<u>**CHAPTER -7**</u>

EVIDENCE OF NEOTECTONIC ACTIVITY

NATURE AND EXPRESSION OF NSF

In the study area Narmada Son Fault (NSF) is expressed by ENE-WSW trending steep mountain front developed in the Deccan Traps, Tertiary sedimentary rocks and Quaternary sediments. The NSF is traversed by several NW-SE trending transverse faults that displace the NSF which has resulted into the segmentation, laterally along the length of the NSF. The segmentation of the NSF has divided the landscape of the study area into four morphotectonic segments (Joshi et al., 2013). The morphotectonic set up of these segments varies which is related to the variation in the magnitude of the tectonic activity along the NSF within each segment.

The segment I located between Narmada River and Karjan River and bounded by Tilakwada Fault and Karjan Fault from the eastern and western sides respectively. This is the only segment of the study area where the Mesozoic rocks of Bagh Formation are exposed on the surface as inliers trending in ENE-WSW direction. The rocks are marine in nature deposited during the transgression and regression phases prevailing in the Cretaceous time.

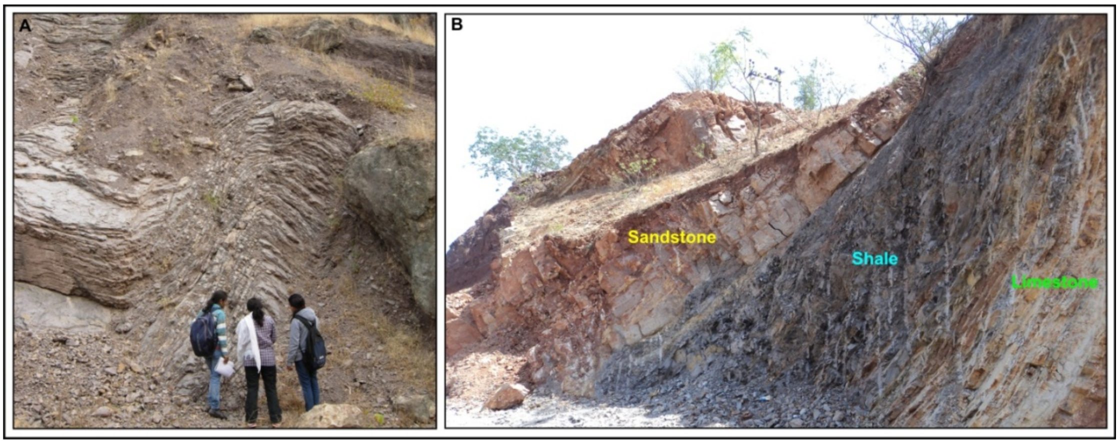

Figure 7.1 Field photographs of deformed Mesozoic inliers in segment I. (A) Photograph showing tight anticlinal folding in the shale beds. (B) Photograph showing tectonic contact between sandstone, shale and limestone.

Tectonic activities along the NSF that took place during the late Cretaceous have deformed and uplifted the Mesozoic rocks. The rocks are folded into tight anticlines and at places show tectonic contact between different formations (Fig.7.1). This phenomenon is related to the reactivation of the NSF. During this period the e NSF reactivated as a reverse fault resulting in the development of tectonic contact between rocks of Bagh Formation and traps. In this segment, the NSF is expressed as a scarp in the rocks of Bagh Formation and basaltic flows. To the north of the scarpline basaltic rocks continue for a short distance before abutting against the Quaternary sediments. The uplift along the NSF has generated steep gradient in the alluvial plains. Also the influence of NSF is clearly visible in the development of 1st order drainage flowing almost parallel to the trend of NSF and meeting Narmada river at it left bank.

The evidence of neotectonic activity along the NSF and transverse faults bounding the segment I is also visible in the drainage characteristics. The segment I is occupied by Shamlayakhadi and Karjan Rivers. The Karjan River Occupies a larger area in the segment I and it is important river basin of the segment I as it possess significant markers of neotectonics. The influence of tectonic movements along the NSF is evident in the upland zone of the river in the vicinity of NSF scarp in the form of anomalous change in the river course direction and southward tilting of the basaltic flows. The course of the river is not only controlled by NSF but also by NNW-SSE trending Karjan Fault. Throughout the path, the course of the Karjan River flows in the N-S direction which shows the strong control of Karjan Fault that confines the river to flow along the trend of the fault. Also the activity along the Karjan Fault makes the basin asymmetrical, tilting towards west. However, as the Karjan River enters in the alluvial plain, it meanders left in a trend of NSF and then again achieves the N-S flow direction. This shows that there is active tectonic movement along the NSF that shaping the present day drainage pattern. Along with the geomorphology, the role of the neotectonics is also noticed in the form of Quaternary fan sedimentation. Tectonic activity along the NSF provided ideal physiographic setup for the deposition of alluvial fan sediments. A group of fan identified in this segment comprises of coarse massive sand, clast supported gravels and matrix supported gravels of Early Holocene age (Bhandari et al., 2001; Chamyal et al., 2002). This suggests the aggradational phase that was prevailing during the time of fan deposition. However, the present day nature of the rivers is incisive. The maximum depth of the incision observed in the upstream area of the Karjan River basin which about 58 m. the present day landscape shows incising drainages, gullies, rugged terrain and v-shape valleys which are the characteristics of the uplifted and rejuvenated terrain. This change from active fan aggradation to present state of dissection is attributed to a change from tectonic subsidence of the fan block to the Late Holocene uplift.

