

LATE CENOZOIC GEOMORPHIC EVOLUTION

The Kim river basin comprises Quaternary and Tertiary sediments which are underlain by the Deccan Trap formation. Previous studies in the study area have mostly focused upon the Tertiary rocks mainly as they form the reservoir rocks for petroleum reserves. These studies have revealed a complex structural pattern and its strong influence on basin development and sedimentation patterns. However, no study exists on the long term geomorphic development, Quaternary stratigraphy and tectonics. The location of the Kim river basin at the intersection of two palaeorifts within the seismically active SONATA zone implies that landscape development in the area is controlled by tectonics.

The present study aims to evolve an integrated model for landscape development of the Kim river basin. This is achieved by critical evaluation of available structural data and detailed geomorphic and stratigraphic studies. The three morphostructural domains – the trappean upland, undulating landscape of Tertiary rocks and alluvial plain have been delineated based on differences of structural

framework and geomorphic configuration. The data suggests that the sequence of geomorphic evolution in Kim river basin can be categorized into a series of key time slices – Late Pliocene to Middle Pleistocene, Late Pleistocene, Early Holocene and Middle to Late Holocene (Table 7.1). Each time slice represents a distinctly separate phase of geomorphic events associated with varying intensities of tectonic activity which led to the development of present landscape. The present study has delineated the role played by the post-Tertiary tectonic movements in controlling the sedimentation pattern and development of topographic relief within the Kim river basin.

LATE PLIOCENE-MIDDLE PLEISTOCENE

The evolutionary history of the Kim river basin began with the formation of basin due to extension followed by deposition of Tertiary rocks accompanied by subsidence of basin floor. A distinct change in stress regime to compression resulted in the Late Cenozoic inversion of the sedimentary basin some time in Late Pliocene. The inversion process continued through the Quaternary with phases of fluvial sedimentation which indicate decrease in tectonic activity. The Kim river basin thus reveals a more complete and different history of tectonogeomorphic evolution as compared to the lower Narmada basin described by Chamyal et al. (2002). The landscape evolution in Kim river basin is therefore the net result of Late Cenozoic tectonic activity related to sedimentary basin inversion. Few minor phases of inversion along specific faults along the deposition of Tertiary rocks are known (Agarwal, 1984). However, these took place along intrabasinal faults, which resulted in local tectonic inversion, folding and thickness variation of the sediments deposited.

Table 7.1 Summary of Late Cenozoic Geomorphic Evolution of the Kim river basin

Geologic Time	Geomorphic Events	Formation of Surfaces	Tectonics
Middle to Late Holocene	<ul style="list-style-type: none"> - uplifted valley fill terrace surface, fluvial in MSD-I & II, estuarine-tidal in MSD-III - incised by 4-6 m 	<ul style="list-style-type: none"> -fluvial valley fill deposition in MSD-I & II, estuarine-tidal deposition in MSD-III -formation of Late Holocene Depositional Surface due to tectonic uplift in recent times. 	Tectonic uplift
Early Holocene	<ul style="list-style-type: none"> -extensively gullied erosional surface -gullies as deep as 5-10 m. -gully formation accompanied by incision in main channel -observed in MSD-I & II 	<ul style="list-style-type: none"> -formed due to severe fluvial erosion of Late Pleistocene sediments in response to tectonic uplift, formation of Early Holocene Erosional Surface (EHES). 	Tectonic uplift
Late Pleistocene	<ul style="list-style-type: none"> -flat alluvial plain surface formed due to fluvial deposition -deposition took place in structural low -sediment comprises fluvial sands, silts and gravels -extensive pedogenesis and calcretisation 	<ul style="list-style-type: none"> -tectonically controlled fluvial deposition in all the three morphostructural domains, formation of Late Pleistocene Depositional Surface (LPDS). 	Weakening of tectonic activity
Late Pliocene to Early Pleistocene	<ul style="list-style-type: none"> -occurs in MSD-II only developed over Tertiary rocks. -Surface occurs as topographic highs which correlate with the structural highs 	<ul style="list-style-type: none"> -formed as a result of a prolonged phase of tectonically controlled fluvial erosion, formation of Early Pleistocene Erosional Surface (EPES). 	Differential uplift in compressive stress regime

These occurred even as the overall environment of basin subsidence continued to prevail.

