Chapter - 6

Chapter 6

DISCUSSION

INTRODUCTION

Significance of Kachchh geology lies in the fact that this is the only region in the entire peninsular India outside the Himalayan terrain (and outside a suture zone), which falls in the Seismic Zone V. An important factor of investigations in seismically active zone is establishing the structure and tectonic framework of the region. This has been a major problem with the terrain because there are different groups of workers who have provided varied inferences for the same structures. This is specifically true for faults in Kachchh region where many researchers have interpreted normal faults, while a few others have inferred them to be reverse faults/thrusts. The present investigation also renders some of the early attempts to attest active nature of largest fault of the region, the Kachchh Mainland Fault, which is believed to be the main zone of crustal weakness in the region. Deformation and faulting of the recent alluvial fan deposits as revealed in the trenches dug along KMF have confirmed that the fault was active in the recent past.

FAULTS AND FOLDS

Origin, nature and orientation of faults and egression of associated domes and anticlines of the region have remained matter of debate amongst the researchers [Hardas (1968), Biswas and Deshpande (1983), Biswas (1987 and 2005), Roy (2005), Karanth (2003), Mathew et al. (2006), Karanth and Gadhavi (2007)]. Structural features observed in sedimentary cover rocks of the region are interpreted differently by the above authors (op. cit.). Similarly different phenomena and mechanisms are proposed for the tectonic evolution of the region (Biswas 1987, Stein et al. 2002, Karanth 2003, Karanth and Gadhavi 2007).

Biswas and Deshpande (1983) and Biswas (1987, 2005), indicated that anticlines and domes observed along the margins of the uplifts are drape folds, wherein, escarpments facing the plains are marginal flexures or monoclines along the master faults of the uplifts. Biswas (2005, p1595) envisaged that "the comparatively thin sediment cover was apparently drape folded over tilted basement blocks producing linear monoclonal flexures". On the other hand, Karanth (2003) and Mathew et al. (2006) considered these anticlines and domes fault related folds/fault-propagation folds. Karanth (2003) and Karanth & Gadhavi (2007) observed that most folds are asymmetric, associated with faults; and many are overturned in nature. They are just not only restricted to frontal portion of uplifts but also the fault-related folds occur in the interior parts. They reported several structural features that are commonly reported from fold-and-thrust belts. They concluded that the region is epitome of fold and thrust-tectonism and escarpments facing low-lying areas are formed due to erosion of Fault-propagation folds.

The nature and orientation of Kachchh Mainland Fault and South Wagad Fault is a matter of major debate among the researchers. Biswas and Khattri (2002), Biswas (2005) have considered KMF as north dipping normal fault and SWF as south dipping normal fault. It was also proposed that both the faults KMF and SWF dip towards each other and they meet at seismogenic depth.

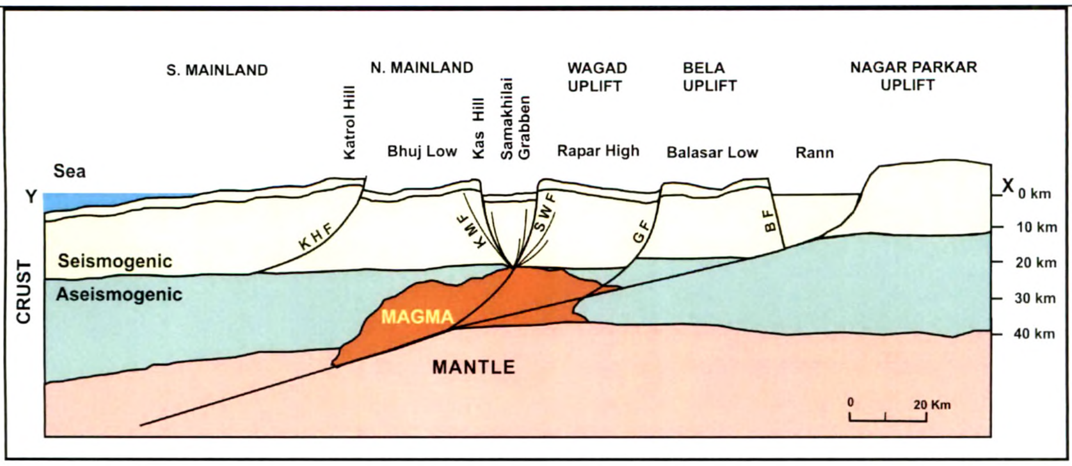


Fig. 6.1: Geological section across Kutch rift across Wagad Uplift and Kachchh Mainland Uplift as postulated by Biswas 2005.

Maurya et al., (2003 and 2007) have considered two faults in the central Kachchh Mainland, i.e. North Katrol Hill Fault and South Katrol Hill Fault and that are of the nature of north-dipping normal faults or vertical upthrusts. However, as far back as 1968, Hardas had regarded Katrol Hill Fault as a reverse fault (*Fig. 2.1*) and the beds along the Katrol Hill Range have been folded into north verging asymmetric fold with more or less vertical northern limb at the vicinity of Katrol Hill Fault and gently south dipping southern limb away from the fault.

Mathew et al. (2006) suggested that, the initial KMF could have been a normal fault during the ancient rift stage, but subsequent reversal during structural inversion resulted in normal fault initially reactivated into strike-slip faults, along with the initiation of a thrust fault at depth. According to them continued compressive stress finally resulted in fault propagation folding of Northern Hill Range on to the south dipping reverse fault.

During present study it was observed that, zone of faulting in Kachchh Mainland Fault is marked by steeply north dipping beds (Fig. 4.14) within a width of 1 to 2 km. Within fault zone the beds are mostly sub-vertical to vertical, at times overturned and erratic (Fig. 4.15). This geometry of fault distinctly suggests that fault is south dipping reverse fault along which Mesozoic rocks are folded. Trench investigations in pediment zone north of Northern Hill Range also revealed moderate to gently south dipping reverse fault. Along the northern most trace of the fault Quaternary deposits are seen to produce exposure scale fault-propagation folds (Fig. 5.5). To the east of Lodai the fault is either buried under the recent cover or replaced by the marginal flexure. Again between Jhuran and Khirsara the fault is indicated by the highly plicated Tertiary beds. The fault appears to fadeout gradually to the east of Bhachau giving rise to Bhachau Nose near Vondh village.

As described in Chapter 4, the anticlines observed along SWF are characterised by steep south dipping forelimb and gentle north dipping backlimb. Here structural style is reverse from that of Kachchh Mainland. Geometry of domes and folds in Wagad region indicates that SWF is south verging reverse fault. Further thrusting of Jurassic rocks over Cretaceous sandstone indicates that SWF is a low angle reverse fault.

From these observations and structural data it is clear that KMF is a south dipping reverse fault and SWF is a north dipping reverse fault. Thus they are dipping away from each other and therefore there is no possibility of them meet at depth. By and large the strike of reverse faults is E-W with southerly dips. The amount of dip of reverse faults ranges from about 45° to sub-horizontal (Karanth 2003). Often they are found to be horizontal.

For the physiographic evolution of the region different views prevail. Some workers (Biswas 1987, 1993, 2005; Biswas and Khattri, 2002) proposed that several intra-basinal sub-parallel strike faults are responsible for the origin of uplifts and low lying flat areas (the Ranns). The origin of uplifts is correlated with tilted basement blocks, forming a series of half grabens with Kachchh basin. Structurally it is considered by them that, the basin contains footwall uplifts and half-grabens along intra-basinal strike fault. It is proposed that the uplifts are the outcropping areas and the grabens/ half-grabens form extensive plains covered by Quaternary sediments.

Biswas (1993, 2005) further elaborates that from north to south, the Great Rann sub-basin is a narrow graben between Nagar Parkar Fault and Island Belt Fault, the Banni half graben (BHG) is formed by southward tilting of the Island Belt block, similar tilting of the Kachchh Mainland block formed the Gulf of Kutch half-graben (GOKHG). Further it is proposed by him that the plains form 'residual depression' and Bhuj Low is a simple down-faulted homocline. In the eastern part the Wagad Uplift, is tilted to the north along Gedi fault (GF) forming Rapar half-graben (RHG). The origin of subsidiary structural features mostly irregular shaped noses/domes in this low is attributed to basement grain by Biswas.

Whereas from evidences gathered and structural interpretation of tectonic style of the region Karanth (2003) and Karanth and Gadhavi (2007) proposed that in the Kachchh Mainland Fault Zone, the southernmost part of Banni area (i.e. foot-hill region of the Kachchh Mainland Hill Range) where steeply north dipping beds are seen, represents the traces of forelimb of fault-propagation fold and the south dipping beds of the hill range (e.g. Kas, Habo, Jhura and Jara range) represent the hinterland limb of fault-propagation fold. The moderate to gently south dipping beds at the crest of hills gradually merge into sub-horizontal beds of the Bhuj Lowland. Further south, these beds abut against steeply north dipping beds at the base of the Katrol Hill Range; passing on to Katrol Hill Fault Zone. The region along the hill range and further south is characterised by gently south dipping beds. Whereas the gently dipping hinterland limbs of fault-propagation folds are exposed all along the interiors of hill ranges that gradually merge with the plains. Thus, it can be ascertained that, (i) the Bhuj Lowland constitutes the 'synclinal footwall' of fault-propagation fold along Katrol Hill Fault and Katrol Hill Range (and the plateau to the south of it) represents the hanging wall anticline of Katrol Hill Fault (Fig. 6.2). (ii) Southern part of Banni Plains constitutes the footwall syncline and Kachchh Mainland Hill Range forms the hanging wall anticline of Kachchh Mainland Fault. (iv) Similarly the Great Rann of Kachchh is situated in the footwall syncline and the hill range at northern fringe of Pachchham, Khadir and Bela represent the hanging wall anticline of the Island Belt Fault.

The difference of opinion also exists about the origin of structures observed within back limbs of these folds observed along the margins; Biswas (1993) attributed the presence of secondary structural features within back-limbs of uplifts (faults, folds and domes) to buried basement topography. He considered the origin of these uplifts related to basement lineaments, which according to him, are the representation of the structural elements of Delhi Synclinorium in the basement. However, Karanth (2003) and Karanth & Gadhavi (2007) attributed their origin to fold-and-thrust belt tectonics.