Segment II located between Karjan Fault and Madhumati Fault is the tectonically most active segment of the study area. The topographic profile, drawn over the alluvial terrain along the trend of the NSF shows that the surface elevation of segment II is the highest compared with the surface elevation of the other segments. The field evidence also supports this physiographic set up of the area through the anomalous pattern of incision. The rivers of segments II show maximum incision in alluvial deposits of up to ~40 m near the scarps. Conspicuously, the depth of incision decreases just 3 km towards north to 6–7 m. These characteristic of significant change in the depth of incision within a very short distance indicates the neotectonism in the area such evidences suggest that the geomorphology of the area is tectonically controlled.

Figure 7.2 Field photographs of the Nandikhadi River in upstream area in segment II. (A) Photograph of the highest waterfall of 16 m height. (B) Photograph taken from the top of the water fall shown in A. Note the deep and narrow meandering channel with frequent occurrence of knick points. Solid arrow indicates downstream direction; doted arrows locate the knick points.

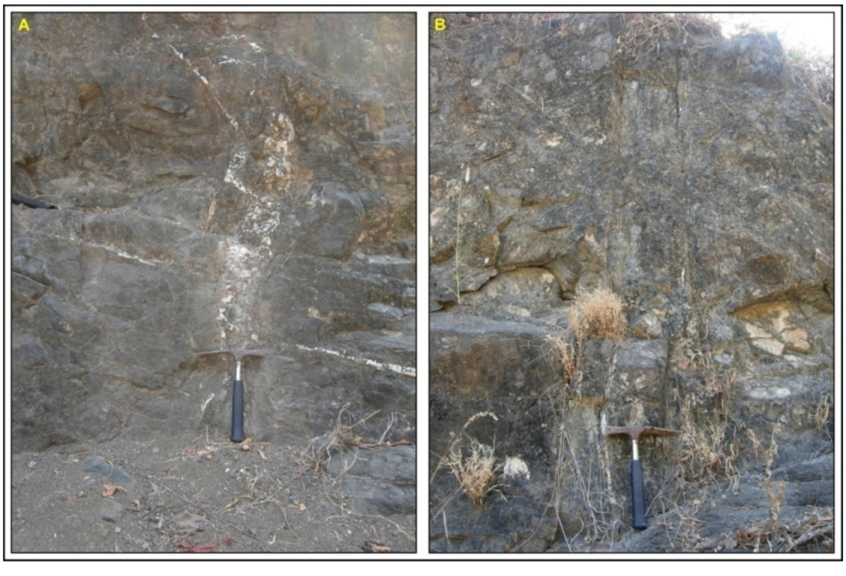

Figure 7.3 Field photographs of the fault planes in the shear zone area of the NSF. (A) Displacement along the steeply northward dipping fault plane showing reverse type of movement. (B) Vertical fault plane within the sheared basaltic rocks.

Further in segment II, in the Nandikhadi river basin there is incision in the basaltic terrain providing good exposures in the form of incised cliff sections. The upland zone of Nandikhadi River is characterized by frequent occurrence of knick points, tight meanders and deeply incised channel (Fig. 7.2). The height of the knick points range from 1 m to 16 m. The total fall of gradient related to knick points is of ~ 37 m which is in a very short distance of 1.5 km.