The major phase of large scale basin inversion involving the deformation of all Tertiary formations, transformation of all normal faults (which includes the NSF) to reverse faults and severe erosion is first recorded during the Late Pliocene. Due to this the basin floor was uplifted and several ENE-WSW trending folds and reverse faults were formed. The Tertiary sequence was uplifted, deformed and exposed to erosion due to inversion of the basin during Post Pliocene. The overall uplift and style of tectonic deformation was governed by regional N-S directed compressional stresses. The pattern of deformation resulted in the development of ENE-WSW oriented anticlines, which were subsequently reverse faulted in the southern limb. The Late Pliocene-Early Pleistocene is therefore a period of net erosion and extensive deformation which formed the Early Pleistocene Erosional Surface (EPES) seen in morphostructural domain-II. The tectonic deformation of this period marks the first phase of the sedimentary basin inversion. The erosion was controlled by the structure as evidenced by the topography, which confirms to the structural highs and lows. The inversion resulted in drastic changes in topography.

The new topography produced corresponded to the structural highs and lows. Concomitant to deformation was intensive erosion of the sedimentary sequence in response to uplift. The presence of structural highs in Tertiary rocks as distinct topographic highs in the present day geomorphic set up suggests the erosion was tectonically controlled. The various faults continued to be active throughout Late Pliocene to Middle Pleistocene thereby maintaining the first order topography. The

shallow structural lows thus created between the anticlinal highs provided the sites for fluvial sedimentation during Late Pleistocene.

LATE PLEISTOCENE

The Late Pleistocene is a period of fluvial sedimentation within the structural lows created along the Late Pliocene to Middle Pleistocene phase of structural deformation. The Late Pleistocene sediments unconformably overlie the eroded topography developed over the Tertiary sequences. Within the morphostructural domain-II, the fluvial sedimentation was confined in the structural lows while in the morphostructural domain-III the deposition resulted in the burial of the Early Pleistocene Erosional Surface (EPES). The culmination of fluvial sedimentation resulted in the formation of the Late Pleistocene Depositional Surface (LPDS) over it.

The fluvial sediments now exposed in incised cliffs, lithologically comprise gravels, sands, silts and a buried soils. The base is marked by a channel gravel which is overlain by thick horizons of sands and silts. These normally show horizontal stratification while the other sedimentary structures like cross bedding are rather sparse. The top part of the sequences show a 2- 4 m thick deeply pedogenised buried soil. The soil is distinctly identifiable almost at all the places and is highly calcretised. The soil marks a phase of pedogenesis of the fluvial sediments. Since the soil appears at similar stratigraphic position, it has been found useful for correlations of the sediments exposed at other places. The buried soil is overlain by fluvial silts which are capped by present day top soil. At places the soil is overlain by cross-stratified gravels with a distinct erosional contact. These gravels comprise mostly clasts of calcretes which have been derived from the underlying soil horizon.

Optically Stimulated Luminescence (OSL) age of 34 ± 5 Ka suggests that the Late Pleistocene sediments in the Kim river are stratigraphically correlatable with the upper part of the Late Pleistocene sequences in the lower Narmada basin described by Chamyal et al. (2002) and Bhandari et al. (2004). However, the buried soil in Kim basin appears as a typical brown soil, the one in Lower Narmada basin is reported as a reddish brown soil. The sedimentation took place under conditions of increasing aridity as indicated by the presence of calcretes.

The Late Pleistocene sedimentation occurred in all the three morphostructural zones. The brief phase of sedimentation after a prolonged period of extreme deformation and erosion indicate significant weakening of the tectonic activity (uplift) during Late Pleistocene. The buried soil also points towards relative tectonic stability attained during this period.

EARLY HOLOCENE

The Early Holocene is again a period of net erosion aided by tectonic uplift. The tectonic uplift of the basin at this time led to the incision of the Late Pleistocene Depositional Surface (LPDS) in all the three morphostructural domains. The incision of ~15 m possibly reflects the total amount of uplift that occurred in the Kim basin during Early Holocene. This phase of tectonic activity marks the second phase of tectonic uplift of the post-Pliocene basin inversion.

