New Insights on Structural Inversion, its impact on depositional model & hydrocarbon potential of Eocene carbonates; emerging exploration plays in Vijaydurg graben, Mumbai Offshore basin, India

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Abstract

Vijaydurg depression is a significant tectonic low located south of Heera high between Ratnagiri composite block in the east & Srivardhan horst in the west in Mumbai offshore basin of India. This NNW-SSE trending elongated feature serves as generation centre for hydrocarbons found in Ratnagiri sector.

Interpretation of reprocessed broadband 3D Anisotropic Pre-Stack Depth Migration (APSDM) seismic data has resulted in better understanding of the tectono-sedimentary evolution of Tertiary sequences.

The 3D seismic data broadly brings out larger thickness of synrift fills (up to Mid. Eocene) on the western flank compared to eastern flank of graben. Due to higher accommodation availability related to active western fault, the graben becomes asymmetric and steeper on the western flank compared to the gentler eastern flank which is more amenable for development of strati-structural traps. Fault reactivated inversion is more pronounced on the western flank within northern part of graben whereas intra-grabenal highs related to strike-slip movements are more pronounced within southern part of graben. Drilling of these traps has opened up Early Eocene & Mid Eocene as new emerging plays & established approx. 31 MMt of inplace hydrocarbons. Paleo structural analysis using MOVE software brings out the existence of graben since Paleocene and presence of synrift sediments has been validated till Mid. to Late Eocene. The initiation of R-13/VGS/VGN inversion structure began in Early Oligocene and reached its acme by the end of Early Miocene. The porosity development within Eocene (Devgarh & Bassein) carbonates is polymodal. The presence of vugs, stylolites along with inter/intra crystalline pores is a testimony of ubiquitous burial diagenetic alterations preserved in conventional cores. Here we present a detailed analysis of development of porosity within carbonates based on integrated analysis of lab studies, structural restoration combined with Vp/Vs slices from prestack inversion using robust rock physics model.

Introduction

The study area (Fig.1a) is bounded by Ratna North fault in the north, Vengurla Arch in the south, Miocene hinge in the west and the coastline in the east (Fig.1b)., with an aerial extent of about 1000 sq km. Ratnagiri sector extends as N-S elongated tectonic block comprising of a narrow shelf and the adjoining homoclinal rise towards east up to the present day shoreline. The paleo shelf encompasses a number of N-S to NNW-SSE trending tectonic elements, which are known (from east to west direction), as the Jaigad Homocline, Ratnagiri Composite block, Vijaydurg graben and the prominent tight anticlinal trend known as the Srivardhan Horst(Fig.1c). Vijaydurg graben is the main tectonic element which runs NNW- SSE having deepest part towards northern part of study area between R-13 and R-12 structures.

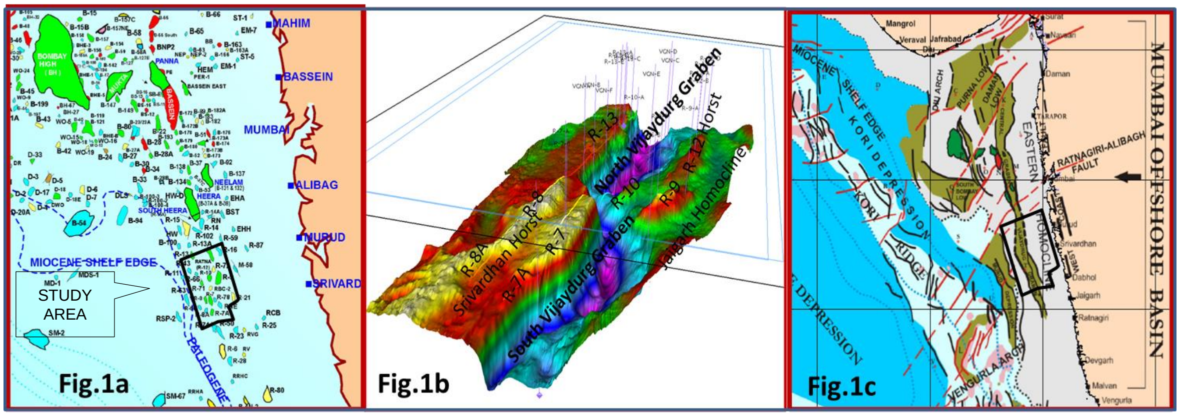

Fig-1a: Study area on prospect map of Mumbai, Fig.1b: 3D perspective view of Early Eocene(H4) showing major tectonic elements and structures, Fig.1c: Study area on tectonic map of Mumbai Offshore Basin

G&G Interpretation

To understand the overall regional facies distribution and variations in the petrophysical character of different stratigraphic units, structural correlation along wells drilled within graben (strike profile) was considered from bottom to top on the basis of log response and bio-stratigraphic age boundaries. Mid. Eocene is hydrocarbon bearing in wells VGN-F (Fig.2a), VGN-C(Fig.2b) and VGN-E. Early Eocene is also hydrocarbon bearing in wells VGN-C & VGN-F (Fig.2c). In general, the Early Eocene to Mid. Eocene thickness is greater within the graben in contrast to the wells drilled over the structural highs on both sides of graben. Early Oligocene thickness appears to be consistent both on R-12 high as well as VGN-F within graben depicting post rift deposition (Fig.3).

