Sequence Stratigraphy as Predictive Tool in Lower Goru Fairway, Lower and Middle Indus Platform, Pakistan*

Nadeem Ahmad[1], Paul Fink[1], Simon Sturrock[2], Tariq Mahmood[1], and Muhammad Ibrahim[1]

Search and Discovery Article #10404 (2012)**
Posted April 23, 2012

* Adapted from oral presentation at PAPG Annual Technical Conference 2004, Islamabad, Pakistan, October 8-9, 2004

[1]OMV (Pakistan) Exploration GmbH, Islamabad, Pakistan (ah_nadeem@ppl.com.pk)
[2]Strat-Trap Pty. Ltd., Australia

Abstract

Despite several discoveries in the Early Cretaceous Lower Goru Fairway of the Lower and Middle Indus Platform, significant potential remains untapped due to a limited understanding of the distribution of reservoir quality sands and a lack of understanding of the subtle stratigraphic trapping mechanism. Creaming curve analysis for the Lower Goru play indicates significant remaining potential. Predictive tools such as sequence stratigraphy are being proposed for the exploration of subtle traps and successful prediction of reservoir sands in the platform part of the Middle Indus Basin in south-central Pakistan.

Integrated use of log motifs, core sedimentology, stratigraphic correlations, and seismic stratigraphy has helped reconstruct a regional sequence stratigraphic framework of the Sembar and Lower Goru Megasequences. The following sequences are identified from bottom upwards: Sembar-1, Sembar-2, Lower Goru "A" Sequence, "B" Sequence, "C" Sequence and the "D" Sequence. Deposition of the Sembar-2 and upper "A" lowstand (potentially aggradational) left behind an extensive shelf on which the Lower Goru paralic sequences were deposited. Between each of the sequences identified, a normal succession of gradual vertical facies stacking is interrupted, with offshore to lower shoreface fines of the previous transgressive/highstand directly overlain by coarse-grained proximal sand with a sharp-based log motif. Such „out-of-sequence" sandy wedges are formed by abrupt basinward shift in coastal onlap. Such forced regressive wedges or detached shoreface wedges (FRW/ DSW) are located in a more basinward position encased within the distal fines. Tidal currents and northerly strong longshore drift stacked the shoreface sands eastward of the NNE-SSW oriented ramp margin. The transgressive facies act as a seal, but transgressive ravinement erosion can often erode the coarse-grained upper shoreface reservoir quality sands.

Eastward tilt, eastward coastal onlap against the fines, and westward and lateral facies changes form subtle stratigraphic traps that offer high-risk high-reward exploration opportunities. In structural traps, precise sand prediction can help find upside. Useful sand prediction criteria

include: (1) Abrupt west/northwestward shift of coastal onlap/offlap-break, (2) Staying eastward of the shelf margin built out by Sembar-2 and "A" lowstand, (3) Within each sequence, staying westward of the coastal onlap and eastward of the offlap-breaks of the progrades, and looking for subtle thickness anomalies eastward of the progrades‟ offlap-breaks, (4) Looking for laterally correlative sharp-based sandy log motifs in the offset wells, (5) A combination of accommodation space, transgressive erosional processes and the extent and period of downstepping (forced regression) before the next transgression can cap the shoreface would determine the preservation of upper shoreface facies, and (6) Ensuring the proximity to fluvial input which allows coarse sand emplacement and fresh-to-marine water mixing that forms early Fe-chlorite coatings around coarse quartz grains. Such early cement is essential for preserving the porosity-permeability during deep burial. These criteria of predicting seal, trap and reservoir sands have helped in the past and can help in the future to tap the remaining hydrocarbon potential associated with the detached regressive and forced-regressive reservoir sands as indicated by the Creaming Curve of the Lower Goru Play.

Introduction

During the last two decades, the Early-Late Cretaceous Lower Goru sands have emerged as significant hydrocarbon producers from the Middle and Lower Indus Platform areas of south and south-central Pakistan. However, significant potential remains untapped due to limited understanding of the distribution of reservoir. Conventional structural traps have already been explored and the exploration of subtle structural and stratigraphic features is a facing relatively lower success rate (Figure 1). Prediction of reservoir quality sands in the case of both the structural and stratigraphic traps and the ability to map and predict the lateral, updip and downdip seals in the case of stratigraphic traps are stratigraphy related reasons of failure. The use of predictive tools of sequence stratigraphy and Lower Goru play‟s creaming curve can help unravel new exploration targets, address the geological uncertainties (risks) and further advance exploration in the Lower Goru play.

