Hydrocarbon Prospectivity of Deccan Trap in Northern Cambay Basin

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Summary

Hydrocarbon discoveries have been made on the north-eastern rising flank of Cambay Basin in reservoirs within Kadi and Olpad formations. Considerable thickness of Deccan Trap is drilled in some wells in the study area and intervals are tested conventionally with promising results. Commercial production of oil from Deccan Trap in Padra and Gamij fields situated further south of the study area near the eastern basin margin proves that Deccan Trap can constitute a viable hydrocarbon reservoir in Cambay Basin. Interpretation and Integration of 2D & 3D seismic data with well data has brought out possible fracture trends and the probable locales for exploration of Deccan basalt reservoir in northern part of Cambay Basin. This paper is an attempt to address the hydrocarbon prospectivity of Deccan Trap in the north-eastern part of the basin by integrating well logs, borehole images & seismic data to explain reservoir properties and the role of faults & fractures in hydrocarbon charging & entrapment. Also discussed is the origin and development of basalt flows as a reservoir, identification and evaluation of trap reservoirs in drilled wells, study of fractures and their relationship with seismic-scale faults, and analysis of initial testing results of objects tested in Deccan Trap section.

Keywords: Deccan Trap, Cambay Basin

Introduction

The study area is situated on the north-eastern rising flank of Cambay Basin (Fig.1). The petroleum system in this part of the basin consists of Cambay shale acting as source rocks, sands within Kalol and Kadi formations constituting the reservoir rocks and Tarapur formation acting as regional cap rock. Cambay Shale acts both as dominant source rock as well as cap rock. Hydrocarbon discoveries have been made in reservoirs within Kadi, Cambay shale, and Olpad formations. Re-interpretation of borehole images of one of the drilled wells that was tested in Cambay Shale indicated that the object which produced oil on testing is actually perforated in a fractured zone in Deccan Traps. This observation prompted us to study well data of all the wells in the area, which brought out that many wells have actually penetrated Deccan Traps. The drilled trap section ranges from about 50m to 400m. Modern multiple depth-of-investigation resistivity logs are available in many wells, and these logs show very clear invasion profile in some of the zones within Deccan Traps where the neutron-density logs show development of porosity. This indicates development of permeable layers within Deccan Traps. Also, the borehole images show presence of vesicles, fractures and weathered zones. Oil shows were observed during drilling of such zones in some wells and frequent mud losses were also observed. Some wells were tested conventionally during initial testing; however, these zones did not become active (except in one case), probably due to cement invasion in fractures during casing cementation. At that time, these zones were interpreted as belonging to Olpad formation based on cuttings description (as Trap derivatives and clay).

Commercial production of oil from Deccan Traps in Padra and Gamij fields situated further south of the study area (Fig.1), near the eastern basin margin of Cambay Basin proves that Deccan Traps can constitute a viable hydrocarbon reservoir in Cambay Basin.

Detailed characterization of fractures seen on borehole images and their relationship with seismic-scale faults has been studied to explain migration and accumulation of hydrocarbon in these basaltic traps.

In this paper, hydrocarbon prospectivity of Deccan Trap is discussed, starting from origin and development of basalt flows as a reservoir, identification and evaluation of trap reservoirs in drilled wells, study of fractures and their relationship with seismic-scale faults, and analysis
of initial testing results of objects tested in Deccan Trap section.

Fig. 1: Generalized tectonic map of Cambay Basin with location of Study Area (modified from source – DGH, India)

**Basalt - Rock to Reservoir**

To appreciate the concept of basalts as reservoir rocks having porosity and permeability, it is essential to understand the processes involved in genesis of basalt flows, flow types, cooling processes, diagenesis, weathering, and genesis of fractures in basalts.

2.1 Genesis of basalt flows and vesicles

When basaltic melts are formed at depths of several kilometers below the surface of the Earth, they contain enough Carbon Dioxide to be above the solubility limit (Sylvie Vergniolle, 1996). This results in formation of gas bubbles which rise through the magma and expand. This leads to an intermittent behavior during basaltic eruptions with alternating phases of gas-rich explosions, called fire fountains, and gas-poor lava effusions. This cyclic activity continues till there is formation of fresh bubbles in the magma. When the gas flux decreases below a critical level, continuous lava effusion takes place.