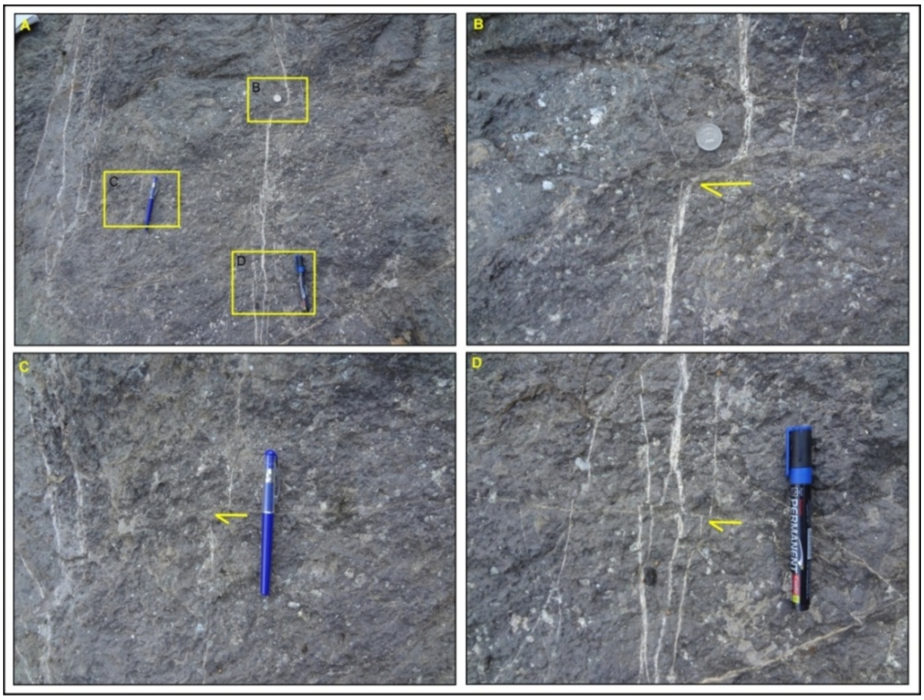

Figure 7.4 Photographs of the basaltic outcrop intruded by veins. (A) Photograph showing numerous displaced veins. Square frames show the location of the displacement. (B), (C) and (D) are the close view of the displaced vein. Note the left lateral movement indicated by the arrow.

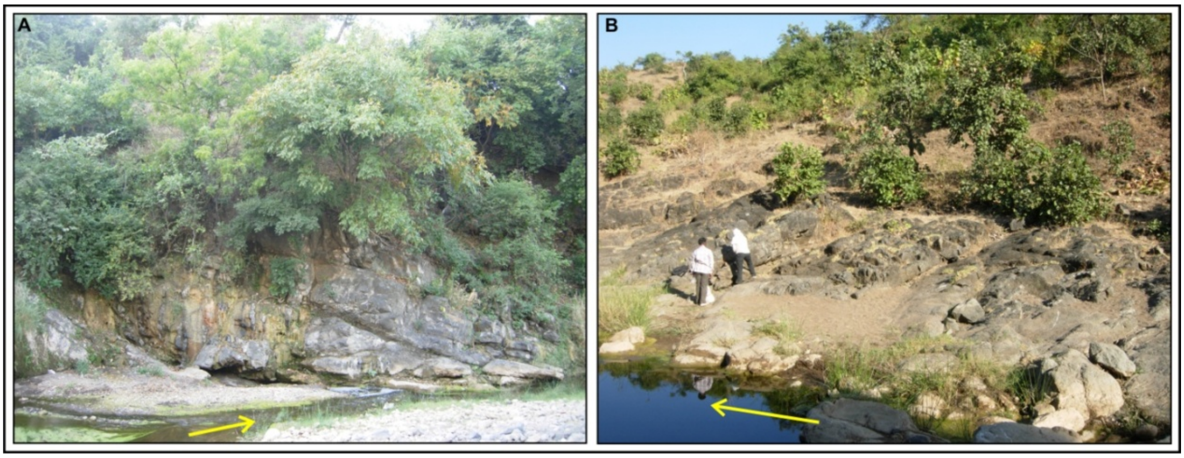

Figure 7.4 Field photographs of the basaltic flows exposed in the Nandikhadi River. Arrow indicates downstream direction which is towards north. (A) Steeply northward dipping basaltic flows in the vicinity of the NSF scarp. (B) Northward dipping basaltic flows few meter downstream from the location of A.

Field investigation of the incised basaltic flows along the length of the Nandikhadi River suggests a presence of several fault planes and shear zones located within the fault zone (Figs. 7.3 and 7.4). The fault zone comprises of a master fault flanked by numerous minor faults. This zone is characterized by the existence of shear zones where the rocks are highly sheared, altered and intruded by numerous veins. The veins in the fault zone are faulted and their number increases significantly towards the location of master fault i.e. NSF. However, the veins show left lateral strike slip faulting along the ENE-WSW to E-W oriented fault plane (Fig. 7.4). This may suggest that along with the vertical movement, NSF may have strike slip component. It can be explained by the influence of extensive compressive stress. Due to inversion of the Narmada rift basin, the area is under compressive stress regime and the normal fault system has replaced by the reverse fault system. Hence, in such a structural set up the accompanying of vertical and strike slip motion is usual. The most significant characteristic observed is the change in the dip direction of the basaltic flows that is located to the north and south of the NSF.

