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FACIES AND DEPOSITIONAL ENVIRONMENT ANALYSIS OF ALTERNATE CHANNEL BODIES IN THE FLANK OF A SAG STRUCTURE

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Abstract

The down-dip (40°) portion turbidite Cenozoic deposits of the western sag structure in the Bohai bay has been characterized for stratigraphy. Laterally tracking continuity in temporal data becomes challenging with increase in offset. In achieving this and ground-truthing results from core data, spatial data is indispensable. A good subsurface resolution on seismic data is key to understanding both the distribution and extent of lithological units earlier identified as hydrocarbon prolific. Rock physics and petrophysical properties when understood and appropriately utilized does well in showing vital correlations inherent in subsurface lithological units. Deterministic approach to linking pattern on logs proved slightly useful in this study. Each have its' distinct depositional cycle ranging from 3 cycles for wells 13-2, 35-4 and 46-2 to 4 cycles for 24-5. It has been discovered that well 13-2 has less complex structure while well 46-2 is most distal occurring at the toe of the sag structure, has the most complex geometry. However, hidden vital information became obvious when methods of seismic interpretation and post-inversion multiattribute analyses were used within the same cross section to discover subtle alternating channel sand lobes that is explorable within an unfaulted and slightly com-pacted synsedimentary sequence. These were presented in log panels, cross-sections and maps.

Keywords: Depositional environment; Facies, Channel; Petrophysics; Geometry; Sequence.

1. Introduction and study area

The sub-hill Xinglontai Majuanxi structure has the prolific Shahejie formation as its major hydrocarbon reservoir, with series of deposition episodes being recorded over the Paleogene to Neogene in the Cenozoic. The extensional setting of the Basin in Northern China (Figure 1) was part of the tectonic changes that initiated the opening of the volcanic basements, fracturing it and creating the containment and accommodation for the emplacement of the sedimentary rocks. Series of horst and graben developed in middle Eocene during the deposition of the middle Shahejie formation. Consequently different architectural pattern emanated from the synsedimentary processes.

1.1 Features of depositional environment on logs

Variations within formations are generally reflected on signatures of Spontaneous Potential (SP), hence the use of this kind of log for correlation and lateral delineation of bed continuity. Although in this case, well spacing was well more than a thousand meters thus making lateral correlation a tedious exercise [2,11-12,16,19-20]. Depositional environment delineated and interpreted were quite divers and the history of lithological formations were more projected than succinct. Sand thickness was used in interpreting depositional history by computing the depth between inflection points on SP log signatures [1,3-5,21,26-27,50]. This was juxtaposed with the computed volume of shale (SP_{VCl}) shown on track 3 of depositional environment log panel. A fundamental rule of interpretation gives a clean formation nomenclature to high negative log signatures that is well sorted while on the contrary there is an increase in volume of shale [8-11,51].

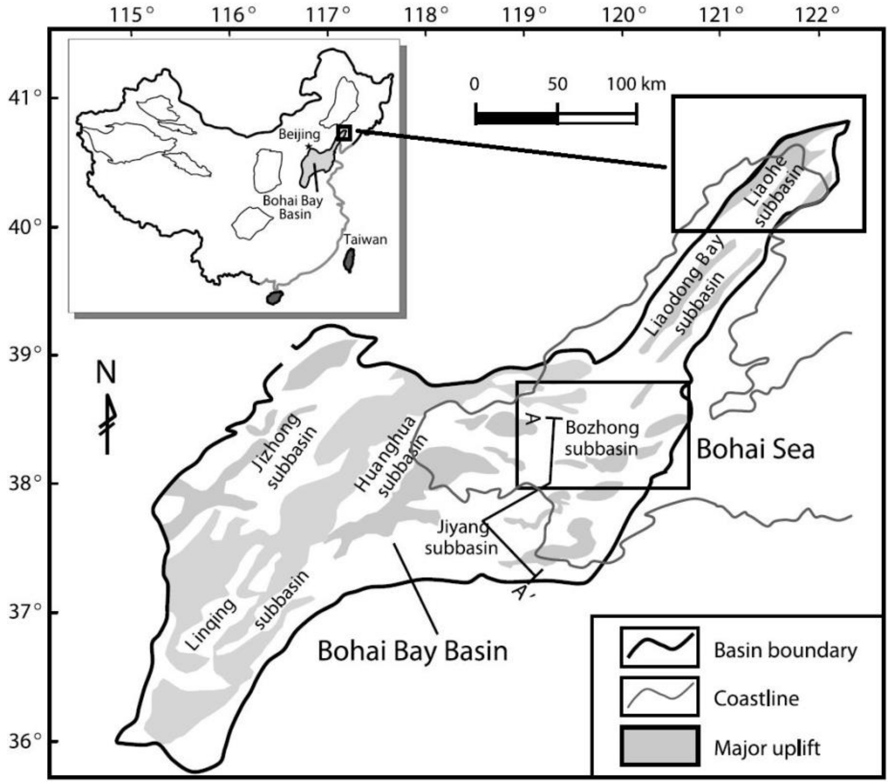

Figure 1 Location of Liaohe subbasin[24] *(Modified)*

Rapid change in energy distribution was also observed as a result of sharp breaks in signature continuity typifying sand and shale units. Here, a meager change in fluvial or marine energy or water depth heralds a high probability of a switch in depositional environment [7,9,12,19,34-36,43,52]. On the contrary, stable conditions would likely result from a wide or gradual transition on SP curves, thus show few variations in environment of deposition.

Rapid fluctuations in conditions of depositions are presented in SP logs as curves with serrated edges. A decrease in sedimentation rate consequently and general decrease in depositional energy (fluvial), will give a picture of a maximum flooding surface having an affinity for shale [20,30,34-36,45-46,49,52]. This causes the upward decrease of SP signature towards the shale base line. Overall geometry of curves was used to characterize lithological units [3-6,23-24]. This used features such as contacts (upper and lower), curve/signature shapes (bell shape – decreasing upwards, funnel shale – increasing upward, cylinder shale – stable and irregular – rapid fluctuation), and curve characteristics (smooth, serrated and complex) [7,11,27-28,34,36,]. These were the parameters sought on the lithology log used. An attempt was also made to understand the origin of the various shapes delineated.