The Late Pleistocene Depositional Surface (LPDS) show severe gully erosion in the vicinity of the various river channels. This zone of fluvial erosion varies from few tens of meters to a couple of kilometers in width and seen to occur almost continuously. This erosional surface called as Early Holocene Erosional Surface (EHES) is particularly well developed in morphostructural domain I and II. This

surface indicates a post-Late Pleistocene phase of fluvial erosion and incision. However, the terraces do not show evidence of this erosional phase, which means that the dissection of Late Pleistocene sediments took place during Early Holocene. The incision and ravine erosion after a depositional phase suggests reactivation of tectonic stresses marking the beginning of another phase of inversion. The tectonic activity took place along the pre existing faults. The various fault blocks suffered differential uplift, however the direction of movements remained the same as during Late Pliocene to Middle Pleistocene inversion phase. This is evidenced by the topography which continued to remain in close correspondence with the structural highs and lows. In the upland zone, the gullies are seen extending from the Late Pleistocene deposits over to the trappean rocks which suggest that the erosional activity was independent of lithologic controls. However, the Late Pleistocene sediments in morphostructural domain-II shows greater incision suggesting that this domain was uplifted more than the upland zone. This suggests differential uplift along the Rajpardi Fault.

Tectonic activity in the trappean upland have been documented by Rachna et al. (2003). Bhandari et al. (2001) have also indicated inversion of the lower Narmada basin due to differential uplift along NSF during Early Holocene. This suggests that the Early Holocene phase of basin inversion in the study area occurred as a part of regional phase of basin inversion. Comparable erosional phase is recorded all over the Gujarat alluvial plain in the north (Maurya et al. 2000) which suggests that all the blocks of the Cambay rift graben suffered tectonic inversion at this time. The Late-Pliocene to Middle Pleistocene phase of inversion though was more intense but was localized to the Narmada block only in contrast to the Early Holocene phase which

was less intense but was uniformly spread over the Cambay basin. The Early Holocene period therefore marks a renewed phase of N-S directed compression.

MIDDLE TO LATE HOLOCENE

The Middle to Late Holocene period in Kim river basin is marked by the deposition of Late Holocene Depositional Surface. The depositional phase followed the erosional phase of Early Holocene which points to weakening of tectonic activity. The deposition took place within the fluvial valley produced by incision of Late Pleistocene Depositional Surface (LPDS). The Middle to Late Holocene sedimentation occurred in all the three morphostructural domains. The upper part of the sequence has been tentatively dated to ~2 Ka by OSL. These sediments form flat terraced depositional surface all along the channel of Kim river and its tributaries and shows a variable incision of 4 – 8 m. In morphostructural domain I and II the sediments comprise fluvial gravels and sands while in the morphostructural domain III the deposition was mainly estuarine-tidal.

In the upland zone i.e. morphostructural domain-I, the sediments of Late Holocene Depositional Surface (LHDS) are mainly channel sands and silts. However, in morphostructural domain-II, these sediments show abundance of stratified and unstratified gravels. The abrupt increase in grain size may be suggestive of tectonic activity along the N-S trending Rajpardi Fault. The grain size however decreases very rapidly in the downstream as the constituent sediments are coarse sand to fine sands and silts. The morphostructural domain-III, shows a marked change in the lithology of the Late Holocene Depositional Surface (LHDS). Here, the sediment succession of this surface consists of alternating horizons of sands, silts and clays. The clays are found to be rich in organic matter and are finely laminated. The sand and silts show

horizontal stratification and cross-stratification. The presence of herringbone structure suggests that the sands were deposited in estuarine-tidal environment. The clays also show lithological characters similar to those of tidal muds. The entire sequence appears to be result of a marine transgression which is believed to have peaked around 6 ka (Hashmi et al., 1995). The sediments of Late Holocene Depositional Surface (LHDS) though show lithological variations in the three morphostructural domains, this deposition is contemporaneous and occurs in similar geomorphic setting. Similar Mid-Late Holocene terrace sediments with comparable sedimentation patterns are reported from the lower Narmada basin and Mahi basin (Maurya et al. 2000; Chamyal et al. 2002). The upliftment of the terraces indicate post depositional uplift of the area marking the youngest phase of inversion.

