

Extension of flood basalt on the northwestern continental margin of India

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Abstract

The Deccan Continental Flood Basalt (DCFB) in central western India is a large igneous province that covers almost one-sixth area of India. It erupted in less than 1 million years during the magnetic Chron 29r (~65.6 - 64.8 Ma) through the Cretaceous-Tertiary boundary. It is believed that nearly an equivalent area of flood basalt, adjoining the DCFB, is submerged on the North Western Continental Margin of India (NWCMI). Onshore information on the DCFB is widely reported in geological and geophysical studies. However, knowledge on the offshore extent of flood basalt is poorly known because of paucity of marine geophysical data and lack of an appropriate approach to determine the flood basalt. To fill this gap in knowledge, P-wave velocity in flood basalt as a proxy, drilled wells results, and published seaward dipping reflectors are used to delineate flood basalt extent on the NWCMI. The results of the study reveal that P-wave velocity in the flood basalt varies from 4.1 to 5.2 km/s. Apart from some isolated basement-high features, it is found that flood basalt lies below sediment and carpets the entire NWCMI extending up to the Laxmi-Laccadive ridges. The depth of occurrence of flood basalt ranges from 800m to 7400m, with a maximum thickness of ~3900m in the eastern part of the Laxmi Basin. The article presents preliminary results about the extension of flood basalt on the western continental margin of India which may be useful for researchers and Indian oil industries planning exploration activities in Mesozoic sediment of the margin for hydrocarbon prospects.

Keywords: Flood basalt, Deccan Trap, P-wave velocity, Laxmi Basin, Northwestern continental margin of India.

1. Introduction

The Western Continental Margin of India (WCMI) is formed due to rifting and drifting of India, Madagascar and Seychelles continental blocks, which experienced multiple phases of extensional tectonics in the geological past and evolved in mainly three phases. The first phase of rifting took place between southwestern India and the eastern Madagascar during the Late Cretaceous under influence of the Marion hotspot volcanism (Norton and Sclater, 1979; White and Mckenzie, 1989; Storey et al., 1995; Torsvik et al., 1998; Raval and Veeraswamy, 2003). The short span of rifting between Seychelles-Laxmi Ridge and India was the second major tectonic phase, which shaped the western continental margin of India. The Laxmi Basin evolved during this phase of rifting but the crustal nature underneath the Laxmi Basin and the adjacent offshore Indus Basin is still being debated from oceanic to stretched continental crust (Bhattacharya et al., 1994; Miles et al., 1998; Talwani and Reif, 1998; Krishna et al., 2006; Bhattacharya and Yatheesh, 2015; Pandey and Pandey, 2015; Ramana et al., 2015). The last phase of rifting commenced between Seychelles and Laxmi Ridge-India (Norton and Sclater, 1979; Naini and Talwani, 1983; Chaubey et al., 2002b) during the Early Paleocene, while the Reunion hotspot activity was in its peak phase. The Eastern Somali Basin and conjugate Western Basin evolved during the phase of seafloor spreading. The crust below the Laxmi Ridge was modified during these phases and interpreted to be either continental or oceanic crust (Naini and Talwani, 1983; Pandey et al., 1995; Todal and Eldholm, 1998; Singh, 1999; Radha Krishna et al., 2002; Collier et al., 2008; Misra et al., 2015; Nair et al., 2015). The well developed Tertiary magnetic lineation established by various researchers indicate oceanic nature for the crust beneath the Arabian and Eastern Somali basins (Miles and Roest, 1993, Chaubey et al., 1998; Miles et al., 1998; Chaubey et al., 2002a, Dyment, 1998; Royer et al., 2002).

The Reunion hotspot related volcanism occurred initially on continental shield and later on oceanic region as the Indian plate moved northwards over the hotspot. It created the Deccan Continental Flood Basalt (DCFB) province on the western and central India (Mahadevan, 1994) as well as continental flood basalt on the Seychelles microcontinent (Devey and Stephens, 1991). Further, it emplaced numerous magmatic intrusions/extrusions within the crust of western continental margin of India as the plate moved over it. The Deccan flood basalt consists of multiple layers of solidified lava flows, which erupted in less than 1 million years (Courtilot et al., 1986; Venkatesan et al., 1993) during the magnetic Chron 29r (~65.6 – 64.8 Ma) through the Cretaceous-Tertiary boundary. Chemical composition of Deccan flood basalt is tholeiitic, highly rich in Mg and Fe. Richards et al. (1989) estimated total area of flood basalts $>1.5 \times 10^6$ km², while Todal and Eldholm (1998) estimated it to be 1.8×10^6 km². The area covered by Deccan flood basalt on the Indian subcontinent is

$5 \times 10^5 \text{ km}^2$ (Mahoney et al., 1989), which is one third of the above estimated area. Therefore, it is believed that nearly an equivalent area of flood basalt adjoining to the DCFB is submerged in the western offshore region of India in the Arabian Sea. Offshore extent of flood basalt is poorly reported till now, because of inadequate geophysical and geological data in the offshore region of the WCMI. In order to overcome this problem, P-wave velocity in flood basalt as a proxy, drilled wells results and published seaward dipping reflectors are used to delineate flood basalt on the northwestern continental margin of India. In this study, spatial distribution, depth of occurrence and thickness of the flood basalt on northwestern offshore region of India is reported for the first time.

2. Structural Framework

The western continental margin of India is a volcanic rifted continental margin. Along with the continental rifting, Reunion hotspot played a major role in shaping up of WCMI and modified the crustal geometry of the region. The northwestern continental margin of India consists of broad shelf as compared to the southwest margin. The present day shelf break along the northwestern continental margin of India occurs at an average water depth of 125 m (Nair, 1975; Rao and Wagle, 1997). The width of the continental shelf is more than 300 km off Mumbai, which makes it one of the largest continental terraces in the world. It decreases towards the north to about 80 km off Saurashtra and to ~120 km off Kutch peninsula. Continental shelf of northwestern India is divided into different sedimentary basins namely Kutch, Bombay Offshore and Konkan basins (Fig.1). A conspicuous southwesterly plunging basement high feature off Saurashtra Peninsula is the Saurashtra Arch, which is a structural high feature on a regional scale and extends from the shelf to slope. Saurashtra Arch separates Kutch Basin from Bombay Offshore Basin (Rao and Talukdar, 1980; Mathur and Nair, 1993). A similar trending feature, Vengurla Arch separates the Bombay Offshore Basin from the Konkan Basin. Bombay Offshore Basin is the largest among them which is controlled by several faults and rift system. The Bombay Offshore Basin is bounded to the north and northwest by Saurashtra peninsula, to the east by Deccan crystalline shield, and to the south by Vengurla Arch.

The major rivers e.g. Indus, Narmada and Tapti drain toward the margin producing a very thick shelf sedimentary column. The shelf in the north is featured typically by longitudinal extensional faults giving rise to a series of narrow Horst Graben structures, which are also responsible for widening of the shelf. The style of faulting along the west coast is the NW-SE to NNW-SSE Dharwar, NE-SW Aravalli and ENE-WSE to E-W Satpura trends (Biswas, 1982, Biswas, 1987). The Dharwar trend dominates from the Kerala offshore to the Bombay offshore. To the north, in the Gulf of Cambay region, the Satpura trend dominates the structural style, while further north in the Kutch-Saurashtra region, the Aravalli-Delhi trends are predominant (Biswas, 1982). These trends have a bearing on the

