Smart Integration of Data and Technology for better Characterization of Deepwater Slope Channel Complexes – A Brown Field Example, Offshore West Africa

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ABSTRACT

The dynamic relationship between field management and reservoir characterization has often been a puzzle, especially in complex Deepwater channel systems. Reservoir management and infill drilling success cases were often due to improved understanding of Deepwater depositional systems and geological controls on channel architecture and the general distribution of individual rock facies. For confined to weakly-confined slope channel complexes, some controls on the degree of channel avulsion and aggradation are the interplay the interplay between flow hydraulics, sediment calibre, depositional gradient, and the interaction of the flow with underlying substrate. This work documents the stratigraphic characterization of a Brownfield Miocene Deepwater Channel system with focus on the historical evolution of the framework interpretation as well as applications of the recent updated in field management. The initial stratigraphic model (2005) was done using the layer cake concept with minimal incision, continuous shales and limited vertical connectivity based on observations from available seismic data (pre-baseline survey acquisition) and limited well control. This was modified in 2009 following acquisition of a 4D Monitor 1 seismic volume and 3 years production data from 20 wells to a more erosive model with compensationally stacked channel complexes of similar width. With new 4D Monitor 2 acquired in 2014, Broadband processed seismic data in 2020, a total of 36 wells and 11 years of production, an updated framework has recently been built. In the new framework, two key fairways namely the Upper and the Lower Fairway were delineated, each comprising of 8 and 6 channel complexes, respectively. We utilized a conceptual basin-fill sequence as well as a genetic classification of the channel complexes into erosional-confined systems, meandering systems, and levee-confined channel systems. The cut-and-fill behaviors of the individual complexes have been tied to changes in depositional gradient, sediment sand vs mud ratio, interaction of the flow with the substrate, and this has impacted the degree of channel amalgamation, avulsion and the degree of preservation of both internal and external levees. At flow unit scale, potential inter, and intra-reservoir connection pathways and compartments defined through integrated use of excess pressures, geobody attributes, well production and 4D data, have been very helpful in defining reservoir connection windows, injector – producer connectivity, and channel compartments. This exercise has provided renewed insights into infill drill-well opportunities, well production performance as well as overall field management strategy.

Keywords: Deepwater, Channel complexes, Turbidites, Connectivity, Slope incised fill.

INTRODUCTION

The field of study has evolved in its stratigraphic representation since the initial framework interpretation. Changes in each phase of the geologic model is driven primarily by improved seismic data quality, additional wells drilled and years of production data. Conventional seismic data are bandlimited and do not contain the frequencies required to make absolute estimates of elastic and petrophysical rock properties (Fig. 1a). In this field, the 4D Baseline (2005), M1 (2009) and M2 (2014) are conventional seismic data. The reprocessed M2 Broadband seismic spectrum contains low frequency content useful for more accurate seismic inversion (Fig. 1b) and enhanced reservoir characterization. We utilized the full broadband in the interpretations following improved resolution and imaging for both structural and stratigraphic features (Fig. 1c). Broadband seismic spectrum with low frequency content will help in more accurate seismic inversion, ultimately better reservoir models and infill development plans.

Progressions in the understanding and stratigraphic subdivisions as displayed in figure 1d show that the initial

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interpretations of fields Deepwater systems were based on the Layer Cake model. The resultant P4 (version 1) geologic model was done after drilling of wells FE and EA with the 2000 Pre-Stack Time Migrated (PSTM) seismic data and the 2005 Hi-Res Baseline survey acquired over the asset due to the FPSO undershoot area. This initial model assumes minimal incision and better lateral connectivity between interpreted channel complexes. The P5 (version 2) geologic model was based on the incision concept and interpreted using the 2005 Baseline survey and the 2009 Monitor 1 (M1) survey. This was after 3 years of production from about 20 wells at the time. Framework interpretations at this time was enhanced by 4D seismic observations giving rise to better understanding of the fluid movements, the channel architecture and possible reservoir connectivity. In 2014, the Monitor 2 survey was acquired and by this time, up to 36 wells had been drilled thereby providing a robust production database. With the 2014 M2 data, internal geometries and additional reflectors – stratigraphic fidelity uplift (not earlier recognized) were better recognized leading to more detailed sub-division of the field stratigraphy (LR1 - LR6, and UR1 – UR8). The current framework provided better definition of the internal geometries and channel architecture as well as greater insights to the production performances of some wells.

In the current interpretation, the Sprague *et al* (2002) sequence-stratigraphic-based 'Deepwater Hierarchical' framework was utilized in grouping the stratigraphic units into two key complex sets. The Deepwater Hierarchy (figure 4a) refers to a series of hierarchically organized, genetically related stratigraphic elements (Sprague et al 2002). This classification is based on the principles of sequence stratigraphy, which is the recognition of genetically related stratal packages and their bounding surfaces (Mitchum, 1977; Van Wagoner et al., 1988; Mitchum and Van Wagoner, 1991). In phase 4 and phase 5 frameworks, the reservoirs were subdivided into 3 key fairways (or channel complex sets) but recent understanding from the 2014 M2 data shows reclassification into 2 main fairways or complex sets (Sprague *et al.,* 2002). Although the primary interpretation is that each complex set is a simple slope incised fill, it is still an ongoing discussion as to the mechanism of deposition of the sedimentary bodies. In Carlson *et al.,* (1982) and Prather (2003), a submarine incised Deepwater system is an underwater slope conduit incomparably deeper than the system largest channels, cut into earlier deposits by excessively erosive sediment-gravity flows. These incised valleys may be unrelated to global sea-level changes and the fluvial incised valleys formed by forced regressions (Dalrymple *et al.,* 1994), but they similarly result from major readjustments of the system morphometric profile. It is our opinion that some submarine canyons could also be result from slope instability and distortions due to underwater quakes or substrate failures.

Our field scale observations show the number of channel complexes has evolved from 7 channel complexes (phase 4; 2000 + 2005 Baseline data) to 8 channel complexes (phase 5; 2005 Baseline + 2009 4D M1 seismic data) and now 14 channel complexes (2019 update; 2014 4D M2 seismic data). Major interpretation challenges in this asset are the complex stratigraphy, reservoir compartmentalization and prediction of lithofacies distribution. The current framework is done using a more genetic and concept-based approach, as well as analog data on observed architectural elements from other fields. For example, detailed studies of side-scan sonar and 3D seismic reflection imagery have revealed a range of architectural elements associated with sinuous channels, such as lateral accretion packages (LAPs) (Abreu et al., 2003; Labourdette, 2007), nested mounds (Clark and Pickering, 1996), and outer-bank bars (Nakajima *et al.,* 2009). Also, in Janocho *et al.* (2013a, 2013b), recognizing architectural elements of ancient deposits in seismic data requires integration of geometry, scale and depositional setting, while facies composition and processes are inferred from other geological data (e.g., outcrop analogues, laboratory experiments and numerical modelling). In this work, we have used robust integration of seismic, well and production data, as well as Deepwater stratigraphic concepts in characterizing the channel complexes. As shown in figure 1d (i and ii), the earliest data is the crudest from both processing and the velocity model, while the latest one (Fig. 1d - iii) is much more refined in its handling of noise, Q and broadband processing, and in the velocity model (much more constrained by the wells).

This basically shows that we always increase the complexity of the subsurface as we gain more information. Often, what was a giant "tank" at exploration scale becomes a fairly heterogeneous reservoir with lots of baffles and barriers as we refine our understanding of the subsurface through more and better information than what we started with.

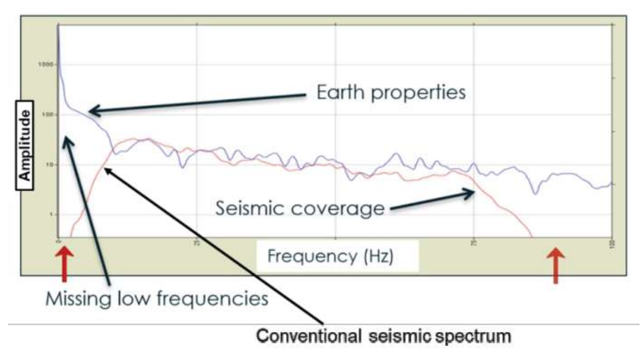

Figure 1a: Seismic spectrum for Conventional data. Note the missing 'low frequencies' not captured within the seismic coverage.

