

A High Resolution Sequence Stratigraphic Approach to Correlate Complex Sub-Seismic Tidally Influenced Estuarine Incised Valley Fill Reservoirs of the Lakshmi Field, Gulf of Cambay, India*

Satyashis Sanyal¹, Lesli Wood², Dibyendu Chatterjee¹, Nikhilesh Dwivedi¹, and Stuart Burley¹

Search and Discovery Article #20180 (2012)

Posted November 19, 2012

*Adapted from extended abstract prepared in conjunction with oral presentation at AAPG International Conference and Exhibition, Singapore, September 16-19, 2012, update of [Search and Discovery article #50647](#), “A Sequence Stratigraphic Framework for the Tide Dominated Lower Tarkeshwar Reservoir in the Lakshmi Field (Gulf of Cambay, India) to Enhance Field Understanding and Production Potential”. AAPG©2012

¹Cairn Energy India, Gurgaon, India (satyashis.sanyal@cairnindia.com)

²Bureau of Economic Geology, University of Texas at Austin

Abstract

The Lower Tarkeshwar reservoir interval in the Lakshmi Field, Gulf of Cambay, Western offshore India was deposited in a tidally-influenced estuarine valley fill setting during Late Oligocene to Early Miocene times. High resolution electric log based sequence stratigraphic correlation suggests that the reservoir sands are deposited within 3rd and 4th order cycles, resulting in a series of coarsening-up and fining-up para-sequences under an overall transgressive global sea-level period. Major phases of shallowing-up identified in the stratigraphic framework enabled the recognition of the log motifs in the reservoir interval comprising of stacked confined tidal bars, unconfined and isolated tidal bars, broad tidal sand sheets, tidal flats comprising of tidal creeks and smaller tidal channels, proximal stacked prograding sand bars and open estuarine background mud. Cross-bed dips derived from image logs supported with inferred sand thickness trends from seismic attribute analysis suggests a major fairway of deposition trending parallel to the long axis of the structure.

The high-resolution log motif based facies classification correlated across the dip of the field indicates that the reservoir interval comprises at least 3 phases of episodic deposition within the incised valleys. The basal fill is dominantly down-dip and consists of stacked low-stand or early transgressive distributary channel and confined bar facies, which occur in an overall fining-up succession, with each smaller cycle of progradation reflecting the development of a bar complex. The second episode of valley fill represents more unconfined tidal bar development grading laterally and upward into a dominantly tidal flat and creek system. These are capped in the downstream direction by broad

transgressive sand sheets, with excellent lateral continuity and reservoir properties. The late stage valley fills are characterized by increased deepening into isolated reworked tidal bars within broad tidal flats, with a significant increase in mud content before a major erosion event marks the end of the incised valley filling.

This high resolution facies correlation approach provided a revolutionary improvement in deciphering the reservoir architectural elements and understanding the lateral and vertical connectivity of individual sand bodies, aspects of which are critical for an optimized field development in complex depositional environments.

Introduction

The offshore Lakshmi Field in the southern part of the hydrocarbon prolific Cambay Basin, Western India, is a success story of a brown-field development, transitioning from a depleting gas field to an oil producing asset (Figure 1). Oil was discovered beneath existing gas reservoirs in the Miocene Lower Tarkeshwar sands during the initial exploration and appraisal phase. However, the full potential of the field was not recognized early in the asset's history. The oil sands were difficult to map seismically given the shallow gas masking effects and relatively thinner sands in the deeper oil reservoir interval. Uncertainties in geological frameworks were enhanced by limited core and borehole imagery data. Hence, early oil in-place and reserve estimates were based on well penetrations, gross fairway definitions from seismic attributes and initial drill stem testing (DST) results, considering simple depletion drive. Over time, the possibility of compartmentalization was recognized based on the occurrence of multiple fluid contacts and abnormal pressure behavior in recently drilled production wells. Increased production data and updated material balance models clearly reflected good aquifer support in most of the oil sands. However, production forecasting based on these simple tank models were unable to provide complete insight to the full potential of the oil sands and additional development opportunities. Thus a need for a field-scale history matched geocellular model was felt necessary. Since seismic and pressure data provided limited answers to the complex reservoir behavior, it was evident that an improved static model of the reservoir would significantly enhance understanding of this complex system. Accordingly, an integrated approach was undertaken to construct a conceptual sequence stratigraphic framework; the essential key for geo-cellular modeling and reservoir simulation to evaluate options for improved recovery.

