Various Characteristics of Deccan Lava flow sequences identified in Core, Wireline and Seismic in Barmer Basin

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Keywords

Diagnostic of Seismic Signature of Deccan Volcanics in Barmer Basin

Summary:

Hydrocarbon exploration in rift basin where volcanics is a common rock type has been a challenge due to its complex nature and style of emplacement within a sedimentary succession. Volcanic emplacement, its erosion, and subsequent burial give rise to complex lithology due to hydrothermal alteration and diagenesis which has led to the drilling of many unsuccessful wells both in exploration and development stage. On the other hand, there are documented examples where volcanics has proved to be a part of a working petroleum system providing migration pathways, reservoir and active top and lateral seal. One major challenge with identifying intra or sub volcanic plays in rift basin for hydrocarbon exploration is poor seismic imaging. Due to the scale (meters of tens of meters) of individual volcanic facies, it is rather impossible to delineate those units individually from the seismic data due to its resolution constraint. In this study, integrating available core data, wireline data and regional 3D seismic data, we have delineated Deccan lava flow sequences and their special distribution in the Central Basin High area of Barmer Basin and demonstrate their implications on reservoir quality, top and lateral seal capacity.

Introduction

The Barmer Basin is a failed continental rift with at least 6 km of sedimentary fill located in the Thar Desert in Rajasthan, India. This basin is oriented more or less N-S, extending 200 km from the Cambay rift in south till Devikot High in the north. It is now established that multiple phases of rifting characterize the Barmer Basin related to India-Africa separation (185-165 Ma) followed by India-Madagascar rifting (92-84 Ma) and subsequent separation of India-Seychelles (70-65 Ma), with subsequent northward plate movement and then collision of the Indian plate with the Asian plate.The exploration activity has mainly focused on unlocking the potential of Fatehgarh reservoirs i.e. Upper Fatehgarh which is Paleocene and Lower Fatehgarh which is now called Ghaggar Hakra is the Cretaceous reservoir. The emplacement of Deccan volcanics is in between this two prolific Fluvial Fatehgarh Sandstone deposition.

In the past, igneous rocks haven't been a key focus for hydrocarbon exploration primarily due to enormous heterogeneity that they possess as compared to clastic sedimentary rocks. However, with recent intra-basalt in the Raageshwari field in the Barmer Basin and other intra-basalt (Mund et al, 2015) and sub-basalt commercial discoveries like Rosebank field within Paleocene-Eocene lava flows of Faroe-Shetland Basin, intra-basalt, and sub-basalt plays can be future of hydrocarbon exploration. Igneous activity in a sedimentary basin can impact all the five principle component of a petroleum system, affecting source maturation, providing migration pathways, reservoir, trap, and seal. With Raageshwari Deep Gas field already in production from Deccan volcanic reservoir, it has become important to understand the lava flow sequences to do strategic exploration and exploit volcanic reservoir within Deccan Volcanism province present in Barmer basin.

Deccan Volcanic Province (DVP) is one the voluminous Continental Flood Basalt (CFB) provinces in the world with a thick, flat-lying basaltic flow sequence presently covering an area more than 500000 sq. km in central and Western India (Figure 1). Considerable work has been done on DVP in terms of modeling the style of emplacement and morphology of lava flow. (e.g. Bondre et al., 2000,2004a; Managave, 2000; Duraiswami et al., 2001, 2003,2004; Jay, 2005; Sheth, 2006). Walker (1973) first used the terms "simple" and "compound" flows to characterize Deccan volcanic and Rajarao et al (1978) categorized them into simple and compound pahoehoe (Duraiswami et. al.2004).

Simple lava flows are abundant in the upper stratigraphic formation of DVP. They occur in the southeastern, eastern and northern part of DVP (figure.1) and exhibit Trappean landscape (Bondre et al, 2004). These flows which appear single unit at outcrop are very extensive and thicker as compared to individual flow lobes of compound pahoehoe. Compound pahoehoe of DVP occupy nearly half of the total area of the province and dominated the lower stratigraphy of DVP.