north to south sequential rifting of Indian subcontinent during the breakup of Gondwanaland (Biswas, 1982). Two major conjugate rift systems, Narmada and Cambay, cross each other south of Saurashtra peninsula in the Surat offshore region forming a deep depression known as Surat depression (Biswas, 1987). The northwestern continental margin of India and adjacent deep sea region consists of number of tectonic elements; notable amongst them are Laxmi Ridge, Laccadive Ridge, Laxmi Basin, Panikkar Ridge, Gop Basin, Palitana Ridge etc. The Laxmi and Laccadive ridges are aseismic ridges, which divide the Eastern Arabian Sea into Eastern and Western basins (Naini and Talwani, 1983). Western Basin is typical oceanic in nature while the nature of crust of the Eastern Basin is still being debated from stretched continental to transitional to oceanic. The Laxmi Ridge trends in NW-SE direction and was identified by Naini and Talwani (1983). It is a basement high feature associated with a broad negative Free-air gravity anomaly of ~ 50 mGal. Laxmi Basin is a relatively gravity high feature in the same trend as of the Laxmi Ridge. In the middle of the Laxmi Basin, a relative gravity low feature trending NW-SE associated with Panikkar Ridge is present and considered to be an extinct spreading center (Bhattacharya et al., 1994; Talwani and Reif, 1998). Gop Basin, a wide region located between north of E-W trending segment of the Laxmi Ridge and India-Pakistan continental shelf, lies between latitudes 19°N and 20°N (Malod et al., 1997; Yatheesh et al., 2009). The Laccadive Ridge is the northern segment of Chagos-Laccadive Ridge corresponds to the general N-S trend and is associated with a negative gravity anomaly. However, relatively positive anomaly can be observed over some crestal region of this ridge. Study area (Fig. 2) includes northwestern continental margin of India and adjoining deep sea region, and is bounded by northwest coast of India in the northeast, Laxmi Ridges in the southwest, Laccadive Ridge in the south and Murray Ridge in the northwest.

3. Data

The northwestern offshore region of India was investigated to provide spatial distribution, depth of occurrence and thickness of flood basalt using two sets of data: onshore as well as offshore geophysical data. The details of data types used here are described briefly in following sections:

3.1 Onshore Data

Onshore data comprises P-wave velocities (Kaila, 1981a; Kaila, 1981b; Kaila, 1987; Kaila, 1989a; Kaila, 1989b; Kaila, 1990; Kaila and Krishna, 1992; Kumar et al., 2000; Reddy, 2005; Murty et al., 2010) in Deccan flood basalt which are derived from Deep Seismic Sounding (DSS) surveys carried out by National Geophysical Research Institute, Hyderabad, India. P-wave velocity derived from earthquake data (Krishna, 2004) and from dispersion of short-period Love wave data (Tandon,

1973), is utilized in this study. In addition, sonic log and litholog data of a drilled-well (Suthari) (Pandey et al., 2009; Pandey et al., 2011) located in Kutch, Gujarat (23.12° N, 68.92° E) are also used in this study.

3.2 Offshore Data

Offshore data consists of published results on litholog of wells drilled by Oil and Natural Gas Corporation (ONGC) and P-wave velocity from refraction survey. Drilled well data where flood basalt was encountered, has been compiled (Fig. 2) from various publications (Sahay, 1978; Roychoudhury and Deshpande, 1982; Parida & Mishra, 1992; Mathur and Nair, 1993; Senapati et al., 1993; Pandey and Dave, 1998) to determine depth of occurrence of flood basalt. In addition, those drilled wells which did not encounter flood basalt are also compiled. Refraction data are compiled (Naini and Talwani, 1983; Rao, 1967; Rao, 1970), which show velocity structure of the Western Basin, Eastern Basin and western continental shelf of India. Total 44 offshore drilled-well, 9 refraction stations on shelf & slope, 11 refraction stations in the Eastern Basin, 5 refraction stations on the Laxmi Ridge and 16 refraction stations on the Western Basin are used in the present study.

4. Delineation of Flood Basalt

To map offshore extent of flood basalt, a typical P-wave velocity in flood basalt is used as a proxy. In addition, drilled well results, and published seaward dipping reflectors are used to delineate flood basalt extent and its thickness on the northwestern continental margin of India.

4.1 Representative P-Wave Velocity in Flood Basalt

Deep Seismic Sounding (DSS) data has provided valuable information about the basement configuration and velocity distribution up to the Moho in Deccan Volcanic Province (DVP). DSS profiles along Dharimanna-Degam (Kaila, 1990); Mehmabad-Billimora (Kaila, 1981b); Hirapur-Mandla (Kaila, 1987; Kaila, 1989b); Thaudara-Sindad (Kaila, 1989a); Navibandar-Amreli (Kaila and Krishna, 1992) and Kelsi-Loni (Kaila, 1981a) have been considered to determine P-wave velocity in the Deccan flood basalt. Velocity-depth plots of different DSS profiles (Fig. 3) show that the P-wave velocity in Deccan flood basalt ranges from 4.3 km/s to 5.2 km/s. Similarly, P-wave velocity in the Deccan flood basalt is also reported from dispersion of short-period Love wave and earthquake data which display a range of 4.7-5.2 km/s (Tandon, 1973) and 4.8-4.9 km/s (Krishna, 2004) respectively. P-wave velocities in Deccan flood basalt derived from available literature are presented in Table 1, which show that it varies from 4.3 to 5.2 km/s.

An onshore drilled-well (Suthari), which is drilled up to ~2750 m but didn't reach up to Precambrian basement (Pandey et al., 2011), is utilized to correlate with sonic log and refraction derived P-wave

velocity. Litholog data of Suthari revealed (i) about 600 m thick sedimentary strata of Quaternary-Tertiary period, (ii) ~600 m thick Deccan basalt layer, (iii) ~1000 m thick sandstone-claystone of Early-Late Cretaceous period, and (iv) Middle to Late Jurassic alternate bands of limestone and sandstone (Fig. 4a). Sedimentary layers of Early-Late Cretaceous and Middle-Late Jurassic period represent Mesozoic sediments, which can have potential for hydrocarbon accumulation. Corresponding sonic log data of the drilled-well Suthari (Pandey et al., 2009) revealed P-wave velocity of 1.9-2.2 km/s in the Tertiary sediment, 4.5-4.6 km/s in the Deccan flood basalt, followed by low velocity ($V_p=3.2$ km/s) Mesozoic sedimentary strata. In order to investigate existence of offshore flood basalt, an offshore refraction station (GK2) is chosen, which is located ~130 km southwest of the onshore drilled well (Suthari). P-wave velocity obtained from an offshore refraction station (GK2) is correlated (Fig. 4a) with the sonic and litholog data of the onshore drilled well (Suthari). The velocity-depth plot at refraction station GK2 revealed that P-wave velocity varies from 2.08 to 3.2 km/s in ~1400 m thick sedimentary strata, which is underlain by a ~2000 m thick crustal layer of velocity 4.3 km/s. The crust underlying the above layer is represented by the velocities 5.27 km/s and 6.24 km/s which are interpreted to be upper and lower continental crust respectively. Thickness of upper crust is ~2000 m but no information is available on thickness of lower crust at this refraction station. Litholog, sonic log and offshore refraction derived P-wave velocity clearly indicate that crustal layer with $V_p=4.3$ km/s underlying the sedimentary strata ($V_p=2.08-3.2$ km/s) closely matches with the velocity (4.5-4.6 km/s) in the Deccan flood basalt observed in Sonic log.

Further, Litholog data of an offshore drilled-well BS-1 (Sahay, 1978), located in the Bombay Offshore Basin (Fig. 2), confirms presence of flood basalt below ~2145 m thick Quaternary-Tertiary sedimentary strata. The well BS-1 is drilled up to ~2150 m and ~5 m thick flood basalt is encountered up to this depth. P-wave velocity obtained from an offshore refraction station S1, located ~180 km southeast of the offshore drilled-well BS-1, is correlated with the litholog data of BS-1 (Fig. 4b). P-wave velocity at this station varies from 1.7 to 2.3 km/s in ~4500 m thick crustal layers, followed by a ~3900 m thick layer of velocity 4.2 km/s. Correlation of the litholog and the refraction derived P-wave velocity suggests that crustal layer with $V_p=1.7-2.3$ km/s represent sedimentary layer and crustal layer underlying it with $V_p=4.2$ km/s represent flood basalt. Location of onshore drilled-well (Suthari), offshore drilled-well BS-1 and refraction stations GK2 & S1 are shown in Figure 2.