INVERSION TECTONICS AND GEOMORPHIC EVOLUTION

Studies on sedimentary basin evolution normally encompass delineating mechanics of basin formation and its subsequent stratigraphic development usually accompanied by syn-sedimentary subsidence. However, changes in stress conditions may induce variations in the pattern of tectonic behaviour of the basin and the associated faults. Long term evolutionary history of such basins record phases of inversion. Basin inversion has long been recognised as an integral part of long term evolution of sedimentary basins. The Kim river basin is located within the Narmada block of the Cambay rift graben whose tectonic history begins during Late Mesozoic which is related to the drift tectonics of the Indian plate. The area witnessed continuous sedimentation during the Tertiary period as a part of the composite Cambay rift graben. However, a significant tectonic event along the Narmada-Son

Fault uplifted the Narmada block while rest of the Cambay basin continued to subside and receive sediments throughout most of the Quaternary (Fig. 7.1). The Narmada-Son Fault therefore appears to have played a major role in the tectonic inversion of Narmada block at the onset of Quaternary.

Visser (1980) defined inversion as 'the interruption of subsidence of a basin or part of it by temporary uplift and erosion - - - - - faults may change direction of throw and appear reversed in inversion stratigraphic levels'. Ziegler (1987a) redefined the term basin inversion as the reversal of the subsidence patterns of a sedimentary basin, which had developed under tension or transtensional tectonic regime, in response to compressional or transpressional stresses. According to him this generally involves uplift of the basin floor and deformation of the basin fill whereby the throw on tensional faults controlling the original structural relief of the respective graben or trough become partly or totally reversed. Numerous inverted basins have been documented worldwide mainly due to extensive geophysical exploration of petroliferous basins. However, study of basin inversion in terms of geomorphic development have received scant attention. Mather (1993) showed that inversion tectonics plays a key role in long term landscape formation in reactivated sedimentary basins.

The Kim river basin drains the interfluvial area between Narmada in the north and Tapi in the south. As stated earlier, this sedimentary basin forms the Narmada block of the Cambay basin which has followed a separate line of basin evolution (Table 7.1) in contrast with the rest of the Cambay basin. However, the formation of the basin and the Tertiary stratigraphic development is largely correlatable with other blocks of the Cambay basin. The Cambay rift graben was formed during Early

