Hydrocarbon Exploration in Sub-Basalt Basins around Peninsular India*

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Abstract

In peninsular geological setting, the Phanerozoic sedimentary sequences are interlayered with Cretaceous basaltic flows. To obtain stratigraphic and structural information below these volcanics has always been a challenge. This study enumerates an approach where remote sensing, magnetic, seismic, and drill hole data sets are integrated. Basement faults and their nature have been established by satellite imagery, where corresponding lineament zones are identified. These faults have been confirmed by magnetic data sets; define basement blocks, and separate different sub- basaltic basins. Vertical gradient derivative has been particularly useful in mapping the dyke swarms, horst, and grabens. Seismic profiles generated by Pre-Stacking and Depth Migration (PSDM) and Pre-Stacking and Time Migration (PSTM) processing techniques have great potential in mapping the sediments below the basaltic units. The lithological logs from drill holes have provided point information, which not only confirmed the interpretation but also helped to extend sections in adjoining areas.

The study has further confirmed that the basaltic units are rift related and are not the product of hot spot activity. The thickness and number of individual units varies in different basins, however, in most of the basins, they are present from the beginning to the end of the Cretaceous period. These basaltic units are often prolific producers of hydrocarbons, particularly natural gas. The disposition of basaltic units has played a significant role in the movement and preferential accumulation of hydrocarbons, both in underlying Mesozoic and overlying Tertiary sequences. It has also been concluded that the basin forming and basin modifying tectonics, as well as volcanism has profound influence of prolonged extensional tectonics.

Introduction

Earlier it was impossible to explore hydrocarbons in sub-basalt basins, because no geological or geophysical methods could provide the required information. The petroliferous basins of peninsular India, such as Kaveri, Krishna-Godavari, Mahanadi, Barmer, Cambay, off-shore regions of Bombay, Saurashtra, and Kutch, are invariably having thick units of basalt, interlayered with sediments ranging from the beginning to the end of the Cretaceous period. Berger et al. (1983) logged basaltic units within the Mesozoic succession of several basins. Because of these problems the exploration and production was confined only to the overlying Tertiary sequence. To start the exploration activity within Mesozoic and older sediments, information is required about the thickness of sediments, their structural deposition as well as the thickness of basaltic units. Several major developments have taken place in the last three decades which have facilitated exploration within Mesozoic and older sediments. An integration of these developments with available methods has been quite encouraging and initial results are presented here. Our understanding of Cretaceous volcanics, concepts of basement tectonics, and data acquisition and processing have now made it possible to explore hydrocarbon in sub-basalt regions. True potential of magnetic, gravity, seismic, and remote sensing are also utilized to address the problems related to sub-basalt exploration.

Cretaceous Volcanics

The Cretaceous volcanic episode encompasses outpouring of basaltic lavas and emplacement of dyke swarms and igneous complexes. The basaltic lavas are sandwiched between older Mesozoic and younger Tertiary sequences(Misra and Misra, 2010) The distribution pattern of Cretaceous volcanics, has not only contributed to our understanding of their origin, but also opens enormous scope for hydrocarbon exploration in vast sub-basalt regions. Earlier, volcanics were known only from the land areas. Exploration in Cambay and other graben and rifts has brought out their presence below the Tertiary sequence. Drilling has established their presence in offshore regions. Furthermore, recent seismic surveys and drilling has shown that they form the floor of almost the entire Bay of Bengal and vast regions of Arabian Sea (Figure 1). On top of these volcanics an uninterrupted Tertiary sequence is identified (Arora and Misra, 2011 and Misra and Joshi, 2013) These interpretations have not only confirmed their lateral continuation from land areas to the oceanic regions, but also the entire succession of the underlying and overlying sediments (Figure 2).

The thickness pattern of Cretaceous volcanics varies greatly in different areas (Misra and Misra, 2010). The thickest pile of volcanics on land can be noted along the western face of the Sahyadri mountain ranges. In Kutch on-land, the thickness varies from 125 to 350 m while in the offshore region of Kutch, the thickness increases from north to south. Within Cambay Basin, the thickness increases from a few meters in the shoulder areas to nearly 2,500 m in the central part. The maximum thickness of >3,000 m is logged in the Ankaleshwar area, below the Tertiary sediments. This enormous thickness is believed by Misra (2008b) to be due to the compounding effect of subsidence in the intersectional area of the Narmada–Tapti tectonic zone and Cambay structure during outpouring of lava flows. Subsidence of over seven kilometers is attributed to the room created by the decompressional melting and effusion of

Cretaceous volcanics. A good amount of information about thickness patterns is available from the drilling data (Figure 3). These logs have also confirmed that the effusion of Cretaceous lava was in pulses and lasted for nearly 90 million years. The most pronounced pulse was however, just before the end of Cretaceous. Another unique observation is the volcanic units have very thick (several hundred meters) of fossil bearing sedimentary rocks interlayered with them. Seismic profiles from the offshore and oceanic areas have shown that the volcanics have rather uniform thickness, ranging between 350 m to 450 m. Proper estimation of thickness of volcanics is very significant in exploration of hydrocarbons in underlying Mesozoic rocks. It has also emerged that the pattern of volcanic eruption and emplacement of plugs and igneous complexes in offshore Saurashtra is quite similar to contiguous land areas. This necessitates proper mapping of dykes, plugs, and igneous complexes by aeromagnetic data, before drilling in offshore regions of Saurashtra and Kutch. Eruption and transportation of lava has also intrigued the geologists. Misra (2002) described the presence of an arterial system by mapping the remnants of lava channels and tubes (Figure 4). Satellite imagery (Figure 5) has helped identification of volcanic craters.

Regarding the origin of the Cretaceous volcanics, an idea was advocated nearly four decades ago, that they have erupted due to a stationary hot spot or mantle plume below the northerly moving Indian plate. The implications of this idea were detrimental for the exploration of hydrocarbon. In such a geological setting where approximately 60 km of thick lithosphere is melting, the heat would have vaporized the hydrocarbons. During the last two decades, it has been established that the volcanism took place mainly along the existing rifts and grabens, more rampant in their intersectional regions (Misra, 2007; Misra, 2008a). Drilling done in different sedimentary basins has also established several pulses that are interlayered with sediments. It is highly improbable to have undisturbed volcano- sedimentary successions of 90 million years above a hot spot or mantle plume. Furthermore, no trail of the hot spot is identified either in land areas or offshore regions. On the contrary, uninterrupted and undeformed sequences across the supposed trail do not support the hot spot idea.

The unique thing is that the Cretaceous volcanics are very good reservoir rocks and are often prolific producers of hydrocarbons. The subsurface Rajol Formation of the Krishna-Godavari Basin represents the Rajahmundry volcanics on the surface. The present disposition is due to faulting along the East Coast Fault Zone. Furthermore, prolific gas fields of Bageshwari in Barmer, Ingoli, and Padhra in the Cambay Basin are producing from the volcanic Cretaceous units. These hydrocarbons are produced from the primary porosity of the rocks due to presence of vesicles and cavities, secondary porosity and permeability due to jointing developed during cooling and subsequent fracturing. It has also been established from the field studies (Misra, 2005) that these volcanics never had very high temperature and fossilized tree trunks by the basaltic rocks are present (Figure 6).

It was earlier visualized that the Cretaceous volcanics are all horizontally disposed. Keeping this view all explorations strategies were planned for Tertiary as well as Mesozoic hydrocarbons. The detailed mapping (Misra,1981; Misra, 1999), however, has established that there are regional dips, more pronounced in the early volcanic sequences (Figure 7). In the Kutch area, they are dipping with different amounts in various sectors. In the southern part, dips are in the southerly direction. In the central and northern parts the dips are either north or east. In the western part they are nearly horizontal (Figure 8). These dips would have certainly influenced the thickness patterns, as well as the preferential accumulation of hydrocarbons.

