CHAPTER 4
STRUCTURAL GEOLOGY

4. STRUCTURAL GEOLOGY

4.1 GENERAL

Kachchh basin in general, is characterised by a variety of structures that reflect a prolonged complex deformational history. Biswas (1987) explained different structural aspects of the basin wherein he identified four major E-W trending regional faults [i.e. the Nagar Parkar Fault (NPF), Island Belt Fault (IBF), The Kachchh Mainland Fault (KMF) and the Katrol Hill Fault (KHF)] (Fig 3.3). The present study (Fig 1.1) that focuses on the *Central Kachchh Mainland* which is traversed by one of the major faults (i.e. the Katrol Hill Fault encountered in the region of Kachchh). Major objective of this study is to give a detailed information on structural aspects of *Katrol Hill Fault Zone* (KHFZ) and a) to contribute to the understanding of structural evolution of Central Kachchh Mainland in general and the study area in particular and b) to suggest possible mechanisms responsible for the present day structural set up of the region.

To achieve the above objectives detailed mapping of major and minor structures was carried out. The area under investigation provides a good avenue to study a variety of structures developed as a result of tectonic and structural evolution of the basin. The features including faults, folds, joints and dykes were mapped taking a number of traverses throughout the Central Kachchh Mainland. With a view to give a detailed picture of the region in terms of different structural features, the author has described a composite picture of various features like faults, folds and joints. Further, an attempt has been made to suggest the mechanisms responsible for their genesis.

Several major faults including the *Katrol Hill Fault* (KHF) alongwith domes and flexures have been mapped. This particular zone referred here to, as Katrol Hill Zone (KHZ) is the most significant structural entity of the study area. The area is characterised by several conspicuous domal structures most of, which are present to the south of KHF. Although major domes either flank the KHF or are located to the south of it, several smaller structures with quaquaversal dips were encountered to the north of KHF. On Bhuj-Mandvi road, 3 km to the south of Bhuj (in Fig 4.1) five such structures were recorded. The amplitude of these structures is, however, very less and if not observed carefully the dips of the beds may be taken in general as due south. Most of the major domes were encountered to the south of KHF. One such feature is present some 14 km south of Bhuj on the Bhuj-Mandvi road (marked 'X' in Fig 4.1). The amplitude of this dome is about 60 m with beds dipping variably on all directions. Several N-S trending faults are seen cutting through this structure, the sense of movement however was difficult to establish and as is generally observed in all the major domes of the area (Hardas, 1969). During the course of mapping, apart from the domal structures several synclinal and anticlinal structures were also observed. Dimensions and amplitude of these largely vary in scale. Katrol Hill Anticline marks one of the most significant anticlinal structures of the area. This ridge rises across the entire area right upto Ratnal and further east (Fig 4.1), however, the height of the ridge becomes insignificant away from Ratnal. This is an asymmetric anticline with dips of the forelimb varying throughout the strike of the fault. The dips of the forelimb are generally quite steep in comparison to backlimbs which are seen decreasing due south. The KHZ starting from the KHF in the north has a width of about 10 km and it is highly faulted and at places folded. The intensity of deformation is limited to areas proximal to the south of the KHF and extends from the Bharasar in the west to the Anjar in the east. However, the intensity of folding and faulting diminishes to the north, south and east of KHZ. The most interesting part of the folding and flexuring is their genesis. Studies have shown that the folding is on account of fault propagation wherein the folds encountered have a steep or overturned forelimb and a comparatively gentler backlimb.

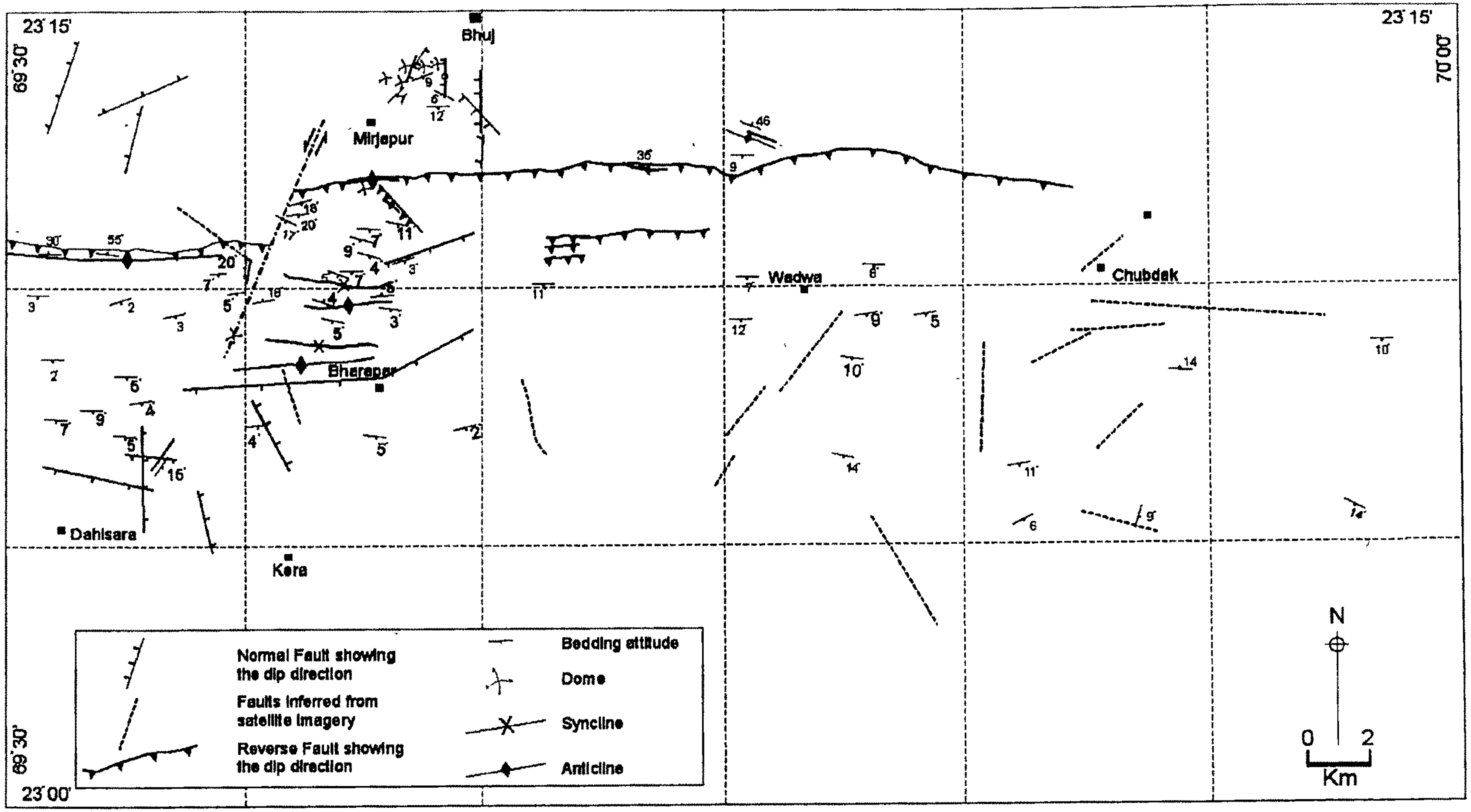


Fig 4.1 Structural map of the study area showing variety of structural features mapped during the field study (modified after Hardas, 1969)

Such a kind of geometry is common with folding events on account of fault propagation (Suppe and Medwedeff, 1990). Besides, the major part of the study area is extensively faulted and jointed with different geometries and morphologies. All major types of faults i.e. normal, reverse and strike slip were encountered. Of these, the normal faults were found to be most varied in terms of their geometry, scale and trends. The faults with reverse slip are mostly confined to *Katrol Hill Zone* (KHZ) and are essentially oriented in the E-W direction. The strike-slip faults having varying geometry and scale were also observed, these generally trend transverse to the Major Katrol Hill dislocation. A marked deformational variation to the north and south of the KHF is observed. Apart from doming, folding and faulting, jointing is one more conspicuous feature observed in the study area. Detailed mapping of joints in the field as well as lineament analysis was also carried out.

4.2 FAULTS

4.2.1 Normal Faults

4.2.1.1 *Distribution*

The normal faults in Central Kachchh Mainland occur throughout the exposed Mesozoic succession and most of these are encountered in the Bhuj Formation as it is the most extensive formation in this zone. Sedimentary succession of the studied region contain several zones of detached normal faults (faults that do not penetrate basement). Many faults are well exposed in cliff sections and show varied morphologic geometry. The exposed faulted sections that apparently appear simple often contain more complex pattern of inter-linked segments. At places variation of geometry at different scale is visible. It is likely that such variation is on account of changing mechanisms and superposed tectonic events. In this study comparisons of fault patterns are made using rose diagrams or bar charts because they offer a better way of comparing strikes and moreover it is difficult to measure dips of the large faults which often are complex zones rather than simple planes.

The distribution of normal faults throughout the Central Kachchh Mainalnd is varied. Most of the normal faults encountered show steep dips with a varied degree of refraction at the lithological heterogeneity. In all, some 104 mesoscopic faults were observed. Fig 4.2 shows strikes of major normal faults mapped in the field. The faults identified dominantly have three general trends i.e. NNE-SSW, E-W and NW-SE. The displacement along all the faults is variable ranging from a few cm to several meters.

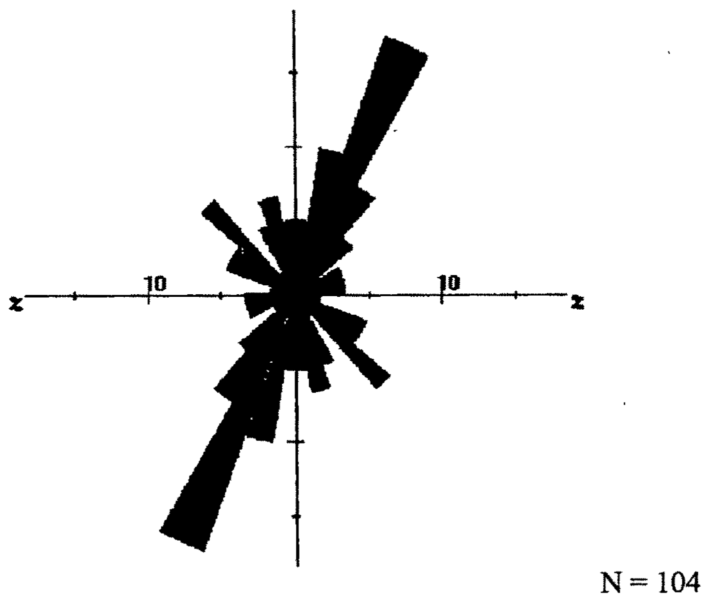
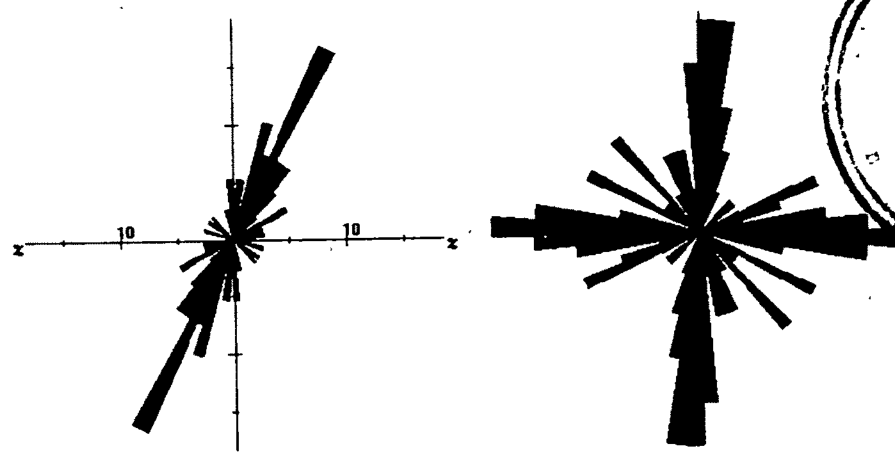


Fig 4.2 Rose plot showing the strikes of observed fault population on Central Kachchh Mainland

To get a more comprehensive picture of the faulting distribution in the area under study, the observed normal fault populations are analysed with respect to the area north and south of Katrol Hill Fault (KHF). Fig 4.3a shows the strikes of normal faults observed in the area to the north of KHF. It is seen that most of the faults strike NNE-SSW. About 65-70 % of the faults strike due NNE and the faults striking in other directions are very less in number. Whereas, the case with the area to the south of KHF (Fig. 4.3b) is different; although about 40 % of the fault population strike nearly N-S (as is seen to the north of KHF), about 40 % of the population show E-W strike.



N = 38 N = 66

a b

Fig 4.3 a) Rose plot showing the strikes of the normal faults encountered to the north of Katrol Hill Fault, b) Rose plot showing strikes of the observed normal faults to the south of Katrol Hill Fault, note the distinct presence of the E-W trend to the south of KHF

This is one of the major distinctions in the area observed to the south of KHF. Thus, it can be deduced that the NNE striking normal faults dominate the area to the north of KHF with N-S and WNW being the minor trends, while north and east striking faults dominate the area to the south of KHF with NW and NE being the minor trends.

4.2.1.2 Geometry and Morphology

The previous work on the structural analysis of Kachchh Mainland was on a regional scale rather than detailed description of geometry and morphology (e.g. Biswas, 1982, 1987). In the last decade, however, there is globally a growing interest in fault geometry and morphology. It is therefore an attempt has been made by the author for the first time to describe faulting geometry and morphology for the Kachchh Mainland.

Normal faults are not simple weak planes but are composed of several complex segments. These zones generally occur in both map and sectional views with variable geometries and morphologies. Often they are found as isolated residual scarps running from meters to several kilometers. These, many a times may be composed of overstepping and linked segments having sizeable bends, the significance of such features have been described from many areas by other workers (e.g. Crone and Haller, 1991; Peacock and Sanderson, 1991; Williams and Vann, 1987; Peacock & Zhang, 1994). The study related to such oversteps and bends is important in light of recent studies on active faults (Aki, 1979; Zhang, et.al, 1991). These workers show that oversteps and bends cause faulting. This in turn helps to understand the general nature of development of a fault zone, which may serve as a potential site for a future earthquake foci (Sibson, 1989; King and Nabelek, 1985).

The geometry of normal faults in Central Kachchh Mainland is quite varied, however, there is much consistency in the general dip angle. Fig 4.4 shows the stereographic projections of the observed normal fault population in Central Kachchh Mainland.

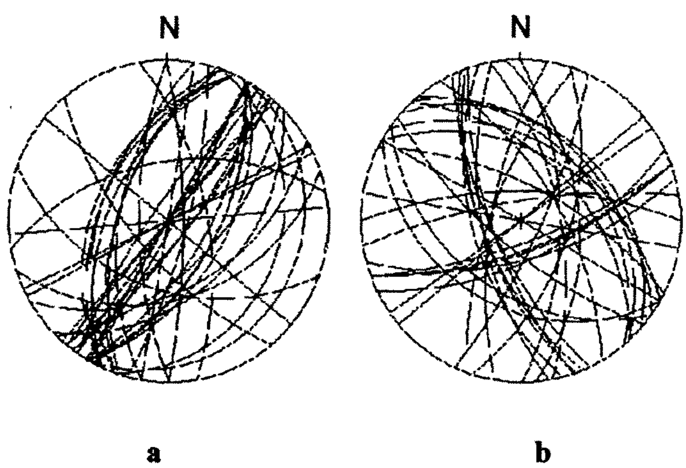


Fig 4.4 a) Stereographic projections showing the attitudes of major normal faults to the north of Katrol Hill Fault, b) Stereographic projections of the observed major normal faults to the south of Katrol Hill Fault (only those faults are plotted where the dip of the fault and the dip-direction are precise)

The displacement characteristics of individual faults are also varied. The observations made at a site to the north of Bhuj indicate that the displacement is generally greatest at or near the center of the fault and decreases towards its tips (Fig 4.5). It is seen that the profiles resemble the shape of an inverted bell, which is generally the case with most of faults (e.g. Sclische et al, 1996).

