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An integrated approach on satellite geodesy data to delineate morpho-tectonic and neotectonic activities in the West Coast off Kerala, Southern India

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Abstract. Better understanding of marine geomorphology plays a vital role in the development of humankind. Therefore, satellite altimetry data serves as a comprehensive and cohesive method. The present study attempts to explore the delineation of submarine structural features and a correlation of tectonic features both on land and offshore of the west coast off Kerala, using Global bathymetric model (GBM) and satellite-derived gravity data. The study observes the south-west coast of Indian peninsula, which has a unique geological and structural features. It is a passive margin, which has undergone drift-rift mechanism associated with the separation of Madagascar–Seychelles–India. The hinterland of the area is an assortment from the Meso-Archean to Neo-Proterozoic crustal blocks sandwiched with shear zones. The study area has been divided into three zones (Zone I, II and

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III) based on major shear zones in continental part to decipher the tectonic control. Satellite altimetry data has been used to derive drainages with different threshold to study submarine drainage system, channel shift, fault, impact crater etc. Conversely, all these observations deduced by satellite altimetry data have been validated with available published data. This study implies that geodesy data is an important and economical tool for preliminary studies, for understanding regional geological niche and its structural/tectonic control.

1. Introduction

Scientific ocean exploration started since Her Majesty's Ship Beagle, and nowadays voyages, using high resolution seismic and sequence stratigraphic studies continue to make discoveries. These studies are essential for sustainable future of humankind and even interplanetary voyages. However, the expenditure towards such studies are enormous and economical probes are essential for disabling those difficulties. The satellite altimetry and remote sensing is an alternate method for the preliminary investigation of marine geomorphological characterization in the regional scale. It also provides the elevation frequency distribution (hypsometry) in the continental and oceanic area which can decipher large-scale manifestations of plate tectonic features [*Gahagan et al.,* 1988; *Sandwell and Smith,* 1994].

More than half of the Earth's continental and continental shelf part is covered with sediments and sedimentary rocks, with maximum accumulations at continental rift margins. Submarine channel-levee complexes act as a conduit for terrigenous material from continental margins to the deep oceans. Details on the evolutionary processes of channel play a major role for the predictions of their individual occurrence, morphology, geo-hazard zone etc.; which are essential for seafloor infrastructure planning and construction [*Allen,* 2008; *Paull et al.,* 2003; *Xu,* 2010].

Indian peninsula has a unique feature: it is bounded by world's largest sedimentary basins like Bengal fan on east and Indus fan on west. Ocean basin calculated by satellite altimetry data has been widely used in Indian Continent mainly for delineating major drainage networks in submarine fans of Bengal, Indus and Ayyeyarwady in Andaman Sea [*Girishbai et al.,* 2017; *Kundu and Pattnaik,* 2011; *Prerna Ramesh et al.,* 2015]. In this paper a detailed investigation has been made to delineate submarine drainages, morphotectonic and neotectonic activities in the west coast off Kerala using Global bathymetric model (GBM) and satellite derived gravity data with an aid of Geographic Information System (GIS) software.

2. Study Area and Regional Geology

The linear feature of the West coast of Indian peninsular (i.e., from Sir Creek in the north to Kanyakumari in the south) is of drift-rift tectonism of Indian Plate since 167 Ma (i.e., after the breakup of eastern Gondwana) that cause the separation of India, Madagascar and Seychelles ($\sim$ 90 ma and $\sim$ 65 ma) [*Chatterjee et al.,* 2013; *Norton and Sclater,* 1979] along with magmatic plume activity. In the entirety west coast of India act as a passive margin and accelerate the voyage and collision of Indian Plate with the Eurasian plate (Himalayan Orogeny), which makes west coast of India, a unique place to explore tectonic features.

The present study area is bounded by Precambrian basement rocks in the east known as Southern Granulite Terrain (SGT), which are followed by a hiatus and overlie by Mesozoic dykes and Cenozoic sediments. Toward the west the continental shelf forms the Kerala-Konkan (KK) Basin, which is the sub-basin of Laccadive Basin (LB). LB dissected by Vishnu Fracture Zone (VFZ), the Laccadive-Chagose Ridges (LCR) [*Bhattacharya and Yatheesh,* 2015; *Gopala Rao et al.,* 2010], which occur on the west of the basin and act as a vital part of oblique rift valley [*Subrahmanyam and Chand,* 2006].

The Basement rocks i.e., SGT, is an amalgamation of Mesoarchecan to Neoproterozoic crustal blocks exposing mid-lower crustal rocks dissected by Palghat-Cauvery Shear System (includes Moyar-Bhavani, Palaghat-Cauvery and Attur shear zones) and Achankovil Shear Zone (ACSZ). These shear zones divide the southern part of SGT from north to south into three major crustal blocks know as Coorg, Madurai and Trivandrum [*Chetty et al.,* 2016; *Collins et al.,* 2014; *Santosh et al.,* 2009] (Figure 1). The marginal part of the west coast of India, is mostly controlled by three principal structural trends (Dharwar (NNW–SSE), Aravalli orogenies (NE–SW) and Narmada graben (E–W), which pageants a straight coastline, with the continental shelf width varying from 345 km off Daman in the north to 120 km off Goa and tapering to 60 km off Kochi to the south [*Faruque and Ramachandran,* 2014].