Methodology

Very significant developments in the concept of basement tectonics have taken place in the last two deccades. The basin forming tectonics in continental areas is largely controlled by nearly vertical faults originting in the basement. Subsidence of basement blocks along these faults is directy related to the geological history of basins. Innumerable case studies are available to demonstrate the develpoment of grabens and rifts and their tectonic evolution. Peninsular India is transected by several major grabens and rifts such as Pranhita- Godavari, Mahanadi, Damodar valley, Cambay, and Kutch. These major rifts are marked by continuing subsidence, host coal seams in land areas, and hydrocarbon pools in areas where they meet the ocean. Apart from major rifts, there are innumerable smaller rifts and grabens(Figure 9). It has been found in many areas that these basement faults can be mapped by satellite imagery, where they can be identified as lineaments (Misra, 2008a). The effect of basement tectonics is not only limited to basin forming but also preferential accumulation of hydrocarbons in structures developed in sedimentary sequence.

Availability of high resolution satellite imagery has opened an enormous scope of detailed geological mapping. Lineaments are one such example of improved understanding of structural geology and tectonics of the area. Mostly they represent subsurface faults and thus help in identification of horsts and grabens in covered areas. In western India, these lineaments are seen transecting from the exposed Achaean region and continue below the volcanics (Figure 10). Higher density of lineaments is found to be related with the margins of sedimentary basins (Misra, 2008a). Geomorphological anomalies are also important in understanding the features in the covered areas. These anomalies are more conspicuous in radar imagery, because it presents an enhanced view of relief. Remote sensing data products have been extremely useful in coastal regions in identifying important features. Lateral extension of features from land areas to offshore regions can also be established (Figure 11 and Figure 12).

It was earlier believed that aeromagnetic data will be of little use in knowing the geology of either volcanics or the sedimentary rocks below them. Therefore, the entire region covered by Cretaceous volcanics was not flown for aeromagnetic surveys. Recent collection of the aeromagnetic data has brought out intricate details of basement tectonics, disposition of sedimentary basins, dyke swarms, intrusive bodies, and the presence of horsts and grabens (Figure 13). In this figure, a large square shaped region is bounded by basement faults. It is interpreted that the Dharanghadhra – Wadhawan Basins located in the NE are extending into this region. Furthermore, the horsts and grabens on both the southern and western sides of Saurashtra are better defined in vertical gradient derivative. The western boundary of the Cambay structure is also very conspicuous because of the contrasting anomalies on either side (Figure 14). Preliminary results from Euler perception has shown that the basement depth can also be estimated (Figure 15). A change in the pattern of depth of basement very well matches with the rifts, hidden below the volcanics. Dykes which form an integral part of volcanism can very well be mapped by interpretation of satellite imagery and their disposition in covered areas by aeromagnetic data. Total field data of Kutch, Saurashtra, and the rest of the Gujarat region is combined to map the dyke swarms of the region. These dyke swarms represent areas which have been experiencing extensional tectonics. The dykes (Misra, 2008b) appear to have been emplaced during a very short duration. However, the tectonic forces have been active both before and after the emplacement activity.

Significant progress is made in seismic data processing techniques. The most significant ones are Pre-Stacking and Depth Mitigation (PSDM) and Pre-Stacking and Time Mitigation (PSTM) Dimri and Misra (2012). Data processed by these techniques have potential not only in estimating the thickness of volcanics, but also interpret the disposition of sediments below them (Figure 16).

Conclusions

The following conclusions have emerged from the study:

1. An integrated methodology using remote sensing, gravity, magnetic, and seismic data sets along with drill hole logs can be effectively utilized for exploration in sub-basalt regions.

2. High resolution radar along with other remote sensing data sets, vertical gradient and Euler depth perception in magnetic, and PSDM and PSTM processing of seismic data are the best options available.

3. Several basaltic units are interlayered with the entire Cretaceous sedimentary sequences in peninsular India. The disposition of uninterrupted and undeformed sequences within rifts and grabens, suggest that the volcanics are also related to rifting.

4. Cretaceous volcanics along with underlying and overlying sedimentary sequences laterally continue from land areas to oceanic regions where they cover almost the entire Bay of Bengal and nearly half of the Arabian Sea.

5. Innumerable evidences emerged during the study do not support hot-spot/mantle plume ideas. Dominant vertical tectonics both at basin forming and basin modifying stages have emerged from these studies.

6. The methodology developed can be utilized in other comparable areas where basalts are associated with the petroliferous basins.

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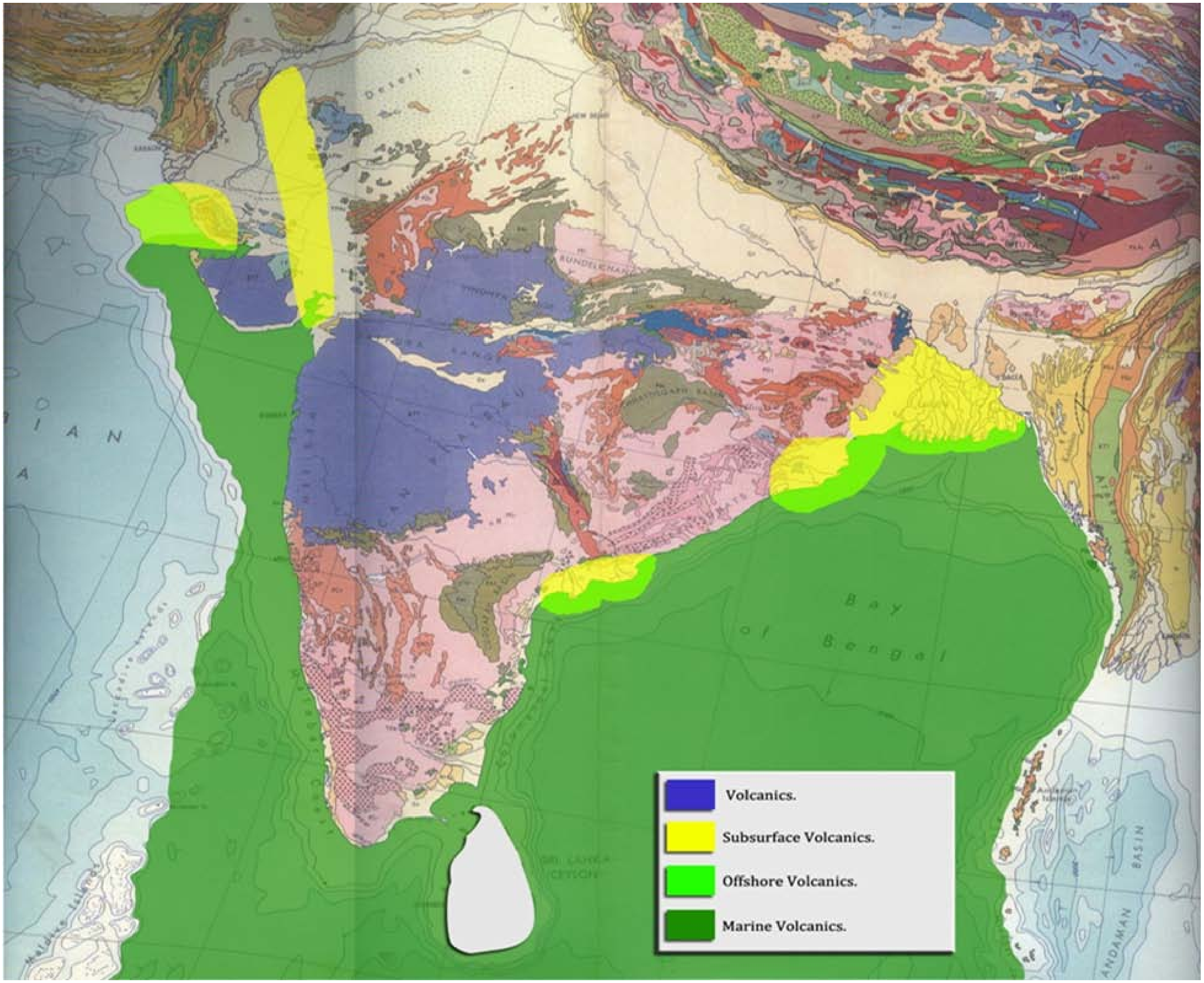

Figure 1. Geological map of peninsular India with adjoining oceanic regions. The distribution of Cretaceous volcanics on land, sub-surface, off-shore, and oceanic regions is shown.