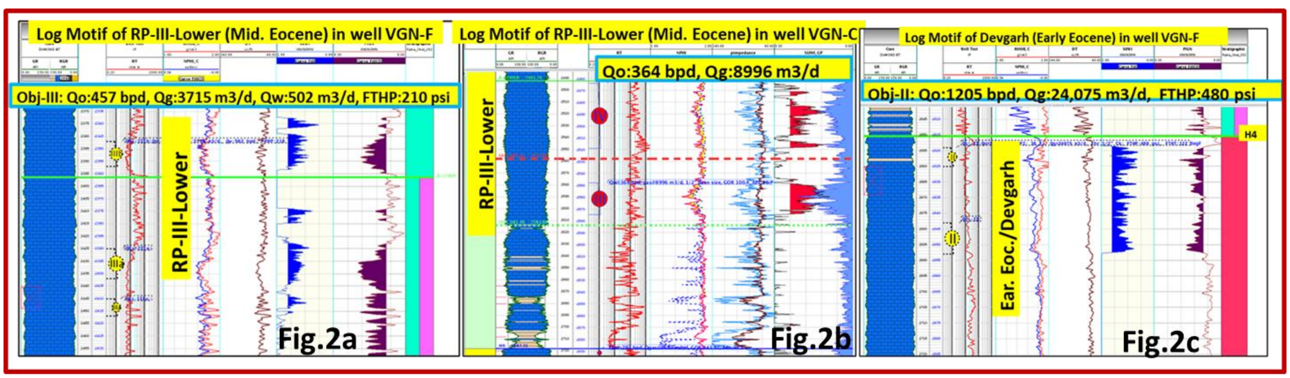

Fig.-2a: Log Motif of tested intervals for Mid. Eocene in well VGN-F, Fig.2b: Mid. Eocene in VGN-C, Fig.2c: Early Eocene in well VGN-F

Well to seismic tie for full log length using APSDM scaled back to time with stratigraphic markers picked in the wells reveals increase in impedance as negative number (seismic trough). Seven seismic horizons corresponding to Basement(H5), Early Eocene/Panna clastic top (H4A), Early Eocene/ Devgarh top (H4), Mid. Eocene/RP-III-Lower top (Bassein), Late Eocene/Upper Bassein top(H3B), Early Oligocene/Mukta top(H3A), Early Oligocene/Heera top (H3G) and Mid. Miocene/Bandra top (H1A) were mapped (Figs.3a & 3b).

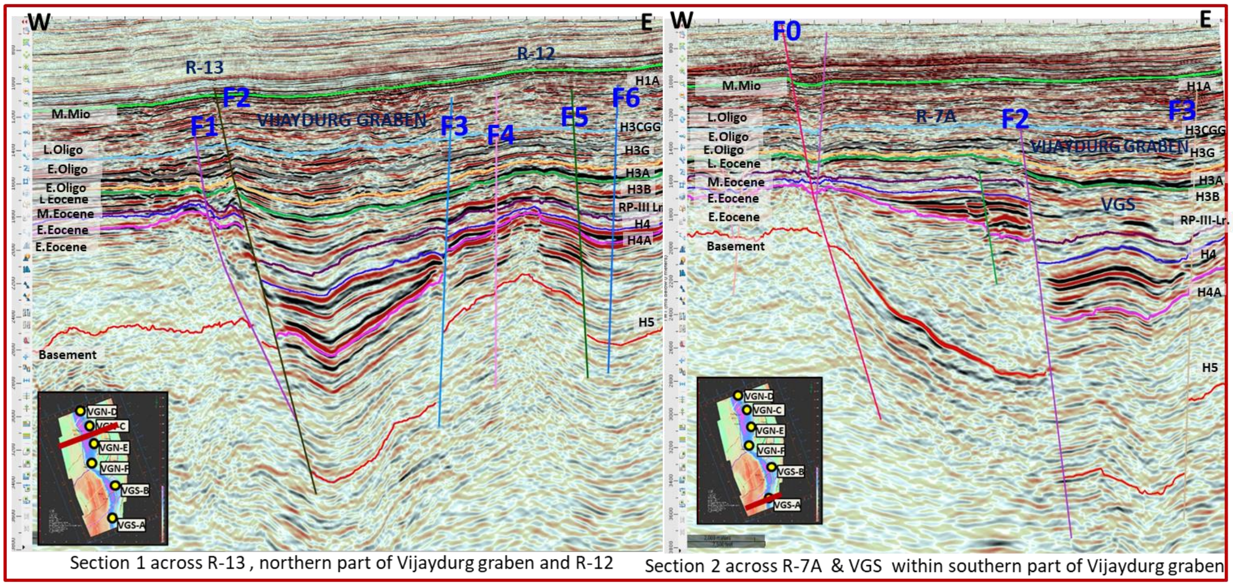

Fig.3a: Seismic Section-1 showing mapped horizons and faults   Fig.3b: Seismic Section-2

Detailed fault interpretation based on attributes like structure cube, inline dip and crossline dip brought out three major tectonic trends in the study area (Fig.4a). The initial synrift basin forming NNW-SSE trending fault responsible for major subsidence has been cut by the second-generation basin modifying NE-SW fault trends. The third generation of ENE-WSW faults, strike-slip in nature are result of post Mid. Miocene inversion tectonics responsible for making different hydrodynamic compartments. Depth thickness map of Early Eocene (Fig.6b) depicts Vijaydurg graben exists in two segments, the north and south. Srivardan horst appears to be connected with paleohigh of R-9/R-10 and R-12 in the east during Early Eocene. Depth thickness map of Early Eocene to Late Eocene (Fig.6c) clearly brings out Vijaydurg graben as a single tectonic element from north to south. It has narrowed down to its present-day shape with maximum accommodation due to high carbonate growth corresponding to Early-Mid. Eocene. The graben had grown to its full extent by end of Mid. Eocene.

