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Evaluating Prospectivity of Cretaceous to Eocene Reservoirs in Sulaiman Foredeep via Sequence Stratigraphic Interpretation in Integration with Advanced Forward Stratigraphic Modeling

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ABSTRACT

A unique workflow was adopted where outcrop sections, seismic, offset wells information and Geologic Process Modeling (Forward Stratigraphic Modeling) was integrated. detailed petrophysical interpretation and depositional facies classification was carried out on wells in offset fields and well based conceptual sequence stratigraphic model was developed. To strengthen the findings, data from outcrop sections around the field was also integrated. The data was then tied with seismic and key horizons were mapped followed by detailed seismic sequence stratigraphic interpretation that was performed on regional transects first and then propagated to all the 2D seismic in study area. The seismic sequence framework was constructed by identifying the bounding surfaces (SB/MFS/TS) with the help of seismic attribute analysis, followed by identification of system tracts and seismic facies, which were analyzed/interpreted based on reflection strength, internal geometry, continuity, and terminations with upper and lower boundaries within the study area. To validate the sequence stratigraphic interpretation, Geologic Process Modeling (GPM) was done. The model was produced using the literature, regional geology and all the available data (sea level information, paleo topography, tectonics etc.) and the results successfully validated the sequence stratigraphic interpretation. GDE maps were prepared by using facies identified in seismic facies analysis and used as input for chance of success mapping. Pab Formation within the area is interpreted to be predominantly comprised of siliciclastic strata prograding towards West/NW, representing fluvio-deltaic settings. Ranikot is predominantly a siliciclastic package, representing transgressive deposits at base, overlain by LST deltaic deposits and transgressive deposits at top as well. Toi Formation SE progradation within identified sequences indicate provenance in NW. The Rubbly sequence is characterized by strong parallel reflections, implying possibly shallow water carbonate platform where the local thickening and thinning may represent shoals developed during HST. The Rubbly is truncating against Miocene unconformity in NE but no closure could be located. Both the carbonates of Kirthar group are represented by strong, parallel, and continuous reflectors present consistently throughout the area. The presence of thick shales above HRL and Pirkoh however indicates periods of rapid transgression and drowning of the carbonate platform resulting in the shut down on carbonate factory.

EXTENDED ABSTRACT

Introduction

Covering an area of ~2200 sq. km, study area is a part of Suleiman foredeep in Middle Indus platform, a broad monocline dipping gently westward (Fig. 1a). Tectonically, it is the least affected area due to its greater distance from collision zones, so chances of encountering a structural trap are meagre. Therefore, the work is focused on evaluating expected reservoir facies & locating stratigraphic trap. The proven reservoirs in the vicinity include Cetaceous & Paleocene strata. Eocene in this area is represented by Kirthar and Ghazij group consists of alternate deposits of shales and carbonates. Therefore, detailed work included these reservoirs as well. Base of Miocene in this region is marked by an angular unconformity against which Cretaceous to Eocene horizons are truncated and above this unconformity lie thick Molasse deposits (mixture of sand & shales) of around ~4000m. In the case of the subsurface reservoirs in this study, only 2D seismic lines covering mainly study area were available along with some 2D seismic lines from neighboring blocks (Fig. 1b).

