Reservoir Nature and Evaluation of Deccan Trap Basement, Cambay Basin, India

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ABSTRACT
The Deccan Trap basalts, laid down by multiple lava flows during Upper Cretaceous to Lower Paleocene form the basement throughout the Cambay basin. The basaltic basement has produced oil on commercial scale from some of the fields, notably Padra field, located near the eastern margin of the basin. A number of studies have been carried out to understand the nature of the Deccan Trap basement from hydrocarbon point of view. In the present paper, an attempt is made to synthesize various findings about the Deccan Trap basement. The analyses of cores and logs have shown the basement frequently fractured and altered. The fractures have played a key role in the alteration of basalt. The slightly altered to pristine (fresh) basalt has no inherent reservoir character, and fractures when present are generally healed. The completely altered basalt is dominantly smectite with no effective porosity and permeability. The moderately altered basalt which shows presence of spheroidal weathering both on megascopic and microscopic level with recognizable igneous texture hosts some porosity and permeability, and seems to be the reservoir rock. The pristine basalt and the completely altered basalt are probably acting as the cap rock. The petrophysical analysis of the Deccan Trap has been attempted. The integrated analysis of cores, logs and production data has enabled to identify and evaluate the oil bearing intervals in the trap section. With uniform PEF and uniform separation between density and neutron logs, the porosity has been estimated from sonic, density or neutron porosity logs by basic empirical relations. The estimated porosity of the reservoir rock ranges from 10 to 40%. The resistivity and porosity data on logRt-logφ plot exhibit linear R_o (100% water) line suggesting that resistivity, porosity and water saturation of the Deccan Trap can probably be linked through Archie’s relation. Thus, water saturation has been estimated by using Archie’s equation. The Trap section has been completed and tested barefoot generally. The processed results have shown good match with production data and production logging results. It is found that oil may be present in the top as well as in the deeper weathered intervals of the basement.

INTRODUCTION
The Cambay basin, host of several small and big hydrocarbon fields, is a narrow elongated rift graben extending N-S on the western margin of India. The basin has Deccan Trap as basement. These are basalts laid down by multiple lava flows during Paleocene to Upper Cretaceous times, and are extensive in the western part of Indian Peninsula. The Deccan Trap in Cambay Basin is overlain by thick sedimentary succession of clastic rocks. The sand-shale-coal sequences provide entrapment of hydrocarbons in several formations in a number of fields in the basin. The basaltic basement itself has produced oil on commercial scale from some of the fields located along the western margin of the Cambay Basin (Figure 1). Padra is the main field producing from the Deccan Trap basement. One of the wells of Gamij field has also given good production of oil from basement (Kumar et al., 2006). Oil has been struck in basement in Karjan near Padra field. Oil production from basement has also been reported from CB-ONN-2000/1 Block of Cambay Basin (Oilfield Review, 2009). The present paper reviews the nature of the Deccan Trap basement and its evaluation based on various studies.