Tectonics, Stratigraphy and Depositional Environment

The Lakshmi Field is located at a major four-way tectonic junction, where the Cambay Rift, the Narmada Rift, the Surat Depression and the Dahanu Depression converge. The junction was offset during the Late Miocene Himalayan collision, which gave rise to the inversion structures as the primary trapping mechanism. Overlying the Deccan Trap basement is the Lower Oligocene Hazira Shale which is the source rock for hydrocarbons (Figure 2). The Late Oligocene-Early Miocene age Tarkeshwar Formation is separated from the underlying Hazira Shale by a Late Oligocene low-stand unconformity of global significance. Published literature indicates major sea-level fluctuation during the Late Oligocene period in the present day Gulf of Cambay area, giving rise to low-relief shallow-marine to coastal plain settings (Pandey,

1986). It is suggested that the Lower Tarkeshwar reservoir sands in the Lakshmi Field were deposited between Late Oligocene to Early-Miocene time in an overall transgressive global sea-level condition following the Late Oligocene low-stand (Figure 3). Ichnological records from the limited core data displayed evidence of salinity fluctuations, episodic deposition, high aggradation rates and variable substrate consistency. The Tarkeshwar Formation is overlain by the transgressive, shallow marine gas bearing Babaguru Formation. The Babaguru Formation is overlain by shallow marine shelfal shale of the Kand Formation which forms the regional seal for the area.

Sequence Stratigraphic Framework

Satellite images and the bathymetry map of the Gulf of Cambay show the presence of well-defined tidal ridges extending from the head of the Gulf, where they coalesce into tidal flats, out into the Arabian Sea. Tidal ranges in the Gulf of Cambay are up to 8 m, giving rise to macro-tidal depositional setting. Given that the overall structure of the Gulf of Cambay has not changed significantly since the formation of the Basin in the earliest Paleocene times, the modern bay is considered to be a good analog for Neogene environments in the basin (Saha, 2006). Therefore, using the depositional systems and geomorphology of the modern Gulf of Cambay, core and electric log based facies associations were defined and integrated with seismic horizon and geomorphologic mapping (Figure 4) to interpret the Miocene sedimentary fill as having been deposited in a tide-dominated estuarine environment with associated complex incised valley fills. This enabled development of a conceptual sequence stratigraphic framework of the Lower Tarkeshwar reservoir. Flooding surfaces and sequence boundaries recognized in electric log motifs and tied to 3D seismic data aided field-wide correlation of reservoir units and also enabled identification of distribution patterns of facies. Log correlations reveal the Lower Tarkeshwar Formation to comprise multiple valley incisions and transgressive fill cycles. Analysis of vertical stacking patterns in well logs revealed the interval to be divided into a number of para-sequences, each of them containing a variety of tide-dominated estuarine depositional elements, including tidal bars, channels and creeks, tidal flats and salt marshes (Figure 5).

Seismic Geomorphology and Areal Facies Distribution

The established sequence stratigraphic framework aided the analysis of seismic geomorphological features, and paleogeographic maps were produced to capture the broad depositional trends within the reservoir interval. To minimize the effect of structural imprints in the seismic attribute extractions, the 3D seismic volume was flattened at the best mappable flooding event nearest to the interval of interest, which is approximately 120 ms shallower in the stratigraphic section. A series of horizon slices at 5 and 10 ms interval were generated from this flattened seismic volume and various seismic attributes, including RMS amplitude, instantaneous frequency, seismic coherency, sweetness, spectral decomposition and continuous wavelet transformation (CWT), were analyzed. Horizon slices showed evidence of low-sinuosity channel architectures approximately 500 to 700 m wide and high sinuosity tidal creeks, all generally trending northeast to southwest and displaying signatures typical of tidally influenced estuarine systems. Some of the amplitudes show a propensity to align with the edges of the channel architectures, suggesting a stratigraphic component to the traps. Few horizon slices displayed striation banding in the attribute images

which are interpreted as migrating stacked prograding tidal sand systems. The seismic attributes revealed four primary geomorphic elements, namely tidal creeks, large estuary systems with channels and bars, muddy tidal flats and migrating tidal bar complexes (Figure 6). The large systems reflect a rejuvenation and sub-areal exposure of the estuary. Paleogeographic maps, showing the conceptual areal facies distribution at key times over the stratigraphic interval of interest, were generated at key stratigraphic levels. Geomorphologic architectures (geo-bodies) were digitized in ArcGIS and georeferenced to the actual well penetrations in the Lower Tarkeshwar interval to verify the interpreted deposits using log motifs. Depo-systems were defined using four primary systems: progradational bay-head deposits, tidal flats/salt marshes, estuarine valley-fill deposits and open marine bars. Confined and unconfined tidal bars, tidal channels and creeks were digitized in each of the facies distribution maps and were referenced to the vertical sequence stratigraphic framework.

Sequence Stratigraphic Interpretation of the Depositional System

The log motif-based facies correlation tied to seismic geomorphology based areal facies distribution pattern established 6 sub-zones within the Lower Tarkeshwar interval. The basal unit is interpreted as a prograding late high-stand to early low-stand systems tract, which is eroded by a major incision surface (sequence boundary). This incision is filled with estuarine deposits, part of the transgressive systems tract of the Lower Tarkeshwar. These early estuarine valley fills lie in the base of the valley in a confined incision and are comprised of stacked amalgamated tidal bars and channels. These depositional elements are best defined in the southwest part of the field. The valley fills are succeeded by two minor and one major regionally mappable flooding event, which give rise to three transgressive fills, each denoting the subsequent deepening of the estuary. These transgressive fills comprise of smaller scale facies that include tidal flats, salt marshes and muddy estuarine deposits. These fills are cut through by numerous poor reservoir quality tidal creeks and high-sinuosity tidal channels which further complicate the subsurface flow behavior. The basal part of the transgressive fill is dominated by possible re-working of the sediments deposited as Upper Flow Regime sand flats, which are often characteristic of the inner mouth of the estuary in a tide dominated setting. Laterally, this transgressive fill grades landward in the estuary into possible bay-head deltaic deposits towards the northeast part of the field. During late transgression, the flooded valley is filled with isolated tidal bars, broad tidal flats and inter-bedded muds. This entire transgressive fill is overlain by a second phase of significant regional incision and development of another sequence boundary which is in turn overlain by a thick stack of fluvial-tidal bar and channel system. In the more basin-ward locations the high-stand systems tract of the previous sequence can be seen preserved beneath the next overlying sequence boundary as a series of stacked tidal bar deposits interbedded with brackish marine mudstones (Figure 7).