To the north of the NSF the dip of the basaltic flows is towards north. The average range of the dip is between 35° to 40°. However the dip increases towards the NSF and approaches to 80° at the fault scarp. The basaltic flows to the south of the NSF scarp are dipping in the south direction. The southward dip of basaltic flows ranges between 12° to 25°. Here, two points were noted; (1) the dip increases by moving from north to south i.e. towards the NSF scarp where it becomes almost vertical, and (2) the northward dip of the basaltic flows is steeper than the southward dip.

Along with the geomorphic set up of the area, sedimentation pattern and type are also influenced by the active tectonics prevailing along the NSF and transverse faults in segment II. The pulses of tectonic upliftment along the NSF have provided favorable physiographic set up and coarse gravelly sediments for the deposition of alluvial fan. The coalesced group of alluvial fans, ‘bajada’, is identified in this segment between the Karjan River and Madhumati River, and shows highest topographic elevation in comparison to the adjacent alluvial plain areas to the east of Karjan valley, to the west of Madhumati valley and the Narmada valley to the north. The altitude of the fan surface near the mountain front is 120 amsl and extends over ~24 km in length along the mountain front. In longitudinal section, the deposits appear to be wedge shaped. The bajada surface displays planoconcave–upward geometry created by the distally decreasing slope. The sediments are readily divisible into seven distinct sedimentary facies. In approximate order of abundance, the principal facies identified are- matrix supported gravel (Gmm), clast supported gravel

(Gcm), massive silty sand (Sm), soil (P), trough cross-bedded gravel (Gt), horizontally stratified gravels (Gh) and massive brick red sand lithofacies (Ss). The OSL age of 25.1$\pm$1.8 ka BP obtained from the middle part of the bajada succession comprises of soil, horizontally stratified gravels and massive silty sand suggests that the sedimentation occurred during the later part of late Pleistocene. This correlates with the slow synsedimentary subsidence of the basin during the late Pleistocene documented earlier (Chamyal et al., 2002). However, the late Pleistocene sediments exposed along the incised cliffs of Narmada River are finer as they were deposited in alluvial plain environment (Bhandari et al., 2005). The bajada sediments are sedimentologically different in terms of grain size but stratigraphically comparable with the sediments exposed along the Narmada River. The deposition of the fan sediments can be explained by tectonic uplift along the NSF which generated tilted block in which coarse gravelly sediments deposited in the fault zone area and simultaneously fine sediments were deposited in the distal part i.e. towardsthe Narmada River.

The segment III located between the Madhumati Fault and Rajparadi fault. It is the smallest segment of the study area occupied by the Madhumati River basin. Geomorphic characteristics of the Madhumati River show strong control of the NSF and transverse faults. It is one of the major tributaries of Narmada that joins it from the south. The river course has a total length of about 41 km. The river arise from the trappean region and traverses through the NSF zone and alluvial plain before joining the Narmada River. The Madhumati River drains western fringe of the trappean upland. The river emerges from the trappean upland near Umarkharda. The drainage of the trappean uplands and alluvial zone presents contrasting characteristics. The drainage pattern in the upper reaches of the basin has been identified as trellis where as the lower reaches of the basin has a dendritic pattern. The density of the tributaries in the upper reaches is high and the tributaries are comparatively straight whereas in the alluvial plain compressed entrenched meandering can be observed. The drainage basin is elongated in NW-SE direction. From Umarkharda to Dholi the river flows along ENE-WSW trending course. At Dholi, the river channel takes a right turn to flow towards north along a remarkably straight N-S oriented course up to Tejpur which lies to the north of the NSF. The straight nature of the river course and the right turn strongly points towards the existence of the N-S trending transverse fault. The geomorphic evidence of the NNW–SSE trending transverse Madhumati fault is observed near Tejpur. The fault is represented by the displaced scarps of the NSF which indicates a dominantly strike slip movement along this transverse fault (Fig. 7.5). The displaced basaltic ridge near Tejpur is locally known as the ‘Khaseli Dungar’ which literally means 'shifted hill' (Fig. 7.5). This fault shows a right lateral offset of the NSF for about 1 km. The presence of the fault is evidenced by the straight channel of the Madhumati River and the formation of a large deeply incised and compressed meander in alluvium as it emerges from the uplands. The slicken sides exposed along the fault plane, in basaltic rocks on the left bank of the river, suggests oblique slip movement (Fig. 7.5). The significance of this N-S trending fault on the geomorphic set up is well brought by the straight deeply incised course of the Madhumati River and the lateral shift in the fault scarps of the NSF. The incision in basaltic rocks observed in the upstream reaches of the river is of the order of 40 m where the southward dipping basaltic flows exposed (Fig. 7.6).

