Neotectonic Evolution of Coastal Rivers of Mangalore, Karavali Karnataka, India

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Abstract: The geomorphic evolution of Mangalore is intimately influenced by Neo-tectonic activities that affected the West Coast and peninsular India that led to the upliftment of Sahyadri Range. Mangalore pediplain has preserved signatures of (1) An older cycle of River system that existed prior to the rise of Sahyadri and (2) Several phases of migration paths of the West flowing Sahyadri Rivers, reflecting geomorphic changes in the pediplain in response to the tectonic strains generated during the rise of the Sahyadri range and northward drift of the Indian subcontinent. The compressional stress derived from the phenomenon of Sea floor spreading is manifested in the Karavali pediplain, in the form of EW and NNW intersecting transform faults that activate periodically and trigger micro-seismic disturbances severe sea erosions or landslides under adverse hydrological conditions. Similarly under the regime of compressional stress, the Mangalore pediplain evinces evidences of sequential development of anticlinal upwarps that broke into horsts and grabens separated by escarpments. The Holocene fluvial evolution of Mangalore consisted of migration of the two Rivers in opposite directions with progressive passage of time in the Holocene. Fluvial geomorphology of Mangalore has also preserved evidences that substantiate shifting of trans-peninsular Mulki - Pulicat Ridge Axis from its original position northwards. The ongoing structural disturbances and micro-seismic and allied recent neo-tectonic activities imply that the processes responsible for the creation of the Sahyadri range have not died down yet and are very much in attendance even today.

Keywords: *Neotectonics, Geomorphology, Fluvial Evolution, Coastal Rivers, Mangalore, Sahyadri, Mulki-Pulicat trans-peninsular Ridge, anticlinal upwarps, laterites.*

Introduction:

Mangalore city is largely enveloped between two West flowing rivers, namely Phalguni (also known as Gurupur River) and Netravati, displays numerous valleys alternating with ridges. Geologically the region consists of a basement of Early Precambrian tonalitic gneisses, invaded by granites, granulites and dolerite dykes. The gneissic rocks (ca 3000Ma) have been invaded by granites (ca 2600 Ma) and granulites (ca.2600-2500). Granulites are mostly restricted to areas south of Mangalore; however, tongues of granulites can be seen in gneissic granite quarries north of Mangalore. High grade alumina rich (corundum bearing) metamorphic schists have been encountered and younger alkaline intrusive rocks like Aegerine-Syenites have been reported from Sullia (Ravindra & Janardhan, 1981). The hard rocks are covered by an allochthonous, transported and deposited veneer of red-beds (reddish brown lateritoid soils) that have been subsequently transformed variably to Laterites (ferricrete duricrusts) in stages. The allochthonous relationship between the hard rocks and the overlying redbeds and laterites is explicit in various quarry sections. The overall field relationship between the underlying hard rocks and the overlying laterites conform to the inferences of Ollier and Sheth (2008).

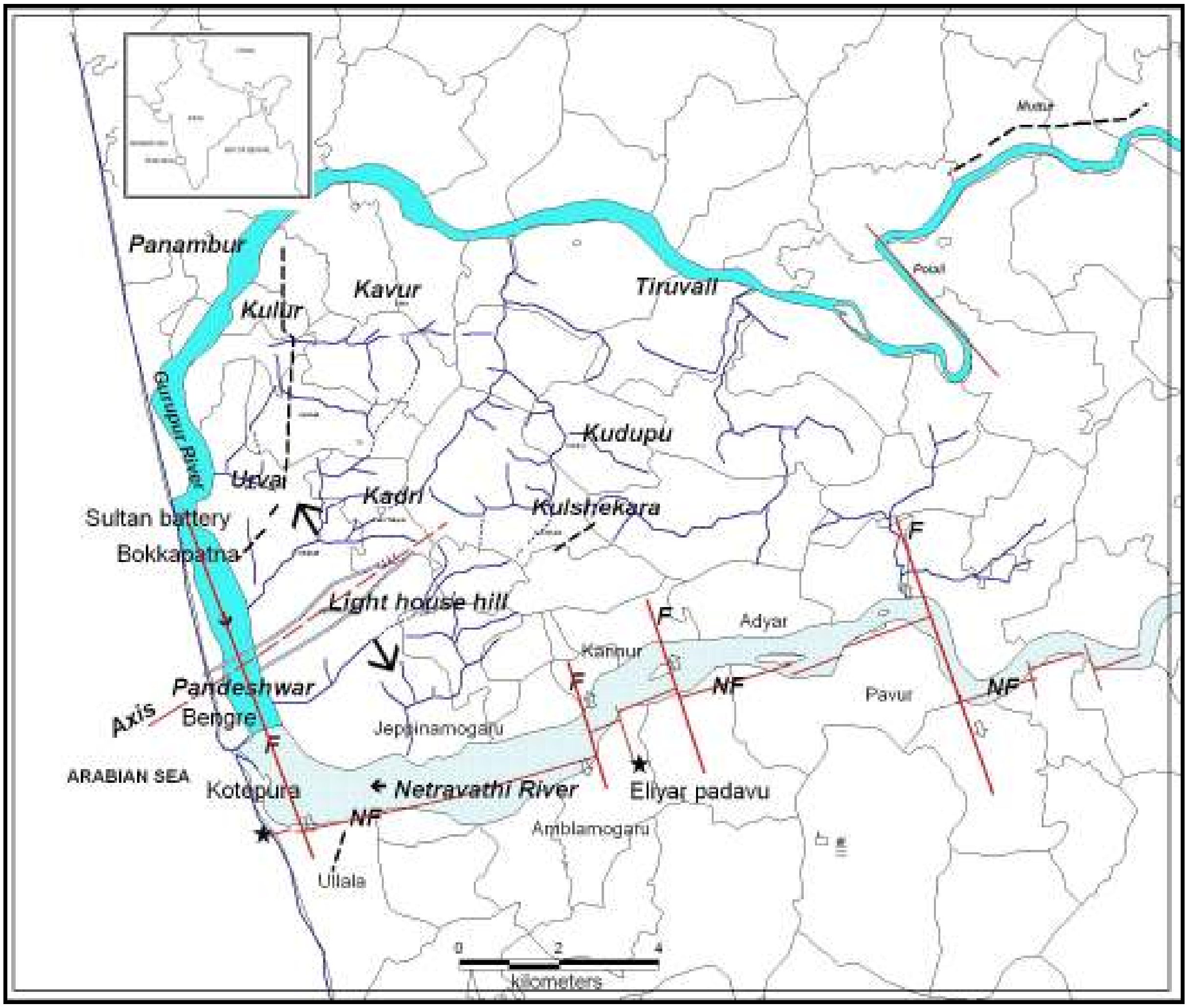

Figure 1: *Paleo-River Systems and the Evolution of Fluvial Courses in the Mangalore Pediplain. Axis' Refers to the Original Axis of Water Divide or Ridge that Existed during the Beginning of Holocene. Large Arrows on Either Side of the 'Axis' Show the General Direction of Migration of Gurupur and Netravati River Channels during the Course of History. Stars Show the Micro-Seismic (Eliyar Padavu) and Sea Erosion (Kotepura) Sites. Heavy Dashes Show Traces of Older Stream Courses, with Black Clay Deposits. Bengre -Tannirbavi Barrier Spit was formed during 1887.*