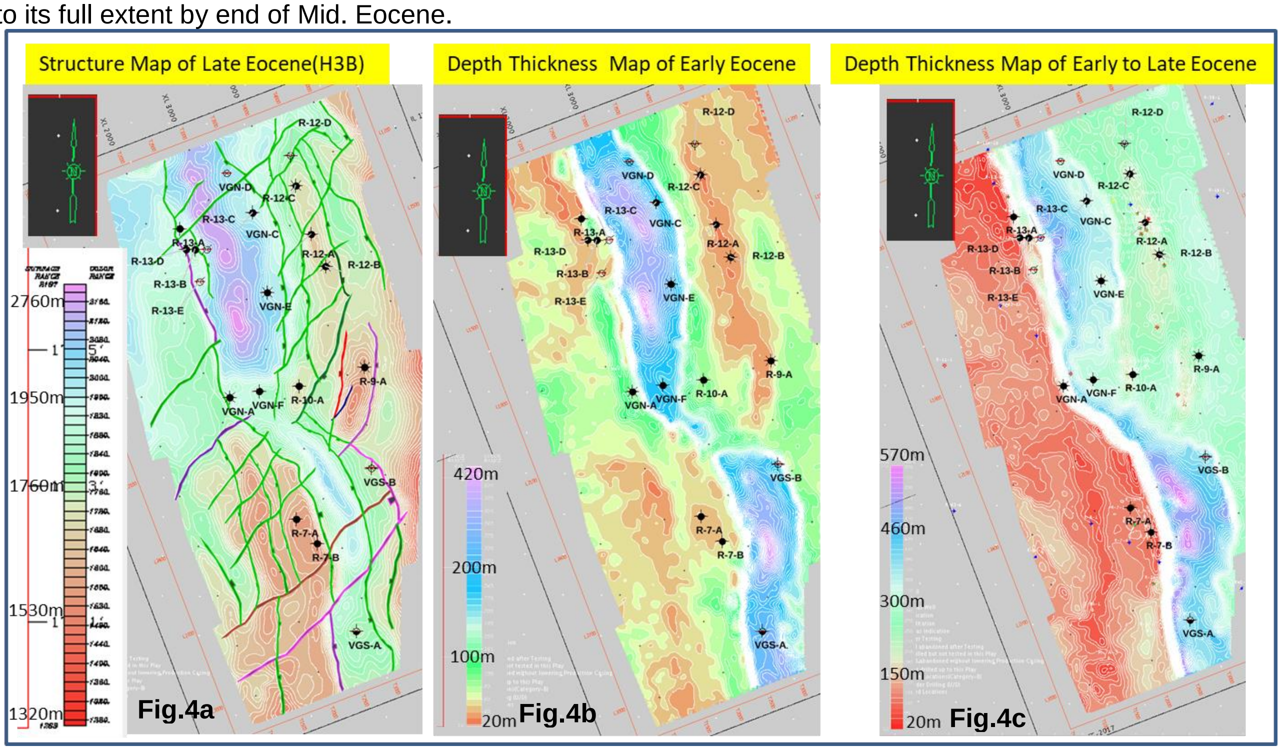

Fig.4a: Structure map of Early Eocene, Fig.4b: Depth thickness map of Early Eocene, Fig.4c: Depth thickness map of Early to Late Eocene

2D Structural Modeling

Structural restoration was carried out along two 2D seismic profiles oriented W-E (Figs.3a & 3b) encompassing major structural features viz. R-12, R-13, R-7A and VGS. Section -1(Fig.3a) is located on the northern part of Vijaydurg graben while Section -2(Fig.3b) is in the southern part. 2D structural restoration was adopted by restoring and decompacting younger most horizon to get the paleotopography of next older horizon unravelling different aspects of structurisation e.g., timing, tectonics, deformation style, spatial and temporal variation in the intensity of deformation through geological time. Structural restoration for different stratigraphic level was carried out by restoring the displacements along the faults by using the 'Fault Parallel Flow'/simple shear algorithm at the beginning and unfolding of the horizons by the Flexural Slip algorithm. Decompaction of horizons was carried out by applying decompaction factor calculated by Sclater and Christie decompaction algorithm and Airy's isostasy compensation.

Present day configuration shows thickening of Pliocene-Pleistocene sediments towards west as a result of westerly tilt of basin at the end of Miocene. Thickness of Eocene sequence significantly increases in the Vijaydurg graben. Syn-rift geometry is preserved up to Late Eocene sequences and post-rift geometry is interpreted for overlying younger sequences. Mild inversion features are observed along the eastern and western graben bounding faults F1 and F2 up to Mid. Miocene(H1A) top (Figs.5a & 5b).