On seismic data, polarity of wavelet was used to delineate break in reflection energy in 2D seismic data [2,12,19,28,33]. Termination of dominant reflection patterns against the top or base of a sequence was accounted for as the peak of a depositional episode while facie pattern preservation was used as a considerable variation on energy of deposition per time in a single sequence [10,19,41,46]. This was done down dip within the well offset space. These were the methods used in interpreting the logs for their depositional environment and lateral expression of lithologies. The following environments were delineated; Transgressive and Regressive marine, Channel and Point bars, and Transitional Deltaic [2,21,37].

2. Results

2.1 Interpretation of curve geometry and contacts on well logs

Transgressive marine environment starts the depositional sequence in Well13-2. This is a gentle serrated bell shaped gradational signature [3]. Well13-2 is typically characterized by cycles of transgressive-regressive depositional sequences with various contacts ranging from gradational to aggradational and progradational signature geometries [16,23,32,35]. Vertices of curve shapes are not in any way smooth typifying non deltaic sequences and less of highstand deposits. Serrated and complex edged signatures characterize the log cross section of Well13-2 (Figure 2 and 6). Towards the end of the first quarter of the total log run of Well13-2, back to back or repeated deposit of transgressive and regressive signatures were delineated signifying a time of continual episodic progradation which was characterized by different depositional energy [27,34-35,40]. This most proximal well has more of fairly massive deposits with less than 45% of it having volume of shale greater than 50%. This translates to an average density of between 2.64 and 2.68. The shaleier portion coincides with the peaks of retrogradational sequence preserved as flooding surfaces and at some instances, marks the onset of progradational regressive marine sequences [46-47,50,52]. This well of the 4 studied is less complex in deposits due to the delineated curve patterns and mature contacts compared to the others. We could only identify 3 major depositional cycles as seen in the bigger colored arrows and triangles.

More complex log signatures characterize Well24-5. The thickest of the delineated sequence is about 30 metres occurring in about 2 locations in the log run with one at the base and another towards the top. The one at the base is a serrated Transgressive marine to channel bar deposit [41,44]. The shape is bell and is 25% shale (Figures 3 and 6). Above and beneath it are also deposits with similar pattern though not as thick as this but appearing stacked and only interfiled by a brief regressive unit. Typically, the smallest unit is a high stand cylindrical shaped smooth edged deposit occurring intermittently within the log section. Patterns observed ranges from abrupt to gradational (both forward and back stepping sequences) [33,44,47]. Irregular, bell, funnel and cylindrical signature shapes are well preserved with most having serrated edges. 4 main depositional cycles are delineated all arising from minor sequences that are transgressional, regressional and fluvial (channel and point bars) [1,13,17,34].

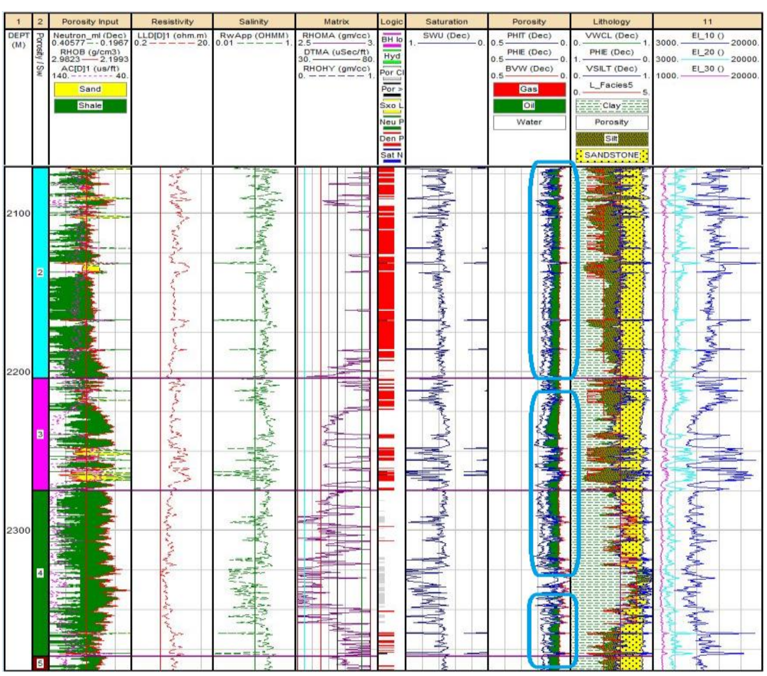

Figure 2 Petrophysical analysis for Well13-2 showing hydrocarbon presence in blue ovals

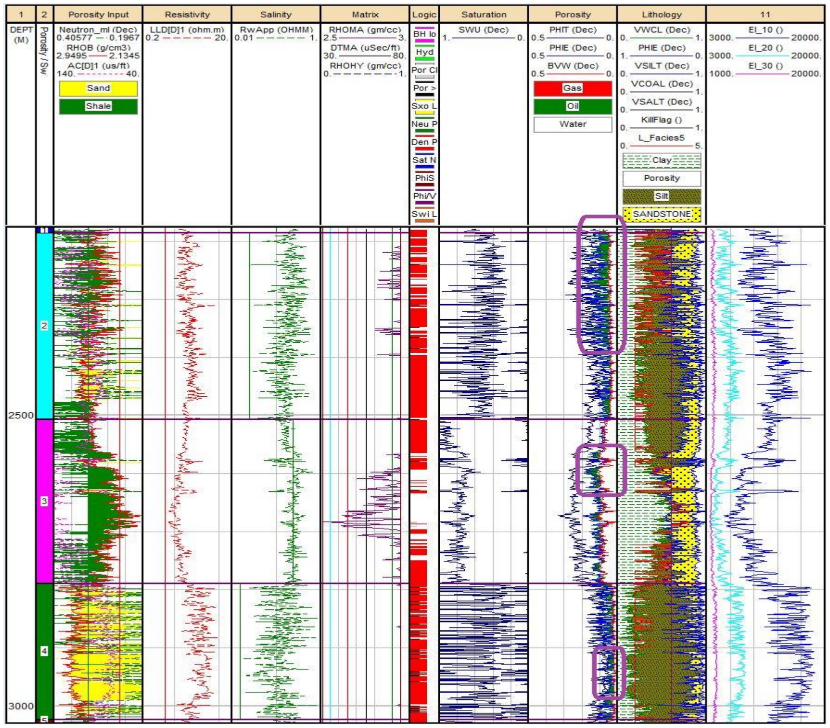

Figure 3 Petrophysical analysis for Well24-5 showing hydrocarbon presence in purple ovals

