

Identification of Reservoir Facies within Carbonate and Mixed Carbonate-Siliciclastic Sequence: Application of Seismic Stratigraphy, Seismic Attributes and 3D Visualization

Harilal*, S. K. Biswal, A. Sood, and V. Rangachari,

GEOPIC, Oil and Natural Gas Corporation Limited, Dehradun

Summary

The 3-D seismic data of NE-Panna and adjoining area within Central Graben in Heera-Panna-Bassein Tectonic block of Bombay Offshore Basin, India, have been evaluated for identification of prospects within Middle to Upper Eocene Sequence (Bassein Formation) which is hydrocarbon bearing in near by areas. In the study area, massive to laminated carbonate sections without hydrocarbons were encountered in three wells, which were drilled on the basis of 2-D seismic data interpretation. Subsequently 3-D data was acquired in 2004 to assess the reservoir and trap potential of the area.

The 3D seismic along with other geo-scientific data of the area have been integrated and interpreted by applying concepts of seismic stratigraphy, seismic attribute analysis and 3D visualization techniques. On the basis of seismic reflection configuration and interpretation of electrolog facies, the Bassein Formation has been divided, seismically, into four units which were deposited under transgressive to highstand regime including late highstand sea level fall. Within units, coeval deposition in different sub-environment has been inferred from the lateral seismic facies variation. Seismic impedance volume generated through model based post-stack stratigraphic inversion, seismic attributes and attributes derived from logs, e.g., %limestone and porosity, were analysed with geostatistical cross-plots method to understand the interrelationship between lithofacies and seismic facies. Moderate to high amplitude and moderate impedances have been found to be associated with carbonates having good porosity. The lateral discontinuities and boundaries between different assemblages have been mapped with 3D visualization of volume and surfaces coupled with coherency slices. Various facies assemblages representing carbonate buildups, off-buildups at slope of big buildups and wedges of debris flows (talus) were identified with consideration of structural configurations, attributes and impedance, and depositional geometries. The inferences of this study are validated at drilled wells.

Introduction

The area of study is situated in the western part of Heera-Panna-Bassein tectonic block of Bombay Offshore Basin on the Western Continental Margin of India (Figure 1). The area is considered prospective due to its proximity to the Central Graben (kitchen of hydrocarbon) and occurrence of carbonate and sandstone reservoir rocks in adjoining areas towards southwest. In this part of basin, sandstones in Paleocene to Lower Eocene sequences and carbonates in Middle to Upper Eocene sequences are dominant reservoirs rocks. Earlier workers in the area have mapped several carbonate buildups in Middle to Upper Eocene sequences on the basis of 2D seismic data. A few exploratory wells were drilled to prove the envisaged strati-structural plays in and around the area but the majority of wells went dry mostly due to lack of reservoir and / or seals.

The 3D data covering 470 km² was acquired in 2004 for assessing the reservoir and trap potential of the area and identification of drillable locations. Three dry wells, (C, D,

and F), which fall within the 3D live data coverage, failed to prove the potential of area. Massive to laminated carbonates and silicilastics inter-layered with carbonates were encountered within the Bassein Formation. The well C was not found worth of testing due to lack of reservoir facies, well D showed no response on testing, and well F produced water. Post drill analysis suggested lack of entrapment at well F and D, lack of reservoir and trapping mechanism both at well C. In light of the dry wells, identification of reservoir rocks and postulation of entrapment models in carbonate and mixed carbonate-siliciclastic sequence are the challenges of current 3-D data interpretation.

The 3-D data has been evaluated with application of seismic sequence analysis, seismic attribute analysis, 3D visualization, seismic trace shape analysis, coherency volume analysis and acoustic impedance inversion. Seismic facies maps were generated through neural network based seismic trace shape analysis. Carbonate buildups, medium amplitude parallel reflection packages (off-buildups) and wedges of debris flows were identified on the basis of seismic facies



analysis. Seismic sequence attributes and acoustic impedance were computed and calibrated at well location to have understanding of interrelationship between seismic and log signatures. Shale/mud dominated carbonate, porous carbonate and tight massive carbonate were discriminated on the basis of attribute and impedance. 3D visualization and coherency volume analysis were used to find the associated geometries of deposition. Reservoir and trap potential of area within Bassein sequence are assessed as good for probing by exploratory drilling. The objective of this paper is to demonstrate the identification of stratigraphic plays within carbonates by using the state-of-the-art technology.