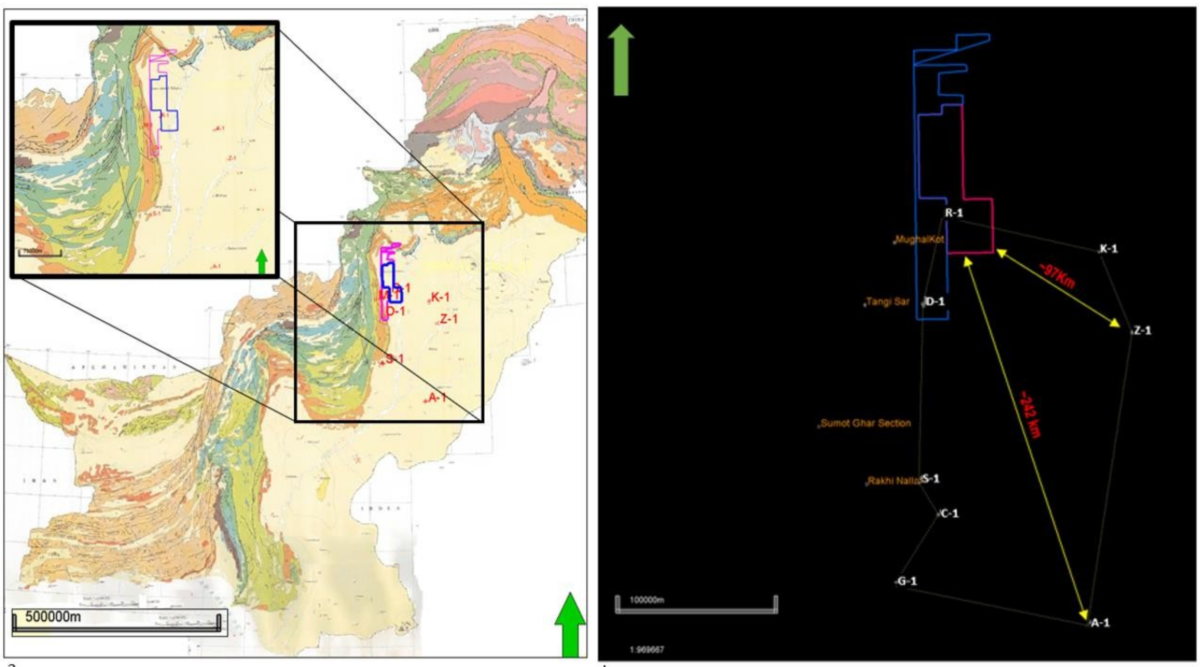
Tectonic Settings

The region was a passive margin until the Late Cretaceous. Paleocurrent studies in the eastern Sulaiman Fold belt suggest a pre-orogenic, west/NW facing, open marine shelf during late Cretaceous time having provenance in South/SE. Pab and Ranikot Formation in study area therefore represents pre-orogenic stratigraphic assemblage of clastics. The main collisional tectonics responsible for Sulaiman foredeep occurred during the early Eocene and resulted in formation of tectonic highland in NW consisting of Pre-Eocene marine shelf of Indian plate. As a result, the newly formed foreland basin in SE started receiving influx of sediments from NW as well. The SE prograding clinoforms on seismic lines in study area seems to represent the above-mentioned syn-orogenic deposition referred to as Ghazij/Toi Formation. Paleocurrents data from nearby outcrops also records shift from westward/NW in the late Cretaceous to more eastward/SE in the early Eocene. By middle Eocene, we entered the post-collision phase and the stratigraphic assemblage constitutes shales and carbonates of Kirthar group. The depocenter of marine sedimentation, which remained restricted in the southern part of the Sulaiman foldbelt and foredeep area during the Oligocene, ceased dramatically during Miocene. And from the Miocene onward, continental environments prevailed, as shown by the thick molasse deposits (Fitzsimmons, 2005 & Siddiqui, 2004).

Workflow

The available 2D seismic lines were analyzed for data quality. A comprehensive mis-tie analysis was performed to adjust the mis-ties identified for dip/strike lines of 2D seismic in study area, dynamic shift was applied separately on Cretaceous and Paleocene/Eocene intervals. After log conditioning/Qc, petrophysical analysis was performed on all the existing offset wells to get an idea about the lithology, porosity, permeability & HC saturation.

Available data & literature/outcrop studies were used to develop the understanding of regional geology & tectono-stratigraphy. Once done, well based correlations & sequence stratigraphic work was carried out. As there were no wells drilled in study area, the wells from surrounding blocks/fields were used to form regional transects. A-1 & Z-1 were the key wells, where seismic to well ties helped in accurate picking of stratigraphic events of interest. Seismic interpretation was then carried out on all available seismic lines. Time/Depth structural maps were prepared for all stratigraphic intervals. Seismic sequence stratigraphic framework was established by following the standard workflow of picking main bounding sequence surfaces (SB/MFS/TS), identifying system tracts & seismic facies interpreted based on reflection strength, internal geometry, continuity, and terminations with upper and lower boundaries and finally extracting the GDE maps combining results from previous inputs. Forward stratigraphic modeling (GPM) was also carried to validate the sequence stratigraphic framework constructed using integrated approach. Finally, some possible leads and leads within/outside AOI were identified, and associated risks were studied.



a b

Fig. 1: a) Study area highlighted by Blue & Pink boundaries along with wells used in study. b) Base map showing location of available wells & outcrop sections (orange).