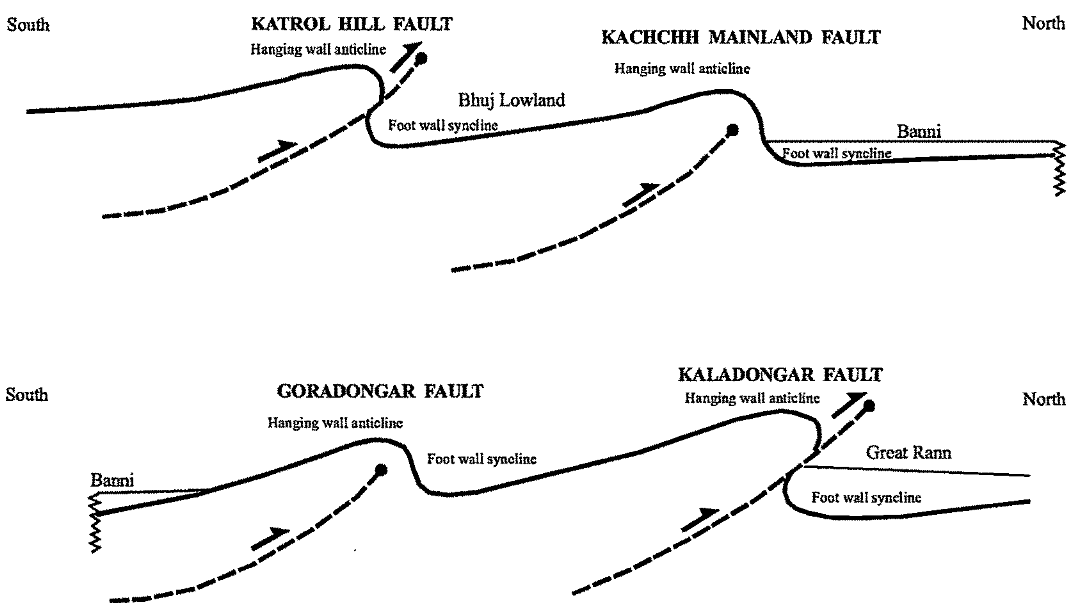


Fig. 6.2: Generalized cross-section from south to north of the fold-and-thrust belts of Kachchh.

Origin of marginal flexures and domes

Fault-related folding

Marginal flexures along the uplifts are interpreted as drape folds by Biswas (2005). Drape folds are usually found to occur over syn-sedimentary normal faults where loose sediments cover subsurface normal fault forming a monocline (Fig. 6.3). Structure formed by steeply inclined strata bounded by more gently inclined strata on either side is known as monocline. In a drape fold it is most unlikely to find overturned beds, the kind found in Kachchh along the forelimbs of flexures.

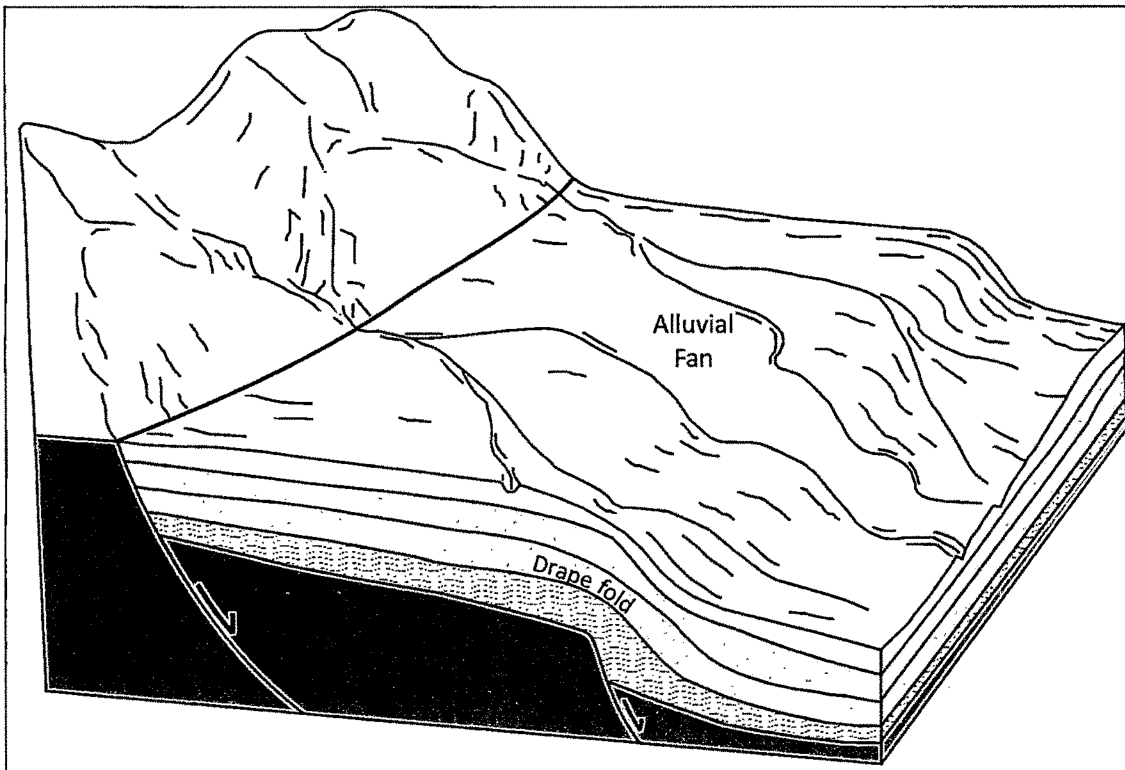


Fig. 6.3: Idealised block diagram showing the development of a drape fold on alluvial-fan on buried normal fault. (After Keller and Pinter, 2002).

Observations during present study reveal that marginal flexures (anticlines and domes) in Kachchh region are characterised by sub horizontal to gently dipping hinterland limbs and steeply dipping (occasionally overturned) forelimbs. This geometry of marginal flexures depicts the morphology of fault-propagation folding formed on account of compression. In a fault-propagation fold, a blind thrust creates a ramp by progressively propagating upward, towards the surface (Suppe and Medwedeff, 1990). Fault-propagation folds are formed typically on the hanging wall of a thrust or reverse fault, where deformation takes place in front of propagating fault tip (Fig. 6.4 and Fig. 6.7). Over the upward propagating fault ramp, at the surface, fold grows progressively as subsurface thrust or reverse fault accumulates more and more slip (Fig. 6.4).

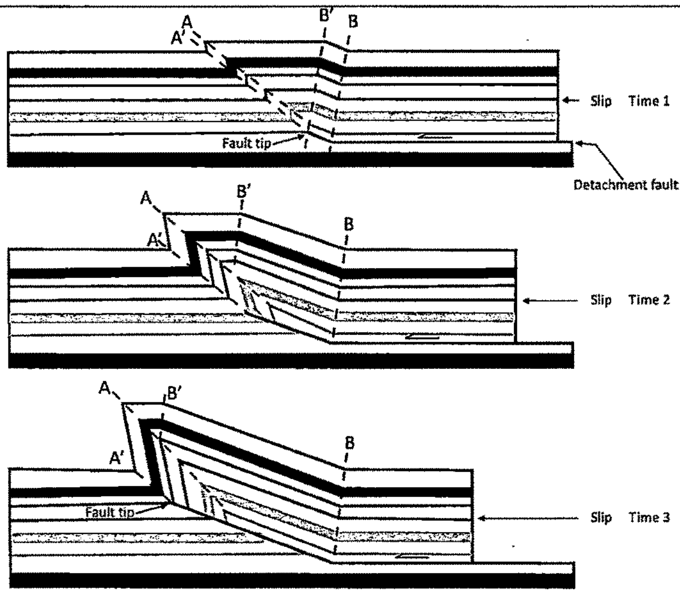


Fig. 6.4: Phases of fault-propagation fold development as a result of slip along a detachment fault. Note that with progressive slip on detachment fault, fold becomes more asymmetric and grows dimension. (Modified after Keller and Pinter, 2002).

The propagating tip diverges from detachment fault that runs along a weak stratigraphic horizon and steps up to form a ramp (Fig. 6.4). As the structure grows through time, the fold becomes asymmetric (Keller and Pinter, 2002). Geological cross section across Kas Hill anticline near Jawaharnagar (Fig. 6.5 and Fig. 6.6) distinctly portrays morphology of a fault-propagation fold. Despite considerable erosion, upright asymmetric to overturned folds are encountered in the hill ranges (e.g. near Adhoi SWF zone, Fig. 4.6 and near Juna in Goradongar range, Fig. 4.13).