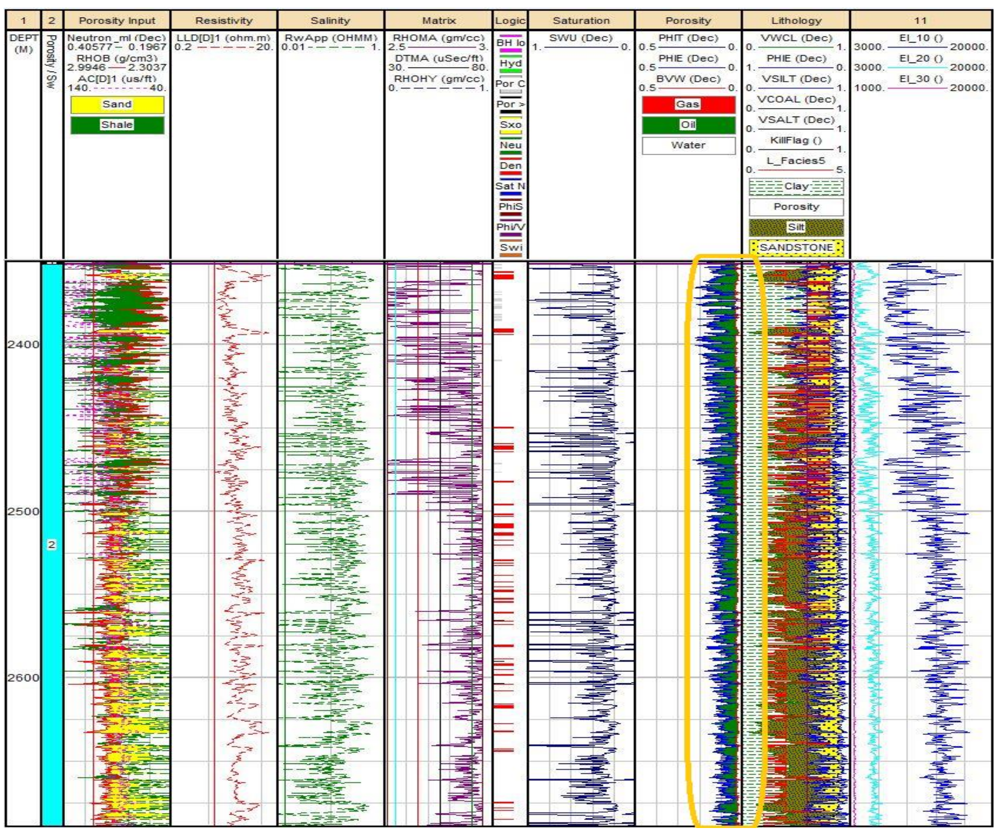

Figure 4 Petrophysical analysis for Well35-4 showing hydrocarbon presence in gold ovals

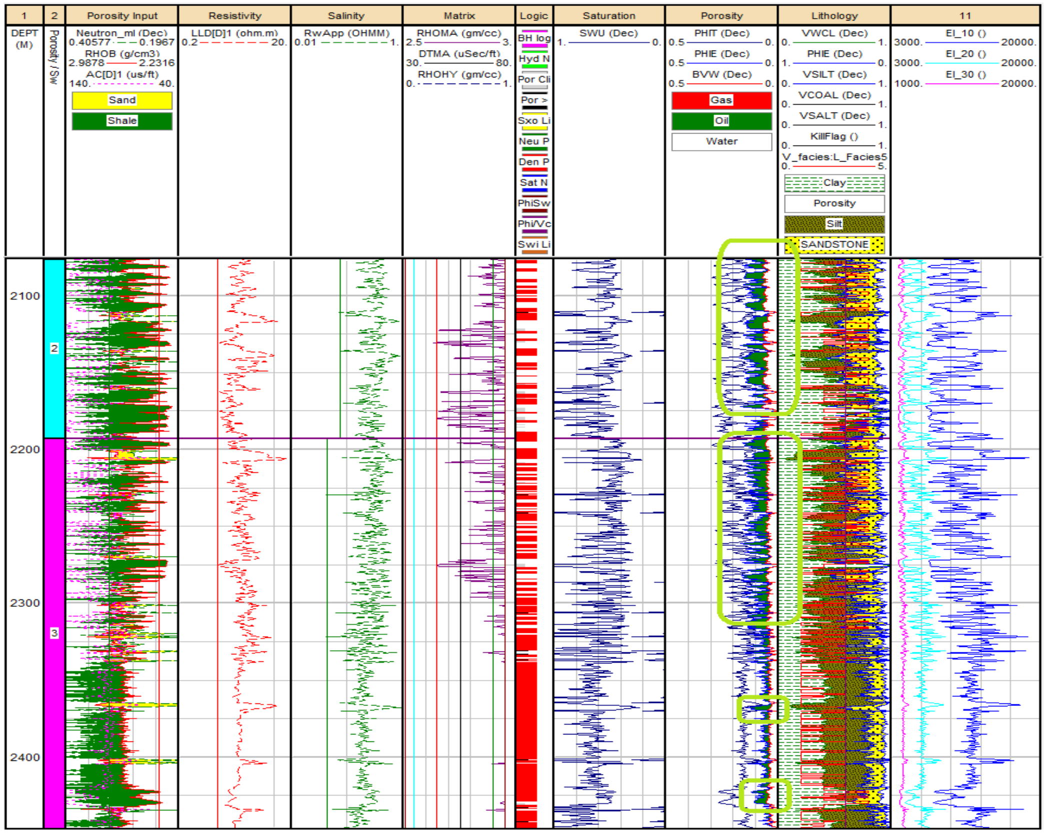

Figure 5 Petrophysical analysis for Well46-2 showing hydrocarbon presence in green ovals

As the field progresses down dip, depositional sequences become more complex and so erratic in pattern and signature. Thus the significant difference seen in the delineated sequences of well 1 and Well24-5, Well35-4 and Well46-2 confirms this. Well35-4 starts with a regressive serrated funnel shaped deposit that is progradational, increasing upward [1,6,19,32]. The contact with the overlaying sequence is gradual grading into a gentle regressional bell shaped sequence (Figures 4 and 7). More than 79% of formations in this well have volume of shale below 30%. A significant shale unit is observed capping the first one third segment of the log section. This level is a potential maximum flooding surface for the area, typifying the base of the channel body delineated on the seismic data and a little above it marks the top of the nose of the channel bar body [19,32]. As with wells 13-2 and 24-5, the geometry is either complex or serrated and never smooth [36-37]. This is probably because of the origin, nature and depositional pattern of the sediment. This will be presented in the following section. 3 depositional cycles are inferred from this log section. They appear as short episodic progradational to aggradational and regressional sequences within few larger cycles delineated.

