limit of MH and KU-BU fault is very likely to extend southeast tangentially to the western nose of WU.

Mandal *et al.*<sup>7</sup> interpreted from seismic tomographic data that the mafic body occurring at the depth between 15 and 25 km is filled with fluid. This appears to be due to the release of fluids during serpentinization process of the mafic body. Apparently, such fluids aid the strain release mecha-

nism by lubricating the fault planes near the mafic body where the hypocentres are located. Therefore, this segment of the principal fault of Kutch (KMF/SWF) seems to be an active site for repeated earthquake nucleation and remains vulnerable for nucleation of earthquake ruptures in future also.

## Conclusions

The Kutch basin was originated as a pericratonic rift during the break up of Gondwanaland in Late Triassic. The basin evolved through three tectonic phases: (1) Rift phase, (2) Late rift divergent wrench phase, and (3) post rift convergent wrench phase. These three phases correspond respectively to break up, drifting and collision of Indian plate. The rift was aborted in Late Cretaceous, following trailing edge uplift prior to collision with the Asian plate and later became a shear zone during inversion stage following collision. Post-collision compressive regime is responsible for present active neotectonic movements. The drift motion and the counter-clockwise rotation induced strike-slip movements. The rifting occurred within the weak zone of the Mid-Proterozoic mobile belt by reactivation of pre-existing faults.

During wrench tectonics, the KMF became the principal right lateral strike-slip fault and active since then. Eastward KMF side steps sinistrally and continues as SWF. The two faults overstep each other, creating a convergent overlapping transfer zone between them. Epicenters of two big earthquakes including the major Bhuj earthquake are situated in this zone. All the aftershock hypocenters are located within this zone. The eastern part of the basin is highly strained between Radhanpur arch and Median High under the present NNE-SSW-directed compressive stress. The KMF-SWF overstep zone is the most strained part. This part is thus seismically active.

Study of intrusive igneous rocks and seismic tomographic data indicate the presence of a deep-seated magmatic



body close to the mantle. A speculative domino-listric link fault model involving lithosphere rupture and consequent subcrustal-lithosphere melting for simple/combined shear rifting is presented here. It is concluded that the SWF zone had been the causative fault for 2001 Bhuj earthquake with the nucleation zone occurring close to the sub-crustal ultramafic body.

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