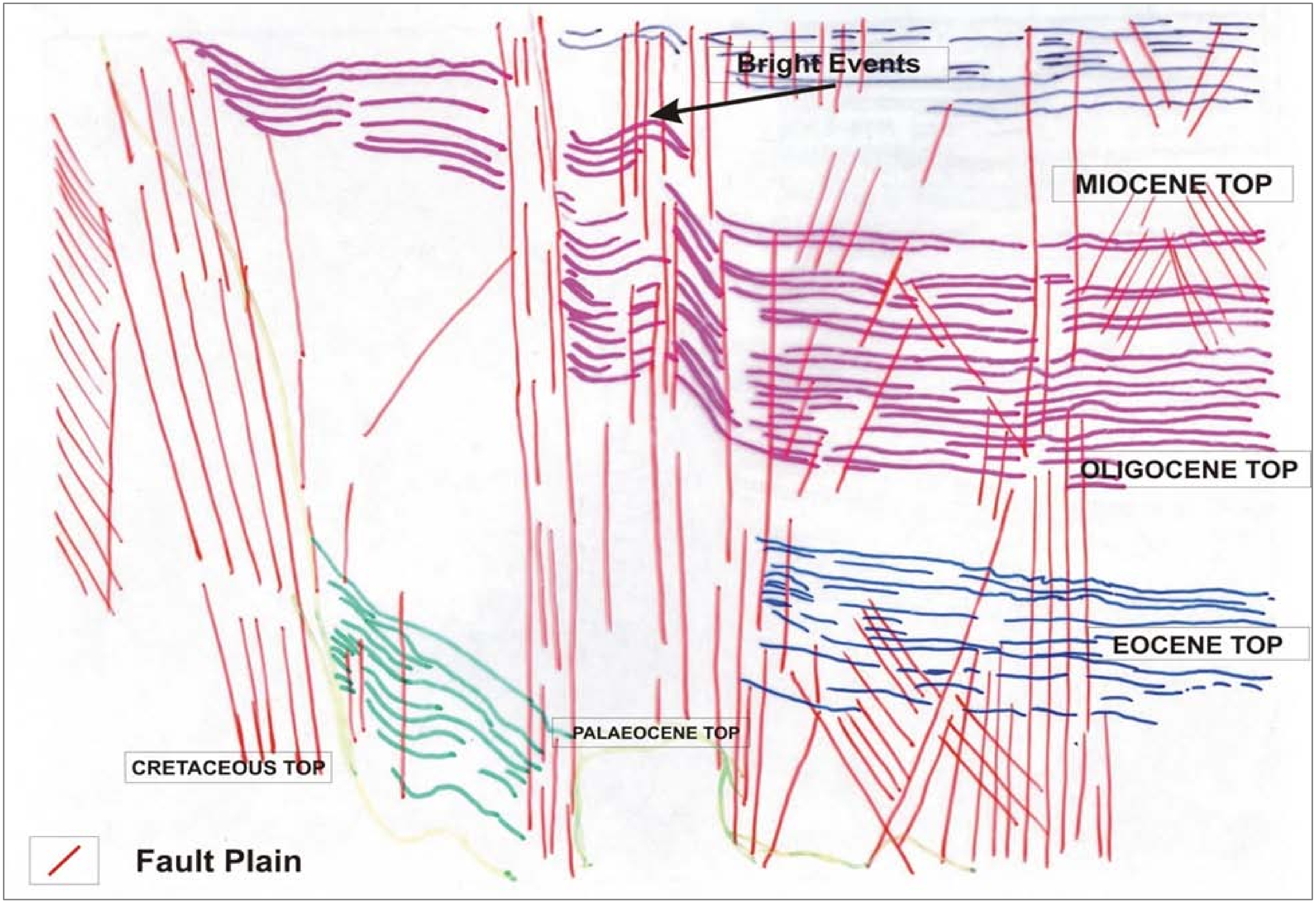

Figure 2. Lateral continuity of Cretaceous volcanics from land areas to oceanic region along with overlying sediments.

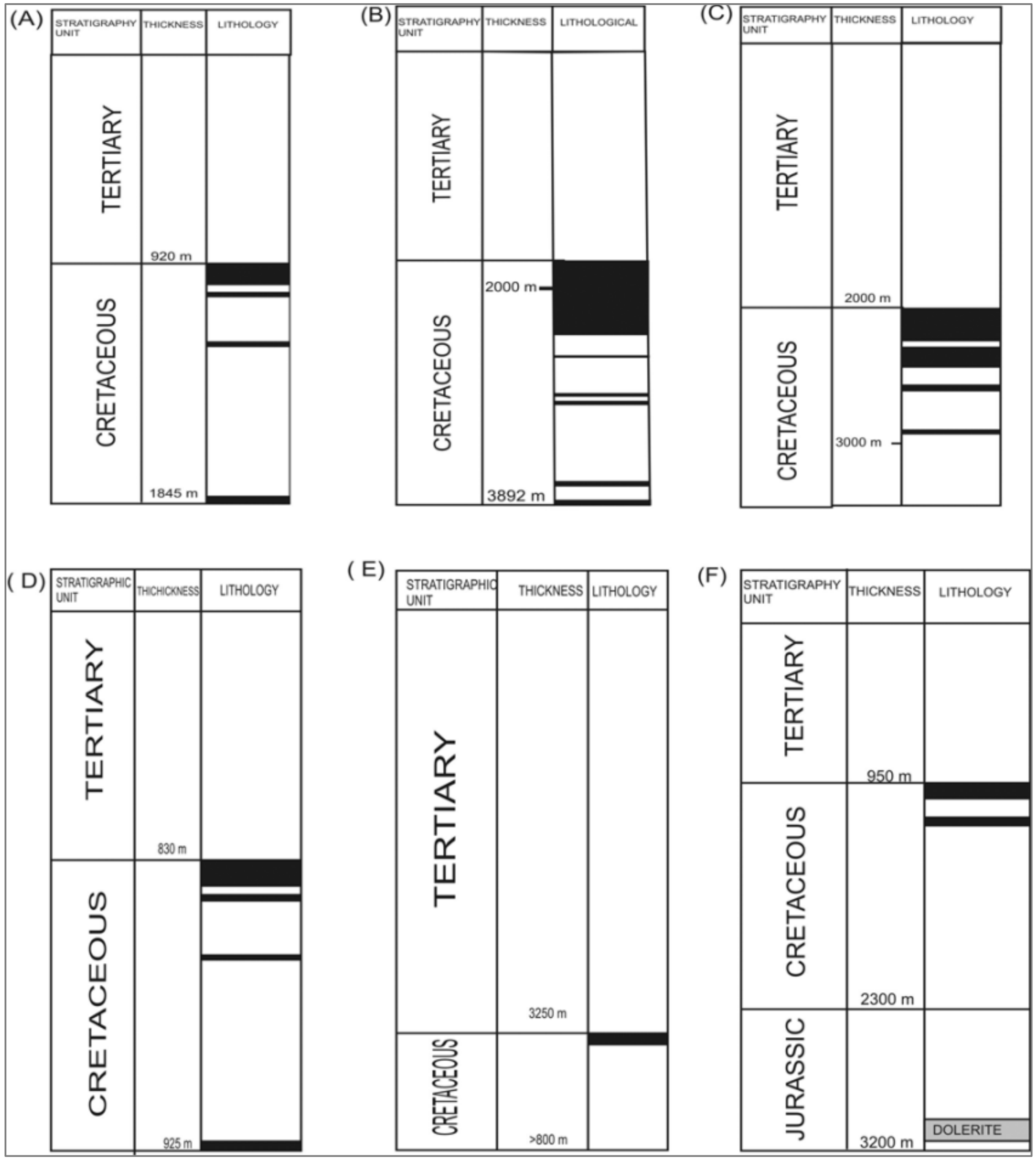

Figure 3. Drill hole logs depicting Cretaceous volcanics from different basins. This information is extracted from published logs by Berger et al., 1983. (A) Lakshdweep Basin, (B) Offshore Saurashtra, (C) Kutch offshore, (D) Krishna – Godavari Basin, (E) Kutch on-land.