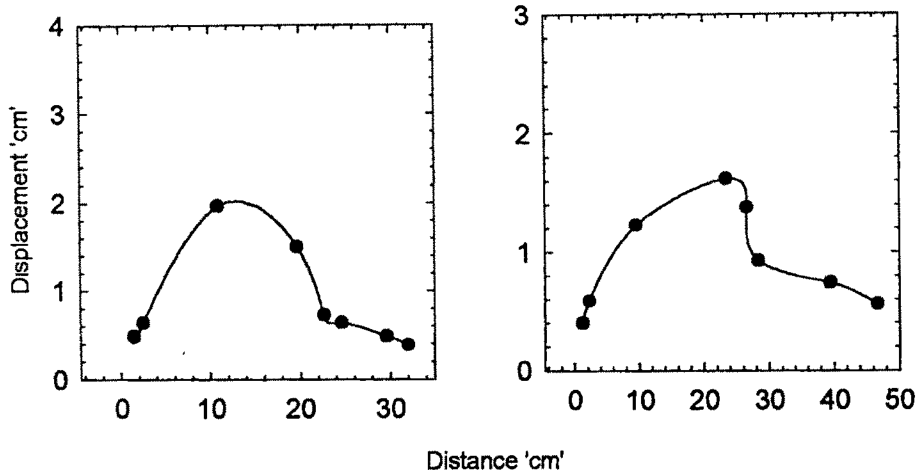


Fig 4.5 Graph showing the displacement profiles of two mesoscopic faults observed near Bhuj, note the general bell shaped nature of the profile indicating the maximum amount of displacement near the center.

Another important feature observed in some of the faults is the refraction of fault planes at a lithological heterogeneity. As has been mentioned earlier, most of the normal faults are seen cutting Bhuj Formation consisting of sandstone-shale succession. Many faults when cut through the shale units of the succession show sudden refraction of fault planes and the dip angle is seen decreasing in most cases. In the present study the description is, however, more generalised and a focused study on geometric aspects would throw much more light on the existing data.

4.2.1.2.1 *Fault Scarps*

Fault generated landforms can serve as sensitive indicators of tectonic activity. The definition of the term '*fault scarp*' varies among workers, and because of this, the fault scarp is referred here to as a tectonic landform coincident with a fault plane along which the movement has taken place and preferably possess kinematic indicator (in the form of the feature slikenslided surface). Throughout the studied region several fault scarps are exposed, especially in Mesozoic sediments. Fig 4.6a & b show some prominent exposures of fault scarps with kinematic indication of dip slip movement.

As mentioned earlier most of the fault scarps observed, are exposed in late Cretaceous Bhuj Formation which consists of sandstone shale sequence. Almost all the scarps are quite distinct from residual fault scarps described by Stewart and Hancock (1990) in Wasath fault zone of United States because, these seem to be fresh, cutting through the sandstone units of Bhuj Formation. These may be taken as the miniature of the features that have been expressed as *fault fins* by Davis (1998). Most of the scarps observed show bladed appearance often having marked lineation showing the sense of displacement along the plane. The exposed scarp height varies from a very meager 10 cm to several meters. Throughout the Central Kachchh Mainland, fault scarp morphology is seen changing from one fault to another, often running for hundreds of meters. At places the fault scarp morphology changes laterally along a fault zone, and such kind of morphology is interpreted commonly as the surface expression of a deeper level segmentation of a fault zone (e.g. Crone and Haller, 1991). The zones of such smaller fault fins when seen collectively are arranged in sets and exhibit preferred orientation. Many a time such a landscape gives pseudo resemblance to the presence of a swarm of resistant dykes (pseudo-dye swarms). One of the major component that controls such fault fins is the deformational banding of tectonic origin (Davis, 1998).

Deformation bands (Fig 4.7) are the smallest visible shear fractures in porous sandstones (also called granulation seams, micro faults or shear bands) (Aydin, 1978; Antonelli et al. 1994) and are commonly observed in a zone at either side of faults, where the faults are defined by discrete slip surfaces (polished) (Fossen and Hesthammer, 1998).

a

Fig 4.6 a. A Mesoscopic fault scarp exposed to the north of Bhuj

b

Fig 4.6 b Fault scarp showing the segmented nature. The fault striking N20°E dies out and reappears with a change in the direction of N45°E. (site studied some 7 km North of Bhuj)

Aydin and Johnson (1978, 1983) showed a close association of deformation bands and faulting. These workers sequentially explained the development of faults with several meters of displacement from a single deformation band through time.

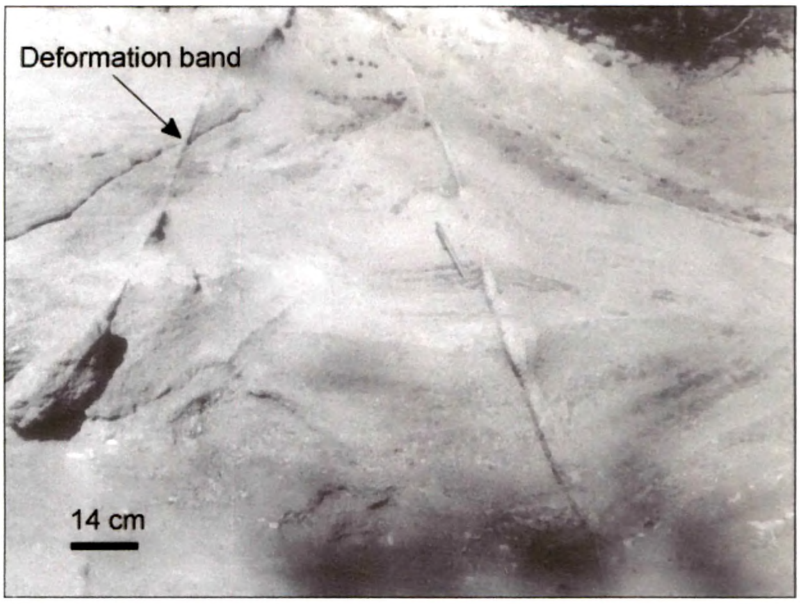


Fig 4.7 Deformational banding observed in Bhuj sandstone south of Bhuj

Many sites in the study area too, show a close association of deformation bands with major fault. As described by Aydin, 1978; Aydin and Johnson, 1983; in highly porous sandstone development of deformation bands infers a preferred deformation mechanism, this happens to be the case in the study area. Although, throughout the region the deformational banding is commonly seen, in the present context it is referred just to show its close association with the fault scarps. This becomes important because many times it is seen that the cohesion between the edge of a band and the wall rock is variable. Where the displacement is of the order of meters there is usually an evidence for fault slip along the outer walls of the band (Davis, 1998).

4.2.1.2.2 *Oversteps and Bends*

The faults may have segmented geometry, either vertical or lateral based on whether they are exposed in cross section or on plan. Although the fault segmentation is more or less a ubiquitous phenomenon a lesser attention has been paid to this aspect and in turn, the published description of normal fault segmentation in cross section is rare (Childs et.al, 1995). The fault segmentation occurs in a variety of environments on a wide range of scales (Stewart and Hancock, 1990; Peacock and Sanderson, 1994a; Morley et.al, 1990). Such fault segments are the features continuously evolving through time and may coalesce and form new segments (Segall and Pollard, 1980; Cartwright et.al, 1995; Childs et.al, 1995; 1996). Throughout the studied region there are several sites where good cross sectional view of normal dip slip faults can be had. The general stratigraphy of the sections involves the intercalating sequence of sandstones and shales. Thereby, the area provides a good opportunity to study the vertical segmentation of normal faults. At various sites in Bhuj lowland, several normal faults exposed in a near vertical cliff section were studied. The sections studied mostly have three litho-units, a) a thick sandstone unit with varying thickness from ~50 cm to ~3m, b) a variably thick (~30cm to 1.5m) shale sequence and c) the intercalating sandstone and shale beds of about ~15cm to ~50cm thickness. Due to the anisotropic litho-nature of the bedded (~5cm to 3m) late Cretaceous sandstone-shale succession, the faults cutting through it are vertically segmented over a wide range of fault sizes. This provides a basis for an attempt to analyse the segmentation. The distribution and genesis of a fault rock is controlled by several parameters including rock type, deformation and physical environment (Blekinsop, 1989).

All the major faults studied are of tectonic origin, however, the analysis presented herein is independent of the origin of the forces which generated the faults.

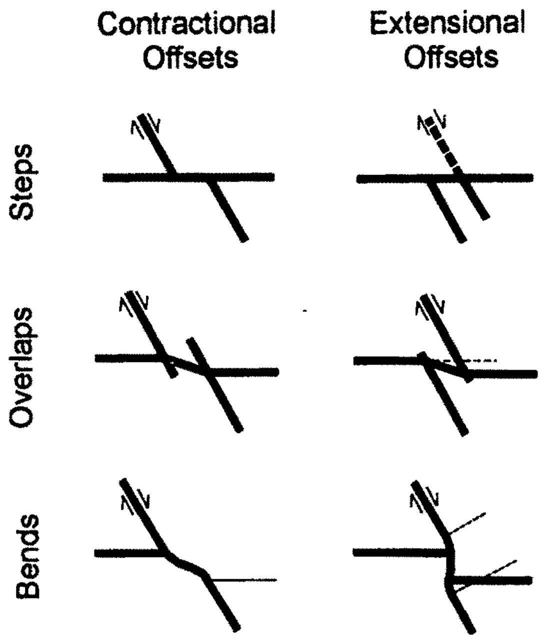


Fig 4.8 Line drawing showing different geometries forming on account of variable slip along a fault plane (after Peacock and Sanderson, 1994a)

The fault traces at the study sites are composed of a series of straight, sub-parallel, non-colinear segments. Fig 4.8 shows different varieties of geometries which, may develop during the fault propagation. The junctions between the adjacent fault segments are either discontinuous (as at fault trace steps or overlaps) or continuous (as at fault tracee bends) such features have been explained by Childs et.al, 1996;. according to these authors the contractional steps and bends are more commonly exposed than contractional overlaps, while extensinal steps and overlaps are more common than extensional bends. At contractional bends the displaced unit involved generally tends to contract and a sizeable (many times 100%) amount of thinning takes place. In total contrast a sizeable amount of thickening takes place at extensional bends.

Extensional oversteps and bends

Extensional oversteps and bends are commonly seen in several of the normal faults in Bhuj Formation. Fig 4.9 shows a good example of extensional bending at which a relative thickening of the marker bed can be seen.

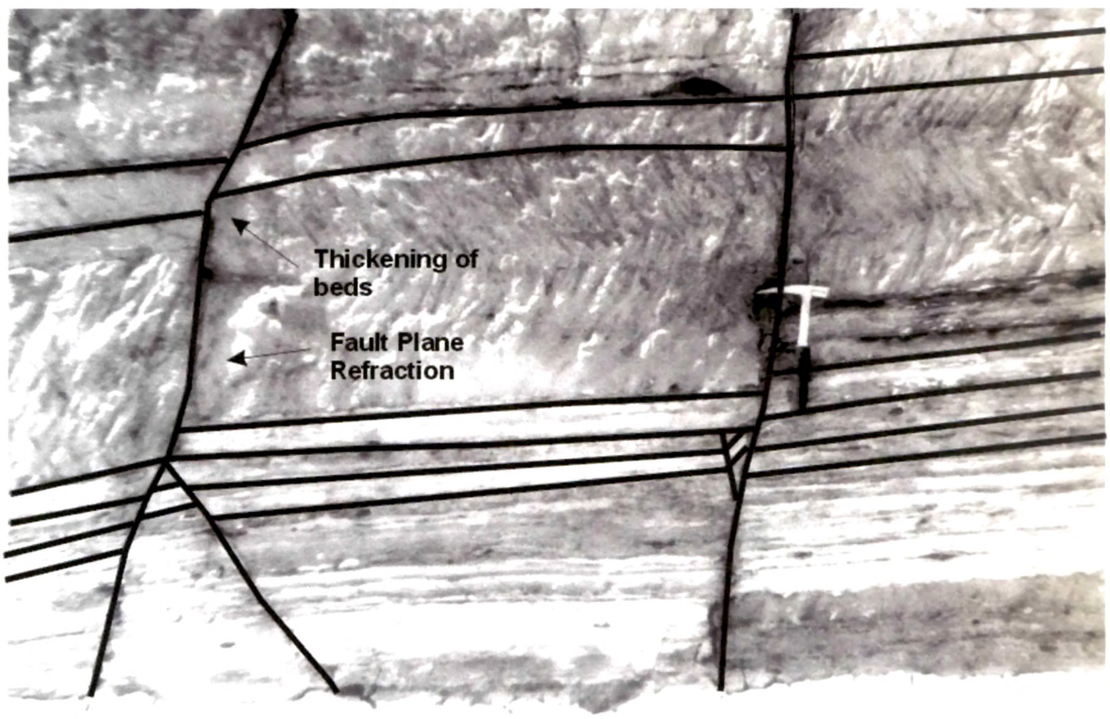


Fig 4.9 Black and white image of an extensional bending observed in Bhuj sandstone, note the refraction of fault plane at the junction of two beds (site: 3 km south of Bhuj)

Such a thickening is characteristic of extensional offset (Peacock and Zhang, 1994). Other good examples (i.e. Fig 4.10a & b, 4.11a & b and 4.12) of extensional overstep and bending can be seen in late Cretaceous sandstone-shale sequence. Fig 4.10a & b in particular shows a very well developed extensional overstep and a bend; important to note here is the increasing amount of thickness near the bend at the fault trace. Oversteps in this case are accomodated by the folding in layers of both, the hanging and the footwall.

Fig 4.10a Photograph showing a well developed overstep and a bend in Bhuj sandstone (site: 7 km WNW of Bhuj)

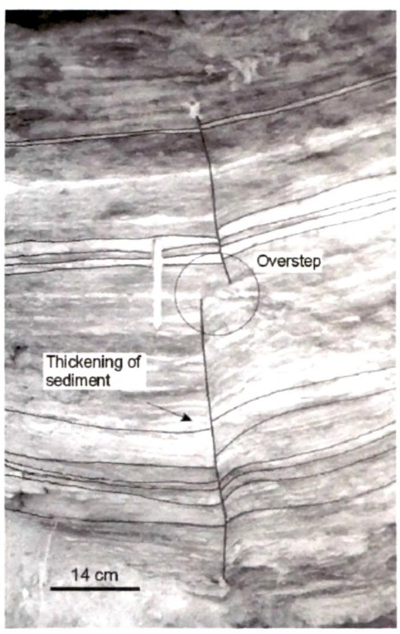


Fig 4.10 b Black & White image of photograph showing the well developed extensional overstep and a bend

It is clearly seen in Fig 4.11a & b that downward warping of beds is developed in the hanging wall and upward warping drag in the footwall.

a

Fig 4.11 a Photograph showing well developed downward warping and upward warping on account of normal fault propagation

b

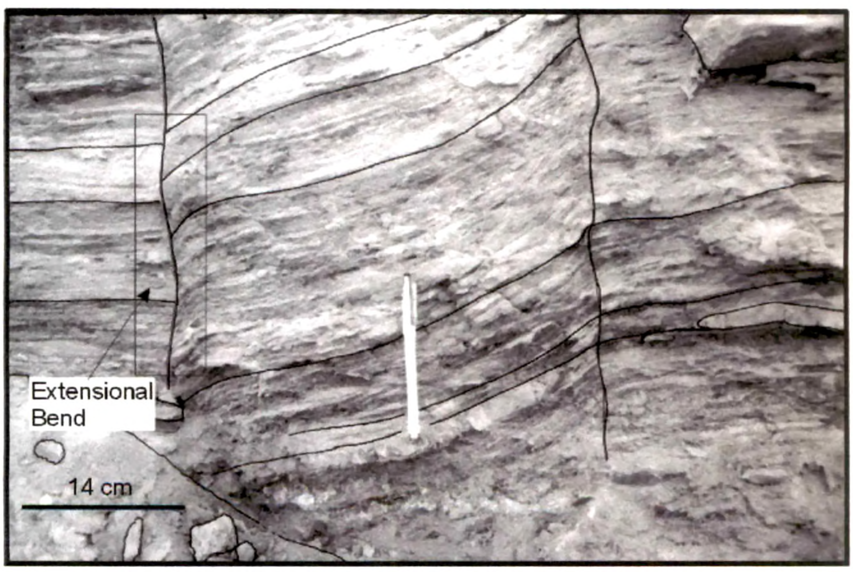


Fig 4.11 b Black & White image of an extensional bend seen in Fig 4.11a, also refer Fig 4.11c for the idealised deformation along the normal and reverse fault

where is 4.11c ?