Results and Interpretation

The regional geology understanding was developed via published literature review & studying seismic sections and available well data. Petrophysical analysis has been carried out on all the wells from adjacent & nearby blocks. All the available well log data including OH logs, petrophysical interpretation, mud logs and nearby outcrop sections were analyzed and interpreted in terms of facies, their association, depositional cycles, parasequences and possible sequence stratigraphic definition at well level. After having developed understanding of regional/local geology, tectono-stratigraphy, facies, seismic to well tie, and interpretation/mapping of all stratigraphic formations of interest on 2D seismic, the seismic sequence stratigraphic framework was constructed for Cretaceous to Eocene section. Generally, seismic character is analyzed from two standpoints: external form (geometry) and internal character. Internal form includes the continuity, frequency, and amplitude of seismic reflections. Many of these parameters relate to lithology or the processes responsible for deposition and thus are often used to interpret sand body origin and reservoir type (John, 2008).

1. Pab Formation in study area: on type section, (Fig. 3) which is flattened at HRL, prograding clinoforms downlapping in west with little or no variation in the geometry of individual reflection but general thickness increase in west can be observed. All appears to be the continuation of same HST observed at type section Similar pattern is observed on all the dip lines in study area. The interpretation confidence is low towards west because of the faulting/data quality. These gentle dipping downlaps can also be observed on strike lines orienting NNW-SSE. Here the general decrease in thickness is observed towards North. This configuration exhibits the depositional conditions with some combination of relatively high sediment supply and a stand-still/slow rise of a sea level to allow rapid basin infill. On some strike lines there are indications of channels/channel complex with flanks dipping in roughly North and South direction, indicating East-West orientation of channel axis. Due to 2d seismic, channels couldn't be mapped with detail (sinuosity & connectivity etc.) but all the locations with possible indications are marked and general trend is captured. These undulations are barely visible on dip lines. Based on the integration of well data, outcrop section and seismic sequence stratigraphic interpretation the Pab is interpreted to be represented by normal regressive sequences with distal delta/shoreface facies (slight coarsening up GR motif) at base and proximal delta/channel facies (erratic GR) at top bounded by SB (Fig. 2).

2. Ranikot Formation in study area: on type section, (Fig. 3) which is flattened at HRL, relatively more gently dipping reflectors running parallel to SB below can be observed, that are expected to downlap in further west, with little or no variation in the geometry of individual reflection but general thickness decrease in west. Towards east however, onlaps of the same strata can be seen on top Pab. Another interesting thing noticeable at top Ranikot is the truncation at top, which is indicating an erosive event at top, the observations are consistent on other dip lines as well. All appears to be the continuation of same LST/transgressive deposits observed at type section, except the platform break which is not visible here and the gentle geometry of the clinoforms suggests distal settings. The seismic frequency is slightly variable, the internal configuration is Parallel to Wavy with highly continuous to semi continuous reflection Comments on geometry, continuity strength etc. The interpretation confidence is low towards west because of the faulting/data quality. These gentle dipping downlaps can also be observed on strike lines orienting NNW-SSE, here the general decrease in thickness is observed towards North. Based on the integration of well data, outcrop section and seismic sequence

stratigraphic interpretation, the Ranikot in study area is interpreted to represent normal regressive deltaic facies of probably LST with transgressive deposits at base (Fig. 2).

3. Dunghan Formation in study area: Dunghan is represented by a thin reflector (poorly resolved at places), running parallel to the basal MFS/SB. Because of the absence of terminations/internal reflection pattern, it was extremely difficult to comment on sequence stratigraphic standing of the package. However, based on literature, and well logs the package is placed in shallow marine deposition reflecting active carbonate factory in slow transgression (catch-up phase) slope deposits/calc turbidites can be anticipated in distal region i.e., towards West. Furthermore, the truncation at top of Ranikot probably indicates pre-Toi erosion which might have gotten Dunghan partially eroded at places in study area.