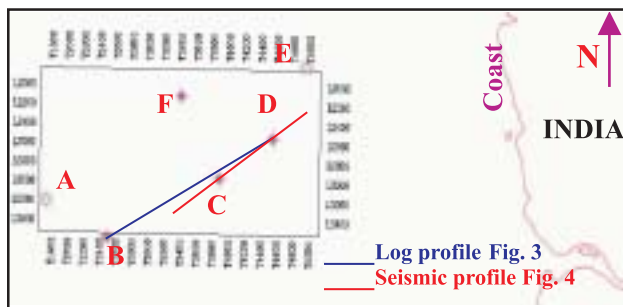


Fig. 1 : Location map of the area

Stratigraphic framework

The general stratigraphy based on a deep well (E) situated towards east of the 3D area is shown in Figure 2. Thick sedimentary section ranging from Paleocene to Recent has 2.5 to 4.3 km thickness. The Panna Formation, between H5 at bottom and H4 at top, of Paleocene to Lower Eocene age unconformably overlies Late Cretaceous Basalt/Basement. Middle to Upper Eocene Bassein Formation, consisting of mainly carbonates, unconformably overlies the Panna Formation and it is bounded by H4 at bottom and H3B at top. The H3BL is a shale-carbonate interface which divides Bassein Formation into two units, i.e., Lower Bassein Unit between H4 and H3BL and Upper Bassein Unit between H3BL and H3B. The Mukta Formation between H3B at bottom and H3A at top unconformably overlies on Bassein Formation. The overlying Heera Formation is bounded by H3A at bottom and H3G at top. Mukta and Heera Formations are of Lower Oligocene age and contain limestone shale alternations. The Upper Oligocene Alibag Formation is shaly. This paper is focused mainly on Bassein carbonates which are potential reservoir rock towards southwest of the area.

Electrolog/Lithofacies interpretation

The lithofacies variations within Bassein Formation

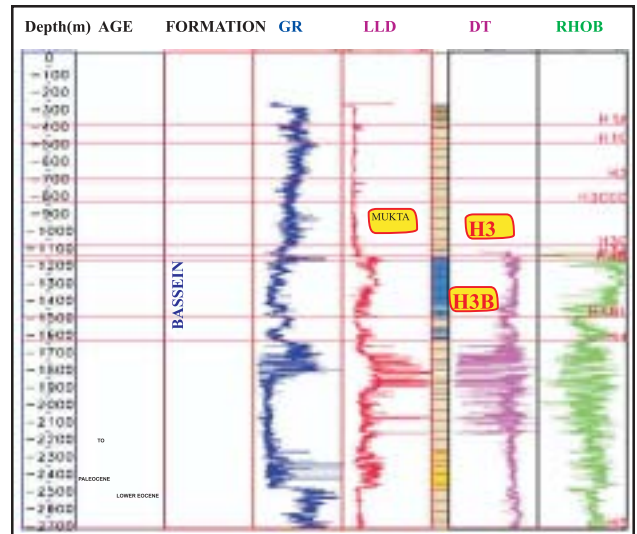


Fig. 2 : General stratigraphy of the area based on the well E.

along an east-west profile connecting wells E, D, C, B and A flattened at H3A is shown in Figure 3A. The Lower Bassein Unit can be divided into two parts, i.e., the lower part consisting dominantly carbonate and the upper part consisting dominantly shale. The shaly section below H3BL is apparently present across the area. The overall log motifs of Lower Bassein unit show deepening upward. The Upper Bassein Unit shows rapid variations in lithofacies in both vertical and lateral direction. The lower part of Upper Bassein unit consists of shale limestone alternations. The Upper part is dominantly limestone in well A, B and D. In well C and E shale-limestone alternations are observed. In general, Upper Bassein unit shows shoaling upward log motifs. Presence of monotonous limestone from 1350-1690 m in well D shows massive carbonate buildup (active growth). Presence of shale limestone alternations in well C and E shows passive intermittent sedimentation. Within equivalent intervals resistivity and impedance are significantly lower at well C as compared to well D (Figure 3B). The neutron porosity (NPHI) is higher at well C. The average velocity and density vary from 3460 m/s and 2.54 gm/c³ to 4300 m/s and 2.48 gm/c³ from well C to D.

The low velocity (3460 m/s) and high neutron porosity in well C as compared to well D may be due to high content of muddy matrix as at higher matrix content, velocity decreases and porosity converges to natural porosity of matrix material (Eberli et al., 2003). Sedimentologically, the interval is interpreted as muddy dolomite in well C. The inferences drawn from the log interpretation are summarized below:

- Non-uniform lithofacies variations in both vertical and lateral directions

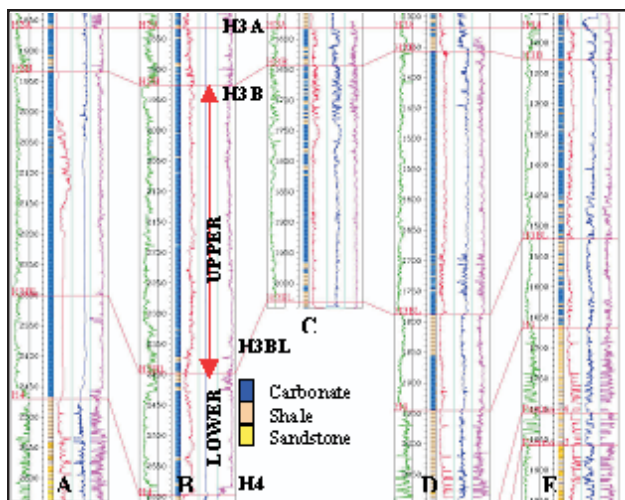


Fig. 3A : Lithofacies variation along E-W profile across the area .