The Deccan basalt flows are said to have evolved from fissures covering a wide area resulting in flood basalts of Pahoehoe type. Pahoehoe lavas are emplaced by inflation - the injection of molten lava underneath a solidified crust. During inflation, a flux of fresh, bubble-laden lava is continually brought into the lobe. Bubbles from the moving lava are trapped in the crust, forming vesicles. Depressurization from the formation of a new breakout leads to a pulse of vesiculation within the liquid lava (Hon et al 1994). These bubbles are trapped to form a horizontal vesicular zone. Meter-scale pahoehoe lobes can coalesce laterally during inflation, producing sheets hundreds or even thousands of meters wide. Such immense sheets are also meters to tens of meters thick and range in length from hundreds of meters to perhaps as much as several tens of kilometers (Self et. al., 1997). Borehole image logs of Deccan Trap section in the area clearly show presence of these vesicular zones (Fig.2).

Thus, basalt flow does not result in a massive crystalline layer with zero porosity but forms alternations of crystalline and porous layers due to formation of vesicles.
These vesicles can be very big in size and can get connected during degassing.

2.2 Role of Fractures in porosity and permeability development:
Another important phenomenon providing permeability is fracture development due to differential cooling rates of the upper and lower surfaces of the lava flow compared to its interior. Different types of fractures have been identified and classified for basalt flows: Column-bounding, column normal, and entablatures fractures. The forth type, inflation fractures, are produced by the mechanical effect of inflation of the flow (C.J. Schaefer et al, 2004).

2.3 Relationship of natural fractures and vesicular layers
The vesicular layers become weak planes along which the natural horizontal fractures travel and provide connectivity between vesicles (Fig.3). Hydrocarbons can migrate through these fractures and accumulate in the vesicles. Thus, the interconnected vesicles provide storage space and the fractures provide the permeability to basalts.

Extensive formation pressure tests were carried out against Deccan Trap section in some of the drilled wells. Integration of pretests and borehole images has brought out that pretests attempted against fractures resulted in seal loss, whereas some pretests against vesicular zones were successful. For example the pretest carried out at 1805m in Well-B resulted in lost seal (Fig. 4). The borehole image clearly shows presence of an open fracture.

Pretest at 1962m in Well-C in a vesicular basalt layer was successful giving formation pressure of 3253.75 psi and drawdown mobility of 0.9 md/cp (Fig. 5).
This observation is significant as Deccan Traps are not like typical basement reservoirs with only fracture porosity. Vesicular porosity can provide significant storage space for hydrocarbons and fractures can provide good permeability.

2.4 Fractures due to Tectonic Stresses
The stress related fracturing of basaltic rocks associated with extensional, seismic-scale faults is probably another very important porosity and permeability development phenomenon in Deccan Traps. Three basic structural trends NNE-SSE Dharwar trend, N-S to NNE-SSW Delhi- Aravali Trend and ENE-WSW Satpura-Narmada trend corresponding to major tectonic episodes, have strongly influenced the overall tectonic framework of the Cambay basin (Kundu and Wani, 1992). Particularly, the NNE-SSW strike-slip faulting connects the depocenters of Cambay Basin to eastern flank where fields like Padra and Gami, producing oil from Deccan Trap, are located. Well-G in the study area has produced commercial quantities of oil from a fractured interval (Fig. 6).

2.5 Diagenesis and porosity alteration
Mineralization of vesicles and fractures is the major cause of destruction of porosity and permeability in basalts. Basalts alter to clay minerals under certain conditions and this destroys the rock texture of basalts. These phenomena are seen on cores of Padra field and Micro-resistivity borehole images of drilled wells in study area.

Identification of Basalt with wireline logs
Trap sections can readily be identified from wireline logs by observing the cyclic nature of basalt flows on density-neutron logs. Alternating high density and low density layers represent stacking of number of basalt flows, with each flow starting at the base with high-density fresh, unaltered basalt overlain by Flow-top breccia/weathered/vesicular low-density basalt. Neutron log follows parallel to density log with almost constant separation. The Resistivity and sonic logs also shows similar alternating high resistivity/velocity, low resistivity/velocity layers. These log responses represent the characteristics of inflated Pahoehoe basalt flow lobes, where a single flow contains a small lower crust followed by a dense core, overlain by the upper crust, which has many vesicular zones and vesicular sheets. This flow is overlain by another flow, and another, giving rise to such log response. Fig. 7 shows a typical log of Deccan Trap section in Well-A.

The top of Deccan Trap is difficult to demarcate just from openhole logs, as the top of the last basalt flow is usually weathered and has often the same density/resistivity/sonic travel time as the overlying sediments.