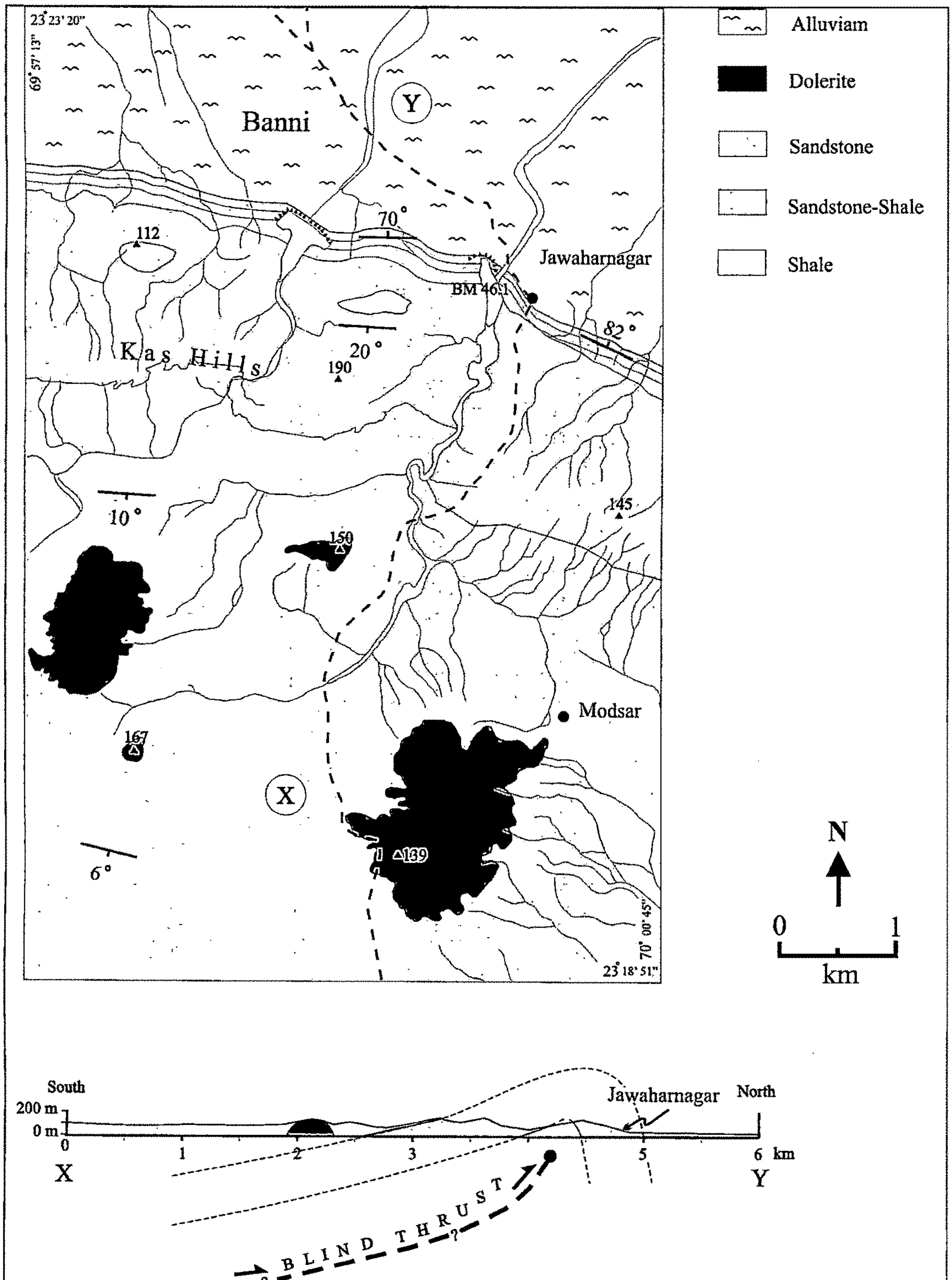


Fig. 6.5: Geological map of the area around Jawaharnagaer (above); Cross section along X-Y (below). (After Karanth and Gadhavi 2007).

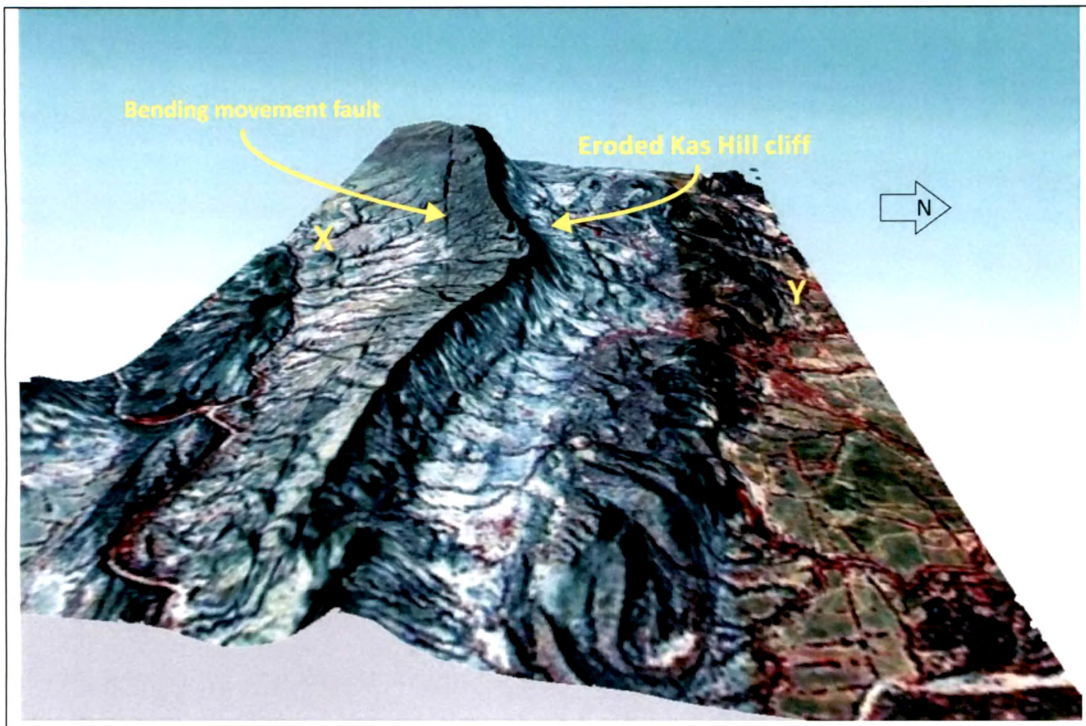


Fig. 6.6: LISS-PAN merged satellite image of Kas Hill cliff. The lineament on the back side of cliff indicates bending movement fault.

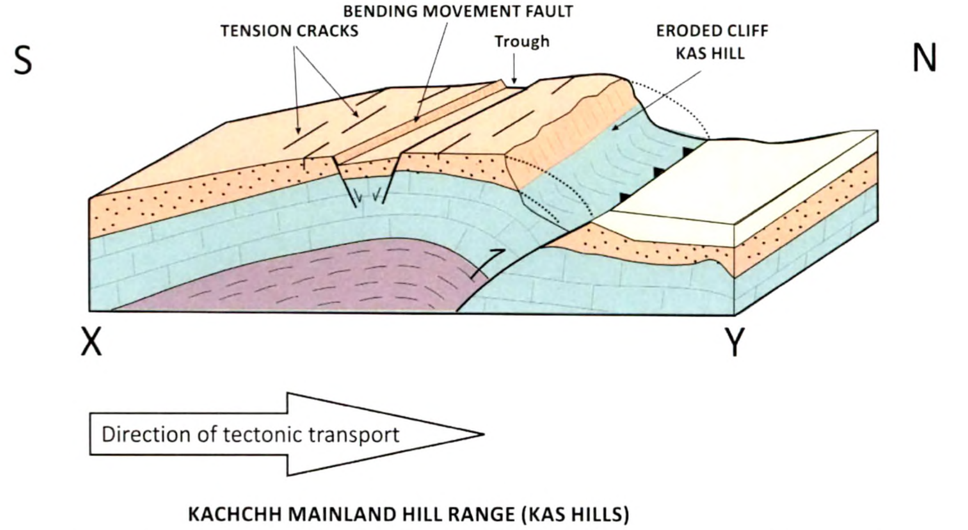


Fig. 6.7: Fig. 6.7: A caricature of the nature of fault-propagation folding at Kas Hill, along Kachchh Mainland Fault. (Modified after Karanth 2003).

A number of structures observed in Kachchh region (described in Chapter-4) are typical example of structures observed in fold-and-thrust belts as discussed below. Mesoscopic scale exposure of fault-propagation fold is observed near Juna in the

Goradongar Range, Pachham Island (Fig. 4.13). Preservation of this macroscopic fold from erosion at Goradongar is appears to be due to a sill of resistant basic rock exposed at the forelimb of the fold. Unlike in other places, the competent concordant igneous body has prevented rapid erosion of forelimb and hinge zone. The continued deformational stresses have further produced recumbent fold (Fig. 4.13).

Discernable thrusting at Kakarwa

Even though at most places the hinges of these folds are seen to have been eroded, the forelimb can be discerned by the traces of steeply inclined to vertical beds; at places the beds are seen to have been overturned. The Kakarwa anticline in Wagad Uplift is one such example which is characterised by near vertical to over turned forelimb and gently north dipping back limb (Fig. 4.20 and Fig. 4.21). The axial part of the anticline is completely eroded. The morphology of the anticline distinctly represents geometry of fault-propagation fold. Near vertical beds of fossiliferous sandstone-shale sequence (Upper Jurassic) forming forelimb of the anticline are observed resting on horizontally placed coarse grain sandstone (Cretaceous) near Kakarwa village (Fig. 4.21). The presence of vertical Jurassic beds resting over horizontal Cretaceous sandstone indicates appreciable horizontal displacement. Just a remnant forelimb and major part of back limb of folded sheet are preserved, whereas hinge portion of the sheet is completely eroded. Looking at the extent of erosion, further, it is suggested that the structure is old enough and not active at present.

Slip deficit on subsurface fault

For the origin of doubly plunging anticlines and domes observed in Kachchh region Biswas (1993 and 2005), Biswas and Khattri (2002) and suggested that the monoclonal flexures are split into individual domes, brachy-anticlines and anticlines. However, the mechanism for origin of domes and anticlines are not explained by them.

It is established fact that faults grow by extending sideways, reverse fault growth in the subsurface will cause the lateral growth of folds at the surface (Burbank and Anderson, 2001). Variations in the displacement along the underlying thrust plane get reflected by the amplitude of folding at the surface. Hence, the size and shape of crest of folds varies in height and fold axis plunges in the direction of slip deficit on the underlying fault (Fig. 6.8).