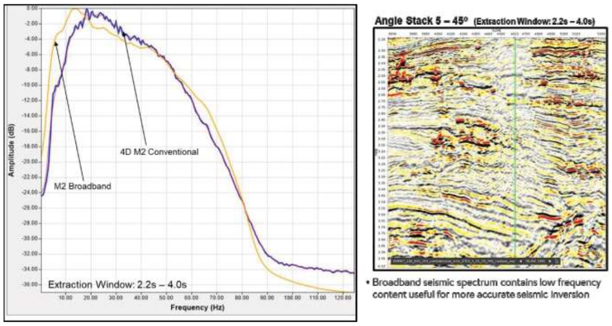

Figure 1b: Seismic spectrum for 2014 4DM2 Conventional data. Observe improvement in captured 'low frequency' spectrum in the 2014 reprocessed 4DM2 Broadband data.

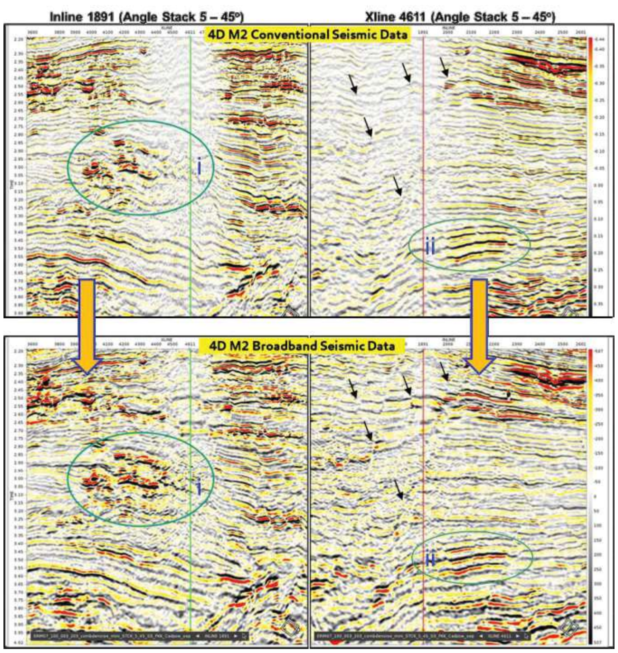

Figure 1c: Conventional vs Broadband seismic data. Note improved imaging and resolution of both structural (black arrows) and stratigraphic (green circles) features on the 4D MD Broadband data.

GEOLOGIC FRAMEWORK

This asset is comprised of deep-water slope channel complexes located offshore western Niger Delta Basin (figure 2) at about 1200m water depth. It is a brown field with over 15 years of production, 20 producer wells and several water and gas injection wells. The field is set-up by large regional detachment fold which is positioned in the boundary between a coupled extensional – contractional system (figure 3). Early development drilling demonstrated the presence of locally sealing shales especially at the deeper intervals. The Niger Delta basin is primarily a linked extensional - compressional tectonic system with distinct structural provinces (Corredor et al. 2005). Up-dip, extension at the shelf margin is composed of landward dipping growth faults and basin-ward dipping normal faults. Downdip and along slope, is dominantly compressional, composed of large mobile shale cored folds, followed by smaller scale buckle folds and finally ends in belts of low relief toe-thrusts (figure 3). This system is driven by gravitational collapse of a prograding deltaic sediment wedge that prograded along with the sediment wedge (Corredor et al., 2005; Obi *et al.,* 2018). In the field area, there are three phases of related depositional and structural history. The first was an early phase of deposition and associated mini-basin development at ~35 ma. This was followed by contraction expressed as buckle folding linked to up-dip extension at ~20 ma. Finally, as the depositional system prograded, the location of extension migrated basin-wards. The geologic column in the Tertiary Niger Delta is subdivided into three lithostratigraphic formations namely the marine Akata Formation, paralic Agbada and continental Benin Formation (Avbovbo, 1978). Deepwater reservoirs in this area are primarily associated with the Agbada formation.

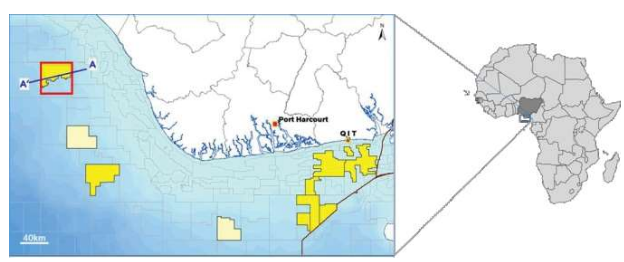

Figure 2: Acreages in the Niger Delta Basin showing study field study location in Red box.

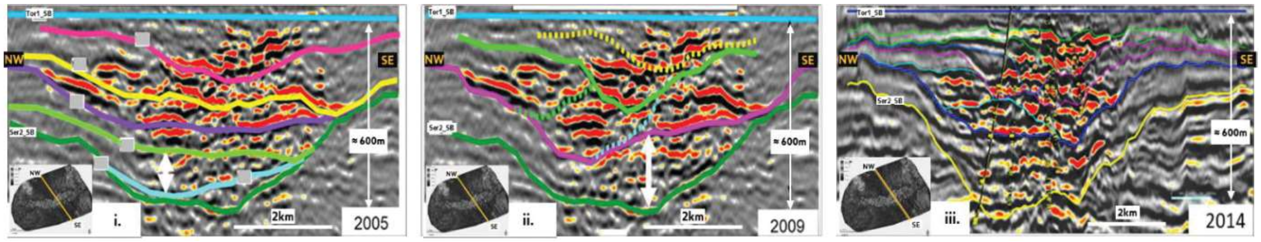

Figure 1d: Note progression in interpretation using 2005/2009 conventional vs 2014 Broadband seismic data. Phase 4 and 5 geologic models (i and ii) were built using 2005 and 2009 seismic data, while the updated framework (iii) was done using reprocessed 2014 4DM2 data and more production well information.

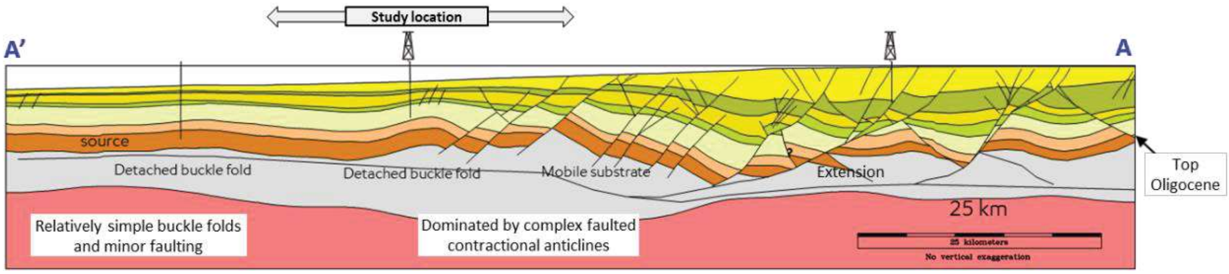

Figure 3: Sub-regional transect showing structural provinces (coupled extensional – compressional system). Study location sits on a detachment fold in central portion of asset.