In view of the above results, we suggest that representative P-wave velocity in flood basalt on the onshore as well as offshore region lies in the range of 4.2-5.2 km/s which is used in this study as a proxy to map flood basalt in the study area.

4.2 Extent and Thickness of Flood Basalt

The Oil and Natural Gas Corporation Limited of India drilled several wells on the northwestern continental shelf of India and encountered flood basalt in several drilled wells. Even though, some of the drilled-wells did not encounter flood basalt in its drilled section, chronostratigraphical section using litholog data indicated occurrence of flood basalt on the shelf except at some isolated high features in Bombay High and Heera-Bassein Block (Mathur and Nair, 1993). Beyond the continental shelf, occurrence of flood basalt is investigated using P-wave velocity as a proxy. P-wave velocity structures along arbitrary line AB (Figs. 2 & 5) is chosen for the comparison of crustal velocities. Line AB spans from onshore to offshore passing through point A at Koyna (onshore region), and refraction stations S2 (continental shelf), L11V34 (Laxmi Basin), L03V34 (Laxmi Ridge) and 61V34 (Western Basin). Velocity-depth plot of Kelsi-Loni profile in Koyna region shows that P-wave velocity varies from 4.6-4.8 km/s in Deccan flood basalt and 5.75-6.29 km/s in the upper continental crust. Refraction station S2 on the continental shelf shows ~3400 m thick sedimentary strata with V_p ranging between 1.7 and 2.7 km/s, followed by ~3200 m thick layer of $V_p=4.4$ km/s. In the Laxmi Basin, velocity structure at refraction station L11V34 reveals ~1300 m thick sedimentary strata of velocity ranging between 1.78 and 2.3 km/s, followed by ~400 m thin layer of velocity 4.6 km/s overlying a layer of velocity 5.4 km/s. On the Laxmi Ridge, refraction station L03V34 reveals ~740 m thin sedimentary strata with V_p ranging from 1.75 to 2.28 km/s, underlain by a thin layer (~650 m) with velocity 4.2 km/s. Underlying this layer, two layers with velocity 5.2 km/s and 6.2 km/s are present. Refraction station 61V34 located in the Western Basin depicts ~3600 m thick sediment with velocity 1.87-3.76 km/s, underlain by layers with velocity of 5.4 km/s and 6.8 km/s, which represents layer 2 and layer 3 of typical oceanic crust at depth of 7.145 km and 9.455 km respectively (Fig. 5). This refraction station doesn't show any layer of velocity ranging between 4.2 and 5.2 km/s.

The velocity structure of the continental shelf, Laxmi Basin and Laxmi Ridge along the line AB reveal a consistent layer ($V_p=4.2-4.6$ km/s) with variable depth and thickness below Quaternary/Tertiary sediments. All the refraction stations located in the Eastern Basin and on the Laxmi Ridge reveal a consistent layer, located immediately below the sedimentary strata, of P-wave velocity ranging from 4.1-4.9 km/s. Therefore, considering V_p in Deccan flood basalt (4.2-5.2 km/s) as proxy and the fact that it lie below the sedimentary strata, the layer with velocity range 4.1-4.9 km/s is interpreted as flood basalt. It may be mentioned here that the adjacent Western Basin is oceanic in nature, and therefore doesn't show any layer of such velocity representing flood basalt (Fig. 5).

High resolution ion-GXT seismic lines indicated presence of Seaward Dipping Reflectors (SDRs) below sedimentary strata on the NWCMI (Misra et al., 2015). Further, study carried out by Planke (1994) using wire line log at Ocean Drilling Program Site 642 located on Voring volcanic margin off Norway revealed tholeiitic lava flow (flood basalt) representing SDRs. Litholog of drilled site in IODP Leg 355 U1457 in the Laxmi Basin also shows the presence of basaltic lava flow underlying the Paleocene sediment at depth of ~1100 m below seafloor (Pandey et al., 2016). These results support our interpretation of occurrence of flood basalt immediately below the sedimentary strata on the NWCMI.

On the basis of drilled-well data, P-wave velocity in flood basalt, and published seismic section, a database of occurrence of flood basalt is prepared. Based on the database, a map showing extent as well as depth of occurrence is prepared and presented in Fig. 6. The results suggest that the flood basalt is present on the entire northwestern continental margin of India and extends up to the Laxmi Ridge, except at some isolated high. Correlation of those drilled-wells which penetrated granitic basement without encountering flood basalt with chronostratigraphical section (Mathur and Nair, 1993) on the northwestern continental shelf of India revealed its location above isolated high features. It may also be possible that some of isolated high features located in the Eastern Basin and on the Laxmi Ridge are devoid of flood basalt.

The thickness of flood basalt is estimated using P-wave velocity structure derived from seismic refraction data is presented in Fig. 7. Though a few refraction stations on the shelf & slope region do show thickness of flood basalt but they are too sparse to prepare flood basalt thickness contour map.

5. Results and Discussion

The results of the present study show that depth of occurrence of flood basalt ranges from 800 m to 7400 m in the study area. Deeper occurrences of flood basalts below the Tertiary sediment are found in the Gop Basin at a depth of ~7400 m, and ~7200 m at the foot of slope of Saurashtra continental slope. Depth of flood basalt decreases from 7400 m in the Gop Basin to 6000 m further northward. Occurrence of flood basalt near the Gop Basin is also reported in recent publications (Carmichael et al., 2009; Corfield et al., 2010; Calves et al., 2011). Further, Carmichael et al. (2009) inferred occurrence of flood basalt at a depth of about 6500 m, north of the deepest occurrence of flood basalt (in the Gop Basin) interpreted in the present study.

The deeper occurrence of flood basalt may be due to post-trappean thick sedimentation and excess subsidence in the region. Further, a large variation in the depth of occurrence of flood basalt in the

study area suggest that the volcanic emplacement was controlled by existing tectonic features in the region.

The occurrence of flood basalt is also interpreted on the Laxmi Ridge where it is observed at an average depth of ~4000 m. Seaward dipping reflector was observed west of Laxmi Ridge (Collier et al., 2008; Krishna et al., 2006; Corfield et al., 2010) which support the extent of flood basalt up to the Laxmi Ridge. SDRs with a wide range of P-wave velocity 3.0 to 5.5 km/s were reported on the volcanic rifted margins by Planke et al. (2000). However, P-wave velocity range 1.5-3.5 km/s correspond to sediments in the study area (Naini and Talwani, 1983; Rao, 1967; Rao, 1970). Therefore, V_p less than 3.5 km/s do not represent SDR (flood basalt) in the study area.

The depth of flood basalt increases eastward from the Laxmi Ridge to the Laxmi Basin. In the Laxmi Basin, it varies from 4000 m to 6000 m. Krishna et al. (2006) suggested that intrusive structures in the form of dykes and accretion of magmatic material in the form of sills emplaced in the Laxmi Basin possibly generated by the Reunion hotspot at the time of Deccan volcanism. Pandey and Pandey (2015) suggested that the Laxmi Basin is heavily intruded by sills and basaltic volcanic which were emplaced due to melting of Sub-Continental Mantle (SCM). They also proposed that Panikkar Ridge is a basaltic volcanic body derived from melting of lower part of the SCM. Results of the drilling at Site U1457 in the Laxmi Basin during International Ocean Discovery Program (Expedition 355) recovered 8.72 m of basalt, as well as associated volcanoclastic sediment above it (Pandey et al., 2016). Shore-based geochemical analysis carried out after the end of the expedition shows that the basalt is Mg-rich, low-K subalkalic tholeiites. All these observations support presence of flood basalt in the Laxmi Basin and on the Laxmi Ridge.