During the Late Mesozoic the region experienced thermal regime associated with the breakup of Gond-

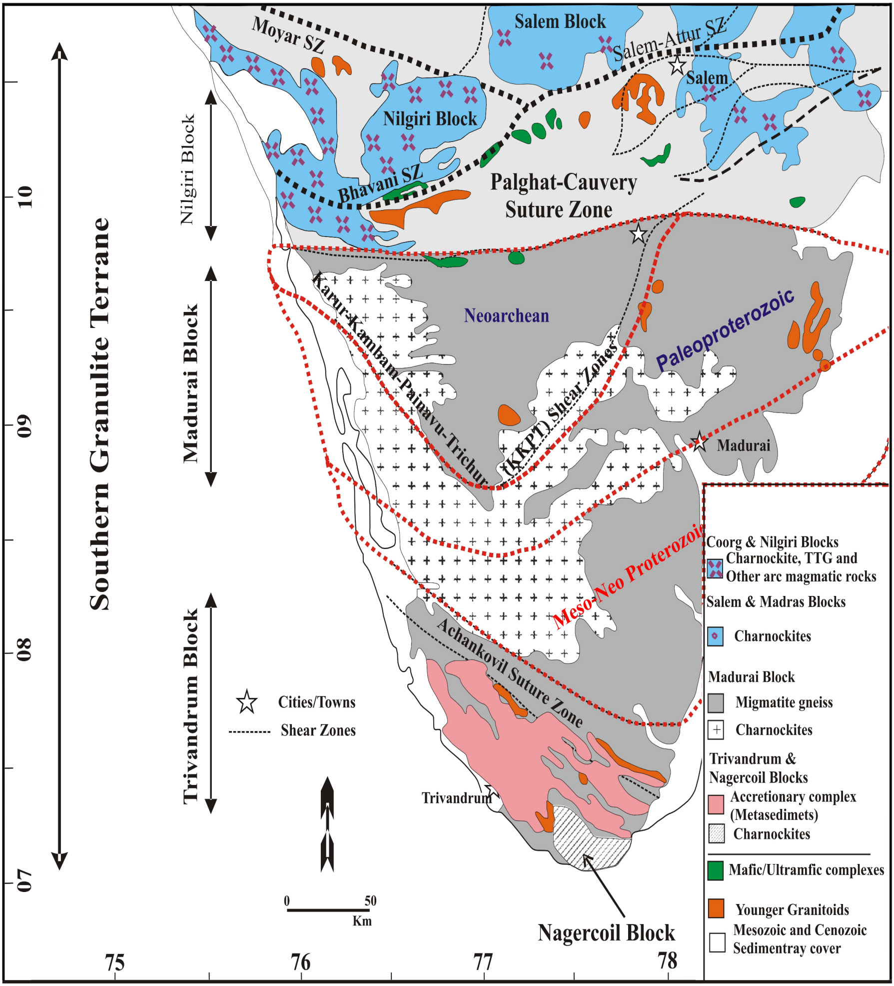
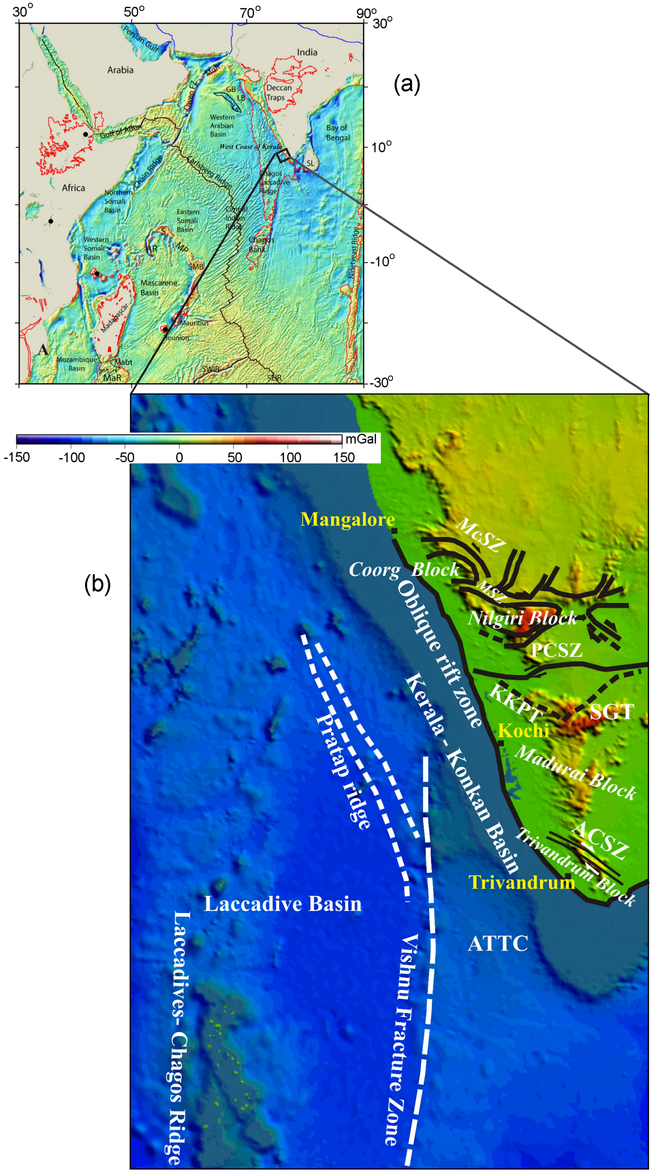


Figure 1. Generalized tectonic framework of Southern India illustrating major crustal blocks and intervening shear/suture zones (after [*Collins et al.*, 2014; *Santosh et al.*, 2015, 2017].

wana resulted pericratonic continental fracturing and emplacement of basaltic dykes in three major episodes (~ 145 Ma, $\sim 90-85$ Ma and $\sim 70-65$ Ma), which made different stage of west coast evolution [*Ajayakumar et al.,* 2017; *Karunakaran and Mahadevan,* 1971; *Radhakrishna,* 1999]. The KK Basin, located on the continental shelf part has evolved by separation of continental masses from western margin of India and suggest it as an oceanic crust between LCR and KK shelf [*Das,* 2013]. LCR is the most significant topographic feature with several islands observed along its strike length. This ridge is recognized as a hot spot trace related to the Reunion plume [*Duncan and Storey,* 1992].