METHODOLOGY, OBSERVATION AND RESULTS

Depositional Sequences

Two distinct fairways or channel complex sets (Sprague et al., 2002) have been interpreted for the field representing 2nd order hierarchical depositional sequences called the Upper and Lower fairways (also called the Upper and Lower Channel Complex Sets – URs and LRs) (figure 4a & 4b). From Isochrons and seismic attribute extractions, there are two distinct vectors for the Upper fairway (URs) and Lower fairway (LRs). The LRs trends on NE – SW direction with no observed change in overall vector in the flow direction. On the other hand, the URs which trends similarly in the eastern area of the field, makes a turn from SW direction where it was originally headed, to the NW trend (figure 5). On a flattened seismic volume shown in time slice taken at -3800ms (figure 4b inset), the upper and lower sequences bifurcate in the SW area of the field, indicating two distinct fairways. The Lower fairway is comprised of 6 channel complexes (LR1 – LR6), while the Upper fairway contains 8 channel complexes (UR1 – UR8) (figure 4b). Based on well and outcrop observations, individual channel complexes are generally sand-prone sedimentary bodies with occasional gravely basal content deposited within areas referred to broadly as channel belts (Bridge, 2003; Kane and Hodgson, 2011).

In the Lower fairway, simultaneous erosion (creation of incisions) as well as deposition of deep-water strata were the earliest phase of activity in the area. Collapse and rotation of unstable deposits in the form of slump deposits in a progressively developing canyon created the LR1. This was followed by deposition of bedload deposits in space-constrained areas of the canyon (LR2) and meandering channel systems within confined to weakly confined settings (LR3 and LR4). The LR3 shows evidence of lateral channel migration as indicated by the presence of lateral accretion packages (LAPS) typical of more sinuous channel systems (Abreu *et al.,* 2003). The LR4 on the other hand is weakly confined with evidence of sand waves and levees both within the channel thalweg and in the off-axis areas. The LR5 and LR6 are levee confined channel complexes with high amounts of preserved internal levees and channel margin facies (figures 4b and 6). The upper fairway is capped by a major re-incision which marks the top of the lower fairway as well as the beginning of the upper fairway.

The Upper fairway, at early stages, featured periodic changes in depocenter location as the main control for repeated switch in position of the individual channel complexes for the first set of erosional confined complexes (UR1 – UR4) (figures 4b and 6). Each time there is a new surge of sediment gravity flow, the new deposits take advantage of adjacent available depositional low (considering the depositional inner bank and erosive outer bank of the preceding cycle), eroding parts of the pre-existing underlying channel complex and placing its sediments in the new location (Oomkens 1967, 1974). The process continues and is repeated when the current depocenter builds elevation thereby creating an adjacent depositional low for the new cycle of deposits to occupy. Gradual reduction in the velocity of submarine turbidity flow (reducing depositional energy) with increased lateral accommodation results in smaller, higher sinuosity, levee confined complexes such as UR5 – UR8 with more preserved internal and external levees (figures 4 and 6). Both levees are associated with confined channel-belt complexes (Kane and Hodgson, 2011).

In this field, the axis portion of individual channel complexes typically stand out when viewed using 4D difference volumes, especially for areas that has had active fluid movement due to production or injection. From the 4D evaluation, it is observed that 4D signals from the M2-M1 difference volumes are preferentially along the base of the channel complexes as well as areas with potentially higher net sand content (figure 7).

Deposequence-1: Lower Channel Complex Sets (Lrs)

The lower channel complexes have been grouped into two based on observed confining features. The first group (LR1, LR2 and LR3) are erosionally confined and generally deposited in channel belts with low sinuosity architecture and formed either within submarine valley or erosional confinement or by simple downcutting and vertical aggradation (Janocko *et al.,* 2013a, 2013b). The second group of channel complexes (LR4, LR5 and LR6)

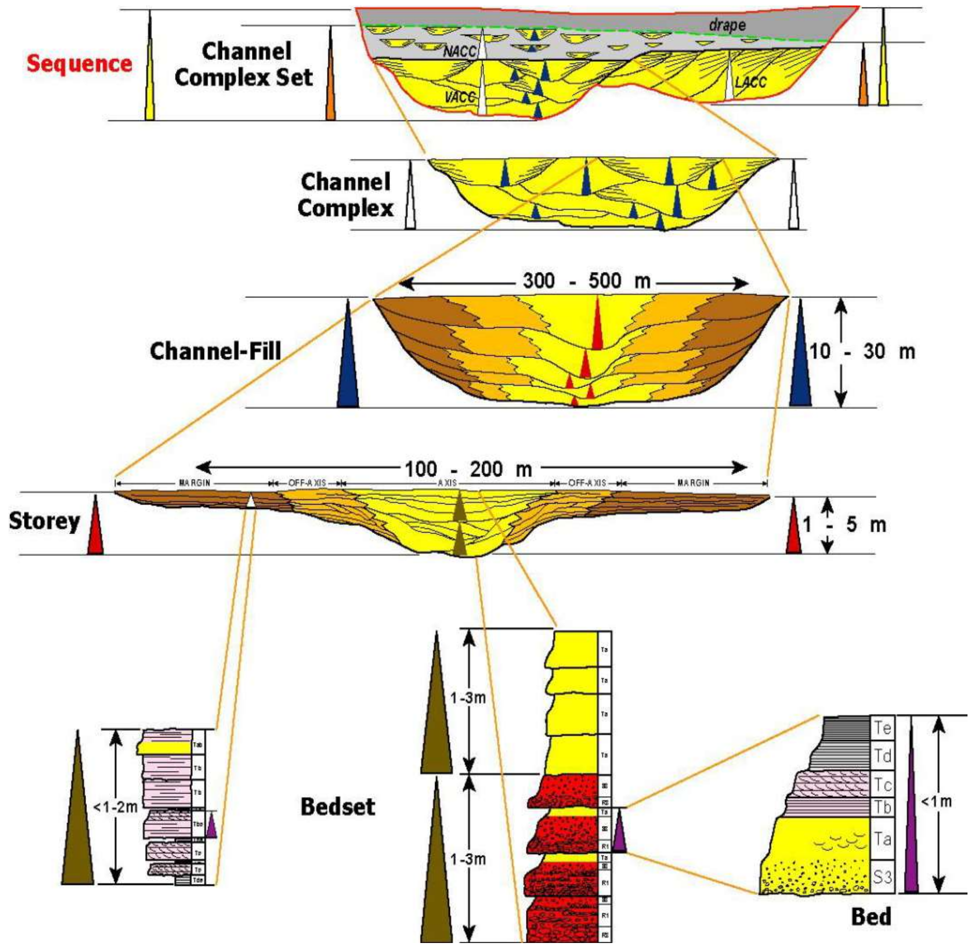

Figure 4a: Deepwater hierarchy for confined depositional settings. Channel complex sets (Sequence or Fairway), channel complex, channel fills and storey defined by Sprague et al., 2002 (modified from Beaubouef et al., 1999, 2000); Bedset, bed, laminaset, and lamina defined by Campbell (1967).

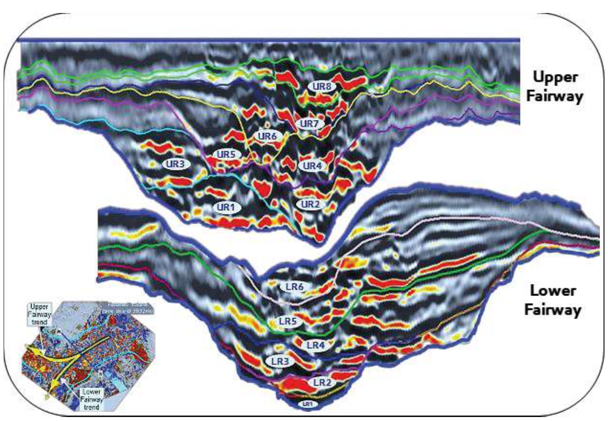

Figure 4b: Stratigraphic framework of study field. Note different vectors for the Upper and Lower Fairways (Inset: Time slice of flattened volume @ -3800ms).