DVP architecture reveals that simple flows with sheet-like geometries were sub-aerially erupted over compound

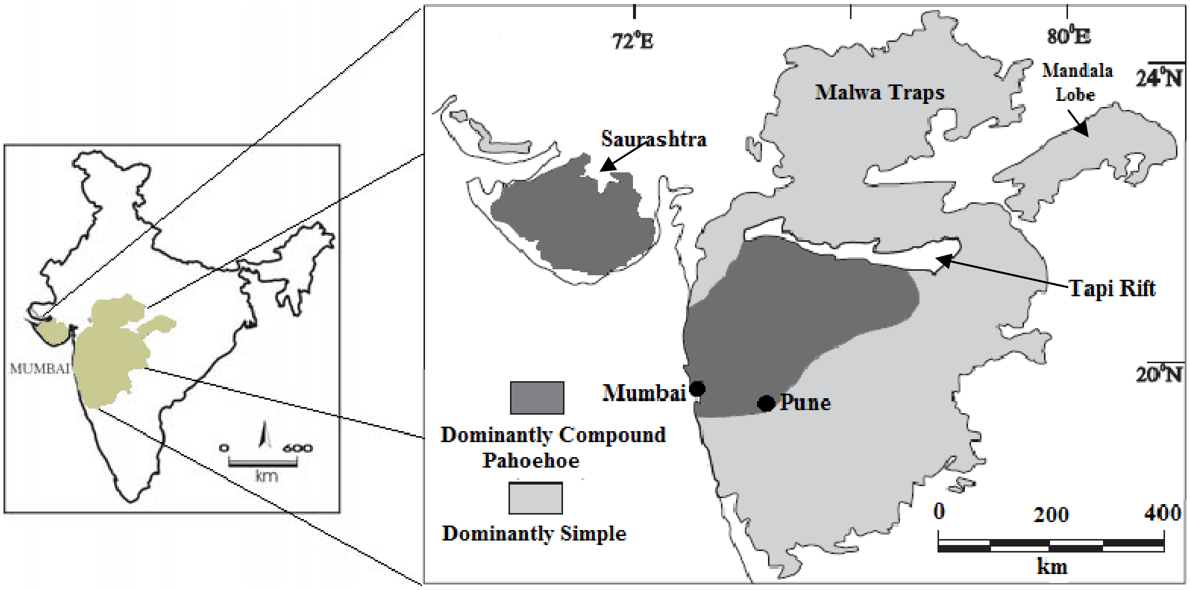

Figure:1 Map showing the outcrop extent of Deccan Volcanic and distribution of compound pahoehoe and simple lava flow (modified after Bondre,2001).

pahoehoe flows indicating a fundamental change in the flow emplacement with time (Duraiswami et al., 2001; Bondre et al., 2004a; Sheth, 2006). Flow morphology of DVP suggests low volume eruptions initially which sustained for significant time gradually transformed into high volume and high effusion rate eruptions giving compound and simple pahoehoe lava flow morphology. The effusion rate and volume erupted during later eruptive pulses were enough to produce laterally extensive simple lava flows.

Geological Setting for Deccan volcanics in Barmer Basin:

During Upper Cretaceous-Eocene time, Barmer basin evolved as a sedimentary basin in Western Rajasthan (fig 2). Barmer Basin developed under the extensional tectonic regime. As the basin was evolving it resulted in volcanic activity at rift margins. The main phase of rifting happened between Late Cretaceous to Mid Eocene with separation of Seychelles continent from western India and is contemporaneous with the main phase of Deccan volcanic eruptions. The common assumption is that the extension is from the impact of mantle plume activity in the Late Cretaceous caused by Reunion hotspot present beneath the continental crust when India was rapidly migrating northwards during middle Jurassic to Eocene (Collier et al. 2008); Armitage et al. 2010, 2011; Eagles & 85 Hoang 2014), however, there are alternate views as well about the cause of extension (Sheth 2005a; Sharma 2007; Collier et 93 al. 2008). In Barmer Basin Deccan volcanic extensively covers the southern part of basin mainly in Central Basin High (CBH) area and is U-Pb dated ~ 68 Ma. Central Basin High is a large rift center horst block located at the southern part of the Barmer basin(fig 2). The exploration wells drilled in the Raageshwari high horst block, Raageshwari South West and Raageswari North have penetrated a thick sequence of volcanic (~1500m) which are found to be of same age as that of Deccan basalts present further south (Dolson et.al.2015). Seismic mapping indicates the volcanism has covered the entire southern part of the Basin from Raageshwari to Guda area which is further south to Raageshwari field. The exploration wells drilled in the Guda area which penetrated the deeper section have also encountered ~1000m thick sequence of basalts. Currently, the volcanics in Raageshwari is divided into Prithvi and Agni members.