Furthermore, Kerala deep-water basin, is bounded by two prominent north-south oriented fracture zones of the Indian Ocean, known as Vishnu fracture zone (in the west) and Indrani fracture zone (in the east). VFZ, a transform fault which cause the separation of Seychelles from India and it extends from the Kerala shelf to the Carlsberg-Ridge, over a length of more than 2500 km [*Bastia et al.,* 2010; *Bhattacharya and Yatheesh,* 2015] (Figure 2). In addition to all tectonic features mentioned above, the Geoidal gravitational low observed along the study area makes it a unique place.



(a)
(b)
30°
50°
70°
90°
30°
10°
-10°
-30°
Persian Gulf
India
Arabia
Deccan Traps
Owen FZ
GB
LB
Western Arabian Basin
West Coast of Kerala
Bay of Bengal
SL
Gulf of Aden
Carlsberg Ridge
Chain Ridge
Chagos Laccadive Ridge
Africa
Northern Somali Basin
Eastern Somali Basin
Central Indian Ridge
Chagos Bank
Ninetyeast Ridge
Western Somali Basin
AR
MP
SMB
Mascarene Basin
Madagascar
Mauritius
Reunion
A
Mozambique Basin
Mabt
MaR
SWIR
SEIR
mGal
-150
-100
-50
0
50
100
150
Mangalore
McSZ
Coorg Block
MSZ
Nilgiri Block
PCSZ
Oblique rift zone
Kerala - Konkan Basin
KKPT
SGT
Kochi
Madurai Block
Pratap ridge
ACSZ
Trivandrum Block
Trivandrum
Laccadive Basin
ATTC
Laccadives- Chagos Ridge
Vishnu Fracture Zone

Figure 2. (a) – Satellite gravity of the western Indian Ocean showing the various tectonic elements referred in the present study. (Modified after *Sandwell and Smith* [2009] and *Ramana et al.* [2015]. (b) – DEM of West Coast of Kerala (from Topex data) with major Shear Zones (McSZ: Mercara Shear Zone, MSZ: Moyar Shear Zone, PCSZ: Palaghat–Cauvery Shear Zone, KKPT: Karur–Kamabam–Painavu–Trichur, ACSZ: Achankovil Shear Zone) and major submarine features like Laccadivine-Chagos Ridge (LCR) Laccadive Basin, Allapey-Trivandrum Terrace Complex (ATTC), Pratap Ridge, Vishnu feracture Zone (VFZ) (Modified after [*Collins et al.,* 2014; *Santosh et al.,* 2015, 2017; *Yatheesh et al.* [2013].

3. Material and Methods

GIS-based hypsmometric data is used extensively on land for detecting streams and channels [*Belknap and Naiman,* 1998; *Imaki and Beechie,* 2008]. It became an integral part of hydrologic studies due to the spatial character and its control on the hydrological processes [*Vieux,* 2001]. In the current study, an effort has been made to find the credibility of GIS on deep sea channels in the Arabian Sea along with the global seafloor topography datasets. To scrupulously constrain the submarine drainage patterns, data from http://topex.ucsd.edu/cgi-bin /get_data.cgi has been used, that pertains to v16.1 of the GBM data compiled by [*Sandwell and Smith,* 1997]. Data was downloaded in .xyz format and converted into a Digital Bathymetric Model (DBM). Further, Gravity data (mGal) has been used for the validation of topographic data. It was generated at a grid resolution of 1.7×1.7 km. High resolution elevation data were collected from LiDAR, SONAR etc., which are specifically suited for managing, processing and integration of three dimensional data (Childs, C., 2011, Terrain Datasets: The Top 10 Reasons to Use Them. Arc User Online, Spring Edition).

4. Result and Discussions

Availability of satellite-derived high resolution Digital Elevation model (DEM) and spatial information technologies has gained rapid attention especially on morphotectonic analysis using geomorphic indices [*Ferraris et al.,* 2012; *Reinfeld et al.,* 2004]. DEM is the best digital tool to automate the morphological characterisation of drainages, their area of influence and hypsometric parameters [*Rahman et al.,* 2010]. *O'Callaghan and Mark* [1984] introduced the computation for DEM pixels based on flow routing model refered as D8 algorithm. Later, *Jensen and Domigree* [1988] has modified it by omitting the sink/depression. It is noted that omission of depressions/sink have a positive influence on the enhancement of the quality of elevation models [*Lin et al.,* 2008]. These sinks may exist as single pixels or alternatively, as a group of multiple pixels with values lesser than all the pixels surrounding them. The process to fill up these sinks may be direct or iterative in nature depending on the number of pixels involved. The DBM generated for the study area, has been corrected for erroneous depressions.

Binary raster network denoting drainage has been deduced from flow accumulation and ordering of drainages has been implemented by methods of [*Horton,* 1945; *Shreve,* 1966; *Strahler,* 1952]. After a cogitation of the channels within their network, basins were also delineated based on channel flow direction and order. Figure 3 and Table 1 are created by adding different threshold values (500, 250, 100 and 50) for the better understanding of the drainage developments. Major sediment distribution along the west coast off Kerala is ranging from terrigenious to carbonaceous sand and clay [*Rao and Wagle,* 1997] (Figure 4). Based on drainage pattern and structural control three zones are selected for detailed study (Figure 5).