4. Ghazij Group (Toi Formation) in study area: Toi Formation has not been encountered in any of the well in adjoining areas. Therefore, we are relying heavily on literature (Edward, 1999) and seismic expression of the formation. The sequence in Eocene package is bounded at its top and base by unconformities as depicted by truncation of reflectors. The internal character is chaotic in general however at-least four 4 sequence boundaries (SB) can be picked and correlated across the field. The sequence-1 appears to be non-clastics based on the continuity and reflection amplitude and possibly is chronostratigraphic equivalent of SML/Nammal. The rest of the sequences are more chaotic and appears to be dominated by siliciclastic. HST/LST sequence sets marked in Toi formation as observed on seismic sections. On seismic type section for Toi; geometry, terminations, and character of clinoforms can be best observed, the SE progradation is evident at places and NW onlaps can also be seen (Fig. 3). On other 2D seismic lines in western part of study area, the seismic data quality is not good, and presence of faults further complicates it. The dip lines although have good data quality but only seeing part individual sequence being roughly parallel to depositional strike. As a result, it was extremely difficult to correlate system tracts within the sequences.

5. Rubbly Formation in study area: In study area, the Rubbly sequences is characterized by strong parallel reflections, implying possibly shallow water carbonate platform where the local thickening and thinning may represent reefs/shoal developed during HST (Growth, Keep-up /progradation). Seismic section showing local thickness variation indicative of mounds and mini basins present in Rubbly. Rubbly is capped at its top by Baska formation, suggesting a slow transgression (catch-up phase), making conditions feasible for shelf evaporites (gypsum). Slow transgressions create an excess of accommodation across the carbonate shelf, which results in the formation of shallow-water subtidal depozones between the shoreline and the rimmed shelf edge. These depozones, or lagoons, are commonly of low energy, being protected from the open sea by distal-shelf barrier reefs.

6. Kirthar Group in study area: Both the carbonates of Kirthar group (Pirkoh and HRL) are represented by strong, parallel, and continuous reflectors present consistently throughout the area. Due to less thickness as suggested by well data (~10-35m), the internal reflection pattern can’t be observed on seismic dip line and strike line flattened at Pirkoh HRL & Baska. Because

of the absence of terminations/internal reflection pattern, it was extremely difficult to comment on sequence stratigraphic standing of the package. But still, the good thickness of basal formations may create local highs which can act as potential depositional sites for shoal/s reefs in Pirkoh. However, based on literature and well logs, the package is placed in shallow marine deposition. A well located close to study area is given more weightage and its log signature clearly indicated both carbonates to be deposited during HST (Keep-up) and slow transgression (catch-up) phase. The presence of thick shales above HRL and Pirkoh however indicates periods of rapid transgression and drowning of the carbonate platform resulting in the shut down on carbonate factory. The reflection pattern within Sirki and Dominda was studied, and an attempt was made to link facies distribution of carbonate with paleo-topography. Due to thickness of Sirki some reflection patterns and geometry can be seen and based on that distribution of carbonate facies of Pirkoh was done. However, HRL/Baska did not allow it because of less thickness and similar paleo-strike and distribution is assumed. there are 3 types of facies interpreted on seismic sections. Facies are classified based on seismic Reflection Geometry, Reflection Continuity and Amplitude Strength. There are three classes of Facies in Rubbly and Kirthar show some parallel reflections in East indicating proximal facies, clinoforms in middle indicating shoreline facies and some parallel reflections with decreasing thickness trend in west indicating distal Facies. Fig. 4 shows facies map prepared as a result of seismic facies analysis.