DECCAN TRAP HYDROCARBON SYSTEM
Since the Deccan Trap yielded oil in Padra field, a number of studies have been carried out to know its reservoir characteristics, hydrocarbon entrapment mechanism and evaluation of reservoir parameters. Deccan Trap basement in Padra field is highly faulted with two sets of faults, one approximately N-S and another E-W dividing the area into several blocks. The N-S faults have resulted in N-S trending alternate horsts and graben structures which have bearing on hydrocarbon accumulation (Figure 2). In general, wells lying on the horsts are oil bearing while those falling in grabens are dry in the basement (Sinha et al., 1998). Different lava flows are recognizable on logs (Figure 3). Individual
lava flows have a layered structure. The bottom of each flow is massive basalt which grades into amygdaoidal and weathered basalt towards the top. Sinha et al. (1998) have attempted well to well correlation of different lava flows in Padra field. Detailed studies and experiments have been carried out on numerous core samples including 110m continuous core from basement (Pendkar et al., 1999, Kumar et al., 2002; Chatterjee et al., 2003). The XRD analysis has shown augite, plagioclase, magnetite, pegeonite, montmorillonite and chlorite to be the main minerals while olivine, serpentine, ilmenite, zeolite, calcite and silica to be present in traces. The core samples have shown basement to be fractured and altered in varying degree (Figures 4 & 5). The amygdales are also present but they are completely filled with zeolite, calcite, feldspar and other secondary minerals. The fractures consist of subvertical shear fractures and extensional horizontal/ subhorizontal fractures. The evidence for the shear fractures is reinforced with the presence of slickenside surfaces (Pendkar et al., 1999). The fractures are filled with mostly calcite and subordinate amounts of silica and zeolite/clay minerals all of which are low temperature minerals and were formed after the main igneous event. Fractures have also shown presence of dead oil/carbonaceous matter. Very few fractures are open with moderate parting space. During periods of quiescence, top surfaces of successive lava flows were exposed subaerially, and subject to weathering by physical and chemical processes. In presence of oxygenated water, chemical processes of oxidation and carbonation/hydrolysis led to the decomposition of unstable mafic and calcic minerals of basalt into stable oxide and clay minerals in varying proportions. The alteration process was accelerated by fractures which increased the surface area and acted as conduits for circulating ground waters. Thus fracturing and weathering are found to be interlinked. Some core samples have shown spheroidal weathering where the sharp corners and edges adjacent to fracture plane have been changed to concentric shells (exfoliation) by the intrusion of water through the fractures (Figure 4). During alteration, the fractures were gradually filled up by precipitation of calcite and silica from Ca and silica rich solutions released by leaching of mafic and Ca-rich plagioclase present in the basaltic rock. Although the fractures facilitated weathering/alteration of basalt, they probably do not have the storage capacity sufficient for hydrocarbon accumulation as they are generally healed. The production behaviour of wells and pressure build up study also indicate that Deccan Traps differ from a typical fracture reservoir. As per degree of alteration, the basalts can be classified into three categories- slightly altered to pristine (fresh) basalt, moderately altered basalt, and completely altered basalt (Pendkar et al., 1999). The representative core samples of these categories are shown in Figure 4. The slightly altered basalts have no inherent reservoir characteristics as they are massive, and the fractures when present are mostly healed. The completely altered basalts are dominantly made up of clay minerals-mostly smectite, and have lost recognizable textural attributes of igneous rock. These clays host microporosity, but have no effective permeability. The moderately altered basalts host remnants of spheroidal weathering on megascopic and microscopic scale. The alteration is partial with preserved igneous texture. These rocks host effective porosity and permeability, and are acting as reservoir rock. The slightly altered (fresh) basalts and completely altered basalts are acting as cap rock. These observations are supported by petrophysical analysis and production logging results as discussed later. Bharktya et al. (1997) have included volcaniclastic /intertrappeans along with weathered basalt as the main reservoir facies in Padra field. However, the presence of the volcaniclastic /intertrappeans, except few minor occurrences, and the role of these facies in oil production have not yet been substantiated by core and other data.

Long before Deccan Trap basalts came to be known as oil producer, they have been source of water through dug wells for centuries in the central parts of India. The hydrogeological studies have shown the weathered basalts to be the main aquifer horizons (Buckley et al., 1990; Singhal et al., 1997). The studies have also shown Deccan Traps to behave as multiple aquifer system because of presence of multiple layered flow units.

There are speculations about how the oil migrated to the Deccan Trap. The Cambay Shale of Lower Eocene age is the source rock in Cambay basin. It has thinned/pinched out towards the eastern and western margins. The oil probably migrated from central parts of the basin towards the up dip margins through faults and unconformities. Sinha et al. (1998) envisaged a model wherein the trap top unconformity together with EW and NS faults net work acted as migration fairway in Padra field. The trap top unconformity juxtaposition against the trap flows in the horst blocks charged the weathered trap layers above the juxtaposition depth (Figure 6). The presence of dead oil/ bitumen in the subvertical fracture planes formed by compressional stresses
indicates that the migration of hydrocarbon took place through these channels. It is likely that the oil migration took place in a narrow tectonic window when the openings were created and then probably partially sealed (Kumar et al., 2002).