The continental shelf north of Ratnagiri, India is associated with Horst-Graben structures. The shelf region hosts several sedimentary basins (Kutch Offshore Basin, Bombay Offshore Basin, Konkan Basin) which are separated by WSW-ENE basement arches (Saurashtra arch, Vengurla arch). The depth of flood basalt in Bombay Offshore Basin is quite random, where it varies from ~1000 m to 4000 m. Flood basalt in Bombay High region occurs at a depth of ~2000 m, except at some isolated high features where flood basalt is not present. Bombay high is an uplifted basement structure and is bounded by faults on either side. It has a gentle dip of 2° to 3° on the western side and steep dip of 8° to 10° on the eastern side (Murti et al., 1981). Therefore, depth of flood basalt increases in either sides of the Bombay High except in the eastern side where it decreases and reaches up to <1000 m. Bombay Offshore Basin is an intracratonic basin which came into existence during upper cretaceous due to faulting in the Deccan trap basement. In the Bombay Offshore Basin, some of the drilled-

wells penetrated into Tertiary strata and entered the Archean basement without encountering the flood basalt (Rao and Srivastava, 1981; Roychoudhury and Deshpande, 1982; Sahay, 1984).

The depth of flood basalt increases up to ~4000 m northeast of the Bombay high, along Surat depression where thick sediment is deposited. Since, the southern part of the Cambay Basin and Surat depression are the depocentres that have received sediments brought down by Narmada-Tapti river system (Nair et al., 1992), therefore observed depth of occurrence of flood basalt of ~5500 m in the region is interpreted due to post-Trappean subsidence of the crust.

Maximum and minimum thickness of flood basalt is interpreted as ~3900 m in the Laxmi Basin and ~400 m on the Laxmi Ridge respectively (Fig. 7). Thickness decreases from east to west over the Laxmi Ridge, where flood basalt layer terminates at the western side of the Laxmi Ridge. All along the Laxmi Basin flood basalt thickness vary from 400 m to 2000 m but northern and southern part of the Laxmi Basin show relatively high thickness. Flood basalt thickness ranges from 500 m to 1000 m in the Gop Basin and decreases further northward. Misra et al. (2015) has shown that the thickness of inner SDRs are less than 5 km. Further, geophysical study carried out by Corfield et al. (2010) on western Indian and Pakistan continental margins revealed major variation in overall thickness and style of volcanism across the margin both in dip and strike direction which they believed to be related to variability in the influence of the Deccan plume, in addition to localization along structural features inherited from older tectonic events.

It is worth mentioning here, that flood basalt thickness map in Fig.7 has been prepared using seismic refraction data which contains crustal information till Moho. Such refraction data are available on the Laxmi Ridge and Eastern Basin only. Though there are few refraction stations on the continental shelf and slope region which provide velocity information and thickness of flood basalt, they are widely spaced and not sufficient to prepare thickness map. Therefore, the thickness of flood basalt in the shelf and slope region is not presented.

The study of Deccan flood basalt is very important due to presence of Mesozoic sediment hidden below it. Worldwide Mesozoic sediment contribute around 54% of oil and 44% of gas reserves of the world. Geophysical surveys carried out in the Indian Mesozoic basins have indicated presence of significant sediment thickness. These basins are mostly overlain by Deccan flood basalt of Late Cretaceous and are least explored. Mesozoic sediments are plausible for hydrocarbon accumulation having suitable trapping mechanism due to overlying thick layer of flood basalt. Further, it is also considered that the Deccan flood basalt volcanism, soon after the Mesozoic sedimentation, has provided sufficient thermal gradient and might have acted as a catalyst in hydrocarbon generation. Further, it is believed that the volcanism must have had a profound influence on the crustal evolution

including the present-day configuration of the continental margin concealing the pre-existing geology and crustal structure. The study provides a first-hand information about flood basalt extent and its thickness on the northwestern continental margin of India, which can help to delineate hydrocarbon potential in Mesozoic sediment hidden below the flood basalt layer. The results of the present study warrant integrated gravity and magnetic modelling under constraints of the results of the present study in order to provide refined maps showing extent, depth of occurrence and thickness of flood basalt on the northwestern continental margin of India.

6. Conclusions

The study presented in this article provides insights on the extent, depth of occurrence and thickness of flood basalt on the northwestern continental margin of India and adjoining deep sea region. Analysis of P-wave velocity in the study area and adjoining onshore region reveals that velocity of 4.1-5.2 km/s represent flood basalt, which is spread all over northwestern continental margin of India. It extends up to the Laxmi and Laccadive ridges, except at some isolated high features, and is absent in the Western Basin, west of the ridges. The flood basalt occurs between 800 and 7400 m below sea level and its maximum thickness (~3900 m) is observed at foot of the continental slope near eastern part of the Laxmi Basin. A large variation in the depth of occurrence and thickness of flood basalt in the study area suggest that the volcanic emplacement was controlled by existing tectonic features in the region. The results of present study have major implications due to presence of Mesozoic sediments hidden below the flood basalt and may be useful to understand hydrocarbon preservation condition for conceptual evaluation of hydrocarbon potential of the region.

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Table 1: *P-wave velocity in Deccan flood basalt derived from Deep Seismic Sounding survey.*

No.	Name of the profile		P-wave velocity (km/s) in flood basalt	Reference
1	Koyna I (Guhagar-Chorochi) Profile		4.7-4.9	(Kaila and Krishna, 1992)
2	Koyna II (Kelsi-Loni) Profile		4.8-5.0	(Kaila, 1981b; Kaila and Krishna, 1992)
3	Saurashtra Peninsula (Navibandar-Amreli) Profile		4.9-5.15	(Kaila and Krishna, 1992)
4	Mehmadabad-Billimora in southern Cambay Basin		4.8-5.2	(Kaila, 1981a; Kaila and Krishna, 1992)
5	Thuadara-Sindad Profile		4.7-5.0	(Kaila, 1989a; Kaila and Krishna, 1992)
6	Ujjain-Mahan Profile.		4.7-5.1	(Kaila and Krishna, 1992)
7	Khajuria Kalan-Pulgaon Profile		4.7-5.1	(Kaila and Krishna, 1992)
8	Hirapur-Mandla Profile.		4.5-4.8	(Kaila, 1987; Kaila, 1989b; Kaila and Krishna, 1992)
9	Narmada region	Profile II (Khajuriakalan-Pulgaon)	4.4-4.6	(Kumar et al., 2000)
		Profile III (Ujjain-Mahan)	4.3-4.5	
10	Narmada-tapti region	Narayanpur- Nandurbar	4.5-4.7	(Murty et al., 2010)
		Kothari-Sakri	4.5-5.2	
11	Jodin-Ansodor profile		4.9 and 5.1	(Reddy, 2005)
12	Tikor-Kolithad profile		5.1	(Reddy, 2005)
13	Kurungo-Latipur profile		4.8	(Reddy, 2005)
14	Sardar-Mangrol profile		5.1	(Reddy, 2005)
15*	Analysis of Jabalpur earthquake		4.8-4.9	(Krishna, 2004)
16*	Bombay-Koyna		4.7-5.2	(Tandon, 1973)

*P-wave velocity 4.8-4.9 km/s and 4.7-5.2 km/s mentioned at S. No. 15 and 16 respectively are obtained from analysis of earthquake data.