Micro-resistivity borehole static and dynamic images can unambiguously identify Deccan Trap section as the characteristic features of basalt flows, viz., vesicular zones and criss-crossing entablature fractures of dense core are clearly visible. Also, the overlying Olpad formation is uniquely identified as sub-angular trap derivatives floating in a clay matrix. This makes it easy to demarcate top of Deccan Trap from borehole images (Fig. 9).
The Olpad formation comprises mainly trap derivatives with clay, claystone and minor sand. The trap derivatives with pebbles and granules unconformably deposited over lava flow of the Deccan Trap. The Olpad formation on borehole image is identified as pebbles floating in clay matrix (Fig. 9).

**Formation Evaluation of Deccan Traps**

Not much work is reported on formation evaluation of Deccan trap reservoirs using conventional logs. Ashok Kumar (2002, 2006) has attempted quantitative analysis of Deccan Trap with basic techniques.

When porosity and resistivity data of trap sections are plotted on log-log scale (log $\Phi$-log $R_o$) i.e. Pickett plot, the points corresponding to low resistivity values show a linear trend, and can be approximated to a straight line corresponding to 100% water bearing formation, i.e. $R_o$. This linear trend suggests that porosity and resistivity of trap section follow Archie’s relation.

$$R_o = a \cdot \Phi^{-m} + R_w$$

The Pickett plot in Deccan Trap section of Well-A (Fig. 8) clearly shows a linear trend on the left side of the cluster of points. Similar trend lines are observed in producing wells of Gamij and Padra fields. This straight line corresponds to water bearing sections. The points to the right of this straight line correspond to higher resistivities due to presence of oil. Total porosity has been estimated from bulk density log and water saturation is estimated using Archie’s equation. Oil bearing zones were identified in Deccan Trap section based on this analysis in six wells in the area.
DT-RT overlays were made to identify zones showing positive separation (i.e., RT > DT) (Fig.10). Such zones invariably show good invasion profile and Sw << 1.0, suggesting permeability and possible hydrocarbon charging.

Integration of Logs and Seismic data

Deccan Trap top was mapped on all the available 2D and 3D seismic lines by calibrating with Deccan trap tops identified from well logs and borehole images. Time structure map at the top of Deccan trap was prepared (Fig. 11). The sedimentary thickness in the basin increases from NE to SW.
The correlation of Deccan Trap top across wells has brought out that one old well in Unawa area is producing oil from Deccan Trap since last 24 years. The conventional log motifs of this well also suggest that the producing zone is within Deccan trap.

The log motifs of Well-A are presented in Fig. 7. The fresh basalt has density of about 2.9 gm/cc, whereas the weathered zones have density of about 2.4 to 2.5 gm/cc. In the interval 1246 – 1266m, conspicuous invasion profile can be seen on the resistivity logs (Fig. 7, 10).

Borehole images of interval clearly 1257.5-1262m show vesicular porosity development and presence of healed fractures (Fig.12).

It is observed from the Wulf Stereonet - Rose diagram of dip direction (Fig. 13) that majority of fractures are dipping towards NE at around 70 to 80° with few fractures dipping towards West.

The hydrocarbon is expected to migrate from the deposition lows in the SW to the NE direction through N-S and NNE-SSW trending cross faults and accumulate in potential traps aligned in NW–SE direction (Fig.14). In Well-A, fractures are dipping towards NE and the fault very close to well is dipping towards SW (Fig. 15). So, there is likelihood of hydrocarbon charging to the well through fractures connected to the main fault.
Another example is presented here to clarify the role of fault and fracture orientation in hydrocarbon migration and entrapment. Well H is situated further south-east of Well A. About 160m of Deccan Traps section is drilled in this well. However, no hydrocarbon indications are seen on the logs. The Borehole image shows high angle, partially open fractures dipping towards NE direction (Figs. 16 and 17). The fractures and the fault in the north of the well, both are dipping towards NE (Fig. 18). The chance of cross cutting between fractures and faults seems remote.

Fig. 15: Seismic line passing through Well-A. The well is charged through fractures associated with the secondary faults (red) antithetic to the main fault (black). Fractures are dipping towards NE and the fault very close to well is dipping towards SW.

Fig. 16: Wulf Stereonet - Rose diagram for fracture dips picked up on borehole images of Well-H in Deccan Trap Section. The major dip direction is North-East.

Fig. 17: Well-H Borehole image showing fractures dipping in NE direction.
Fig. 18: Map view of faults in Well-H area, and fracture dip azimuth rose diagram at Well-H. Fractures are dipping towards NE and Fault to the North of the well is also dipping towards NE. The chance of cross cutting between fractures and faults seems remote.