Geological process modeling technique aims to model the processes of erosion, transport and deposition of clastic sediments, as well as carbonate growth and redistribution on the basis of quantitative deterministic physical principles (Cross 1990; Tetzlaff & Priddy 2001; Merriam & Davis 2001). At Pab, similar westward prograding clinoforms are observed on GPM when geologic conditions in cretaceous were attempted to be reproduced by using Exxon global sea level curve, local paleo topography, tectonics/subsidence, steady flow and sediment diffusion. However, another Lowstand delta is produced @ 67.6 Ma further West of study area. The lowstand couldn't be observed on seismic due to bad quality/faulting but the presence of fluvial channels/incisions at top clearly indicates lowstand and SB at Top. The Highstand prograding Pab deposits below fluvial channels appear to be sand rich in study area – depocenter in West (Fig. 5). At base of Ranikot, some transgressive sands are observed on GPM, these sands couldn't be located on seismic section due to low resolution. Transgressive shales and LST delta can be clearly observable. GPM also confirmed the position of Ranikot sedimentary wedge more proximal than Pab. Truncation of both Pab and Ranikot outside study area in NE can be potential stratigraphic traps (Fig. 5). Rubbly and Kirthar group were successfully reproduced when carbonates were allowed to grow/deposit at HST's, and slow transgression phases while the shales representing the periods of rapid transgressions. The facies distribution from seismic were used to define areas of carbonate growth. In geologic processes, carbonate growth was used instead of steady flow. There are events recording LST-FSST before each transgression, but the signature of those events couldn't be observed on seismic.