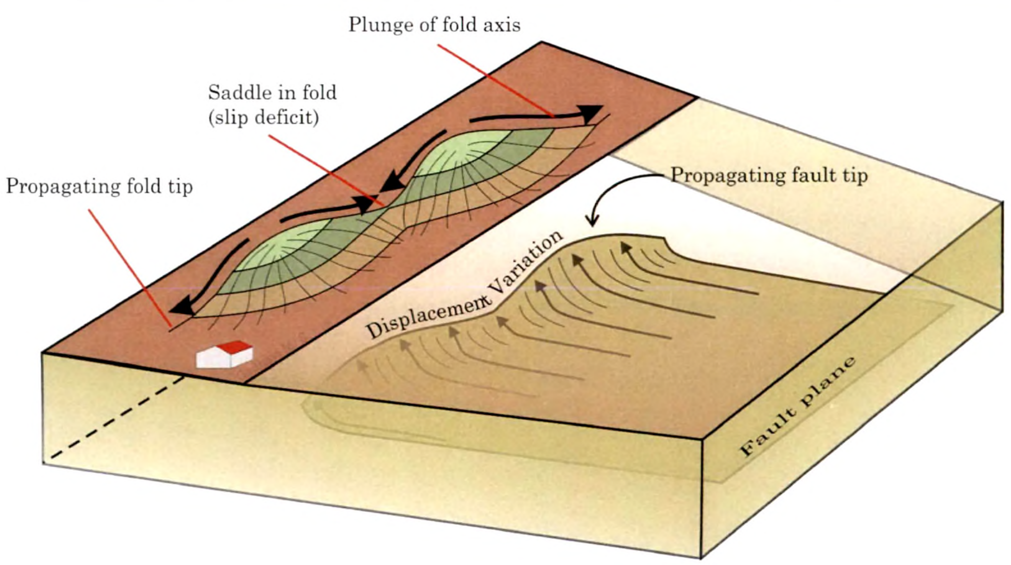


Fig. 6.8: Slip deficit on subsurface fault, reflected as saddle in fold on the surface. (redrawn after Burbank and Anderson, 2001).

Typical example of slip deficit on subsurface thrust reflected by saddle on the surface is demonstrated by Mea and Vamka dome along South Wagad Fault (Fig. 4.4). Steeply south dipping shale-sandstone sequence along South Wagad Fault constitutes forelimb of both the domes, whereas, gently north dipping layers give rise to back limb. Central parts of both the domes are eroded and only rim is preserved. Saddle between these two domes is clear reflection of slip deficit on subsurface thrust (Fig. 4.4).

Growth of fault in segments

As illustrated in Fig. 4.9 individual faults (or segments of a fault) are often linked together with adjacent faults. If the linked structures are blind thrusts, variations in displacement along them will create multiple plunging folds at the surface with structural saddles marking the zone of linkage.

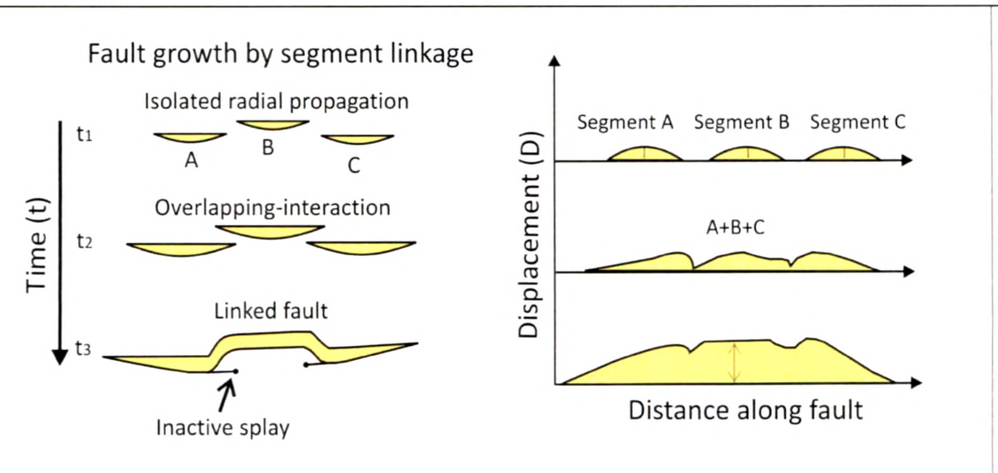


Fig. 6.9: Fault growth by segment linkage. (Redrawn after Burbank and Anderson, 2001).

Occurrence of oblong, dome-like structures elongated parallel to the axis of hill ranges in Kachchh region suggests that initially the folds formed as individual segments over the tip of thrust sheets. With progressive growth on either side they coalesced to form a continuous stretch of folds. In the eastern part of the Kachchh Mainland Fault such coalesced domes have given rise to 'linked-segments' (Mathew et. al. 2006). Similarly along the South Wagad Fault coalesced domes have marked southern margin of Wagad Uplift.

Kachchh Mainland Hill Range is also characterised by several domal structures of which Habo and Jhura domes are most prominent. These domes are seen intimately associated with igneous intrusive bodies at the core. The presence of intrusive stocks/plugs within the Mesozoic sediments appears to have interfered with the style of fault-propagation folding. Erosion of the envelop of incompetent (shale) layers alternating with competent (sandstone) layers superimposed by conjugate fractures developed on account of compressional stresses, has given rise to *'petal-like pattern of a lotus flower'* (Karanth 2003).

Out-of-syncline thrust

Examples of structures generated from compressive stresses are observed within Bhuj Low in association with Palara Syncline, which further strengthen the view that Kachchh region is prototype of fold-and-thrust belt. Persistent contraction of Palara Synclines has given rise to Saraspar Thrust at northern fringe of the syncline. When strata are folded, local stresses are created on curved surface of strata. Thrust faults associated with progressive plication of synclines are termed as 'out-of-syncline thrusts' (Mitra, 2002).

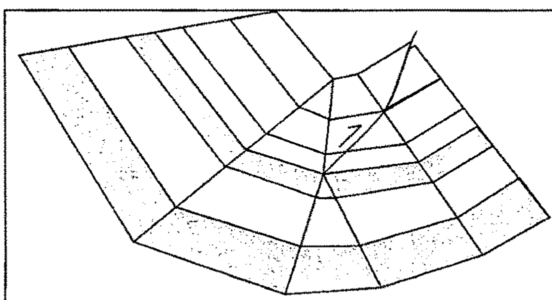
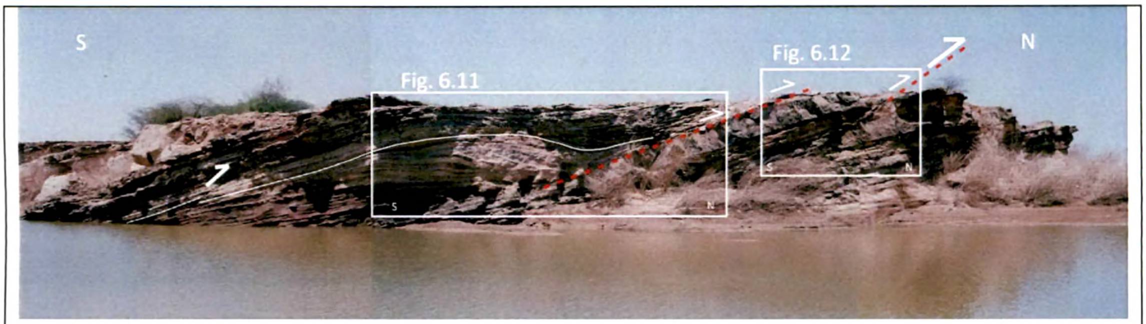


Fig. 6.10: Out-of-syncline thrust propagating on the gently dipping limb. (after Mitra 2002).

Out-of-syncline thrusts originate in synclinal cores and transfer slip along the hinge zone or to the forelimbs or back limbs of structures. Some of these faults transfers slip to bedding-plane detachments, whereas others lose their slip through penetrative deformation within incompetent units (Mitra, 2002) (Fig. 6.10). In such type of thrusts the upper units are thrust toward the anticlinal hinge and away from the synclinal hinge. Mitra, 2002 suggested main three mechanisms for the formation of out-of-syncline thrusts. According to him the most important mechanism is; (i) an increase in curvature toward the core of the syncline, other than that slip can occur due to (ii) differential penetrative strain between units and (iii) due to formation of secondary structures or disharmonic folds in one or more units. Mitra (2002) observed that out-of-syncline thrust propagate on the gently dipping limb of syncline. The structure described by him is exemplified at Saraspar, where thrust faults are seen in gently dipping northern limb of Palara Syncline (Fig. 4.24 and Fig. 4.25).

Bedding parallel slip is common phenomenon associated with out-of-syncline thrusts occurring in strata characterised by alternate layers of competent and incompetent rocks. Due to progressive tightening of syncline, development of flexural-slip folding is observed in the incompetent beds. Bedding-plane slip periodically climb section through competent units, transferring slip to other bedding-plane thrust within a relatively incompetent unit (Mitra, 2002). When observed in isolation, such out-of-syncline thrusts are interpreted as contractional wedge thrust. The sense of shear on the wedge thrust is commonly congruous with associated flexural-slip folding. Saraspar Thrust distinctly portrays flexural slip folding (Fig. 6.11) as well as wedge thrusting (Fig. 6.12). The incompetent shale layers suitably serve as weak planes for bedding parallel slip, whereas, competent sandtone beds are seen displaced giving rise to wedge thrust. Wedge thrusts are primarily formed in competent units because of variations in penetrative layer-parallel strain between adjacent units (Mitra, 2002).



Saraspar thrust as shown in Fig. 4.25.

Fig. 6.11: Flexural slip folding at Saraspar thrust..

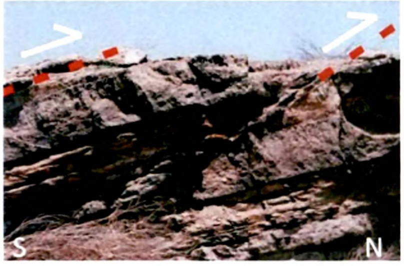


Fig. 6.12: Wedge thrust seen along northern margin of Palara Syncline.

Fault-bend folding

Another distinctive structure, confirming progressive tightening of Palara Syncline is an exposure-scale Fault-bend-folding observed within northern limb of the syncline. Fault-bend folds consist of two or more planar panels separated by sharp kinks (Keller and Pinter 2002) (Fig. 6.13). When beds in the hanging wall of a thrust fault are thrust up along a relatively high angle ramp to follow again low angle displacement plane at a structurally higher position the geometry is termed as 'flat-ramp-flat' structure. In the region typified by competent and incompetent sedimentary layers, bedding parallel slip along incompetent bed serves as flat, whereas, because of variations in penetrative layer-parallel strain between adjacent units (Mitra, 2002); competent units are dislocated to produce ramp. Bedding-plane slip transports through such ramps, transferring slip to other bedding-plane thrust at higher structural position. Due to non-planner shape of the thrust surface rocks in the hangingwall are forced to bend/fold. Thus the fold would grow over the ramp. Fault-bend fold observed within Palara Syncline has a ramp angle of around 30° in the direction of tectonic transport.

