CHAPTER 7
CONCLUDING DISCUSSION

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7.1 HIGHLIGHTS

Kachchh peninsula, an intra-cratonic basin, forms a part of the western continental margin. Numerous E-W and WNW-ESE trending parallel sets of faults in the region have played vital role in the evolution of the present day landscape of Kachchh represented by uplifts and depressions (Srivastava et al., 1964; Biswas, 1987). A detailed structural, tectonogeomorphic and seismotectonic aspects of Kachchh region have, however, not received adequate attention in the past. The present study, that involves the central part of the Mainland Kachchh provides information which enables a better understanding of tectonic aspects of Katrol Hill Fault Zone (KHFZ). The results of the investigations carried out by the present author have provided vital information, which is of considerable relevance towards unraveling the tectonic and seismic setup of the region as a whole. An attempt has been made for the first time to describe the spatial distribution and geometry of various faults. Also, the folding and Doming in CKM are described in detail and the model suggesting the genetic mechanism responsible for the folding in KHFZ has been proposed.

7.1.1 Structure

The region provides an avenue to study spatio- temporal distribution of a variety of structures. Although the study emphasizes on general structural pattern of the area, due to conspicuous occurrence of numerous faults, the attributes of faulting in *Central Kachchh Mainland* has been given a major attention. In the study area all the three types i.e. normal, reverse and strike-slip faults were observed.

The normal faults in Central Kachchh Mainland occur throughout the exposed Mesozoic succession, but most of these are encountered in the *Bhuj* (Late Cretaceous) formation. Sedimentary succession of the studied region characterise several zones of detached normal faults (faults that do not penetrate basement). The faults are well exposed in cliff sections and show differential morphologic geometry. The exposed sections, which appear simple at the mesoscopic scale often contain more complex pattern of *interacting and linked segments.* Such a variation is on account of changing mechanisms and superposed tectonic events. In the present study comparision of fault patterns have been made using strike diagrams because they offer a better way of comparing strikes and moreover it is difficult to measure dips and the amount of displacement of the large faults which often are complex zones rather than simple planes. From the field observations it is deduced that all major normal faulting predate the major structural inversion.

Field observations indicate that the reverse faults are present within Katrol Hill Zone only (i.e. the zone to the south of KHF). Almost all the faults observed are oriented roughly in the E-W direction and the associated beds show conspicuous drag effect, indicative of N-S crustal shortening. Interestingly it has been observed that no fault with a reverse slip is present to the north of KHF. On the basis of the field evidences it is envisaged that the major Katrol Hill Fault was selectively reactivated during the post-rift phase of structural inversion brought about on already existing rift-related normal fault. The structural inversion must have taken place sometime in Oligo-Miocene times coinciding with Himalayan orogeny in the north. A similar behaviour of regional faults has been observed by Sant and Karanth (1993) in the Lower Narmada Valley. This conclusion is drawn on the basis of the general geological and structural setup of Kachchh region i.e. the reverse nature of major Katrol Hill Fault and subordinate faults suggest the reverse reactivation of the existing normal faults under the influence of horizontal compressional stress which must have come into effect after the seizure of the large scale vocanic activity in Cretaceo-Eocene times and onset of Himalayan orogeny.

Various small and large strike-slip faults, exposed throughout the study area at most places show a distinct segmentation, a phenomena typical of strike-slip fault zones (Wilcox, 1973). All the major strike-slip faults encountered in the area trend dominantly in N-S, NNW-SSE and NNE-SSW directions, transverse to KHF. Most of these are exposed in big as well as small zones consisting of several synthetic and antithetic fault segments. Sylvester (1988), Wilcox (1973) and others have observed a close association of the faults caused on account of shortening (i.e. the reverse faults) and the strike-slip faults. Thakkar (1999) has shown several strike-slip faults cutting the KHF, which according to him are of a younger generation (i.e. post-dating the KHF). However, the present author is of the view that the strike slip faults, abutting as well as cutting the KHF are related to the stress pattern that caused reversal along KHF, and thus are coeval and genetically part and parcel of the same stress field.