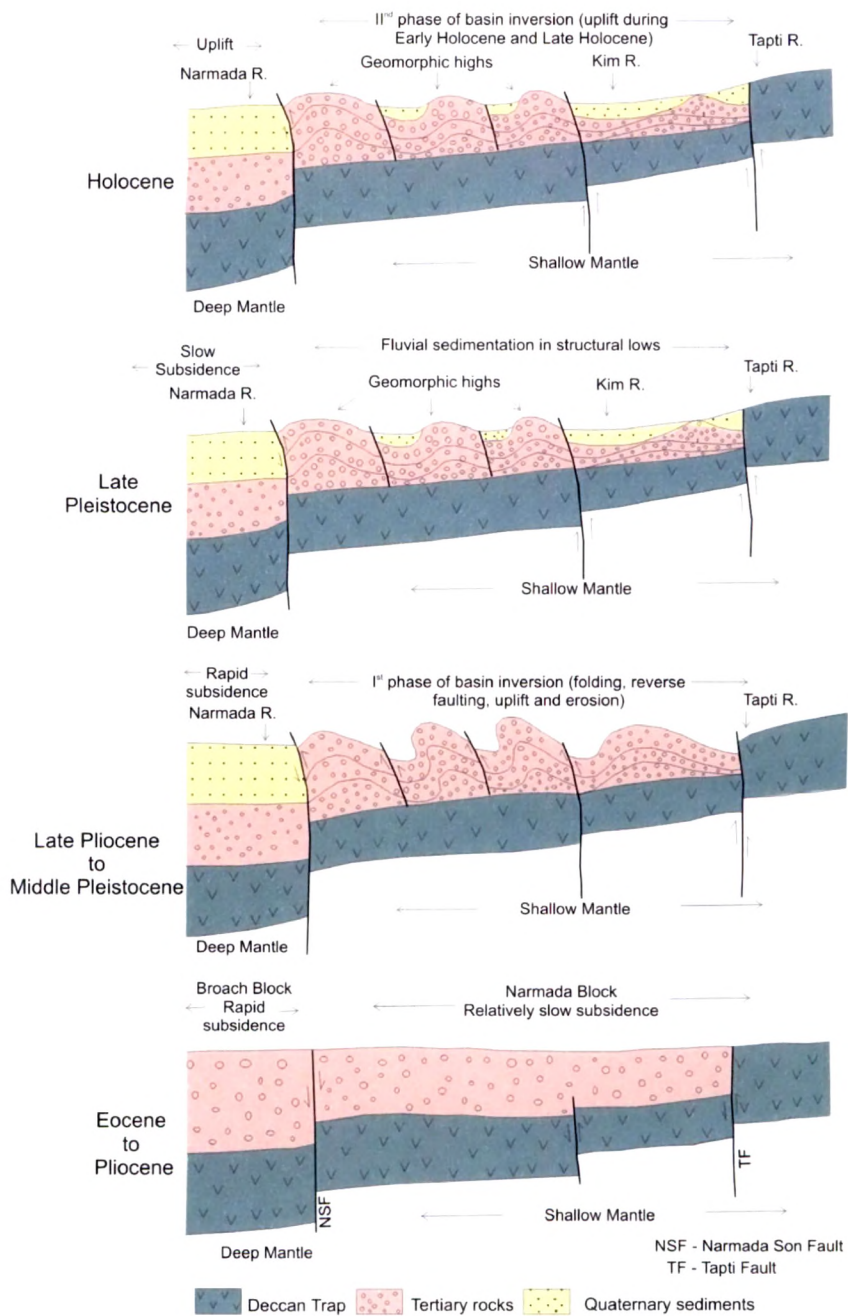


Fig. 7.1. Diagrammatic sketches depicting the phases of sedimentary basin inversion related to the geomorphic evolution of Kim river basin.

Cretaceous as a consequence of tensional stresses created at the continental margin due to northward drift of the Indian plate (Biswas, 1982). The rifting took place along the N-S Dharwar trend of Precambrian antiquity (Biswas, 1987). The N-S trending Rajpardi Fault marking the eastern limit of the Tertiary sedimentation in the Narmada block is the southern extension of the East Cambay Basin Margin Fault. The West Cambay Basin Margin Fault (WCBMF) lies in the offshore within the Gulf of Cambay. The initiation of rifting was also accompanied by high thermal regime and mantle updoming which resulted in the outpouring of the basaltic lavas of Deccan Trap Formation which formed the basement of the Tertiary sediments in the entire Cambay basin. The thinning of the crust associated with mantle updoming therefore a key element in the formation of the basin. This phenomenon of stretching, thinning and weakening of the competent crustal layers is known as 'necking' and is of greatest importance in rift basin formation (Hansen and Nielsen, 2003). At the present time also, the area between Narmada and Tapi rivers is a lithospheric neck due to the shallow depth of the Mohorovicic discontinuity.

The E-W trending Narmada rift opened up in early Cretaceous. However, after the deposition of Mesozoic marine sediments and subsequent outpouring of trappean lavas the rifting was aborted. A renewed cycle of rifting along the Cambay basin trend was superimposed over the Narmada rift during Paleocene (Agrawal, 1984) which formed N-S trending linear basin forming a major depocentre of Tertiary sediments. The Tertiary sedimentation was largely marine except during Oligocene where major regression limited the marine sedimentation only in the deeper part of the Cambay basin. The Babaguru Formation of continental origin was deposited in the study area during this time (Agrawal, 1984).

The onset of Quaternary heralded a major episode of basin inversion which was limited to the Narmada block of the Cambay basin (Fig. 7.1). The Broach block located to the north of NSF continues to subside rapidly throughout Quaternary (Agrawal, 1984). This phase of basin inversion continued upto the beginning of the Late Pleistocene as described earlier this period in the Kim river basin is characterized by intensive tectonically controlled erosion. Basin inversion is normally a phase of erosion (Mather, 1993). The inversion of the basin occurred due to severe N-S directed compressive stresses. The Narmada-Son Fault which behaved as a normal fault during Tertiary became reversed (Roy, 1990) under the influence of these compressive stresses. The original normal faults are known to become reverse due to compressive stress regime during basin inversion (Koopman et al. 1987). The Tertiary sediments were severely deformed leading to formation of ENE-WSW trending folds. The reverse faulting took place at the southern limbs of the all anticlines. These faults not related to any weak plane in the basement and had been newly formed in response to inversion related compressive stress regime. Experimental studies on inversion tectonics have demonstrated that the compressive stresses can produce reverse faults which become progressively important during the later inversion phase (Koopman et al. 1987). It has also been found that the inversion is completely or partly accommodated along the newly developed reverse faults whose positions and shapes are determined by the orientations and magnitudes of the principal stresses (Koopman et al. 1987). The principal stress direction in the study area being roughly N-S. Intrabasinal thrusting and reverse faulting are the major mechanism which transform a subsiding basin into an uplift one (Lake and Karner, 1987). In such cases explanation

involving eustatic or relative sea level changes are relatively insignificant in comparison to the demonstrable tectonic control