The orientation of weaknesses within rocks that are subjected to stresses can exert a strong control on how they deform (Mitra, 2002). In Palara Syncline bedding confined joints (with a dip of around 30° in most parts of the region) are observed in sandstone bed lying between shale beds (Fig. 4.25), which in turn have facilitated the formation of 'flat-ramp-flat' structure (Fig. 4.27, Fig. 4.28 and Fig. 6.13).

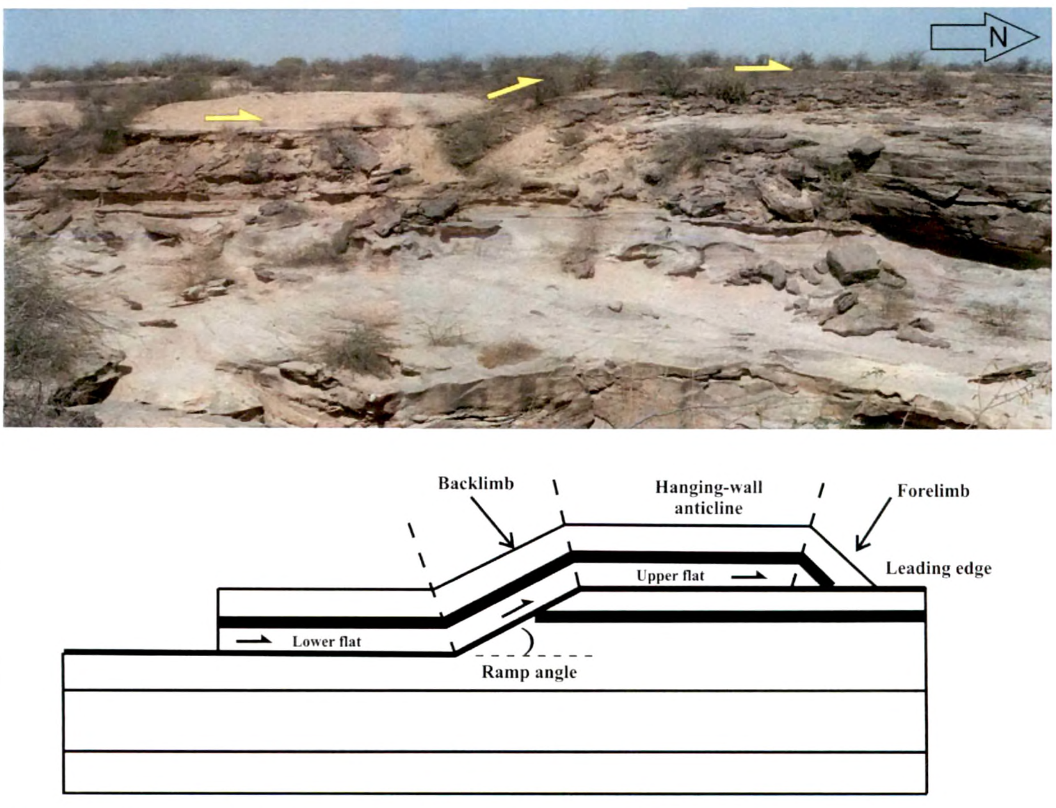


Fig. 6.13: Flat-ramp-flat structure observed within Palara syncline.

Development of drag folds and shearing of incompetent beds are evident at the base of bedding parallel thrust sheet (Fig. 4.18 and Fig. 4.19) (Karanth 2003, Karanth and

Gadhavi 2007). Commonly it is observed that shale layers are sheared at the base of bedding parallel thrust; whereas, brittle sandstone layers are displaced along thrust faults.

These structures indicate that back limbs of marginal flexures are also folded, which can not be explained by theory of vertical tectonics. Thus the structural features described above indicate that the region of Kachchh is under the spell of compressive regime.

ACTIVE TECTONIC STUDIES

Seismic history and geomorphology of Kachchh region distinctly indicates that region is under influence of active tectonic forces. Compression induced active deformation of Palara Syncline has given rise to number of active tectonic landforms. Hanging paleochannel, paired alluvial and strath terraces; aggradation, ponding and deep bedrock incision are examples of active tectonic landforms observed from Palara Syncline area.

Active Deformation of Palara Syncline

Hanging paleochannel

Present day Khari River at the western fringe of Palara Syncline has cut across a pre-existing channel (Fig. 5.10), which in the past had a flow-direction approximately perpendicular to current channel flow. This unique geomorphic feature, oriented almost parallel (E-W direction) to fold axis of Palara Syncline demonstrates dramatic geomorphologic changes in the area. Incision along Khari River demonstrates a sequence of incision, followed by aggradation and incision. The geological history of this unique active tectonic feature commences with incision of Mesozoic rock sequence by an unnamed paleochannel. In the first stage of chronological sequence this paleochannel has incised Mesozoic shale sequence producing about 10 m deep and 30 m wide channel. This incised paleochannel subsequently became defunct. Aggradation by valley filled deposits then occurred (Mathew et al. 2006). The age of sediments at the top of filled paleochannel is estimated to 12.4 ±1.6 ka by Mathew et al. (2006). At later stage present day Khari River, flowing approximately perpendicular to the paleochannel, incised Mesozoic strata. In this process it also has incised sediments aggraded in the paleochannel and Mesozoic strata below the base level of paleochannel by ≈9 m giving it appearance of hanging channel. This incision was followed by aggradation within Khari River. Again due to base level changes Khari River incised it's on deposits that resulted in formation of 3.25 m high paired valley filled terraces (Fig. 5.9). Here it is worth mentioning that during present study it was observed that base level changes received by Khari River are directly associated with constraining Palara Syncline.

River terraces

Terraces are found to be good tools for studying distribution and timing of tectonic deformation (Keller and Pinter, 2002). A river that is neither aggrading nor degrading can be considered to be in equilibrium (Bull, 1991) and to be at the threshold of critical power (Burnbank and Anderson, 2001). Stream power of a river in equilibrium is just sufficient to transport the sediment load that is being supplied from upstream. Thus neither deposition nor erosion will occur along the course of a river which is in equilibrium. Tectonic perturbation can bring change in baselevel of a river. Increase or decrease in river slope will cause the river to cross the threshold of critical power and river will begin to erode its bed or will shift to aggradation. Where uplift occurs base level falls, a river may incise through its floodplain in order to reach a new graded profile (Keller and Pinter, 2002). Two classes of river terraces are typically defined;

aggradational (or fill) and degradational (or strath). The aggradational (alluvial) river terrace results by down cutting of river-transported alluvium along its own course. This can be regarded as a consequence of crossing the threshold of critical power, such that the river moves from an aggradational mode to degradational mode.

Paired alluvial terraces are observed along the course of Khari River as it flows at the western margin of Palara Syncline. Khari River has incised it's own deposits by 3.25 m while flowing in approximately perpendicular direction to the axis of the syncline. It can be envisaged here that tectonic perturbation in the area caused by progressive plication of Palara Syncline has resulted into the base level change of the river. Consequently river action has switched from aggradational to degradational in the area. Incised alluvial terrace is found to be 5 ka to 4 ka old, whereas, hanging paleochannel is dated back to 12 ka by Mathew et al 2006. This indicates that area is under influence of active tectonics.

When a river incise into bedrock, strath terrace is formed. Strath terraces are considered useful local geomorphic markers as they provide rates of river incision at localized spots on the river profile (Burbank and Anderson, 2001). They are found to occur adjacent to axis of deformation and hence could directly be correlated with the deforming structure. They have been suggested to result from episodic tectonic uplift (Burbank and Anderson, 2001).

Pat River has incised two paired strath terraces (T_1 and T_2) while crossing southern steeper limb of Palara Syncline, the primary surface is distinguish as T_0. It is evident that change of base level at this location along the course of Pat River that flows across the syncline is caused by progressive folding of Palara Syncline. The formation of strath terraces along its course is direct effect of localised base level changes.

Aggradation and incision

River Pur and River Pat have entrenched their courses across Palara Syncline. While passing through Palara Syncline both the seasonal streams have suffered base level changes with different intensities. As both the channels have incised their courses in bedrock, flow of both the channels is confined. Due to base level changes caused by tectonic perturbation within Palara Syncline; aggradation of sediments (Fig. 5.12) and ponding (Fig. 5.13) are common sights along their courses. Uplift at a point along the course of these streams has caused ponding to the upstream of axis of deformation.

Bedrock incision

Narrow and deep bedrock incision observed in a small 2nd order stream flowing almost parallel to the Saraspar Thrust attests active uplift in the area. The stream is situated within back limb of the thrust (Fig. 4.14). Cretaceous sandstone is observed incised by about 30 m along a hardly 3 m wide gorge.

In view of above discussed active tectonic landforms it is evident that Palara Syncline is actively undergoing deformation.

ACTIVE FAULT STUDIES ALONG KMF

As explained in the Chapter-5, trench investigations carried out in pediment zone north of KMF have demonstrated that KMF is active and has displaced Quaternary deposits. Active fault strands of KMF were observed in Trench T1 (Fig. 5.4 and Fig. 5.5) excavated near Jhura village and in Trench T2 (Fig. 5.6, Fig. 5.7 and Fig. 5.8) excavated near Khirsara village (see Fig. 5.2 for map locations).

Trench investigation near Jhura village revealed active fault displacing alluvial fan deposits of Kaila River (Fig. 5.4). Two fault strands F1 and F2 were identified in the trench

(Fig. 5.5). The northern fault F1 shows a low-angle reverse fault with inclination of 15° toward south. Three seismic events were inferred in the trench from upward fault termination and angular unconformities.

Only one active fault strand was observed in a trench (Trench T2) near Khirsara village. Along the western wall of Trench T2, it was observed that Quaternary units are displaced by 30 cm to 56 cm along a south dipping fault. However, rupture along eastern wall was not well defined.