Table 7.1 Major deformational events of CKM

Age	Deformational Event/s	Mode of Deformation	Evidences	Source
Jurassic- L. Cretaceous	Rifting and Major normal faulting	Extension	Development of major regional faults; stratigraphic correlation indicating pattern of deposition under the rifting conditions.	Hardas, 1969; Biswas, 1982, 1987.
U. Cretaceous- Eocene	Major igneous activity and formation of domes	Extension	Formation of domes due to major igneous intrusions.	Hardas, 1969; Biswas, 1982, 1987; This study
Oligo-Miocene to late Tertiary	Major structural inversion and folding alongwith the formation of major strike-slip faults. ------------------------ Normal faulting related to the inversion	Compression, Transpression (?) Extension	Change over of regional rift related normal faults into reverse faults. Development of fault propagation folds.	This study
Post Early Pliestocene - Holocene	Two events of uplifts in the Central Kachchh Mainland.	Compression	Development of paired terraces within the CKM	This study
Recent	Many small and large magnitude earthquakes.	Compression and Extension	Generation of related faults; field evidences and fault plane mechanisms	Chung et al, 1995; This study

In Kachchh region, the maximum principal stress axes is oriented in the NE direction (Gowd et al, 1996) and this seems to have prevailed right from the Oligo-Miocene times coinciding with the major Himalayan orogeny in the north and under the influence of which the structural inversion took place along KHF. It is therefore envisaged that all the strike slip faults are the net result of same forces that led to the reversal of all the major faults of the area. A summary of various deformational events is given in Table 7.1.

Apart from faulting, conspicuous folding is other phenomenon observed in Central Kachchh Mainland. The region of Kachchh is marked by several rift related normal faults, these were subsequently upthrusted along almost vertical fault planes (Biswas, 1982, 1987). According to Biswas (1987) the folding seen along the major faults is on account of gravitational necking of sediment along the fault planes. According to him the structural style of Kachchh basin may well be correlated with that of Colorado Plateau and Central Montana Rockies of North America. The deformation in Kachchh region, according to Biswas (1987) is on account of vertical displacement, based on the models of Prucha et al (1965). However, the conclusions of the present studies based on various field observations are at variance to Biswas (1987). Several evidences such as mesoscopic scale detachment folds and fault propagation folds exposed along the KHF and KMF point to the influence of *compressional shortening*. Such evidences therefore, lead to the difficulty to explain both i.e. a) the vertical uplift along major faults and b) compressional horizontal shortening with similar mechanism. Many basement related folds do not possess a bedding parallel thrust (flat) onto a ramp which is generally a characteristic of thin-skinned fault related folds (Brown, 1988; McConnell, 1994). Similar explanation is given for the Laramide structures of Colorado plateau and Central Montana Rockies. For these, the theory of lateral compression is more satisfying (Rodgers, 1987). During the present study, observations indicate that all major faults of the area have push from south and point to the fact that all these dip due south in the direction of displacement. The structure of Kachchh region is complex and exhibits differential pattern of separation, growth and structural relief of individual areas and such a kind of complexity is common with inversion structures formed by the compressional reactivation of pre-existing normal faults (Mitra, 1993). The present day structure of the region is thus a case of structural inversion with all major faults showing reverse slip on account of horizontal shortening due to compressive stresses. Also, the analysis of folding along Kachchh Mainland Fault and Katrol Hill Fault leads to the interpretation that the initial dip of all major normal faults must have been modified making them gentle in nature due to horizontal shortening.

Jointing is another group of meso-scale structure seen widely developed on Central Kachchh Mainland. Extensive jointing is seen in the rocks of practically all the age groups. However, the Lower Cretaceous Bhuj sandstone shows the most intensive jointing. Table 7.2 shows the orientations of joint sets cutting rocks of different age groups. The most interesting part as can be seen from various field exposures is that all the three Mesozoic formations (i.e. Bhuj, Katrol and Chari) show the development of orthogonal joint sets, where one set is roughly perpendicular to the fold axis and the other near orthogonal to it. Such orthogonal sets are commonly seen in the areas where there is sudden change in the 'least principal stress axis', commonly known as '*stress swap*'. (Hancock, 1987; Caputo, 1995). Recent work by Caputo (1995) suggests that the near orthogonal sets are formed on account of the sudden change in the direction of least principal stress axis in near perpendicular directions. The presence of such joint sets in Central Kachchh Mainland and essentially in Katrol Hill Range indicate that these must have formed in relation with the major structural inversion resulting into the development of the fault propagation folds.