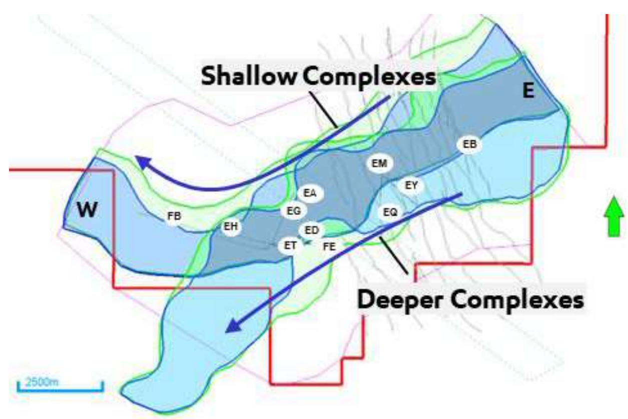

Figure 5: Individual vector of the Shallow and Deeper Complexes. Note bifurcation in SW area.

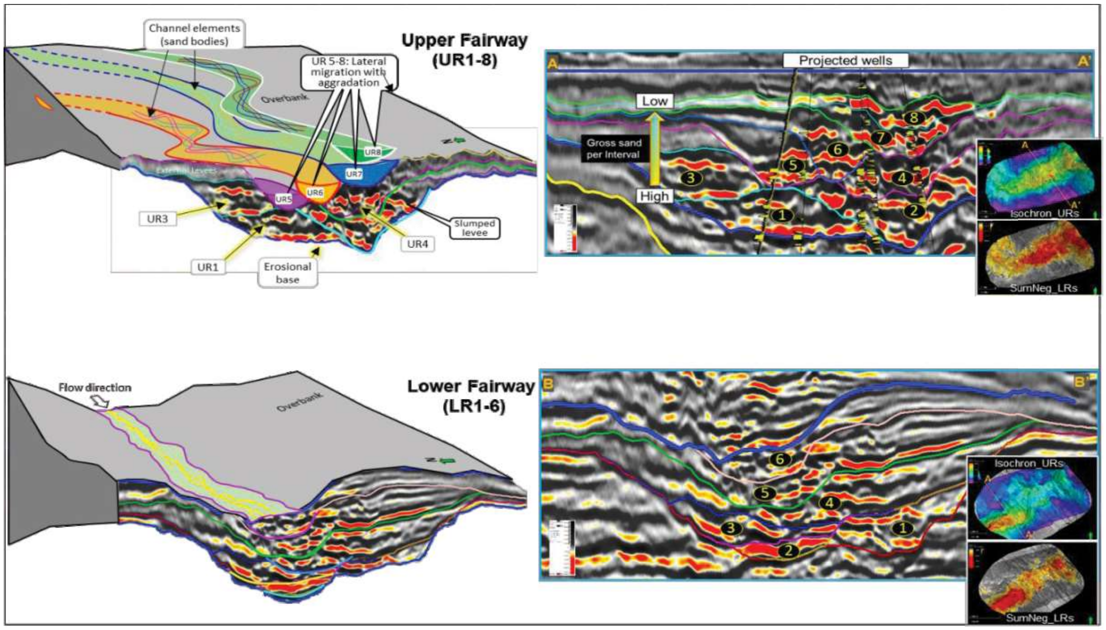

Figure 6: Seismic sections showing depositional profile and fill sequence for both Upper and Lower Channel Complex Sets (URs and LRs).

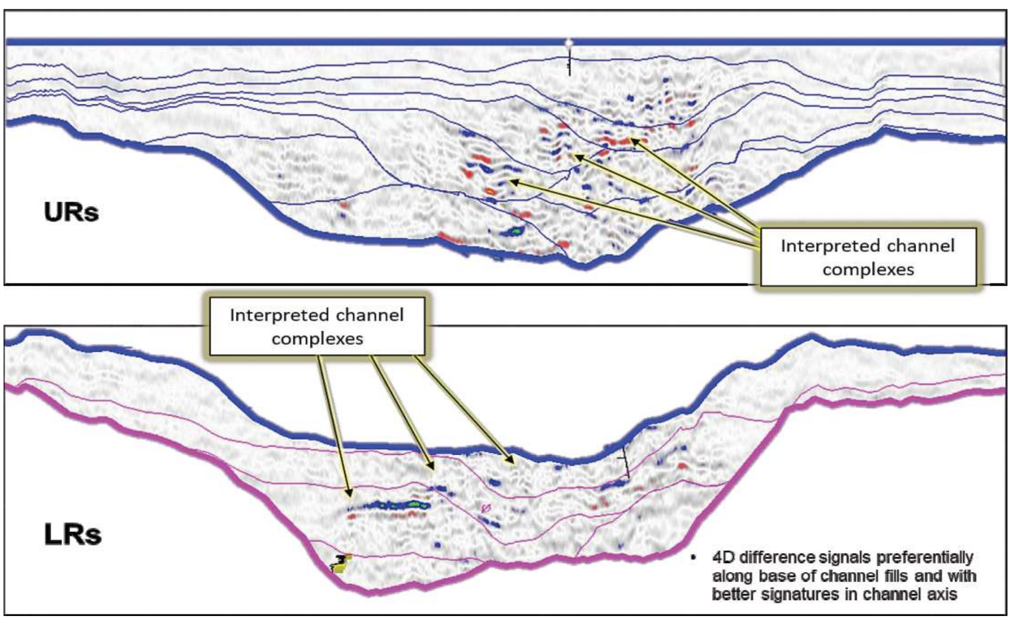

Figure 7: 4D seismic section utilized as guide for interpreting base of individual complexes. Note dominance of fluid movement signatures at areas with axis-to-axis incision especially in the URs.

are interpreted as levee confined and bounded by large scale external levées that flank the valley cut (Kane and Hodgson, 2011). There are also smaller scale levées flanking individual channels called internal levées (Kane and Hodgson, 2011). In figure 8, the LRs is genetically subdivided into erosive-based space confined channel complexes (LR2 and LR3), meandering or weakly confined channel complex (LR4), and levee confined channel complexes (LR5 and LR6). The LR1 is interpreted as rotated slump beds. The LR2 and LR3 are multi-vertically stacked complexes deposited in low confining space and are interpreted to contain basal lag and bedload facies, as well as high net-to-gross (NtG) deposits. There are some interpreters who describe the LR3 differently based on observed inclined reflectors indicating lateral accretion and conduit sideways migration in a meandering channel belt (Nanson and Knighton, 1996). The LR4 was deposited in settings with sufficient depositional space leading to better preservation of some of its internal levees (Kane and Hodgson, 2011). A significant portion of the LR4 has been eroded by the overlying LR5 and LR6 (figure 8).

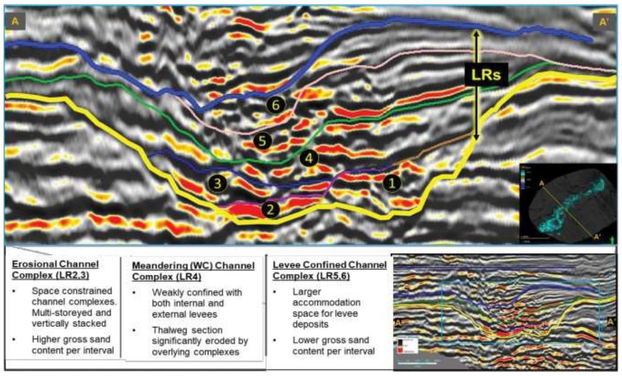

Figure 8: Internal architecture and genetic units of the lower complexes (Deposequence-1).

Deposequence-2: Upper Channel Complex Sets (Urs)

The upper complexes are more confined, erosive-based systems (figure 9). The oldest 4 channel complexes (UR1, UR2, UR3 and UR4) are interpreted to have been deposited during conditions with high sediment gravity flow. Several pulses of underwater landslides or sediment laden turbidity flows (Piper and Normark 2009; Talling *et al* 2013) probably resulted in multi-stacked channel complexes with good vertical and lateral amalgamation. The cut-and-fill relationship between these channel complexes explains why the levees (as well as the late-stage mud fills) facies are poorly preserved during this phase and in some cases, preferentially eroded in one flank of individual complex by overlying strata. The next 4 channel complexes (UR5, UR6, UR7 and UR8) were deposited during reduced or waning velocity of subsequent turbidity flows. By this time, the sand content of individual pulses has become reduced and reflects in the reduction in sizes of the channel complexes. This period was characterized by channel avulsion and aggradation (no switching in depocenter) probably impacted by the waning depositional energy (figure 9). There is better preservation of levee facies especially in the UR7 and Ur8.