Such a geometry of folding on account of normal fault propagation is exactly opposite to that of reverse fault (Fig 4.11c). Reverse fault propagation folding results into a hanging wall anticline and a footwall syncline. And also, at many sites a close association of synthetic and antithetic faults is common where the normal drag and extension is accomodated; this according to Peacock and Zhang (1994) is one of the most common phenomena in extensional offsets. Fig 4.12a & b demonstrate the scree filled extensional bend (pull apart) near Bhuj; here the lithounits involved comprise Jurassic limestone and shale succession.

a

Fig 4.12 a) Photograph showing pull-apart structure observed 5 km south of Bhuj

b

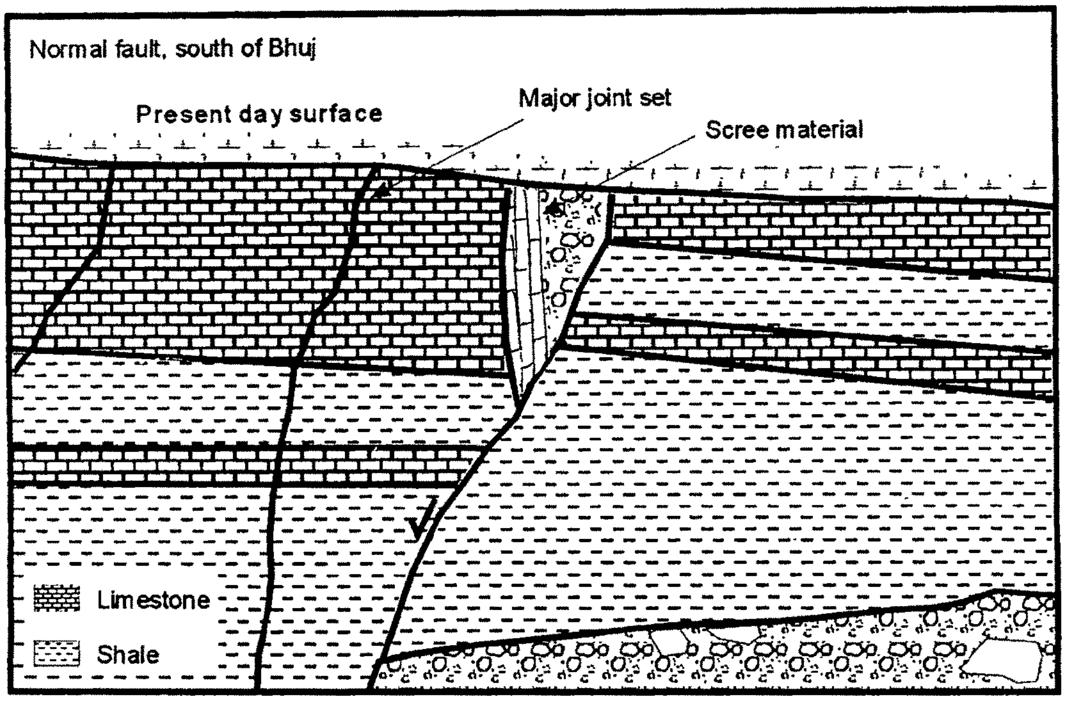


Fig 4.12 b) Line drawing of the pull apart structure observed 5 km south of Bhuj

One of the other major points to note is that the faults in all the above stated cases apparently change their dips as soon as some heterogenity is encountered (in terms of thickness and brittleness). It is also seen that the faults at almost all sites tend to cut less brittle layers at a lower angle than brittle layers. Owing to this, it seems that the amount of lithological heterogenity in terms of brittleness and thickness has controlled the fault tip propagation, a phenomenon seen by Peocock and Zhang (1994).

Contractional oversteps and bends

Contractional oversteps and bends are seen commonly developed in relatively thin shaly sequences of late Cretaceous Bhuj Formation. Fig 4.13a & b, 4.14a & b show some good examples of contractional bends formed in sandstone-shale succession. In Fig 4.13a & b it can be seen that the displacement varies from .50 cm to 3.2 m.

a

Fig 4.13 a Photograph showing contractional bending 7 km WNW of Bhuj

B

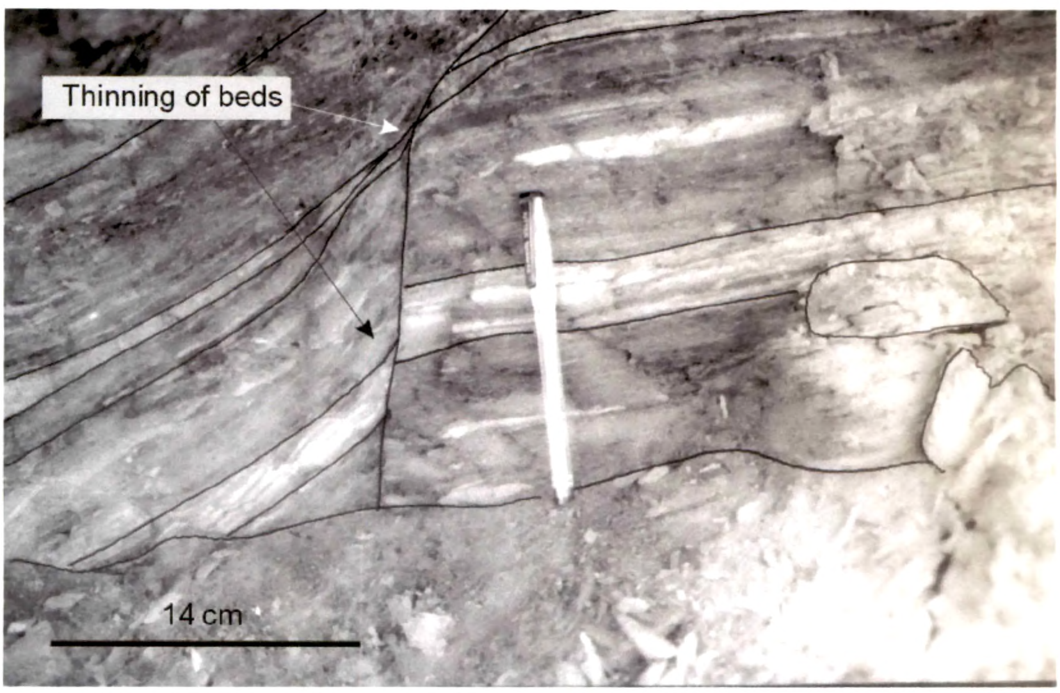


Fig 4.13 b Black and White image of contractional bending, note the thinning of beds near fault palne

It is obvious from the above examples that the thinning of beds takes places near the fault plane. Here, the displacement is transferred around bends by thinning and drag folding of shale layers or by synthetic and antithetic faults. In several cases the beds are seen to have thinned by over 50% (Fig 4.13a & b). Several faults also show a typical ramp-flat geometry (Fig 4.14a & b).

a

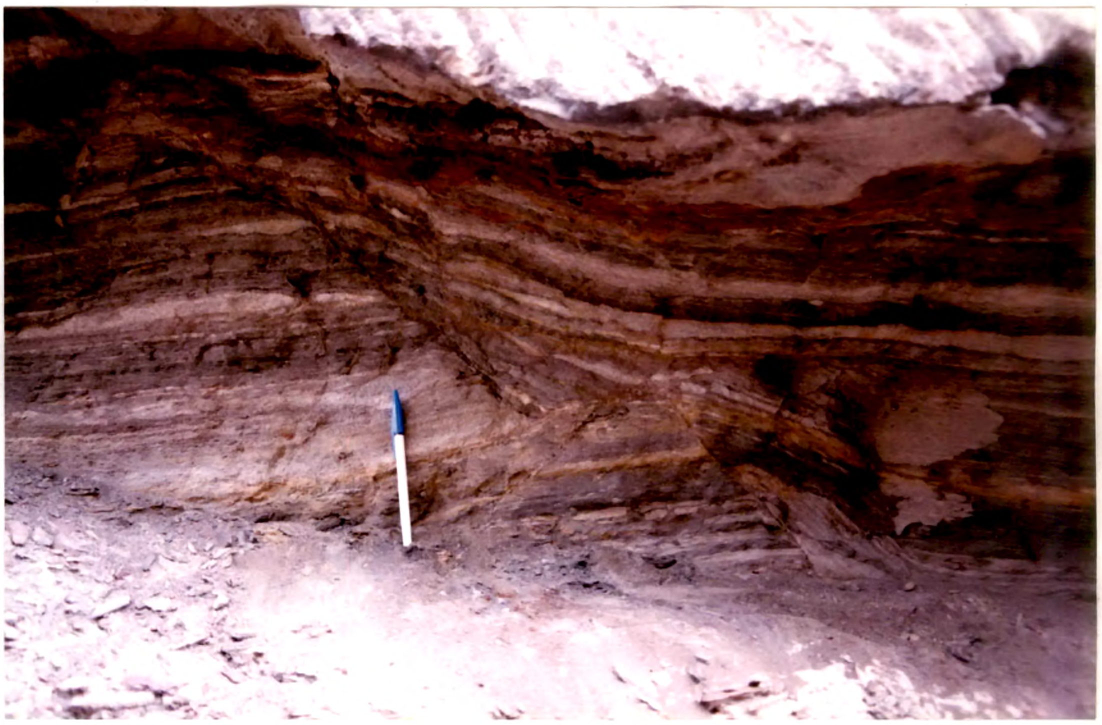


Fig 4.14 a Photograph showing a clear flat on to a ramp structure on a very small scale

Plate 4.15 typically demonstrates a contractional bend alongwith a radial fracturing and faulting (both synthetic and antithetic). According to Peacock and Zhang (1994), based on the numerical modelling of contractional bends, the radial fracturing is the net result of radial stresses developed at the contractional bends.

b

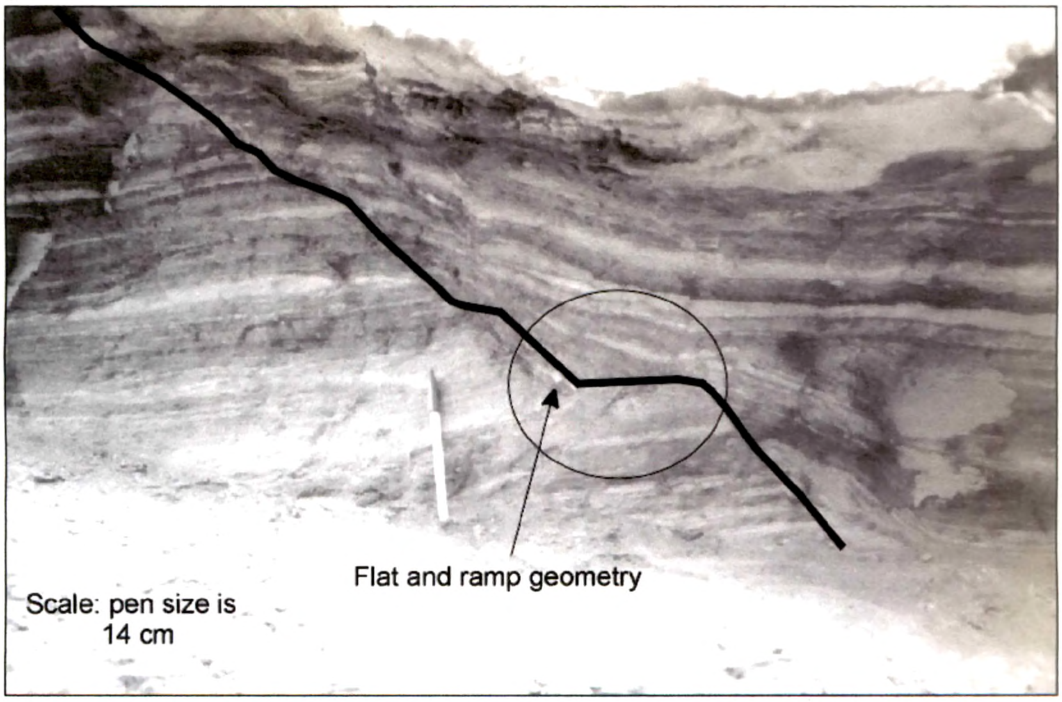


Fig 4.14 b Black & White image of flate and ramp structure observed 7 km WNW of Bhuj

Fig 4.15 Photograph showing a clear contractional bend wherein a near 50% thinning has taken place, note the radial fracturing emerging from all the sides of the plane

4.2.1.2.3 *Fault splays*

Many workers have described abrupt termination and initiation of segments referred here to as fault splays, which are essentially the faults (in some cases may be a major joint set) in association with some meso exposure faults with several oversteps and bends. Splays (Fig 4.16) generally initiate at some point on a relatively major fault and then may act as a synthetic or an antithetic with respect to the parent fault. In most cases the splays generally accommodate the higher amount of strain developed at the particular bend or a point of inhomogenity of rock type (Peacock and Zhang, 1994). Splays many times may just be in the form of a deformation band where the relative amount of slip is negligible. While interpreting such a morphology, care must be taken to study exposure in terms of their relative density, attitude and the most important being a possibility that these should not be a result of subsequent faulting episode.

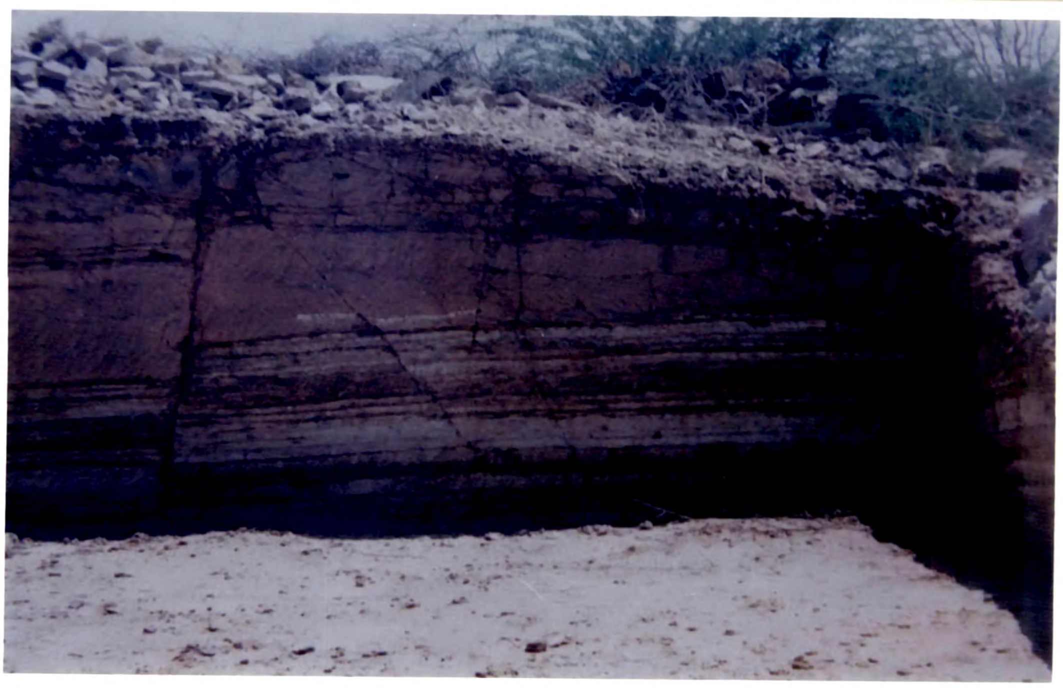


Fig 4.16 Photograph showing a fault splay at a location near Bhuj

4.2.1.2.4 *Other geometries*

At several places in the study area, conjugate faults are seen exposed more often in the Bhuj sandstone. Fig 4.17 illustrates one such site south of Bhuj on the Bhuj-Mundra road in a quarry section. This site has a number of normal faults exposed with slip varying from ~2mm to ~5m.

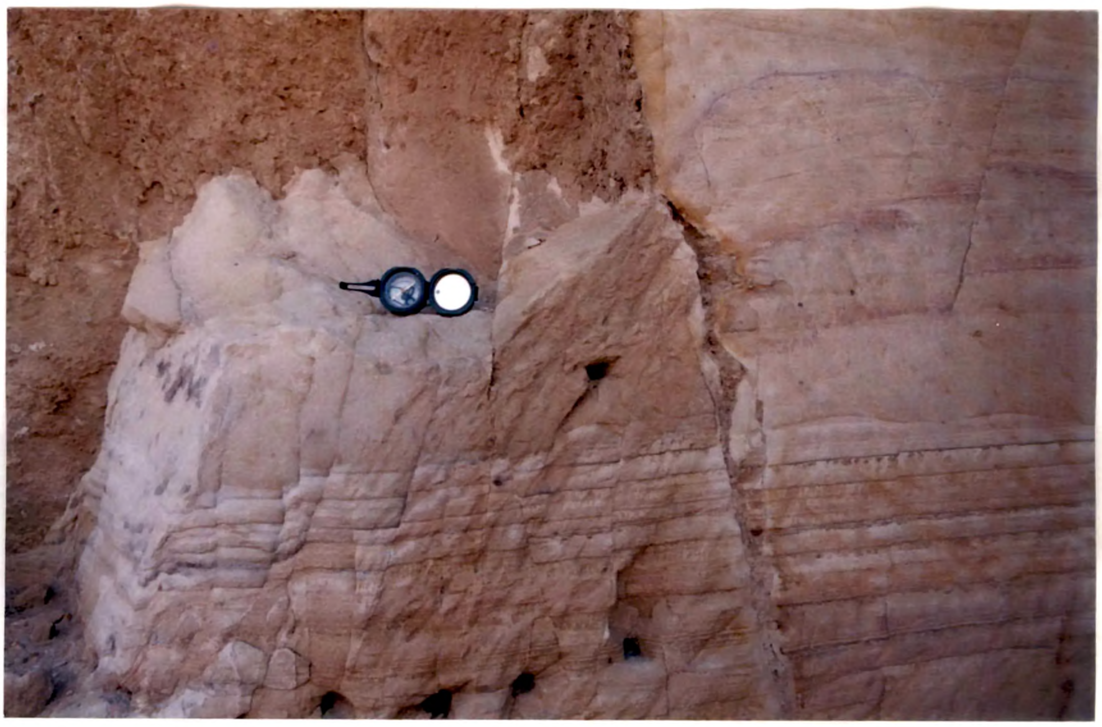


Fig 4.17 Photograph showing a number of small faults exposed in a quarry section about 12 km south of Bhuj

Several normal faults in association with the sets of the conjugate faults which have the interplane angle of ~35° (Fig 4.18) are exposed around Bhuj. The general attribute of the fault population exposed here has a major strike direction of ENE-WSW.