A large entrenched meander is present near Tejpur where the incised cliffs up to 35 m high are present (Fig. 7.5). Downstream of Tejpur, the river follows a general NW direction with several entrenched meanders in the alluvial zone (Fig. 7.5). The best and highest exposed section from alluvial zone is available in the incised cliff section near Tejpur. Here, the Quaternary sediments abruptly abut against the trappean rocks along the NSF. Quaternary sediments comprise of fluvial deposits and are characterized by a regular and cyclic sequence of sand and gravel. The clasts of the gravel bed consist of basalt derived from the upland. The clasts are poorly sorted and the matrix is mainly coarse to medium sand. In the lower reaches these cyclic sequence of sand and gravel overlie the clay horizon. Further downstream at Rajpardi, the river takes a northwesterly turn because of the influence of the Rajpardi fault.

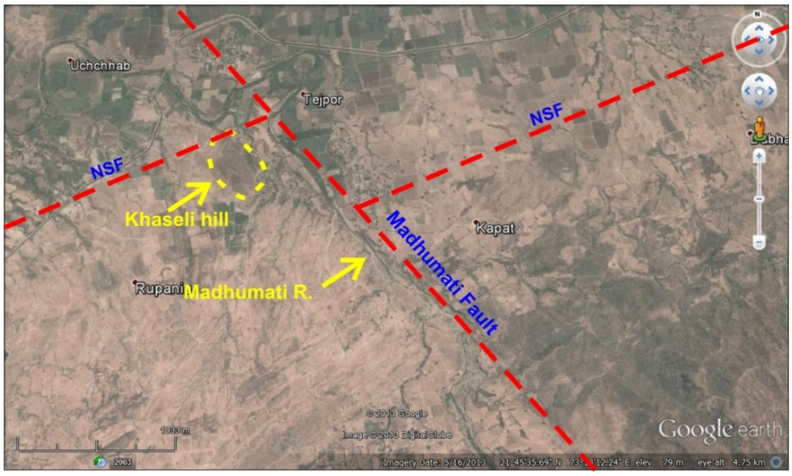

Figure 7.5 Satellite imagery of NSF zone in the vicinity of Madhumati River. Note the straight course of Madhumati River which follows NNW-SSE trending transverse fault and compressed meander near Tejpur.

Beyond segment III, west of Rajpardi Fault is the segment IV. The landscape of the segment IV shows strong control of NSF and Rajpardi Fault. In this segment NSF is geomorphologically expresses by steep escarpments formed in Tertiary highlands, whereas further west it is expressed in the form of palaeobank of the Narmada River. The active tectonics along NSF, has also deformed the Tertiary sedimentary rocks. The entire Tertiary sequence exposed over the surface is folded and faulted. Theexposed Tertiary rocks exhibit linear anticlinal structure trending SW to WSW, plunging SW to WSW and flanked by reverse faults along southern limbs. The entire Tertiary sequence ranges in age from Paleocene to Mio-Pliocene. The rudaceous to calcareous facies and to highly ferruginous, cyclic sedimentation of calcareous sandstone and marls, calcareous clays, formainiferal limestone and fossiliferous beds are some of the important features of the Tertiary sequence.

Figure 7.6 Field photographs of the upstream area of the Madhumati River near Tejpur. (A) Photograph of the southward dipping basaltic flows. (B) Shear zone located few meter downstream from the location of A. (C) Slickensides related to the Madhumati fault exposed in the shear zone shown in B.

Along with the NSF, the tectonic movements of the Rajpardi Fault has also played significant role in shaping the present day geomorphic set up of the segment IV. The strike slip movement occurred along the transverse fault has displaced the trappean ridge and the NSF as well (Fig. 7.7) in this segment. The displaced hill named the Sarsia hill is located at the NE fringe of the Jhagadia anticline where it terminates against N-S trending Trap rocks. This is attributed to the strike slip movement along the N-S trending Rajpardi Fault. It marks the sharp tectonic contact between the Deccan Traps in the east and the folded, faulted Tertiary rocks to the west. As is the case with the NSF, the Rajpardi Fault also presents an excellent geomorphic expression and is well evidenced by the rugged topography of the trappean uplands in the east and the low hummocky topography of the Tertiary rocks to the west of the fault.