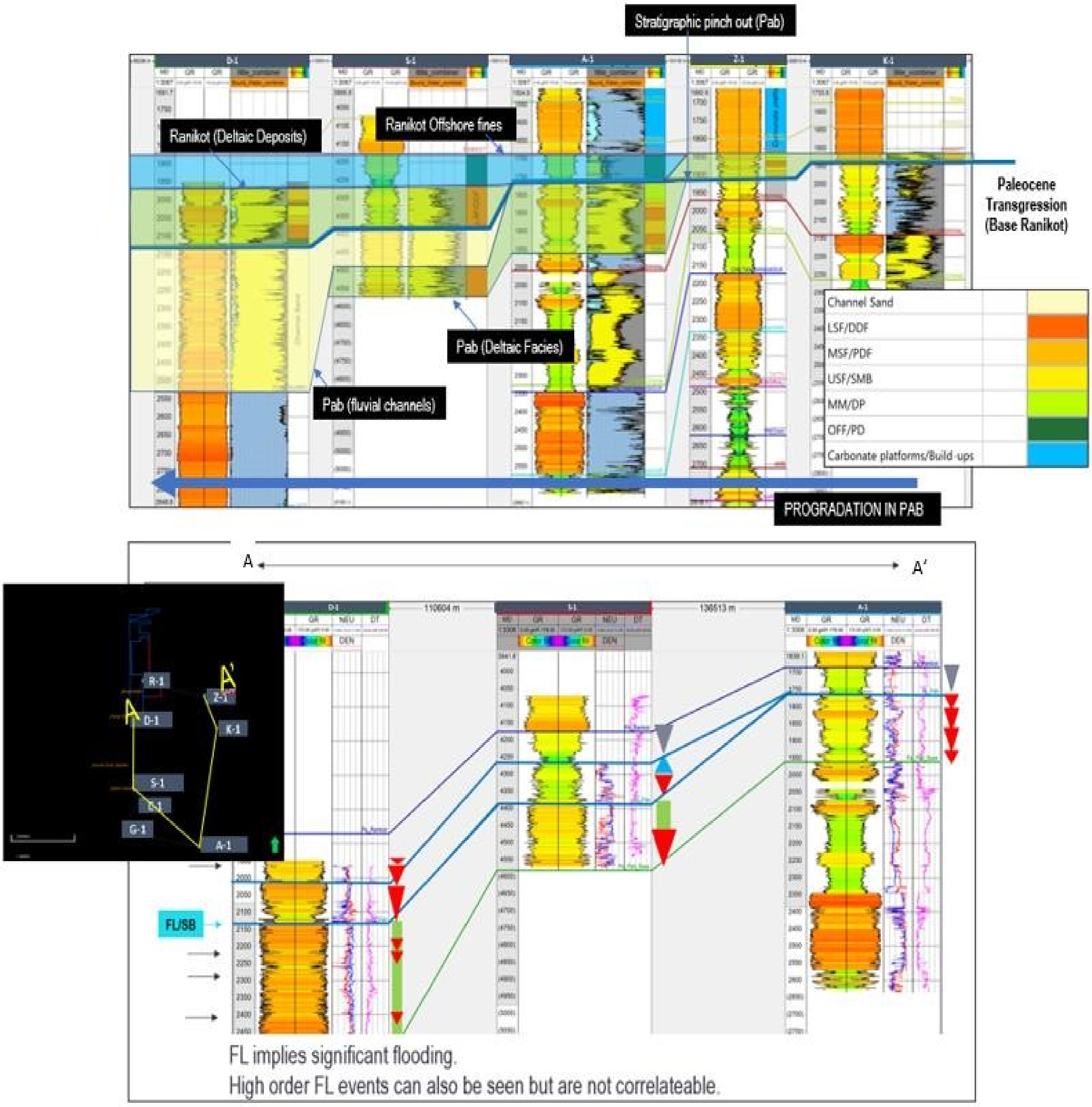


Fig. 2: Well based facies, parasequence & correlation.

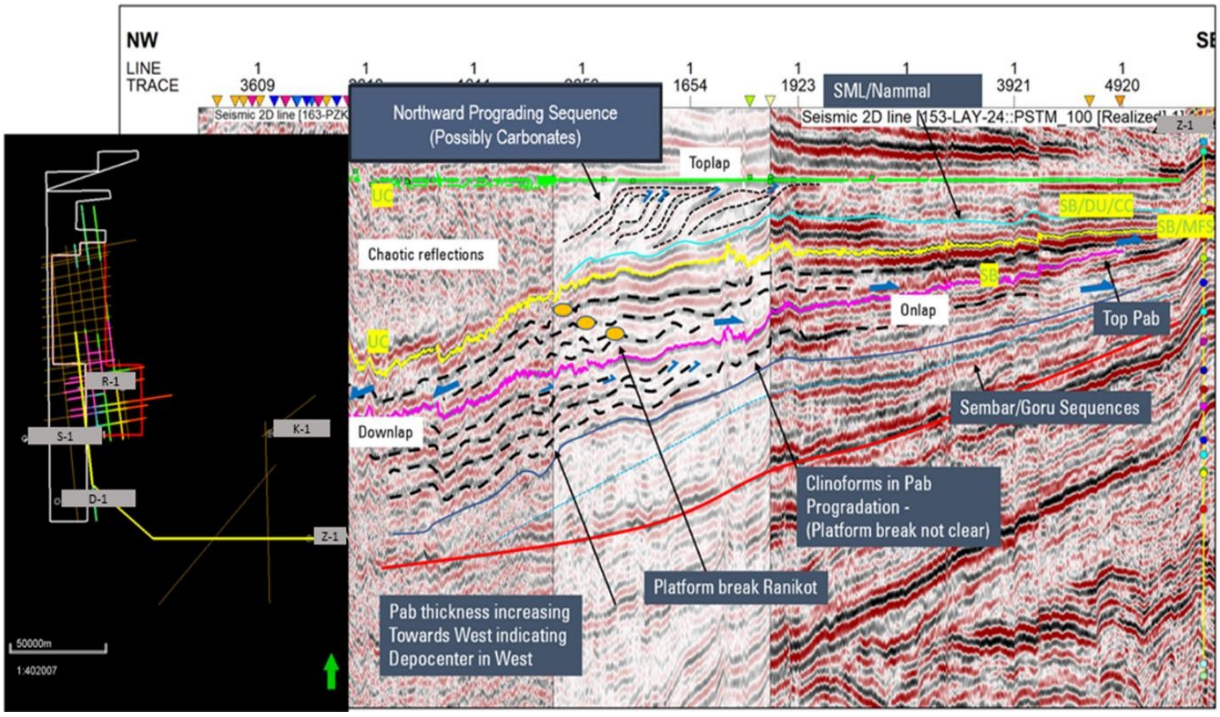


Fig. 3: Type section Pab-Toi sequence.