Sediment Fill History and Depositional Model

Lower Complexes (LRs): The depositional fairway sediment fill history for deposequence-1 is described using two possible scenarios summarized in figures 10 and 11. The first depositional scenario (figure 10) assumes an initial rapid loading of LR1 deposits on to an unstable, relatively high angle slope (figure 10, plate 1). This

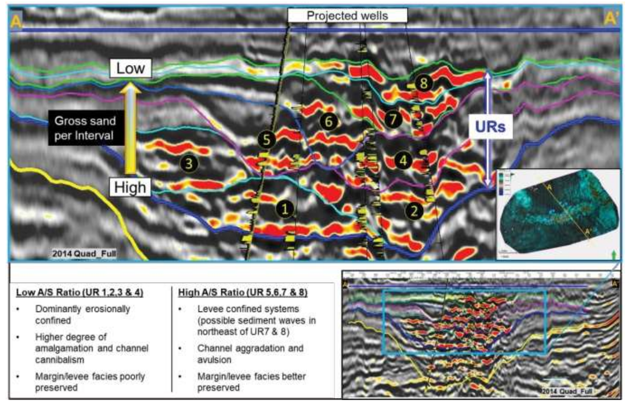

Figure 9: Internal architecture and genetic units of the upper complexes (Deposequence-2).

happened during the onset of a new sequence associated with massive erosion and sediment gravity flow delivery into the field area. Asymmetrical loading and slope failure led to slight rotation of the deposit-substrate combination which have become mixed to form slumps or rotated blocks (figure 10, plate 2). A new sediment influx cycle led to deposition of LR2 which are dominantly erosion confined, channel complexes with gravelly basal facies (figure 10, plate 3). With continued loading and subsidence accompanied by withdrawal of the underlying substrate, more accommodation space is created leading to deposition of weakly confined, moderate to high sinuosity LR3 complexes with distinct lateral accretion packages (LAPS) (figure 10, plate 4). The LAPs generally represent point bars formed by the lateral migration of an open channel or the lateral stacking of successive cut-and-fill channels (Kolla et al., 2001, 2007; Arnot et al., 2007; Labourdette and Bez, 2010). The LR3 is overlain by the LR4 complex deposited during conditions with unconstrained depositional space. By this time, the slope had reached a sub-horizontal state with slight depositional lows in medial portions and each episode of pulses of sediment influx takes on available space with the thalweg of individual channels almost vertically stacked with each other (figure 10, plate 5). A thalweg, as defined by Bridge (2003) is the deepest hydraulic axial zone of a channel. Depositional lows within the outer levees are occupied by sand pulses captured as crevasses splay facies (figure 10, plate 5). The LR5 and LR6 are both levee-confined with better preservation of both inner and outer levee facies (figure 10, plate 6).

In an alternate scenario (figure 11), it is interpreted that the deep-water strata were deposited in a pre-existing submarine valley or submarine valley with unstable side walls (figure 11, plate 1). An early collapse of high-angle portions of the canyon wall created slump beds (or rotated strata) called LR1 at the base as the earliest fill (figure 11, plate 2). This was followed by deposition of bedload deposits in space-constrained areas of the valley (LR2) (figure 11, plate 3) and meandering channel systems within confined to weakly confined settings (LR3 and LR4). The LR3 shows evidence of lateral channel migration as indicated by the presence of lateral accretion packages (LAPS) typical of more sinuous channel systems (figure 11, plate 4). Lateral-accretion packages (Abreu et al., 2003) appear in attribute maps and time slices as features similar to fluvial scroll bars or as crescent-shaped high-amplitude reflection patches (Janocko et al., 2013a, 2013b).

The LR4 on the other hand is weakly confined with evidence of sand waves and levees both within the channel thalweg and in the off-axis areas (figure 11, plate 5). Sand waves in the outer margin areas are interpreted as episodic packages which may have taken advantage of depositional lows outside the main axis of the channel path. The LR5 and LR6 are levee confined channel complexes with high amounts of preserved internal levees and channel margin facies (figure 11, plate 6). The LRs is capped by a major sequence boundary or re-incision which marks the top of the lower sequence as well as the beginning of the upper sequence.

Upper Complexes (URs): The fill history for the first four channel complexes of the upper fairway is shown in figure 12. As represented by the conceptual model shown, periodic changes in depocenter location are the main control for repeated switch in position of the individual channel complexes (figure 12, plate 3). This suggests that, at each surge of sediment supply, energy-laden deposits take advantage of adjacent depositional lows within the channel belt (Janocko et al., 2013a) (recall the depositional inner bank and erosive outer bank of the preceding cycle), eroding parts of the pre-existing underlying channel complex and placing its deposits in the new location (figure 12, plate 1 and 2). The process continues and is repeated when the current depocenter builds elevation there-by creating an adjacent depositional low for the new cycle of deposits to occupy. It is observed that remnant portions of

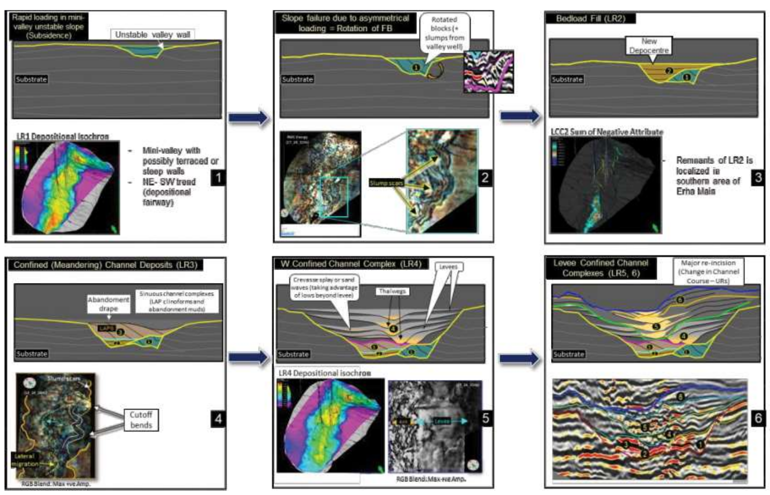

Figure 10: Sediment fill sequence for Deposequence-1 (Lower Fairway) – Scenario A.

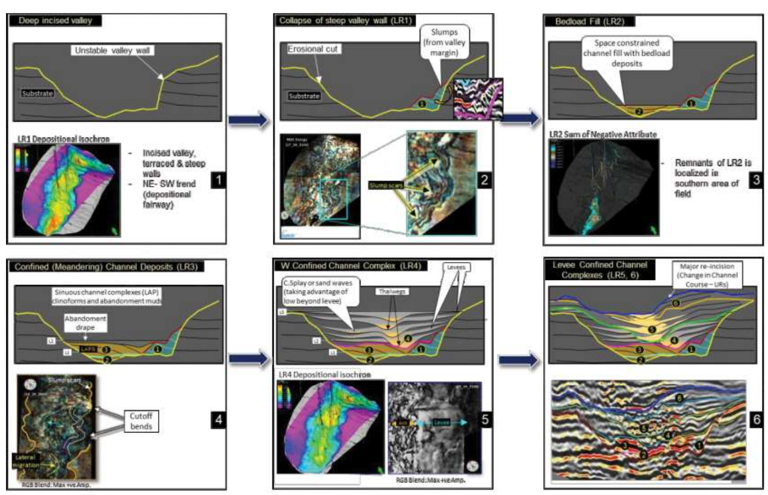

Figure 11: Sediment fill sequence for Deposequence-1 (Lower Fairway) – Scenario B.