As opposed to the conventional wisdom that the "cream of the crop" is found early in the exploration history of a play, i.e. a steep rise in cumulative discovered reserves followed by a terrace (Snedden et al., 2003), the Lower Goru discoveries (Figure 2) point to more than one steep limb on the creaming curve (DGPC, 2003). A rather complex curve (Figure 2), instead of a simple creaming pattern of rising limb followed by a plateau phase, can be explained by considering the lateral and vertical position of the producing Lower Goru reservoirs within a sequence stratigraphic framework. The early discoveries of 1981- 85 ("cream") came from the Badin area where UTPI (now BPP) and later OGDCL discovered oil, condensate and gas in the "C" and "D" sequences (Upper and Middle Sands) of the Lower Goru. Initially, the prospects in the Lower Goru play were based on structural play concept in horst blocks and these discoveries exhibit rising trend followed by a plateau in the late 1980‟s (Figure 2). In the 1990‟s, new fields were discovered on the down-thrown side of the fault blocks (e.g. Rehmat and several Badin area fields) where the reservoir extent and geometry are partly controlled by stratigraphy. Reservoir sands are associated with forced-regressive detached shorelines, shoreface barrier bars (Miano), shelf edge deltas (Sawan), and laterally restricted deltaic distributary channels and lobes. The discovery of detached shoreface sands under the structures in a basinward position (e.g. Mari High, Rehmat and Badin), added another major rising limb on the Lower Goru cumulative discovered IGIP and reserves (Figure 2). The youngest segment on the creaming curve has a rising shape that is attributed to the recent oil, condensate and gas discoveries in the Sinjoro and Mirpur Khas blocks. This creaming curve trend suggests that the Lower Goru lowstand detached sand play has not yet entered a mature stage and many more discoveries are still to come from the Lower and Middle Indus platform area, particularly in the form of upside from the existing D&P leases.

This paper shows how the jumps, or multiple pairs of rising limb and flattening tendency, in the creaming curve are related to the discoveries in previously undrilled or by-passed depositional systems tracts, especially those related to detached forced-regressive shoreface sand bodies in the Lower Goru sequences. We present and discuss the sequence stratigraphy tools that can be useful in exploring for this untapped potential of the Lower Goru Play. Predictive value of the sequence stratigraphy will be demonstrated through an integrated use of cores, wireline logs and seismic data. It will be shown that the scope for further exploration successes and the remaining untapped potential can be predicted by deploying these tools.

Sembar-Goru Petroleum System

The Lower Goru play discoveries are located within the platform part of the Middle and Lower Indus Basin, from near the Mari High all the way down to the Badin area (Figure 3). A number of studies exist in the exploration companies" files and public domain (mostly unpublished) that have documented the depositional framework and reservoir stratigraphy of the Lower Goru in this area (Milan and Rodgers, 1993; I.E.D.S., 1995; Krois et al., 1998). A more recent account of the Lower Goru shelf and shelf margin sequences and reservoir facies distribution is presented by Khan, Moghal and Jamil (1999).

Stratigraphy and Sedimentation

The stratigraphic interval of interest is comprised of: (1) thick basinal (bathyal/pelagic) shale unit and the overlying interbedded turbidite lobes and progradational wedges of sand and shale conventionally referred to as the Sembar Formation, and (2) the overlying deltaic and shelfal paralics referred to as the Lower Goru Member (Figure 4). The sand-prone Lower Goru sequences are prospective and consist of interbedded sandstone-shale paralics deposited in deltaic marine, strand plain and barrier bar shoreface to offshore setting on a ramp. Lithostratigraphically, the Lower Goru units are named as the Lower Goru members “A”, “B”, “C” and “D” and are interpreted on the seismic as the “A”, “B” and “C” and “D” Intervals (Krois et al., 1998; Khan et al., 1999). However, in terms of sequence stratigraphy, the boundaries of genetic stratigraphic units are established differently (Figure 5). The present-day eastward tilt in the areas close to structural highs works with the westwards facies related shale-out of the prograding sand wedges to provide stratigraphic traps (Figure 4).

The Early Cretaceous Sembar siliciclastics were deposited on top of an extensive carbonate platform (Chiltan Limestone). Carbonate sedimentation was terminated in Kimmeridgian-Oxfordian times. This was a result of renewed rifting between the African and Indian plates and the associated environmental and tectonic changes. Carbonate production was not reestablished during the subsequent marine transgression in the latest Jurassic. Instead, a drowning unconformity and condensed section developed above the subsiding carbonate, indicating that subsidence occurred in the continued absence of a significant sediment supply.

The Late Jurassic drowning unconformity and the lower Sembar condensed section (Figure 5) has therefore been used to flatten regional seismic sections. This removes the younger structural complexity and helps study the sequence stratigraphic relationships in a near depositional form. Internal downlaps within the prograding wedge and a downward shift in topset reflections onto the dipping slope reflections are clearly evident on seismic. These observations, together with the erosion of topsets in the east, suggest that the initial part of the wedge, referred to here as the Sembar-1 Sequence, was uplifted while the front of the wedge was prograding and down stepping towards the west. Further evidence for a significant sequence boundary within the prograding complex, referred to here as the Sembar-2 sequence boundary, is provided by some of the deeper well penetrations (e.g. Miano-1), where sandy paralics of the Sembar-2 and Lower Goru "A" lowstand are abruptly juxtaposed on the shaly slope facies of the Sembar-1 sequence. Sandy submarine fans and a pronounced lowstand wedge, which prograded towards the west, developed above the "Sembar-1" sequence boundary. The Sembar-2 Sequence wedge contains both the argillaceous slope facies akin to the Sembar Formation and sandy topset deposits belonging to the "A" Interval of the Lower Goru Formation. Progradation of the Sembar-2 sequence and "A" lowstand wedge reached a maximum when relative sea level started to rise and equilibrium with sediment supply was reached. However, sediment supply remained sufficient to produce an aggradational stack of sandy paralics which over-steepened the "A" Sequence slope. The "A" Sequence lowstand wedge in the west and aggradational paralics in the east represent the westward limit of Lower Goru progradation into the deep basin. Together, the Sembar sequences and the "A" lowstand wedge form a broad, flat shelf on the eastern side of the Lower and Middle Indus Basin upon which subsequent Cretaceous paralic deposits accumulated, but could not extend beyond the shelf margin. Therefore, the shelf margin built by these regressive wedges controls the distribution of subsequent paralic reservoir targets in the Lower Goru Formation. The only sands developed beyond the Sembar-2 shelf edge are submarine fan deposits, a play that has yet to be proven.