One of the other important geometry observed resembles an *inverted flower*, a feature referred here to as *flower structure* as described by Sylvester (1988). Such structure (Fig 4.19) is generally common in the zones of *transpression* or *transtension* (Sylvester, 1988).

Fig 4.18 Photograph showing a number of small faults in association with two major conjugate faults exposed in a quarry section near Bharapar

Fig 4.19 Photograph showing a number of small fault segments emerging out of a single fault resembling an *inverted flower structure* of Sylvester (1988) on small scale.

In this case a lot of splays initiate out of a single major fault and basically are strike slip faults with a considerable dip-slip component. Of course, the strike-slip planes are difficult to observe in the field and hence only the normal dip-slip can be observed when seen in cross section. Although, such structures are not found very often in the study area, the evidence suggests strike slip faulting is also an important component operating in the area.

4.2.2 Reverse faults

4.2.2.1 *Distribution and Geometry*

All the major and minor reverse faults found during this study essentially occupy Katrol Hill Zone, extending for nearly 10 km in width and over 50 km in length. These faults though common, are found only in fortuitous exposures within the Katrol Hill Zone. In general, all the faults encountered strike in E-W direction (Fig 4.20) and inclinations of the faults are of low angle.

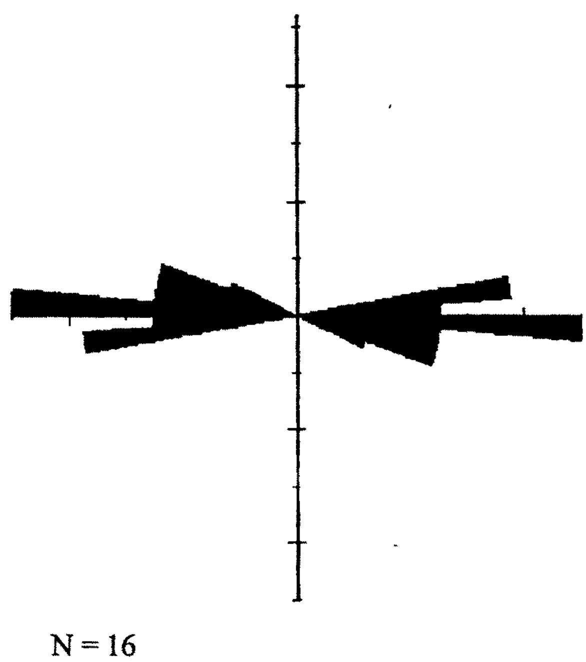


Fig 4.20 Rose plot of reverse faults encountered to the south of Katrol Hill Fault. Important to note is that no exposure of a reverse fault was encountered to the north of Katrol Hill Fault

Some of these follow the bedding and form a ramp when they cut upward through it. Fig 4.21 shows a near horizontal fault with a reverse slip, which follows the bedding and then creps up.

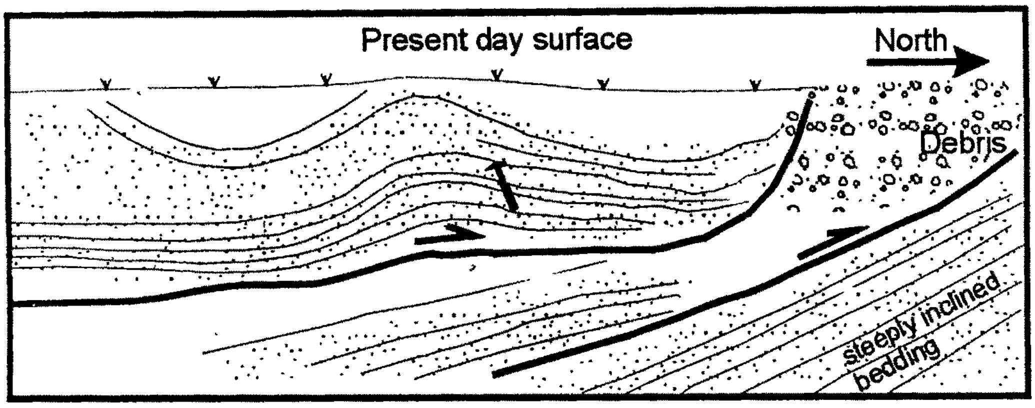


Fig 4.21 Line drawing of a reverse fault parallel to bedding plane observed in the vicinity of Katrol Hill Fault (see also, Fig 4.29)

Even within a single zone, dip of the fault planes is not consistant from one mesoscopic fault to another. It can be seen from one such exposure where several minor faults are exposed to the south of Hamadra Talai (Fig 4.22), note the group of several faults with inconsistant dip angles. This forms as good example of an apparent imbricate system of faults, wherein several wedges are formed on account of slip propagation along several parallel to sub-parallel faults.

As is seen from the Fig 4.22 the drag features and folding is common along the most of the thrust faults studied, at several places the dip of the beds at the geomorphic junctions is opposite to the general bedding dip in the area. At such places the beds are seen to have been overturned dipping due north, indicative of the fault propagation folding (described further under the section on folding) which is a clear indication of thrusting/reverse faulting. Several other mesoscopic exposures were encountered which indicate the slip propagation on the faults in the sub-surface. Almost all the faults observed dip due south, this is one of the most significant feature pointing towards north-south crustal shortening and a push from the south.

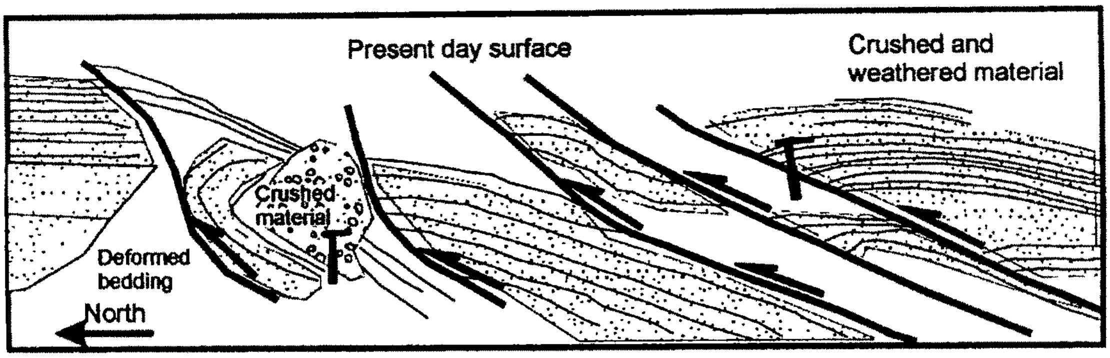


Fig 4.22 Line drawing of an apparent imbricate system of sub-parallel reverse faults observed near Hamadra Talai, about 11 km south of Bhuj (see also, Fig 4.31)

Field studies show that the reverse faults are essentially present within the deformed Katrol Hill Zone concentrated to the south of KHF. Almost all the faults observed are oriented roughly in the E-W direction (Fig 4.20) and the associated beds show the conspicuous drag effect, indicative of the push from the south. It is interesting to mention that during the field studies fault with a reverse slip are seen preferably to the south of KHF, but not to its north. On the basis of the field evidences it is envisaged that the major Katrol Hill Fault was generated during the post-rift phase of structural inversion brought about on the already existing rift-related normal fault. According to Ziegler (1995) the intraplate compressional deformation is related to the plate collision and such deformations can occur at distances upto 1600 km from the collision front. Thus, the structural inversion is envisaged to have taken place sometime in Oligo-Miocene coinciding with Himalayan orogeny in the north.

4.2.3 Strike-slip faults

It is very important to locate the strike-slip fault zones in the region because the recent palaeoseismic investigations indicate that earthquakes occur more frequently on strike-slip faults (Sylvester, 1988). Throughout the study area the strike-slip faults (both with dextral and sinistral slip) are commonly encountered. These faults are characterised with displacement ranging from a few cm to several km. In the present study the strike slip faults are studied both in the field and also interpreted from the satellite data. The sole purpose of the study is to document the general morphology and geometry. Many small and large strike slip faults are exposed throughout the study area and at most places show segmentation which is typical of strike-slip fault zones (Wilcox et al. 1973). Most of these have the dominant N-S, NNW-SSE and NNE-SSW orientations (Fig 4.23).

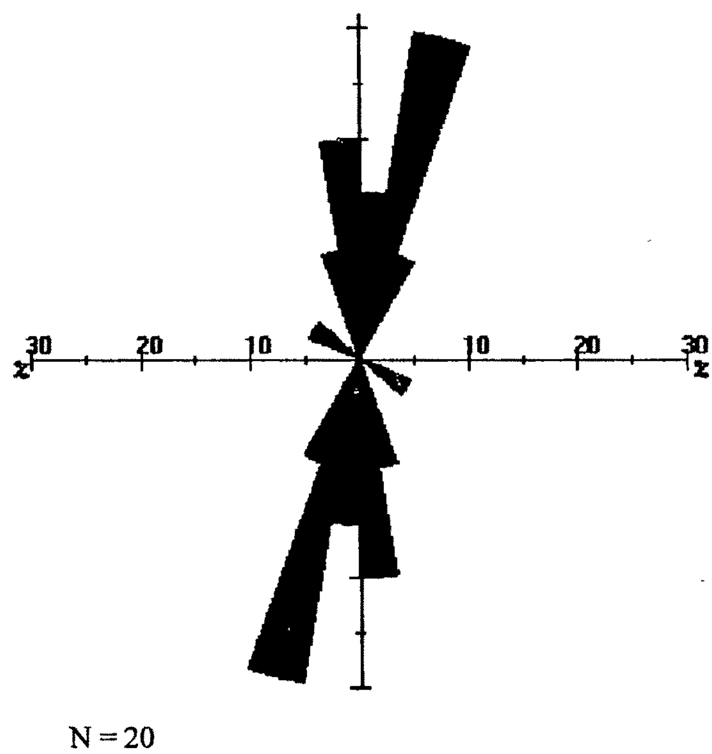


Fig 4.23 Rose plot of strike slip faults encountered within the study area. Important to note is that almost all the faults observed have the trend transverse to the major Katrol Hill Fault

All the major strike-slip faults encountered in the area are oriented transverse to KHF. Most of these are exposed in mesoscopic to macroscopic scale consisting of several synthetic and antithetic fault segments. Several mesoscopic zones consisting of synthetic and the antithetic faults were encountered to the south of Bhuj. Fig 4.24 shows a strike-slip fault displacing a fossil Belemnite observed about 7 km south of Bhuj.

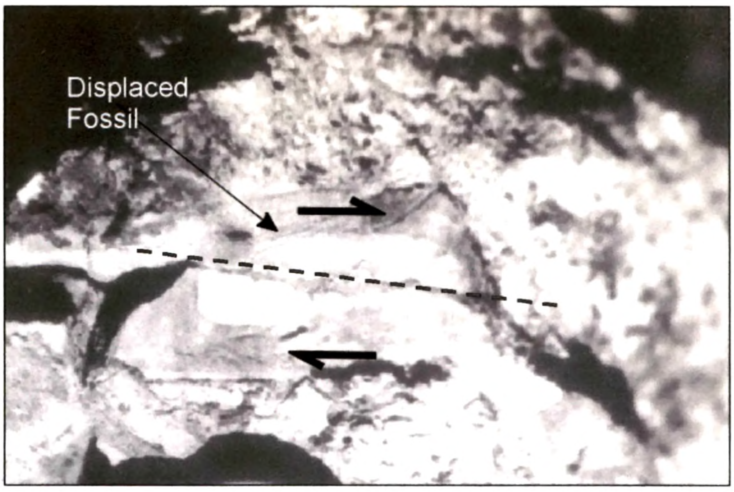


Fig 4.24 Black & White image of a small strike slip fault displacing a fossil Belemnite, encountered about 7 km south of Bhuj.

Fig 4.25 shows a major strike-slip fault along which the late Tertiary sediments have moved. Thakkar (1999) show several strike-slip faults cutting the KHF, these according to the him are of the younger generation (i.e. post-dating the KHF). However, the present author is of the view that the strike slip faults (both abutting and cutting the KHF) are related to the general stress pattern that brought structural inversion on major faults. Many studies in other areas indicate that there is a close association of the reverse faults caused on account of shortening and the strike-slip faults (e.g. Sylvester, 1988; Wilcox et al.1973 amongst others). 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. Under the influence of this all the major normal faults of the area related to Kachchh rift were reactivated in the form of the reverse faults (i.e. structural inversion took place along KHF and subordinate faults) as has been observed by Sant and Karanth (1995) in the Lower Narmada Valley. It is therefore envisaged that all the strike slip faults are the net result of the shortening and these are geologically coeval with the reverse faulting activity in the area.

Fig 4.25 IRS-FCC image showing a left lateral strike slip fault displacing the late Tertiary sediments, WSW of Bhuj

4.2.4 Strike slip versus Dip slip faulting modes

As is seen in the previous section all major and minor strike slip faults dominantly strike in NNE-SSW and N-S directions. However, some field evidences do suggest the motion in WNW-ESE and E-W directions. Some of the major strike slip faults in Central Kachchh Mainland cut across the major structure (i.e. KHF) and traverse a long way in land and thus Thakkar (1999) opines that these are younger with reference to KHF.

By and Large the dip slip faults (both normal and reverse) dominantly strike in E-W directions to the south of KHF. Normal faults in Central Kachchh Mainland are the most commonly observed and are formed on account of the extensional forces caused on account of rifting. However, some major normal faults essentially striking in E-W are also envisaged to have formed on account of post-rift inversion (compression) and subsequent cessation of compressional pulses. The reverse faults in the area are restricted to Katrol Hill Zone striking E-W.

Many of the strike slip faults are seen cutting the present day Katrol Hill Fault (KHF) which is essentially a reverse fault formed on account of post rift horizontal shortening. Some of the major-strike slip faults (eg. NRF) are also seen displacing the late Tertiary sediments and hence their age obviously post-date the late Tertiary deposits. This fact enables a better understanding of the relationship between the strike slip and dip slip faults and in turn reveals the fact that these faults are unrelated to the rifting phenomenon. Of late, extensive work has been carried out on the relationship between the strike slip faults and the compressional structures (e.g. Sylvester, 1988). It has been observed that a close relationship exists between strike slip faults and the compressional structures. The principal stress axis (σ_1) in peninsular India is directed to NE direction in general (Gowd, 1996) and hence most of the intra-plate deformation can be related to this stress regime. Intra-plate compressional structures occur on many continents and are commonly associated with continent-continent collisional orogens (Zieglar, 1995) but are rarely observed on modern passive margins. However, in most cases the development of intra-plate compressional features appear to coincide with major orogenic events affecting one or more passive margins on respective cratons (Zeiglar, 1995). According to Zieglar (1995), amongst different intra-plate discontinuities, rifts are the most vulnerable to an early inversion in response to the build up of collision related intra-palte horizontal compressional stresses as in case of the present area under study.

The region Kachchh is under the influence of NE directed σ_1 which can also be inferred from the folded sedimentary sequence. The strike slip faults in Central Kachchh Mainland lie in NE direction (i.e. in the direction of principal stress axis, σ_1) and hence the genesis of these can be related with the compressional structures that have formed under the influence of same stress field. Therefore, it is envisaged that the strike slip faults in Central Kachchh Mainland are the net result of differential block movements under the forces that have caused the compressional reactivation of the rift related normal faults.

4.3 DOMES AND FOLDS

Doming and folding are the one, which comprise most conspicuous group of structures in Central Kachchh Mainland. Although for the purpose of description both folding and doming are clubbed together, the genetic mechanisms for the two are quite distinct from each other.