Figure 4. Remnants of lava channels and tubes mapped north of Ahmednagar in western Maharashtra.

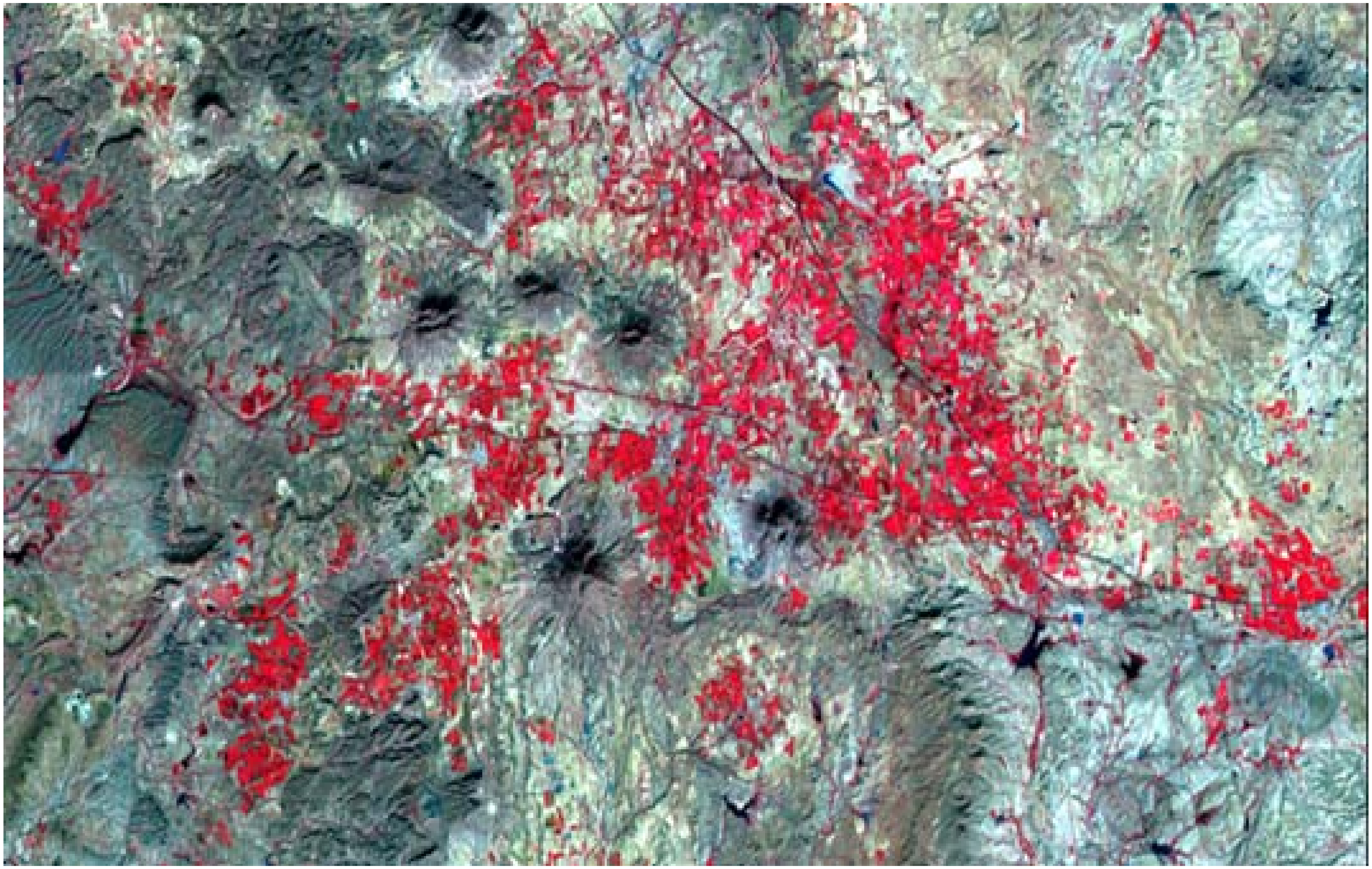

Figure 5. Satellite imagery of central Kutch, showing a number of volcanic craters.

Figure 6. Fossilized tree trunk by the basaltic lava is found near Omkareshwar in Madhya Pradesh. The fossilization by basalt and the cavity filling zeolites suggest low temperature of lavas would have been around 800°C.

Figure 7. Early sequence of felsic volcanics are dipping in southern Saurashtara. These felsic volcanics comprise a number of units of rhyolite (light colored) and obsidian (dark colored).

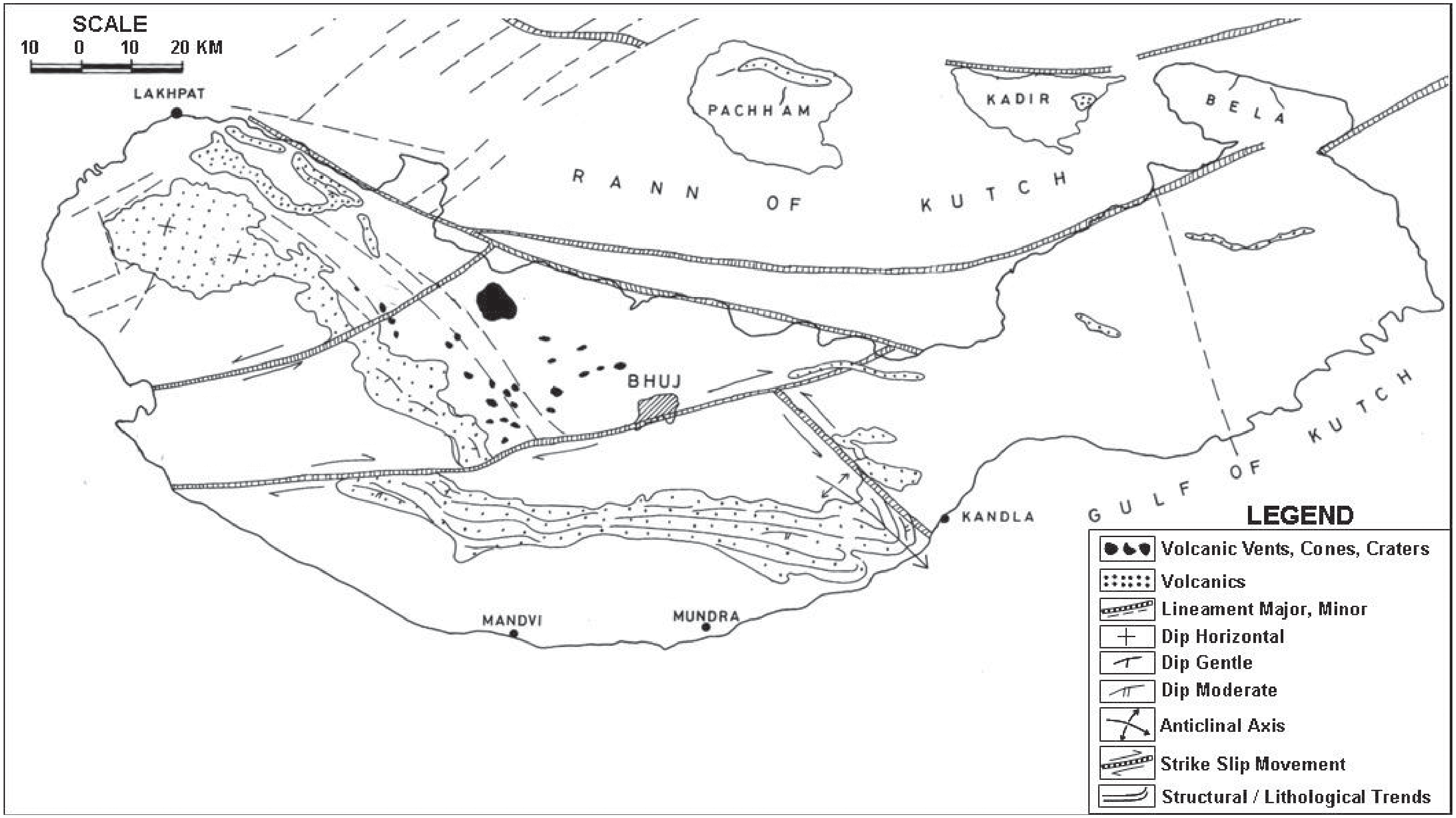

Figure 8. Image interpretation map of the Kutch region. The disposition of major faults and volcanics is very interesting. In the western block the volcanics are horizontal, in the central block they are gently dipping in a SW direction, and in the eastern block they have moderate dips in a southerly and southeasterly direction.