Figure Caption:

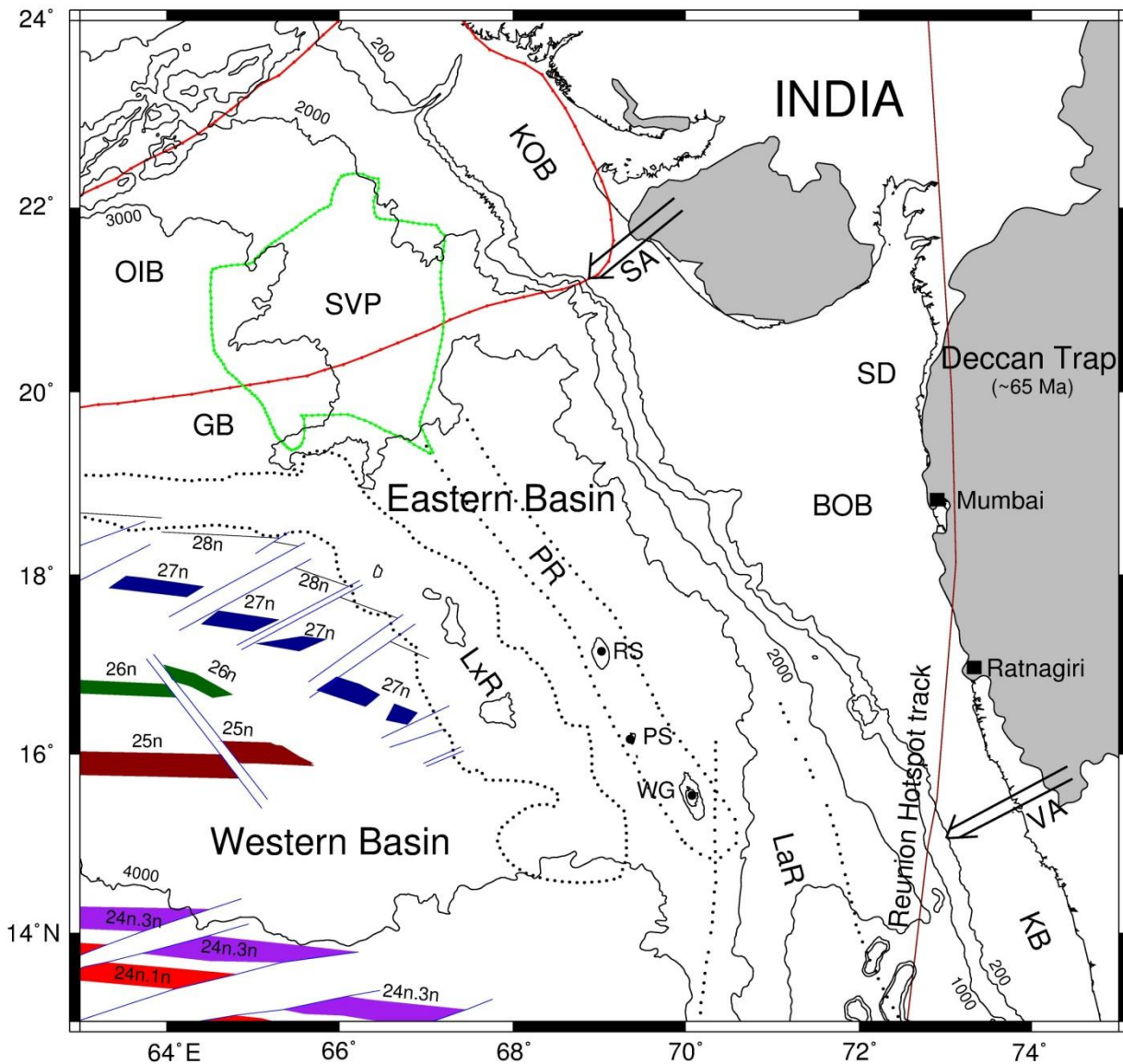


Fig. 1 Generalized tectonic map of the Western Continental Margin of India (WCMI) showing major physiographic features and selected bathymetric contours (m). Annotated magnetic lineation (colored strips) are from Chaubey et al. (2002a). Boundaries (dotted lines) of the Laxmi Ridge (LxR), Laccadive Ridge (LaR) and Panikkar Ridge (PR) are from Sreejith et al. (2016), Naini and Talwani (1983) and Krishna et al. (2006) respectively. Offshore Indus Basin (OIB) and Saurashtra Volcanic Platform (SVP) are shown with red and green color polygons respectively (Carmichael et al., 2009; Corfield et al., 2010). Various sub-basins and basement arches along the WCMI are taken from Biswas (1988). Solid black circles are seamounts. GB: Gop Basin, RS: Raman Seamount, PS: Panikkar Seamount, WG: Wadia Guyot, KOB: Kutch Offshore Basin, SA: Saurashtra Arch, SD: Surat Depression, BOB: Bombay Offshore Basin, VA: Vengurla Arch, KB: Konkan Basin.

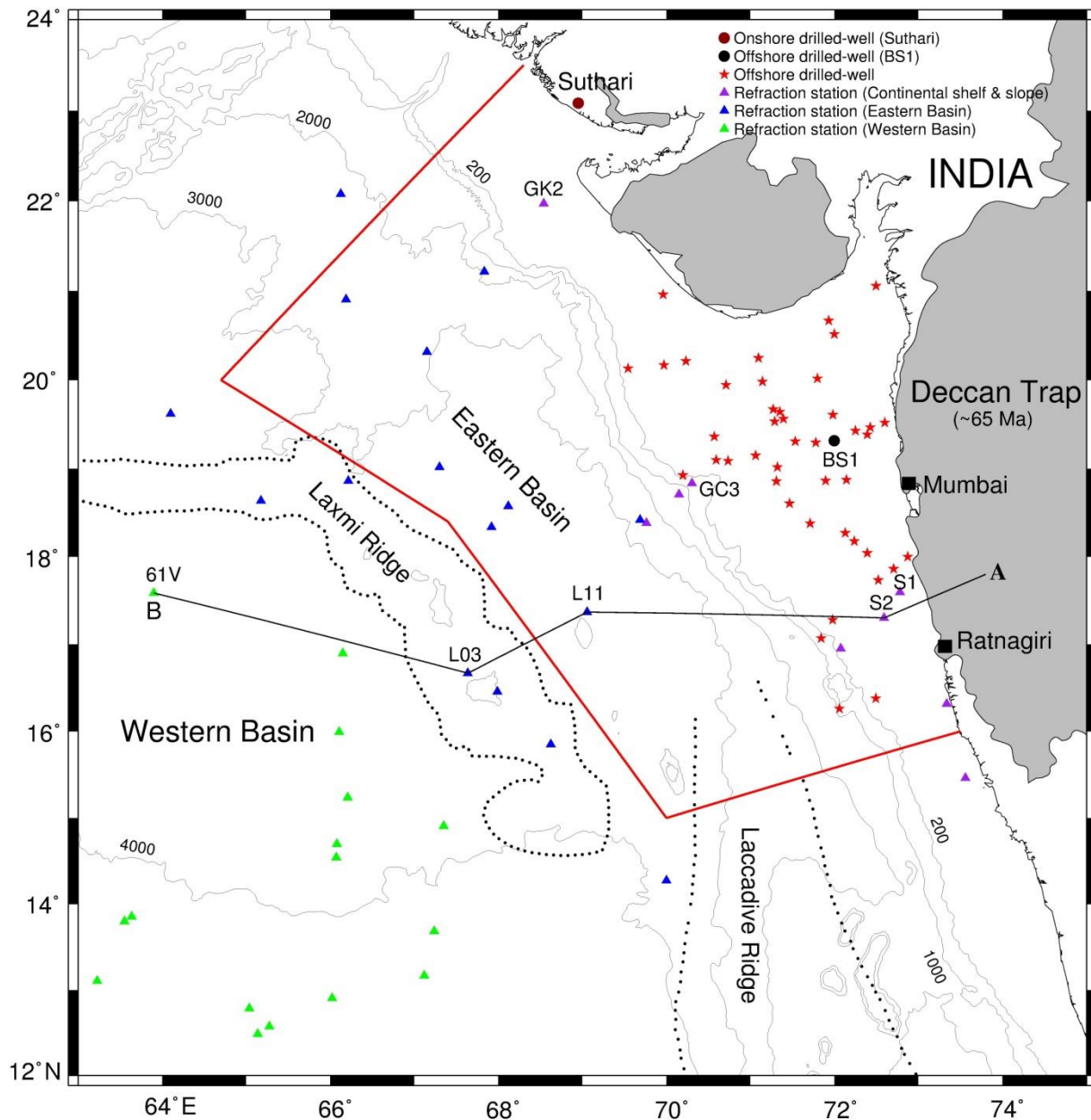


Fig. 2 Map showing location of geophysical data in the study area bounded by red polygon. Dark red solid circle on onshore represents drilled-well Suthari (Pandey et al., 2011). Black solid circle: offshore drilled-well BS-1, Red solid stars: drilled-wells in western offshore, Purple solid triangles: refraction stations on the continental shelf & slope region (Rao, 1967; Rao, 1970), Blue solid triangles: refraction stations in the Eastern Basin (Naini and Talwani, 1983), Green solid triangles: refraction stations in the Western Basin (Naini and Talwani, 1983). Selected bathymetric contours (m) are shown as continuous back line. An arbitrary line AB is chosen for correlation of P-wave velocity of crustal layers from onshore to offshore.

