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Analysis of Sand and its Seismic Manifestations, Kerala Deepwater Basin - A Case Study:

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Summary

Exploration in Kerala basin deep water blocks has established deepwater depositional system in the area with the identification of Paleocene/Early Eocene shelf-slope system. Eustatic oscillations during Paleocene/Early Eocene period have brought in quality reservoir high impedance radioactive sands into the area as basin floor fan lobes. Though all major present day rivers tend east, mapping of shelf-slope system and various seismic attributes indicate the existence of a coarser clastic input system from the east.

The drilled well has established the absence of quality Tertiary source rocks facies in Kerala deep water. The study brings out the genesis of the sand and highlights the anomalous AVO effect. Through Simultaneous Inversion (SI), lithology classification was carried out to understand sand type and its spatial distribution. Besides, the study highlights various manifestations of Early Eocene (?) sill intrusions, subsequent hydrothermal activities and their effects on the sediments.

Introduction

The study area lies on the Passive margin setup of Western India Continental Shelf and is located in the Laccadive depression of Kerala-Konkan deep water basin. Bathymetry along the eastern part of the area is relatively shallow (400m) and deepens towards west with a maximum of 2700 m in the SW part (Figure-01 & 02).

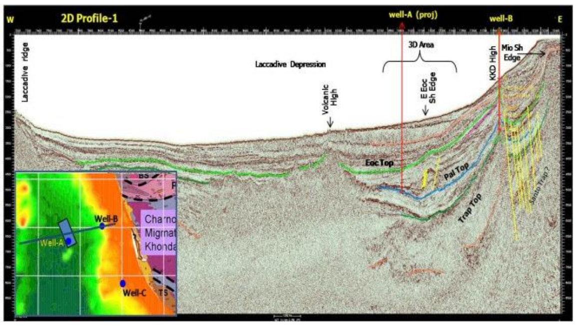

Figure-1: EW regional seismic long offset 2D profile

The first deep water well, well-B, was drilled on the KKD structure (Figure-03), which encountered 1700 m of dominantly sand from Paleocene to Early Eocene section. The top of the KKD structure is capped by Mid-Late Eocene carbonate followed by a distinct unconformity, hiatus ranging from Oligocene to Miocene. The well-A was drilled recently up to 6205m at a bathymetry of 2110m to test the hydrocarbon potential of Tertiary deep water clastics in the area. The well, as prognosticated has confirmed the presence of envisaged deep water reservoir facies corresponding to Early Eocene basin floor fans. However, source rock analysis of the well has failed to prove the presence of quality Tertiary source rocks throughout the entire Paleocene and Eocene section in the well.

The Onshore geology map (Figure-02) prepared by Geological Survey of India), indicates that the Deccan Trap is limited to north of 15030' N, whereas a vast granitic/metamorphic terrain, exposed to the south, must have contributed sand to the basin. Though all major rivers tend east, there are ample evidences of existence of west bound paleo river, contributing sediments to the basin. Thick coarser clastic sediments present during Paleocene-Early Eocene period could be the result of such drainage systems. Mapping of Early Eocene shelf-slope system and various seismic attribute maps pertaining to Paleocene section indicate existence of definite clastic inputs from the east.

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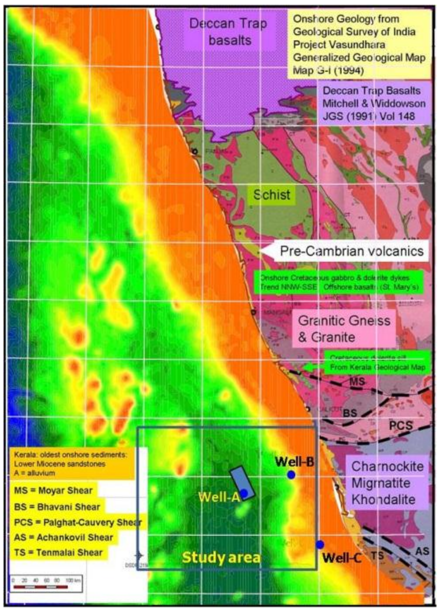

Figure-02: Onshore Geology (GSI), bathymetry & study area

Tectonic Setup

The well-B has penetrated 140 m of Paleocene Trap, capped by trap wash. The well-A ended in multiple episodes of sill intrusions, with sand in-between, of Late Paleocene or older age.