The West Coast and the Karavali pediplain have been affected by Neogene Sea floor spreading in the Indian Ocean and the Arabian Sea. Geologists earlier considered that West Coast of India is shaped by a major West Coast Fault. However, recent studies revealed that the West Coast Fault lies to the West of present coast-line and has been disrupted by development of several transverse shears that have broken the West Coast fault into number of units (Balakrishnan, 2001). Karavali pediplain has been transected by a number of parallel EW transform faults that apparently extended from the Carlsberg Ridge during the development of Sea floor spreading in Arabian Sea (Ravindra & Krishna Rao, 1987; Nair & Subramanian, 1989). Besides, there are also other sets of transform faults that have affected the region. Mangalore region is bound by a couple of significant East-West transform faults (Fig 6) such as:

1. Hejamadi- Kudremukh E-W Transform Fault. 2. Netravati E-W Transform Fault. The EW transform fault passing through Hejamadi in the West Coast and Kudremukh

in the East (arcuate portion of Sahyadri escarpment) evinces lateral strike slip movement. The BIF bands exposed in the Dharmastala area can be inferred as dislocated fragments of the BIF bands on the Western limbs of Bababudan schist belt (Fig 7).Similarly, the Netravati transform Fault extends from Kotepura, Ullal in the West Coast and cuts across the Sahyadri escarpment near Subramanya.

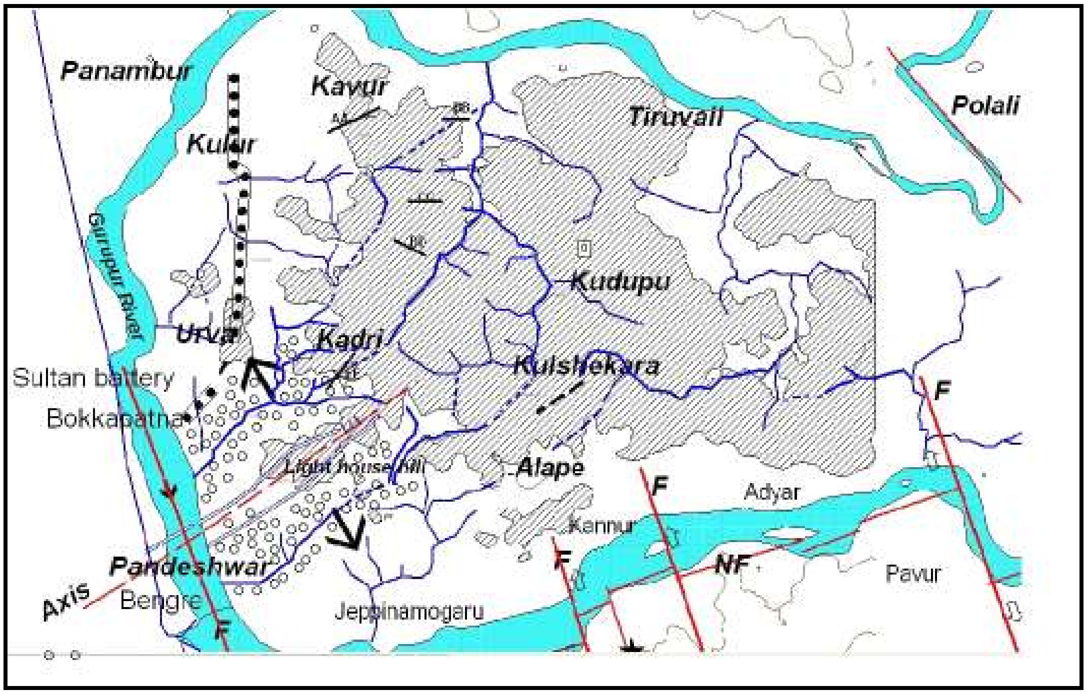

Figure 2: *The Shape of Kadri-Kulashekar Laterite Plateau, consisting of Several Minor Horst Structures. Etched Block Shows the Composite Block of Horsts, Delineated by 40 m Contour. Examples of Anticlinal Upwarp Sections along Lines AA, BB, CC, DD and EE have been shown in Fig 3. Small Circles show Distribution of Paleo-Fluvial Quartz-Pebble Formations (Mangalore Beds).Arrows Show Directions of Migration of Paleo-Rivers with Passage of Time.*

The neo-tectonic stress on peninsular India also led to the development of a number of trans-peninsular ridges (Cymatogenic arches: Vaidyanathan, 1977)and depressions. The Mulki - Pulicat ridge (Subrahmanya, 1994) [or Mangalore-Chennai topo-high: Ramasamy,2006] is one such trans-peninsular ridge. Palghat gap is an example of a major trans-peninsular depression. Mulki- Pulicat axis is an irregular line of water divide (Ravindra & Sharma, 2007) approximately along 13^{o} N latitude, connecting Mulki on the West Coast with Pulicat Lake on the East Coast of Tamilnadu (Subrahmanya, 1994, 1996).

Marine expeditions conducted by Geological Survey of India, identified the existence of sandy paleo-beach ridges some 25 km offshore of Mangalore coast. The three offshore core logs from the expedition show beach sand formations overlying stiff compact, clays with plant remains (Shankar & Karbassi, 1992). Similar occurrences of black clays admixed with lignite/peat (or plant fossils) have been reported widely from the coastal tract and offshore (Mascarenhas, 1997). Earlier, Murty (1977) reported occurrence of lignite in clays from the foundation wells of Netravati Bridge, south of Mangalore. Black Clays occur in some of the paleo-fluvial courses, such as Baikampadi, Kulur and Kottara, usually admixed with plant remains (peat or lignite).