Conclusions

The vertical sequence stratigraphic framework and the seismic geomorphology derived areal facies distribution maps were used to generate a 3-dimensional facies model of the field based on the conceptual depositional environment of the area. The subsequent geocellular model using the high resolution facies correlation approach provided an enhanced understanding of the geospatial distribution of the architectural

elements and the lateral and vertical connectivity of sand bodies, aspects of which are critical for an optimized field development in these complex depositional environments.

Acknowledgements

The authors gratefully acknowledge the full support of the CB/OS-2 Field Joint Venture partners, Oil and Natural Gas Corporation and TATA Petrodyne Limited to carry out the integrated geological studies and their permission to publish this work.

References

Dalrymple, R.W., B.A. Zaitlin, and R. Boyd, 1992, Estuarine Facies Models: Conceptual Basis and Stratigraphic Implications: Journal of Sedimentary Petrology, v. 62/6, p. 1130-1146.

Off, T., 1963, Rhythmic Linear and Units caused by Tidal Currents: AAPG Bulletin, v. 47/2, p. 324-341.

Pandey, J., 1986, Some Recent Paleontological Studies and Their Implications on the Cenozoic Stratigraphy of Indian Subcontinent: Bulletin of the Oil and Natural Gas Corporation, v. 23/2, p. 1-44.

Saha, S., A. Ghosh, S. Burley, S. Banerjee, and P.K. Saraswati, 2006, Tidal Bars in a Macrotidal Estuarine Embayment: the Gulf of Khambat, Western India: Indian Journal of Petroleum Geology, v. 15/2, p. 69-78.

Shanmugam, G., M., Poffenberger, and J. Toro Alava, 2000, Tide-Dominated Estuarine Facies in the Hollin and Napo ("T" and "U") Formations (Cretaceous), Sacha Field, Oriente Basin, Ecuador: AAPG Bulletin, v. 84/5, p. 652-682.

Wood, L.J., and B. Willis, 2000, Characterizing tidally influenced reservoirs through integrated sequence stratigraphic study of the subsurface and outcrop data: Sego Sandstone, Book Cliffs, Utah, U.S.A.; AAPG Search and Discovery Article #90913. Web accessed 6 November 2012. <http://www.searchanddiscovery.com/abstracts/html/2000/intl/abstracts/474.htm>

Wood, L.J., 2004, Predicting Tidal Sand Reservoir Architecture Using Data from Modern and Ancient Depositional Systems: AAPG Memoir 80, p. 45-66.