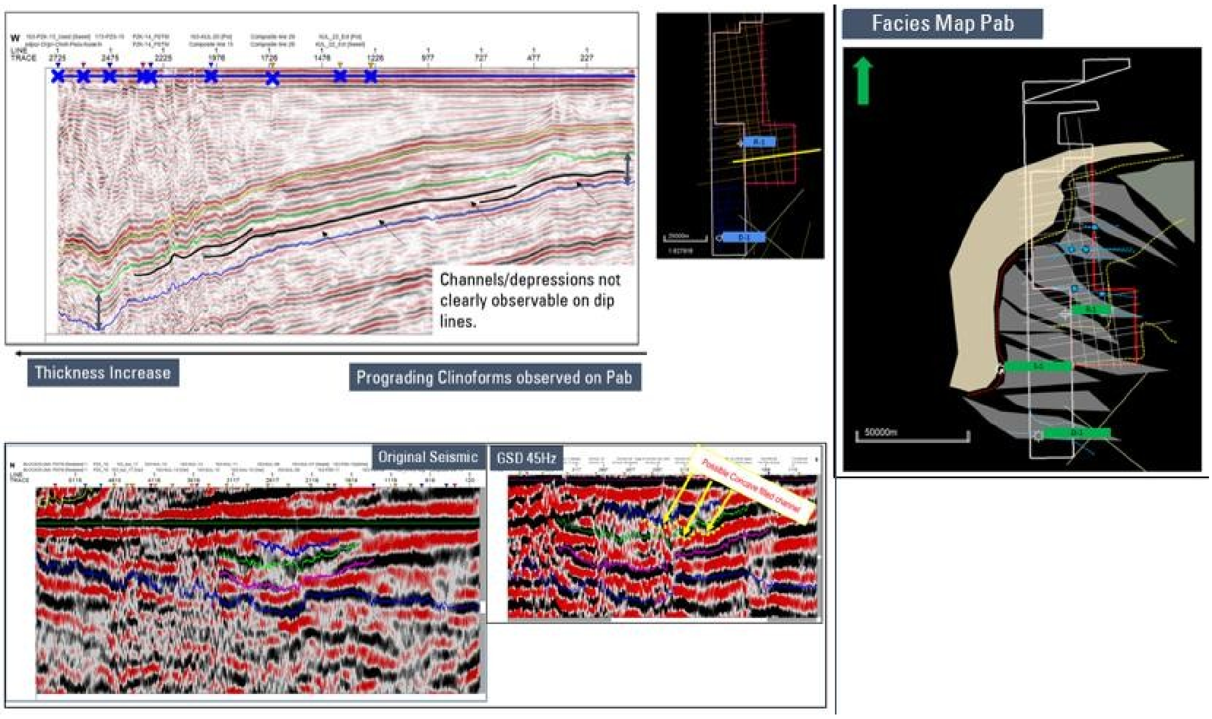


Fig. 4: Pab Formation on seismic dip line, strike line & facies map.