Few initial wells of Padra field were completed and tested by conventional method i.e. by lowering casing against the basement, and yet produced oil albeit at low flow rates. Later, keeping in view the fractured nature of the trap basement, wells were completed barefoot in trap section by keeping casing shoe slightly down the trap top. Still later, in order to keep trap section totally intact from cement, a new practice was adopted according to which drilling was stopped near the trap top, casing lowered and cemented, and then narrower 6” hole drilled into the trap. The same practice is in use presently. The trap section has been drilled to varying thickness initially, but later the drilled thickness was standardized to 100m. Production logging and log analysis results have shown that some wells have produced from top portion of the trap (upper flows) while some have produced from the lower portion (deeper flows). It is interesting to note that unlike other hard rocks like granites etc., Deccan Trap basalts can have multiple pay zones corresponding to different flow units, somewhat similar to a sedimentary rock sequence. In some wells, 100% water level has been observed in the logs. It is about 150m below the trap top. However, a uniform water level in the whole area is unlikely due to presence of faults and non uniform weathering. Mud acid job is used for well activation. Some wells have produced on self flow. The individual well cumulative oil production from trap is as high as 41K MT. In barefoot completion, water control has been a major problem. Sand plugs have been used for isolation with limited success. Because of water problem, conventional completion by lowering casing against trap has been suggested on experimental basis (Sinha et al., 1998; Kumar et al., 2002; Varun et al., 2004). In Gamij field, one well has given very good oil production ($N_p \approx 33K m^3$) from Deccan trap top portion on conventional completion (Kumar et al., 2006). However, the other wells tested in Deccan trap gave poor influx of oil with water.

**LOG CHARACTERISTICS AND ANALYSIS**

Continuous cores have been matched with logs to know the log responses of different types of basalts and the prospective reservoir rock character (Figures 5). Photographs of some of the core samples are also shown. The core log relationship shows that massive fresh basalts are characterized by high density, low neutron porosity, low sonic transit time, high resistivity and very little or no borehole caving. On the other hand, weathered/ALTERED basalts show lower density, higher neutron porosity, higher sonic transit time, lower resistivity and occasionally some caving. The gamma ray log, although not very distinctive, shows lower values against weathered basalts generally. The MSFL log shows fractures very well. Remarkably, the photoelectric absorption coefficient (PEF) has almost uniform value close to 5 throughout the basalt section irrespective of fresh or weathered basalt implying that weathering/alteration of basalt has not changed its effective atomic number. Almost uniform separation between the density and neutron porosity logs is another significant log characteristic of the basalt section. Special logs like FMI and NMR have also been run in few wells in Padra field. While FMI borehole resistivity images are helpful in facies and fracture identification, the NMR log has not been much useful as it was severely affected by ferromagnesium minerals present in the basalts.