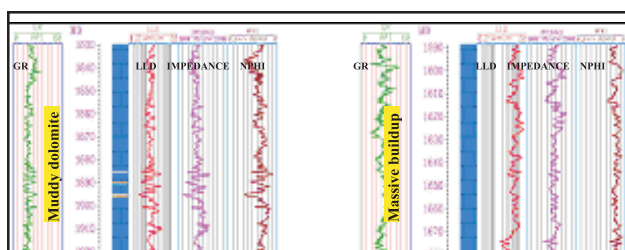


Fig. 3B. Log and lithofacies between well C and well D in the equivalent interval. Profile is flattened at H3BL.

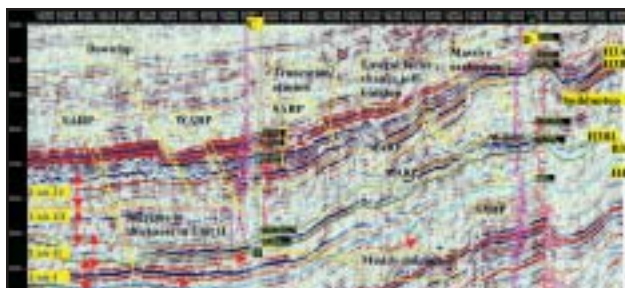


Fig.4. RC profile showing sequence boundaries and reflection package within Bassein Formation.

- Low gamma and high resistivity correspond to high sonic velocity and high density (i.e. high impedance).
- Shale limestone alternations in well C and E suggest either sedimentation in low energy environment or influx of silicilastics.

Seismic sequence analysis

Principles of seismic sequence stratigraphy are successfully used for visualization of exploration targets in carbonates (Handford, 1998). It helps in finding time and

spatial distribution of reservoir-, source-, and seal-prone depositional facies. The sequence boundaries and reflection packages along a NE-SW profile passing through well C and D are shown in Figure 4. Six horizons named as H4, B3, H3BL, builduptop, H3B and H3A are correlated along the section. H4, H3BL, H3B and H3A correspond to Lower Eocene Top, Middle Eocene Top, Upper Eocene Top and within Lower Oligocene respectively. B3 and builduptop are seismic markers within Lower and Upper Bassein unit respectively. The Bassein Formation is seismically divided into four units, namely, Unit-I between H4 and B3, Unit-II between B3 to H3BL, Unit-III between H3BL and buildup top and Unit-IV between buildup top and H3B.

Unit-I consists high amplitude parallel reflection towards down dip and parallel weak amplitude reflection towards up dip. The high amplitude reflections progressively shift towards updip showing retrogradational stratal pattern, which is product of transgressive regime. Unit-II consists of pair of strong amplitude reflections with varying thickness trends. In western part of area a high thickness trend is observed which is caused by deposition of extra layers appearing as carbonate buildup. This unit dominantly represents shales. Unit-III generally represents very low amplitude reflections with exception of moderate to high amplitude layered reflections flanking the big transparent zone (carbonate buildup) enclosing well D. The moderate amplitude reflections represent the off-buildup facies and form a halo surrounding the weak amplitude buildup. These characteristics indicate deposition of this layer under highstand regime. Though similar seismic facies (low amplitude chaotic reflections) are observed in well C and D but sedimentological and petrophysical properties are quite different (Figure 3B). The Unit-IV consists of high amplitude parallel reflections at top of buildup, high amplitude divergent reflections at slope and parallel reflections towards down dip. The thickness of this unit progressively decreases towards east and it is very thin in well D. The reflections onlap towards updip (east) and down lap towards down dip (west) onto the buildup top surface. The Unit was deposited during late stage of highstand regime under sea level fall. Here it is highstand wedge of carbonate and shales.

The reflections below H3B often have truncational relationship. Based on the amplitude three sets of reflection packages are recognized:

- SARP**: Strong amplitude reflection package representing the shale-limestone intercalation. This is predominant in Unit-I and Unit-IV.
- MARP**: Medium amplitude reflection package representing lateral facies change surrounding the large



buildups. This is predominant in Unit-III and also present in Unit-IV.

- III. WARP: Weak amplitude reflection package representing massive (non-bedded) carbonates at well D and muddy dolomite at well C. It is predominant in Unit-III.