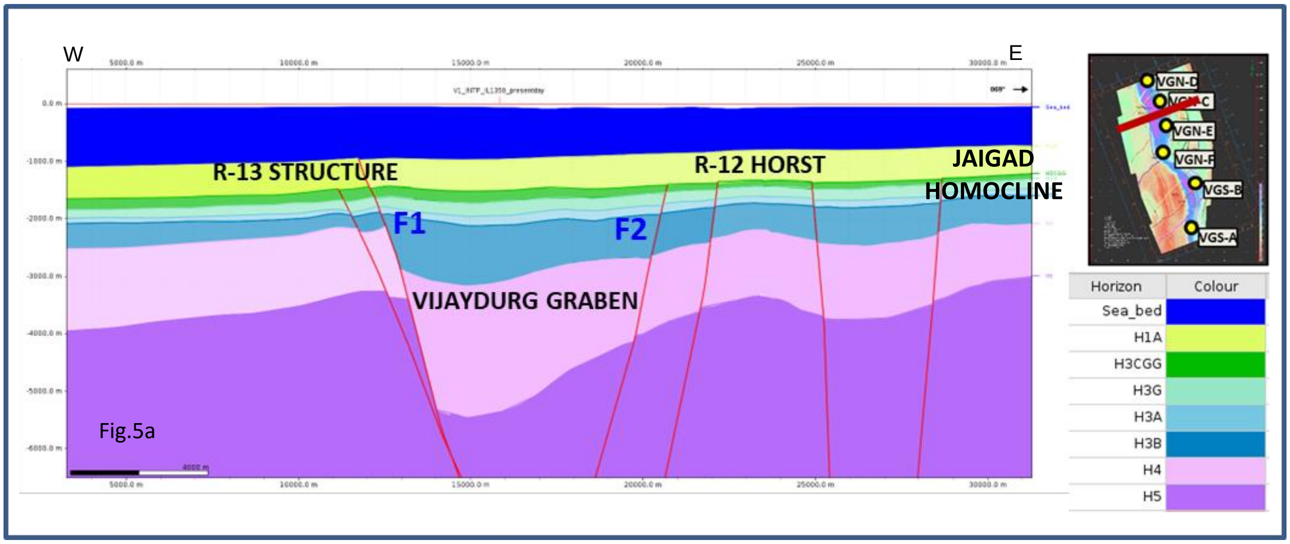

Fig.5a: Present day structural configuration along Section-1

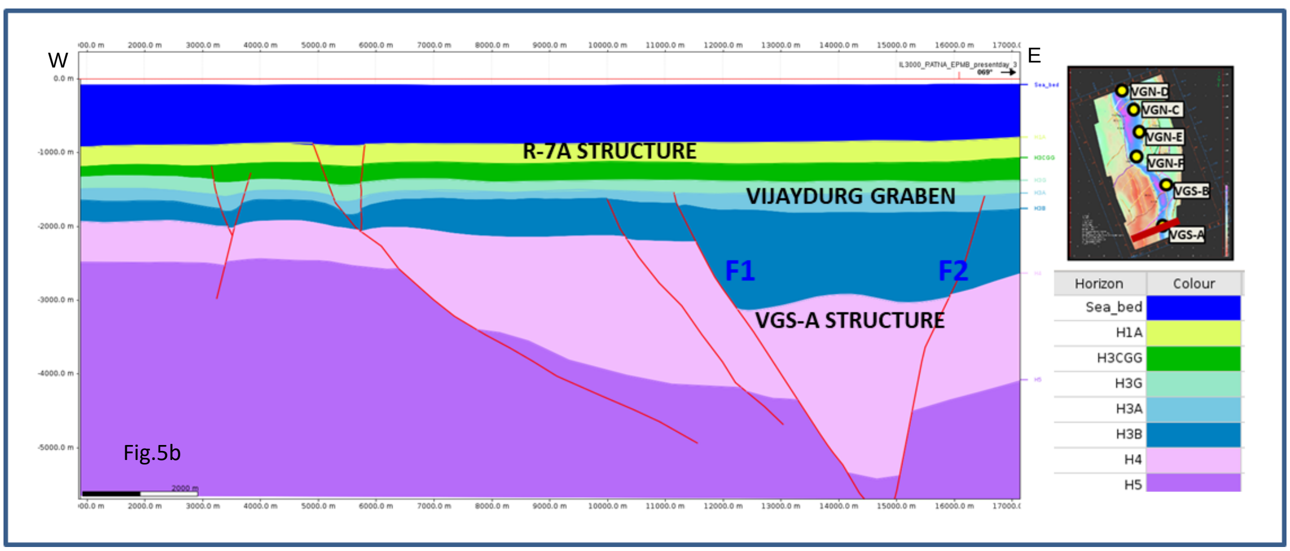

Fig.5b: Present day structural configuration along Section-2

Mid-Miocene restored stage indicates uniform sedimentation across the profile for Mid Miocene sediments. A mild westerly basin tilt was present indicating deposition in post rift stable shelf condition. (Figs.6a & 6b).

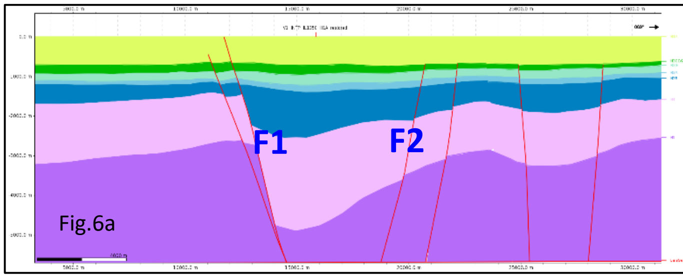

Fig.6a: Section-1 restored at Mid. Miocene (H1A)

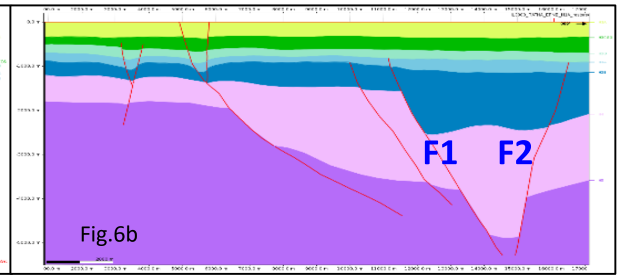

Fig.6b: Section-2 restored at Mid. Miocene (H1A)

Restoration at Late Oligocene (H3CGG) stage indicates that graben bounding faults F1 and F2 were reactivated (Figs.7a & 7b). No westerly basinal tilting is observed. Mild inversion structure due to reactivation of master fault (F1) is observed at Eocene top(Fig.7a). Culmination of VGS-A inversion structure is observed (Fig.7b). Vijayadurg graben and graben between R-12 and Jaigad homocline have more sediment thickness indicating greater accommodation space generated by differential subsidence during thermal cooling stage. (Fig.7a)

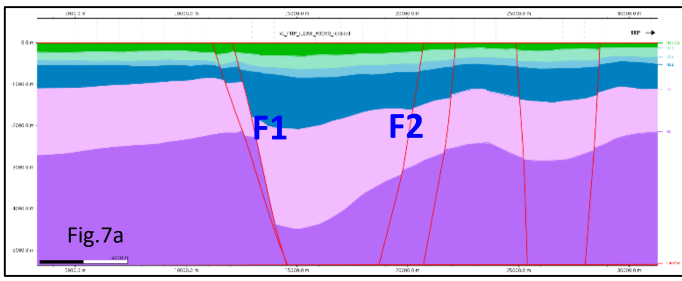

Fig.7a: Section-1 restored at Late Oligocene (H3CGG)

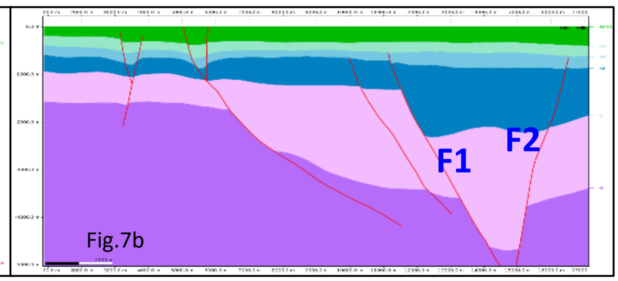

Fig.7b: Section-2 restored at Late Oligocene (H3CGG)