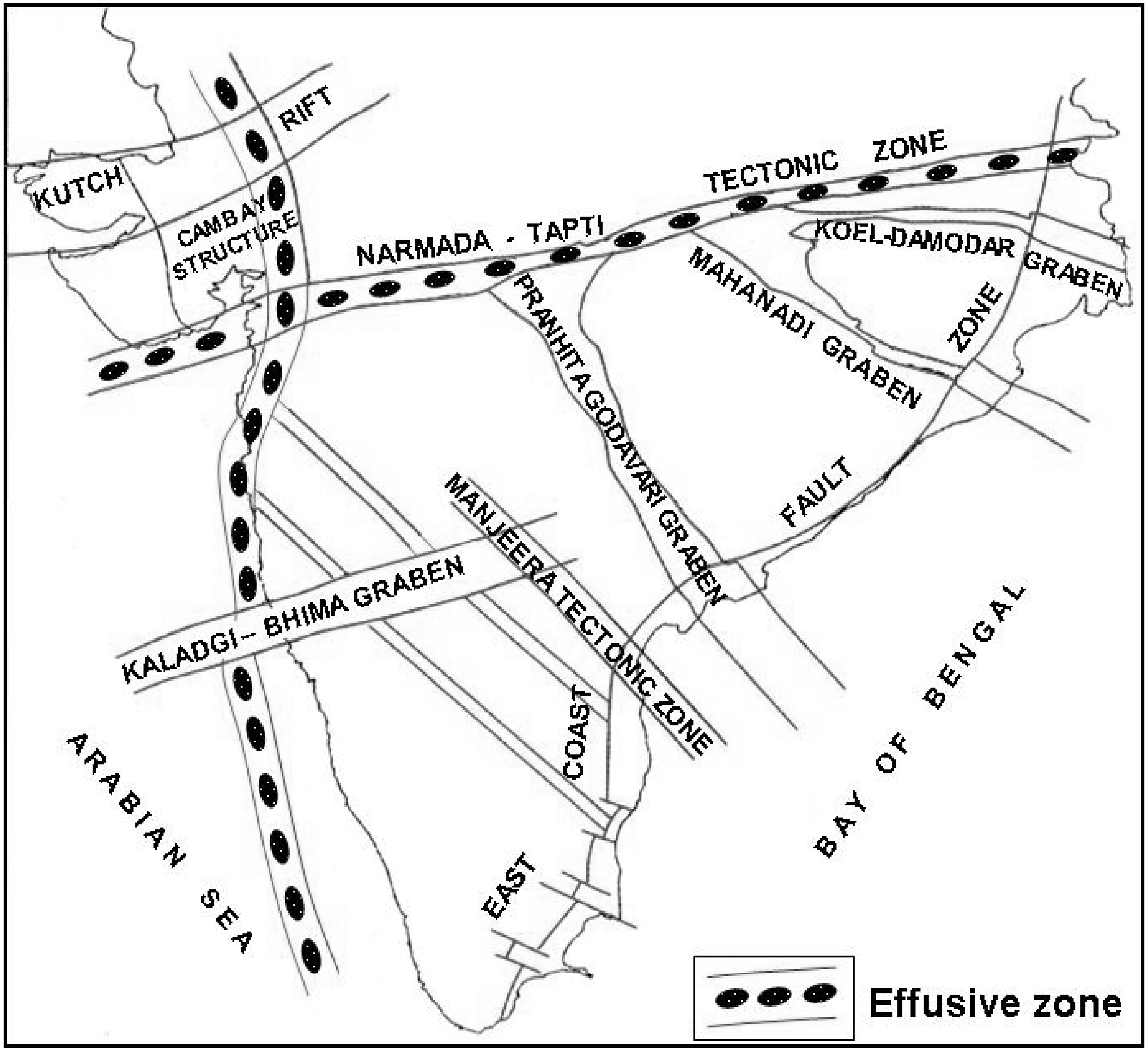

Figure 9. Outline map of peninsular India showing rifts, grabens, and tectonic zones. Prolonged subsidence due to extensional tectonics is recorded along them. In land areas, they have thick coal seams of the Gondwana period, while in coastal regions they have off-shore petroliferous basins.

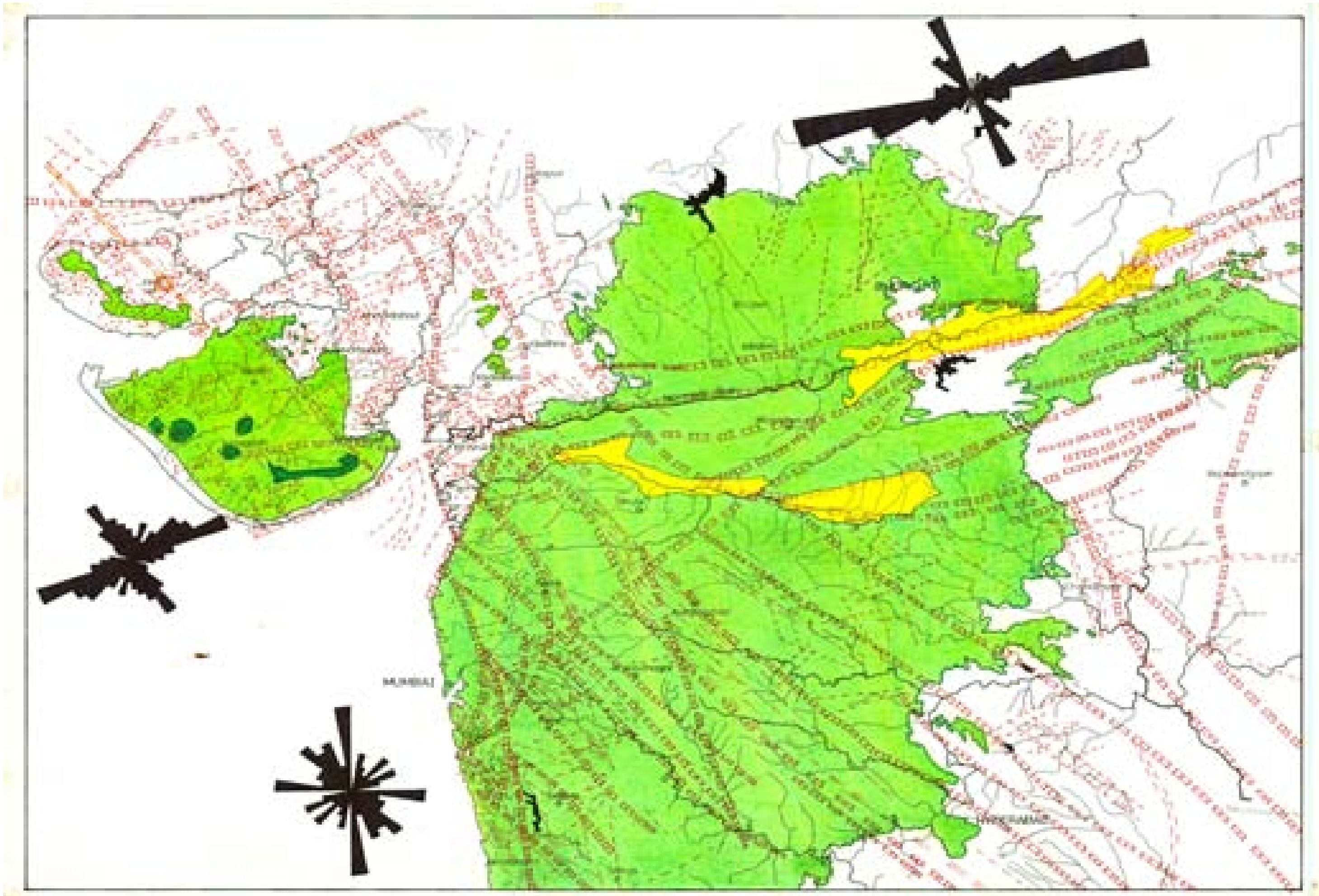

Figure 10. Map of peninsular India depicting the distribution of satellite lineaments. These lineaments are parallel to major tectonic features suggesting their tectonic origin. Lineaments can also be seen continuing from the Achaean basement to the region covered by volcanics.