Interrelationship between log responses

The seismic reflection response mainly depends on acoustic and elastic impedance contrasts and stratal configuration of subsurface layers. All the geologic and petrophysical variations are inherent in impedance contrasts. For determination of lithofacies and reservoir parameters from seismic data thorough understanding of interrelationship between litho-logs and impedance within area is required. Statistical cross-plots quantify the interrelationships.

Cross-plot between GR and Impedance

Cross-plots between impedance and gamma log within carbonate dominant intervals in well C and D are shown in Figure 5A and 5B respectively. The RHOB log has been used for colour coding of shale/carbonate dominant lithofacies. GR and impedance have inverse relationship (negative correlation coefficient). Though low-density high gamma shales are clustered with low impedance but significant overlap is observed for medium densities.

Cross-plot between Porosity (NPHI) and Impedance

Cross-plots between impedance and neutron-porosity log (NPHI) within carbonate dominant intervals in well C and D are shown in Figure 6A and 6B respectively. The GR log has been used for colour coding of shale/carbonate dominant lithofacies. Porosity and impedance have inverse relationship (negative correlation coefficient). Though low gamma high impedance carbonates are clustered with low porosity but large variations are observed within the clusters.

The inferences drawn from study of cross-plots are summarized below:

- Low density high gamma shales are discriminated on the basis of impedance
- Moderate density relatively low gamma calcareous shales have significant overlap in impedance
- Contaminated carbonates (mixing of shales and muds with matrix) are expected to give weak reflection due to insignificant impedance contrasts.

- When lithology is known the impedance may be diagnostic for discriminating between good (10-20 %) and poor (<10%) porosities. Impedance range between 8000 to 10000 ($\text{g/cm}^3 \cdot \text{m/s}$) corresponds to good porosity.

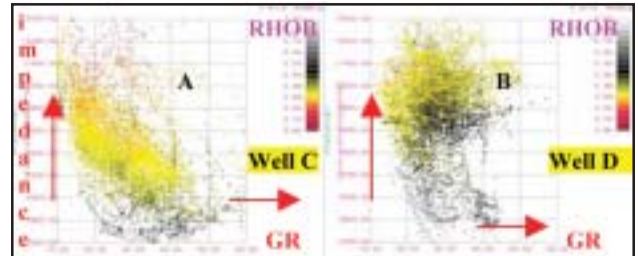


Fig. 5 : Cross-plots between impedance (Y-axis) and GR (X-axis). A and B are for well C and well D respectively.

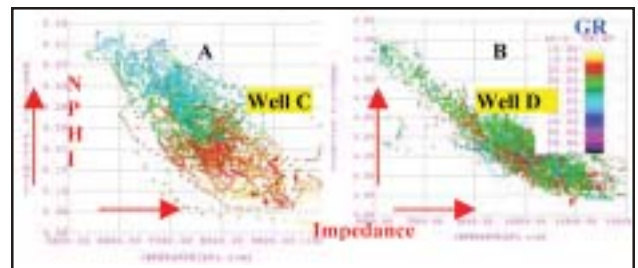


Fig. 6 : Cross-plots between NPHI (Y-axis) and impedance (X-axis). A and B are for well C and well D respectively.

Seismic attributes

Seismic attributes derived from seismic trace data are used for evaluation of carbonate sequences (Pacht et al., 1996, San and Mohamad, 1996). In the area, Bassien Formation has given good response in terms of instantaneous amplitude and frequency. The sweetness attribute, which is computed as ratio of amplitude and square root of frequency, may discriminate between different sub-lithofacies within Bassein carbonate. The sweetness section extracted from sweetness volume connecting well C and D is shown in Figure 7. The section is flattened at H3A with overlay of GR and LLD logs. The Massive clean carbonate at well D and muddy dolomite at well C are characterized by extremely low sweetness values. Shale- limestone alternations and shale dominant sections have moderate to high sweetness values respectively.

Acoustic impedance volume analysis

Impedance volume was generated from seismic volume by using model based inversion method. Calibrated DT and RHOB logs of C and D wells were used in model

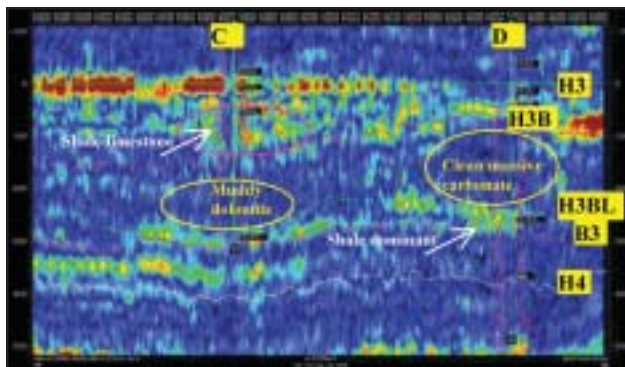


Fig.7 : RC profile showing sweetness attribute. The section is flattened at H3A. Red and blue colours for high and low sweetness respectively.