A curvilinear NNE-SSW high trend (Figure-03), KKD High, is separated from Miocene shelf by a low (KKD east low) which trends NNW-SSE in the north to N-S in the south. Time thickness in the section shows a major Paleocene-Eocene depo-center to the west of well-B where well-A was drilled. The Paleocene Eocene low, tend NW-SE, was subsequently peneplained through Early Eocene.

The maps at shallower levels have shown less number of faults. Post Eocene thickening, visible in seismic 2D profile-1 (Figure-01), to the east of well-B suggests that KKD east fault to be post Eocene one.

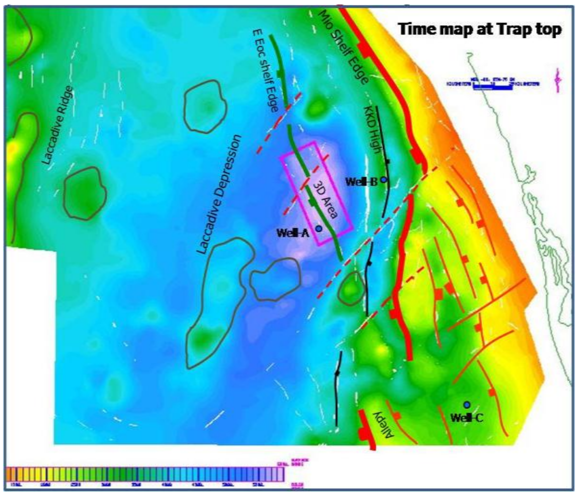

Figure-03: Time map at Trap Top depicts major tectonic features

A strong right lateral strike slip fault (Figure-04), runs NNW-SSE direction, evident in 3D area, has given rise to Early Eocene shelf edge system. Further, this right-lateral strike slip fault system has given rise to NE-SW riedel shear system during Early Eocene. These riedel shears are non-listric and show variable normal throw, mainly dipping towards NW. Most of these faults have very insignificant dip-slip component at Trap level; dip component increases at shallower level, at Early Eocene, a typical character of strike slip regime.

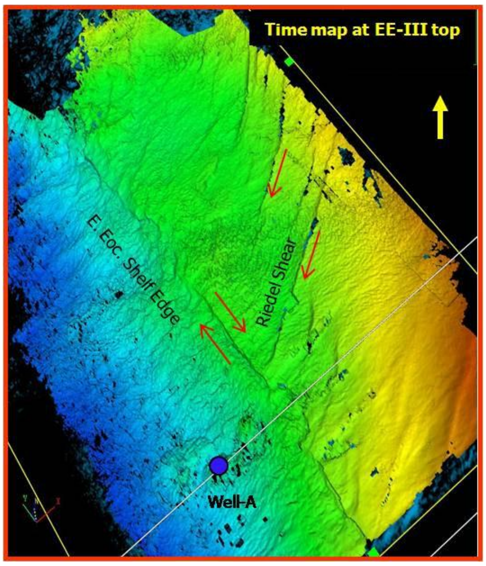

Figure-04: Time map at Early Eocene-III

During Early Eocene sea level falls, sediments were directly fed on to the slope, bypassing the shelf, causing sediment loading and instability and growth faults development (Figure-06 & 20A). These faults are highly listric, with fault surface concave towards basin. Numerous such systems run parallel to the Eocene shelf edge.

Sand Dispersal

Across Paleocene top in the wells, resistivity and density log show a definite baseline shift, indicating major change of facies and environment of deposition. Presence of foraminifera in early part of Paleocene section in well-B infers marine regime.

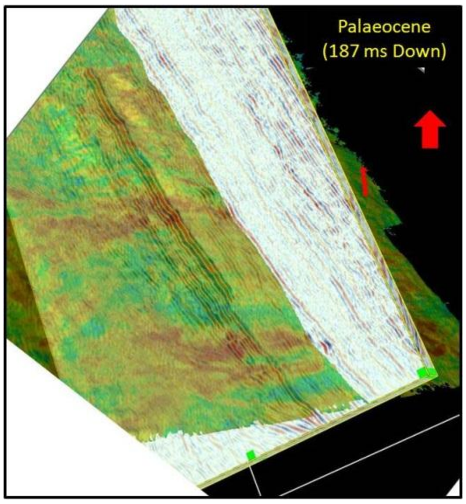

Figure-05: Sweetness on horizon slice within Paleocene

The Paleocene sedimentary unit consisting of mainly tight to very tight sandstone with minor shale/clay stones has been deposited in a shallow marine condition overlying the trap with minor limestone streaks on palaeo highs. The later part passes on to fluvial regime and subsequently established Early Eocene shelf edge, evident in well-B. The Paleocene section was monoclinally dipping towards west, without a break in slope. The sweetness horizon slice (Figure-05) within Paleocene section (187 ms down Pal Top) shows Paleocene clastic system from the east.