4.3.1 Domes

Several large and small domes occupy the Central Kachchh Mainland. Many of these are concerntrated in the Katrol Hill Fault Zone, and a number of small and large domal structures are also encountered in Bhuj lowland (Fig 4.1). Amplitude of these structures in Bhuj lowland, however, is rather less, so much so could go unnoticed unless mapped carefully. Dips of the beds in domal structures hardly exceed 7° in any direction. Apart from these low amplitude domal features, three well-developed domes have been observed. Some of the important domes recorded by the author are given below. 1) One such structure is developed immediately to the south of KHF on road to Bharasar with the beds having quaquaversal dips. Amplitude of this dome is about 180 m with the dips not exceeding 10° in all the directions. 2) Another domal feature is seen with beds dipping very gently in all the directions about 2 km east of Bhuj-Mandvi road, at the geomorphic divide south of KHF. The amplitude of this dome is about 100 m and is about 50 m wide. 3) About 14 km south of Bhuj, another domal feature with the amplitude of about 100m was observed, here the dips never exceed 10° in any direction and several N-S trending faults were found cutting through this structure, the sense of slip along these faults, however, was difficult to establish. In general two types of domes are identified in the region a) Elongated domes (structural) and b) Circular domes (intrusion). Hardas (1969) and Biswas (1987) have shown several other domal structures flanking KHF. However, many of these are the elongated structures with greater amount of dips of beds dipping due north than their southern counterpart. All such structures elongated parallel to the KHF seem to be a part of the activity in this zone. Therefore all such elongated structures with steeper northern limbs are dealt as fault propagation folds. For all such linear domal structures the present author would prefer to refer them as asymmetric anticlines instead of elongated domes. This is because, during the present studies the author has observed well developed fault propagated anticlines flanking along the KHF and implying the fact that due to reverse reactivation of KHF the strata are asymmetrically folded.

The genesis of the major domes in Central Kachchh Mainland is not clearly understood. Some recent studies have shown that the intrusive igneous plugs occupy the core of these domal features (Biswas, 1973; De, 1981). According to them many of these plugs are alkaline in composition. Hardas (1969) and Biswas (1987) also made such observations. It is therefore not unlikely that some genetic relationship exists between igneous activity and doming.

4.3.2 Folds

The most interesting part of the folding in Central Kachchh Mainland is the consistency in the fold axis orientation and the genesis of the folds on account of the mechanism of fault propagation folding. Conspicuous folded strata were observed all over the Central Kachchh Mainland, however, the Katrol Hill Zone (KHZ) forms as a potential area to study these in detail. The folding has affected the rocks of practically all the age groups (i.e. from Mesozoics to Quaternary) and essentially has deformed the Mesozoics the most. In general the observed folds are asymmetric to overturned in nature. The axial trend of almost all the folds irrespective of their amplitude and nature of rocks tend to strike in between N60°E & N110°E. The intensity and style of folding, however, varies from the Mesozoic to Quaternary formation.

4.3.2.1 *Mesozoic sediments*

Conspicuous flexuring alongwith several open to tight and even overturned folds was encountered within Katrol Hill Zone. From the field investigations it is very clear that most of the folding in KHZ is on account of fault propagation. Alongwith this several synclinal and anticlinal structures were observed outside KHZ.

4.3.2.1.1 *Fault Propagation folding*

Entire Kachchh sedimentary sequence i.e. both Mesozoic and Cenozoic especially on the Mainland shows isolated but widespread flexuring/folding at various scales. Apart from conspicuous domes and half-domes flanking the KMF and KHF, the strata exhibit at mesoscopic scale a variety of flexuring related to slipping along faults.

The folds that are asymmetric and have one steep or overturned limb and the other a gentler one (Fig 4.26) are termed as fault propagation folds (Suppe, 1983, 1985, Suppe and Medwedeff, 1984). Such folds grow at the tips of the thrust faults as they propagate (Suppe, 1990; Mitra, 1993). Geometry of the folds and flexures, throw some light on the behaviour and orientation of the fault planes in sub-surface. Asymmetric to overturned nature of folds points to their being moderately to low dipping thrust planes, rather than high-angled reverse faults. Biswas (1987) invoked vertical uplifts to explain the folds, whereas the current belief is that they comprise rifts that have changed over to reverse faults during northward push that caused closing of the original rifts.

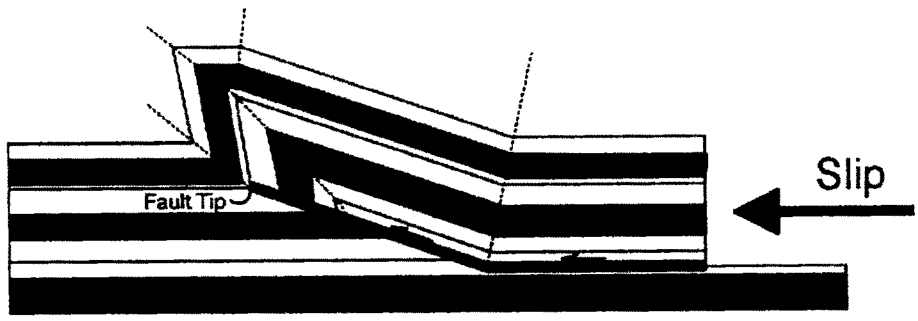


Fig 4.26 Line drawing of an ideal fault propagation fold (after Suppe and Medwedeff, 1990)

Conspicuous folding was encountered at several places in Central Kachchh Mainland (Fig 4.27); where good exposures of folding on account of fault propagation were observed. The investigation pertains to locations mainly along the Katrol Hill Fault and a few locatins along Kachchh Mainland Fault and emphasis is on the geometry of folds found along faults and thereby enumerating an idea of structural inversion.

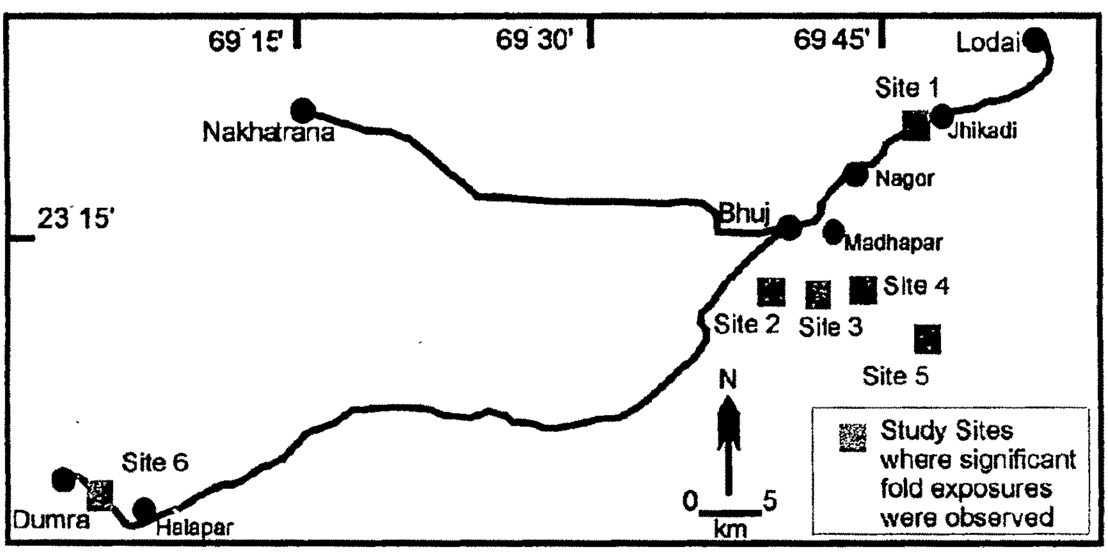


Fig 4.27 Map showing the locations where good folding exposures were observed

The Kachchh Mainland characterises a series of monoclinal flexures exposed along both the major faults (i.e. the Kachchh Mainland and the Katrol Hill Faults) (Biswas, 1987). Both of these are the reverse faults and are almost parallel to each other. These are again in parallelism with the other two major faults of the region (i.e. the Island Belt Fault and the Nagar Parkar Fault). All of these seem to be a part of one system, with differential amounts of uplifts along individual dislocations. The Kachchh Mainland fault, forms the northern margin of Kachchh Mainland along which, many domes are exposed. According to a rough estimate based on the stratigraphic correlation the structural relief of both the faults is of the order of ~ 2.5 km.

On way to Lodai (Fig 4.27) [*site 1*] a very good exposure of north verging fault propagation fold can be observed in a road cut section. Relief of this fold in section is about 20 m. The structure comprises mainly the rocks of Katrol series involving intercalating sequence of sandstones and shales. The back limb of this fold dips 45° due south which becomes gentler further south where dip is around 10°. The forelimb is steep to overturned. The geometry of this fold is constrained only by field data as no appreciable geophysical information exists for the area. The other areas where such folds are seen lie to the south of Bhuj (Fig 4.27).

Good exposures recorded lie on the Bhuj-Mundra road (*site 2*), near Hamadra Talai (*site 3*) and on the way to Jadura Mota (*site 5*). Fig 4.28 shows a mesoscopic scale fault propagation folding. The drag seems to have developed along a low angled thrust fault. Another exposure of similar kind of folding is seen on the Bhuj-Mundra road. The structure seems to have developed along sedimentary bedding parallel thrust which emerges as a gently dipping ramp (Fig 4.29 & 4.21) formed on account of lateral shortening. Several such small scale folds are exposed here; the axial trend of all such folds encountered here is roughly E-W.

Fig 4.28 Photograph showing an exposure scale fault propagation fold

Fig 4.29 Photograph showing fault propagation fold developed along a bedding parallel thrust.

Fig 4.30 reveals a classic fault propagation fold exposed at the geomorphic divide on Bhuj-Mundra road. It is tightly folded with forelimb almost overturned and a comparatively gently dipping backlimb (Fig 4.30).

Fig 4.30 A well developed fault propagation fold in the vicinity of Katrol Hill Fault

No thickening or thinning of forelimb is observed. The inter-limb angle is about 35°. Good exposures of such folds (Fig 4.31) were also recorded on the way to Jadura mota (*sites 4 & 5* of Fig 4.27). In all above mentioned cases the rocks involved are mainly sandstones and shales of Mesozoic age.

Fig 4.31 Exposure scale fault propagation folds observed on way to Jadura Mota, note the wedges emerging along sub parallel thrust faults (also see: Fig 4.22)

4.3.2.2 *Tertiary sediments*

Several mesoscopic folds have been recorded in Tertiary rocks (Fig 4.32, 4.33 and 4.34) exposed in and around the study area. The prevalence of folding, however, is quite less than the folding observed in Mesozoic rocks. Fig 4.32 shows mesoscopic folding exposed near Anjar. Apart from few sequences in the east and the south, the study area mostly constitutes the pre-Tertiary sediments.

The axis of almost all the folds encountered in the Tertiary sediments tend to strike inbetween N60°E – N100°E in general, which very well matches with that of the folds in the Mesozoic rocks.

Fig 4.32 Photograph showing mesoscopic folding near Anjar

Fig 4.33 Photograph showing gentle folds exposed in late Tertiary rocks near Dumra

Fig 4.34 Photograph showing conspicuous folding in siltstones of late Tertiary age (site: 4 km east of Naliya)

4.3.2.3 *Quaternary sediments*

The geological features indicative of active tectonism not only include uplifts, subsidences and lateral slips in hard rocks and liquefaction features in unconsolidated soft sediments, but there also exist clear evidences of mesoscopic scale flexuring. Small scale warping is ideally seen about 7 km south of Madhapar. This divide marks the Katrol Hill Fault. At this site rocks of Katrol Series are exposed, which are highly faulted, folded and jointed (Biswas, 1987). Just a few metres further south of this divide, miliolitic rocks that occur as sheets within the hill zone are seen gently warped (Fig 4.35) into E-W trending anticlinal and synclinal flexures (Sohoni, et al., 1999).

Fig 4.35 Photograph showing gentle warps in Miliolitic rocks exposed in the northern flank of Katrol Hill Fault

The southern and the northern flanks of these folds are clearly exposed showing dips due north and south. These warps occur in association with an ESE-WNW trending and south dipping fault. In addition, these rocks are highly jointed with a major set trending N65°E/79°S, and the joint orientations in general are observed falling between N65°E and

N85°E. The folding is seen within Katrol Hill Fault zone and the fold axis broadly coincides with the trend of the fault. The folding thus shows a definite drag relationship with movement along the main fault. These flexures provide conclusive evidence of post-Miliolite reactivation of the Katrol Hill Fault.

4.4 JOINTS

The term joint is used for fractures without any visible displacement (Bergaret, et al, 1992). Joints are the ubiquitous fracture phenomena and are virtually seen in every outcrop, found from solid plutonic rocks to extremely friable recent sediments (Scheidegger, 1978). These are the most persistent meso-structures and most of these have no obvious explanation in terms of their origin and age, hence are subject of controversy (Price, 1966). In the present study area extensive jointing is recorded and they are analysed to understand their tectonic significance. The study, in general aims at, a) mapping characteristic joint sets in the rocks of different ages and b) to try and analyse their tectonic significance in terms of space and time.

4.4.1 Mapping

The joints were mapped at about 26 locations throughout the Central Kachchh Mainland. The orientations were measured by determining the strike azimuth (clockwise from N) alongwith dip angle and direction. About 15 to 20 measurements were made at each outcrop visited (Fig 4.35).

Number of measurements was restricted from 10 to 40 data following Scheiddeger & Schubert (1989), wherein the workers explain that more number of data does'nt significantly enhance the accuracy of results. Apart from this usual measurement procedure, care was taken to note the general morphology of joints i.e. whether it is an open joint and any secondary mineralisation has taken place, whether surface of the joint plane is smooth or is having some secondary marking.

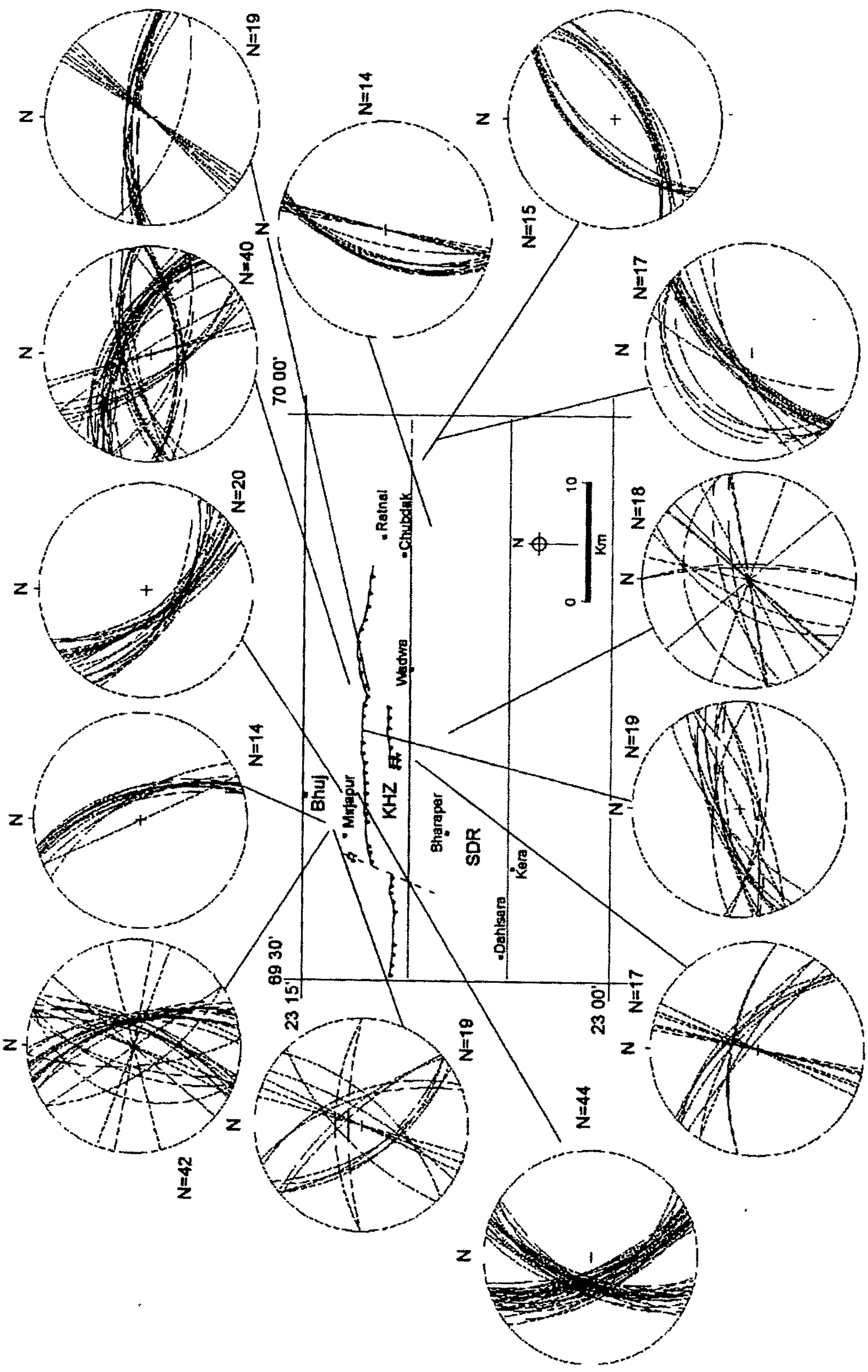


Fig 4.36 Map showing the joint orientations at various locations within Central Kachchh Mainland (only significant locations are shown)

4.4.2 Distribution and morphology

Around 1500 readings of joints were measured at various sites throughout the study area, in rocks ranging in age from Jurassic to Quaternary (Fig 4.36). Most of the joints observed in the field are having steep dips or are even vertical at many places. The rocks of all age groups are highly jointed, but the most intensive jointing is seen in the Mesozoic rocks. In all, irrespective of where they occur, six different sets of joints can be recognised by their average azimuthal distribution i.e. N115° ± 10°, N60° ± 10°, N140° ± 10°, N15° ± 10°, N180° ± 10° and N90° ± 10°. Most of the joints sets encountered were found to be as open joints. Hence, are interpreted to be due to extension.