building. In well F, DT and RHOB logs are not recorded in zone of interest, therefore, it could not be used. The impedance profile through wells C and D is shown in Figure 8. Units I to IV are readily identified on the impedance section. Unit I (shale-limestone alternation) shows moderate impedance, Unit II (dominantly shale) shows low impedance, Unit III (carbonate dominant) shows very high to moderate impedance and Unit IV (shale- carbonate alternation) shows low to moderate impedance. Moderate impedance within units II (high within low), Unit III (low within high) and Unit IV (high within low) is considered interesting for porosity development. Interrelationship between Log and Seismic attributes

Seismic attribute (amplitude and impedance) and log attributes (% limestone and porosity) were computed in Unit-III and maps were generated. At well locations values were extracted and cross plots between RMS amplitude and %limestone (Figure 9A), impedance and %limestone (Figure 9B), porosity and RMS amplitude (Figure 9C), and porosity and impedance (Figure 9D) were generated. Within the interval RMS amplitude and %limestone have inverse relationship, %limestone and impedance have direct relationship, RMS amplitude and porosity have direct relationship and porosity and impedance have inverse relationship. From the cross-plots following interpretational inferences are drawn:

- Zones with high amplitude and moderate impedance may represent porous zones
- Zones with low amplitude and low impedance represent muddy dolomite/limestone without any effective porosity
- Zones with extremely high impedance and extremely low amplitude represent massive carbonate buildup without significant porosity.

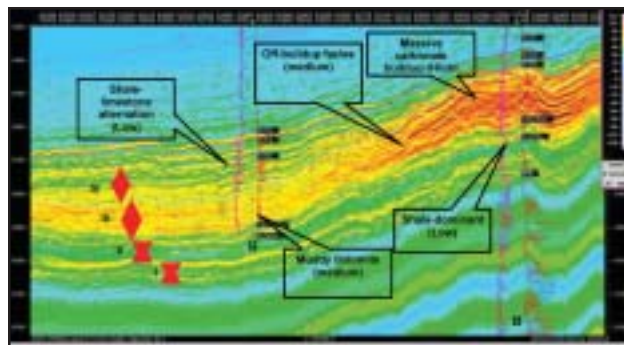


Fig. 8. RC profile showing variation of impedance

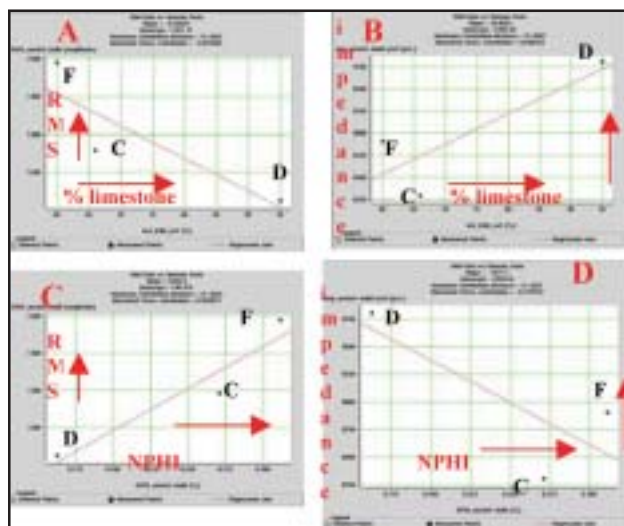


Fig .9 : Cross plots between seismic and log attributes.

Identification of potential reservoirs

Structural maps, isochronopachs, attribute maps and 3D visualization of volumes and surfaces suggested porous carbonates zones consisting of buildups, off-buildups and talus of debris flows. These zones are delineated as follows:

A. Buildups within Unit-II

It is identified through vertical section (Figure 10A), isochronopach between B3 and H3BL (Figure 10B) and it is located just below the H3BL unconformity. The buildup is recognized by a pattern of increased thickness in NW-SE orientation. The time structure map of H3BL, overlaid on isochronopach, shows a fault closure. This type of buildup may be considered as "Late-Growth Reef (LGR)" as described by Erlich et al., 1993, within Miocene sequence in the Pearl River Mouth Basin, South China Sea. Impedance map (Figure



10C) shows higher impedance within buildup than surrounding shale dominant section.

B. Buildups within Unit-III

Carbonate buildup just above the H3BL within Unit-III is identified by relatively higher amplitudes mounded reflection configuration (Figure 11A). It is characterized by relatively higher sweetness (Figure 11B) and lower impedance than tight buildup towards east (Figure 11C). Time structure of enveloping surface shows a nosing feature with good relief (Figure 11D). This feature is located on toe-of-slope of larger massive buildup towards east (Figure 11E).