Early Eocene-I (EE-I) was initiated as normal regressive (progradational) sequences characterized by few cycles of topsets which progressively downlap westward on to the Paleocene surface (seismic line-1600, Figure-06).

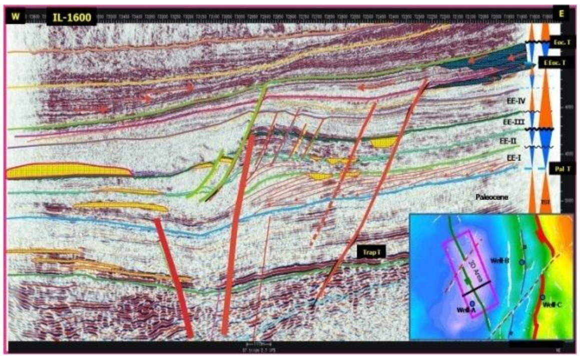

Figure-06: EW 3D Seismic InLine-1600, depositional features overlaid

It passed on to forced regressive sequence, indicated by toplap and truncations at the top of the unit. The unit thickens abnormally near off-lap breaks which suggests a possible initiation of delta building activity at the Early Eocene shelf edge, created on account of right lateral strike slip fault(Figure-04), with the input distinctly from east. A mild break in slope in Figure-07 (dotted line) indicates probable Early Eocene (EE-1) shelf edge.

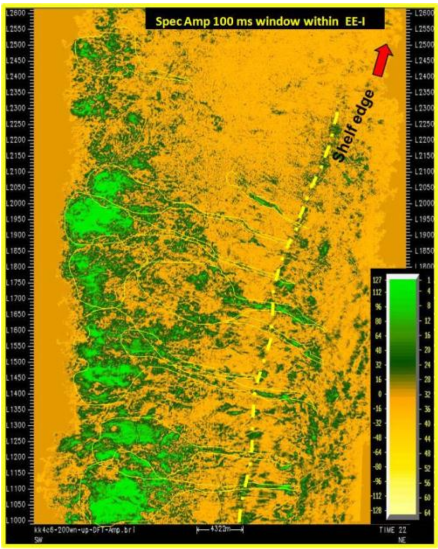

Figure-07: Spectral Amp on a 100 ms window within EE-I.

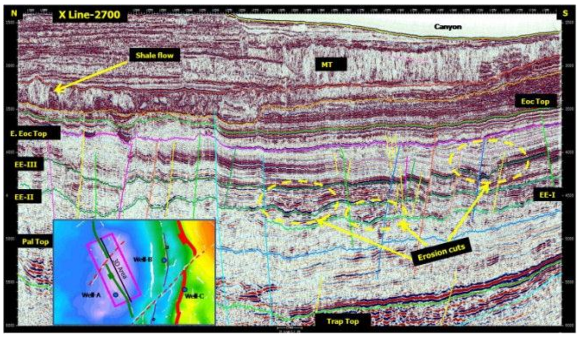

Figure-08: NS 3D X-Line 2700 passing on the shelf.

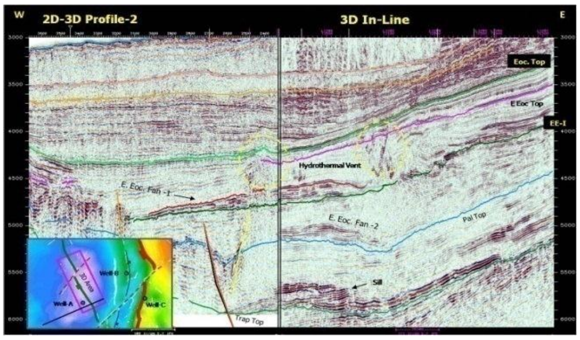

Figure-09: EW Seismic 2D-3D profile passing through BF-1.