The weathered basalt layers can be identified easily by their log character as discussed above. However, to ascertain whether the weathered layers are oil bearing or not seems difficult. It is observed that resistivity and porosity logs show more similarity against the trap section in wells in which trap did not produce oil, and is mainly water bearing than the wells in which the trap produced oil. This is due to the fact that porosity tools respond to the oil and water more or less the same way whereas resistivity tool response is very different for oil and water. Therefore, a proper comparison of resistivity and the porosity logs should be able to bring out the oil bearing layers. Kumar et al. (2002, 2006), transformed porosity log, with the help of log-\(\phi\)-log\(R_h\) (Pickett) Plot, into equivalent resistivity (\(R_o\)) log assuming as if all the pores were fully saturated with formation water, and compared it with actual deep resistivity (\(R_o\)) log to delineate oil bearing layers. The Pickett Plot itself also gives good indication about the presence of oil in the trap section (Figure 7). The method also provides quantitative estimation of porosity and water saturation as discussed in the next paragraph. Attempts have also been made to know presence of oil in trap section by Resistivity-Acoustic Impedance Cross Plot (Prasad & Singh, 2002) and by Resistivity-Sonic or Neutron-Sonic overlays (Subba Rao, 2008). Based on the analysis of Padra wells, Kumar et al. (2002) formulated criteria for qualitative interpretation of trap section. As per the criteria, intervals having porosity more than 9%
(bulk density $\rho_b < 2.80 \text{ gm/cc}$, $\phi_N > 0.21$ and sonic travel time $\Delta t > 60 \mu\text{sec/ft}$) and resistivity more than 10$\Omega$m are likely to be oil bearing. However, in case of high porosity, the resistivity may be as low as 4Ωm in partly oil bearing intervals. Also, the resistivity curves LLD and LLS show separation ($R_{\text{LLD}} > R_{\text{LLS}}$), and MSFL which is normally higher than LLD and LLS (in case of fresh water mud) reads comparatively lesser against oil bearing intervals. Sometimes, good SP development is also observed against oil bearing intervals. It is also observed that oil bearing weathered layers sandwiched between thick massive layers make good producers. These observations are based on integrated study of logs, well testing results, production logging results and production data, and quantitative analysis of logs which is covered next.

In granitic reservoirs, which are more common in occurrence than Deccan Trap like basaltic reservoirs, the fractures play a dominant role, and, therefore, emphasis is on fracture characterization. As discussed earlier, Deccan Trap is not a typical fracture reservoir; it rather resembles, in certain ways, to conventional reservoirs. So evaluation of reservoir parameters of Deccan Trap is of particular significance. However, not much work on quantitative evaluation of volcanic formations like Deccan Trap is reported in the literature. Kumar et al. (2002, 2006) have attempted quantitative analysis of Deccan Trap with basic techniques as it is customary to apply basic log interpretation techniques to analysis of unconventional reservoirs. They have treated trap, from petrophysical point of view, as a single lithologic unit on the basis of uniform photoelectric absorption coefficient ($P_e$) and constant density- neutron separation, and have used the following basic empirical relations for porosity estimation -

$$\phi = \phi_N - (\phi_N - \phi) \text{ (From Neutron Log)}$$

$$= (\rho_m - \rho_b)/(\rho_m - \rho_l) \text{ (From Density Log)}$$

$$=(\Delta t - \Delta t_m)/(\Delta t - \Delta t_m) \text{ (From Sonic Log)}$$

where $(\phi_N)_{ma}$, $\rho_m$ and $\Delta t_m$ are neutron porosity, density and transit time for matrix respectively. Fresh basalt with zero porosity is the matrix. The values of the above matrix parameters have been chosen from the respective tool response against fresh basalt. These are $(\phi_N)_{ma} = 0.12$ 1pu, $\rho_m = 2.98 \text{ gm/cc}$ and $\Delta t_m = 47 \mu\text{sec/ft}$. The porosity values so obtained range 1-9% for slightly (fresh) basalt and 10-40% for weathered basalt, and as they represent total porosity, they are on the higher side than core derived effective porosities measured up to 27% value (Kumar et al., 1998). It was observed that porosity and resistivity data plotted on log-log scale i.e. log$\phi$-log$R_t$ Pickett Plot shows a well defined pattern. The points corresponding to least resistivity values (supposedly water bearing zones) show a linear trend, and can be approximated by straight line i.e. $R_o$ line (Figures 7, 8 & 9). The linear trend between log$R_t$ and log$\phi$ suggests that porosity and resistivity of the trap section follow Archie’s relation, i.e.