The uplift of the basin, the folding and reverse faulting within the Tertiary sediments is therefore an expression of sedimentary basin inversion that was initiated after the deposition of Jhagadia Formation of Pliocene age. Since the exposed Late Pleistocene sediments do not show extreme deformation of the type seen in Tertiary sediments, it suggests the period of extreme compressional tectonism died out or significantly slowed down in the beginning of the Late Pleistocene. The erosional surface which developed over the Tertiary uplift allows for separating the tectonic phase which affected the area from Early Pleistocene to Late Pleistocene. This event also helps in categorizing the inversion related tectonic activity to a pre-erosional phase of extreme tectonic activity from a relatively sudden post-erosional tectonic activity. However, as explained in earlier chapters, the Late Pleistocene sedimentation took place in E-W trending synclinal lows, while the crest portions of the anticlines remained as topographic highs. The Kim river basin formed the principal depositional basin which was differentiated by the Vagadkhol, Dinod, Dungri and Kosamba anticlines to the north. Reverse faulting at the southern limbs of each of these anticlines led to the formation of the depositional basin (Fig. 7.1). DSS profile (Kaila et al. 1981) shows a major crustal fault (F4) at the northern edge of the Kim river basin. The Late Pleistocene sediments comprise fluvial gravels, sands and silts and a buried brown soil at the upper part of the exposed sediment column. The sediments suggest climatic control over relatively shorter time periods. Mather (1993) has shown that climatic changes may influence landscape evolution due to increasing continentality associated with basin inversion. In Kim river basin the dominance of

climate in Late Pleistocene has been possible due to condition of tectonic activity related to basin inversion. The Late Pleistocene sediments indicate deposition by small ephemeral channels which points towards the existence of a strongly seasonal climate. The preferred development of calcretes, especially in the upper part of the stratigraphic column including the palaeosol, indicate that the climate was semi-arid. In general, an increasing aridity of climate is inferred which corresponds to the onset of the arid phase of Last Glacial Maximum (LGM).

The dissection of the Late Pleistocene sediments combined with distinct phase of river incision, recorded in all these morphostructural domains, indicates a renewed phase of inversion related tectonic activity. This phase of tectonic uplift makes a late stage of sedimentary basin inversion in the study area. Though the magnitude of tectonic activity was as intense as the earlier phase, it has nevertheless left an unmistakable imprint of the landscape of the area. The deep gullies in the Late Pleistocene sediments and incised cliffs and entrenched meanders are all related to this phase of tectonic uplift which took place during Early Holocene. A correlatable phase of inversion related tectonic uplift is shown in the nearby Narmada river basin (Chamyal et al., 2002) and the Gujarat alluvial plain further north (Maurya et al., 2000). However, there is a definite time lag between the inversion of the basin to the north of the Narmada-Son Fault and the area to the north of the Narmada (Fig. 7.1). While the Tertiary sedimentary basin to the south of the Narmada-Son Fault suffered extreme compression and inversion, the area to the north of the NSF continued to subside through much of the Pleistocene and was inverted during Early Holocene only (Chamyal et al., 2002). This provides a clear evidence that during the Early Pleistocene inversion phase, the bulk of the compression stress was absorbed by the

newly formed reverse faults and the transformation of the NSF into a major reverse fault, thus shielding the area to the north from early inversion. This may also have been facilitated by the fact that the crust to the south of NSF is much thinner than from the northern side. It has been demonstrated that basins with the thinnest crust are prone to early inversion Ziegler (1987b) It is obvious that this inversion tectonics of the Late Cenozoic in the area is related to the collision and northward movement of the Indian plate. Due to continued compression (northward movement) the inversion may proceed to basins more proximal to the collision front and characterized by an apparently less thinned crust. The inversion of the sedimentary basins to the north of the NSF clearly post-dates the inversion of the basin to the south of the NSF. This phenomena is termed as 'inversion retrogradation' (Ziegler, 1987b) wherein the Narmada-Son Fault has played an important role. The continued underthrusting of the Indian plate in the north indicates that compression continues to dominate the tectonic stress regime of the area.