The lower portion of Well46-2 has complex geometry due to its location as the most distal of the 4 wells. 3 distinct major sequences were delineated here. Minor deposits undelays the log section starting from bell shaped serrated section that regressed and transformed into a series of repeated prograding sequences before regressing again [37,50-52]. The shale blankets seen on the previous well has now become more obvious appearing in a cyclic manner. The upper portion has thicker sand deposit which translates to the thicker part of the channel body 2 delineated. The overall volume of shale more in the middle to lower portion at 60% while the upper part of the logs section mostly characterized by the bell shaped massive fairly serrated deposit, the mid part of the second channel body (Figures 5 and 7). Contacts between sequences on signatures of Well46-2 are more distinct than others although not abrupt, they are still gradational. Curve characteristics are serrated to complex [19].

2.2 Depositional environment on well logs

Depositional environment fluctuates between fluvial to transitional and marine environments. Across all wells these patterns were represented. Disparities observed from one well to another is a function of record of episodic strata deposition characterized by energy of the depositional event and the nature of sediment deposited [11]. Predominantly, fluvial to marine environment is interpreted for Well13-2 (Figures 6, 8 and 9).

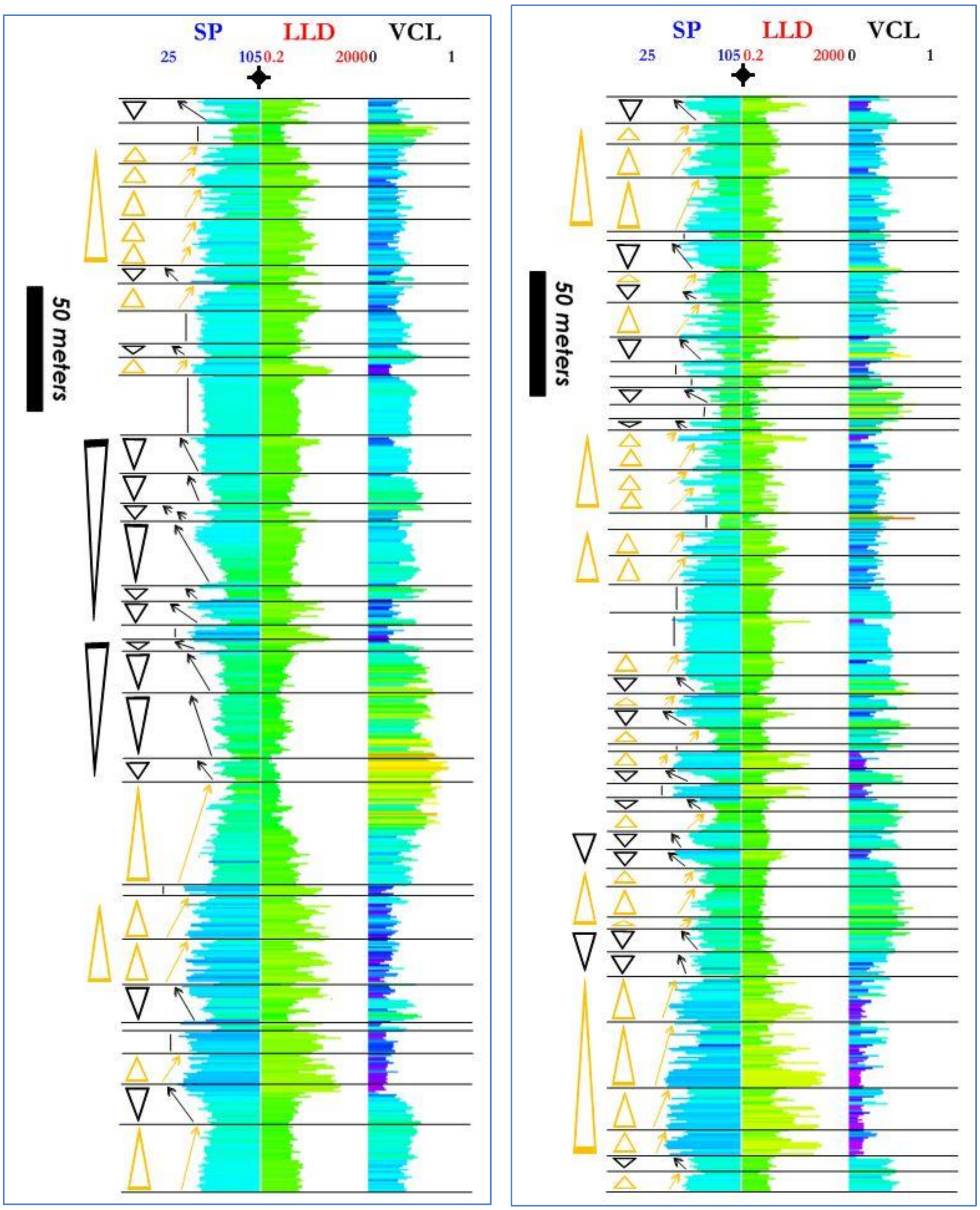

Figure 6 Depositional Environment and sequence analyses panel for Wells 13-2 and 24-5

Some highstand portions are characterized by stable cylindrical shaped signature typical of transitional-deltaic environment [16]. This zone is observed to have average volume of shale of about 62%. This blocky signature could be a poorly sorted tidal or alluvial sand ridge. Aggradational non-serrated signature patterns inter-pret as stable high energy transitional depositional conditions with proactive finning upward deposition truncated by shale blankets [11,46,48]. Channel-point bar, alluvial sand ridge deposits having a plunging basal nose shaped pattern is characteristic of this subsurface section [43,45]. The log signatures are bell shaped with serrated edges signifying rapid transitions in energy with destructive conditions.