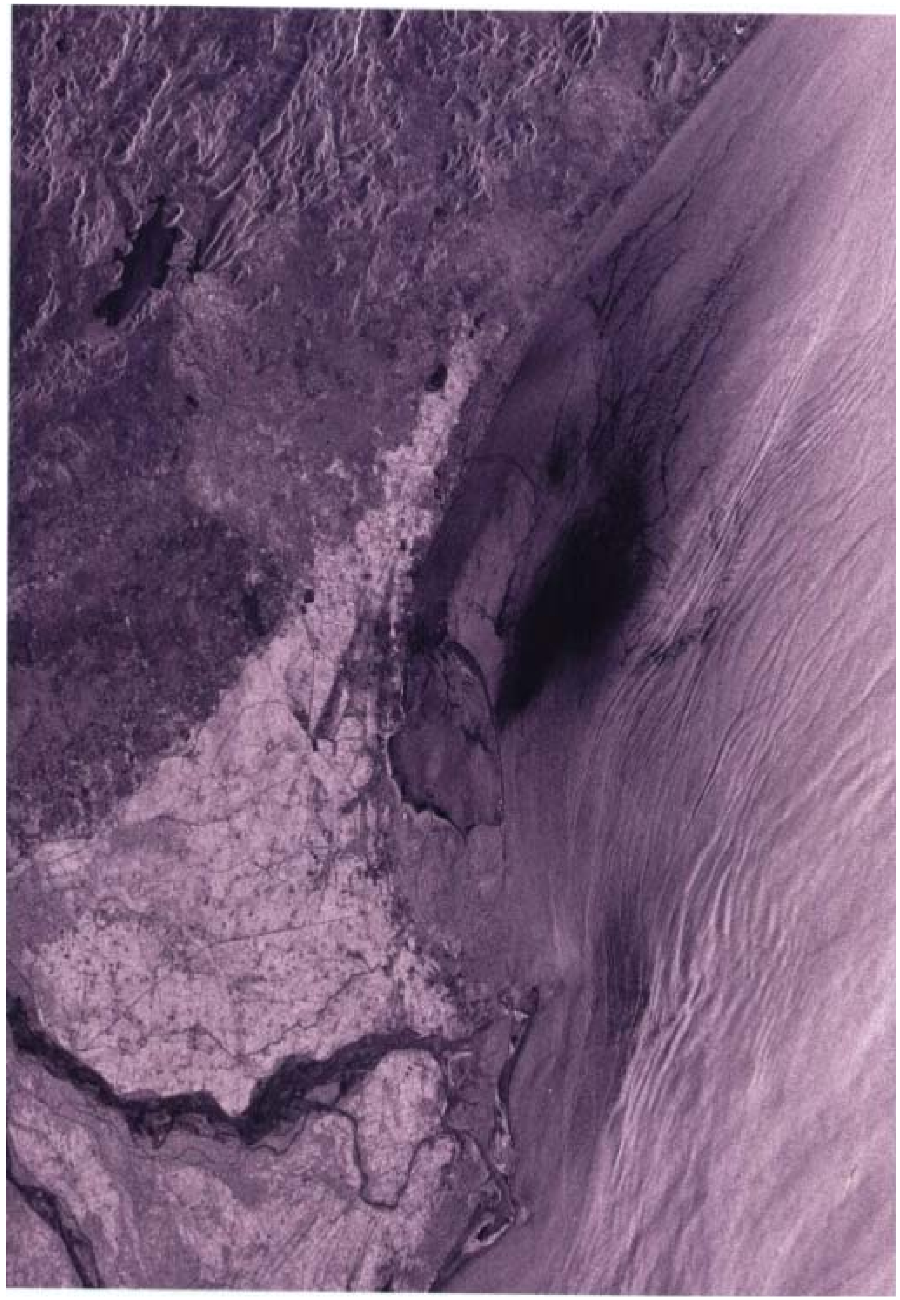

Figure 11. European Radar Satellite Imagery of the upper part of Krishna- Godavari Basin.

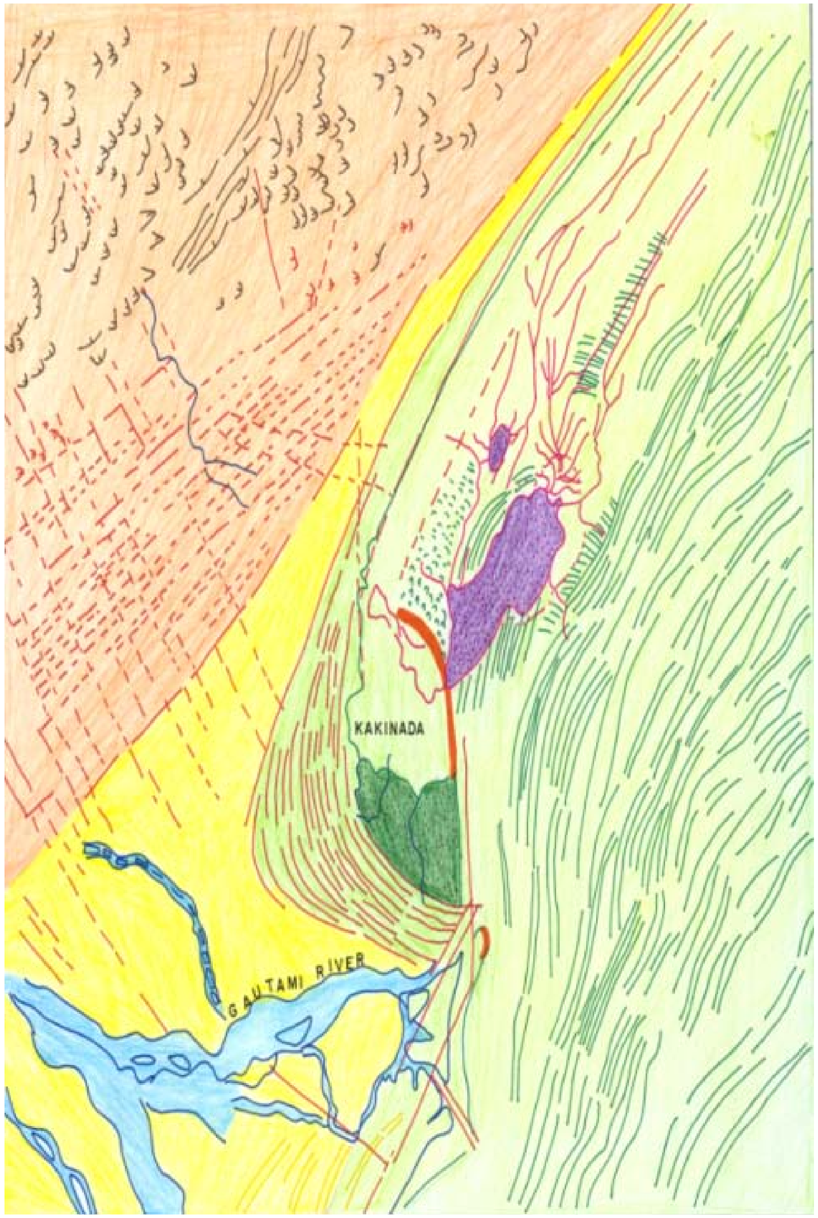

Figure 12. Interpretation shows that in oceanic areas, approaching waves along with their diffraction and refraction pattern can be seen due to surface roughness of the oceanic water. A large dark area indicates the absence of waves and can be interpreted as the deeper part of the basin related to continuing subsidence. A number of streams, having dark tone can also be seen opening into this subsiding basin.