Table 1. Drainage extracted using different threshold value and its ordering

Sl No	Stream Threshold Value	Total Streams	# Land (Unclassified) Channels	# Ocean Channels	1st Order	2nd Order	3rd Order	4th Order
1	500	35	2	33	31	2	-	-
2	250	151	28	123	107	16	-	-
3	100	433	74	359	298	55	6	-
4	50	900	148	752	584	149	18	1

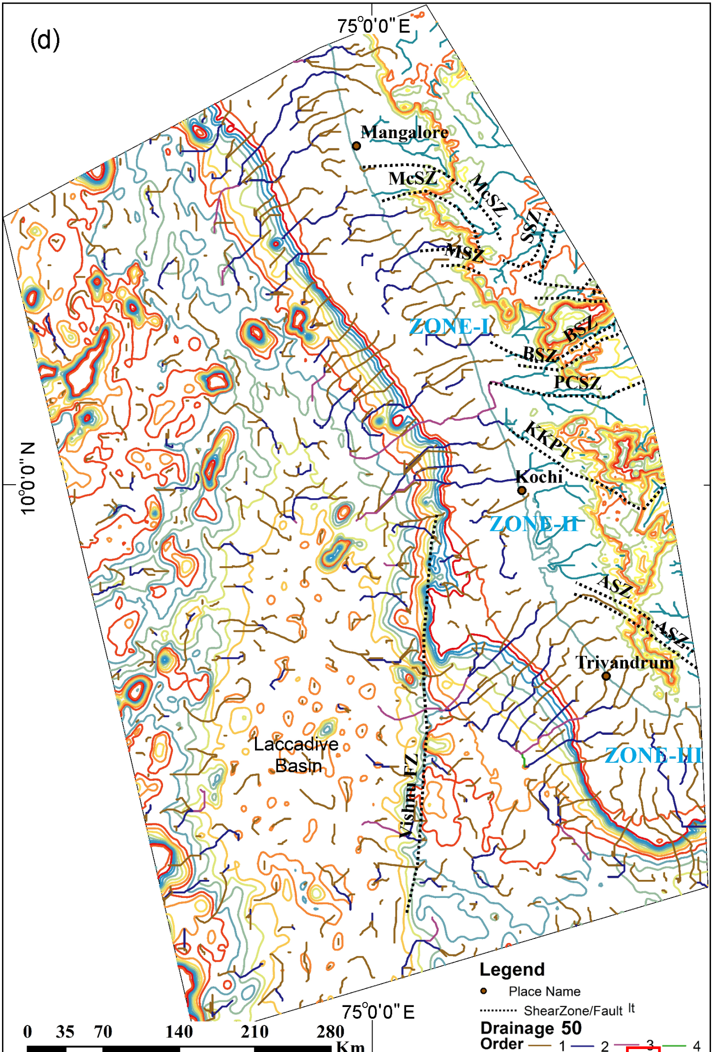


Figure 3. Drainage with thresholds values: a – 500, b – 250, c – 100, and d – 50 values. *Editorial note: To zoom selected image click on the corresponding number in red square, make one more click to return back.*

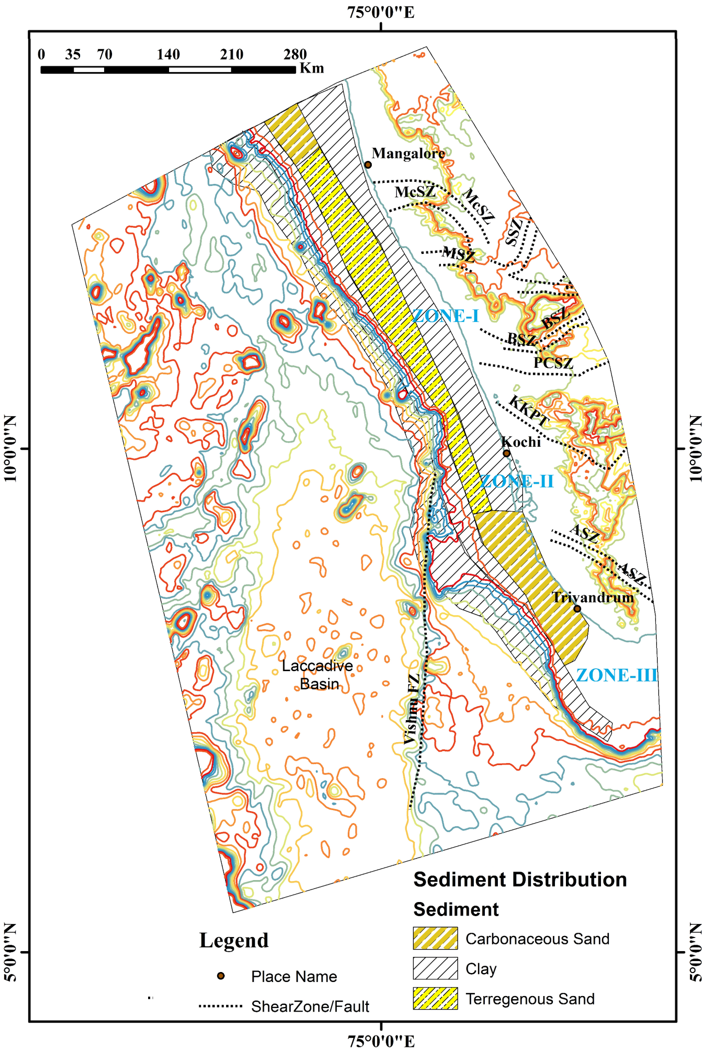


Figure 4. Sedimentary distribution of west coast of Kerala and exhibit classification of Zones I–III based on Major Shear Zones on land.