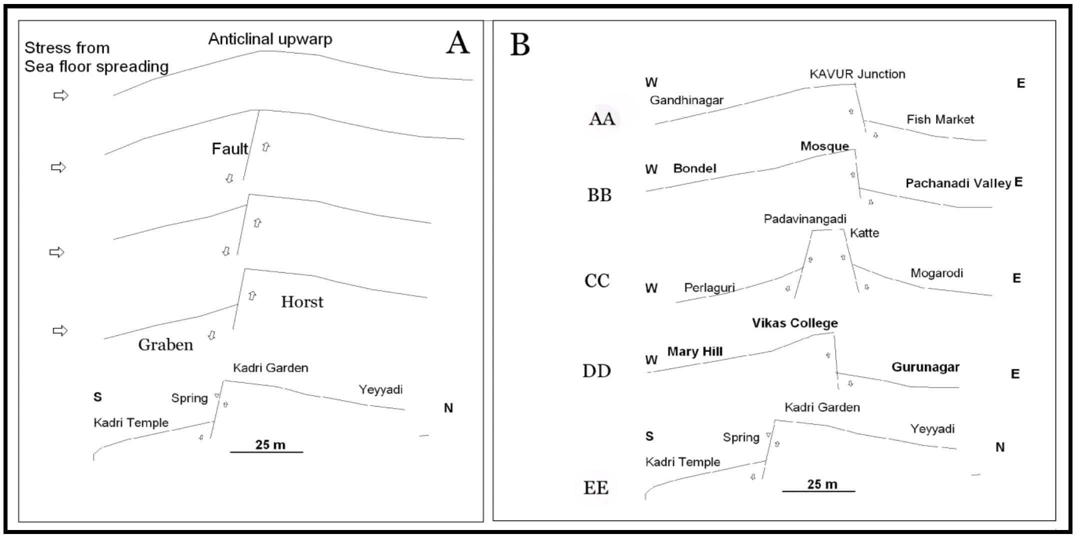

Figure 3: *(A) Thematic Evolution of Anticlinal Upwarps into Horsts and Grabens, Separated by Vertical Cliffs in the Lateritic Cover of Mangalore. (B) Sectional Views of Some of the Horst-Graben Structures in Laterite Caps within the Kadri Kulashekar Laterite Plateau (Fig 2). AA: Kavur Junction. BB: Bondel Mosque.CC: Padavinangadi Katte, DD: Gurunagar EE: Kadri Park-Kadri temple.*

Paleo-Fluvial Valleys:

The valleys explicit in the topography of the Mangalore represent the fluvial courses that drained the terrain in the past, as evident from the presence of detrital deposits of black clays with plant remains or rounded quartz pebble beds. Several quartz pebble formations with lateritic matrix have been identified from localities of Mangalore such as Kadri (Fox, 1936), Kodialbail, Attavara, Kankanadi, Kadri, Kudroli and Pandeshwara. The quartz pebble formations consisting of sheared quartz pebbles embedded in lateritic soil material have been reported as 'Mangalore beds '(Subrahmanya et al, 1991) and have been correlated with Ratnagiri beds and Warkalli beds. Overall analysis of paleo- drainage patterns in Mangalore area reveals broadly two generations of fluvial drainages: [1] An older set of relict fluvial courses that can be relegated to a period prior to the rise of Sahyadri ranges (Pre - Sahyadri) and [2] A later set of West flowing fluvial courses modified or introduced along with or after the rise of Sahyadri ranges.

Older Pre-Sahyadri Rivers:

The Karavali pediplain has preserved relicts of an older generation of rivers that flowed more or less in NNE to SSW direction and carried Black Clays to the West Coast (Fig 1). One of such relict river courses, now a backwater swamp, in Baikampadi -Tokur area, contains black clay deposits that show evidences of former drainage course running through Kulur and Kottara Chowki –Urva and joining the sea near Alike in the historical past. The upper reaches of this river apparently have been eroded recently and hence are not easily traceable at present.

It has been suggested that Black Soils of Karnataka were the transported sediments derived from the weathering of Deccan Traps (Ravindra, 1994). Balakrishnan (2001) similarly suggested that the Black Shales hosting the major petroliferous formations in the Arabian Sea were derived from the Deccan basalts. The Black Shales appear to be the indurated versions of the black clays. It is inferred that the black soils derived from Deccan Traps were carried to the Karavali coast by Deccan Rivers that drained the peninsula prior to the upliftment of Sahyadri ranges. Thus a Pre-Sahyadri time relation may be assigned to the older generation of fluvial event, as the black clays derived from the Deccan Traps could have been carried to the West Coast only before the rise of Sahyadri hill ranges.

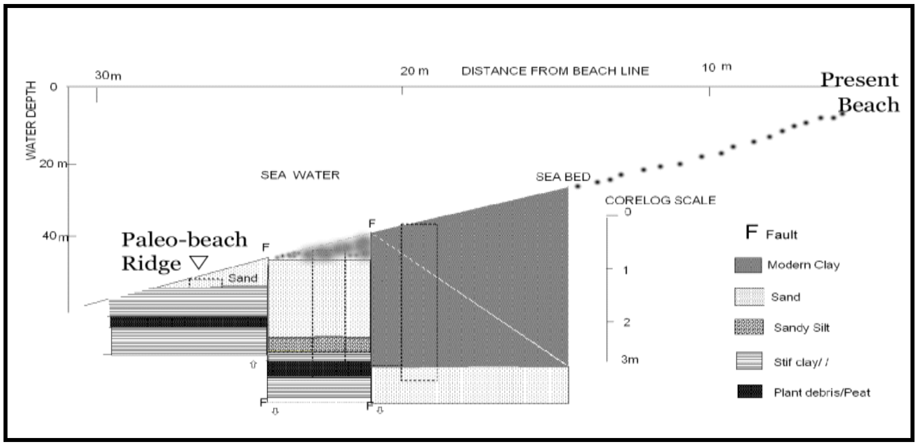

Figure 4: *Horst-Graben Structures in the Continental Shelf (Paleo-Beach Ridge) off Mangalore Coast, based on Re-Interpretation of Core Log Data from GSI (Marine Geology Expeditions) and Shankar & Karbassi (1992).Lateral Variations in Offshore Sedimentation can be Attributed to Vertical Movements forming Horsts and Grabens due to Neo-Tectonic Activities. Submergence of Paleo-Beaches due to Sinking during the Neo-Tectonic Activity can be Visualized.*

West Flowing Sahyadri Rivers:

The eruption of Deccan Traps (ca.60 Ma ago) initiated several major changes in the geological history of peninsular India. With the sea floor spreading centered on the Carlsberg ridge adding new crustal material to the Arabian Sea floor and the counter-clockwise northward drift of Indian subcontinent towards Eurasia lead to the drastic upheaval of intervening Tethys sediments into lofty Himalayas. Subsequent to the docking of Indian subcontinent plate onto the Eurasian plate, the accumulated stress on the Western continental shelf and the Coastal pediplain led to the development of series of anticlinal upwarps that culminated in the development of disruptive fractures and escarpments, altogether forming horsts and grabens (Biswas, 1988). The perpetuation of the compressive stress since India-Asia collision has led to the upliftment of Sahyadri ranges.

Consequently, the fluvial pattern in peninsular India drastically changed as Sahyadri ranges formed a major water divide in the Indian peninsula. As a consequence of neo-tectonic uprise of Sahyadri, the older set of peninsular rivers were either modified or captured by 'piracy' (e.g., Sharavati River piracy, Radhakrishna, 1964). Thus, distinct west flowing and east flowing rivers were formed on the respective flanks of the Sahyadri ranges. Of these, the Mangalore city area has been drained by two rivers namely Netravati and Gurupur.