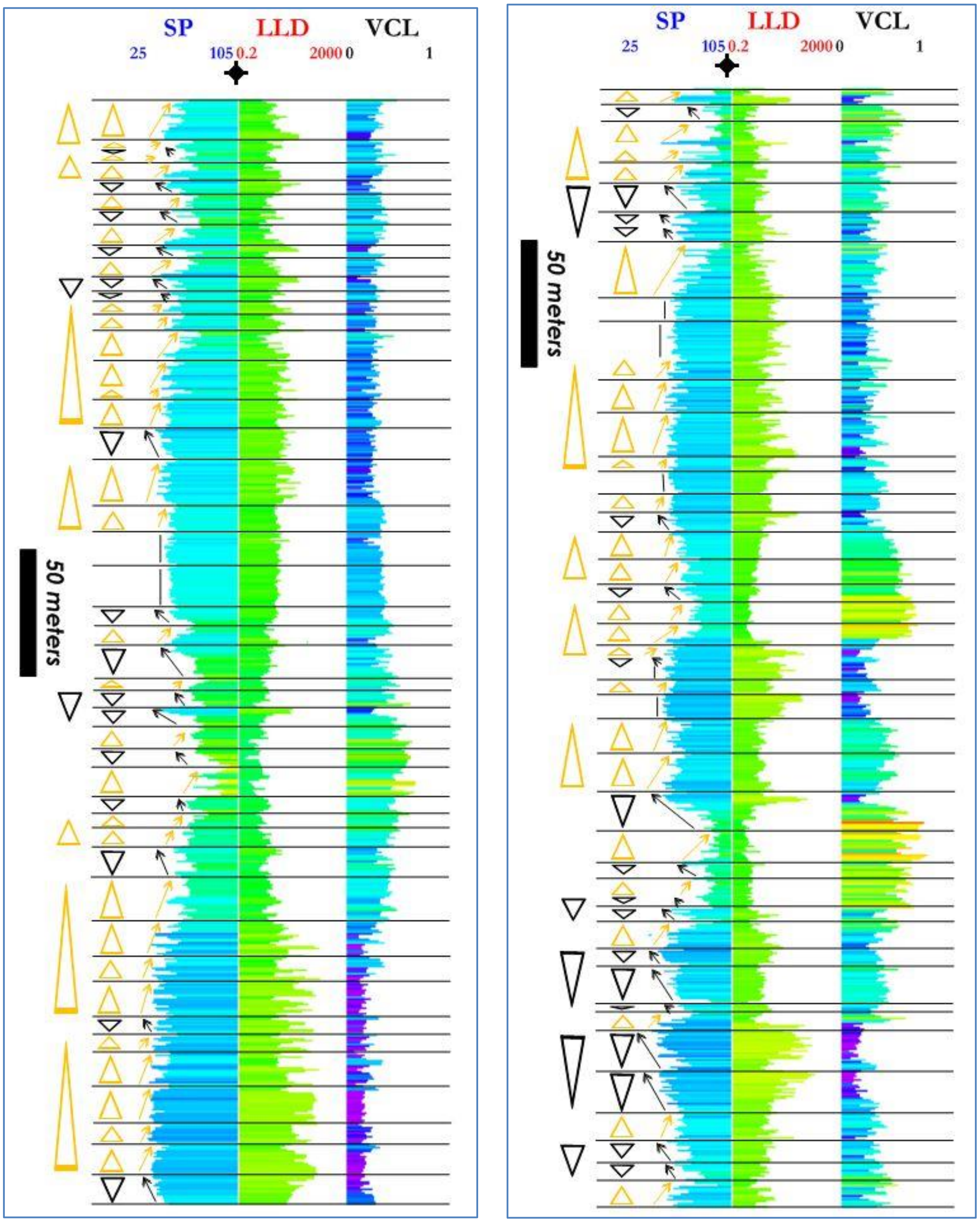

Figure 7 Depositional Environment and sequence analyses panel for Wells 35-4 and 46-2.

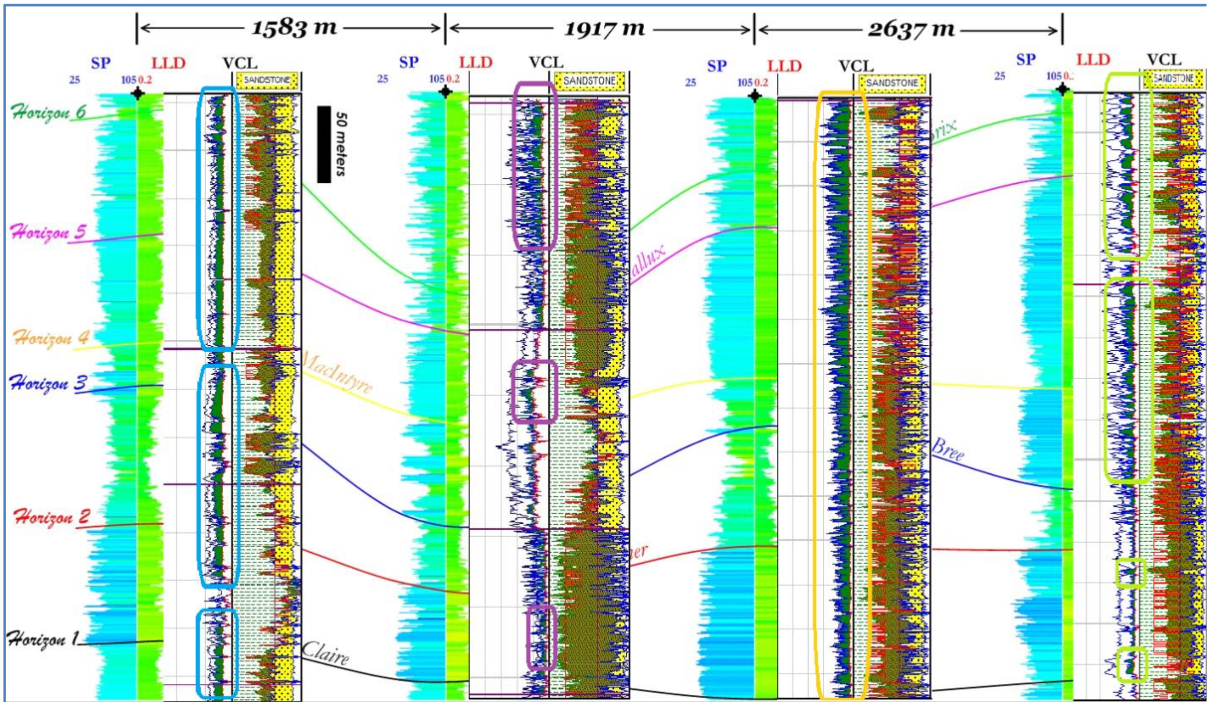

Figure 8 Interpreted 4 wells lateral correlation with strips of petrophysical analysis overlay

This is the most predominant environment of deposition for Well24-5 (Figures 6, 8 and 9). Contacts against other suggested environment are distinct and spell a rapid switching in energy of deposition. Regressive marine environment follows as the second dominant depositional condition. It is characterized by funnel shaped curves with serrated edges. They are progradational and complemented by the more stable high-stand blocky deposits of transitional (fluvial to deltaic marine) origin. Some of these have complex mixed signatures and fairly distinct contacts with adjoining transgressive-regressive deposits [43,45,51-52].