UR1, UR2, UR3 and UR4 show evidence of Lateral-accretion packages (Abreu et al., 2003) indicating ancient point bars with complimentary inner and outer bends as shown in figure 12. In figure 13, note the placement and sizes of the next set of channel complexes (UR5 – UR8). From observation of the seismic and schematics, it is inferred that there was gradual reduction in the overall depositional energy with increased accommodation (lateral) leading to increasingly higher sinuosity systems. This waning phase is characterized by less switching in channel placement, progressive avulsion and aggradation, as well as relatively smaller sized complexes - UR5, UR6, UR7 and UR8 (figure 13).

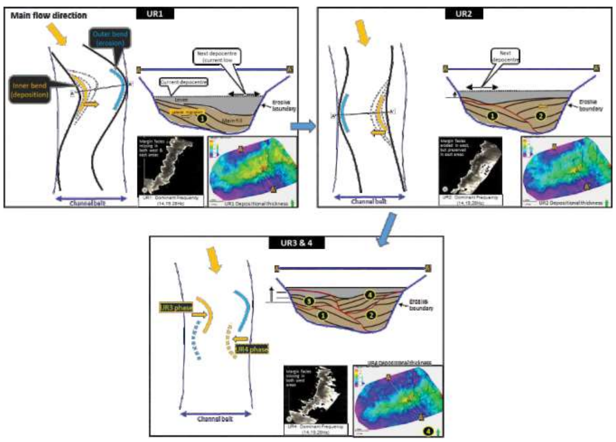

Figure 12: Sediment fill sequence for UR1 – UR4 complexes in Deposequence-2 (Upper Fairway).

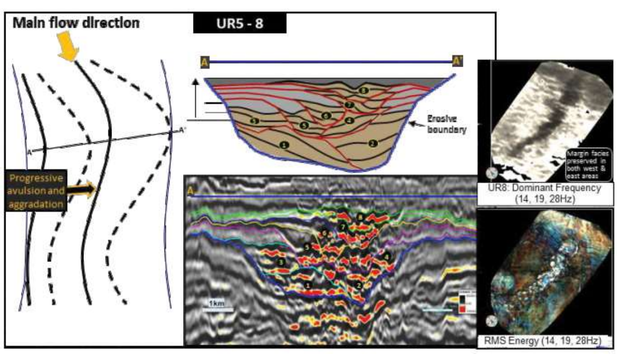

Figure 13: Sediment fill sequence for UR5 – UR5 complexes in Deposequence-2 (Upper Fairway).

Core Data Integration - Deepwater Genetic Turbidite Facies

Seven genetic turbidite lithofacies were defined from core-log relationships to group the rocks into petrofacies assemblages. An integration is also made between the Bouma sequence of 1962 (low energy turbidite sequence represented by Ta, Tb, Tc, Td and Te beds) and the Lowe sequence of 1982 (high energy turbidite sequence represented by the R and S beds) (figure 14). The R-beds are coarse grained units with >30% gravelly content while S-beds contain 5-30% gravel content. The sandy beds are subdivided into 3 types- Ta, Tb and Tc beds (figure 15). Ta beds are massive to normally graded coarse to fine-grained sands. Tb are parallel laminated sandstones while Tc are current rippled sands. Td beds are parallel laminated siltstones while Te are laminated to massive mudstones (figure 15). Porosity-permeability cross plots and core interpretation from 5 wells were used to generate lithofacies transforms representing rock groups with petrophysical significance for model property distribution, namely High concentration turbidites (HCTs), Low concentration turbidites (LCT), Very Low concentration turbidites (VLCT) and non-net facies. The first transform also called the HCT is comprised mainly of bedload and traction facies namely R, S, Ta and Tb beds. The LCTs (Transform 2) is dominated by Tc beds, while the VLCT (Transform 3) are mainly Td beds. The Te and other slump and debritic beds which make up one end member of the VLCT are classified as non-nets. In this grouping, the best

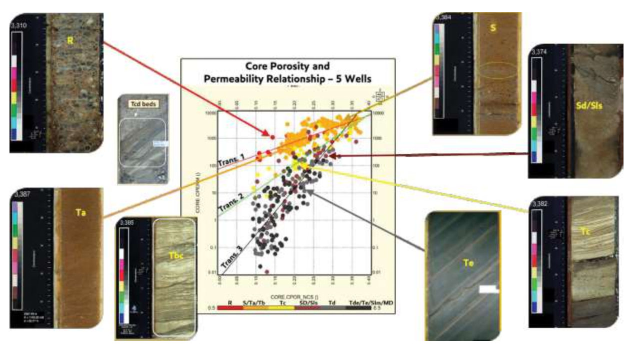

Figure 14: Core Porosity-Permeability cross plot from selected wells showing both Bouma and Lowes facies. Also note all 3 transforms and clustering of individual turbidite facies.

reservoirs are R, S, Ta, Tb and Tc beds while the poorest reservoirs are those containing Td and Te beds. With regards to the individual turbidites, the sandy rocks contain mostly R, S and Ta beds while the shaly rocks are dominated by Td and Te beds.

DATA INTEGRATION – RESULTS AND DISCUSSION

1. Reservoir Characterization and Environment of Deposition (EOD) Integration

A seismic to well integration exercise involved the examination of the overall position of wells in each channel fairway, evaluation of the log signatures and how they tied to channel boundaries, comparison of amplitude strength with quality of penetrated logs, and observed channel geometries (figure 15). Figure 16 shows seismic facies (reflection strength and continuity) mapping for LR4 and LR5. Recall that most of what is seen on the seismic attribute and thickness maps are post-erosion remnants and the distribution of the good net rocks looks patchy, hence, we used our understanding of Deepwater facies concepts in the integrated EOD interpretation. For such LRs, the interpreted seismic reservoir facies (internal levee, axis or off-axis) were based on expected location within the fairway of a conceptual levee-confined channel complex (figure 16). In all, items utilized for reservoir characterization and EOD definition include spectral

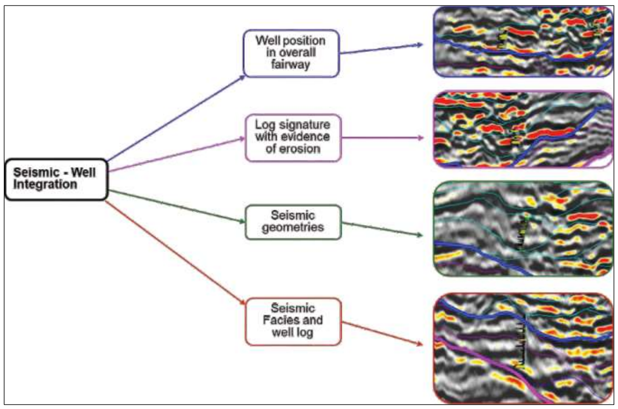

Figure 15: Seismic-to-well integration.