Anticlinal Upwarps, Escarpments, Horst and Grabens:

Karavali pediplain evinces neotectonic signatures such as crustal shortening (anticlinal upwarps broken into cliffs), leading to vertical subsidences (grabens) and upheavals (horsts) and also transform (strike slip) lateral sliding of coastal blocks. The initiation of Sea floor spreading phenomenon with addition of new crustal material at the Carlsberg Ridge has continuously applied stress that led to the development of anticlinal upwarps in the coastal pediplain. Widdowson (1997) described similar anticlinal monoclinal structures in the Konkan pediplain. Alternately, the anticlinal upwarps have been described as monoclines (Dixit, 1981; Vaidyanadhan, 2001) or homoclines (Gunnell, 2001). With perpetuation and increase in the horizontal stress, the anticlinal flexure breaks into blocks that vertically slide past each other forming grabens and horsts (Fig. 3 and Fig.4).

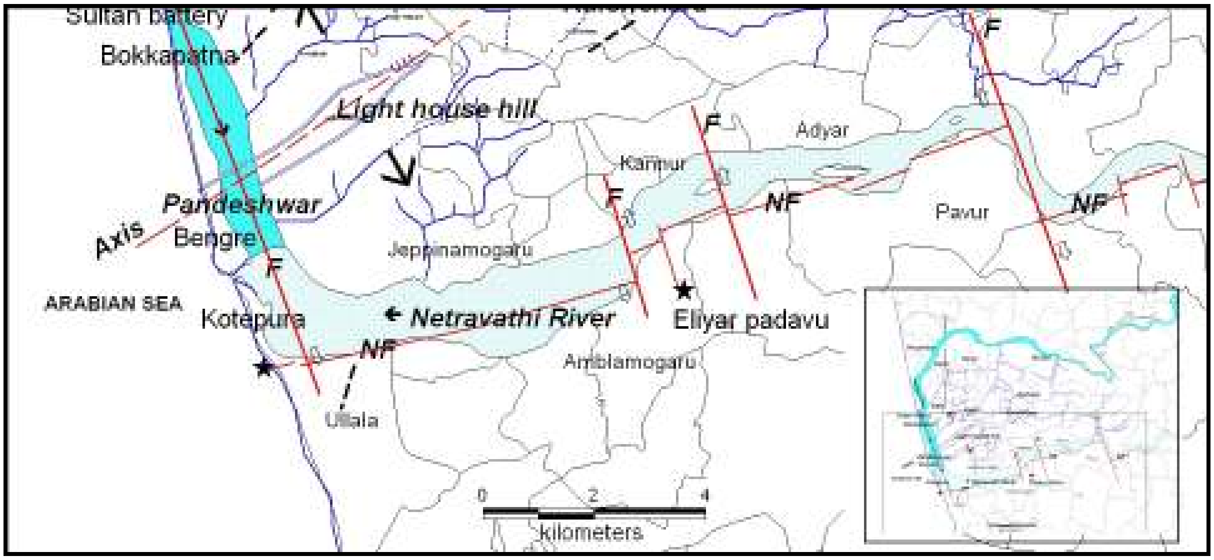

Figure 5: *Present Configuration of the River Netravati: West Flowing River Netravati is dominantly controlled by an EW Netravati Lineament Fault. Structural disturbances in the NNW-SSE Trending Transform (Strike Slip) Lateral Faults Cutting across the Netravati River are Responsible for some of the Earth Movements (like Eliyar padavu, August 2010). Note Ribbon like flexures in Netravati River suggestive of Crustal shortening. The Southward Drift of Jeppina Mogaru Segment and Simultaneous Northward Drift of Kannur and Adyar Segments in the Recent Decades are Reflected in the Morphological changes in the River.*

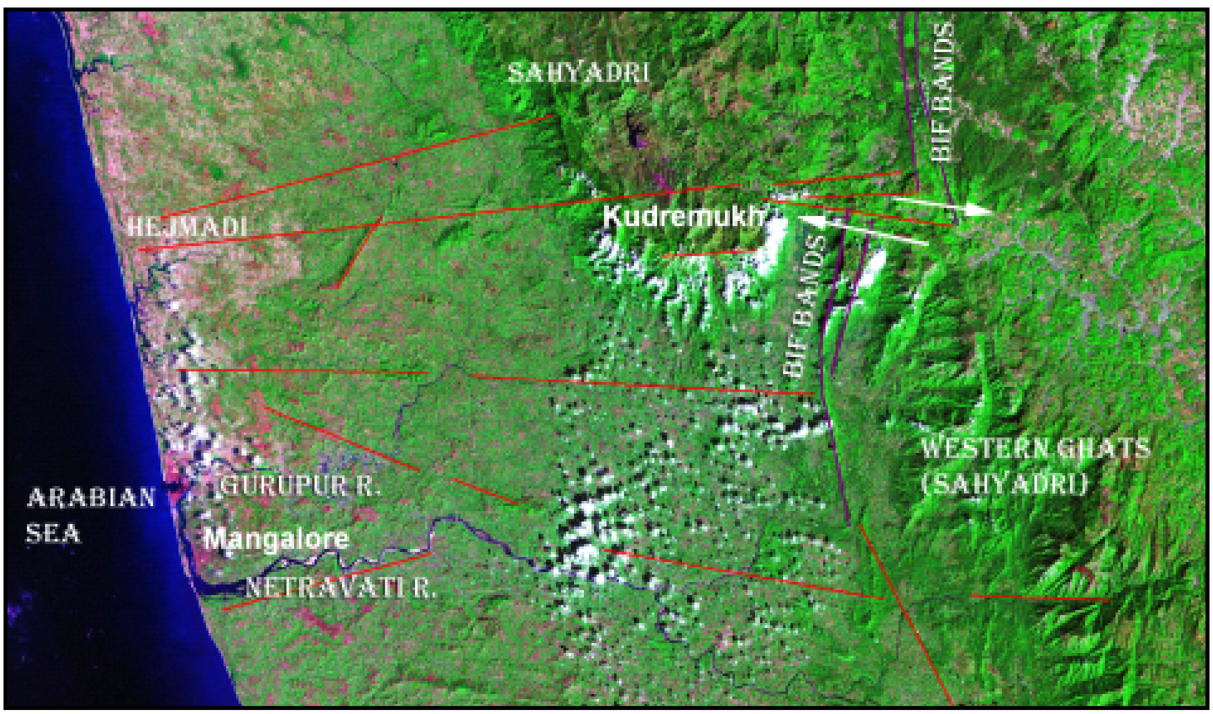

Figure 6: *Linear Traces of some of the EW Transform Faults across the Karavali Pediplain. Note the Strike Slip Lateral Displacement in Banded Iron Formations (BIF) of Southwestern Bababudan-Dharmastala BIF Bands (Indicated by Arrow Marks) along the Hejamadi-Kudremukh Transform Faults.*

Rising of Mangalore Ridge:

Tide gauge data reveal that Mangalore area is rising at a rate of 1.3mm/year (Emery & Aubrey, 1989; Manjunatha, 1994). The rising of Mangalore region can be attributed to stress developed on the West Coast by the Sea floor spreading in the Arabian Sea and consequent development of Mangalore Ridge (Mulki-Pulicat water divide or trans-peninsular ridge). In that case, considering that the Mangalore area is undergoing steady rise at an average rate of 1.3mm/year, it can be deduced that the Mangalore coastal terrain was about 325cm (or 3.25m) below present MSL about 2500 years ago during the period of transgression.