$$R_o = a \phi^m R_w$$

and

$$R_t = R_a S_a^{1-n}$$

The parameters $m$ and $aR_w$ in the above relation are obtained by the Pickett plot itself ($m$ is the slope of the $R_o$ line and $aR_w$ is given by $R_t$ corresponding to $\phi=1$). The values of $m$ and $aR_w$ are in the range of 1.3-1.7 and 0.3-0.4 $\Omega$m respectively. Resistivity $R_o$ is computed as above, and compared with $R_t$ to delineate the oil-bearing intervals (Figures 8 & 9). Water saturation $S_w$ is also computed by assuming $n=m$. Results of two wells processed with the above method are presented in figures 8 & 9. The figures show the Pickett plot, $R_o$- $R_w$, overlay, $\phi$, $S_w$ and $\phi S_w$ in addition to full log suite. The production logs are shown in the last two tracks. The processed results broadly agree with the production data and production logs. In both the wells, oil production is from the weathered basalt. The above method does not account for clay and ferromagnesian minerals present in the basalts. It may, therefore, have more uncertainty in the Deccan Trap than in the conventional formations. Nevertheless, the method is simple to use and provides a workable solution. It has scope for further improvement. Quantitative analysis by multimineral model has also been tried but it also has not given any better results.

**CONCLUSIONS**

The Deccan Trap basalts are intensely fractured and altered. The fractures have played a key role in the alteration of basalts, and during the alteration process they were gradually filled up by secondary minerals. The moderately altered basalt with recognizable igneous texture hosts some porosity and permeability, and seems to be the reservoir rock. The slightly altered basalt and the completely altered basalt are probably acting as the cap rock. They can be easily identified from well logs. The logs, particularly porosity and resistivity, are well behaved, and, hence, interpretable against the trap section. Criteria for identification of oil bearing intervals in the trap section have been formulated. The quantitative analysis has been attempted and
given satisfactory results with further scope for improvement. The log analysis and production logging results have shown that oil may be present in the top as well as in the deeper weathered intervals of the Deccan Trap.

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REFERENCES


Kumar, A., Pendkar, N. and Sangeeta, 2002, Delineation and evaluation of basaltic Deccan basin reservoir of Padra Field, Cambay Basin, India- a field study, paper AA, in 43rd Annual Logging Symposium, Transactions: SPWLA


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Ashok Kumar is Dy. General Manager in Well Logging Services, ONGC, Vadodara. He joined ONGC Ltd. in 1982 and started his career as logging field engineer. Later, he worked as a log analyst and undertook several projects as team leader in K.D.M.Institute of Petroleum Exploration, Dehradun. He was also involved as a faculty member in several training programmes for ONGC officers and university students. He conducted courses on log interpretation at ONGC Academy, Dehradun. During his recent tenure in Assam Asset Nazira, he carried out a comprehensive study of Lakwa field for its current status and production enhancement. He has about fifteen publications. He earned his M. Tech with gold medal in Applied Geophysics from University of Roorkee (now IIT Roorkee) in 1980. He is a member of SPWLA.
Figure 2. Structural style of Padra Field depicting the faults pattern. The faulting activity has given rise to successive horst (Brown) and graben (Yellow) blocks. In general, the wells falling on the horsts are oil bearing in the Deecan Trap while those falling in the grabens are dry. (After Sinha et al., 1998)

Figure 1. Location of Gamij and Padra-Karjan Fields and CB-ONN-2000/1 Block in Cambay Basin. The Deecan Trap outcrops around Cambay Basin are also shown.
Figure 3. Log suite against the Deccan Trap in Padra field. Different lava flows of Deccan Trap can be identified with the help of porosity logs - sonic, neutron and density, and resistivity logs. Each flow starts with massive fresh basalt at the bottom and gradually changes to weathered/ altered basalt towards the top. The porosity development in weathered basalt is reflected by the logs.
**Completely altered basalt:** Basalt has completely altered to smectite. It has lost textural attributes of igneous rock. Probably the alteration took place on or near surface in hot and humid climate. With extremely low permeability, rock of this type can not make a good reservoir but may act as a cap rock.

**Intensely fractured basalt:** Dark greenish grey basalt with intense fracturing. The fractures are subhorizontal to subvertical filled with calcite veins. The amygdules are also filled with greenish clay minerals with no open space. The core piece is very fragile and broken up into a number of pieces along the fracture planes.