Net-slip along Fault F1 in Jhura Trench considering deformation

The net-slip for single event considering deformation on the hanging wall at Jhura is proposed to be ≈5 m (Morino et. al. 2008b). On western wall of the Trench T1 the displacement of units along the fault plane of F1-1 strand is ≈116 cm, whereas same is ≈60 cm along the fault plane of F1-2 strand. However, looking at the extent of deformation of the hanging-wall it can be envisaged that a greater amount of deformation is consumed by folding at shallow depths on the hanging wall. The layers on footwall are also deformed. This indicates that the displacement of units observed along the fault plane of F1 fault is much less than actual displacement.

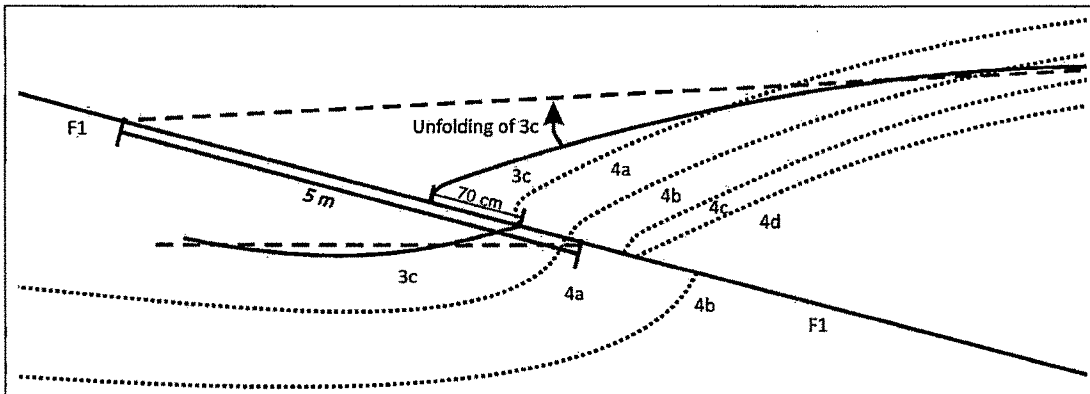


Fig. 6.14: Schematic diagram to demonstrate net-slip considering fault drag of Subunit 3c along eastern wall of Trench T1 (see Fig. 5.5).

To decipher amount of displacement consumed by folding on hanging-wall and footwall during latest event (along F1-2 strand) in Trench T1, Subunit 3c is restored to its original sedimentary inclination (Fig. 6.14). It is assumed that at the time of deposition Subunit 3c had a primary dip of about 3° due north, adapting slope of alluvial fan. It seems that the length of Subunit 3c is also shortened due to effect of towing of the forelimb. Amount of slip between dislocated tangents of unfolded Subunit 3c on the fault plane of strand F1-2 is 5 m (Fig. 5.5). Thus Net slip for strand F1-2 calculated in this manner happens to be 5 m.

Characteristic displacement along KMF

Trench investigation along KMF near Jhura village (Trench T1) revealed that fault has moved twice along younger fault strand F1. Interestingly it has been noticed that during both the events, fault-slip is nearly equal. Along the eastern wall of the trench the displacement of Subunit 4a happens to be about 144 cm, whereas, Subunit 3c is displaced by 70 cm (Morino et al. 2008b). Displacement of Subunit 4a observed in the trench is cumulative of two events, if slip during youngest event (strand F1-2) is restored, displacement along strand F1-1 for Subunit 4a during penultimate event happens to be 74 cm, which is nearly equal the slip observed during youngest event (i.e. 70 cm). Western wall of the trench also exhibits similar outcome, where Subunit 4a is displaced by 116 cm and Subunit 3c is displaced by 60 cm (Fig. 5.5). Again here slip on fault F1 is nearly equal during both the events. Moreover, dip of Unit 4 along western wall of the Trench T1 is 25° due north, whereas, dip of Unit 3 is 10° to 15° due north. The dip of Unit 4 is cumulative of two events, also this indicates equal amount of deformation during both the events. Similarly along eastern segment of the KMF in trench T2 near Khirsara village it has been observed that Unit 4 has moved 30 cm whereas, underlying Unit 5 has moved by about 56 cm. An angular unconformity is recognised between units 5 and 4, where dip of Unit 4 is 14° and dip of underlying Unit 5 is 30° due north. Based on slip variation observed between Unit 5 and Unit 4; and angular unconformity between both the units; two events are inferred in the trench. The amount of slip and tilting of units during both the events in this part of the fault also are similar indicating that KMF has moved during last two events with same amount of slip along its length.

Trench investigations near Lodai village along KMF by Malik et al. (2008b) also revealed existence of two events, wherein, latest event registered displacement of ≈33 cm and penultimate event registered displacement of ≈40 cm.

If a fault or a segment of fault ruptures repeatedly and displays approximately the same amount and distribution of slip during each successive event, the fault is said to be typified by characteristic earthquake (Schwartz and coppersmith, 1984). On a fault typified by characteristic earthquake the strain build-up and release, stress drops during faulting, variations in displacements along the fault, and the length of the rupture would be approximately same in successive earthquakes (Fig. 6.15). Depending upon slip distribution along a fault or a segment of fault Schwartz and coppersmith (1984) classified various slip distribution patterns, for random slip distribution they proposed variable slip model.

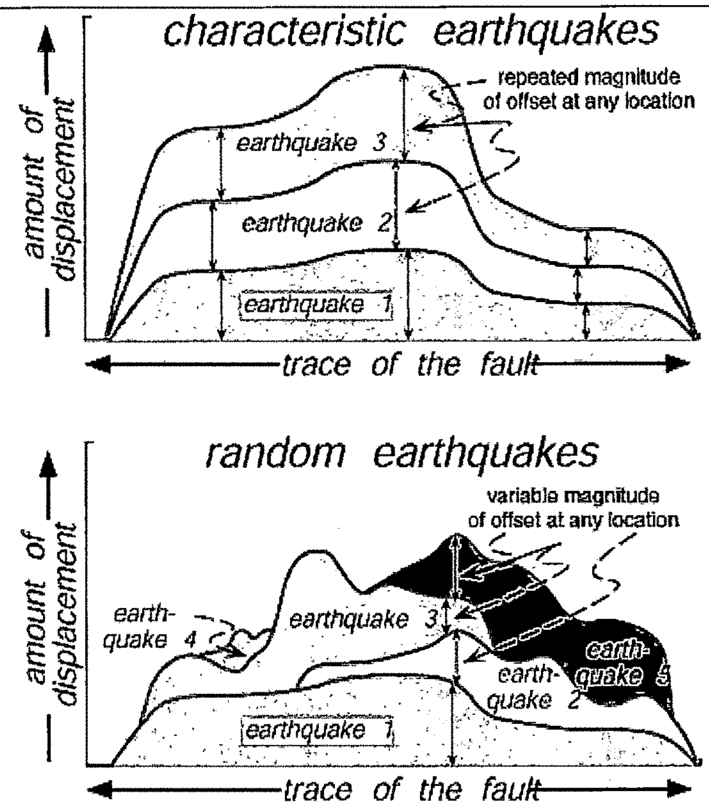


Fig. 6.15: Schematic illustration of characteristic earthquake displacements versus unpredictable, variable slip (after Barbank and Anderson, 2001).

Variable slip model

In variable slip model displacement and rupture lengths are randomly distributed in such a fashion that, over the time, all regional strain is accommodated, and there is an essentially uniform slip rate along the length of the fault. In this model the displacement experienced at any given point, the size of the earthquake, and the position of the rupture segment each vary unpredictably between successive events. Consequently there is no fault exhibiting characteristic earthquake in this scenario.

Characteristic earthquake model

In characteristic earthquake model there is a consistent displacement at a point from one event to the next. Over the time, however, the slip rate varies along the fault because the displacement varies along the length of the fault. Each large earthquake represents a repetition of the rupture location, length and displacement pattern of the previous large earthquake, and there are infrequent moderate-sized earthquakes that only accommodate a fraction of the residual slip variation along the fault.

Slip distribution along the KMF as observed in trench investigations suggests that KMF is typified by characteristic earthquake. However, as dating of OLS samples collected from these trenches is still pending; events observed in one trench can not be correlated with the events observed in other trench. Nevertheless, events of a single trench can be correlated. This indicates that, for a given segment or length, the fault is typified by characteristic earthquakes.

Tremendous predictive power exists in the faults that rupture via characteristic earthquake. If rupture along a fault were controlled by stable asperities and barriers (i.e. constant failure stress and terminating stress), that persisted from one earthquake to the next, this could provide a mechanism for generating similar "characteristic" slip along the fault in multiple events (Burbank and Anderson, 2001).

ACTIVE FAULTS OF KACHCHH

Seismic history of Kachchh and recently carried out palaeoseimic and active fault studies in the region have attested that region is quite active and still undergoing changes due to ongoing tectonic processes. As discussed earlier physiography of Kachchh region is characterised by fault bound uplifts. Region is characterised by number of large faults. Based on seismic history, current seismicity and recently carried out active fault studies along KMF and KHF and evidences gathered during present study; active faults of the region are determined. Accordingly this information is plotted on DEM of Kachchh region to produce first ever active fault map of Kachchh region (Fig. 6.16).