The pattern of evolution of West flowing river valleys in Mangalore suggests that the conjugate Rivers (Gurupur and Netravati) originating from the Sahyadri ranges were initially flowing on either sides of the Light house hill, Hampankatta, at the beginning of Holocene Age. Of these, northern Gurupur river gradually migrated northwards from its original position and Netravati shifted southward with passage of time corresponding with progressive rising of the Mangalore Ridge. The early West flowing rivers deposited quartz pebbles in the valleys and flood plains of Mangalore. The quartz pebbles, intensely sheared, suggesting possible recycled derivation from quartz or quartzite rich provenances, during older fluvial cycles, have been concentrated in the shallower reaches of the paleo-fluvial valleys as a consequence of upliftment of blocks in the Kadri- Kulashekar plateau (Fig 2).

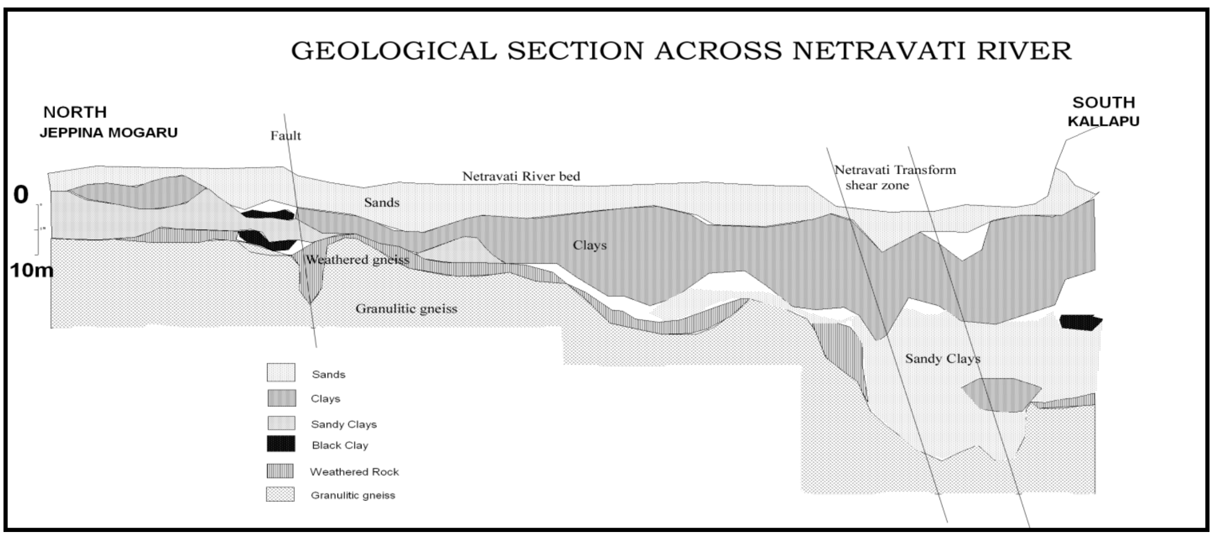

Figure 7: *A Geological Section across new Netravati Bridge on NH17 Connecting Jeppina Mogaru and Kallapu in Mangalore Taluk. The Variable Weathering of the Bed Rock Granulitic Gneiss in Profile, with Deeperalluvial Sections near the Southern Bank Testifies the Existence of faults across River Netravati.*

Several stages in history of northward migration of Gurupur (Phalguni) River can be recognized. River valleys occupying the following paleo courses:

(1) Tiruvail- Kudupu- Kadri valley- Kodialbail- Alake. (2) Padushedde - Pachanadi- Gurunagar- Kadri valley – Kodialbail- Kudroli. (3) Marakada- Kavur- Vyasanagar- Anegundi- Bijai- Bokkapatna. (4) Panjimogaru- Maladi- Kottara- Urwa- Bokkapatna. Etc

Similarly a few stages in history of southward migration of Netravati River can be recognized mainly in variations of the following path: Kulashekar - Alape – Adumaroli – Bendur - Palnir- Attavara - Pandeshwara.