The **Prithvi member** volcanics in Raageshwari is of basic composition comprising of trachybasalts (hawaiite) and trachybasaltic (mugearite). This member does not have any acidic rocks within them (fig 4). The thickness of this member varied from 0-700m in the Raageshwari field. As identified from the logs and core, it consists of stacked sections of 15-40m thick cycles of extrusive basaltic lava flow units at the top which are associated with flow base, flow core and oxidized brecciated flow (fig 3). These flows are termed as rubbly pahoehoe flows or simple lava flows. As seen in the core, some of these flow units have well-developed soil horizon on top of it due to prolonged exposure and weathering before deposition of next flow unit(fig 3). They are rich in phenocryst of altered olivine, pyroxene, and plagioclase feldspar. Hydrothermal mineralization has variably altered these flows (fig 3). The basaltic lava flow is interbedded with

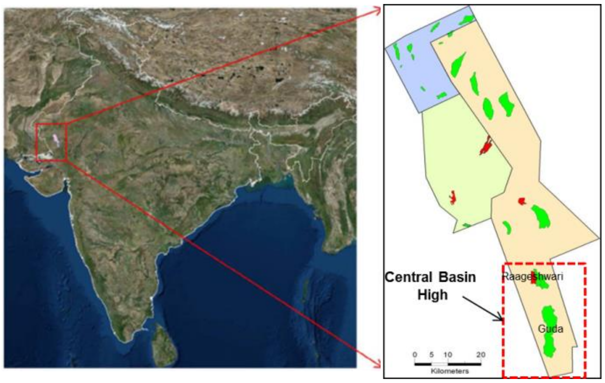

Fig 2: Location Map of Central Basin High (CBH) with Raageshwari and Guda Fields.

pyroclastic facies and partly welded tuffs. These tuffs are quite correlatable in logs over the entire Raageshwari area.

Flows of acidic igneous rocks which are termed as ignimbrites marks the top of the **Agni member** volcanics (fig 3).These ignimbrites contain fragments of the volcanic vents, along with pumice, glass and crystal pyroclasts. The composition of these ignimbrites varies from basanite to trachyte. This member also containg basic rocks (fig 4). Only ~550m of this member has been drilled till date and the base is yet to be drilled. From seismic, the thickness of this member is inferred in excess of 1000m.

The top of volcanic is an unconformity surface, irregular with considerable relief because of erosion. Overlying Paleocene volcanoclastic sediments formed by reworking of coarse clasts of basaltic lava in a sandy to muddy matrix forming the base of Fatehgarh Formation are onlapped on volcanics and transition between Fatehgarh- volcanics is quite sharp in the wireline logs (fig 3). Sonic log clearly shows the sudden change in velocity (fig 4).

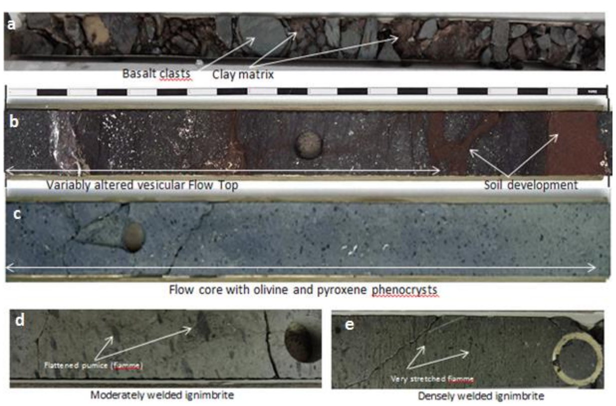

Fig 3: Deccan volcanics and overlying lower Fatehgarh rocks from the core of Raageshwari field wells (scale=1m). a) lower Fatehgarh with basalt clast in a clay matrix; b)soil developed over a highly altered flow top of a simple flow unit; c) a flow core; d,e) welded ignimbrite with flattened pumice (fiamme).