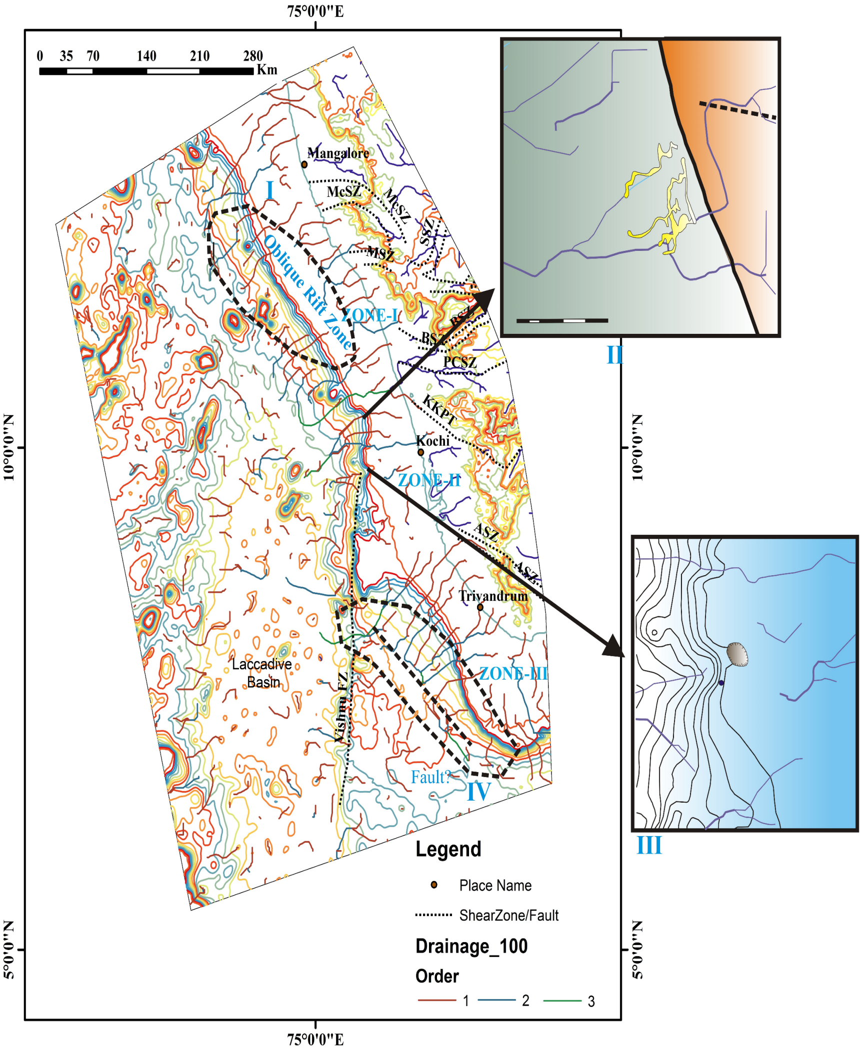


Figure 5. Major Features identified using topex/GBM data;features like submarine palaeochannels and impact craters are kept as inset.

4.1. Zone I

In Zone I, the continental area is bound by Mercara and Bhavani Shear Zones. The Continental shelf is wider and more open towards north with minor protuberances of positive heights at 1500 isobaths, which is a part of Pratap Ridge, a coast parallel running ridge (Figure 5 and profile A–A' of Figure 6). The submarine drainages are parallel and their Hortonian higher order [*Horton,* 1945] shows a tilting/sinuosity in the NNW and then towards the SSE. The sediment distribution in the inner shelf of Zone I is mainly of modern clayey silt and silty clay with high organic matter (low carbonate content) and with less heavy minerals. On the other hand, mid-shelf is uneven and outer shelf is commonly interrupted by shore-parallel ridges and reefs [*Faruque and Ramachandran,* 2014; *Rao and Wagle,* 1997].

Similar morphotectonic studies on land has been carried out by [*Vijith et al.,* 2015] in Mahe River, Northern Kerala. They observed that tilt in river mouth (in NNW and SSE) from head water, implies neotectonic activities. So the sinuosity observed on submarine drainage may be of shear zone extension. Furthermore, this observation has been exemplified by the magnetic studies of [*Gopala Rao et al.,* 2010; *Subrahmanyam and Chand,*