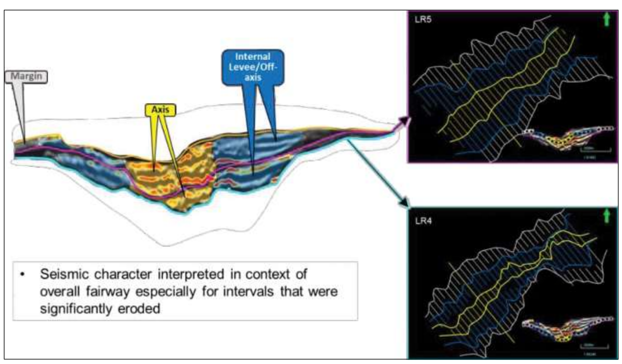

Figure 16: Seismic facies map utilized for conceptual EOD interpretation.

decomposition probes, seismic attribute maps, core interpretations, depositional isochrons, seismic rock facies interpretations, 4D difference signatures, 2D seismic geometries, and lithofacies associations (figure 17). Additional use of seismic inversion volumes for attribute extraction improved the fidelity of delineated EOD boundaries (figure 18)

2. Connectivity Analysis and Compartment Definition

Vertical and lateral connectivity and compartmentalization of individual channel complexes as well as intra-channel flow units is one key element in

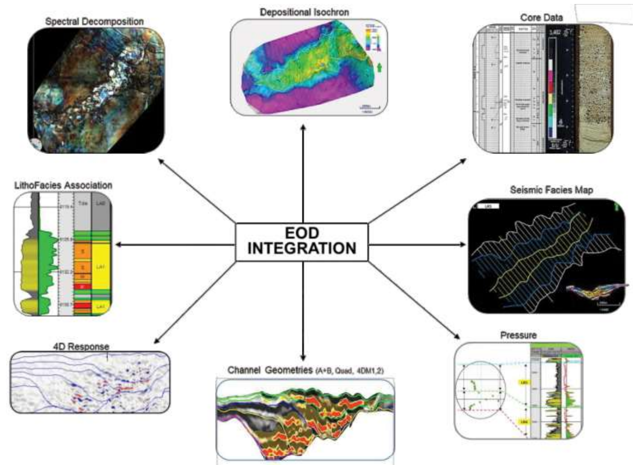

Figure 17: Sample data inputs utilized for reservoir characterization and integrated Environment of Deposition (EOD) definition.

Deepwater reservoir characterization. For this work, inter channel plumbing was initially evaluated by highlighting areas where there is axis-on-axis incision or vertical stacking (figure 19). It is interpreted that those incision points form important fluid migration routes (and reservoir pressure communication) being locations where there is significant sand-on-sand stacking. For producer – injector well reservoir connectivity, geobody probes played a key role in defining possible pathways or compartment boundaries between injector and producer wells. For example, in figure 20, baffled connectivity between the water injector EU and producer wells EI and ET is noted, although both producer wells have good connectivity between them. In figure 21, we show a case where excess pressure points were integrated with GR-log in delineating possible flow units between and within LR4 and LR5 reservoirs. Note separation between LR4 and LR5 sands, as well as scattered pressure points in shaly portions of LR4 (figure 21). In another example shown in figure 22, flow compartments between injector – producer well pairs were delineated through integration of seismic mapping, 4D fluid movement signals and excess pressure plots matched with well logs. The excess pressure plots show that sands in the producer well are potentially connected while those of the gas injector well are possibly separated into 2 or more flow units. This is consistent with observations from the seismic interpretation on the 2014 ApB (lithology seismic derivative volume) and 4D seismic volumes (figure 22).

3. Reservoir Management and Opportunity Maturation

Integrated use of seismic, 4D, well and production data is very important for effective reservoir management and

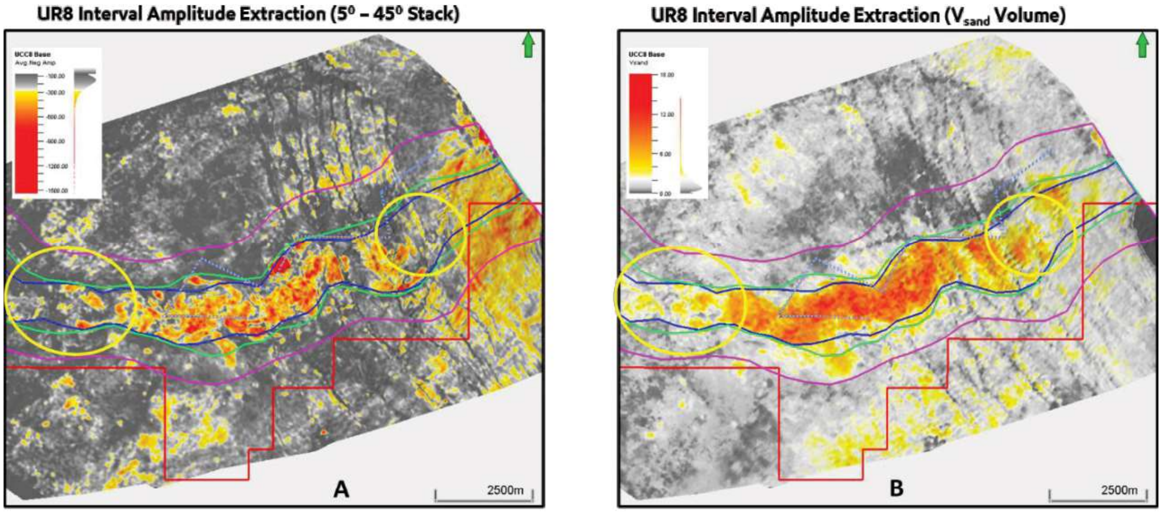

Figure 18: Data integration for EOD interpretation. Observe yellow circles highlighting areas where JIFI inversion volume (figure 19b) shows improved reservoir fairway definition compared to the primary full stack seismic data (figure 19a).

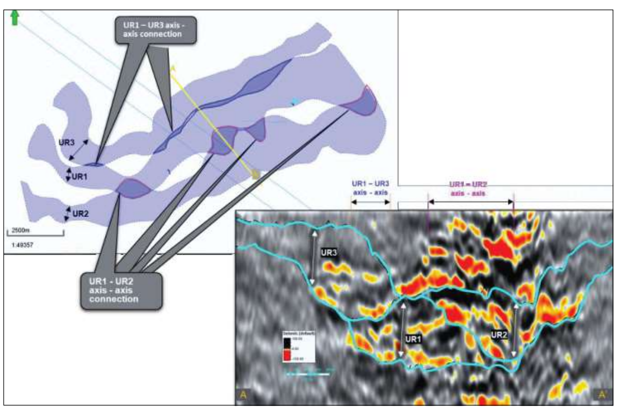

Figure 19: Highlighting inter-channel connection pathways. Note are zones showing vertical stacking of axial portion of a channel complex with underlying complex. These axis-on-axis overlaps are typical of cut-and-fill systems and are candidate routes for fluid connectivity between reservoir complexes.

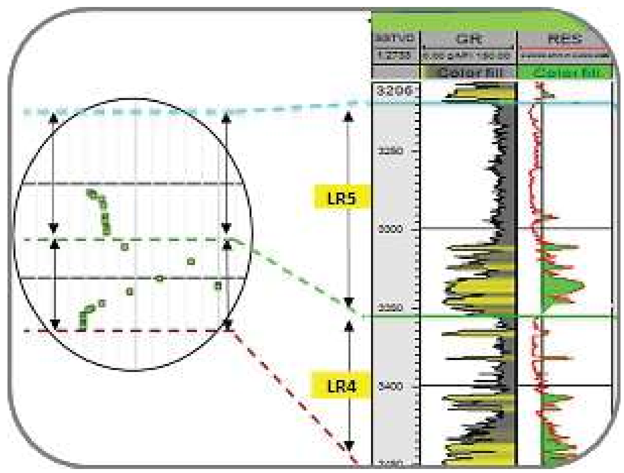

Figure 21: Inter-reservoir and flow scale connectivity using excess pressure plots. Note separation between LR4 and LR5 sands, as well as scattered pressure points in shaly portions of LR4. Excess pressure plots do help in vertical separation of individual channel complexes especially when separated by internal levees.

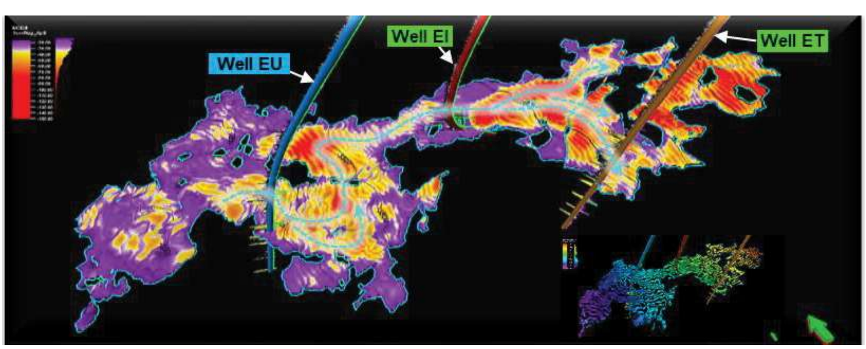

Figure 20: Producer-Injector connectivity investigation using geobody probe. Note cyan colored dashed lines indicating possible connectivity pathway between both wells in this reservoir.