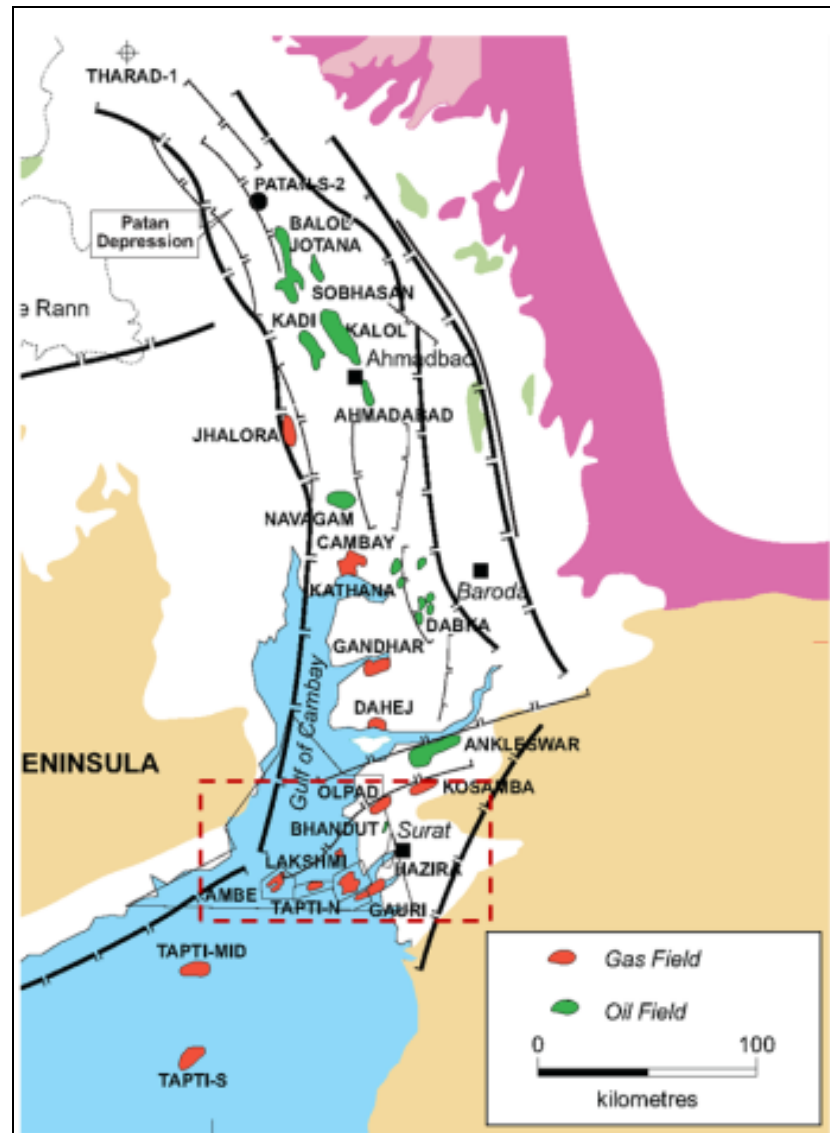


Figure 1. Location of Lakshmi Field in Gulf of Cambay, India

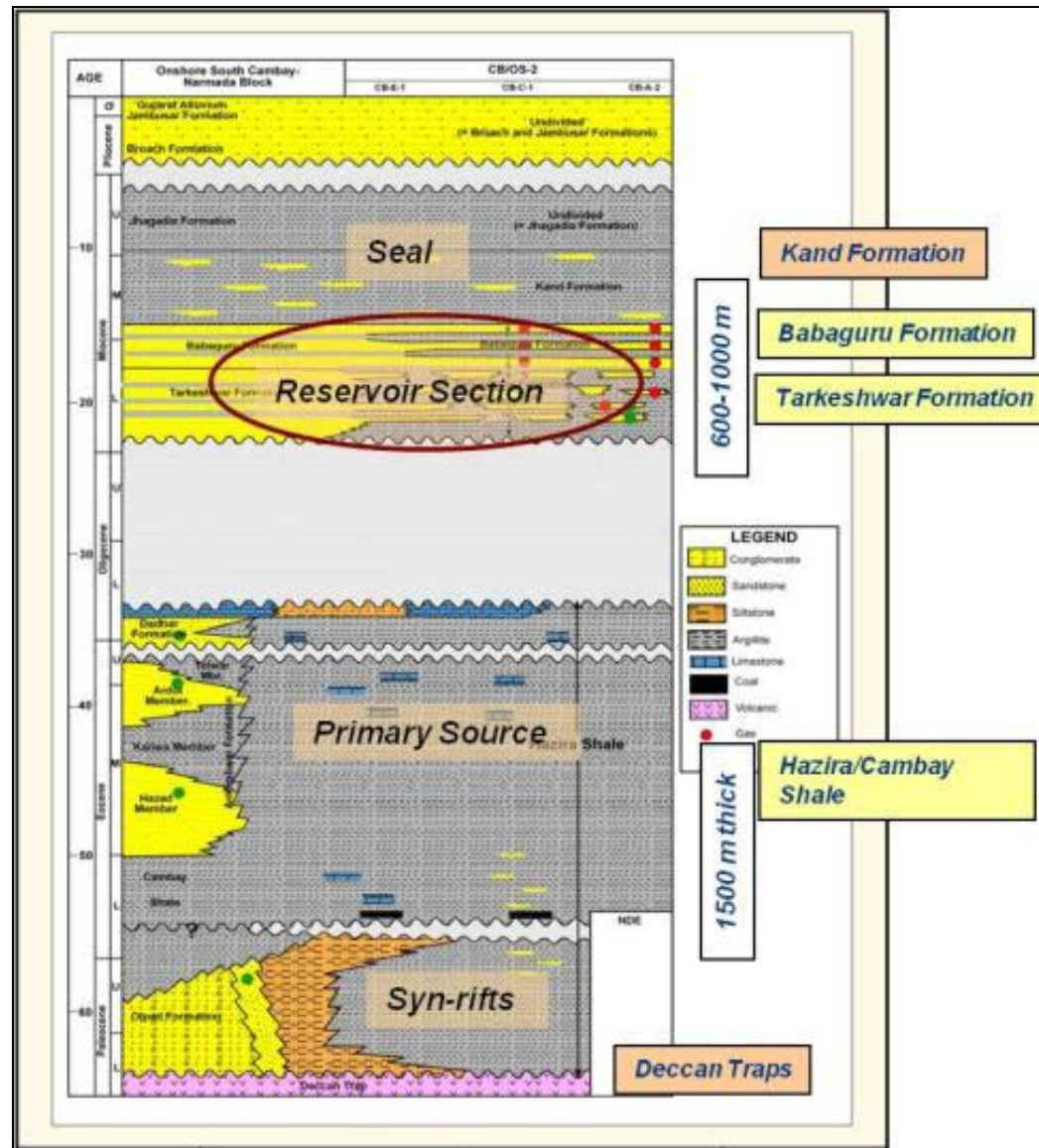


Figure 2. Stratigraphic Framework of Cambay Basin.