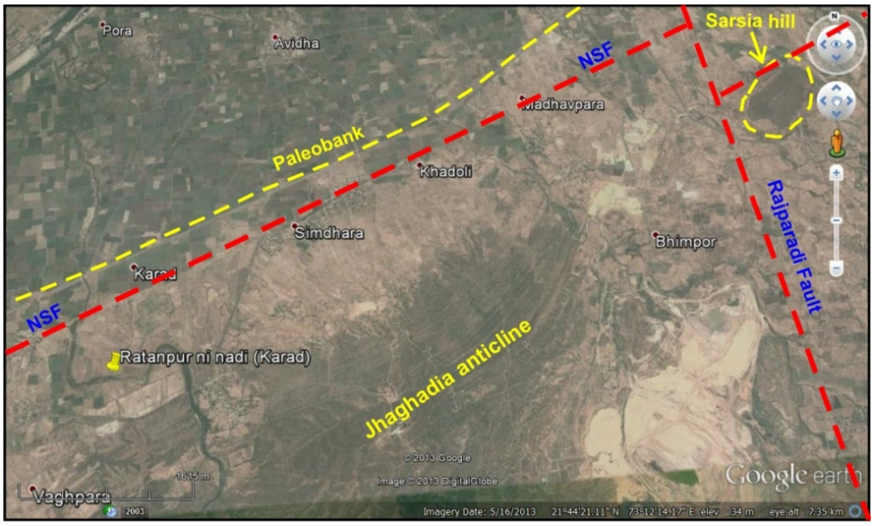

Figure.7.7 Satellite imagery of NSF zone in segment IV showing the locations of paleobank, Sarasia hill and Rajparadi Fault.

In the extreme western part of the segment IV, the NSF is marked by ENE-WSW trending straight linear feature called palaeobank of Narmada River. The palaeobank is marked by straight linear alluvial cliffs formed in the Quaternary sediments. It is formed by the migration of Narmada River to the NW.. It represents abandoned left bank of the river when it used to flow through this cours, which is SE of present day course. The Narmada River has migrated to as much as 6 km towardse NW due to tilting caused by upliftment of the Jhagadia-Ankleshwar area. The linearity of the feature again suggests the presence of a fault along the palaeobank. Previous seismic studies suggest presence of reverse fault along the palaeobank with the down-throw side to the NW and the SE side as the upthrow side (Agarwal, 1983). The drainage pattern of the segment IV shows strong structural control. The major river basins of the segments are Kaveri and Amravati River basins. The drainage pattern of this segment ideally reveals its adoption to the change in the topographic expressions related to the uplift of the Tertiary and Quaternary sequences.

EVIDENCE OF LATE QUATERNARY OFFSET ALONG THE NSF

In segment I, the Quaternary offset is well evidenced in the Karjan River basin. This was observed through the study of incised cliff sections all along the length of the Karjan River. The vertical and lateral logs were prepared for the incised sediments and accordingly fluvial lithofacies were assigned. Also the sediments were correlated with the geomorphic surfaces identified by the Chamyal et al., 2002. In this segment three surfaces are identified, alluvial plain surface, alluvial fan surface and terrace surface. The alluvial plain surface comprises of pedoginized sand, soil and silty sand of Late Pleistocene age. The alluvial fan surface is bounded by NW-SE trending Tilakvada Fault in the East and by NNW-SSE trending Karjan Fault in the west. In the south of the fan surface abuts against the steep mountain front of basaltic lava which is the geomorphic expression of NSF. The alluvial fan surface comprises of coarse massive sand, clast supported gravels and matrix supported gravels of Early Holocene age (Bhandari et al., 2001; Chamyal et al., 2002). The sedimentary facies identified in the alluvial fan sediments suggest debris flows and sheet flows as two primary aggradation processes. Through the detailed analysis of sediments exposed along the length of Karjan River remarkable offset have been observed by moving from downstream to upstream area which is discussed below.

At Nani-Limatvada village 21 - 22 m incised vertical cliffs are exposed. The lower part of the section represents the deposits of Late Pleistocene surface whereas the uppermost section made up of sediments of Early Holocene alluvial fan sediments. The Late Pleistocene sediments made up of sandy gravel, horizontally stratified gravel, vertisoil (brown) and red soil (reddish brown) over which lies the sediments of alluvial fan surface. The sediments of alluvial fan surface comprises of coarse sand gravels and colluvium deposits. Stratigraphically the red soil is comparable to Late Pleistocene red soils of Narmada, Mahi and Sabarmati. This is capped by massive sand sheet devoid of any internal stratification.