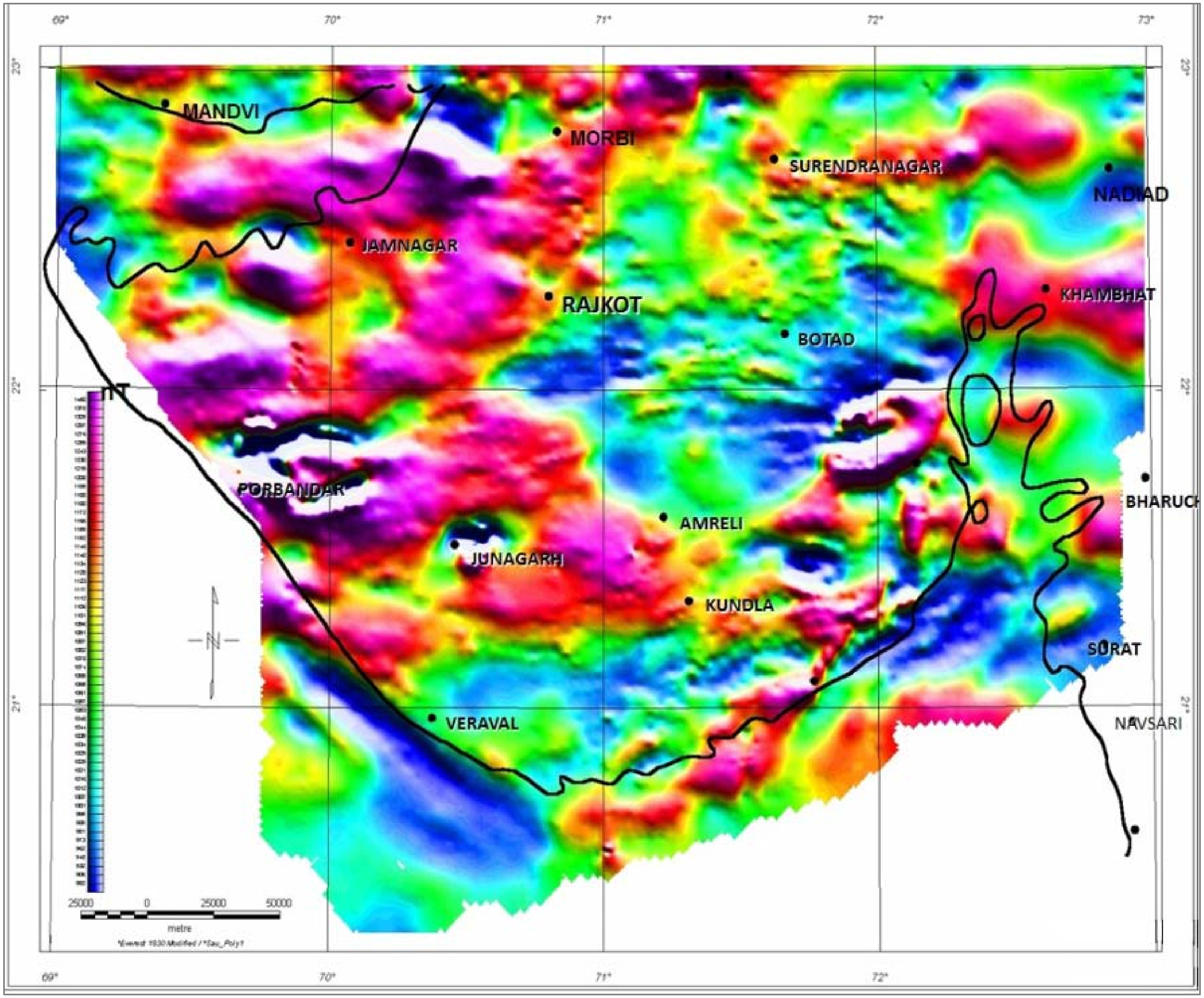

Figure 13. Colour plot of total field aeromagnetic data of the Saurashtra region. Many NE-SW and NW-SE trending lineaments representing basement faults can be identified.

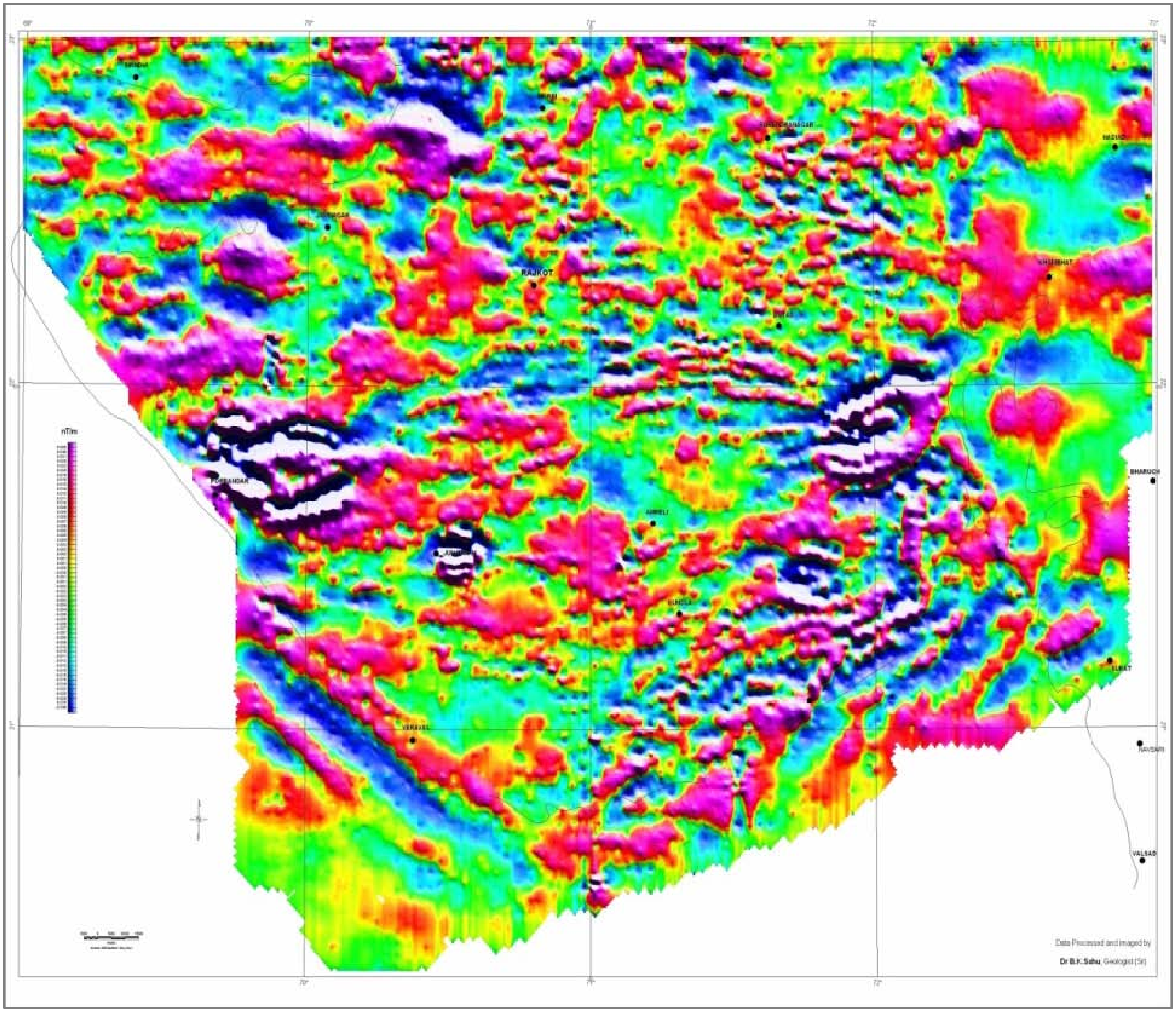

Figure 14. Vertical gradient derivative of the aeromagnetic data of Saurashtra and adjoining areas. Basement faults, dolerite dykes, areas of high magnetic susceptibility, and anomalies related to the western margin of the Cambay structure can very well be seen. Horsts and grabens on the western and southern sides can also be visualized by elongated high and low magnetic anomalies.