Deccan Volcanic Province (Indian shield)

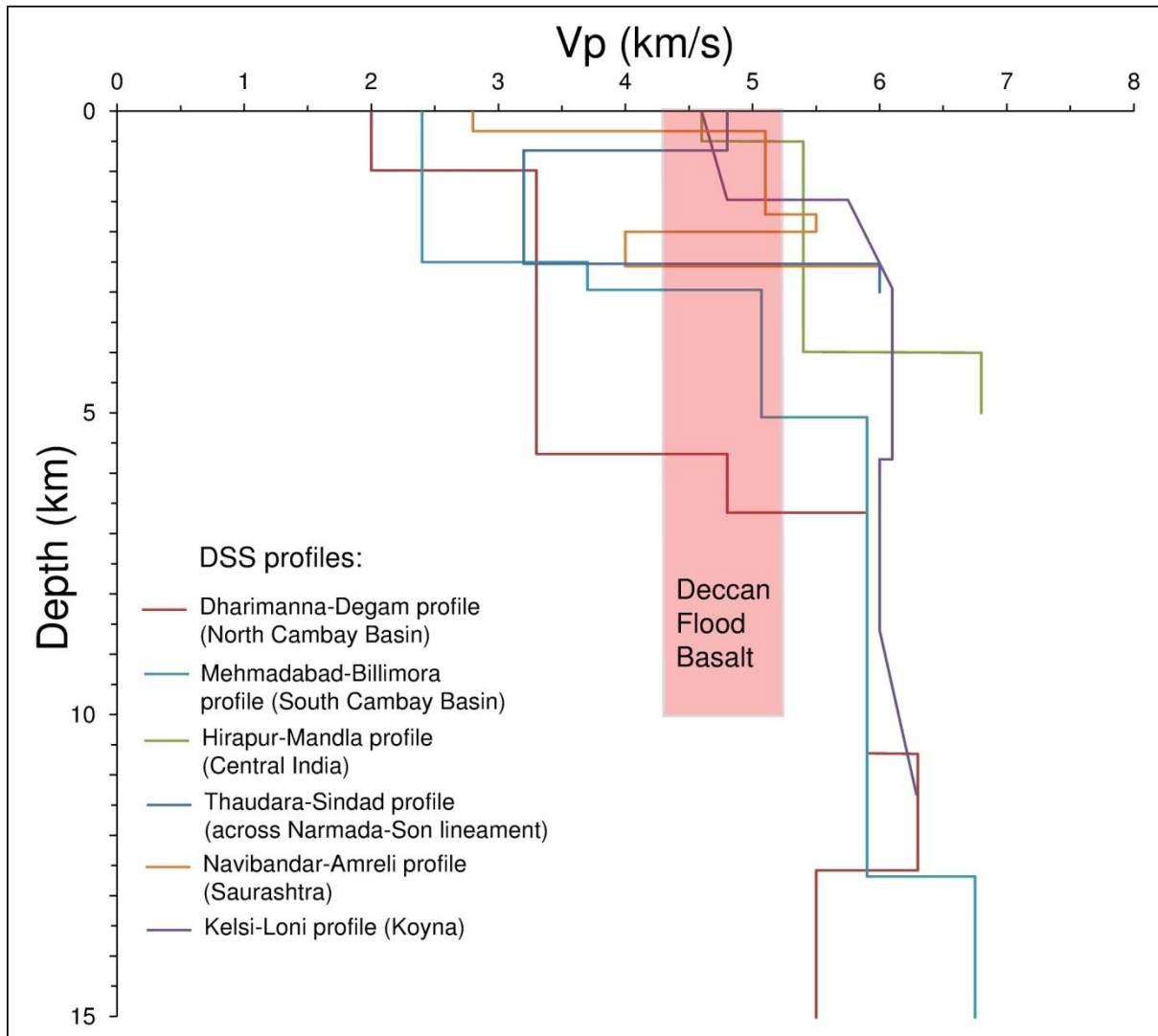
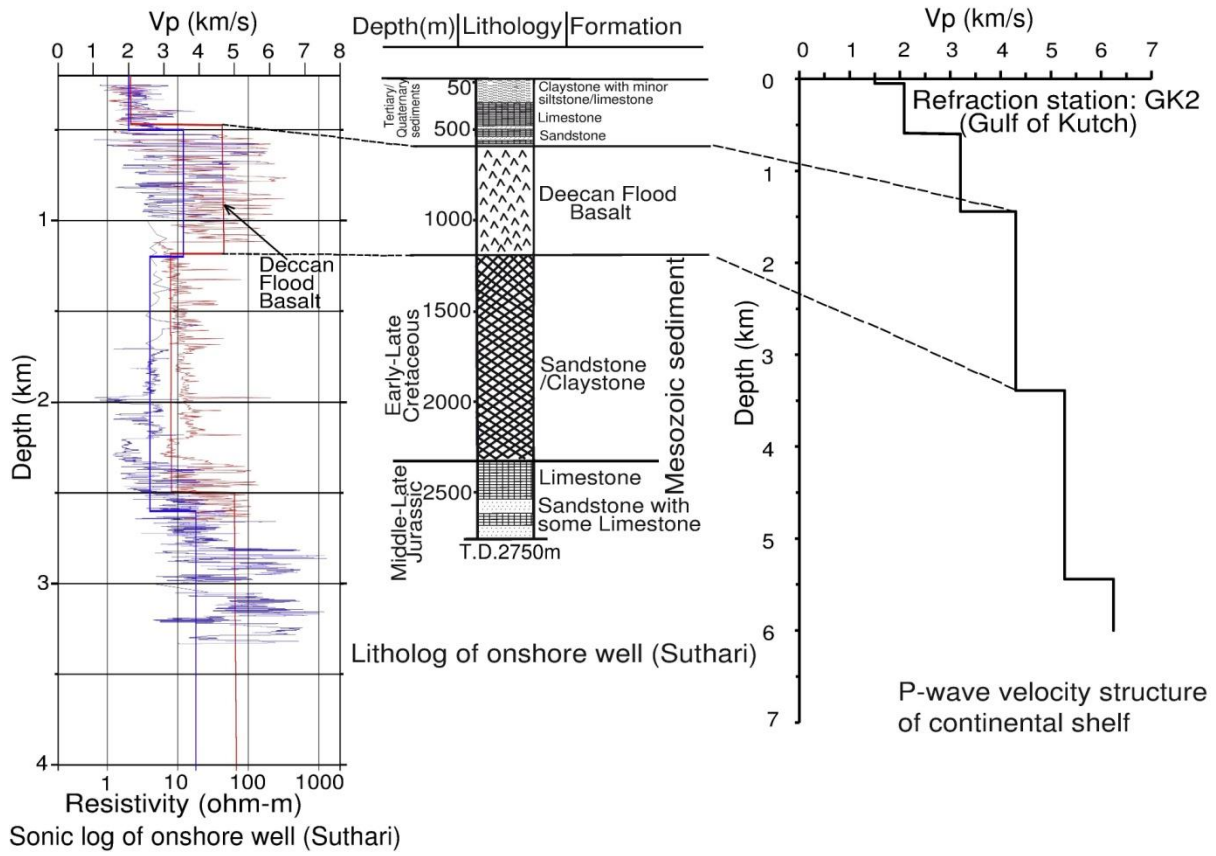
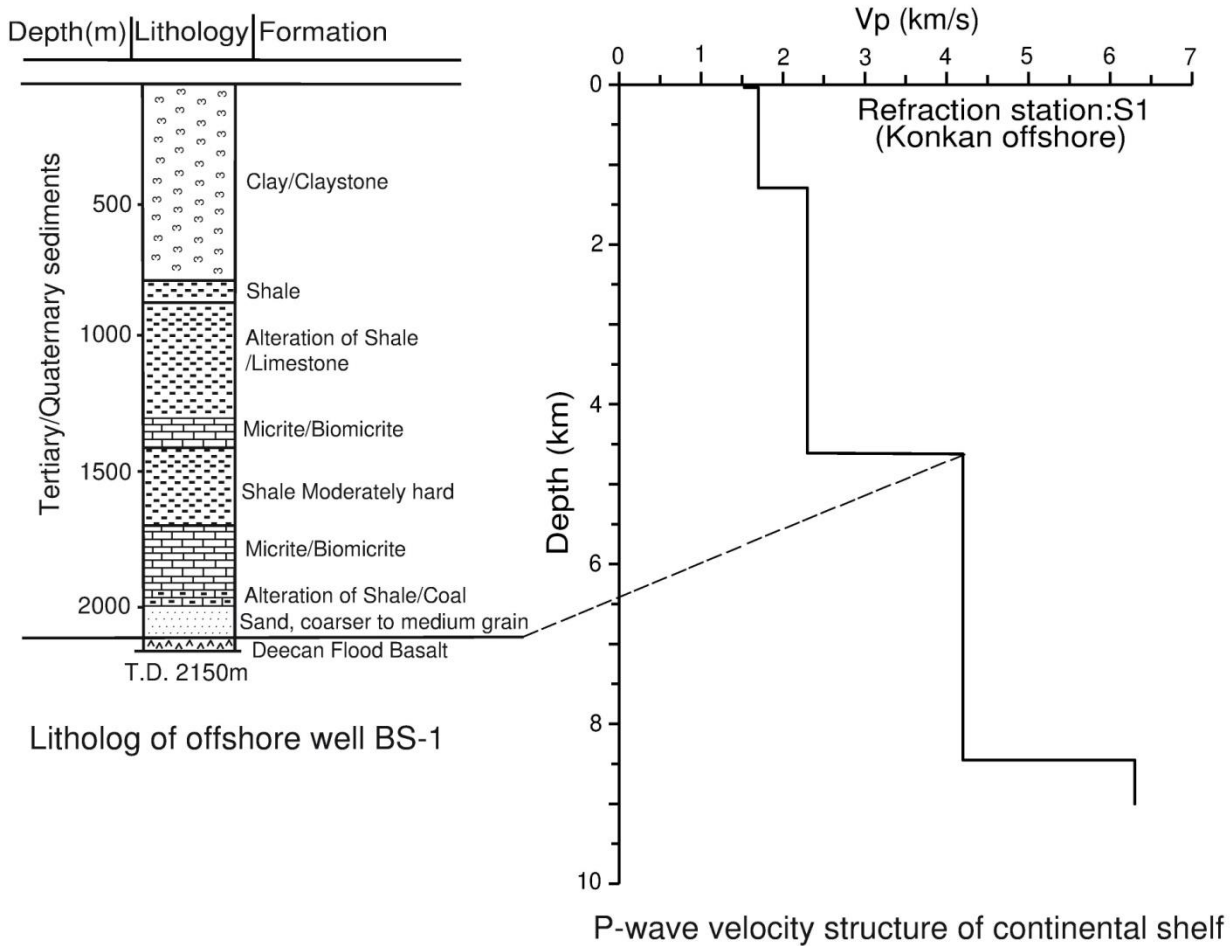