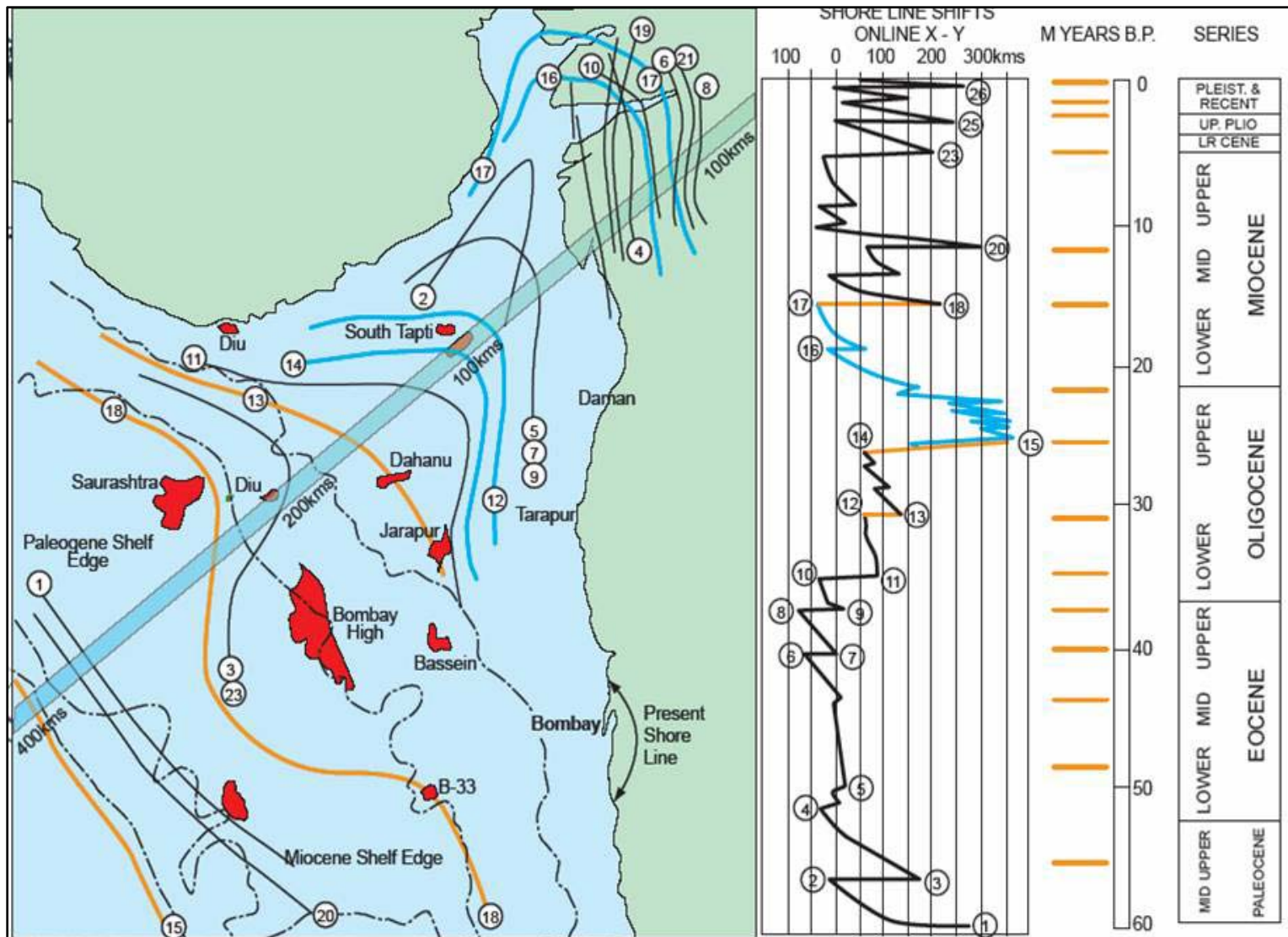


Figure 3. Shoreline shifts during Oligo-Miocene times in the Gulf of Cambay (after Pandey, 1986).