As the slope was moderate we observe non-meandering long feeder system cutting through upper slope deltaic system. These thin feeders could be captured by spectral tuning cube attribute (Figure-07) on a 100 ms window of seismic section within EE-1 as small burst of amplitudes. To the south on outer ramp, small basin floor fan lobes are observed without much mounded structure, contemporaneous to the upper forced regression system during early (EE-1) fall of sea level. Thus overall condition is favorable for mixed mud-sand rich fan system.

Early Eocene-II (EE-II) seems progradational as the off-lap break has advanced further to the west (Figure-6 & 10). Similar to the EE-1, the EE-II top is an erosional surface (erosional cuts observed in the strike lines Figure-08) caused on account of a short period of sea level fall. Coeval to this fall of sea, there is small, limited aerial extent, thin fan systems, which are captured in Spectral Amplitude attribute over a window of 100 ms (Figure-10) within EE-II. The fans are with long feeders which indicate a relatively less gradient slope system and fans may be of mixed sand-mud rich type. Bifurcation of the fan lobes indicates tidal influences. Towards the shore side of the shelf edge, intense scouring is observed, which are subsequently filled. The shape, geographical location and environment infer these to be tidal scouring and tidal channel-fill system (wash-over fan).

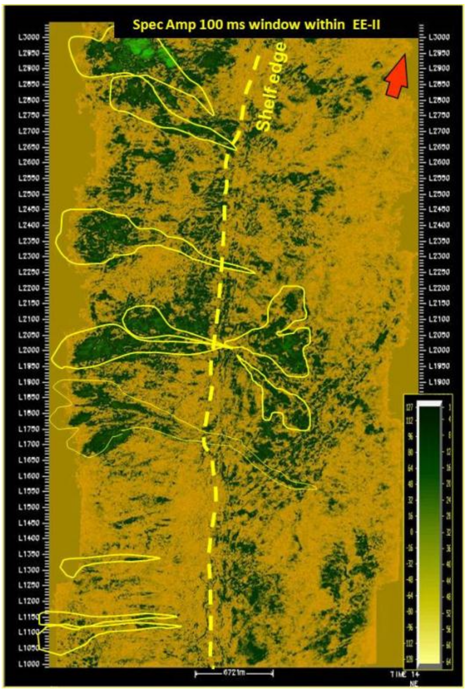

Figure-10: Spectral amp on a 100 ms window within EE-II.

Early Eocene-III (EE-III) seems to be aggradational to initiation of retrogradational system. The unit top is highly eroded one, an unconformity surface. Shelf edge intense scar is visible (Figure-04, 08 & 11), indicating sharp sea level fall. In the basin, the biggest basin floor fan-1 (In-Line in Figure-09 & X-Line in 20B) sits over this unconformity surface, contemporaneous to the erosion,

Deep water, lowstand depositional systems recognize two major types of fans. These comprise of a 'basin-floor' or lowstand fan and 'slope-fan' forming part of the lowstand wedge (Emery et al). The basin-floor fan is considered to form a more sand-prone system in response to the increased stream capacity and enhanced alluvial gradients associated with the early phase of relative sea-level fall. During this period, the shelf system is largely bypassed and major locus of coarse sand deposition is shifted to basin (Posmentier and Vail, 1988; Van Wagoner et al., 1990).

Sand-rich basin-floor fan system is expressed as a single envelope (mounded) developed within a basin-floor location, with a distinct boundaries. The fan thickens towards centre with bidirectional downlap (X-Line, Figure-20B) on to sequence boundary and it is without any typical channel-levee system (Rechards et al, 1998). There is a single point source with short feeder system where the canyon or entry point taps a sand-rich provenance to give a high sand/mud ratio basin floor fan. High reflection strength over fan top indicates shale drape over it. The seismic polarity being similar to the sea bottom suggests high impedance sand, most common in the deep water systems. Occurrence of turbidity current might have enhanced the reservoir facies distribution.