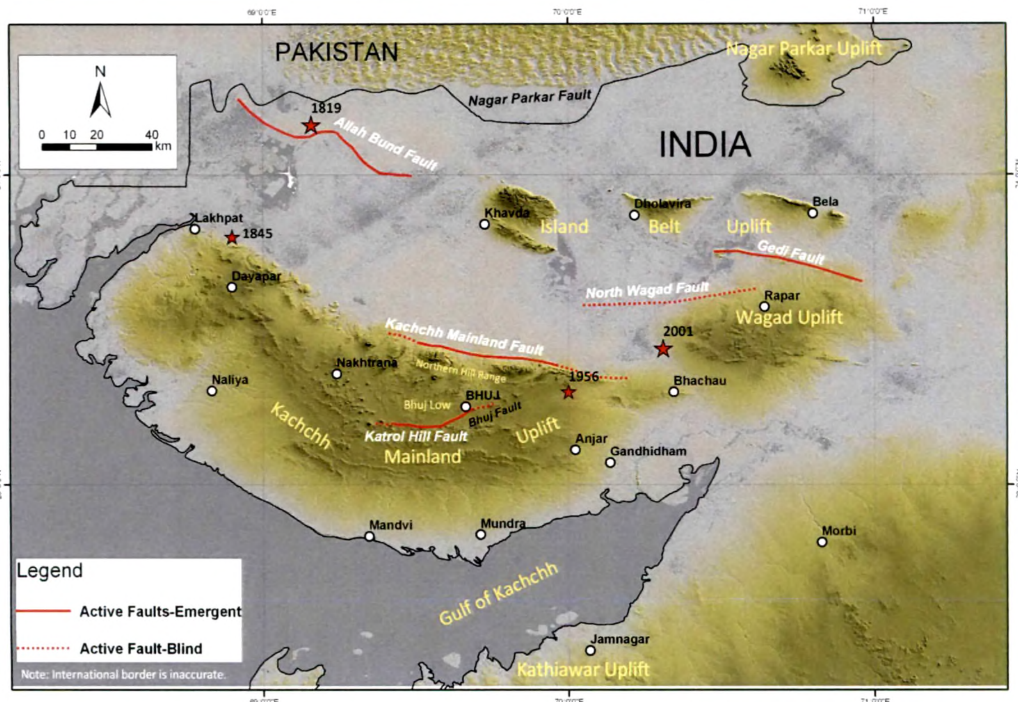


Fig. 6.16: Active fault map of Kachchh prepared based on palaeoseimic and active fault studies; as well as recent seismic data of the region.

Nature of faults (blind or emergent) and location are adopted from various sources; Allah Bund Fault: after Oldham, 1926 and Bilham, 1999; Gedi Fault after Mandal et al. 2006; North Wagad Fault after Mandal et al. 2004; Kachchh Mainland Fault after Mathew et al., 2006; Karanth and Gadhavi, 2007; Malik et al. 2008; Morino et al. 2008b; Katrol Hill Fault and Bhuj Fault after Morino et al. 2008a)

Branch fault of KMF

The exposure of folded and gently north dipping tertiary rocks are observed about 7 km north of KMF near Kharod village (Fig. 4.16 and Fig. 4.17) constituting an east-west oriented small ridge hardly 2m high with steep south slope and gentle dip-slope due north and a chain of small domal exposures of gritty sandstones to the west of former at the margin of Lotia Nala (River) Fan to the northwest of Khengarpar Village are collectively interpreted as a branch fault of KMF (Fig. 6.17).

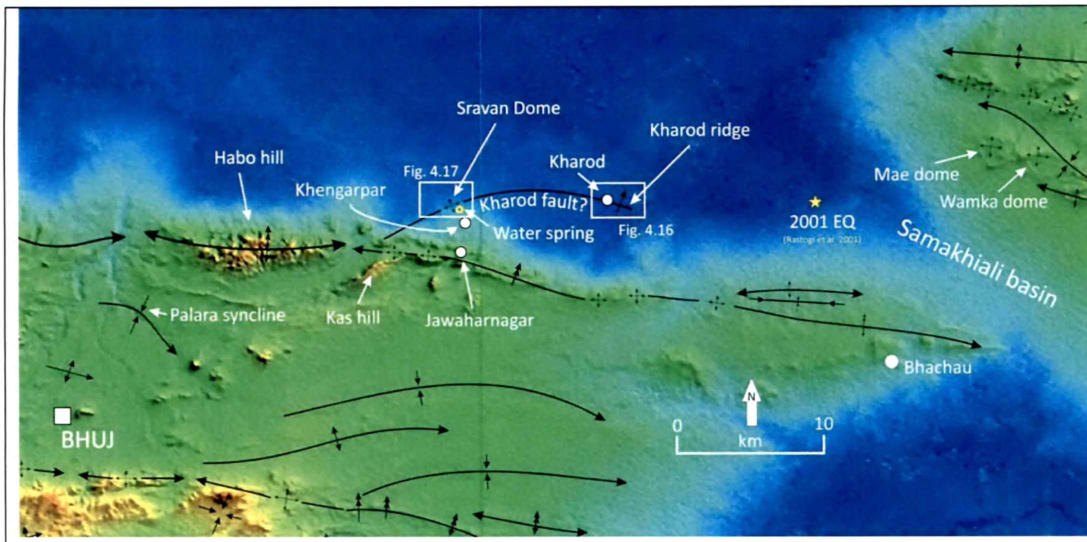


Fig. 6.17: Structural map of Kharod region (see trend of proposed Kharod fault).

Fig. 6.18: An exposure scale splay observed near Jadura.

Branching of subsidiary thrusts from a main thrust is prevalent in fold-and-thrust belts; such subsidiary thrusts are termed as splay (Fig. 6.18). Depending upon different splay settings Ghosh, 1993 has described four types of splay geometries (i) isolated splay, (ii) diverging splay, (iii) connecting splay, and (iv) rejoining splay. Intersection of two fault planes at subsurface will be a line, which is termed as branch line (Fig. 6.19).

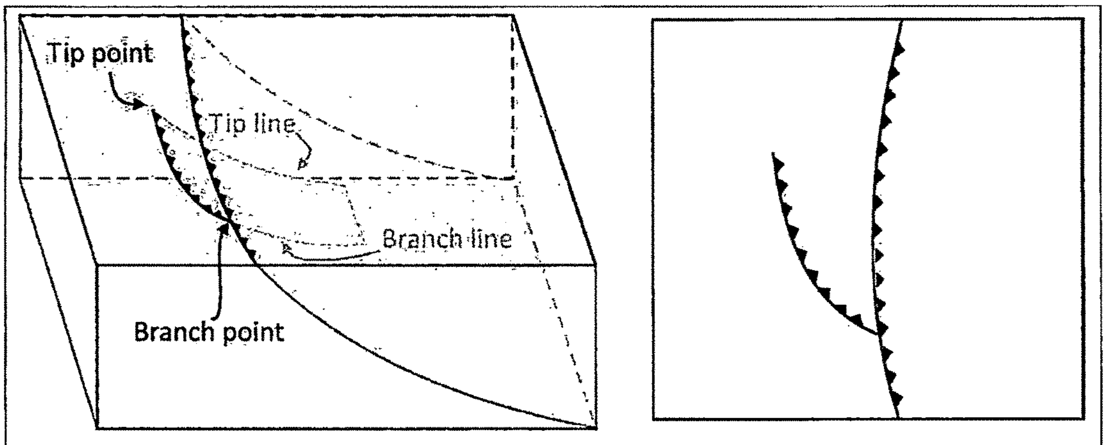


Fig. 6.19: Geometry of a diverging splay (modified after Ghosh, 1993).

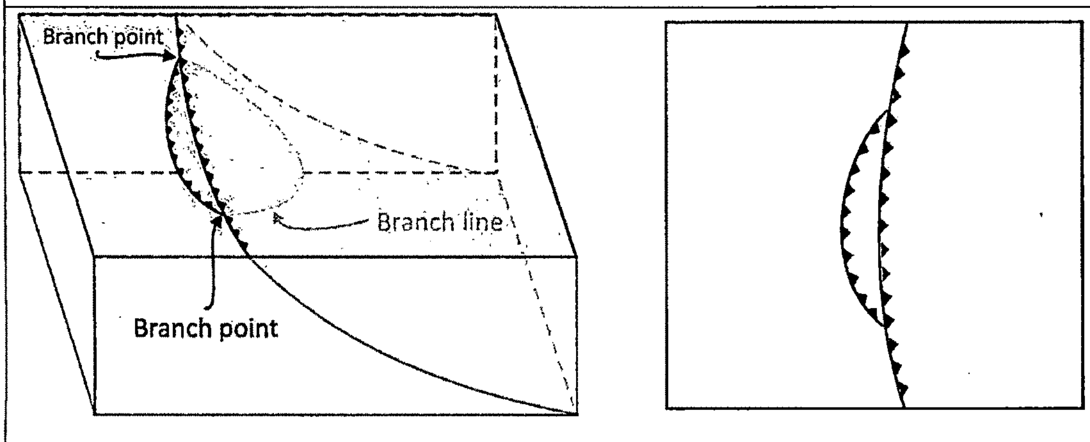


Fig. 6.20: Geometry of a rejoining splay (modified after Ghosh, 1993; Fig. 18.19, p441).

On the surface of the earth, in map view, the junction of main thrust and its splay is termed as branch point. After branching out from a main thrust a splay may join the same thrust at a distance, such geometry is termed as rejoining splay. Thus, in a rejoining splay the trace of the splay on the ground surface will have two branch points (Fig. 6.20). If branched out splay dies out as open end, away from the main thrust the geometry is termed as diverging splay. In such case loose end of the splay is termed as tip point (Fig. 6.19). A diverging splay would exhibit only one branch point. In an isolated splay the two tip points of the splay are exposed, while the trace of the fault is isolated from the main fault trace. A connecting splay connects two different faults (Ghosh, 1993).

It is perceived during present study that Kharod fault is diverging splay of KMF. In western part Kharod fault is expressed as a chain of domal structures gradually changing its trend from east-west to northeast-southwest (Fig. 4.16 adn Fig. 4.17). The changed orientation of this splay leads it close to Northern Hill Range, and the trend appears to match with that of Wantra dome (see Fig. 4.1 and Fig. 6.17). This finding adds another dimension to structural, tectonic and active-fault modelling in the region. Perhaps this splay consumes some part of slip on KMF in eastern segment and therefore the KMF is behaving as blind fault along its eastern extent. The proposed branch fault may provide clues to blind nature of KMF at eastern end. Here it is suggested that a part of slip on KMF in eastern part is probably occupied by this branch fault.

This branch fault has significant implications on structural aspects of overlap zone between KMF and SWF. The overlap zone is defined by the presence of Samkhiyali Basin, where, according to Biswas and Khattri (2002) and Biswas (2005) presently the Kachchh Mainland Fault is behaving as a right lateral strike-slip fault, and is overstepped by the South Wagad Fault. According to them the overlap zone between the two wrench faults is a convergent transfer zone undergoing transpressional stress in the strained eastern part of the basin. Biswas (2005) proposed that the overlapping tips of both KMF and SWF dip steeply (80°–85°) towards each other and the overlapped step over zone is a convergent transfer zone, where the KMF fades out and SWF continues eastward as the principal deformation zone.