At most places *systamatic joints* were found to predominate. As such joints are most significant because of its genetic relationship with the major structure, have been dealt in detail.

4.4.2.1 *Orthogonal joint sets*

Systematic joints may be defined as those which predominate over all the other exposed joint sets and are traceable over a considerable area (Caputo, 1995). Such kind of joint sets were observed at various sites in the area under investigation. For example, about 6 km south of Bhuj (Fig 4.37) an array of systematic joint sets was observed with one set trending 150° ± 10° was found to be predominant and traced over a sizeable area.

Orthogonal joint sets have been defined by several workers (Hancock, 1985; Caputo, 1995) as systematic smooth planar surfaces which, normally constitute two near vertical, near perpendicular sets of joints. Such joints generally show no evidence of relative motion and it is frequently observed that predominant joint systems run parallel to faults or fault zones. In such cases it is reasonable to consider that joints and faults are the product of the same tectonic forces.

Fig 4.37 Photograph showing and array of systematic joint sets observed 6 km south of Bhuj.

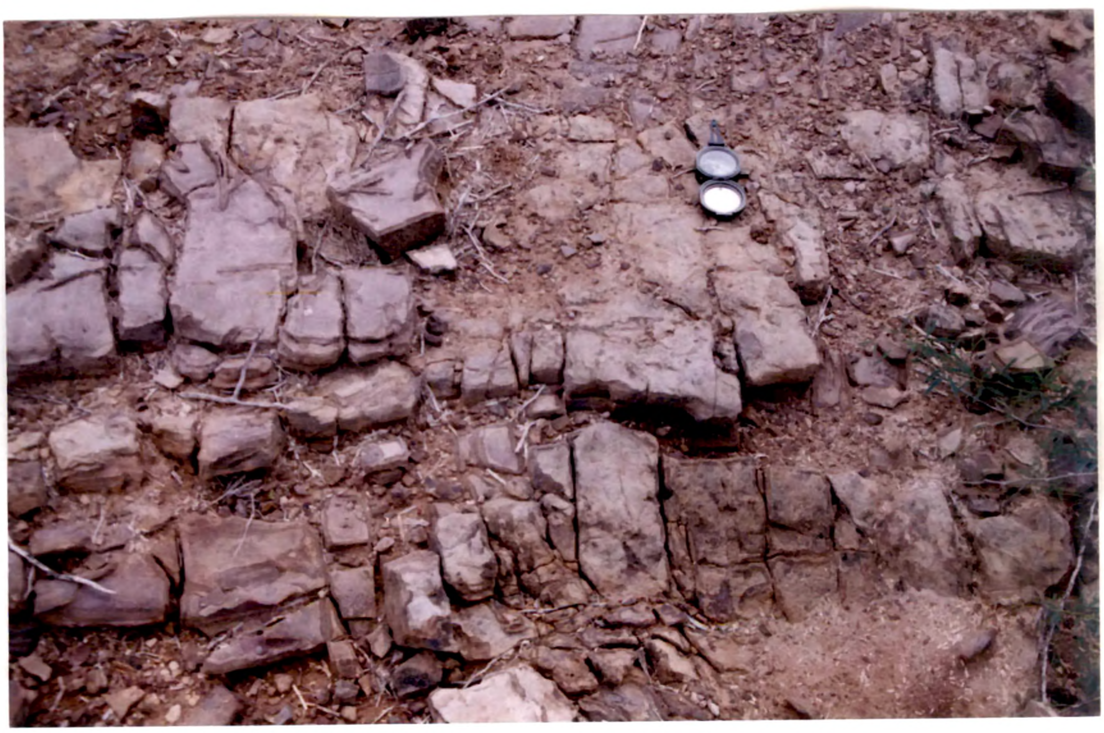


Fig 4.38a Photograph showing well developed orthogonal sets of joints in Mesozoic rocks in the near vicinity of Katrol Hill Fault

Throughout the investigated area, orthogonal joint sets are quite common. However, they are preferentially exposed within the Katrol Hill Zone, and at several sites such sets were recorded which are essentially seen in the rocks of Katrol and Chari formations in the near vicinity of Katrol Hill Fault. The observed joint sets generally strike around E-W° and N-S.

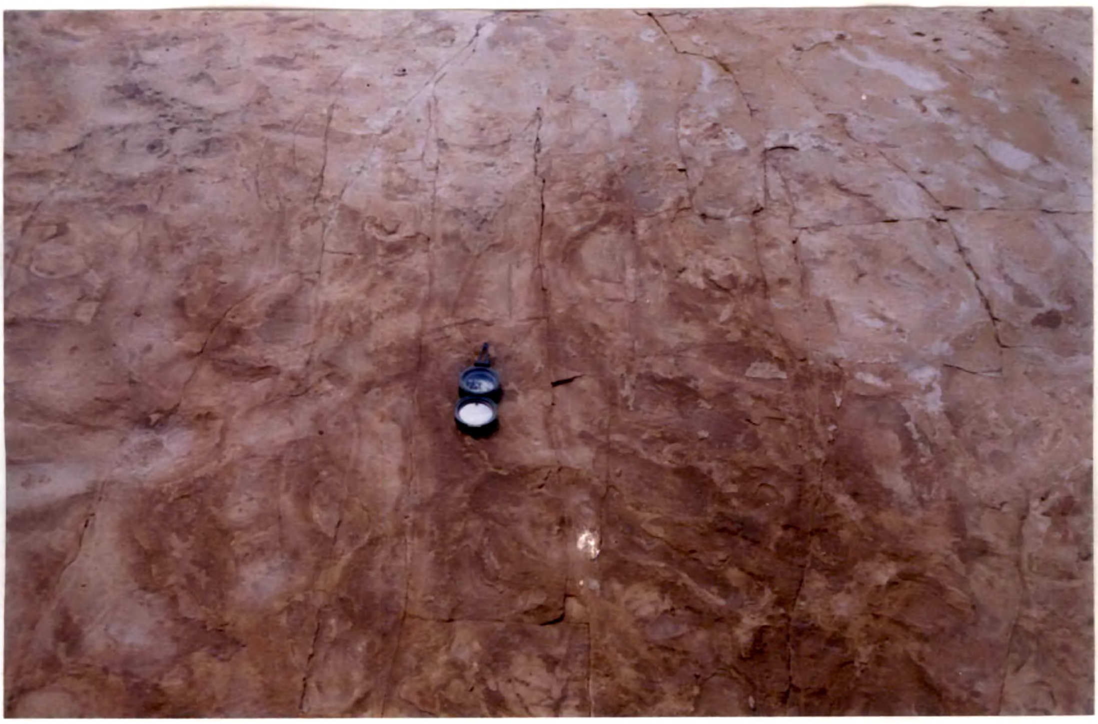


Fig 4.38b Photograph showing prominent orthogonal sets of joints about 6 km south of Madhapar

These sets were studied in greater detail at three locations in the vicinity of KHF. Fig 4.38a & b show the orthogonal set of joints to the south of Madhapar, exposed in the Katrol formation. It is clearly seen that both the sets are quite prominent. However, due to the N-S perspective of the Photographs the E-W trending set does not appear to be more prominent but from the field relationships it is seen that both the sets are equally developed and cut across each other, hence can be taken as geological coeval. It is observed that the N-S trending set is more prominent at the Katrol Hill dislocation. At several places both the joint sets are so closely spaced that the rocks apparently look like a mesh a feature termed as fracture grid lock by Hancock (1985). A good exposure of fracture grid lock was observed at a site near Kukma (Fig 4.39).

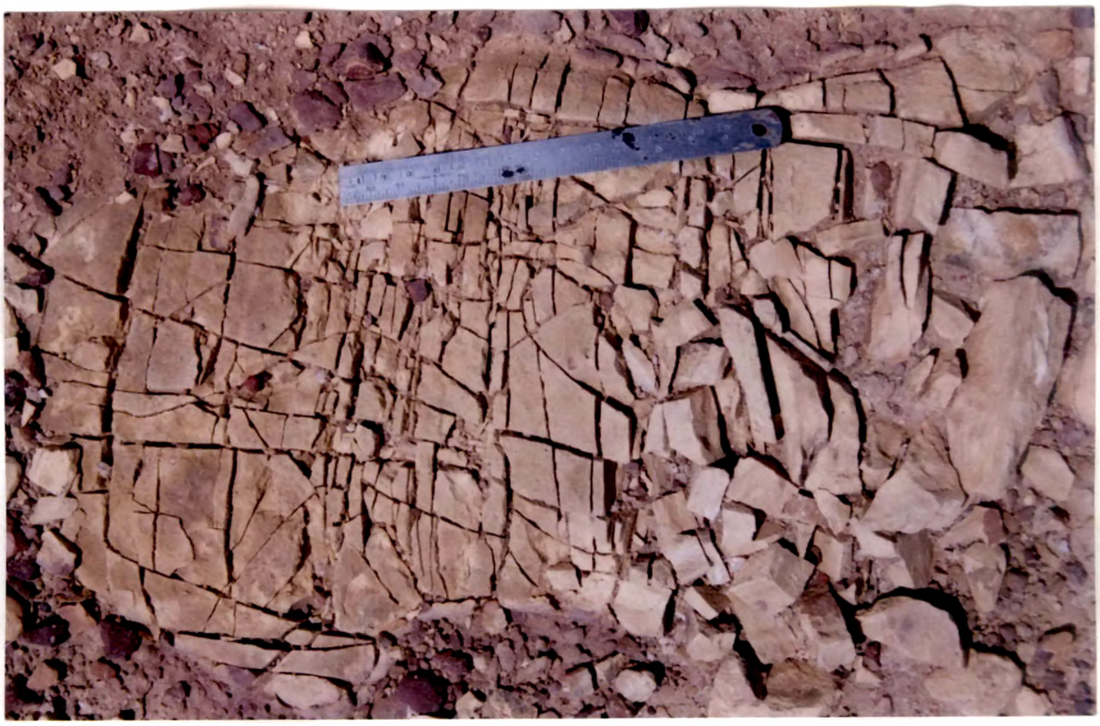


Fig 4.39 Photograph showing a fracture grid lock at a location near Kukma.

Here the mesh is formed in the rocks of Katrol formation at the hinge portion of the fault-propagated anticline. The joint sets at this site trend N28°E ± 10° and N110°E ± 10° and the spacing between these is very less, varying between .7 cm and 2.7 cm. It is interesting to note that the spacing between the joints trending N110°E ± 10° go on increasing due south. In general, it was observed that the joint spacing is minimum and density is maximum at the near vicinity of Katrol Hill Fault. Hence it can be envisaged that the jointing intensity and joint spacing are the function of increasing strain and therefore the spacing was minimum at the fault vicinity with increasing joint intensity and density.

The analysis of the orthogonal joint sets suggests that these joint systems must have formed in concurrence with the phenomenon of structural inversion that took place along KHF. According to Hancock (1985) development of joint systems perpendicular and parallel to the fold axis are quite common (Fig 4.40).

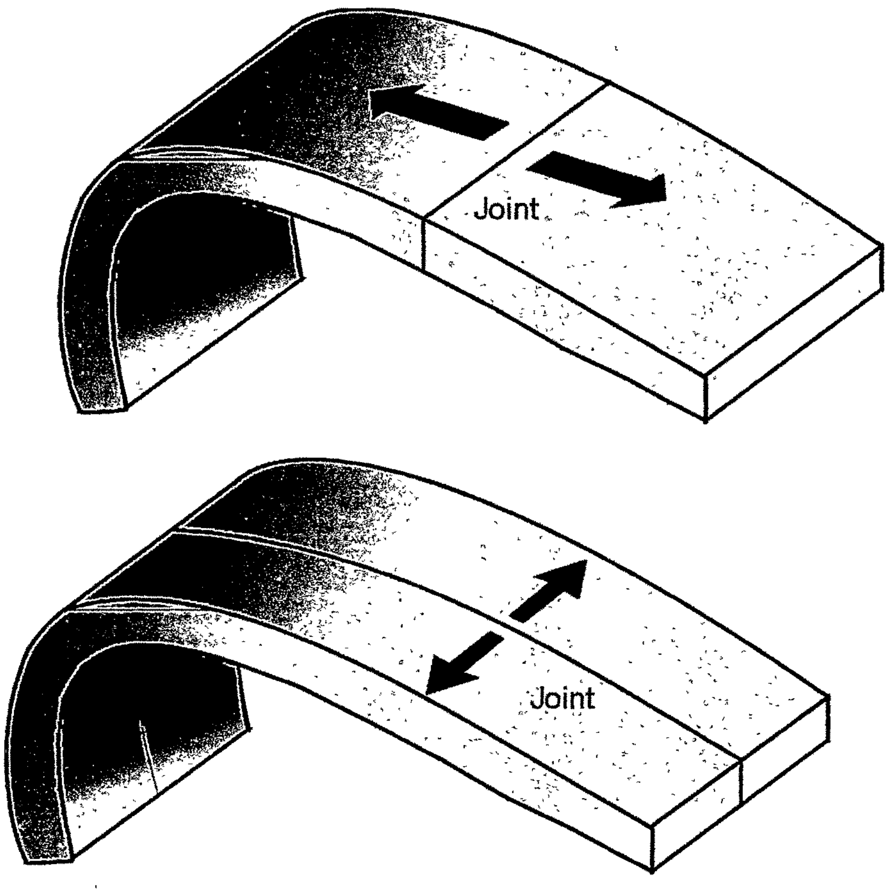


Fig 4.40 Formation of different joints sets, i.e. one perpendicular to the hinge of the fold and the other parallel to it (after Hancock, 1985)

In the present context it is envisaged that both sets of joints were formed due to extensional forces in compressional setting. The E-W set appears to have formed on account of extension parallel to hinge caused on account uplift and under the influence of gravity (e.g. Hancock, 1985). The second N-S set must have formed on account of the least principal stress axes perpendicular to NNE oriented maximum compressive stress.

4.4.3 Liesengang structures

These are essentially the features developed in jointed rocks and show conspicuous development essentially in the sandstones of Bhuj Formation. Development of Liesegang structures is observed at two places in ferrugenous and jointed sandstone exposed about 2 to 5 km north of Bhuj along Bhuj-Khavda and Bhuj-Kodki roads. This structure in rocks is characterised by blocks of concentric rings of variable shapes and sizes comprising of iron rich and iron poor alternating lamellae (shells). The shape of the structure, composed of a core and alternating concentric shells follow the configuration of the overall outer shape of the block which inturn, is a reflection of that of the joint polygons. These structures simulate concretionary aggregates or spheroidal weathering in jointed rocks. Studies by a number of workers on such structures have, however, established that the Liesegang bands or rings are indicative of a phenomenon somewhat distinct from that of spheroidal weathering.

The nomenclature 'Liesegang rings' is after the German chemist and photographer R. E. Liesegang (Liesegang, 1913) who artificially produced rings in a gelatine medium containing potassium dichromate and silver nitrate. In his experiment silver dichromate was precipitated in concentric rings separated by areas that lacked precipitation. He established that the formation of these rings was on account of gradual diffusion between one salt and the other which was contained by gelatine. He found them to be similar to the limonitic banding in jointed and weathered rocks. The factors involved in the formation of a Liesegang block are; i) chemical composition of the host rock, ii) intersecting joint pattern, iii) availability of surface water, iv) low gradient topography and v) appropriate bed thickness (Shahabpour, 1998). Whereas some workers (Carl and Amstutz, 1958; Gindy et al, 1985) have considered these structures as the preceding stage of exfoliation or spheroidal weathering and a few others (Augustithis and Otteman, 1966; Heald, et al, 1979) are of the view that Liesegang structures do not necessarily always occur in association with spheroidal weathering. Although the mechanism of chemical transfer of elements, viz. diffusions and periodic precipitations in a colloidal matrix or intra-granular film is same, the two may occur quite independent of each other as well. The present study, however, deals only with the physical morphology of these structures in the field. The author has made an attempt to relate the morphological anomalies with tectonic instability.