This could explain the absence of hydrocarbons in the trap section in this well in spite of having a local basement high and number of partially open fractures. The development history of Padra field points out to this where a large number of dry wells were drilled though these were located near faults (Sushil Kumar, 2011).

**Understanding of migration, charge and entrapment**

The migration of oil from the source rock of Cambay shale formations to Deccan Traps may take place in two ways. First, the oil generated in the overlying sediments above Deccan Traps can be squeezed out in the top, weathered layer of Deccan Trap due to overburden pressure. This weathered layer can help in the migration of oil up-dip, locally to suitable places providing entrapment conditions. Dead oil was observed during drilling weathered top of Deccan Trap in Well-D (Fig.19). Second, the faults cutting across Deccan Traps, Olpad and Cambay shales may provide permeable conduits for oil to migrate for long distances and charge porous and permeable beds up-dip within Deccan Traps. Particularly, the N-S and NE-SW trending faults in areas near north-eastern flank can bring hydrocarbons from deeper parts of the basin and charge basaltic layers up dip (Fig. 19).

As most of the wells in the northern area were targeted at fault closures for Kadi formation/Cambay shale exploration, almost all wells have shown indications of oil in Deccan Traps as well.

The characterization of fractures and study of their relationship with faults in the wells has brought out that the stress relieving fractures antithetic to seismic scale faults can provide the charging mechanism whereas the juxtaposition of non-vesicular layers against connected vesicular beds and up dip pinch-out of vesicular zones may provide the entrapment.

Fig. 19: N-S and NE-SW trending faults providing migration pathways (red arrows). The area near the faults (yellow) could be the primary targets for oil exploration in Deccan Trap.

**Quality of Oil in Deccan Trap**

In northern Cambay basin, the quality of oil in Kalol formation is bio-degraded due to percolation of meteoric water along faults. Almost all the fields in the area are producing heavy oil from Kalol formation. Linch pay is producing oil of 33° to 39° API from lenticular sands within Cambay shale (Table 2).
<table>
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<tr>
<th>Field</th>
<th>Formation</th>
<th>Depth m</th>
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<td>Lanwa</td>
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Table 2: Oil density in producing fields near study area (Source: Modified from Oil & Gas Field of India, Lakshman Singh, 2000)

Within the study area, the oil gravity is 16° to 31° API in Kadi formation. Deccan Trap has produced oil of 35° to 39° API from two wells in the study area.

It seems that Cambay Shale provides barrier to percolation of waters and preserves the oil quality in underlying reservoirs (Fig. 20).

Conclusions

- Oil bearing zones are interpreted in 6 wells in the area in Deccan Trap based on oil shows during drilling / interpretation of log motifs.
- One well has produced commercial quantity of oil during initial production testing after lowering casing and perforating a 4m zone in fractured basalt near top of Deccan Trap.
- One nearby well in Unawa area is producing oil from Deccan Trap since last 24 years. This conclusively proves prospectivity of Deccan Traps in this part of the basin.
- Deccan Traps can be identified from well logs and Micro-resistivity borehole images. It is sometimes difficult to distinguish Deccan Traps from overlying Olpad formation from drill cuttings as highly altered basalt results in clays, so cuttings of Deccan Trap are described as trap derivatives/clay. The top of Deccan Traps could be successfully traced on 2D and 3D seismic lines, particularly in shallower part of the block.
- Integration of micro-resistivity borehole images and formation pressure test results point towards existence of primary (vesicular) porosity and secondary (fracture) porosity in Deccan Traps. Also, presence of mega-vesicles seen on borehole images of some wells and resistivity logs showing good invasion profile indicates that vesicular zones can be good reservoirs.
- Fracture characterization based on micro-resistivity borehole images has brought out preferred fracture orientation at each well location. The fractures are generally related to faults as stress relieving antithetic fractures. These fractures can provide conduits for hydrocarbon charging through faults.
- The study of fault pattern in the area coupled with occurrence of oil bearing zones in the Deccan Trap suggests that the N-S and NE-SW trending faults are the main migratory pathways for oil. Thus, areas of local highs near these faults could be the main targets for exploration of Deccan Trap in northern part of Cambay Basin.

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References


Ashok Kumar, Formation Evaluation of Unconventional Basaltic Deccan Trap, Basement Reservoir of Gamij Field, Cambay Basin, India.


Sushil Kumar, Fracture Characterization and its Significance in Production from Unconventional Fractured Deccan Trap Reservoir, Padra Field, Cambay Basin, India, GeoIndia 2011.