C. Off-buildup facies surrounding the massive buildup

The massive carbonate buildup in the eastern part of area is visualized on vertical section (Figure 4) and opacity controlled 3D cube (Figure 12A). The core of buildup is characterized by low amplitude chaotic reflections (Figure 4) and high impedance (Figure 11C). The off-buildup facies (Figure 4, 12A) within Unit-III having medium sweetness (Figure 11B) and impedance (Figure 11C) may form good reservoir. These have been deposited by shedding of carbonate detritus from top of buildup during highstand regime. During highstand shedding fine-grained sediments are also produced (Handford and Loucks, 1993) which may be contemporaneously deposited by suspension towards further down dip (basinal side). On the slope coarser materials consisting rubbles (carbonate sands) derived from main buildup are expected. The interface between massive buildup facies and off-buildup facies separates relatively low amplitude parallel bedded reflections from low amplitude chaotic reflections (Figure 4) and it is easily recognized from coherency slice (Figure 12B) and 3D voxel image of buildup top reflector (Figure 12C). Surrounding reflection package on slope are expected to have good porosity. Updip barrier is expected from the tight massive buildup.

D. Wedges of debris flows

The debris flow deposits in Unit-IV are identified by complex reflection configuration (Figure 4), isochronopach between buildup top and H3B (Figure 13A) and seismic facies map (Figure 13 B) and section (Figure 13C). The thickness of the unit progressively decreases towards East. Impedance map (Figure 13D) shows trend of intermediate impedance between high impedance (surrounding well D) and low impedance (towards well C).

This moderate impedance may be indicating of good porosity development between well D and C. The unit has been deposited during late stage of highstand under relative sea level fall.

Discussion and results

The area is complex due to existence of coeval sub-environment of deposition causing lateral facies variations (Figure 3A). The post-depositional tectonic activities and diagenesis processes have further modified the original depositional fabrics. Massive carbonate buildups, shale-limestone alternations and mixed carbonate-mud were deposited contemporaneously (Figure 4). Different lithological assemblages having different petrophysical properties may have produced similar seismic facies and attribute, e.g., massive clean carbonate and muddy carbonate have given same transparent facies (Figure 3B, and Figure 4). Porous carbonate and shale-limestone alternation (when not temporally separated) give similar low impedance. Within carbonate sequence, seismic attributes and impedance alone cannot discriminate between potential reservoir and non-reservoir rock. The seismic attribute and impedance when supplemented with seismic stratigraphy and paleostructural reconstruction may identify potential reservoir rocks, e.g., moderate impedance, moderate to high sweetness (Figure 11B, 11C) qualify for the prospect only when it is apparently has been deposited at slope and wave energy was sufficient to clean it from fine particles. Similarly sub-aerial erosion and leaching by fresh meteoric water may generate good porosity neat top of Unit-IV (Figure 13C). Voxel based 3D

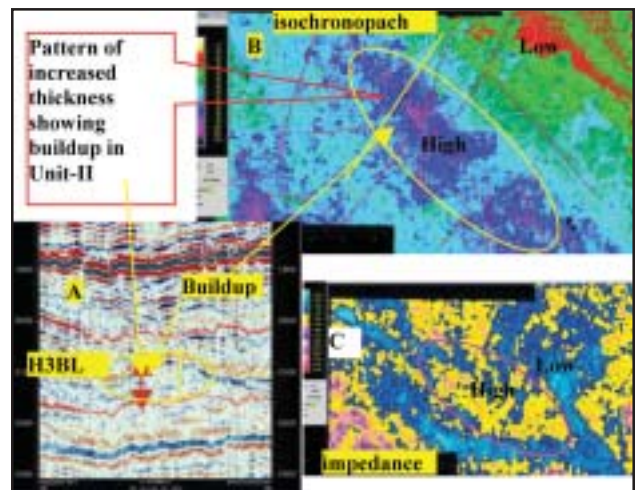


Fig.10 : Carbonate build up within Unit-II. A. Vertical section, B. Isochronopach between B3 and H3BL and C. Impedance within 8 ms window with reference to stratal slice corresponding to middle of B3 and H3BL.