The frequency of repetition of the predominant Channel bar and alluvial sand deposit is significant. These sequences appear in more than 25 points on the log as indicated with right tilting orange colored arrows that populates the log section. The curve characteristics is serrated and complexly preserved as bell shaped signatures. The contact these signatures makes with adjacent formations are gradational to abrupt, with the abrupt seen at transition between regressional and channel sequences [40-42]. Formations deposited in regressional environment are the next popular features of Well35-4 (Figures 7-9). These sequences take the funnel shape, some also with serrated edges but often having non-distinct contact with adjacent units especially the overlaying deltaic sequences. The deltaic sequences are not well represented in Well35-4 but for the middle of the sequence where a cyclic log replication of the nose of the delineated channel sand body overlaps. Depositional environment did not significantly change in observed pattern from Well35-4 to Well46-2. The first environment characterized by the deposit of Well46-2 is the channel bar/ alluvial sand ridge (Figure 7-9). Conformably overlaying this are two repeated sequences of regressional marine deposit typified by its funnel shaped curves [1,6,19,42,52].

The pattern degenerates further into a brief (<25 m) channel bar unit that transforms into another repeated regressive marine environment deposit having abrupt contact. Thus the cycle progresses within the log section it was interjected by two conformable transitional deltaic formations corresponding to the middle of the channel sand body 2. Generally, the irregular curve shapes dominates. They are primarily either having decreasing upward signatures increasing upward signatures or highstand/ stable to blocky cylindrical signature with gradational to abrupt contacts/ bedding planes [9,12,16,35].

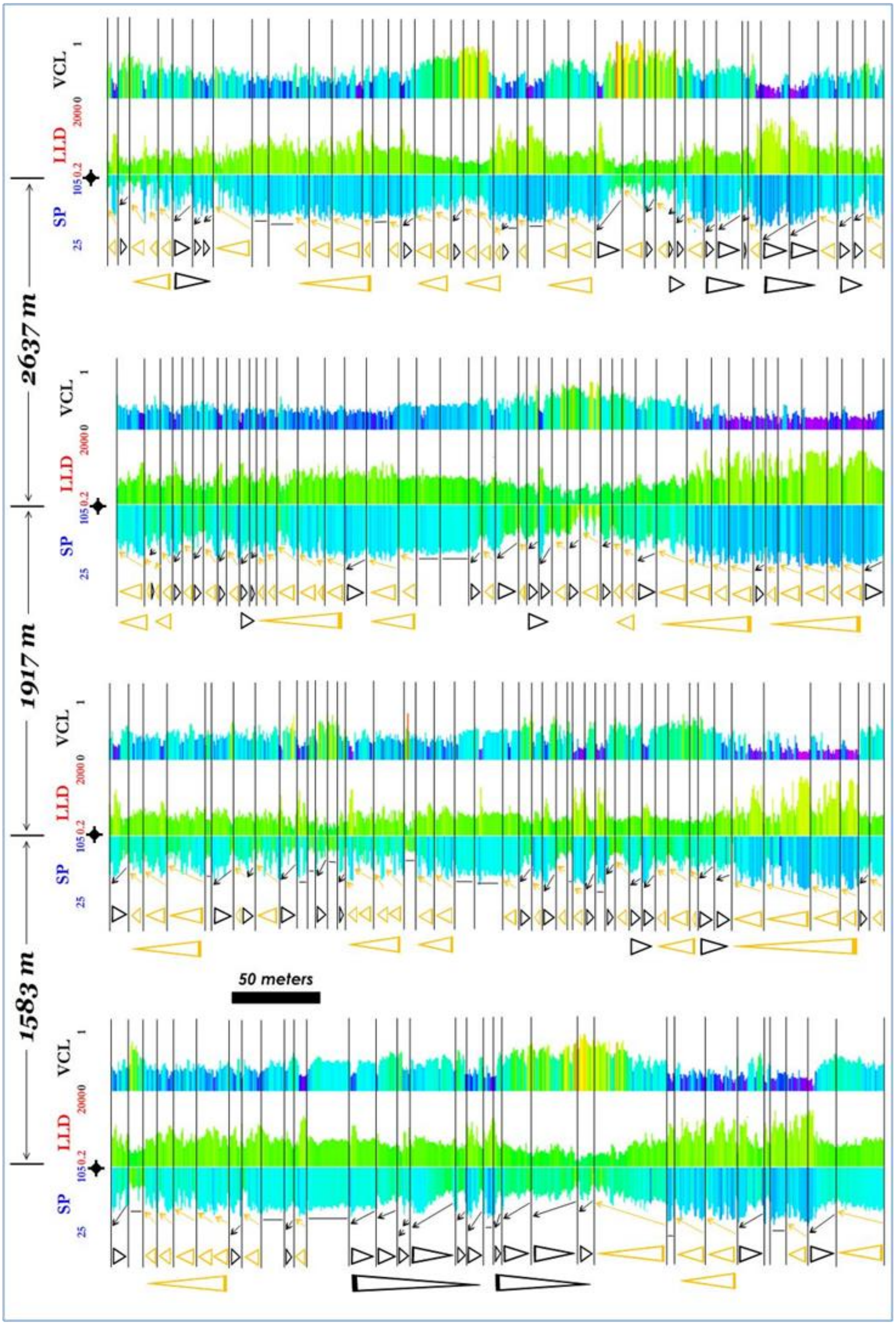

Figure 9 Depositional Environment and sequence analyses interpreted for 4 wells with lateral offset relation

3. Interpretation on seismic data

3.1 Lateral horizon tracking and facies delineation

Right across the subsurface formation studied, are two prominent horizons that are clearly marked through the span of the 3D seismic data. The first is identified at the base of the section while the other caps the section. Both are marked as black broken lines on Figure 10. Both horizons were tracked using dominant positive reflection on the seismic section. This represents the more parallel facies having conformable contacts with underlying and overlying reflections [2,9,12,21,24]. However, within this isolated segment are observed various facies patterns typical of different depositional environment. The reflection patterns range from chaotic to parallel, sub-parallel and sigmoidal. The chaotic portions are those occurring within the isolated channel lobe interpreted (Figure 10).