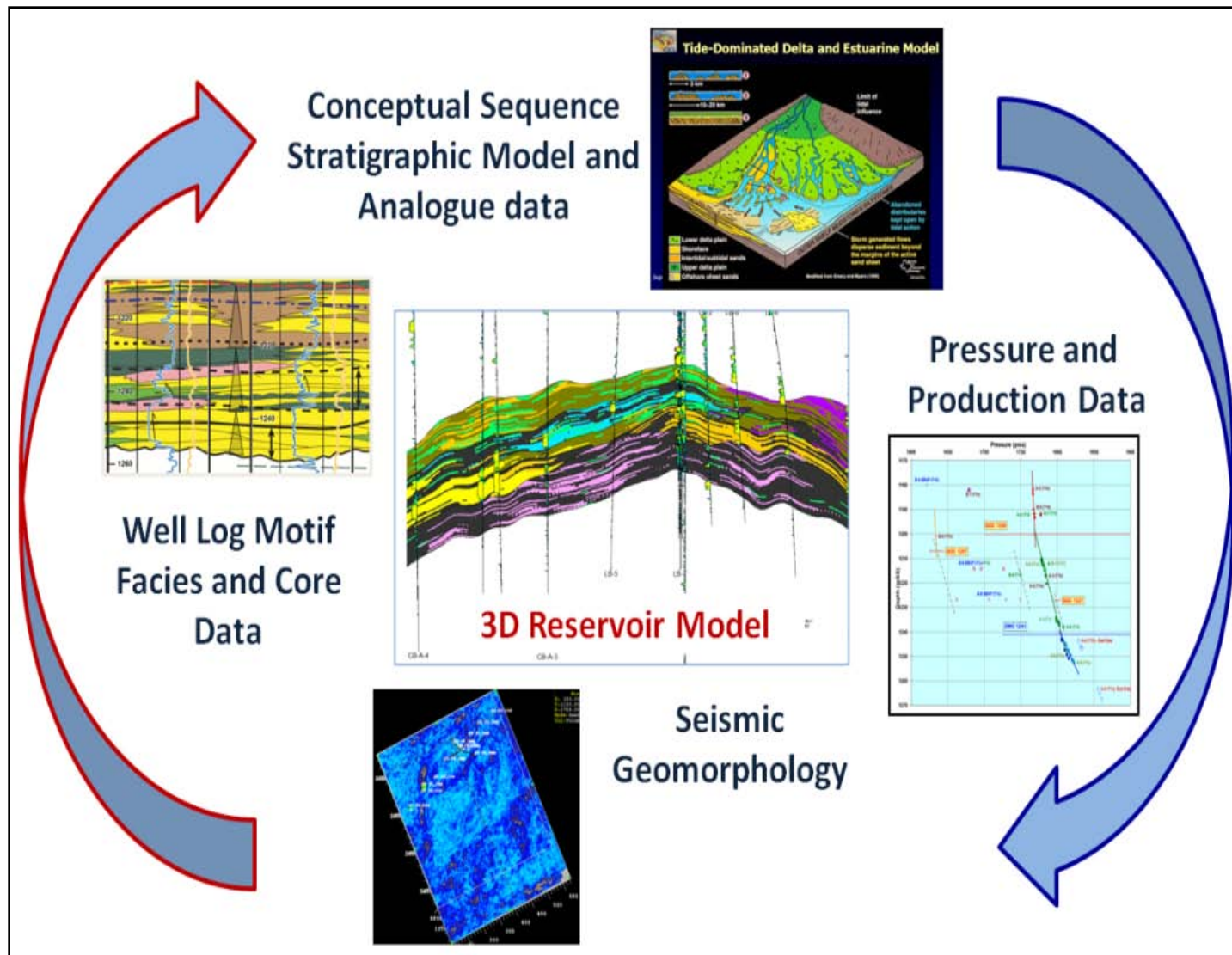


Figure 4. Integrated Geological Modeling Workflow. The iterative process involved an integration of conceptual geological model, well log motifs and offset core data, pressure and production history and seismic geomorphology.