7.1.2 Tectonic Geomorphology

Of late tectonic geomorphology has become an important tool to study recent crustal deformations and is even more relevant in the areas such as the present one where the information is lacking in terms of *in-situ* stress measurements and other geophysical data by which some information on the recent crustal instability could be obtained. In the present study different methods and approaches of modern tectonic geomorphology are used to study neotectonics aspects. The observations such as formation of paired terraces and narrow and deep river gorges point to the strong influence of the tectonic activity on the Central Kachchh Mainland in the Quaternary times. The conclusions drawn from the field observations are well supported by the morphometric analysis of the various geomorphic parameters. The author has carried out studies on individual longitudinal profiles of a number of streams draining north and south of KHF, essentially with a view to identify river response to active tectonism. Various morphometric parameters viz. Pseudo Hypsometric Integral (PHI), Sinuosity Fractal Dimension (*SFD*), Gradient Index (GI) and Gradient (Slope) were studied to estimate the role of active tectonics on river channel morphology. Along with this, a relatively new approach suggested by Hovius (1996) and Talling et al, (1997) to study the drainage behaviour on individual fault blocks has also been followed. The drainage related morphometric parameters indicate that there is a strong influence of active tectonic activity on the rivers draining the Central Kachchh Mainland. However, it is seen that area to the south of KHF is comparatively tectonically more unstable than its northern counterpart. The studies based on the methods of Wells et al (1988), Hovius (1996) and Talling et al (1997) indicate that the KHFZ is one of the most active areas of Kachchh region.

The alluvial fan formation along the Kachchh Mainland Hill Range and subsequent incision of fans further add to the evidences suggesting an active tectonic control on the general architecture of the Central Kachchh Mainland. Successive uplifts along the various regional as well as local faults during the late Quaternary have brought about following changes: (i) generated the colluvial debris in the catchment areas, (ii) controlled the northward flow of the rivers, and (iii) caused formation and subsequent incision of the alluvial fan lobes. It is envisaged that of the two factors i.e. tectonic adjustment and climate responsible for the formation and incision of the Kaila and Kaswali alluvial fans, tectonism predominated. The uplift of Katrol Hill Range was responsible for the evolution of north-flowing rivers, which drained Central Kachchh Mainland, and the Kachchh Mainland Fault related Northern Hill Range demarcating the northern fringe of the Kachchh mainland, provided ideal geomorphic setting for the development of the alluvial fans. The north flowing rivers emerging from the upland in the south after crossing the Northern Hill Range became unconfined over the flat low-lying Banni Plains and deposited semi-conical shaped alluvial fans at the base.

On the basis of the lithofacies analysis it is envisaged that the debris flows in Kaila fan point to two fan aggradational phases. The Kachchh mainland is characterised by ephemeral rivers that currently carry only sand and gravel as bedload. These have incised the older (? late Quaternary) fan deposits forming steep banks ranging in height from 10 to 25 m along their valleys in the lower reaches in the fan lobe areas. NNE-SSW, ENE-WSW, N-S and WNW-ESE trending fractures that are periodically activated control the present day channel courses of Kachchh mainland. These features are reflected in their straight courses and entrenched valleys, widening and narrowing of channels and valleys, and abrupt high angle deflections in channel courses. Conspicuous local braiding of the trunk channels within the fan lobes also indicate post-depositional tectonism. Incision of Mesozoic and Tertiary sedimentary succession in the rocky upland along the trunk streams have given rise to 5-10 m wide and 20-25 m deep gorges or narrow valleys. Incision of the