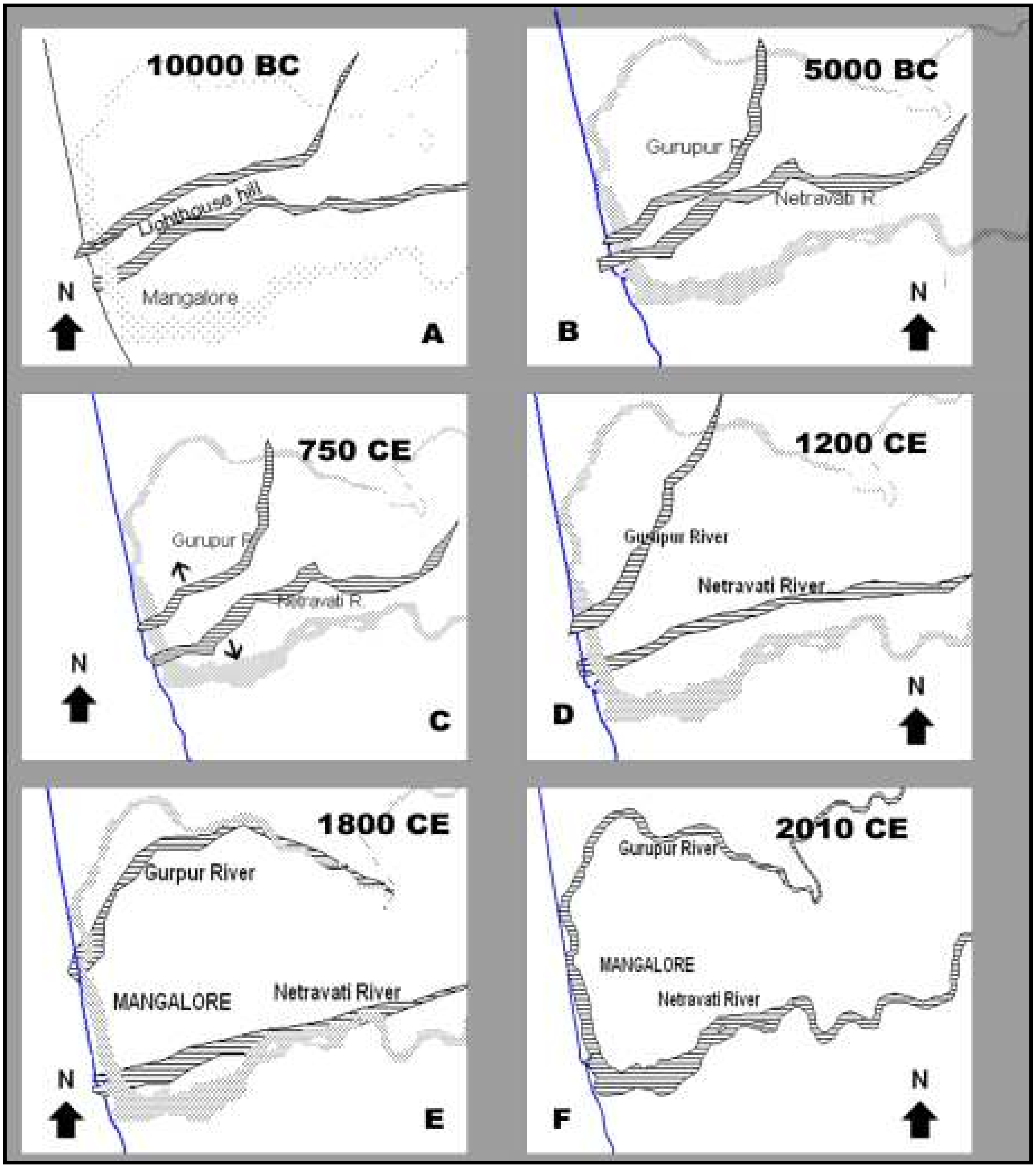

Figure 8: *Schematic Sequence of Stages in the Evolution of Rivers of Mangalore. Hatches show Position of Paleo-Rivers Schematically; present Position of the Two Rivers is shown in Shade for Comparative Reference. Changes in Position of Coast-Line not shown.* ***A:*** *About 10000 BC, the Two Rivers Flowed West on either Sides of Light House Hill, which Served as Initial Axis of Mangalore Ridge.* ***B:*** *About 5000 BC, the Rivers Showed Signs of Digression from their Original Courses in Opposite Directions. River Gurupur flowed along the Kodialbail Valley. River Netravati flowed along Attavara- Pandeshwara Valley Course.* ***C:*** *Around 750 CE, River Netravati Shifted its Course Southward from Attavara-Pandeshwara Valleys.* ***D:*** *Around1200 CE, with Further Digression of rivers, Formation of Bokkapatna Estuary and Port.* ***E:*** *About 1800 CE, Further Digression of the Two Rivers. with Gradual Shifting of Axis of Mangalore Ridge Northwards, Formation of Bengre-Tannirbavi Barrier Spit in the year 1887.* ***F:*** *Current Configuration of Gurupur and Netravati Rivers.*

It can also be seen that the quantum of digression of river courses is more on the northern side (River Gurupur) than on the southern side (River Netravati) with respect to the initial position of Mangalore Ridge Axis. This kind of migration of flow path can be attributed to the northward migration of the Indian subcontinent in a counter-clockwise fashion and related uplift of the trans-peninsular ridge. The available data also suggests that the Light house hill was the original axis of the trans-peninsular ridge. The position of the Ridge also shifted from Light house hill northwards towards Mulki as a consequence of counter-clockwise drift of the Indian subcontinent (Fig.1).

Holocene Transgression:

Bruckner (1989) inferred a period of transgression in Konkan Coast of India around 2200-2600 years before present. He reported beach ridges in Konkan area located 2 m above high tide line and 100 to 150 m inland from the present beach-line suggesting that these areas were inundated during the said Holocene transgression. Considering that the Konkan transgression extended south to Karavali Mangalore coast and that the terrain was about 3.25 m below present level, it can be presumed that areas up to 5.25 m above MSL were inundated during the transgression.

Historical Data on Rivers and Ports:

Alupe valley: Historical data on Mangalore suggests that the village of Alupe, located about 6 km east of present beach line, was the estuary and port at the mouth of Netravati about 2500 years ago, corresponding with the Holocene transgression inferred by Bruckner(1989). Alupe village, along the ancient course of River Netravati, evinces a deep semicircular river valley bounded by elevated laterite plateaus. Ancient Alupa Rulers of Mangalore area, hailed from the ancient port town of Alupe. After the regression of Sea in the beginning of Common Era (ca 400 -200 BC), the Estuary and Port of Netravati was shifted to Pandeshwara, in southern Mangalore. Consequently, the abandoned Alupe port was forgotten in the history.

Kudla Kudupu: Analysis of place-names like Kudla, Kudupu, Kudthadka and Kudpadi hamlets located on the flanks of ancient Rivers of Mangalore suggests that these were the sites of early agricultural activity in the Karavali, as the term '**Kudu**' in these place-names stands for horse-gram, the earliest grown popular pulse (food grain) in Southern India.

Migration of Estuaries:

Migration of Rivers in Mangalore has resulted in the changes in the location of estuaries and Ports during the historical period. Geological studies reveal that Netravati River was flowing through Attavara and Pandeshwara valleys and joining the Sea near Goods shed and Nire-Shivalaya, West of Pandeshwara. Similarly, the Gurpur River was formerly joining the Sea near Alake, Kudroli and Bokkapatna successively.

Pandeshwara Port: The Arabian Sea receded by ca.200 BC and consequently the River Netravati joined the Sea west of Pandeshwara. Following the changes, Alupa Kings shifted their base from Alupe valley to Pandeshwara as evident from the construction of a temple dedicated to Lord Pandeshwara (Shiva).The Pandeshwara port was used by Alupa merchants for trading through the Sea between the period 3rd and 7th Century CE. Historical data reveals that Alupas abandoned Pandeshwara Port abruptly, during 7th century CE, migrated and settled in Udyavara, near Udupi. One of the possible reasons for the emigration could be the abrupt southward drift of River Netravati that forced the rulers to abandon the unstable port of Pandeshwara.

Bokkapatna Port: Bokkapatna, named after 'Bokka' a King of Vijayanagar, was the ancient port of northern Mangalore active during the Vijayanagar period (13th to 14th Century CE. The Phalguni (Gurupur) river then flowed in the valleys of (1) Panjimogaru, Maladi and Kottara while the Phalguni estuary was near Bokkapatna. Subsequently, during 1784, Tippu Sultan, built a magazine (Battery) in the proximity of this port, to store ammunitions at Sultans Battery in order to fight the British Army.