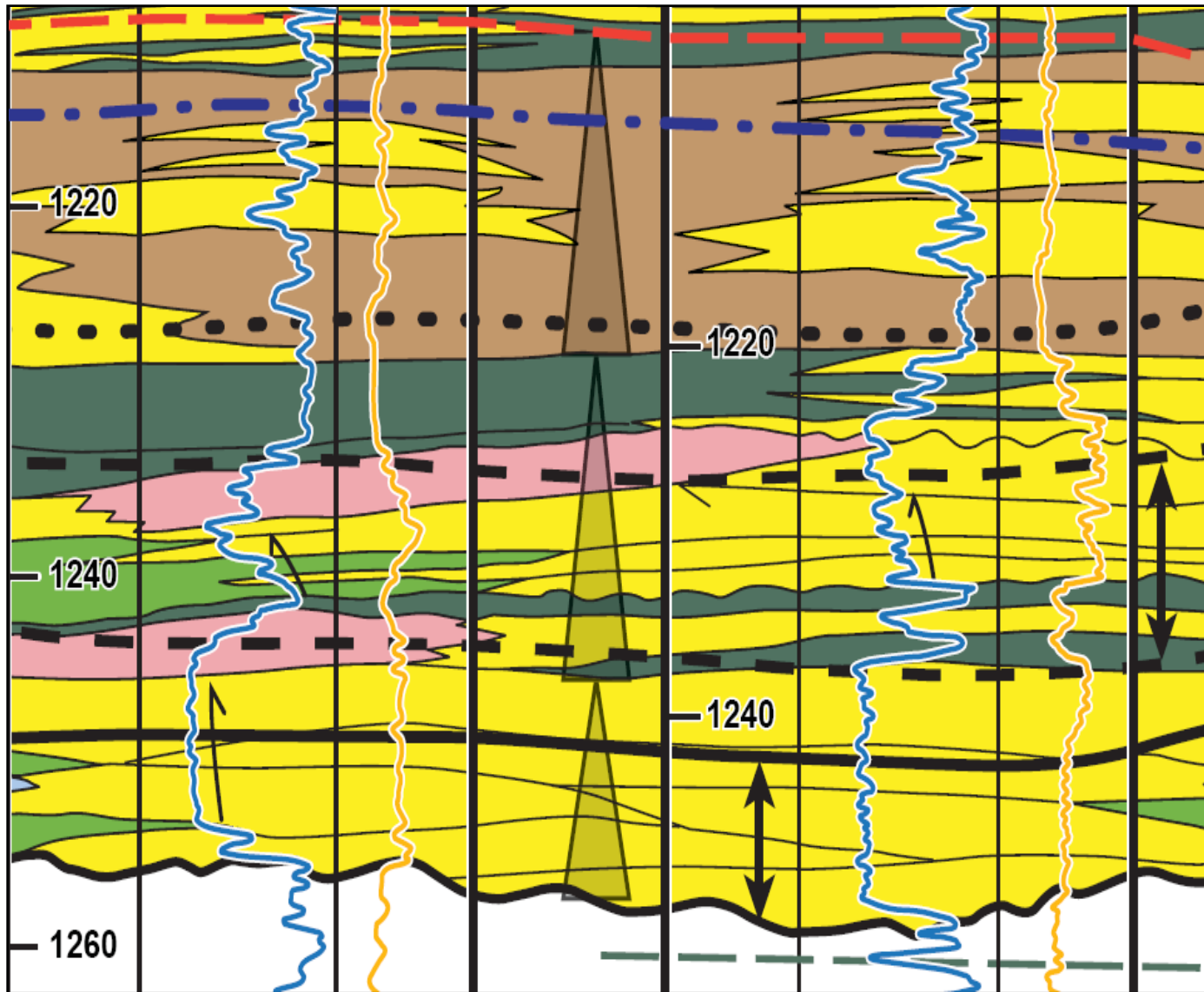


Figure 5. Estuarine depositional elements from log motifs. Note some of the depositional elements marked in the log motifs, including bar tops and the stacked bar.