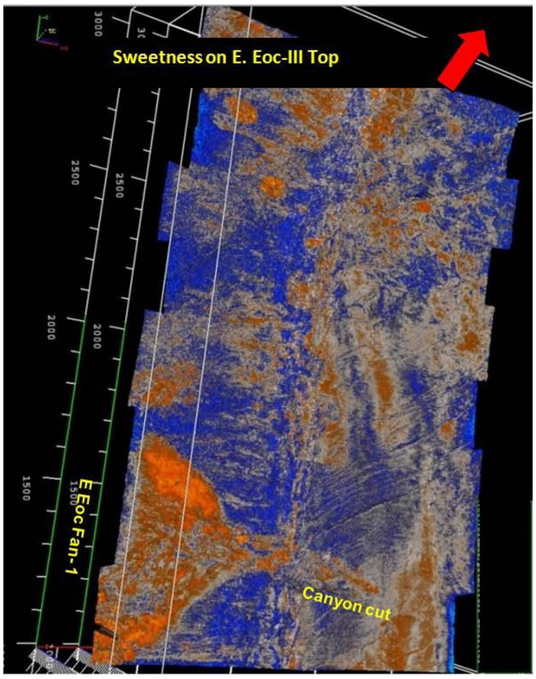

Figure-11: Early Eocene Horizon slice shows sweetness attribute of fan 1 geometry and its feeder canyon.

Early Eocene-IV (EE-IV) top is a well corelatable surface in the shelf, shows parallel to sub parallel seismic facies. Carbonate production/deposition might have been initiated during the onset of transgression. As the shelf edge transgresses towards east, carbonate facies belt shifted (Figure-06 & 12) up dip in retro-gradational manner. This unit thickens towards east, which is a characteristic of back stepping (retro-gradational) carbonate bank system. The underlying section shows apparent truncation, a characteristic of transgressive facies.

During Middle to Late Eocene high stand, the basin experienced carbonate production and shedding which was the maximum at well-B. The end of the Late Eocene is marked by a prominent unconformity in the well, indicated by the absence of Oligo-Miocene sediments, suggesting post Eocene upliftment and formation of KKD ridge.

Whereas post Eocene upper bathyal carbonates were deposited in the western basinal part to the west (well-A). The sediments from Oligocene to recent are dominated by finer clastics.

The sediment process is modeled in Figure-12 along a seismic profile considering various seismic characters, paleo-geographic locations and available well data in the area.

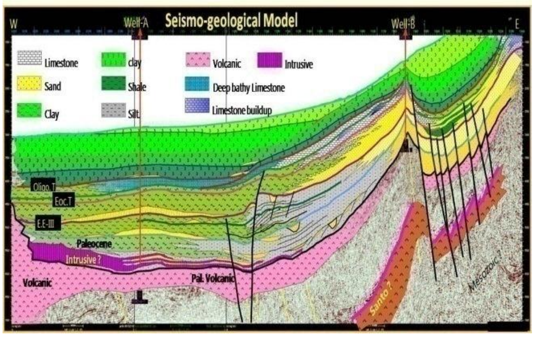

Figure-12: Seismo-geological model

The conceptual spatial model (Figure-13) gives an idea about the Paleocene-Early Eocene sand dispersal system, various major tectonic elements and carbonate banks.

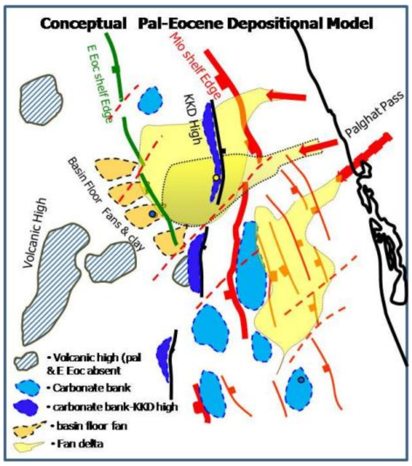

Figure-13: Conceptual depositional Pal-Eoc Depositional model

Analysis of Sand

The well encountered two major stacks (Fan 1 & Fan 2, Figure-14 and 15) of reservoir grade basin floor fan sand encased in deep bathymetry clay, without any organic content. Electrolog evaluation suggests the sand encountered are water bearing and indicates no movable hydrocarbon.

Sand shows high gamma and high velocity. Spectral Gamma count contribution is mostly from Thorium, moderately from Potassium and least from Uranium, distinct in Th~K cross plot (Figure-16). High thorium indicates the sediments proximity to the provenance, the southern granulitic terrain. The provenance being very near, the terrestrial sediments, clay and sands, bypassed the narrow shelf and directly fed on to the deep water system (fan delta).