In the upland zone of Karjan River near the Karjan dam axis the rocks have been incised and exposed in the cliff section. These rocks are various southward dipping basaltic flows that represent the part of the tilted block which is attributed to the tectonic movements along the NSF. Exposed section represents the terrace surface which occurs at the conspicuous height of 58 m from the present day channel (Fig. 7.8). The sediments are mainly sand and silty sand deposits. Calcite sheets and nodules occur in the middle of the section. OSL dating of the upper silty sand layer has been carried out which gave the date of 32.7±3.9 Ka (Fig. 7.8) On the basis of sediment fabric, grain size and lithofacies association, sediments exposed at Karjan dam site are correlatble with the sediments of Nani Limatwada locality. However, there is a significant difference between the altitude at which sediments are exposed at both sites (i.e. Karjan Dam and Nani-Limatvada). This difference in the altitude is attributed to the displacement occurred along the NSF.

The other evidence of tectonic upliftment along the NSF identified through the study of cliff section located within the trappean uplands further southward from the Karjan dam location. Here, the exposed Quaternary sediment succession comprises of gravelly deposits..

The coarse sandy gravel deposit overlies the basalts and occurs well above the present high discharge levels. The sediment texture indicates the deposition by debris flows. On the basis of sediment fabrics, the sediments are correlatble with the sediments deposited in the north of scarpline. It could be interpreted that the sediments deposited in the same time range at both locations, but tectonic activity along the NSF uplifted the sediments located at Nana Thavadiya. This could be attributed to the vertical offset along the NSF.

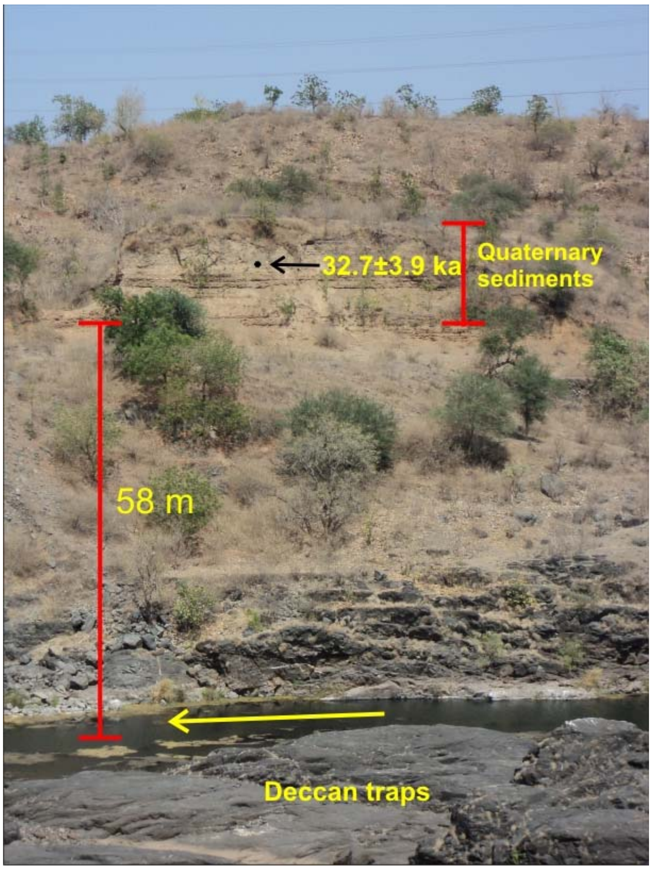

Figure 7.8 Cliff on the right bank Karjan River near Karjan dam. Arrow indicates the downstream direction of Karjan River. Notice the elevation of Quaternary sediments above the river bed.

INFERRED PATTERN OF NEOTECTONIC ACTIVITY

The seismically active NSF is geomorphologically expressed as ENE-WSW trending scarps that bound the rugged hilly terrain to the south and the alluvial depositional basin to the north. The hilly terrain comprises basaltic flow of Late Cretaceous–Paleocene age in the western part and Tertiary rocks in the eastern part. The alluvial plain to the north of the NSF scarp consists of unconsolidated Late Quaternary fluvial sands, silts with gravel. On the basis of the field evidences it can be inferred that the pattern of the neotectonic activity varies laterally along the length of the NSF. It is also manifested in the geomorphic set up and Quaternary sedimentation pattern of the segments. This variation could be related to the transverse faults that crossing and displacing NSF which have been resulted into the segmentation of the landscape and spatial variation in the magnitude of tectonic activity. The transverse faults include Tilakwada Fault, Karjan Fault, Madhumati Fault and Rajparadi Fault. These transverse faults divides the NSF in the study area into four morphotectonic segments (I to IV) from east to west. Close correspondence between the elevation of the alluvial plain to the scarp height and strong northward slope of the alluvial surface in various segments point to a major role of neotectonic reactivation of the NSF in the very recent past. The youthful nature of the mountain front scarp further corroborates the active nature of the NSF. The rivers flow along deeply incised and highly sinuous meandering channel all through their courses. All rivers show rapid decrease in incision away from the scarps which is in conformity with the northward slope of the alluvium, suggesting an obvious control of neotectonic activity along the NSF on the fluvial incision in the study area. The depth of fluvial incision is also found to variableall along the length of the NSF.