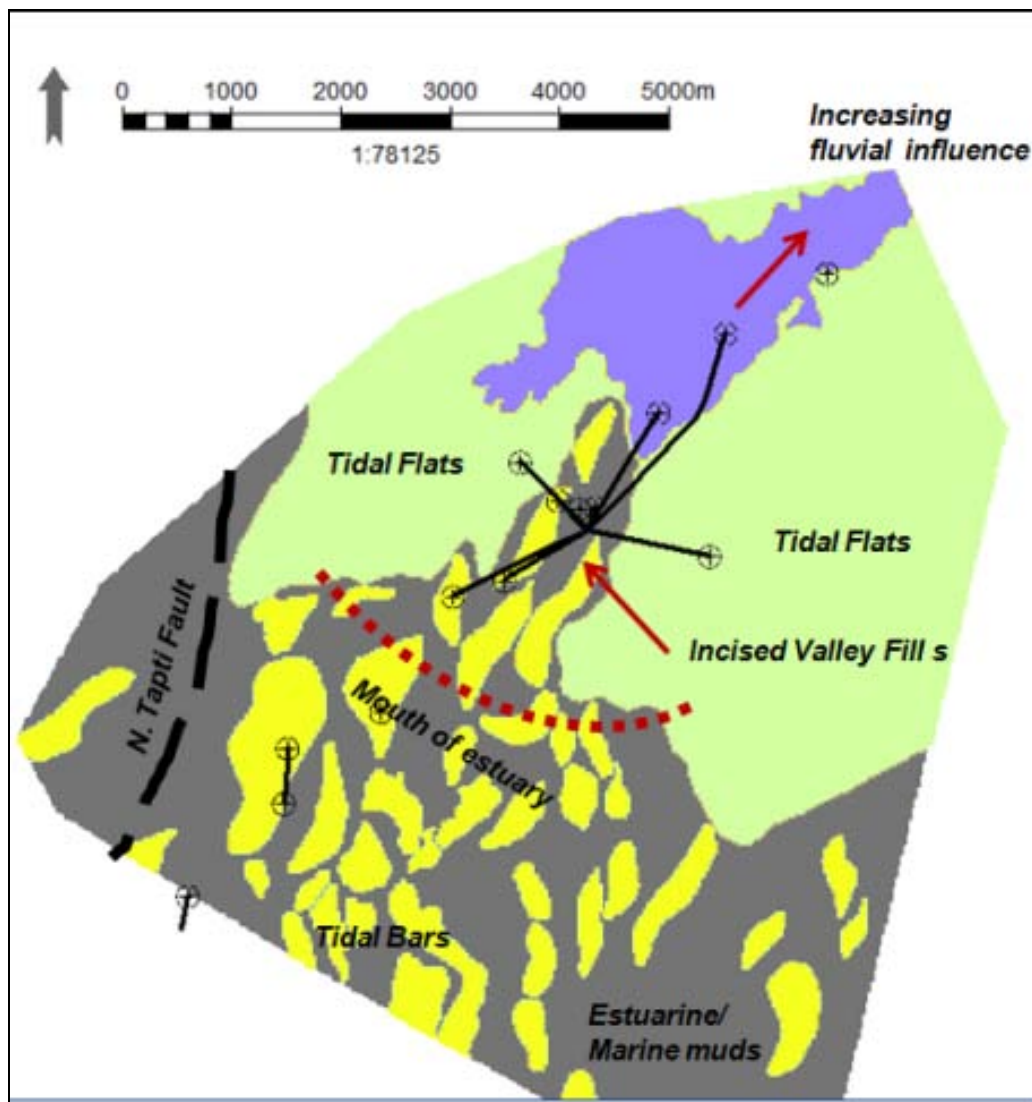


Figure 6. Areal Facies Distribution from Seismic Geomorphology. A-A' shows the approximate line of section along which the sequence stratigraphic framework was built in [Figure 7](#).

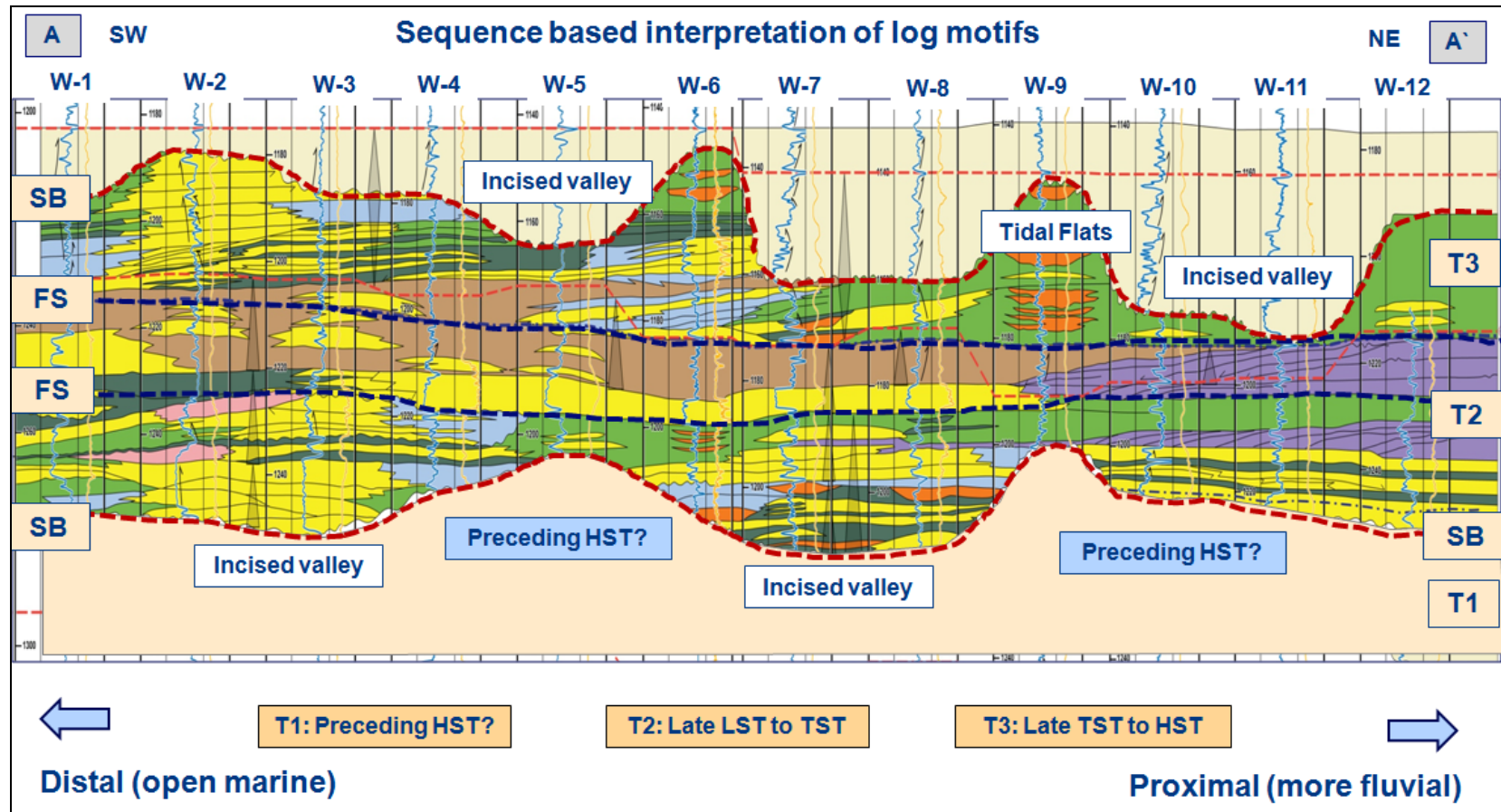


Figure 7. Sequence stratigraphic framework of the study area (SB: Sequence Boundary, FS: Flooding Surface, HST: Highstand systems tract, TST: Lowstand systems tract, TST: Transgressive systems tract).