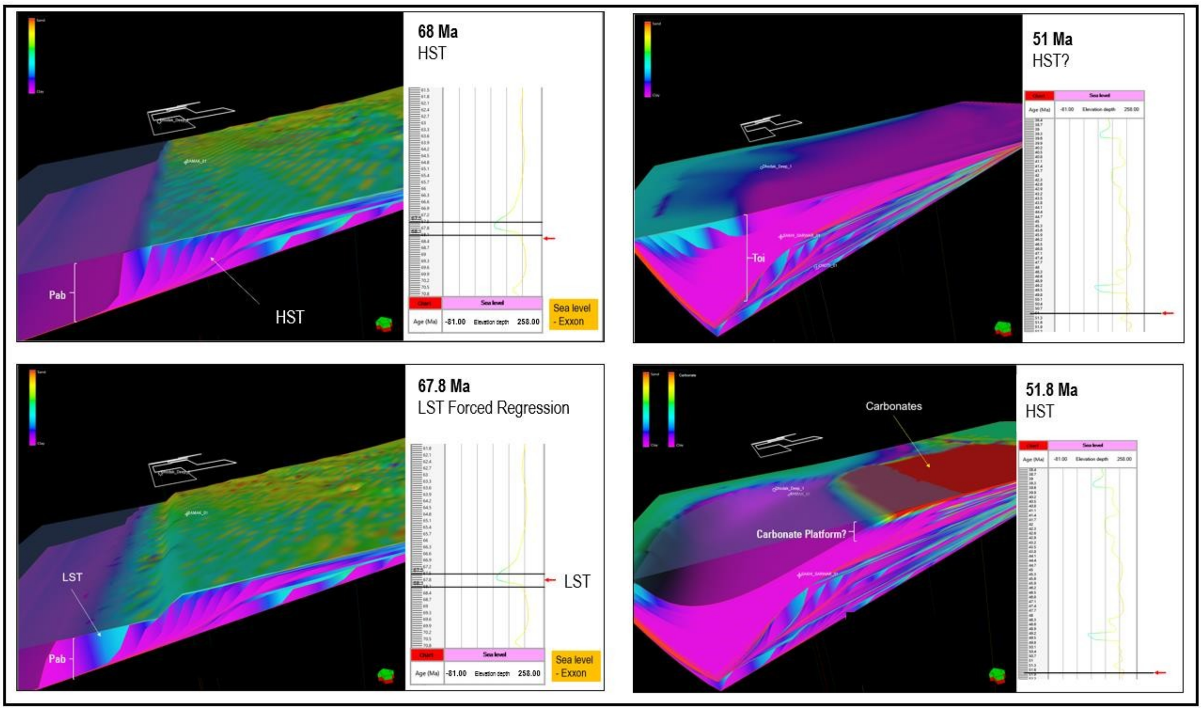


Fig. 5: GPM predictions between 68 & 51.8 Ma.

Conclusions

Based on integrated sequence stratigraphic work, the reservoir character of discussed formations in study area was predicted keeping in view the facies distribution & expected porosity in study area (empirical equations used to account for impact (increase/decrease in porosity) with depth/facies) and finally, several stratigraphic / combination traps/leads were identified in and around study area. The Pab Formation is expected to exhibit porosities of~5-9% in study area and the potential of stratigraphic trap in Pab is restricted to the channel complex, the eastward onlap, truncations in East/SE and Lowstand predicted by GPM can be matured & evaluated further. In Ranikot Formation., the expected porosities in study area ranges from 4-7 % and the potential of stratigraphic trap in Ranikot is restricted to the onlap located in study area and the eastward onlap in East & SE can also be matured along with the transgressive sands predicted by GPM. SE progradation within Toi Formation's identified sequences indicate provenance in NW. Seismic character suggests package to be dominated by fine sediments (Silts/shales), Hence suggesting poor reservoir quality in the study area. The intra-sequence shales can provide seals, but trap identification is questionable with available data. Rubbly is truncating against Miocene unconformity in NE but no closure could be located. Both the carbonates of Kirthar group (Pirkoh and HRL) are represented by strong, parallel, and continuous reflectors present consistently throughout the area. The presence of thick shales above HRL and Pirkoh however indicates periods of rapid transgression and drowning of the carbonate platform resulting in the shut down on carbonate factory. Expected porosity ranges in Pirkoh & HRL are 2-4% & 4-9% respectively, and stratigraphic traps in both Pirkoh and HRL are identified at their NE truncation against Miocene unconformity.

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References

1. Re Edward, A., Johnson, Peter. D., Warwick, Stephen. B., Roberts and Intizar, H. Khan., 1999, Lithofacies, Depositional Environments, and Regional Stratigraphy of the Lower Eocene Ghazij Formation, Baluchistan, Pakistan, U.S. Geological Survey Professional Paper 1599.
2. Fitzsimmons, R., Buchanan, J and Isett, C., 2005, The role of outcrop geology in predicting reservoir presence in the Cretaceous and Paleocene successions of the Sulaiman Range, Pakistan, AAPG Bulletin, vol. 89, no.2, pp. 231-254.
3. John, W. Snedden and J, F. Sarg., 2008, Seismic Stratigraphy-A Primer on Methodology, Search and Discovery Article, no.40270.
4. Siddiqui, N. K., 2004, 'Sui Main Limestone: Regional geology and the analysis of original pressures of a closed-system reservoir in central Pakistan', AAPG Bulletin.
5. Tetzlaff, D. M and G. Priddy., 2001, Sedimentary Process Modeling: From Academia to Industry. In: Geologic Modeling and Simulation, Sedimentary Systems (Ed. by D.F. Merriam & J.C. Davis), Kluwer Academic/Plenum Publishers, New York, 352 pp.