The uplands especially the basaltic ones show several evidences of rejuvenation in the form of youthful topography, narrow and deeply incised fluvial valleys with occasional gorges. In the segment I, due to the tectonic activity Mesozoic sedimentary rocks are outcropped as inliers. The rocks are tightly folded into the anticlinal structure and shows tectonic contact between different rock formations. The NSF fault zone is well exposed in the upland zone of segment II within the incised channel of the Nandikhadi River. In the vicinity of the NSF, the rocks are intruded by numerous veins. At several places veins are displaced along the ENE-WSW to E-W oriented fault plane in a strike-slip motion. The dip of the basaltic flows also changes which suggests arching of the terrain due to the tectonic uplift along the NSF. To the north of the NSF, basaltic flows dipp towardsnorth while towards the south they dip southward. The tectonic activity along the NSF has also affected the Quaternary sedimentation. In the vicinity of the NSF scarp the incision is of 40 m height. This depth of the incision decreases to 6 m in a very short distance indicating the tectonically generated steep slope.

The sedimentation pattern also shows significant control of the tectonic activities which is well exposed and studied in the segment I and II. Active tectonic uplift along NSF has produced steep mountain front escarpments and abundant north flowing parallel drainages that have provided appropriate physiographic setup for alluvial fan sediments to be deposited in the segments I and II. In the segment I previous studies have identified occurrence of alluvial fan bounded by NW-SE trending Tilakwada Fault on eastern side and by NNW-SSE oriented Karjan Fault on western side. In the segment II, the coalesced group of alluvial fans, ‘bajada’ sedimentary environment has been recognized and characterized along the length of the NSF. The extension of bajada sediments is confined by the NW-SE trending Karjan Fault. The bajada surface displays planoconcave – upward geometry created by the distally decreasing slope in ENE-WSW cross section. The altitude of proximal fan surface is 120 m. It shows highest topographic elevation in comparison to the adjacent area to the east of Karjan valley and to the west of Madhumati valley which could be related to the higher degree of tectonic activity prevailing in the segment II.

In the segment III, the evidences of neotectonic activity related to the NSF and transverse faults observed in the upland area of the Madhumati River. The path of the Madhumati River is controlled by the NSF and transverse faults. In the upland zone, river flows along the N-S course which is controlled by Madhumati fault. As the River enters into the Tertiary high land it swings into the ENE-WSW direction for few meters before meeting Narmada River which shows the influence of the NSF. The river has incised basaltic terrain and exposed the thick succession of basaltic flows. The basaltic flows are dipping in the southward direction which related to the neotectonics of NSF. In the shear zone, slickensides are observed which shows oblique slip movement. This is also observed on larger scale through the displaced trappean hill called ‘Khaseli Dungar’.

In the segment IV, the deformed Tertiary rocks forming the eastern part of the uplands comprises of conglomerates, sandstones and limestones. They show comparatively subdued but structurally controlled hummocky topography. The rocks are folded into the narrow anticlines trending SW to WSW and flanked by reverse faults along the southern limbs. The rivers of this segment show strong structural control and flow around the structural highs before swinging northwards to meet the Narmada River. The NSF is located to the northern limb anticlines which abuts against the Quaternary sediments and probably merge with the palaeobank of the Narmada River in the north. The development of the palaeobank is also related to the upliftment of the terrain related to the NSF and northward migration of the Narmada River.

The geomorphic and sedimentological characteristics suggest that the pattern of neotectonic activity along the NSF varies segment wise. This could be related to segmented nature of the NSF and the transverse faults. Because of the continuous northward movement of the Indian plate, the compressive stress being accumulated within the weak zones along the geofracture of crustal scale i.e. NSF. Due to the segmentation of NSF, there is spatial variation in the distribution of compressive stress. Because of this, the magnitude of tectonic activity also varies in all the segments which further resulted in the difference of morphotectonic settings of the segments.