Fig. 3 Velocity-depth plot of Deep Seismic Sounding (DSS) profiles in Deccan Volcanic Province. P-wave velocity in Deccan flood basalt (shaded portion) varies from 4.3 to 5.2 km/s.



(a)



(b)

Fig. 4 (a) Correlation of sonic log and litholog of onshore well (Suthari) (modified from Pandey et al., 2009; Pandey et al., 2011) shows that P-wave velocity ranges from 4.5 to 4.6 km/s in Deccan flood basalt. Their further correlation with refraction derived P-wave velocity at refraction station GK2 (Gulf of Kutch) suggest that velocity of 4.3 km/s represents flood basalt. (b) Correlation of litholog data of offshore well (BS-1) (modified from Sahay, 1978) and refraction derived P-wave velocity at refraction station S1 (Konkan shelf) suggest that P-wave velocity of 4.2 km/s represents flood basalt.

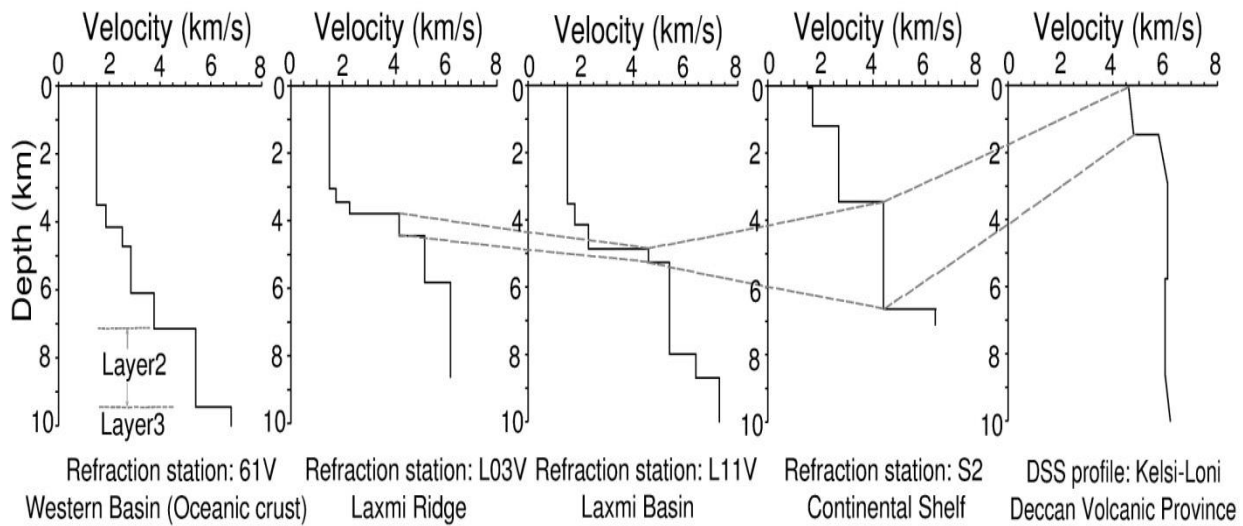


Fig. 5 Velocity-depth plots along an arbitrary line AB (shown in Fig. 2), starting from point A at Koyna (onshore region) and passing through refraction stations S2 (continental shelf), L11V34 (Laxmi Basin), L03V34 (Laxmi Ridge) and 61V34 (Western Basin). Velocity correlation from onshore region to the Laxmi Ridge along line AB reveals a consistent layer with P-wave velocity ranging from 4.2 to 4.6 km/s, which represents flood basalt. Such velocity range is absent in the Western Basin.