**Moderately altered basalt:** Basalt is moderately altered, shows exfoliation structures and remnants of spheroidal weathering both on megascopic (Left) and microscopic scale (Right). The alteration is prominent along the fracture planes. The fractures are filled with calcite/zeolite. The moderately altered basalt probably makes good reservoir by development of open space associated with limited alteration and development of channel porosity.

**Amydaloidal basalt:** Dark grey basalt with amygdules and vesicles. The vesicles are filled with crystalline zeolite. Petrographic examination shows that basalt is made up of Ca rich plagioclase, pyroxenes (mostly augite), and magnetite. Olivine microphenocrysts are present as weekly developed euhedral crystals. Amygdules are filled with dark greenish chlorite clusters, silica and fibrous zeolites.

**Fresh (pristine) basalt:** Unaltered massive basalt with hairline fracture. Petrographic examination shows that it is made up of fine grained plagioclase and ferro-magnesian minerals. The fresh unaltered basalt with mostly healed fractures has no inherent reservoir characteristics but it can act as cap rock.

Figure 4. Deccan Trap Core samples from Padra Field showing basalts of different categories. The moderately altered basalt with recognizable igneous texture hosts some effective porosity and permeability, and is acting as suitable reservoir rock. The completely altered basalt and unaltered fresh basalt are acting as cap rock.
Figure 5. Composite log suite vis-à-vis core lithology of a Padra well where continuous coring was done in Deccan Trap. Photographs of some of the core pieces of some of the cores are also shown against the respective cores. Hydrocarbon shows were observed in the weathered/ altered portions of CC-10, CC-11, CC-12 and CC-17. On testing (barefoot), well became active after mud acid job and compressor applications, and gave influx of 6.36 m$^3$/d liquid with 57% oil and rest water. (Photos courtesy RGL Lab, Vadodara)
Figure 6. Geological cross section depicting possible mechanism of oil migration to Deecan Trap in Padra field. In the above model, the trap top unconformity together with the faults network is envisaged as migration fairway from central deeper parts of the basin to shallower margins. The juxtaposition of the trap top unconformity in the hanging wall against the trap section in the footwall charged the weathered layers of the trap section. The model is supported by well data and PLT results. (After Sinha et al., 1998)

Figure 7. Log Rt - Log $\phi$ Pickett cross plots of Deecan Trap sections in two wells A and B of Gamij Field. The least resistivity values corresponding to water bearing layers show a linear trend and can be approximated by straight $R_o$ line. The range of resistivity values above $R_o$ line and the porosity values indicate the hydrocarbon potential of the well. From comparison of the two cross plots, Well-A has more potential than Well-B. Well-A gave 33K m$^3$ cumulative oil in conventional completion while Well-B yielded water with traces of oil on testing in barefoot condition.
Figure 8. (Top) Pickett cross plot; (Bottom) open hole logs (1st to 5th tracks), processed results - R_o & R_t overlay (6th track), S_o, \phi and \phi S_o (7th track), and PLT logs (8th & 9th tracks) of one of the best producing wells of Padra Field. As per log analysis, the weathered trap intervals 626-664m and 685-696m are the major oil bearing zones. The lower zone is the major contributor as per PLT survey. The well has given about 41K MT cumulative oil production from the trap section on barefoot completion, and is still flowing oil @ 5m^3/d on SRP.
Figure 9. (Top) Pickett cross plot; (Bottom) open hole logs (1st to 4th tracks), processed results- \( R_o \) & \( R_{t} \) overlay (5th track), \( S_w \), \( \phi \) and \( \phi S_w \) (6th track), and PLT logs (7th & 8th tracks) of another well of Padra Field. The log analysis shows weathered trap zones 684-700m and 655-660m as the major oil bearing intervals. The middle interval 666-678m is mainly water bearing. The PLT survey shows interval 684-700m to be the major producing layer. The well cumulative production from the trap section is 6.7K MT oil and 2.2K m\(^3\) water on barefoot completion.