The restoration at Early Oligocene (H3G & H3A) stage brings out absence of structure over R-13 structure and hence it may be inferred that R-13 inversion began post Early Oligocene. Inversion was in its nascent stage and might have begun probably prior to the deposition of Late part of Early Oligocene(H3G). (Figs.8a,8b, 9a & 9b)

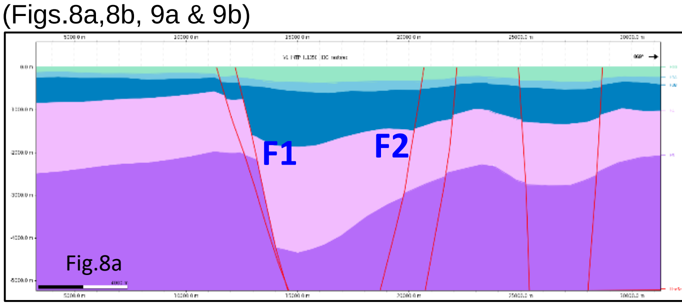

Fig.8a: Section-1 restored at Early Oligocene (H3G)

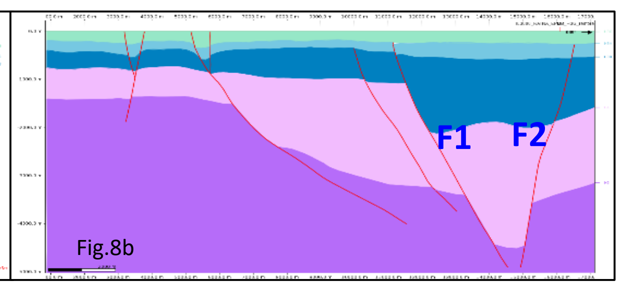

Fig.8b: Section-2 restored at Late Oligocene (H3G)

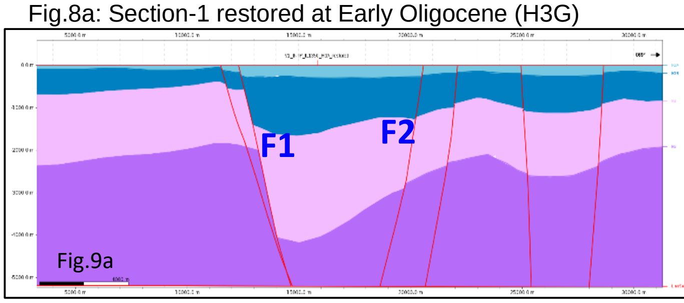

Fig.9a: Section-1 restored at Early Oligocene (H3A)

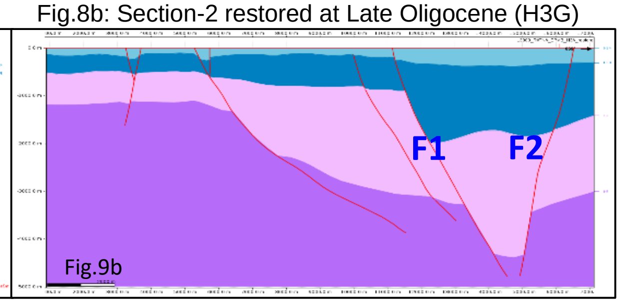

Fig.9b: Section-2 restored at Late Oligocene (H3A)

Late Eocene (H3B) restoration indicates rift related faults F1 and F2 in R-12 and R-13 structures were active controlling the sedimentation (Fig.10a & 10b). Vijaydurg graben and the graben between R-12 and Jaigad homocline have more sediment thickness indicating greater accommodation space generated by differential subsidence during thermal cooling stage. The low at R-13 is conspicuous. Huge thickness of carbonate is accommodated within depocentre. The western graben bounding fault F1 was more active compared to that of eastern bounding fault F2.

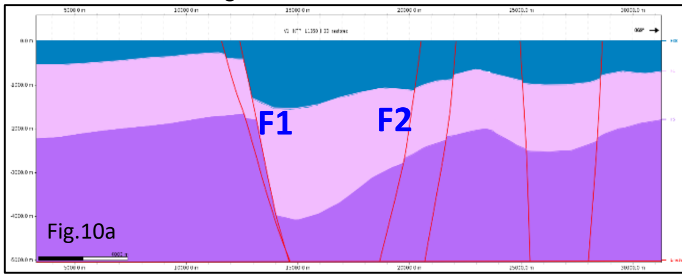

Fig.10a: Section-1 restored at Late Eocene (H3B)

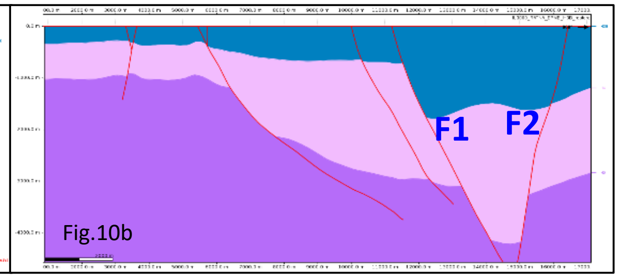

Fig.10b: Section-2 restored at Late Eocene (H3B)

Paleocene-Early Eocene(H4) restored sections indicate evolution of structures due to rifting parallel to Dharwarian NNW-SSE trend. Sediments were deposited in three grabens separated by R-12 and R-13 structures and Vijaydurg graben was the main depocentre (Figs.11a, 11b, 12a &12b). One splay is emanating from the master fault in the footwall side to accommodate excess stress regime due to excessive syn-kinematic loading. The master fault is dominant and pervasive as a result of which, excess thickness of sediments is observed in the western part of the graben compared to that in the eastern part of graben. Pre-existing low is still visible at H5 level (Fig.12a & 12b) which shows the architecture of basement. The major weakness planes are shown which became active subsequently as faults during rifting. Total extension calculated after restoration is ~1608 m (Section-1) and ~2802m (Section-2).