Methodology

Identification of Volcanics Facies from Core and Wireline Logs:

Different key volcanic facies have been identified from the study of different volcanic provinces worldwide. Based on their internal structure and external geometry, (Jerram 2002) characterized the continental flood basalt into four key facies.

Tabular-classic or Simple flows are thick (10-50m) extensive lava flow unit that cannot be internally divided into flow lobes. A simple lava flow of DVP consists of a flow base, flow core and a variably preserved, vesicular flow crust gradually transitioning into a discontinuous layer of oxidized flow top breccia. Pipe vesicles, segregations, and joints perpendicular to their base are also been seen in simple lava flow at the outcrop. A **compound-braided flow** is massive, constituted of tens of vertically superposed, laterally discontinuous flow lobes or flow toes of 10cm-3m thick. They are laterally heterogeneous. Compound pahoehoe flows of DVP consists of multiple, stacked flow lobes, sheets and shows a finer texture and different vesicle distribution pattern compared to simple lava flows. The **Intrusions** consists of internally homogenous dike and sills. Other facies is **Hyaloclastite**.

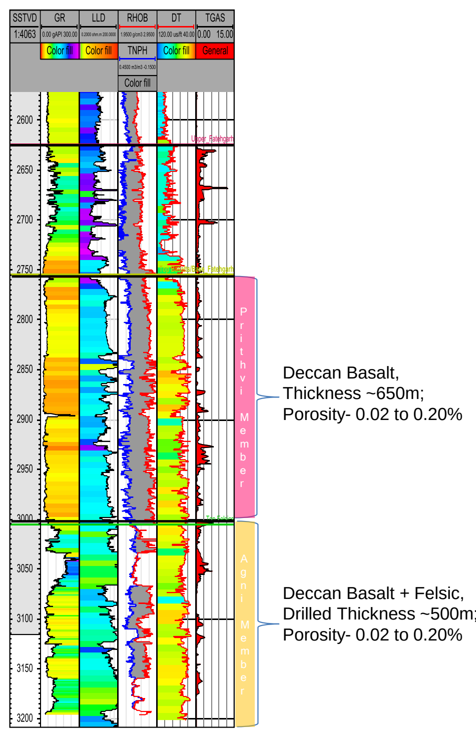

Fig 4: Deccan volcanics and overlying lower Fatehgarh rocks in Wireline logs of Raageshwari field

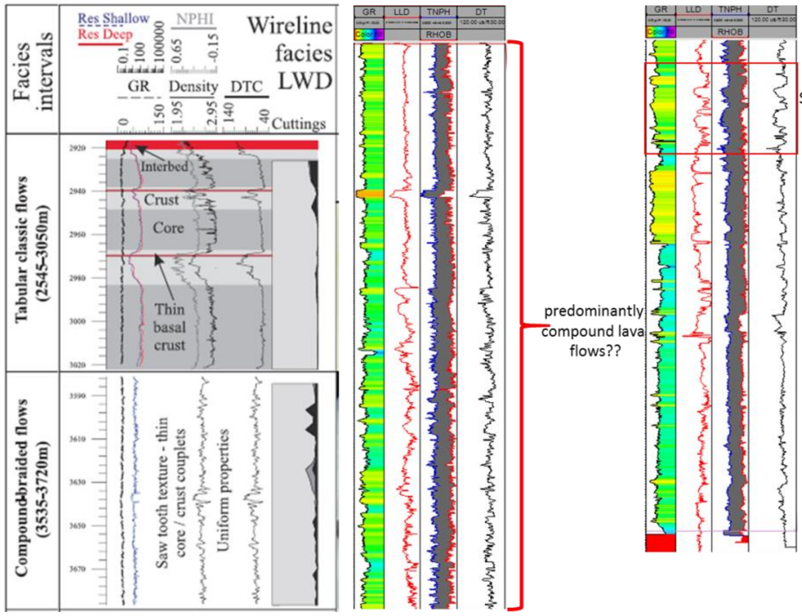

Fig 5: Identification of possible compound lava flows and simple lava flows in wire line logs. Log profiles on the left from Millett, 2016.