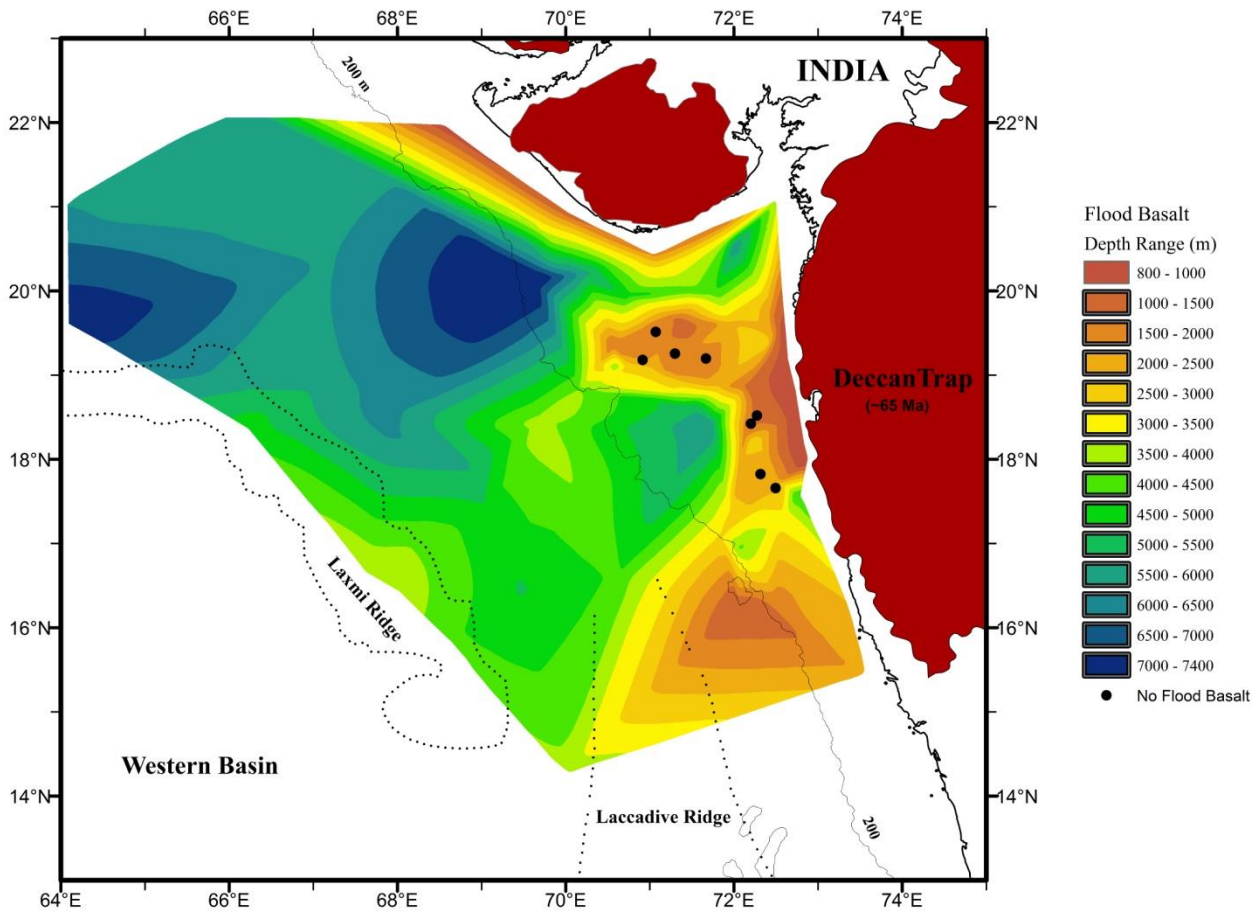


Fig. 6 Map depicting extent and depth of occurrence of flood basalt. Circles represent those drilled-wells which reached up to granitic basement without encountering flood basalt.

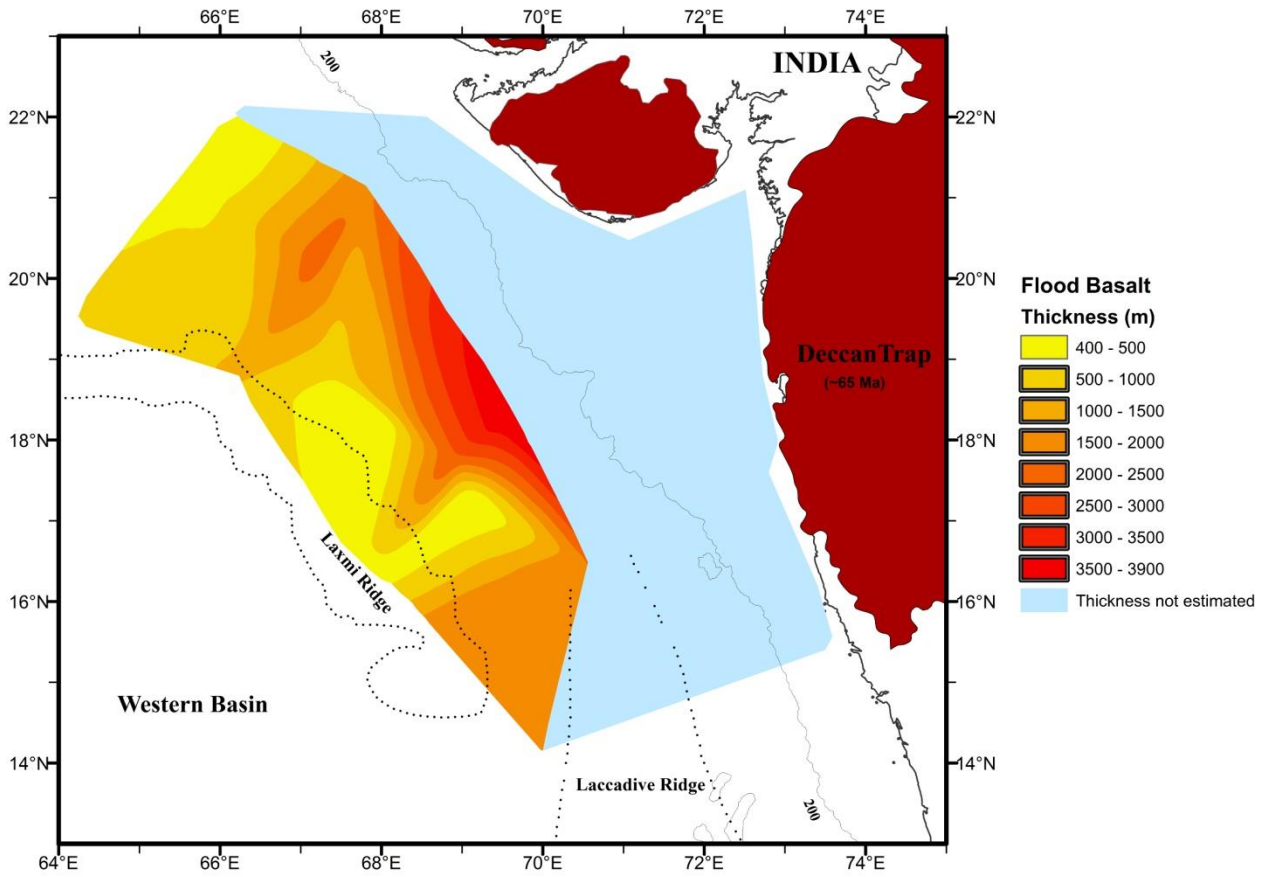


Fig. 7 Map showing thickness of flood basalt determined from the present study. Light blue color shaded area represents presence of flood basalt but its thickness could not be determined. Though a few refraction stations, in this area, do show thickness of flood basalt but they are too sparse to prepare flood basalt thickness contour map. Boundaries of the Laxmi and Laccadive ridges are shown with dotted curve.