Quaternary sediment succession along with the bedrock resulting into formation of paired terraces (10-25 m high) suggest, uplifts in region during Quaternary. However, the precise dating of the terrace sediments would throw more light on the lower bound in terms of dates. One more fact that needs to be highlighted is that whereas the fan areas of both the rivers are similar (i.e. the Kaswali fan is 35 sq.km and the Kaila fan 39 sq.km), the drainage basin area of Kaila river (180 sq.km) is much larger than that of the Kaswali river (66 sq.km). The rivers flow across identical terrains made up of Mesozoic and Tertiary rocks. It is likely that the Kaswali fan was produced by a bigger river with a catchment further south, quite close to Katrol Hill Range, and the present day Kaswali river is a truncated remnant of this older channel which stands obliterated today. The Kaila and Kaswali fans are comparable to the other fans occurring at the base of Northern Hill Range in Kachchh region. Uplift along Kachchh Mainland Fault was the common factor that provided unconfinement to all north flowing rivers over the low-lying Banni Plains and controlled the alluvial fan architecture. The alluvial fans of Kachchh are thus typical example of fans that are reported from the tectonically active regions with arid to semi-arid climatic conditions.

7.1.3 Palaeoseismicity and Seismotectonics

The Kachchh region has a long history of earthquakes of varying magnitudes. According to Khattri (1994), the seismicity of the Kachchh basin is related to a N-S compressional stress regime originating in the collision of the Indian plate and has brought about reactivation of the major Kachchh basin faults in thrust faulting mode. The Kachchh region including the Great Rann and Banni Plains fall in the seismically active region (Zone V), which has experienced several large magnitude earthquakes. It is interesting to know that all the major towns of the region have a long history of recurring earthquakes. The Rann sediments comprise sand, silts and silty-clay marked by alternate layering, such sediments are susceptible to liquefaction and plastic deformation at earthquake magnitude 5.5-6 (Ambraseys, 1988; Obermeier, 1996).

The widespread occurrence of deformational features (around Bhirandiala, Ludiya and Allah Band), originally flat topography and absence of overburden rules out the possibilities of the structures being influenced by burial related non-seismic deformation or by slope failure. Thus, the structures identified near Ludiya are interpreted to be of seismic origin. It is quite possible that almost all the structures observed were formed by a single seismic event of large magnitude. The lack of soil development at all the sites indicates that the event must have occurred sometime in recent past.

Though, the evidence of structural offset and sand dike is rather inconclusive from the point of view of magnitude estimation. However, the formation of the seismicity-related structures in the upper portion of the Rann sediments definitely points to these being related to some of the more recent historical earthquake of relatively high magnitude.

Several deformational structures in Mesozoic and Tertiary strata were also recorded which are similar to seismites. Occurrence of small-scale folding and associated micro-faulting have been observed in the sandstone strata of Mesozoic age near Bhuj. Seth et al., (1990) have also described imprints of seismicity, like dying growth faults, rupture of shale beds and sand volcanoes from the marine Katrol Formation (Mesozoic age) near Jumara and Keera village in western Kachchh. Occurrences of seismites in earthquake prone areas, provide vital clues regarding the seismicity of an area. The structures in unconsolidated sediments provide a window towards understanding the numerous occurrences of comparable/identical structures in older consolidated sequences. It is thus possible not only to conclusively establish a seismic origin of such deformational structures, but also enable to explain the origin of similar structures in older consolidated sequences whose origin could otherwise have remained ambiguous.