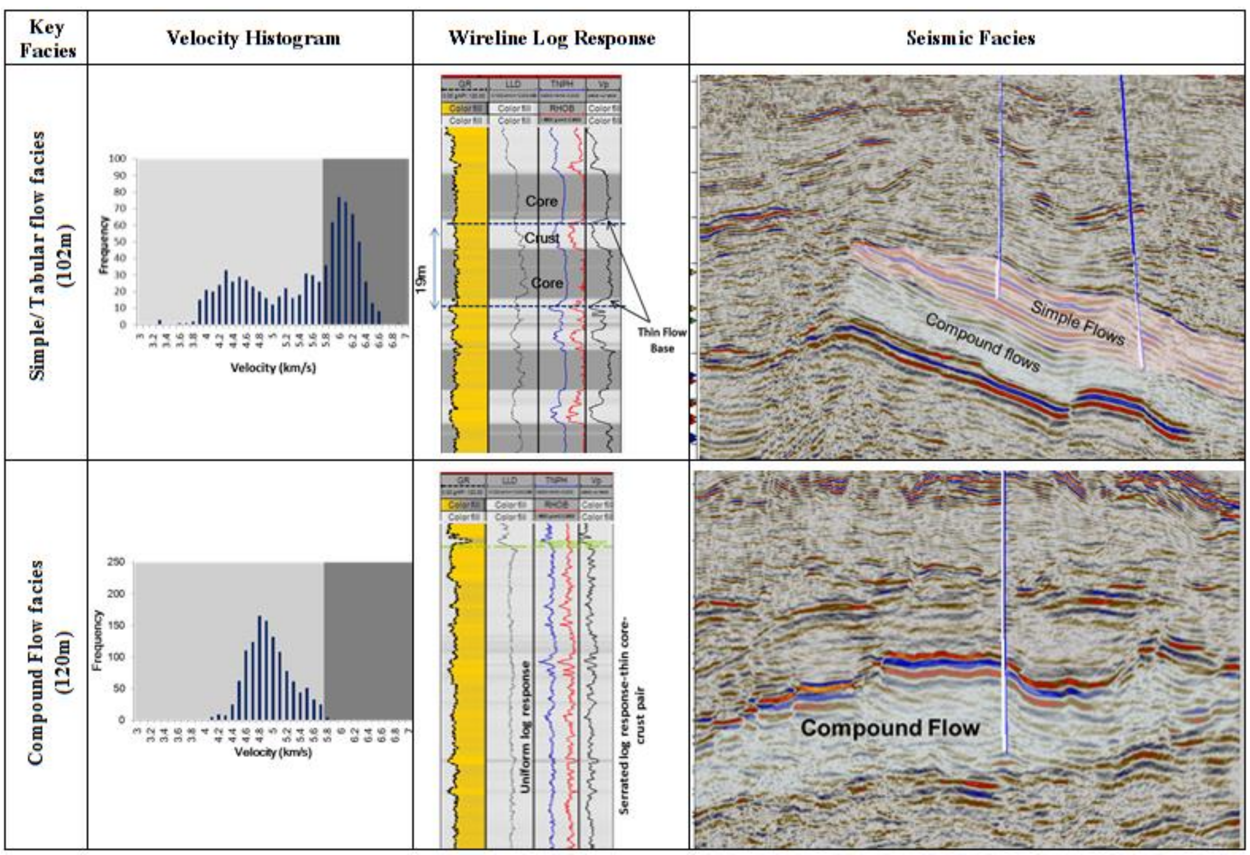

Fig 6: Summary of key facies velocity histogram from sonic log data, wireline response, and seismic response from Raageshwari and Guda, Barmer basin.