Development of Liesegang structures is invariably a weathering phenomenon in rocks having more than one set of joints, and are generally seen to form mostly in blocks of 6 to 12 cm by 4 to 8 cm in area with ferrugenous beds of thickness 10 cm or more (Shahabpour, 1998).

Fig 4.41a Photograph showing a view of the different types of Liesegang structures encountered in the field (Loc: 5 km north of Bhuj along Bhuj-Khavda road)

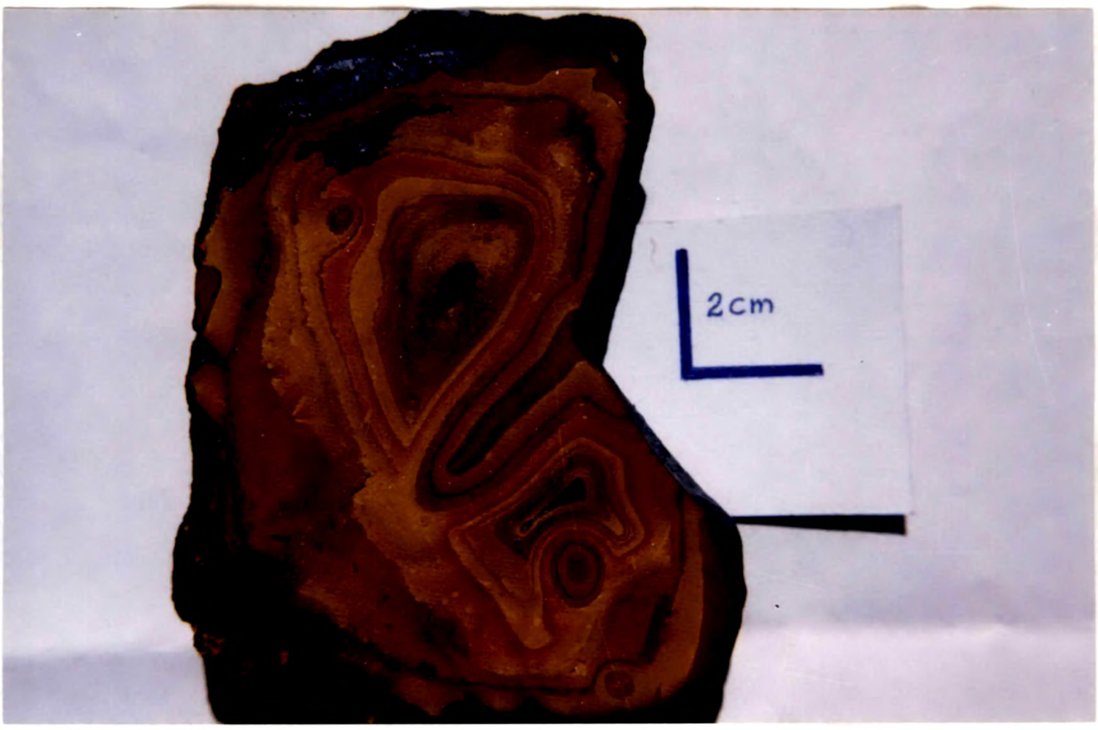


Fig 4.41b Photograph showing a close up view of simple Liesegang structure, note the deviation of the Liesegang lamellae around a concretion (Loc: About 5 km NW of Bhuj on Bhuj-Kodki road)

These structures broadly fall into two categories, namely, a) simple (primitive and ordinary) Liesegang blocks and b) compound Liesegang blocks (Fig 4.41a). The early stages with only one ring formed have been referred to as primitive Liesegang blocks while the ordinary ones are characterised by multiple rings (Fig 4.41b). This category is the product related to a single polygonal joint set. The compound blocks on the other hand are the products of more than one set of Liesegang patterns, wherein the earlier Liesegang patterns are significantly modified to give rise to new pattern on account of the subsequent formation of jointing. Depending on the position of joints and fractures, the following possibilities may arise a) the later joint polygon may either overlap or enhance the earlier one and b) the later joint polygon with different orientation than the earlier joint polygon may develop within the earlier Liesegang block. In both the cases the earlier Liesegang pattern may either be enhanced or slightly get modified or an altogether different set of

Liesegang pattern may replace the former one (Shahabpour, 1998). Whenever any joint polygon with different orientation transects or forms within the earlier joint polygon, a pattern with new configuration develops. If it is not possible to determine age relationship between the joint sets, this overprint of one joint set over the other is useful for determination of age relationship.

Main emphasis of this study is on the general physical morphology of structures. Here, the Bhuj sandstone surface is dotted with areas marked by formation of Liesegang blocks showing various stages of their development. Studies have revealed that the Liesegang structural blocks owe their origin to the usual contributing factors viz. a) appropriate bed thickness, b) appropriate ferrugenous content in host rock, c) extensive jointing, d) appropriate topographic site, and e) surface water.

a

Fig 4.42a Photograph showing the simultaneous occurrence of joints and Liesegang structures

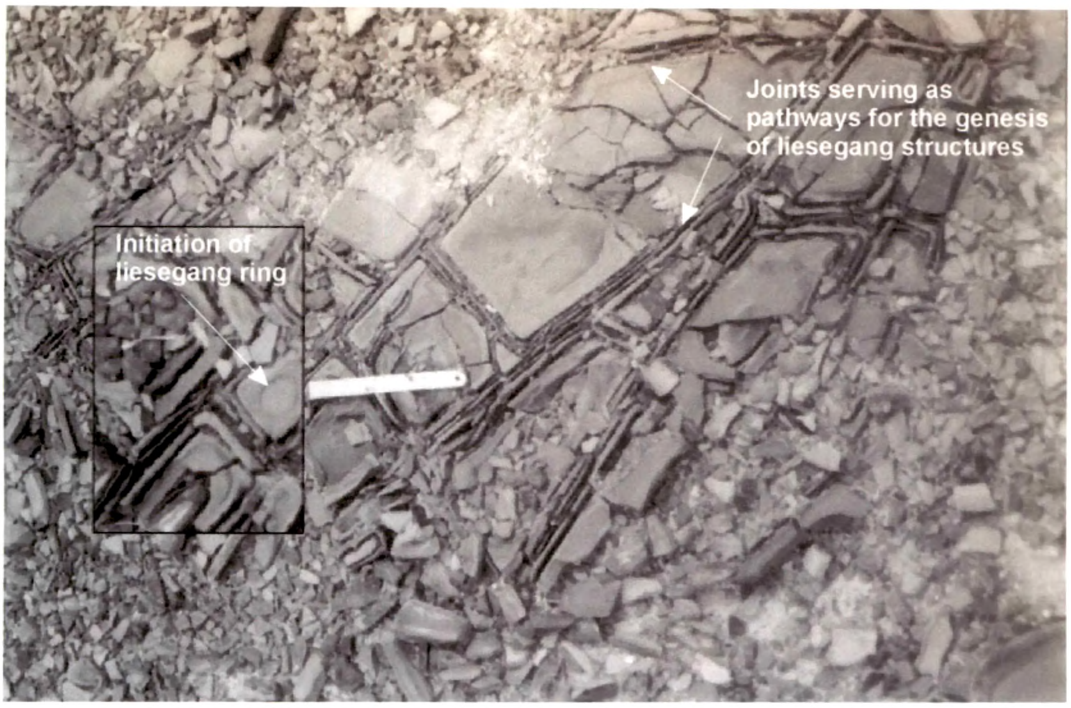


Fig 4.42b Black & White image demostrating the relationship of joints and formation of Liesegang structures (inset block is magnified (1.6x) to show the initiation of Lisegang structure)

It is evident that the joint systems in the rocks at an ideal topographic site have genetic relationship with Liesegang structures (Fig. 4.42a & b). These structures owe their genesis to the surface water, which made its way through the available joint sets.

Both morphological types viz. simple (primitive & ordinary) and compound structures are encountered. Fig 4.41a and b show the various types of Liesegang structures developed in the area. It is observed that the Liesegang blocks have variable sizes and range from 12 cm to 20 cm by 4cm to 10 cm in aerial extent. The structures fade out laterally to the drainage sides and vertically down beneath. The width of the inner relief rings varies between 0.1 and 0.6 cm. The shapes of shells are seen controlled by the shapes of the joint polygons. The Liesegang structures that are encountered belong to both; one generation of joint polygons and those formed by two or more generations. Wherever two generations of jointing are involved the Liesegang structures are generally of compound variety (Fig. 4.43a).

a

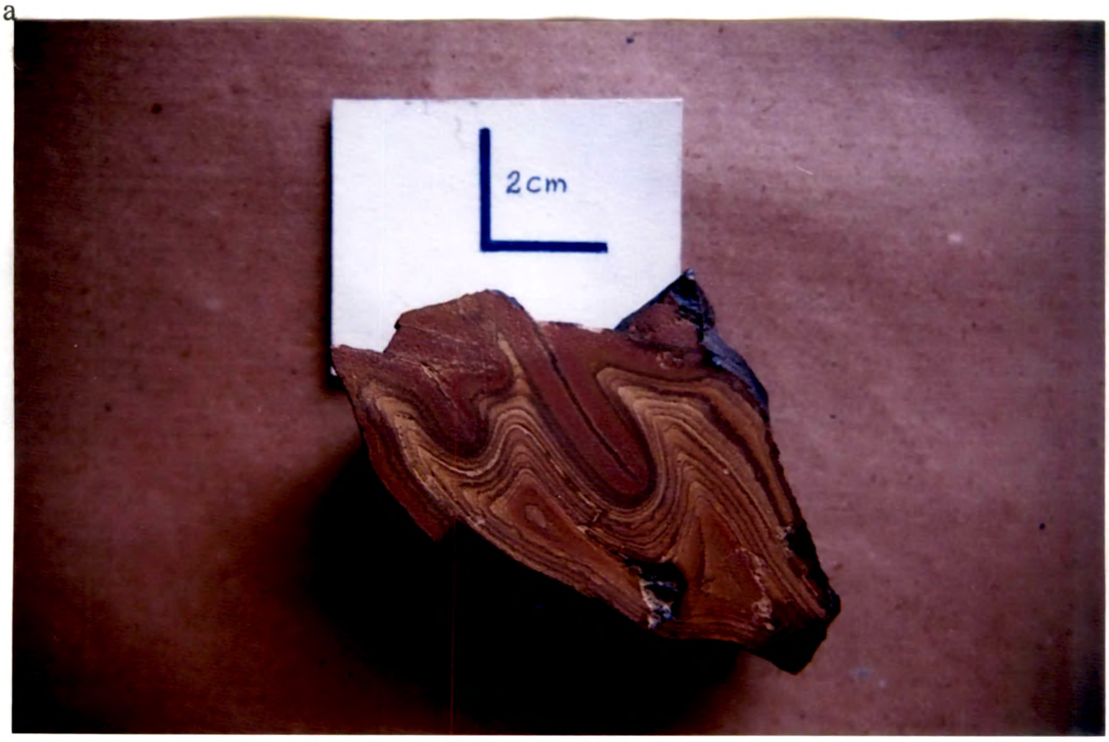


Fig 4.43a A close up view (from top) of a compound Liesegang block showing the relicts of the preexisting structure (the sample is baked and polished for more clarity)

It has been possible to recognise successive stages of transformation of primary structures into compound structures (Fig. 4.43b) on account of superimposition of later joints on older sets.

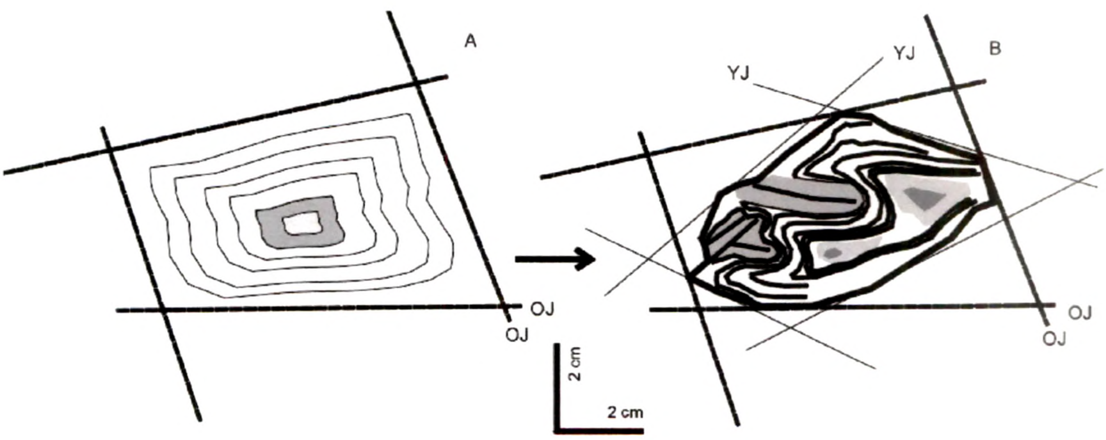


Fig 4.43b A line drawing showing the interference of the joint sets responsible for the genesis of the compound structure. The drawing diagrammatically demonstrates the evolution of the compound Liesegang block (B) from the preexisting simple one (A).OJ is the older joint polygon which served a conduit for the solutions involved for the formations of an earlier Liesegang pattern (reconstructed) and YJ is the subsequent joint polygon responsible for the modification of the preexisting Liesegang pattern.

With the help of actual field evidences, an attempt has been to explain the genesis of ordinary as well as compound Liesegang structures by reconstructing the successive stages of interference of joint polygons of two generations. The complexity of pattern, with the younger superimposition of another set of joint polygon is shown in Fig 4.43b and 4.44b. OJ is the older joint polygon, which was involved in serving the conduit for solutions responsible for the formation of the earlier (reconstructed) pattern, and YJ is the younger joint polygon responsible for modifying the earlier pattern. Earlier Liesegang pattern is delineated by the joint polygon responsible for its formation, which is followed by construction of a joint polygon responsible for the subsequent modification of the earlier weathering rings. In the study area, effect of tectonic movements as envisaged from the modification of weathering rings manifest itself in the order of decreasing age:

i) earlier Liesegang pattern modified by the later one,

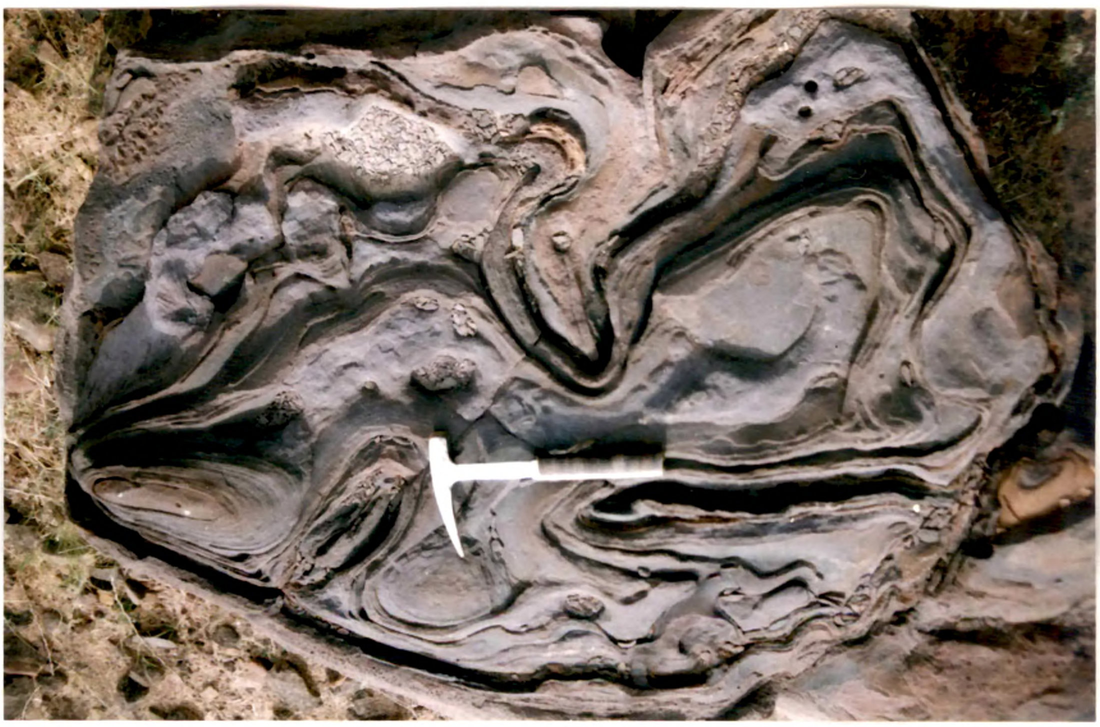


Fig 4.44aPhotograph showing the compound Liesegang structures at study site on Bhuj-Kodki road