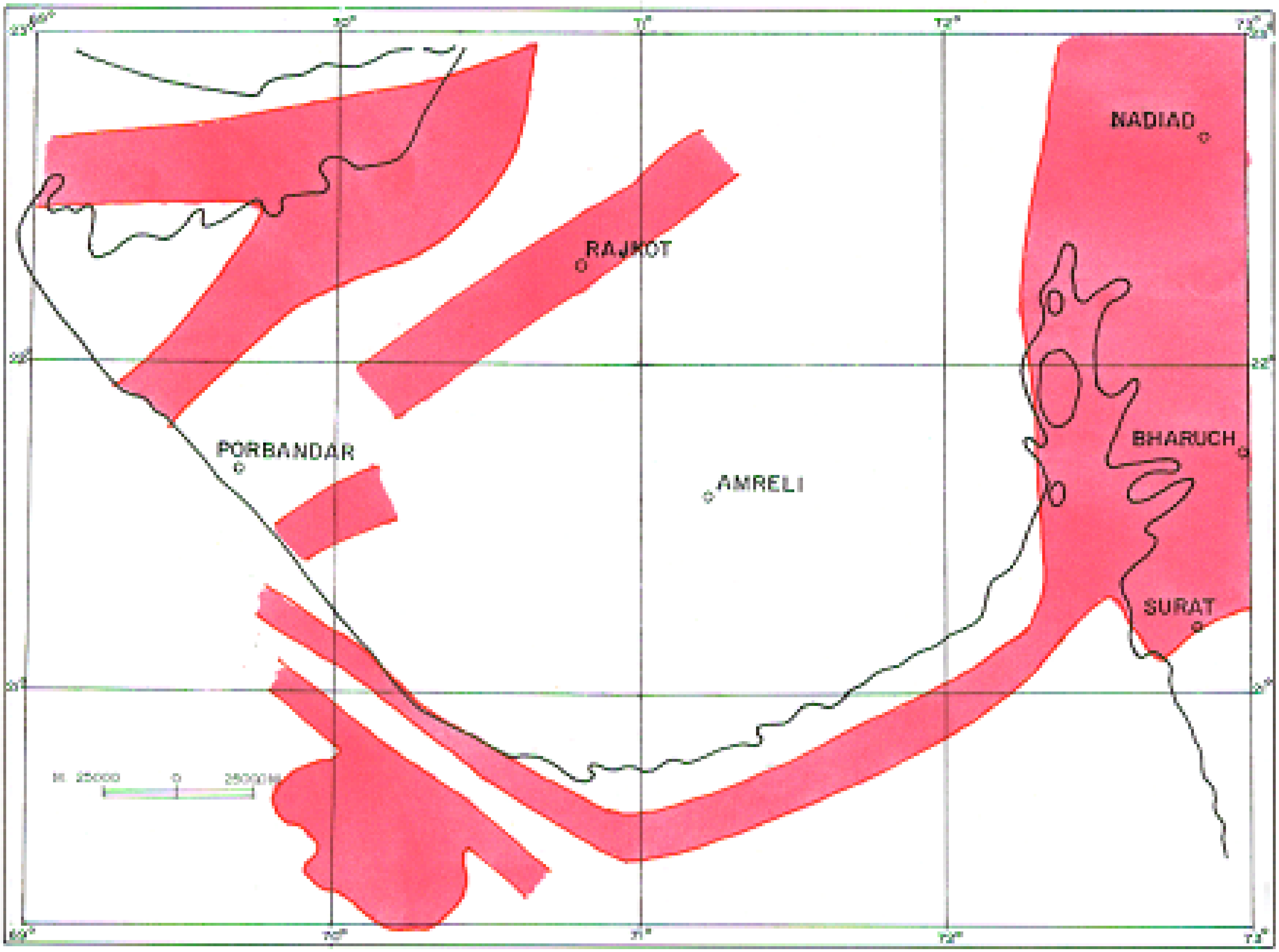

Figure15. Euler depth perception map of the Saurahstra and Cambay grabens. The regions coloured in red are showing areas where the depth of basement is more than 5 km. Hidden rifts below the volcanics are interpreted by the elongated nature of basement subsidence.

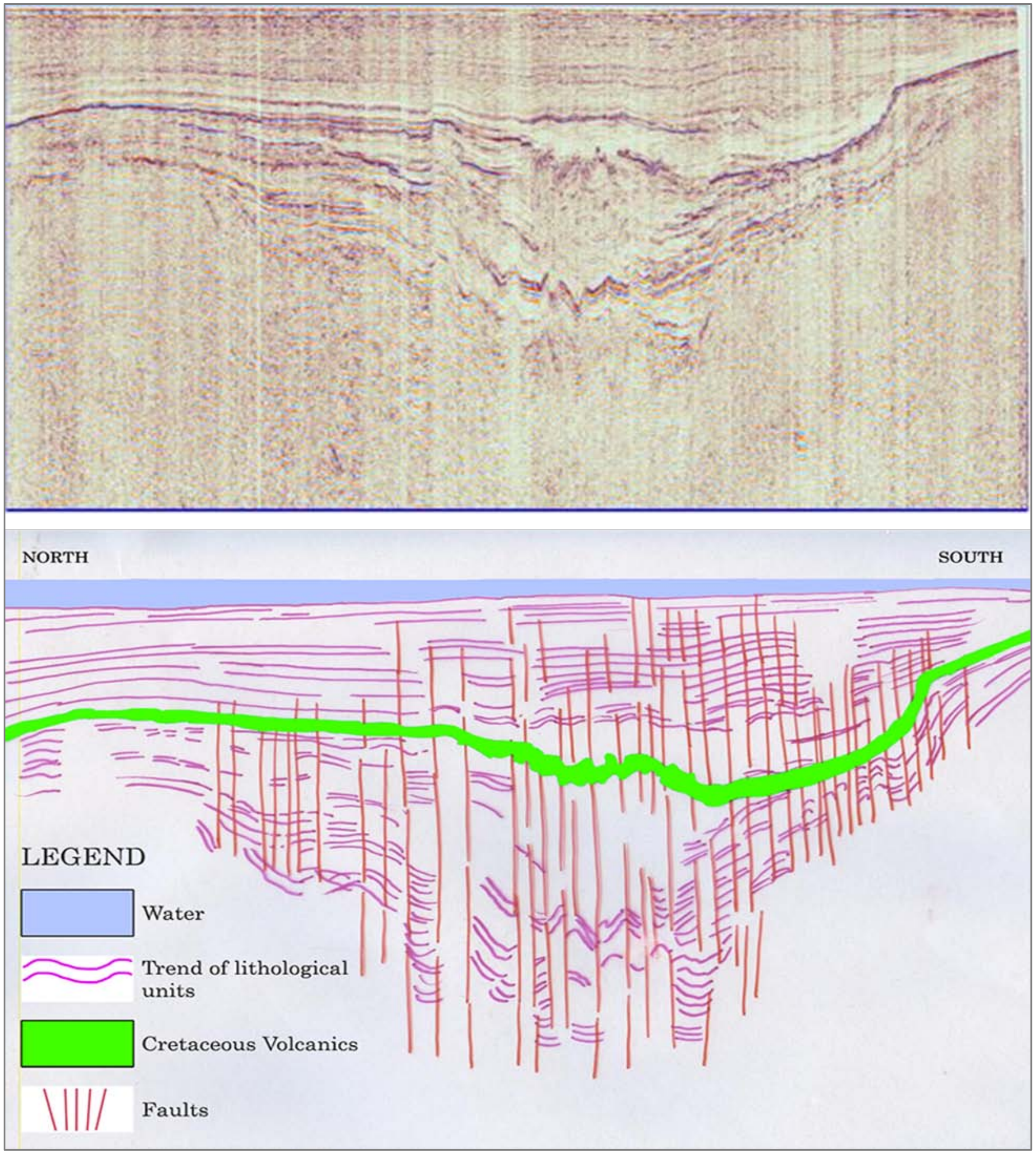

Figure 16. The upper image represents seismic profile (processed by Pre-Staking and Depth Migration technique) across the Surat depression. The lower part of the figure shows the interpretation of the profile. The volcanics stand out prominently because of their high density. However, many details below the volcanics are also seen.