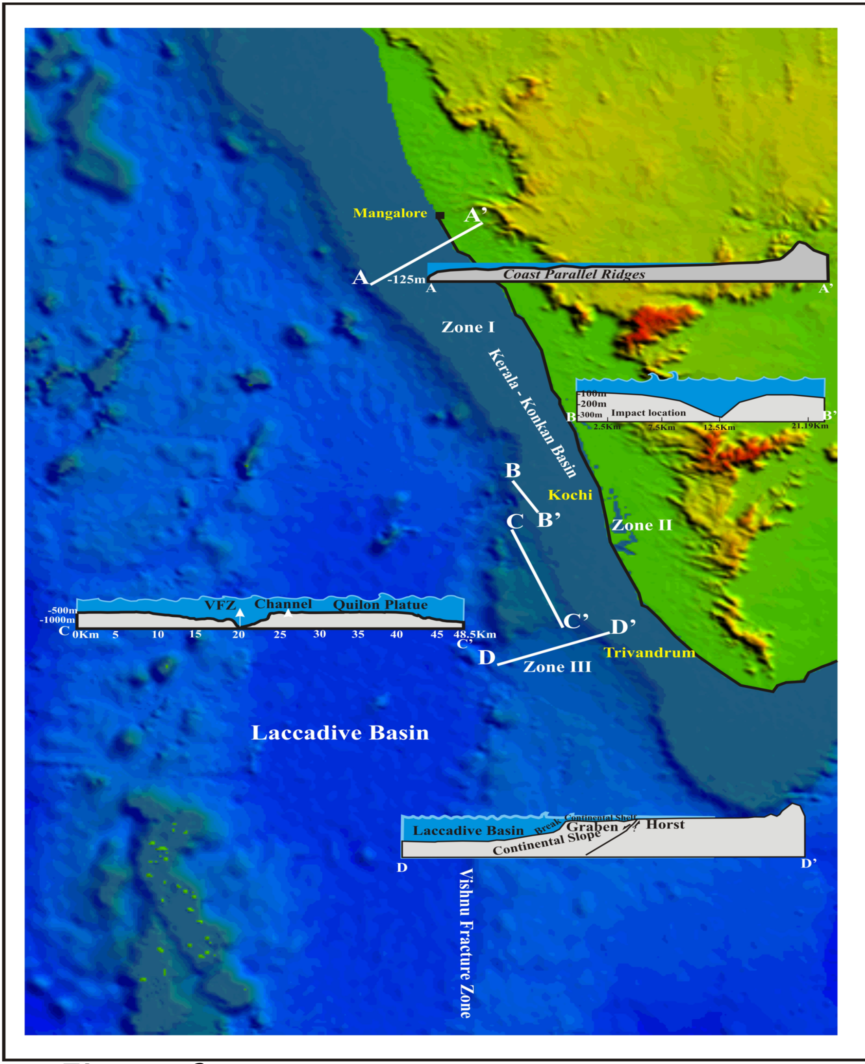


Figure 6. Maps with profiles showing major tectonic and morphologoical features in Zones I–III (A–A', B–B', C–C', and D–D').

2006; *Subrahmanyam et al.,* 1993] on the extension of Palaghat Cauvery Lineament (mega lineament).

4.2. Zone II

Central part of the study area, i.e., Zone II, belongs to Madhurai Block which is bounded by E–W running Palaghat Cauvery shear zone (PCSZ) in the North and South by Achankovil Shear Zone (ACSZ) of Pan African Orogeny with the NW–SE trend. Moreover, the continental part of the area includes the Western Ghats major break, known as Palaghat Gap along with the most active Karur–Kamabam–Painavu–Trichur (KKPT) lineament [*Rajendran and Rajendran,* 1996; *Singh,* 2016]. Satellite altimetry data has given signatures of the mount like features at 2000 m isobath; with submarine dendritic drainage pattern and a deep cut valley off Ponnani. *Faruque and Ramachandran* [2014] revealed that these deep cut valleys are the structural continuity of Palaghat Gap. Two major submerged paleo channels observed south off Ponnani. These paleo channels are supported by prominent occurrence of sand [*Rao et al.,* 2003; *Sukumaran et al.,* 2010] and existence of paleo channels [*Hashimi et al.,* 1995; *Shareef et al.,* 2015] (Figure 4 and Figure 5).

Furthermore, most rivers in the central part of Kerala show highly sinuous nature and asymmetric basin characteristics which indirectly point towards the planform changes of the river and watershed as a whole in response to the neotectonic activities in KKPT. Recent studies indicate that, minor tremors are occurring with KKPT, suggesting a significant tectonic activity [*Ajayakumar et al.,* 2017; *Dhanya and Renoy,* 2015; *Girish Gopinath et al.,* 2016; *Rajendran and Rajendran,* 1996].

An isolated circular depression observed south off Kochi (Figure 5 and profile B–B' of Figure 6). *Pillay et al.* [2016] marked this feature as an impact crater. Moreover, coast parallel isobaths in Zone I (NNW–SSE) show a sudden shift in Zone II (NNE–SSW), which makes an escarpment in the west of Quilon Plateau (QP). This change in direction of isobaths may be of fault. Similar observation was made by *Yatheesh et al.* [2013] and *Nathaniel* [2013] and inferred as landward extension of the VFZ, whose expression continues southward into the Central Indian Basin. Recent studies by *Unnikrishnan et al.* [2017] has observed that VFZ is a crustal scale feature and plays a significant role on the sedimentation pattern on either side (east and west) of the fracture zone.

Furthermore, step like features, similar to Horst and Graben has also been identified in Zone II of profile C–C' of Figure 6.

4.3. Zone III

The southern part of the study area belongs to the Trivandrum block, which lies below the ACSZ. The continental shelf in this part narrows down and becomes 50 km at off Trivandrum. Moreover, Zone III is important in global perspective due to the gravitational geoidal anomaly. Three set of drainages occurring south of QP are parallel to sub parallel in nature, which meets its higher order streams in right angle having a trend of NW–SE. (Figure 5, profile D–D' of Figure 6). The southern part of QP has a gentle slope with step-like features/terraces. These terraces are part of Allepy Trivandrum Terrace Complexes (ATTC), [*Biswas,* 1987; *Yatheesh et al.,* 2006, 2013]. It is inferred that these terraces are rifted and sheared segment of pre-drift plate boundary related to India–Madagascar separation during 86.5 Ma.

4.4. Satellite Derived Gravity Data

The lithological contrast is clearly visible in gravity data downloaded from satellite altimetry data (Figure 7). In Figure 7, ridge-like features identified in Zone I of study area similar to the bathymetric studies. Earlier studies imply that these structural features are deep seated faults with rifted fragment of Western continental margin of India formed during the north ward movement and during the Paleogene, these ridges exposed to subareal erosion create flat top mounts and in the Neogene it has been submerged, [*Gopala Rao et al.,* 2010; *Rao and Wagle,* 1997; *Ramana et al.,* 2015].

In Zone II we observed that the gravity changes rapidly and it overlaps very well with early identified VFZ. Furthermore, gravity data clearly shows the concealed lithology and Escarpment in QP.