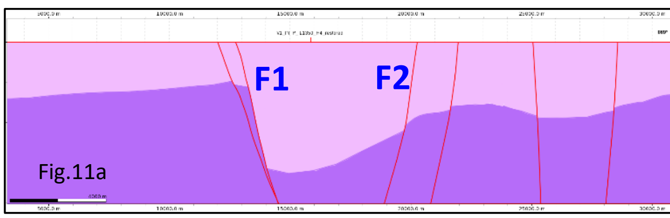

Fig.11a: Section-1 restored at Early Eocene (H4)

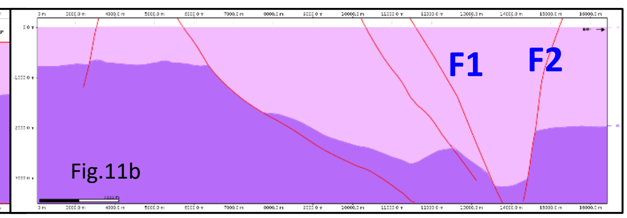

Fig.11b: Section-2 restored at Early Eocene (H4)

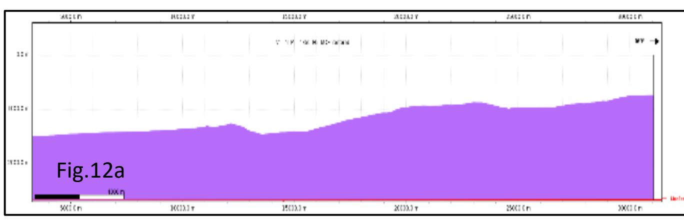

Fig.12a: Section-1 restored at Late Paleocene

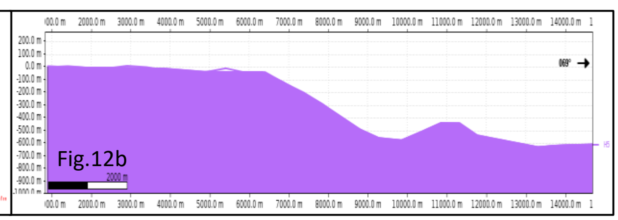

Fig.12b: Section-2 restored at Late Paleocene

Analysis & Discussion

Two inversion styles, namely fault reactivated and cover-folded inversions are recognized in Vijaydurg graben. The cover-folded inversions are observed in VGS-A/VGN-F (Fig.4a & 5b) which is controlled by strike slip movement of deep-seated faults in the basement. The fault reactivated inversions as observed in R-13 (Fig.5a), where all shortening is accommodated by reverse dip-slip components along pre-existing normal faults F2. Hence the geometry of inversion is controlled by amount of contraction owing to the temporal change in the stress regime. The compressional inversion of the earlier extensional faults, development of incipient footwall shortcut structure is noticed in R-13 field (Fig.5a). The drilling of few wells on the northern plunge of Srivardhan horst has proved the non-occurrences of accumulation thus limiting the migration of hydrocarbons within the incipient footwall structure for Eocene carbonates

Facies analysis and diagenetic imprints of Eocene carbonates

The paleoecological and sedimentological signals recorded in sedimentary successions are key elements for understanding the evolution of carbonate depositional systems. As observed in core CC#2 of well VGN-F, Early Eocene carbonates are low energy dolomitic foraminiferal bioclastic wackestone (Fig.13) and show good porosity in the form of organic porosity, intraparticle, moldic and vugs. Various diagenetic processes especially dolomitization have affected the porosity and enhancement of secondary porosity is noticed throughout the sample.

Mid Eocene carbonates are represented by high energy foraminiferal bioclastic packstone, foraminiferal pelloidal packstone and low energy dolomitic foraminiferal wackestone (Fig.14). Diagenetic processes such as sparitization and dolomitization have diminished primary porosity. Enhancement of secondary porosity in the form of major vugs (ranging from few mm to 7cm) is observed.

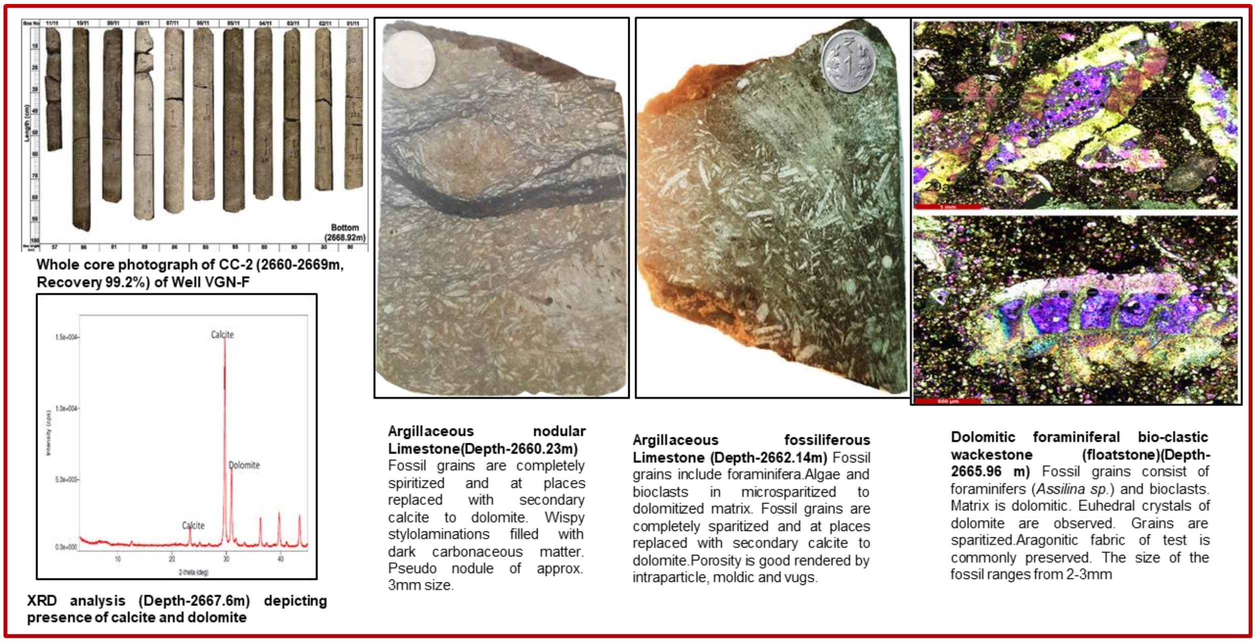

Fig-13: Core analysis (CC#2) belonging to Early Eocene carbonate (2660-2669m) of well VGN-F