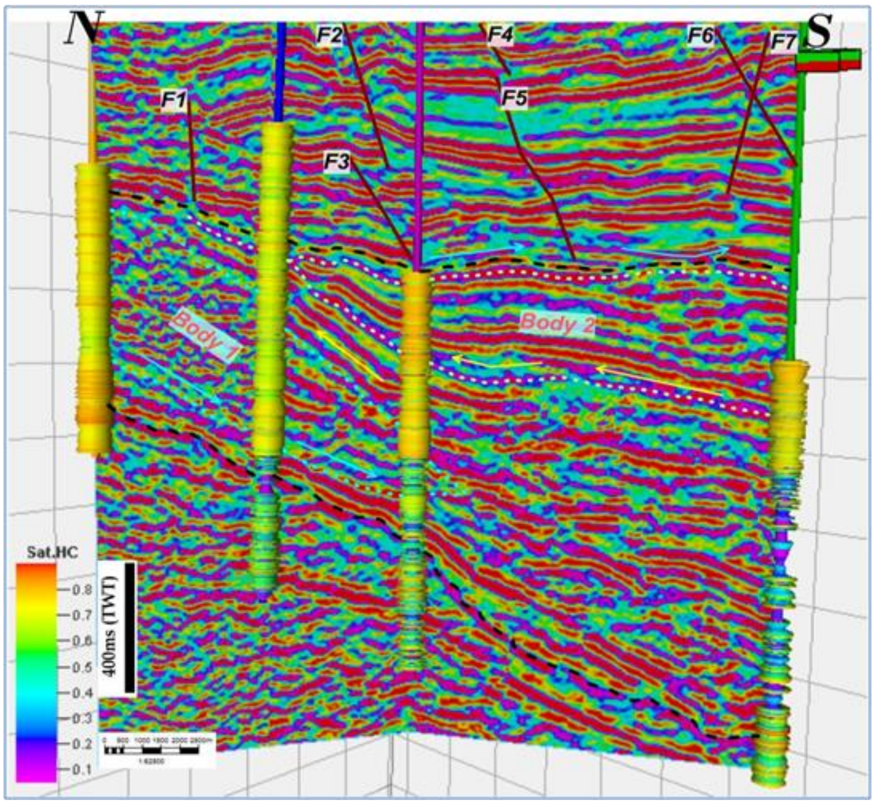

Figure 10 Seismic line with 4 wells and outline of stratigraphic and structural imprint

This style is seen in both channel bodies 1 and 2 (Figures 10-11). The nose or tip of channel body 1 culminates in a transgressive-regressive portion of Well35-4. This appears as a folded or back-stepped portion indicating an encapsulation of the channel unit preserved as body 1. Predominantly, channel body 1 has more disseminated formation and thus is not preserved as parallel facies. This is typical of high energy of deposition within a fluviomarine system [21,28,33]. On the converse, channel body 2 has reflections that are gentle with parallel to sub-parallel reflection patterns interpreted. The facies underlaying channel body 2 (i.e. those occurring beyond channel body 1) are characterized by sigmoidal to chaotic reflection patterns signifying medium to high energy of deposition within a dipping containment (Figure 10-11). A high mix of shale units must be present and has been validated by the log signatures interpreted earlier. Volume of shale here is well above 60% and constitutes the toe of the dipping stratigraphic receptacle. Both channel bodies 1 and 2 are interpreted as reservoir units with high hydrocarbon saturation recorded. The segment interpreted is the sub-faulted portion and settles under the influence of gravity naturally [20,33,38]. The structural configuration observed above it is probably as a result of the pressure exerted on the stable formation deposited post-slope progressively filling the space available. It is observed clearly that reflection patterns beyond the interpreted segment are predominantly parallel but well faulted. However, this structural influence stopped on the top of the channel sand body 2, obviously a distinction made of facies and consequently of depositional environment.