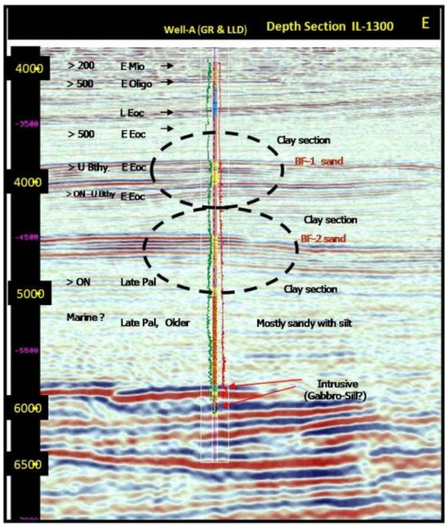

Figure-14: Depth Section of 3D Inline-1300 shows the Early Eoc. Basin Floor Fans and multiple sill intrusions.

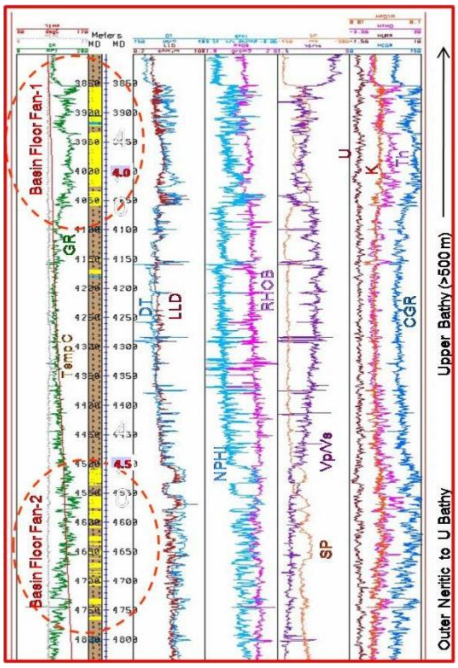

Figure-15: Well log response of high impedance radioactive sands (Fan 1 & Fan 2 in well A).

Vp/Vs clearly discriminate basin floor sand section from encasing clay section which has low shear rigidity. In addition, positive deflection of SP (saline mud) confirms the porous sand from clay section.

Vp/Vs verses DT and SP clearly differentiate the sand from clay section (Figure-17). However for the 2nd fan, it is less discriminatory (figures not given in the article).

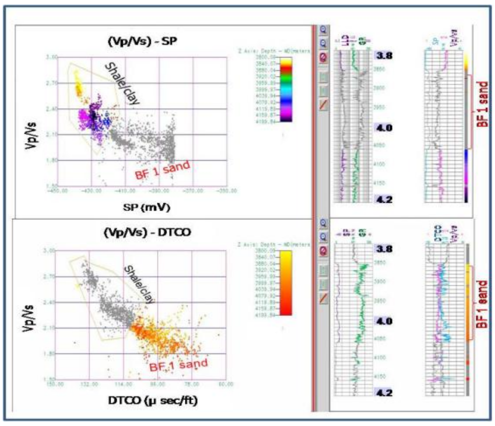

Figure-16: Thorium-Potassium cross plot of fan-1 sand.

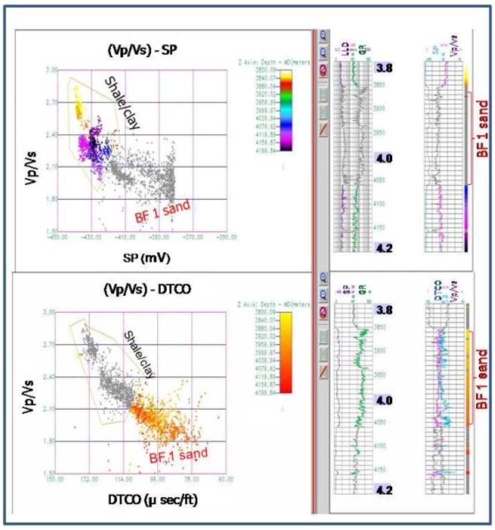

Figure-17: Vp/Vs verses SP and DT clearly differentiate the sand (BF-1) from clay section.

AVO study

Pre-stack simultaneous inversion of the 3D volume was carried out in Hampson-Russel's software. The Vp/Vs ratio plot (Figure-18A) and the shear Impedance (Figure-18B) reasonably map the sand geometry of the basin floor fan-1 and their cross-plot (Figure-18C) clearly discriminates the sand from low rigidity shale section (Figure-18D).