Southerly Shifting of Netravati:

The Netravati River evinced sequential southward migration of fluvial channels with progress of historical time. It shifted path from Attavara-Pandeshwara valley southwards sometime during 7^{th} Century CE and by 16^{th} Century it had occupied the northern edge of Kotepura.

Kotepura Ullal: The northern part of Ullal where the historical fort of Queen Abbakka (ca. 1525-1570) existed is known as 'Kotepura' (=Fort town). After 16^{th} Century as a result of further southward migration of the River Netravati, a large part of the former Kotepura was destroyed and occupied by the river. Kotepura now, remains as a slim elongated tonsil like barrier spit in the northern tip of Ullal (Fig. 1).

Coast-Parallel Bends:

The West flowing rivers of Western India are characterized by development of coast-parallel bends in their coastal estuary zones (Ravindra and Krishna Rao, 1987). It can be seen that the width of the tidal reaches enclosed by these coast-parallel bends in the West Coast gradually increases from North to South. The feature of coast parallel bends associated with backwaters is almost absent in the northern Konkan Coast, whereas it becomes conspicuous progressively southwards, with development of widest backwaters ('kayals') in Kerala. The increase in the size of coast-parallel tidal backwater lagoons can be attributed to the counterclockwise northward drift of the Indian subcontinent. The data on the recent formation of Bengre Sand spit on coast-parallel bend of Gurupur River reveals that most of these coast parallel bends and related backwaters in the West Coast could have been formed in the recent history probably some 200-300 years ago.

Gurupur river diversion 1887: Records of Mangalore city reveal that the Gurpur River took an abrupt coast parallel diversion to conjugate with River Netravati during a monsoon day in the year 1887. Such an abrupt formation of barrier spit can be attributed to the neo-tectonic subsidence of coastal stretch parallel to the beach-line that guided the coast-parallel migration of the river.

Kadri -Kulashekar Composite Horst:

Kadri Kulashekar Horst block in central part of Mangalore is a laterite plateau with serrated, eroded borders (Fig.2). It is a composite block, consisting of several individual horsts that have been uplifted sequentially as a result of neo-tectonic compressive stress (Fig.3). The uplifted sub-block of Kadri Padavu straddles the paleo-channel of Gurupur River that followed the path of Vamanjur- Gurunagar- Kadri valley earlier. The Kadri Temple spring on the margin of the horst block evinces a disrupted line of seepage of water stream from the cited paleo fluvial path. There were more similar springs that existed in different parts of the Kadri - Kulashekar horst, especially along the valley margin of plateaus, but many of these springs have almost dried up in recent years.

The anticlinal upwarp flexures in the coastal structures are suggestive of application of stress from the western side, corresponding with effects of Sea floor spreading in the Arabian Sea-bed compounded with northward drift of the Indian subcontinent. The stress fields applied on the area were migratory in nature, as a consequence of northward gliding of the Indian subcontinent. Thus stress fields affected different blocks of terrain with passage of time. In other words the anticlinal (or monoclinal) flexures and consequent escarpment margins within the Kadri-Kulashekar horst (Fig 3) have been formed at different time sequences, reflecting the shifting of stress fields with time. Thus the paleo channel of River Gurupur flowing through Vamanjur- Gurunagar- Kulashekar track towards Kaibattal - Kadri temple-Kodialbail- Alake track was disrupted by the upheaval of a horst block across the flow path near Kadri Padavu (Kadri Park) plateau. Consequently, the river was forced to bypass this block and adopt a new flow-path northward. The data on the blocking of post Sahyadri West flowing fluvial courses by disruptive horsts, suggest that some components of the Kadri - Kulashekar horsts (Fig 2) were uplifted after (1) the upliftment of Sahyadri Ranges and (2) the formation of West flowing Rivers.

Kadri Kulashekar Horst block is a representative block and similar evidences of neo-tectonic signatures can be identified in other areas in the Karavali. The Sahyadri (Western Ghat) came into being as a consequence of regional scale composite anticlinal flexures that eventually ruptured into a massive escarpment with Coastal pediplain forming a huge graben as against the massive horst block of the peninsular mainland. This model also explains the gentle Westward slope of the Coastal topography (and formations) and Eastward slope of the peninsular mainland terrain.

Lateral Displacement of River Segments:

Evidences of neotectonic crustal movements are well displayed in the Netravati River. Netravati EW Transform Fault extends from Kotepura, Ullal in the West to Subramanya hills in the Sahyadri ranges in the East. The shear zone nature of the Netravati Transform Fault is also confirmed by depth of weathering in the bed rock (granulite gneiss) of the Netravati River as verified in the NS geological profile (Fig.7). The Netravati Transform Fault has been further offset by subsequent strike slip lateral movements along intersecting NNW - SSE faults (Fig.5). River Netravati in its current disposition shows two loopy bends dragged in opposite directions near (1) Jeppina Mogaru and (2) Kannur- Adyar. These two river segments in River Netravati obviously affected by cross-cutting NNW-SSE transform faults evince movement of river segments in opposite directions,that occurred during the last two centuries (Fig. 5)

Jappina Mogaru: The actual village of Jeppina Mogaru was located on the, southern flank of River Netravati, circa beginning of 19^{th} century. In the later part of the 19^{th} Century, probably corresponding with the migration event of River Gurpur (1887), the River Netravati migrated further southward, dividing the village of Jeppina Mogaru in the middle. Thus, in the revenue cadastral maps prepared during 1894 we find the village of Jeppina Mogaru separated into two fragments by the River Netravati. Thus now the northern part of Jeppina Mogaru lies on the north bank of the River Netravati (Mangalore A Taluk) and the southern part lies in the southern bank of the river (Mangalore B Taluk). At present there are significant ponding of parallel streams of water on the southern bank of Netravati. These may be indications of further southward migration of Netravati in future. Town planners have to note this aspect and plan advance evacuation in view of possible damage to the civic structures in the event of further southerly migration of River Netravati. Kannur- Adyar component**:** While the Jeppina-mogaru component of River Netravati migrated slowly southward during last few centuries, the Kannur- Adyar component of the River Netravati is migrating in the opposite direction, northward as evident from the submergence of revenue survey plots on the north bank of the river. The process of northward migration is concomitant with accretion of land on the southern bank of the river at Pavur (Fig.5). As a consequence of northward migration of this river segment, the old Kannur Mosque that formerly existed on the northern bank of Netravati at Kannur about two centuries ago has been rendered an island within the river.

Micro-Seismicity, Landslides and Sea erosions:

Mangalore area is being affected by a number of hazards directly influenced by neotectonic disturbances apart from imbalances in pent up pore water pressure accumulated in alluvial sediments. Some of the salient hazards that affected parts of Mangalore in the recent years are discussed below:

Kethikal Landslides:

Severe landslides damaged the National Highway 13, near Vamanjur, during the monsoon periods of the years 1996-98. Impounding of flood water in the Gurupur river at Tiruvail, soaked the clayey material in the Kethikal plateau, wherein the increase of pore water pressure within the clays led to disruption and landslides. The seasonal landslides connected with annual Gurupur river floods persisted for a few years during 1996 to 1998.