Nelson et al, 2004; Watton et al, 2014a, investigated volcanic facies from different volcanic margins and established the petrophysical and wireline log responses of main volcanic facies namely simple tabular lavas, compound-braided lavas, hyaloclastite, intrusions and interbeds. Nelson et al.2009, published the wireline profiles and velocity histogram profiles for identifying different volcanics facies and in this study, we have used these to identify volcanic facies in wells of Raageshwari and Guda area. Fig 5 shoes P wale velocity and density profile for lava flow facies as published by Millett (2016) from NE Faroe-Shetland basin.

Fig 6 shows wireline log behavior including velocity profiles for selected key packages of volcanic facies present in lava flow units of Prithvi and Agni members of Raageshwari filed. The 102m interval interpreted as Simple/ Tabular flow facies show a similar velocity histogram profiles and the wireline log behavior to that of proposed by Nelson (2009) using borehole data of Faroe Island and also shown by Millett (2016) from Faroe-Shetland basin giving confidence in facies interpretation of Raageshwari volcanics. Relatively low density and low p wave velocity of flow crust of Simple flow is because of high vesicle density and fracturing of crust as compared to flow core. Flow core is generally very dense and less altered than flow crust and base. Velocity of flow core (c. 6 km/s) is slightly higher than the velocity of Simple flow core (c. 5.8 km/s) of Faroe Island. This is attributed to the olivine concentration in flow core as demonstrated in Hawain Basalts (Manghnani & Woollard, 1965). The core data of Raageshwari also validates the wireline response against simple lava flow unit. A total of 11 flow units are identified in the interval and presented velocity histogram was prepared. Thickness of these units ranges from 6-20 m.

The compound flow facies interval also shows good accord with wireline response and velocity histogram presented for wells of Faroe Island (Nelson et al., 2009; Millett et al, 2016). The velocity histogram shows a restricted range and single peak distribution similar to presented by Millet (2016). The uniform/ serrated nature of log is attributed to thin flow core-crust and greater degree of alteration of compound flows. This section could not be validated due to absence of the core data; however, because of similar velocity histogram and log response from flows of Faroe-Shetland basin, we envisage it to be compound flow facies.

Volcanic facies in Seismic Data:

Seismic reflections also reveal the layered internal structure of upper basaltic lava flows presumed to have deposited by high volume, high effusion rate successive eruptions, very similar to the simple lava flow outcrops of Deccan trap seen in Mahabaleshwar. This layering can be seen in the seismic over the whole Raageshwari area. The layered internal structure is not seen towards Guda area and in the deeper part of the volcanics in Raageshwari area which is Agni member and not yet drilled suggesting the simple lava flows of Prithvi member is present locally in and around. The seismic facies of the Agni member is a transparent unit with no clearly visible internal reflections. Very low amplitude internal reflections are present at places but they are not laterally consistent giving rise to the possibility of compound lava flow unit present beneath simple lava flows of Agni member which is very typical of Deccan stratigraphy. Sonic and density log response of the well drilled in this transparent facies in Guda area also suggest the presence of compound flow unit. The seismic amplitudes are quite consistent laterally over the entire Raageshwari area but inconsistent on a regional scale because of the lateral heterogeneity of basaltic lava flows. Local change in seismic facies is also seen at some places due to lateral change is facies is also observed.

Conclusions:

Facies which are of tens of meter to kilometer scale affect the seismic response of the volcanic sequence. Simple flows show lateral continuity and are present as bright amplitude, continuous reflectors in seismic (fig 6). They allow better imaging than the diffused, complex reflectors of compound flow facies. Key volcanic facies identification by integrating core data, wireline log and interpreting those facies in seismic help us constrain the 3D nature and structure of Deccan volcanic sequence present in Central Basin High area of Barmer Basin. Key facies knowledge from borehole data and its validation against core data provided a control for inter-basalt facies interpretation. This is very useful in exploration as it allows defining volcanic boundaries and likely thickness of different facies. Such type of study also help us in devising future drilling strategy in volcanics as the rock properties of simple and compound flows are very different. By identification of key facies and mapping them in seismic, the occurrence and thickness of ‘hard’ and ‘soft’ basalt sections can be identified which can have huge implications while drilling exploration wells.

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