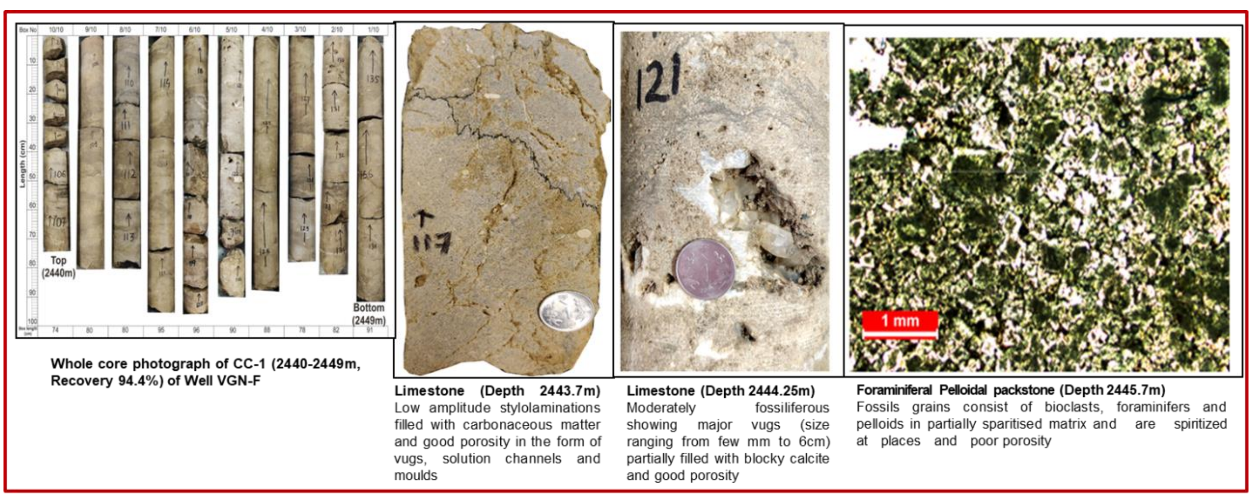

Fig.14: Core analysis (CC#1) belonging to Mid. Eocene carbonate (2440-2449m) of well VGN-F

Rock Physics Modeling & Pre-Stack Inversion

For Early Eocene play, VGN-F and VGN-B were taken into consideration for feasibility study**.** The well based cross plot of well VGN-F for Early Eocene with a window of H4 minus 10 plus 50 meter is shown in (Fig.-15a).Wells VGN-C, VGN-E and VGN-F were considered pertaining to Late Eocene play for cross plot analysis, where discrimination between hydrocarbon facies and non-hydrocarbon facies with minor overlap is observed (Fig.15b & 15c).

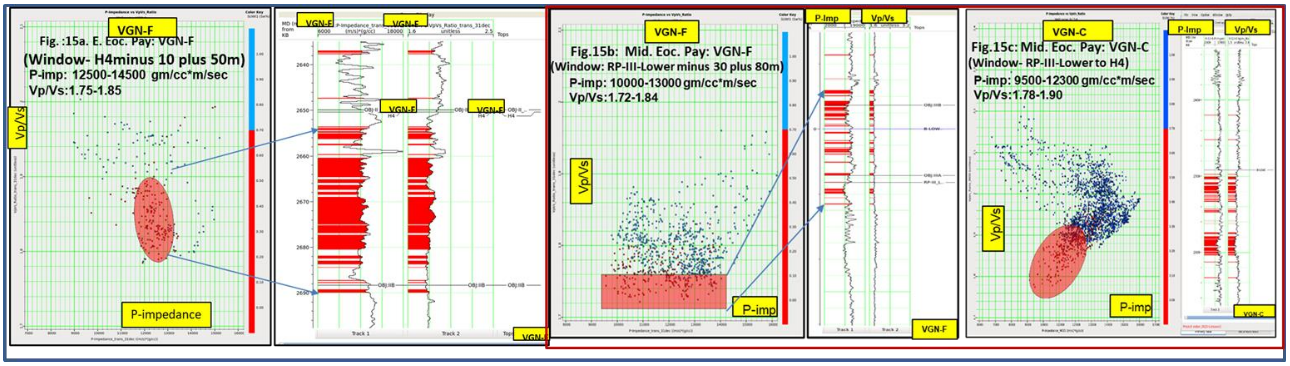

Fig.15: Cross-plot between P-impedance and Vp/Vs for well VGN-F (a. E. Eoc. Pay, b. Mid. Eoc. pay) and VGN-C (c. Mid. Eoc. pay)

The Mid. Eocene pay has been tested as HC bearing in three wells VGN-C, VGN-E and VGN-F within graben. Well log-based cross-plot analysis of P-impedance vs Vp/Vs in wells VGN-C and VGN-F shows overlap of HC bearing zones with the background in P-impedance (Fig.15b & 15c). However, HC bearing zones shows significant amount of separation in Vp/Vs.

Pre-stack simultaneous inversion was carried out using wells, four partial angle stacks and multi-well wavelets with a zone of interest between H3G (-50ms) to H4A (+50ms). Using optimized window-based slices from P-impedance & Vp/Vs volume, the extension of Eocene pays of wells in VGN-F & VGN-C are brought out in addition to prospective leads within graben.