Eliyar Padavu Micro-Seismicity:

A residential colony in Eliyar Padavu area, Ambala Mogaru village, on the southern bank of River Netravati has experienced micro-seismic vibrations along an east-westerly oriented Netravati EW Transform Fault during the monsoon period of 2010 (August,1-3). The Netravati E-W transform fault, intersected by NNW-SSE trending transform Fault, passes through the affected area (Fig 5). The Geological analysis revealed that impounding of flood waters in a streamlet connected with River Netravati, located close to the affected area has triggered the micro-seismic vibrations in the Fault zone that resulted in severe damages to three houses in the colony.

Kotepura Sea Erosion:

Severe sea erosions have continued to haunt the Kotepura barrier spit in the recent years, especially after the construction of vented dam at Tumbe for supply of drinking water to Mangalore city. The increased inflow of excessive monsoon water exerts pressure on the fluvial channel, blocked by tonsil shaped barrier spit of Kotepura. Thus impounding of flood water on the River Netravati as well as on the Netravati Transform Fault (Fig.5) triggers micro-seismicity and Sea erosion on the Kotepura Spit during the attack of storm waves on the Kotepura beach.

Discussion:

1. The Baikampadi - Tokur swamp in northern Mangalore represents relict of an older generation of rivers of the peninsula. The Tokur swamp is underlain by Black clays admixed with plant remains and these can be traced southward along a NNE-SSW track passing through Kulur, Kottara Chowki, Urwa, Kudroli and Alike. Considering that the Black clays were derived from the Deccan Traps (Ravindra, 1994), it follows that the Rivers that carried Black clays from the provenance of Deccan Traps (in Maharastra and northern Karnataka) to the Karavali coast existed before the rise of the Sahyadri Range. Alternately, it also follows that the Pre-Sahyadri Rivers that existed prior to the upheaval of the Sahyadri Range drained ambient sediments along with water from the Deccan Trap country to the Karavali. The Black Clay sediments reached the Karavali before the rise of Sahyadri ranges. The paleo-beaches discovered in the offshore of Mangalore can be connected to a period of Pre-Sahyadri Rivers, since the sandy paleo-beaches are also underlain by similar stiff Black clays associated with plant remains.
2. Consequent on the Sea-floor spreading centered on Carlsberg Ridge in the Arabian Sea, and northward journey of the Indian plate towards Eurasia, The Indian peninsula developed a number of transverse ridges and troughs and also a number of transverse (transform) fractures (Fig 6). Mangalore (Mulki-Pulicat) ridge is one of such trans-peninsular cymatogenic arches. The Karavali tract is dissected by a number of East - Westerly transform faults (Ravindra & Krishna Rao, 1987). One such EW transform fault passes through Hejamadi and cuts across the Sahyadri Range near Kudremukh (Fig.6). Another one is Netravati Fault that passes through Kotepura, Ullal, in the West Coast and cuts across the Sahyadri near Subramanya hills. The Coastal block in between these two transform faults shows evidence of westward sliding.
3. The unequal distribution of sandy and Stiff Clay formations (with plant remains) in the vertical sections of core logs of offshore paleo-beaches of Mangalore, can be attributed to vertical sliding of blocks into horsts and grabens after the deposition of clays and beach sands.
4. The analysis of evolutionary pattern of Gurupur and Netravati Rivers in Mangalore reveal that the Mangalore (Mulki-Pulicat) Ridge axis had its origin along the ridge of Light house hill, Mangalore. With passage of time, the position of the Ridge Axis was shifted northward toward Mulki. By the time, Sahyadri range was rising as a huge horst, with coastal block sinking as a graben and the west flowing Rivers had taken over('captured') the older streams

that existed prior to the rise of Sahyadri Range.

5. The Mangalore Ridge axis gradually shifted its position northward, possibly coinciding with the northward drift of the Indian plate with a counter clockwise twist. This drift is reflected in the changing positions of the rivers Gurupur ad Netravati during the Holocene. It appears that a major shift in the Mangalore Ridge axis from Light house hill axis to present position of Mulki was accomplished between the years ca 800 CE and 1850 CE.
6. The upheaval of Sahyadri ranges resulted after the docking of Indian plate onto the Eurasian plate and the attendant rise of Himalayas. The stress regime developed due to continuation of the Sea floor spreading process at about 3cm/year and the continued northward pushing of the Indian plate created anticlinal upwarps and faults that uplifted the peninsula into lofty Sahyadri Range (Western Ghats). Further, the uplifted Sahyadri Range acted as a major water divide that enabled piracy of older river courses and eventually modified the fluvial paths that prevailed before the upliftment.
7. A number of anticlinal upwarps, faulted and broken into horsts and grabens, bound by sharp cliffs can be seen within the Kadri- Kulashekar composite horst block.(Fig 2). Circumstantial evidences based on archeo-botanical evolution in South India suggest that the Kadri temple – Kadri Park horst (section EE, Fig 3) has possibly been uplifted after 1500 -500 BC, blocking and diverting the Pachanadi-Kudupu - Kadri - Kodial bail paleo-course of River Gurupur. Similar, sequential neotectonic formation of anticlinal upwarps > fault > cliff > horst/ graben structural deformations during the recent history have resulted in rivers Gurupur and Netravati sequentially changing their fluvial courses in divergent directions.
8. Historical data reveals that Pandeshwara was the main Port of Mangalore between the period ca 300 CE and 700 CE. River Netravati shifted southward ca 700 CE as a consequence of rise of blocks around Kulashekar. Similarly, the available data reveal that Bokkapatna was the estuary and Port of River Gurupur from ca 1200 to 1887.
9. The processes suggest that the stress fields derived from the drift of Indian plate sequentially changed with respect to space and time resulting in composite horst blocks like the one exemplified by Kadri-Kulashekar composite horst (Fig 2). The sequential nature of these stress related structural processes indicate that Sahyadri Ranges were uplifted gradually and sequentially over a long duration of Neogene time. The various stages of evolution of Gurupur and Netravati Rivers are shown schematically in Fig.8.
10. The abrupt coast-parallel southerly turn taken by river Gurupur in the year 1887 created a barrier spit extending from Tannirbavi to Bengre. By the time, the Mangalore Ridge Axis had been shifted northwards to its current position at Mulki. Neotectonic activities related to the Sea floor spreading are still in force as suggested by drift of two segments of River Netravati in opposite directions during the last three centuries (Fig 5). Similarly recurring micro-seismic activities (for example Eliyar Padavu), severe sea erosions (like Kotepura) and landslides (like Kettikallu) reveal the evident role of neotectonic stress that triggers natural hazards under unbalanced oversaturation of monsoon water in allied fault zones.

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