In Zone III, negative gravity anomaly has been observed; [*Rao et al.,* 2014] described this negative geoidal anomaly towards south of Indian Continent as Indian Ocean Geoid Low. Moreover, we observed gravitational value in sigmoidal shape with the same value as in Trivandrum block in the south of India. So we are proposing that the sigmoidal portion in Zone III may be of the submerged part of continental crust of the

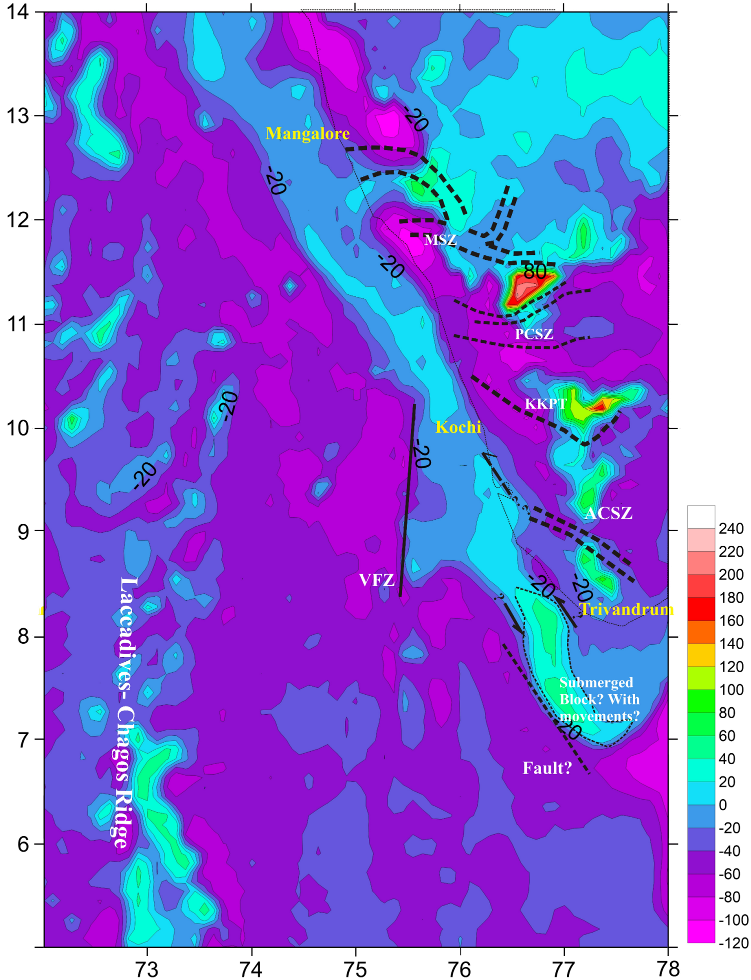


Figure 7. Satellite derived Gravity map (from topex) with inferred faults and submerged continental crust/Trivandrum block?. The Sigmoidal shape of the submerged portion indicate major tectonic movement. The probable direction of movement of submerged block is also marked.

Trivandrum block. This gravity data also proves the lithological contrast and possibility of fault/lineament which runs parallel to ACSZ and this observation is very well supported by [*Rao et al.,* 2017].

4.5. Bathymetric Profiling From North to South and 3D Modelling

The bathymetric profiles from N–S exemplifies the major structural features described in Zones (I–III) for regional understanding of the west coast off Kerala (Figure 8 WCP-1 to 7). The Host and graben structures are magnified as step-like features in profiles. In Figure 9 and Figure 10 an attempt has been made to integrate data through vertical stacking of satellite derived GBM and Gravity data. It shows morphotectonic and neotectonic features of the west coast passive margin on a regional scale.

5. Conclusions

Transition from oceanic to continental crust is structurally complex and is often obscured by thick layers of sediment, with these sediment layers being of con-

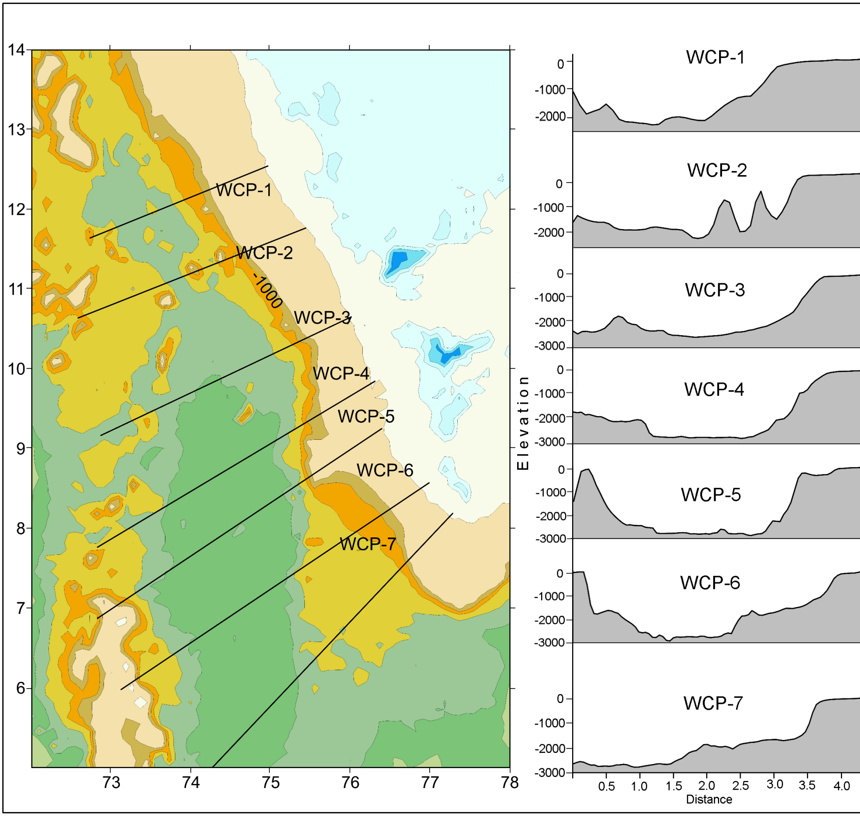


Figure 8. DBM map along with profiles along the west coast off Kerala.

trasting composition and density. To understand the morphotectonic setup of land and sea areas an integrated approach in analysis of geological, geophysical and spatial data can be used. Higher resolution satel-