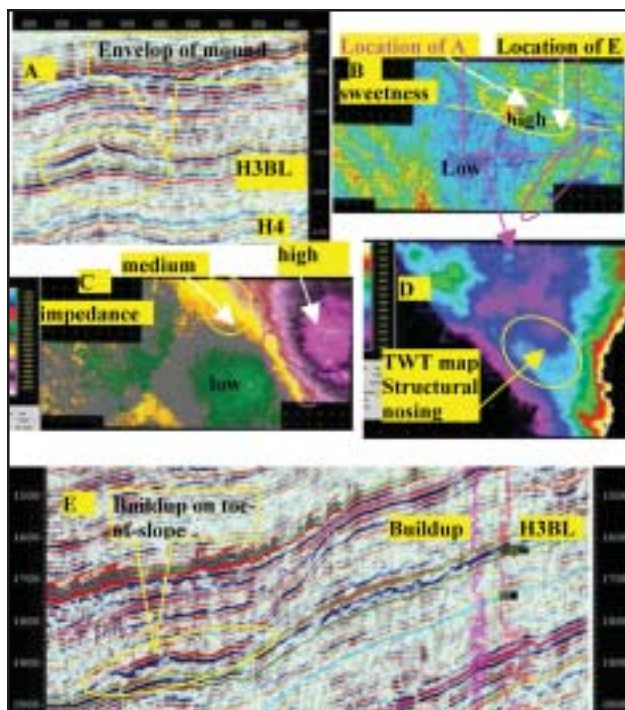


Fig.11 : Buildup feature within Unit-III

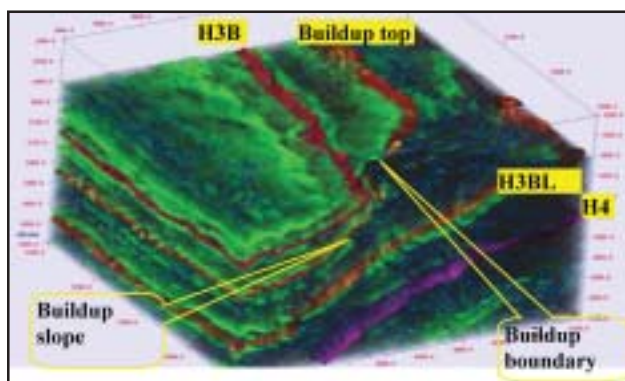


Fig. 12A. Opacity cube showing massive buildup and slope facies (off-buildups).

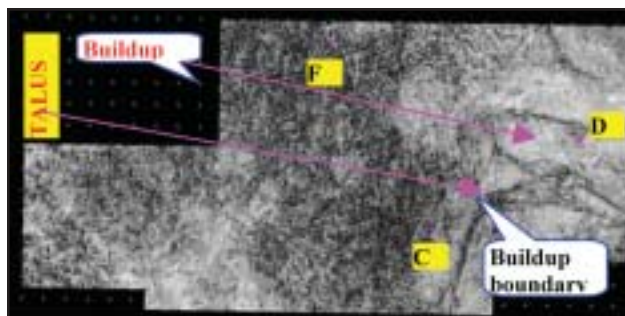


Fig.12B : Coherency horizon slice of buildup top showing buildup boundary and other discontinuities.

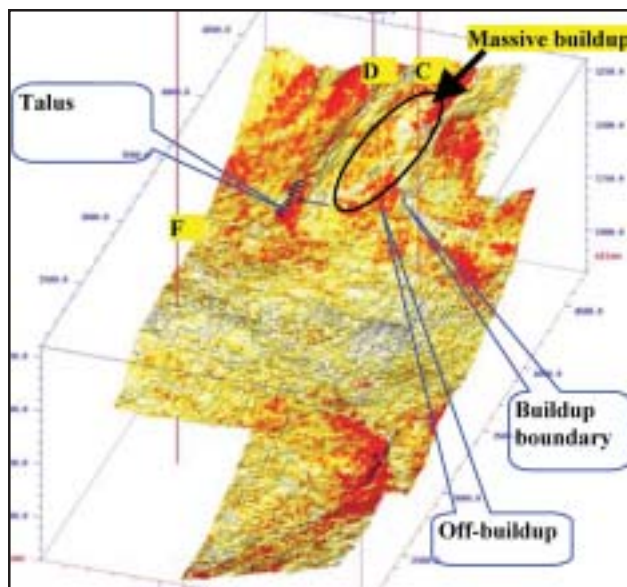


Fig.12C : 3D voxel image of buildup top reflector showing buildup boundary and surrounding talus (off-buildup) features

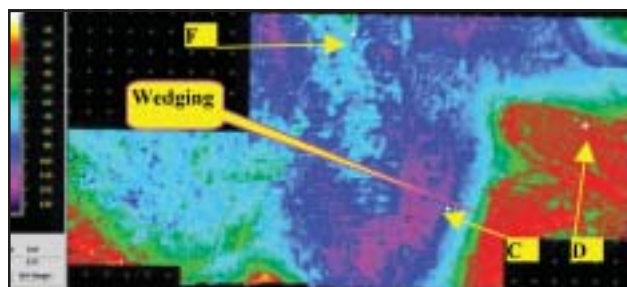


Fig.13A : Isochronopach between buildup top and H3B.