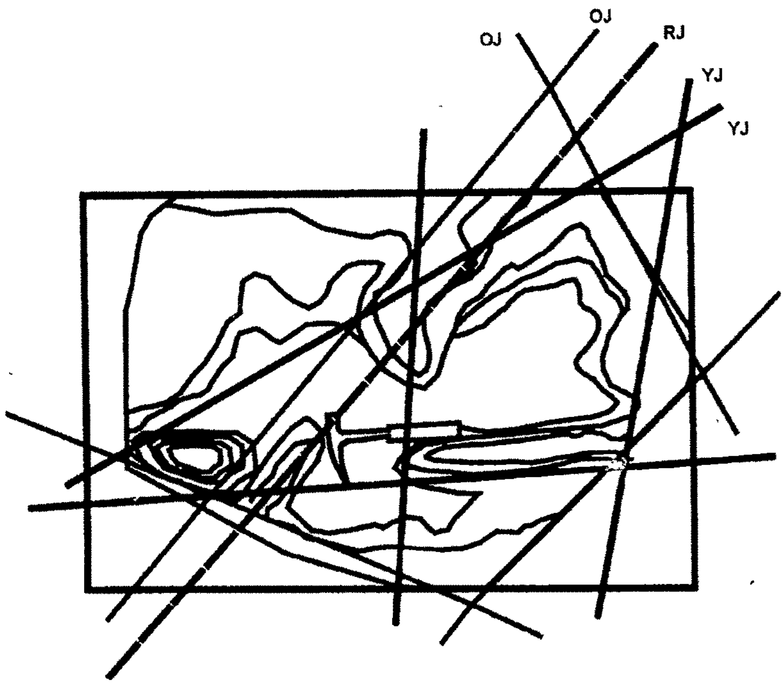


Fig 4.44b A line drawing showing the superimposition of subsequent joint sets responsible for the modification of the preexisting structures (OJ – older joint polygon, RJ – a joint set showing no signs of weathering, which is seen to cut through the compound structures and hence considered to have developed in recent times, YJ – a joint polygon responsible for the modification of the already existing structures which is subsequent to OJ but has formed prior to RJ

ii) the formation of daughter blocks on account of tectonically induced joints and

iii) recent tectonically induced joints and fractures with no signs of weathering (Fig 4.44a & b), cutting through the earlier Liesegang pattern.

Although such types of structures are local, yet they provide vital supportive information towards understanding the overall tectonic activity of the region.

4.4.4 Lineament Analysis

The lineament analysis of Kachchh was carried out for the first time by Sharma (1990) who with the help of FCC and 5 and 7 bands of B/W MSS Landsat Imageries and Toposheets on 1:2,50,000 scale investigated the Kachchh region. His studies aimed at locating shallow to deep-seated structures and to establish their genetic significance towards influencing the Quaternary landscape of the Kachchh coastline. The present author has made an attempt to analyse lineaments observed in the area. The term 'fracture' used herein denotes any linear break or cut in the rocks which may be a major joint or a fault or a trace of them; no line of demarcation has been visualised between faulting and jointing since both of them essentially comprise one single phenomenon i.e. fractures. Wherever the displacement along larger fractures have been significant, they have been marked as faults and rest of them have been shown as joints.

The criteria used by Sharma (1990) for delineation of these fractures or linear features are: (i) displacement and abrupt truncation of rocks; (ii) sudden variation in foliation trends; (iii) long and straight linear river/stream courses; (iv) right angled offsetting of stream bends; and (v) linear sharp tonal variations/alignments. His fracture pattern map shows three dominant trends, viz. ENE-WSW to F W, NW-SE and NE-SW.

The ENE-WSW to E-W fracture trends coincide with the general strike of the rocks and also with major regional longitudinal faults (KMF, KHF, GKF). The NW-SE and NE-SW trends too, appear to be related to the regional bounding faults (WCF, LRKFS). This analysis evidently brings out following facts, 1). Almost all the structural lineaments are the outcome of repeated reactivation of planes of weakness at different dates and may in a way related with one or the other major regional bounding faults, 2). Frequency and the pattern of these linear features vary from segment to segment, 3). These trends are one of the major determinants for the geological and geomorphological evolution especially during Quaternary period.

The major objective of this analysis is to determine general lineament pattern for Central Kachchh Mainland (CKM) and to analyse their possible relationship with the general structural pattern. For this work, B/W MSS Landsat and IRS FCC images alongwith the toposgraphic sheets were used to delineate the linear structures.

The analysis was carried out to get a general vision of the linear structures present in the area.

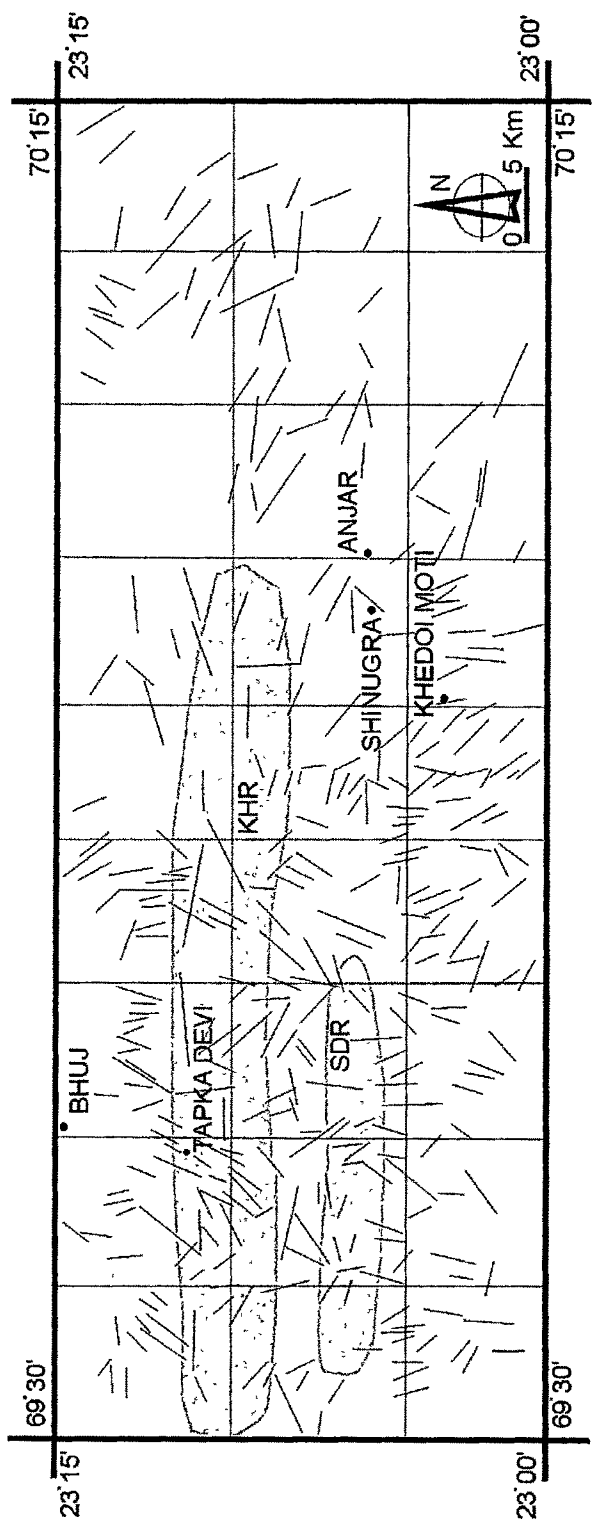


Fig 4.45 Lineament map of study area

For this, the satellite imageries and topographic maps (1:50,000) were used (Fig 4.45). In the study related with the structure and tectonics, satellite imageries help to identify the general structural attitude irrespective of the age and type of deformation (Jutz and Chorowicz, 1993; Nash et al, 1996). The imageries are specially useful in recognising linear structures and lineaments. Such a group of lineaments may have been caused by relief, or lithologic contrast differences, however, according to Heddi and Eastaff (1995) these may correspond to several kinds of structures or bed contours especially in folded and/or thrust areas, such as the present one. The number of lineaments inferred is very high, in general, in the western part of the area. The largest number of these is found to be present in the central part comprising the Katrol Hill Zone.

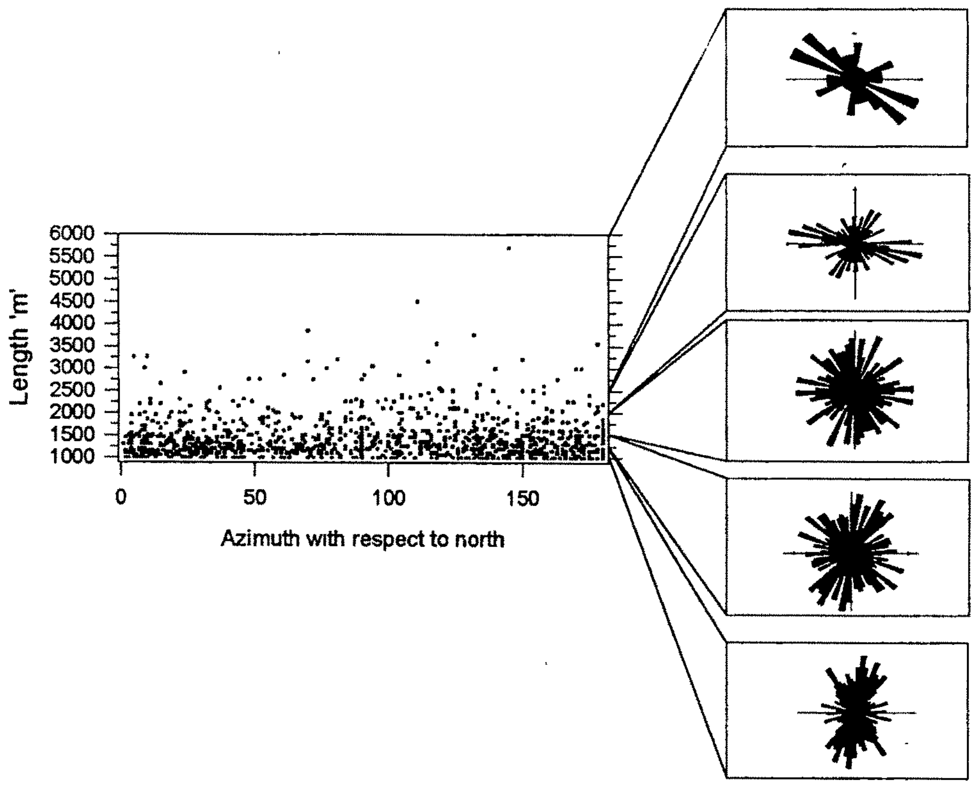


Fig 4.46 Graph showing the Length-Azimuth relationship of the lineaments

However, the density goes on decreasing towards the eastern part of the area, this is mainly due to presence of Quaternary deposits in the eastern part of the area which tend to merge with the coastal plains further east. Similar conditions prevail in the northeastern and southeastern part of the area. The quantitative analysis of lineaments was carried out to determine the size and orientation patterns of lineaments sets. The lengths of the lineaments vary from 800m to over 6000m.

The results of directional analyses show that there are three general trends i.e. NNE-SSW, NW-SE and ENE-WSW, various other subsidiary directions were also found (Fig 4.46). The relationship between the azimuth and length shows that the highest density of lineaments correspond to the length in between 800m and 3000m. NNE-SSW and NW-SE trending lineaments are dominant in the length range of 800m to 3000m. The most significant part of the length-azimuth analysis is that ESE-WNW lineaments are increasing important as length increases.

4.4.4.1 *Spatial variation and Density*

To determine the spatial variation and density of lineaments, the studied area was divided into 26 cells, each covering an area of about 64 sq km (Fig 4.47). The sectorial analysis by such means shows three most prominent trends i.e. NNE-SSW, NNW-SSE and E-W (in general, with a deviation of about 15°). The density and variation of lineaments is prominent in the central part of the study area. The strongest variations in terms of main tendency and density are seen when the area to the west and east of Shinugra are compared (Fig 4.45). The density is maximum in the western part, which is on account of the hard rocks exposed to the west of Shinugra and their practical absence near Anjar and further east. The lineament map (Fig 4.45 & Fig 4.47), when observed carefully, shows a greater and consistent degree of lineament density in between 23°05' latitude and 23°12' latitude throughout the area from west to east.

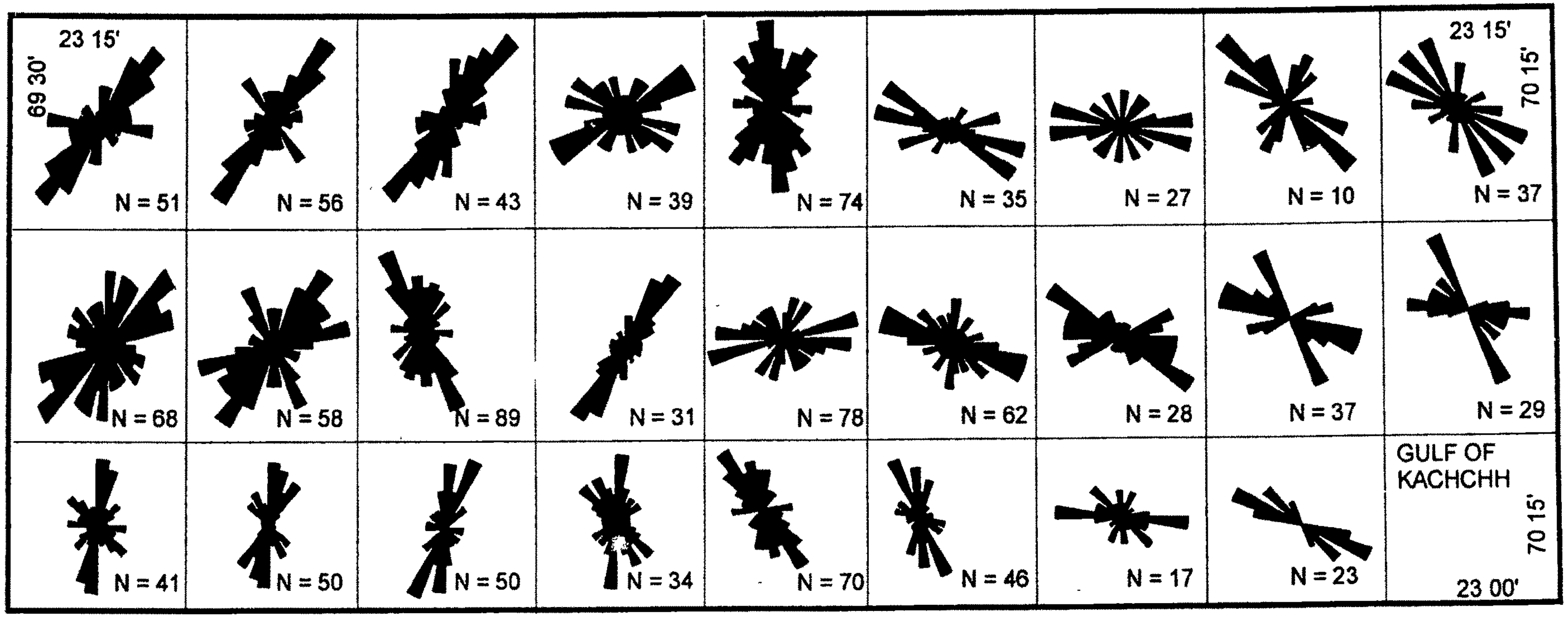


Fig 4.47 Lineament rosettes showing spatial distribution

This is on account of the deformational domain of Katrol Hill dislocation extending E-W from west to east. The most significant and interesting part of this analysis is the density of lineaments in the eastern part of the area where the Quaternary soft sediments are exposed.

It is seen that the maximum density in this part is coinciding with the possible eastern extremity of Katrol Hill Zone. This adds to the other evidences suggesting Quaternary activity tectonic along Katrol Hill Fault.

The results of the study suggest that there is a close association of the lineaments with the general structural pattern seen in the field. The genesis of NNE-SSW and NNW-SSE lineaments can broadly be correlated with the faults and fractures developed transverse to the major east-west trending structures. The occurrence of E-W set suggests its close association with the flexuring activity along major and minor faults within the Katrol Hill Zone. The presence of all these in KHZ in Quaternary sediments in general and along the eastern extremity of KHF in particular suggests continuous tectonic instability in this region during the Quaternary.