Inverted P-impedance and Vp/Vs (Fig.-16a) horizon slices were extracted within window of H4 minus 5 plus 30 ms for characterizing Early Eocene play. The slice corresponding to Early Eocene play depicts higher acoustic Impedance ranging from 12500-14500 ((gm/cc)*(m/s)) around successful wells VGN-F and VGN-C. However, inverted Vp/Vs slice shows lowering within range of 1.75-1.85 around the successful wells VGN-F & VGN-B(Fig.-16a). The zoomed map of Vp/ Vs slice shows extension of pay zone around VGN-F and it is represented by a corridor of low Vp/Vs (Fig.16a).

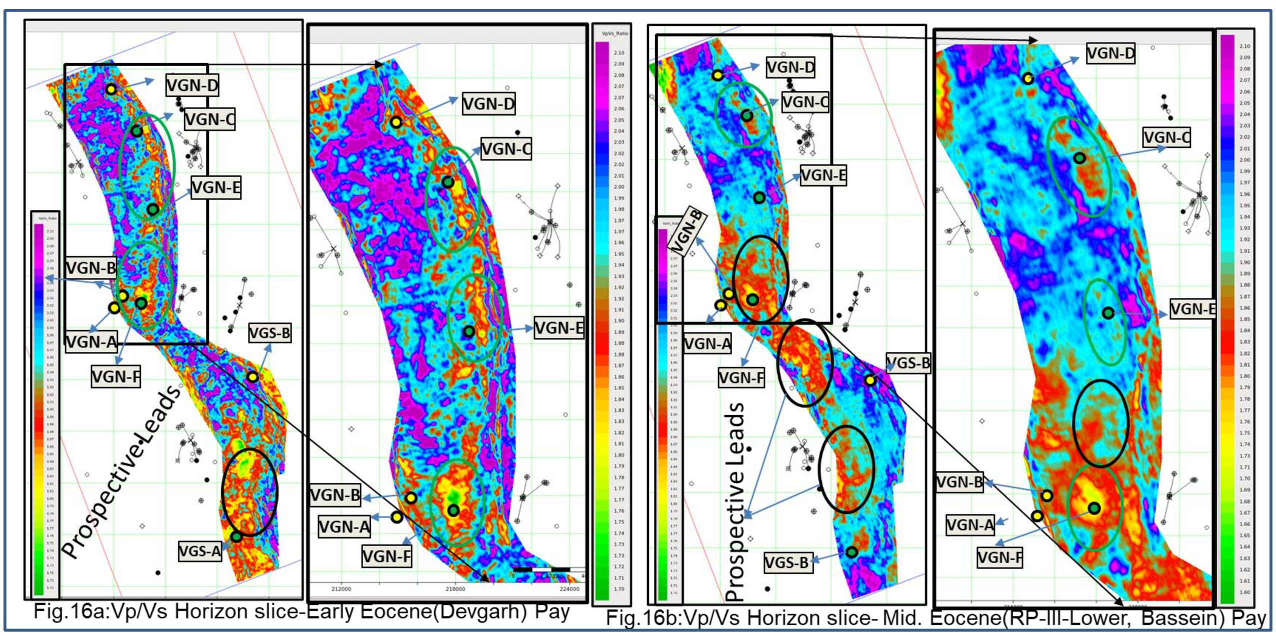

Fig.-16. Vp/Vs Horizon slice showing the extent of Early Eocene and Mid. Eocene pay within Vijaydurg graben

Inverted P-impedance and Vp/Vs horizon slices were extracted within window of RP-III-Lower+40 ms. The slice corresponding to Mid. Eocene depict moderate to high acoustic Impedance around successful wells VGN-C, VGN-E and VGN-F with values ranging between 10000 to 13000 ((gm/cc)*(m/s)). However, Inverted Vp/Vs shows relatively higher Vp/Vs around VGN-E (range 1.9 to 1.95) as compared to VGN-C (range 1.78 to 1.9) and VGN-F (range 1.72 to 1.84) (Fig-16b).

Conclusion

The present workflow of structural restoration, integrating cores, biofacies, logs to seismic, rock physics modeling, and prestack inversion studies addresses the complexities of reservoir characterization for Early Eocene & Middle Eocene carbonate plays in Vijaydurg graben. Two inversion styles, namely fault reactivated and cover-folded inversions are recognized in Vijaydurg graben. Paleo-structural analysis indicates the western graben bounding fault was more active in creating accommodation compared to that of eastern graben bounding fault up to Middle Eocene time as a result of which, sediment thickness is more in the western part of graben compared to eastern part. This has led to the asymmetrical shape of graben with a major tilt towards west. The preferential migration of hydrocarbons generated from pre rift/ syn rift sources have a tendency to accumulate on the gentler slope both in syn rift and post rift sediments. The steeper gradient in the western flanks of graben is more likely to create smaller prospects with risk of trap failures whereas the eastern rising gentler flanks are more favorable for hydrocarbon accumulations with larger prospect size.

The porosity development in the top part of Early Eocene play is mostly linked to unconformity related dissolution processes during the short exposure as well as prevailing lesser bathymetry on the eastern flanks compared to the western flanks and hence, more favorable for better primary depositional facies. However, the porosity development below 150m from the Early Eocene unconformity as evident in wells VGS-A and VGN-F may be linked to mesogenetic deep burial dissolution processes.

The eastern rising flank of Vijaydurg graben has become hugely prospective owing to porosity generation during late burial mesogenetic dissolution due the movement of corrosive fluids along the faults. Early Eocene & Mid. Eocene carbonates have emerged as the new plays through drilling of successful wells VGS-A, VGN-F and VGN-C. The commercial success of these wells corroborates the suitability of eastern rising flanks as sweet spots for exploration.

The Vp/Vs slices corresponding to same demonstrate the extent of reservoir within graben along with prospective areas for future exploration. Further integrated study may open up huge locked up potential elsewhere in mature Mumbai Offshore basin.

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