Pre-drill study of these high impedance sands indicated the class-1 type AVO response (Figure-19) which yet remains a major challenge. The lithology effect, the sharp drop in Vp/Vs across shale-sand interface, is the primary cause of these pseudo AVO anomalies

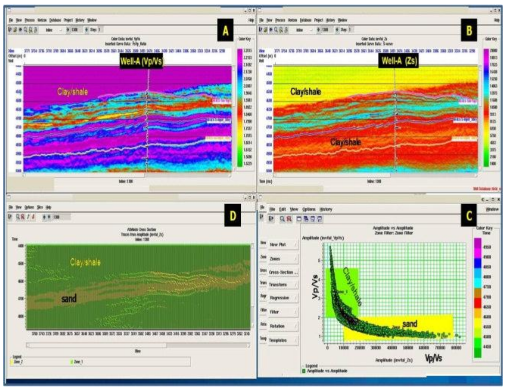

Figure-18: Partial stack simultaneous inversion along BF-1. Vp/Vs, Zs(shear impedance), Vp/Vs ~Zs cross p[lot and sand-shale section, clockwise.

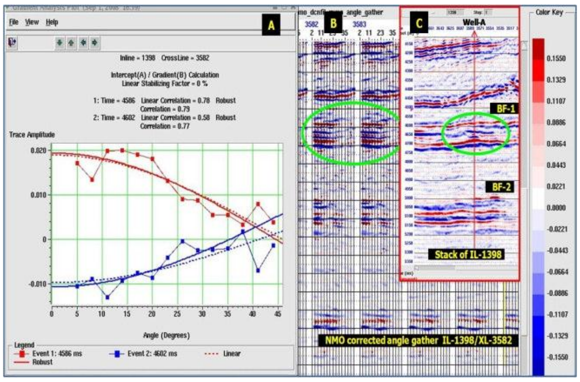

Figure-19: Class-1 AVO response of the sand, Pre-drill analysis.

Sill intrusion, Contact metamorphism and Hydrothermal vents

The log response becomes relatively less discriminatory towards the bottom of the second fan around 4700 m. The Vp/Vs ratio drops much below the value 2, reaches 1.5, which indicates that the sediments are fused together to have any porosity left. SP and Neutron deflection confirms this total loss of porosity. Subsequently, the logs become less discriminatory in the entire Paleocene section.

Besides sheet like sill intrusions, numerous isolated high impedance lens shaped reflections are observed well within Early Eocene sections. These features being several times brighter than the adjacent reflections, often giving migration smiles (yellow ellipses in Figure-09 & 20), can be interpreted as lacolith and lopolith. However, often sill intrusion is associated with hydrothermal activities which might have given rise to sand injectites into softer clay section, thus giving rise to high impedance contrast. Sub-volcanic intrusions in sedimentary basin cause strong thermal perturbation and extensive hydrothermal activities. Hydrothermal vent complexes emanates from the tip of transgressive sills. High fluid pressures, fluidization process, and channelized flow play a major role in restructuring sediments around sills and vents. Numerous such vents, often misinterpreted as gas chimney, are reported throughout KK basin. Often these vent complexes are associated with a positive topographic relief at Early Eocene top, which infers indirectly the age of the sill intrusion.

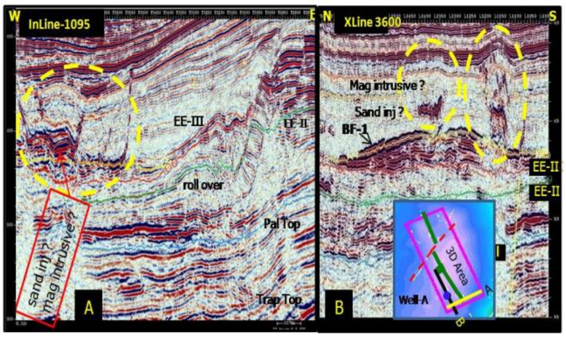

Figure-20: A. In-line 1095, B.X-line 3600 shows low frequency bright anomalous objects and strike section of BF-1.

Contact metamorphism occurs adjacent to igneous intrusions and results from high temperatures associated with it. Further, rocks would have been altered at high temperatures and moderate pressures by hydrothermal fluids. Presence of multiple layers of intrusive sills within Paleocene sections in well-A and well-C confirms probable younger episodes of volcanism in the area. Although cataclastic metamorphism is reported in the wells in the vicinity sills, absence of any major fault does not support this.

Conclusions

The authors have tried to analyze the Tertiary sediment dispersal pattern in Kerala basin. Establishing the absence of Tertiary source facies has helped to shift the focus of exploration to the speculative sub-basalt Mesozoic hydrocarbon system in the basin.

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