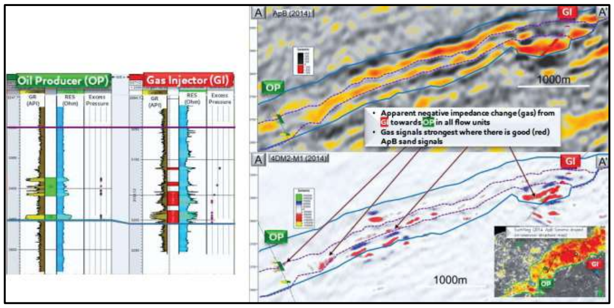

Figure 22: Flow unit delineation through integration of seismic mapping, 4D fluid movement signals and excess pressure plots matched with well logs. Note that sands in the producer well are potentially connected based on observed excess pressures while those of the gas injector well are possibly separated into 2 or more flow units. Also note the guided interpretation of the flow units between producer and injector wells using both 4D and primary seismic volumes.

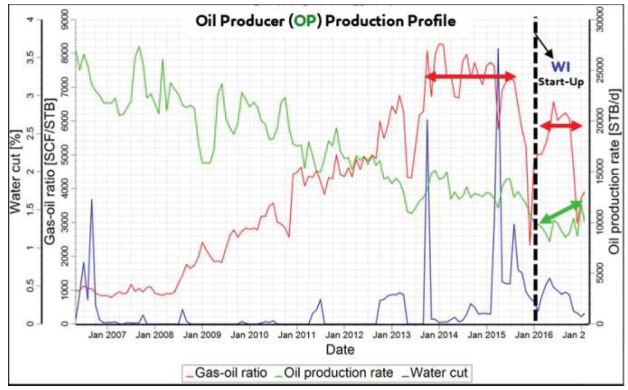

Figure 24: Positive impact of streaming water injector (WI) on the oil producer (OP). Note continued increase in post-2008 gas oil ratio till early 2014 and reduction in gas rates after drilling of the WI in 2016. Observe increase in oil production rate after the decline preceding the WI well.

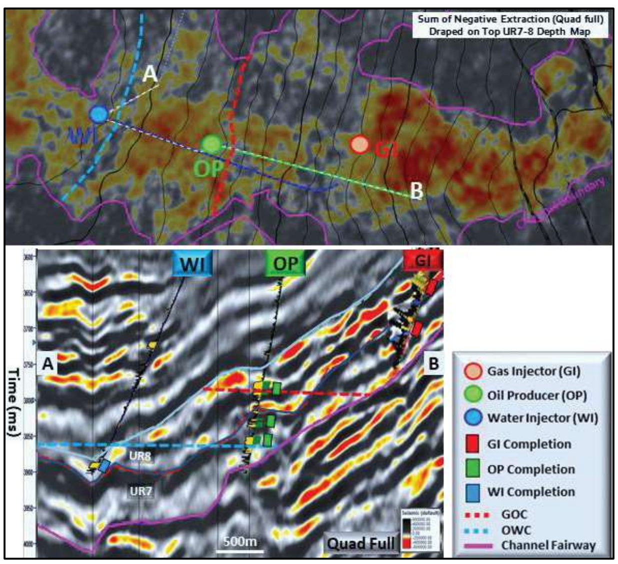

Figure 23: In this section, observe location of oil producer (OP) and gas injector (GI) pair. Prior to drilling of the water injector (WI), the OP has increasing gas-oil ratio (GOR) due to gas advancement from updip GI well. Streaming of the WI helped arrest the encroaching gas leading to improved oil production from the OP.

opportunity maturation for any brown field. In the example shown from this work, we applied knowledge of sand distribution within the fairway, connectivity between the channel complexes, and as well as production behavior (oil, gas and water rates) from a producer-injector well pair to select new water injector placement for optimal oil production. In figure 23, the seismic section shows an oil producer (OP) with a gas injector updip and water injector downdip of producer well. Prior to streaming the water injector, the OP well had a history of high gas-oil ratio (GOR) post-2008. This was even amplified by the nearby gas injector whose continued injection led to gas advancement towards the producer well. To arrest the gas advancement and sweep the oil downdip of the producer into the perforation interval, a water injector well was drilled in early 2016. A look at the production profile of the OP shows reduction in gas rates after drilling of the WI as well as observed increase in oil production rate post-2016 arresting the declines preceding the streaming of the water injector well (figure 24).

SUMMARY AND CONCLUSION

In this paper, we have documented smart data driven integration of seismic, well and production data in characterizing Miocene Deepwater slope channel complexes. Improvements in seismic data quality and increased number of wells and years of production data had significant influence on the interpretation philosophy and internal characterization of the channel systems. The stratigraphic model had evolved from an initial layer cake interpretation (2005 baseline seismic) to more incision-based interpretation (2009 seismic + 3 years of production from 20 wells). This was further re-characterized into a compensationally stacked incision model using 2014 seismic data with over 11 years production from over 30 wells.

The current framework has been split into two 2nd order depositional sequences called the upper and lower fairway, containing eight and six 4th order channel complexes, respectively. In the basin fill history presented, the channel placement, degree of amalgamation, size and lithofacies make-up of individual channel complexes were related to the interplay between sediment gravity flow characteristics, depositional geometry and gradient, accommodation, and sand mud distribution of the sediments. Due to the cut-and-fill nature of the complexes, there has been preferential preservation of both internal and external levees in most of the channels and the interpreted intervals are mostly remnants components of the channels. In the Lower fairway, deposition of bedload deposits in space-constrained areas of submarine valleys led to the deposition of the LR2 channel complex. This was followed by LR3 and LR4 which are meandering channel systems while LR5 and LR6 are levee confined complexes with better preserved internal levees and channel margin facies. Early stages of the upper fairway featured periodic changes in depocenter leading to repeated switch in position of the individual channel complexes as seen in the erosionally confined UR1 – UR4. Gradual reduction in the overall depositional energy with increased accommodation resulted in smaller, higher sinuosity, levee confined UR5 – UR8 complexes with more preserved internal and external levees.

In defining the environment of deposition (EOD), a robust integration of seismic geometries, facies mapping, core and well integration, isochron thickness maps and seismic attribute maps was utilized in defining the EOD boundaries. It is observed that within the lower fairway, individual complexes had broader channel widths and most of the systems almost vertically stacked. The upper fairway recorded more erosive signatures, hence, there is preferential erosion of levees, and some EODs have only remnant axis. In terms of producer – injector and inter-channel connectivity, interpreted vertical or lateral connections were based on 4D seismic signals, pressure data, 3D geobody probes, and observed axis-on-axis incision. Other production and dynamic data such as produced cumulative oil, oil and gas rates and reservoir pressures were also integrated in delineating connection pathways between the channel complexes. Ultimately, a demonstration of this integration for decision on an injector well placement was presented. In the example given, an oil producer started showing increased gas-oil ratio (GOR) after a few years of streaming. After investigation, it was noticed that increased GOR was due to gas advancement from an up-dip gas injector leading to the declining oil rates and high GOR. A decision was made to drill a water injector well, optimally placed below the original oil-water contact and streamed to provide flood front for oil below the production zone into the well perforation, as well as arrest the gas advancement from the up-dip gas injector. This decision had a positive impact on the producer well whose production showed remarkable increase in its oil production and this change has been tied to the timing of streaming of the water injector, as well as its placement.

In summary, utilizing every available data as well as improvements in seismic data led to an improved framework and flow-scale characterization of Deepwater complexes in this brown field. Other products from this exercise include updated EOD definition, detailed understanding of the reservoir connectivity and well delineated connection between producer-injector paths. Ultimately, we shared an example where learnings from this study helped in decision making, leading to improved asset value.

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