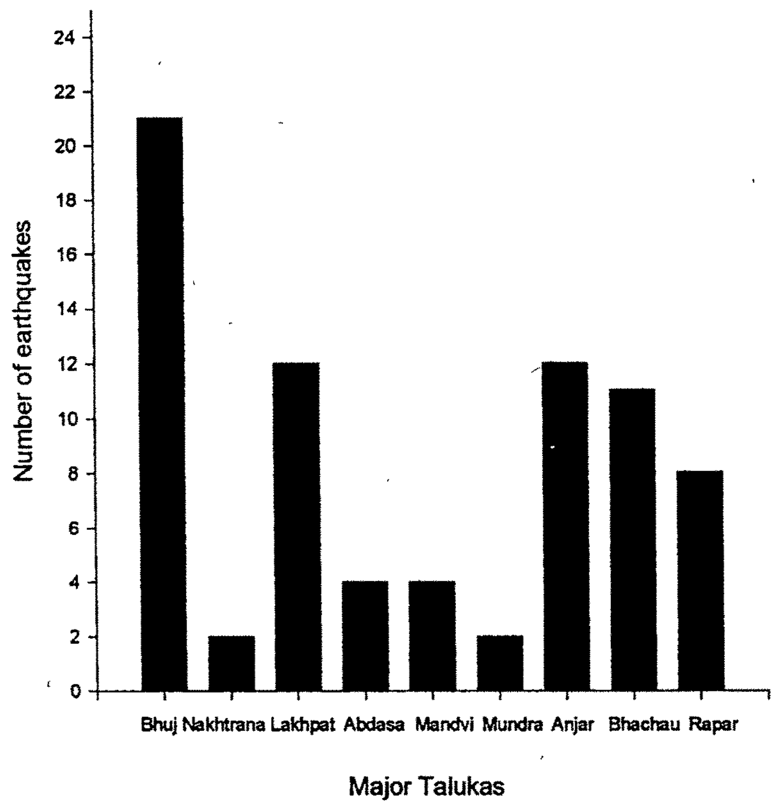

Fig 7.1 Earthquakes felt in different major talukas in the last 200 years (based on the data of Kachchh gazetteer (1971) and Malik et al, (1999)

The genetic mechanisms responsible for the occurrence of 1819 AllahBand earthquake are poorly understood. Most of the recent literature suggests that the mode of faulting responsible for the event was reverse. However, review of the earlier literature and the present-day geomorphic configuration indicate that the normal faulting must have been responsible for the 1819 AllahBand earthquake.

7.2 CONCLUSIONS

Some of the important conclusions are summarised in the following section.

1. Kachchh region in general and study area in particular has undergone structural inversion from extensional regime to compressional regime resulting into the formation of the reverse faults and the fault propagation folds.
2. Doming and folding in the area are genetically unrelated, wherein the doming in Central Kachchh Mainland appears to have been on account of igneous activity and the folding on account of horizontal shortening.
3. Most of the normal faults predate the phenomenon of structural inversion, however, some which essentially strike E-W and N-W in general are related to the extension related to horizontal shortening. The reverse faults are essentially found in Katrol Hill Range and are the result of the compressional stresses responsible for bringing out the reactivation of then existing normal faults. Most of the strike-slip faults essentially strike N-S, NNW-SSE, NNE-SSW, these are the part of the northeasterly directed compressional stresses.
4. The near orthogonal joint sets in Central Kachchh Mainland are related to major folding on account of fault propagation and sudden change in least principal stress axes in the perpendicular directions.
5. Katrol Hill Fault Zone (KHFZ) has experienced at least three events of uplift, one coinciding with the major inversion event which resulted in the large scale drainage reversal and the other two post dating it. The chronology of the later events is inferred on the basis of individual paired terraces exposed within the KHFZ.
6. Morphometric analysis of the Central Kachchh Mainland shows that the Katrol Hill Fault (KHF) is one of the most active faults of Kachchh region.

7. The drainage related geomorphic parameters indicate that the area to the south of Katrol Hill Fault is tectonically more unstable than its northern counterpart.
8. Integration of the structural, tectonogeomorphic and the seismic aspects indicate that the Kachchh region in general and the Central Kachchh Mainland in particular are traversed by several active faults viz. Kachchh Mainland Fault, Katrol Hill Fault, Allah Bund Fault, Mahadev Temple fault, Naira river Fault, Bhujpur Fault, Marutonk Dungar Fault, Wadwa Fault, Godpar Fakirwari Fault, Sanosra Dungar Fault and Wagad Fault.
9. Presence of the soft sediment deformational structures in the Great-Rann sediments near Khavda indicate that an earthquake of Magnitude > 5.5-6 must have occurred in the recent past. The future work, however, would enhance the existing knowledge.
10. Studies related to the genesis of Allah Bund indicate that the faulting involved was of normal nature.
11. The seismic hazard analysis indicates the presence of four major seismo-active zones in Kachchh region.