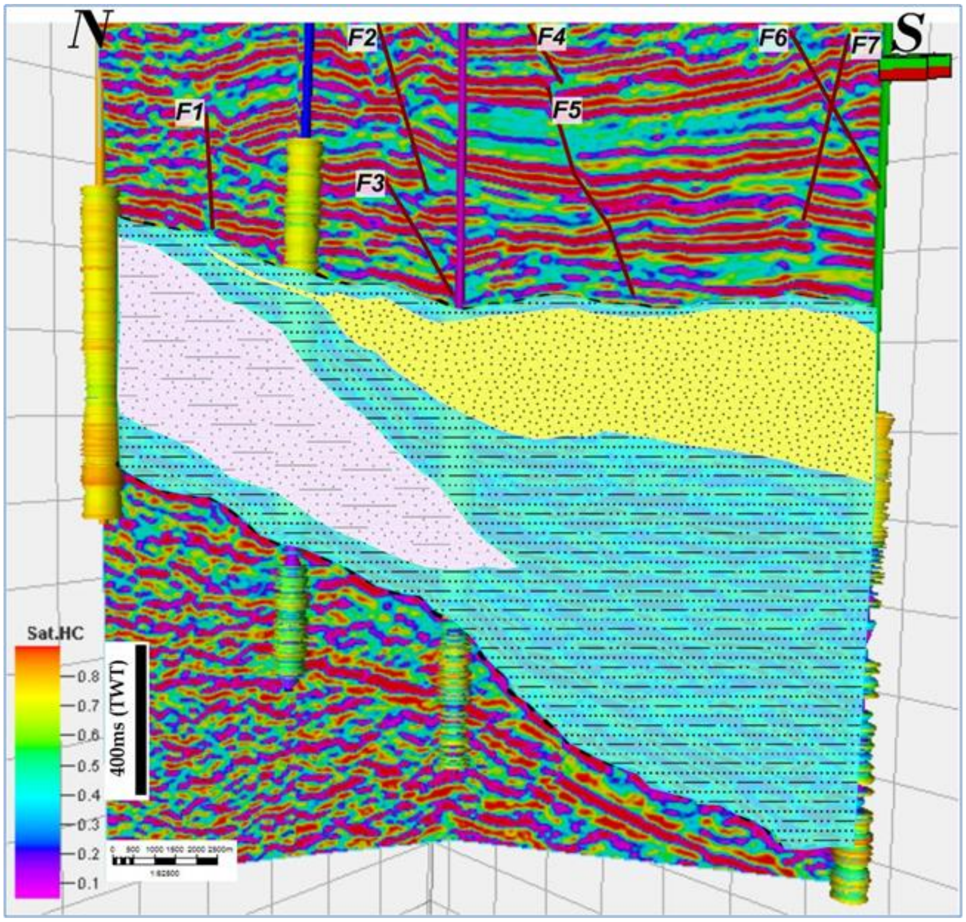

Figure 11 Interpreted seismic line with 4 wells and outlined channel facies

3.2 Petrophysical/ Rock physics properties analyses

Well35-4 is most hydrocarbon prolific in the study area (Figure 4 and 8). Average porosity on this well is 25% with permeability of 175mD. Other 3 wells have porosity significantly less than 24% and fair permeability. Hydrocarbon saturation is very good at above 65% on the average (Figure 10 and 11). Multiattribute seismic derived petrophysical properties over the area indicates unique patterns outlining the 2 channel bodies and isolated as triangles (Figure 12). Elastic Impedance (EI) 10, 20 and 30 evaluation supported petrophysical analyses (Figures 2-5). Their orthogonal occurrence well outlined. Evidently from Figures10 and 11, all seismic facies are likely candidates for hydrocarbon accumulation. However those that occur at the flanks and middle of the channel bodies are most preferred. Also the chaotic facies have higher percentage of shale thus having lower permeability except for where the shale marks boundaries of major stratigraphic envelops delineating the channel bodies as seen in Figures 10 and 11. Cross plots of rock physics and petrophysical properties assisted in defining distributions of rock types by depth. Porosity – between 0.10 and 0.25, Permeability – between 1 and 1.8mD, V_{Cl} – between 0.2 and 0.4, S_{hc} – between 65% and 76%. V_p~ (5.6-6.0km/s) and V_s~ (2.6 -3.0km/s). EI 10, 20 and 30 did well in complementing petrophysical information.

Direction of deposition current was for lobe 1, north-south (basin-ward). This was followed by series of transgressive-regressive periods of current and sediments were deposited accordingly. Alternating wedge patterns were observed on surface maps captured over the study area covering the 4 wells.

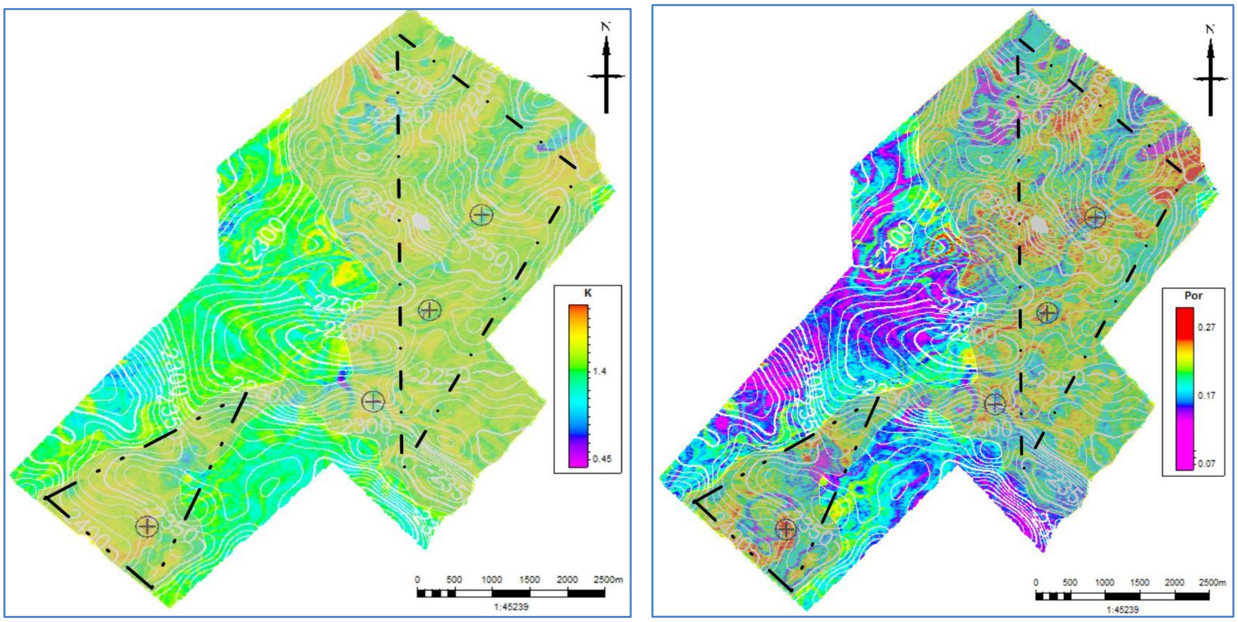

Figure 12 Petrophysical properties map extract with channel outline. Left is Permeability, right is porosity

4. Conclusions

Two alternating alluvial channel sand lobes were delineated with an average of 40^0 dip and average thickness of 127 meters for lobe 1 and 107 meters for lobe 2. Facies and depositional environment of the alternate channel bodies in the flank of the sag structure has been analyzed and described from well logs, petrophysical data and seismic data. Curve geometry and contacts on well logs have been interpreted and depositional cycles delineated for the 4 wells. Each have its' distinct depositional cycle ranging from 3 cycles for wells 13-2, 35-4 and 46-2 to 4 cycles for 24-5. It has been discovered that well 13-2 has less complex structure while well 46-2 is most distal occurring at the toe of the sag structure, has the most complex geometry. From the depositional environment analysis on well logs, a fluvial to transitional marine environment has been depicted for all wells. Rock physics evaluation done on all 4 wells using EI results in a good correlation for hydrocarbon saturation especially on well 35-4 being the most hydrocarbon prolific compared to other wells and the hydrocarbon saturation generally has been determined to be good with average value of 0.65.

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