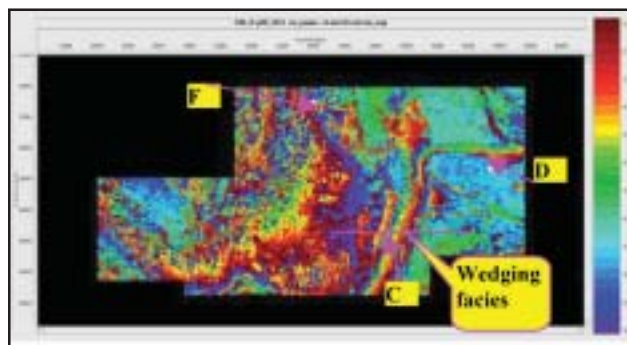


Fig.13B : Seismic facies map within an interval of 0 to +60 ms window with respect to H3B.

visualization (Figure 12A and 12C) and coherency time slices (Figure 12B) may give discontinuities and boundaries between different lithological assemblages.

Conclusions

Integrated evaluation of 3D data has been done

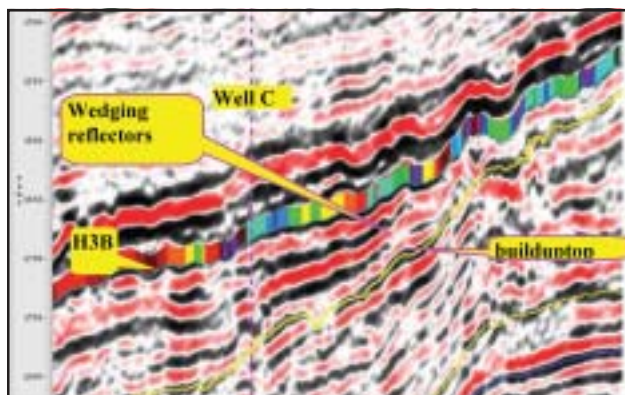


Fig. 13C: Seismic section showing wedging reflector between buildup top and H3B. The seismic facies is overlaid on the section.

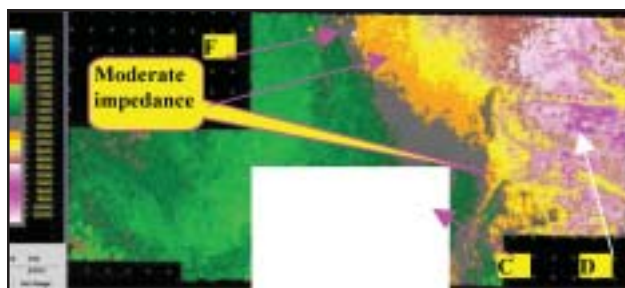


Fig. 13D. Impedance map between buildup top and H3B

using seismic stratigraphy, seismic attributes and 3D visualization. The Bassein Formation has been divided into four units, seismically, and depositional environments were inferred as transgressive to highstand. Seismic reflection patterns within units were delineated in terms of associated lithological assemblage and porosity and trap development. Carbonate and mixed-carbonate-silicilastics were deposited within these units. Carbonate buildups, off-buildups surrounding the big buildups and wedges of debris flows are identified as potential reservoirs. The interpretation is qualitatively validated at drilled wells in the area. Concepts and methods of this study may be applied to carbonate

sequences having similar setting.

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Views expressed in this paper are that of the author (s) only and may not necessarily be of ONGC.

References

- Erlich, R. N., Longo, A. P. Jr., and Hyare, S., 1993, Response of carbonate platform to drowning: Evidence of environmental collapse, in *Robert G. Locucks and J. Fredrick Sarg eds., AAPG, Memoir 57*, p. 241-266.
- Eberli G. P., Baechle G. T., Anselmetti F. S. and Incze M. L., 2003, Factors controlling elastic properties in carbonate sediments and rocks, *TLE*, June 2003, p. 654-660.
- Pacht, J. A., L. Brooks, and F. Messa, 1996, Stratigraphic analysis of 3-D and 2-D seismic data to delineate porous carbonate debris flows in Permian strata along the north western margin of Midland Basin, West Texas, USA, in *P. Weimer and T. L. Davis, eds., AAPG studies in Geology No. 42 and SEG Geophysical Development Series No. 5*, AAPG/SEG, Tulsa, p. 161-170.
- Handford C. R., and Loucks R. G., 1993, Carbonate depositional tracts and system tracts-Response of carbonate platforms to relative sea-level change, in *Robert G. Locucks and J. Fredrick Sarg eds., AAPG, Memoir 57*, p. 3-41.
- Handford C. R., 1998, Visualizing Exploration targets through carbonate sequence stratigraphy, *TLE*, July 1998, p. 891-894.
- Ng Tong San, and M. Mohamad, 1996 A quantitative analysis of seismic reflection in a gas-bearing carbonate buildup, offshore Malaysia, in *P. Weimer and T. L. Davis, eds., AAPG studies in Geology No. 42 and SEG Geophysical Development Series No. 5*, AAPG/SEG, Tulsa, p. 219-224.