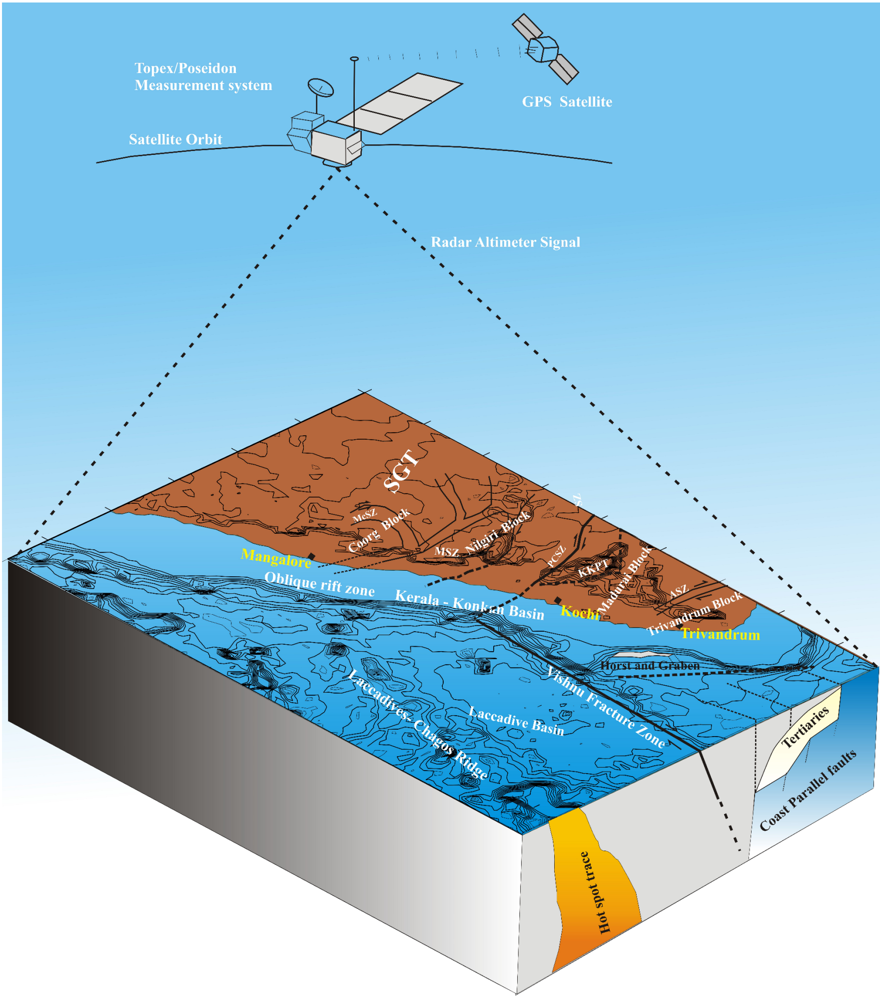


Figure 9. Three Dimensional 3D model of West Coast India with major tectonic features derived from GBM data.

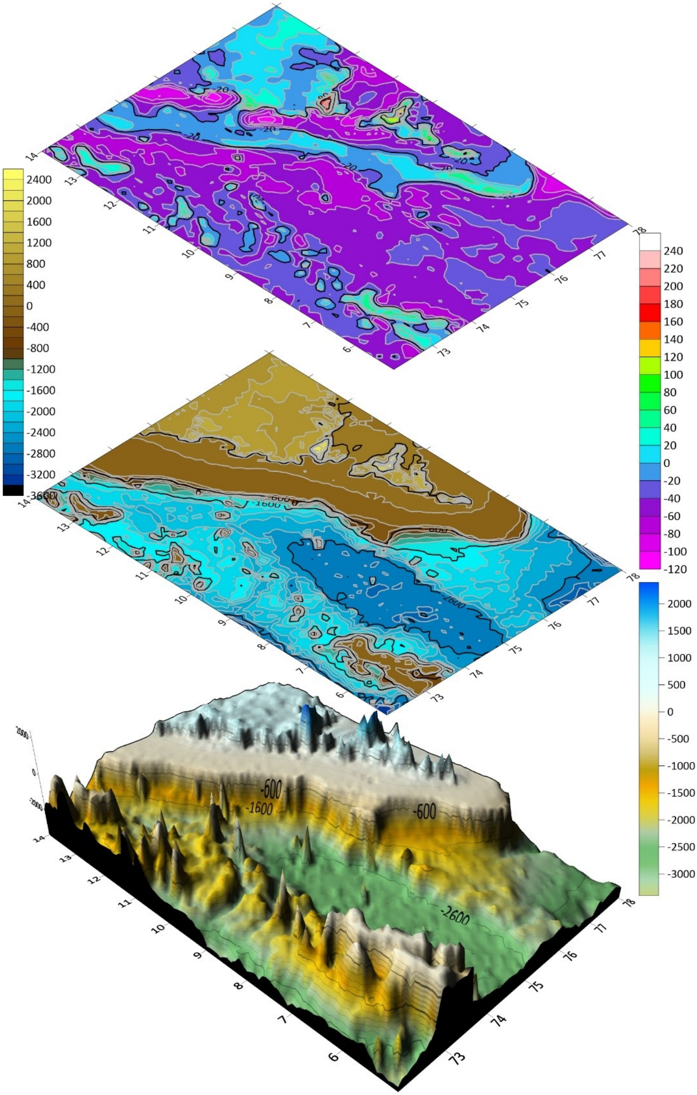


Figure 10. An Integrated map of gravity and bathymetry(3D & 2D) along West Coast off Kerala.

lite altimetry and gravity data along the west coast off Kerala has revealed many submarine morphotectonic features and its relation with the land. It serves as an important tool for the identification of neotectonic activities in and along the passive margin of the west coast off Kerala (Zone I, Zone II and Zone III). Other significant features like impact crater, submerged terraces etc. have also been observed using this technique. The morphotectonic evolution of drainage basins is a reliable indicator of tectonically reactivated strain zones, which helps to study submarine landslides and seismoturbidites.

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