On the other hand Mathew et al. (2006) suggested that the step over zone between KMF and SWF is a convergent transfer zone. They proposed a new hidden fault;

South Wagad Master Fault (SWMF), along which, according to them lateral deformation across the eastern portion of KMF has continued and has resulted in an increasing transpressional deformation of the Samakhiali basin. They proposed that SWF is antithetic reverse fault of south dipping SWMF. They considered SWMF as causative fault for the 2001 Bhuj event. They also proposed that the increasing strain on this basin may cause enhanced seismicity in the future along the eastern KMF and Wagad region. Branch fault of KMF (the Kharod fault) perceived during present study is situated significantly within epicentral area of 2001 Bhuj event (Fig. 6.17). Present study proposes that a part of the slip in eastern part of KMF is consumed by this branch fault and hence it is likely that the propagation of KMF to the east of Devisar (see Fig. 3.4) is curtailed.

Segmented nature of KMF

The phenomenon of fault segmentation implies that for a long/regional fault, an earthquake seldom ruptures along the entire length of the fault. It is observed that surface rupture along a fault often terminate at geometric or structural changes in the fault zone (McCalpin, 1996). Hence, it is hypothesized that an earthquake rupture on a long fault zone would always be restricted to the individual segment in which it began. Thus, an earthquake segment is defined as those parts of a fault zone that rupture as a unit during an earthquake. More commonly it is observed that only one or two segments rupture during a large earthquake. There is general agreement that faults may be segmented at a variety of scales; from few meters to several tens of kilometres in length. The most basic approach to find segments of a fault is to define earthquake segments based on rupture behaviour during earthquakes. Earthquake segmentation may be determined from historical earthquakes or by palaeoseimic evaluation.

Another approach to determine segments of a fault is to recognise changes in fault-zone geomorphology or fault-trace orientation, such as bends, step-overs and separations or gaps. Such kind of segmentation of a fault is termed as structural segmentation. Structural segmentation also occurs where segments intersect with other faults or folds. The end of a segment is a structural discontinuity.

Active fault studies along the KMF indicated that KMF has ruptured pediment zone to the north of Jhura, Habo and Khirsara domes/anticlines in recent times. However, age determination of samples collected from trenches during these studies is still pending. In absence of dates for different events recognised during trench studies, it is difficult to correlate events recognised in one trench with that of recognised in other trench at distance of few tens of kilometres. Moreover, there are no historical records of any earthquake along KMF. Therefore, to determine earthquake segments for KMF is not achievable at this juncture. Based on geomorphology of KMF along strike Mathew et al. 2006 proposed that Lobate-shaped anticlines at the eastern end of Northern Hill Range indicate that initially these formed as individual segments and subsequently, fold growth on either side created Linked Segments (LS) along the KMF. According to them physiography of Wagad region also comprises lobate-shaped anticlines forming several linked segments. Subsequently, based on fault-trace orientation, structural segmentation of KMF is proposed by Morino (2009) wherein three segments of KMF are determined as shown in Fig. 6.21.

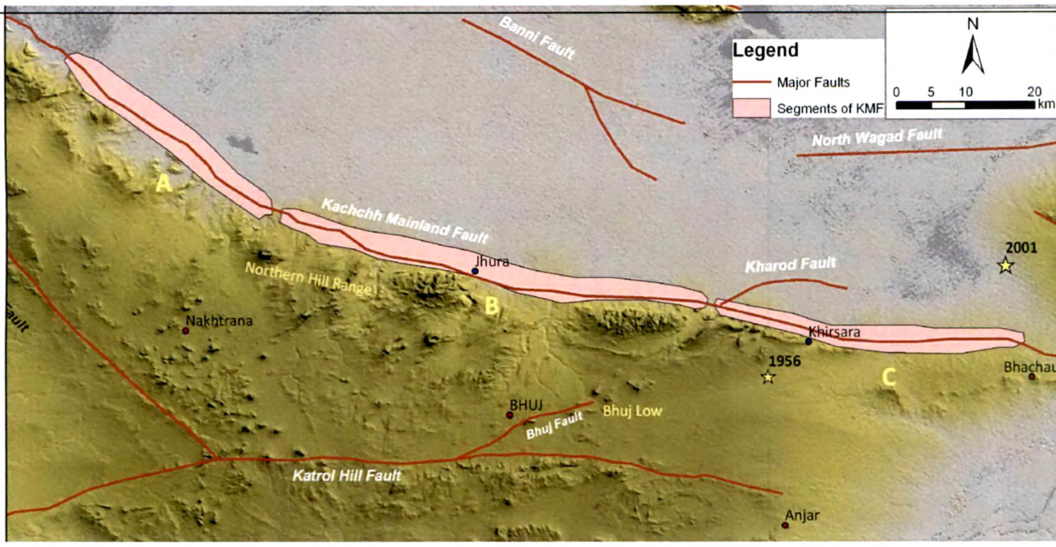


Fig. 6.21: Structural segments of KMF shown as A, B and C.

Based on this segmentation, different setting of events can be suggested for KMF depending upon varied segment linkage and cascade of rupture (Table 6.1). It is anticipated that if rupture occurs along all the three determined segments (A+B+C), the length of the rupture would be 138 km and possible earthquake magnitude would be Mw 8.0. Other possibility is that the expected rupture occurring along segment A and B (A+B), in this scenario, the rupture length would be 95 km and possible magnitude could be Mw 7.9. Third possibility of predictable rupture when only C segment is involved, length of rupture would be 43 km and possible magnitude could be Mw 7.6 (Table 6.1).
An improved understanding of all types of fault segmentation is necessary to understand earthquake mechanics better, including why and where ruptures start and terminate. For earthquake hazard assessment of any particular region of importance anticipating major earthquakes (Mw > 7) is the need to know how rupture of multiple fault segments occurs during earthquakes.

Table 6.1: Segment length for KMF and possible magnitude on different geometries. Based on Morino et al. 2009.

Fault segment	*Length L (km)*	*Potential magnitude- Mw*	*Remark*
C	43	7.6	Blind fault
A+B	95	7.9	The amount of net slip is ~5 m
A+B+C	138	8.0	The amount of net slip is ~5 m

The concept of fault segmentation is important because it has implication for (i) long-term earthquake forecasting involving probabilistic assessment of seismic hazard, (ii) estimates of maximum magnitude of possible earthquake likely to occur on a particular fault, (iii) estimating ground motion produced by an earthquakes, it is believed that rupture propagation is related to fault zone structure, and thus to segmentation; (iv) identifying areas along a fault zone where earthquakes nucleate and areas where rupture may end,

Paleoearthquake magnitude along KMF:

The length of surface rupture and/or the maximum displacement on continental fault traces are most commonly used parameters to infer magnitudes for paleoearthquakes (Wells and Coppersmith, 1994). The inferred rupture length and/or slip for paleoearthquakes are compared with data on rupture length and slip of instrumentally recorded or historically documented known magnitude earthquakes (McCalpin, 1996).

Other than this there are methods in which secondary evidences such as ground-shaking evidences, surface-deformation or liquefaction are taken into consideration to estimate magnitude of a paleoearthquake (McCalpin 1996, Bilham 1999, Rajendran and Rajendran, 2001).

Surface-rupture length (SLR) method

This method of paleomagnitude estimation involves estimating the length of prehistoric surface rupture, and comparing its length to the surface rupture lengths (SLRs) of historic earthquakes of known magnitude or intensity. McCalpin (1996), however, has pointed out two sources of uncertainties in this method (i) deficiencies in the lengths cited in historic data sets and (ii) difficulties in accurately measuring the length of prehistoric ruptures.

Wells and Coppersmith (1994) evaluated various rupture parameters using empirical regressions. They observed that there exists strongest correlation between Moment magnitudes (M), surface rupture length and rupture area. They derived regression coefficient for different variables.

Empirical relationship between Moment magnitude (M) and surface rupture length (SLR) will have the form of $M = a + b * \log(SRL)$. Where a and b are regression coefficients. Wells and Coppersmith (1994) derived regression coefficients for Moment magnitude and surface rupture length, where $a = 5.08$ and $b = 1.16$.

For Kachchh region 1819 Allah Bund earthquake is the only earthquake which has produced surface scarp. For this event no direct records for magnitude are available as it occurred before instrumental era, however, excellent documentation of damage caused by it and felt reports provide good check of intensity. On Modified Mercalli (MM) scale, intensity of 1819 Allah Bund earthquake is measured as IX to X, based on intensity, magnitude for the earthquake is estimated to 8.0 (M_L) (Malik et al. 1999). Based on surface expression of the scarp (the Allah Bund) Bilham (1999) considered 80 km long rupture length for the event.

However, paleoseismic data for estimates of rupture length along KMF or its segments is inadequate. As mentioned earlier, paleoseismic studies carried out along

KMF cannot be correlated along strike until there are dates available for the samples collected from different trenches.

Maximum Displacement Method

The maximum displacement method involves determining the maximum displacement (*MD*) associated with a paleoearthquake, and comparing that value to the maximum displacement measured or computed for a historic or instrumentally recorded earthquake (Wells and Coppersmith, 1994).

Empirical relationship between Moment magnitude (M) and maximum displacement (*MD*) will have the form of $M = a + b * \log(MD)$. Regressions coefficient derived by Wells and Coppersmith (1994) for Moment magnitudes (M) and maximum displacement (*MD*) indicate $a = 6.69$ and $b = 0.74$.

Along KMF at the surface maximum displacement of 5 m is measured in trench near Jhura village (Trench T1 this study). Thus for KMF in above equation $MD = 5$. With this method possible Moment magnitude along KMF during latest event will be M = 7.2. However, during 2001 Bhuj Earthquake (Mw 7.6) displacement along North Wagad Fault was 5 m and the rupture stopped at a depth of about 10 km from the surface. Thus event of Mw 7.6 occurred on a blind fault in Kachchh region. Along the KMF rupture has reached up to the surface which implies that rupture area for KMF is larger than NWF. Considering these facts magnitude greater than 2001 Bhuj Earthquake is expected on KMF. As discussed earlier KMF has demonstrated characteristic earthquake pattern in different trenches this implies that KMF has potential to generate earthquake greater than of 7.6 (M) in future.