After the deposition of Sembar sequences, relative sea level continued to rise during the latter part of the Early Cretaceous and into the Late Cretaceous Lower Goru times, causing overall retrogradation of the basin margin. This gradual and long-term base level rise and sea level still stand (3^{rd} order eustatic or tectono-eustatic sea level cycles), punctuated by high-frequency 4^{th} and 5^{th} order relative sea level fluctuations, led to the deposition of aggradational to westerly prograding clastic wedges that rarely reached the edge of the shelf built by the Sembar and "A" lowstand. An active longshore drift and tidal influence (wave- and tide-dominated systems) restricted these sands to the east on the shelf where they formed a ramp that gradually deepened to the west.

Tectonics and Structure

Almost all of the Lower Goru discoveries are located on or near (mostly east- to southeastwards of) one or the other structural high (e.g. Mari High, Jacobabad- Khairpur High, Badin Uplift, Lakhra High, etc., Figure 3) which has implications for the migration pathways, timing of the reservoir charge, and hydrocarbon entrapment in the structural and subtle stratigraphic features. Most of these structural highs are inversion features identified on the regional seismic lines. The first uplift episode occurred near the K-T boundary and is manifested as the base Tertiary unconformity. The Paleocene Ranikot clastics thin-out towards and, prograde out and thicken, away from these highs. Moreover, the majority of the deep basement related and shallower wrench-tectonics related faults terminate against this unconformity. Generally, the NW-SE oriented wrench faults cut the entire Cretaceous section, changing character from strongly linear and single fault at the top Chiltan to multiple en echelon left-lateral segments at the Lower and Upper Goru levels. This tectonic event was a result of trans-tensional tectonics related to the first docking of the India-Eurasia plates and counter-clockwise rotation of the Indian Plate. The second uplift event in the Middle and Lower Indus Basin took place during the Late Eocene-Oligocene. The structural highs probably underwent recurrent phases of upheaval (as peripheral bulge or fore-bulge) in response to the successive phases of thrust loading in the west and northwest. The final modification of the shapes of the traps and potentially the secondary hydrocarbon migration and reservoir charge took place during this period.

Source, Migration and Hydrocarbon Charge

Reservoir sands in the Middle Indus Platform area were charged from the underlying Lower Cretaceous regionally proven organic-rich shales (Sembar Formation) and from the organic-rich shales within the Lower Goru Member (Analogues: nearby Sawan, Miano and Kadanwari gas fields). These shales contain terrestrial organic matter, a TOC in the range of 0.5-1.7%, with Type III kerogen and have been in the gas generation phase since late Cretaceous-early Tertiary times. This timing of HC generation, expulsion, and migration coincides with the Early Paleocene and the Late Eocene structuring discussed above. A part of the most significant phase of hydrocarbon generation that took place in the Eocene and younger times is preserved in the form of present-day gas and condensate accumulations in the Middle and Lower Indus Platform fields. Perhaps early liquid hydrocarbon generations of Late Cretaceous times were trapped within the generally west-dipping detached stratigraphic wedges (e.g. paleo-oil column in Umar-1 found in the “A” sequence sands in Mirpur Khas Block). However, these early hydrocarbons were later redistributed and were rarely preserved during the later inversion in the Eocene-Oligocene.

Dataset and Workflow

The Lower Goru play is setup through a combination of facies related reservoir deterioration in three directions (west-, north- and southwards) and structural tilt towards the east. Only an integrated use of different datasets and a comprehensive knowledge base of depositional and field analogues can ensure successful exploration, appraisal and exploitation of the Lower Goru opportunities. The data used by OMV (Pakistan) typically include 3D and/or 2D seismic, wireline and cores with accurate log-to-seismic tie, core-derived facies analysis and reservoir attribute computations from the offset wells. The following workflow is used to successfully exploit the Lower Goru play:

1) Well log-to-seismic tie for identifying the regionally extensive mappable horizons and sequence stratigraphic surfaces such as flooding/maximum flooding surfaces and sequence boundaries.

2) Core-based sedimentology and high-resolution core calibrated well log stratigraphic correlations. The correlations are fine-tuned iteratively based on comparisons with seismic sections and maps generated in (4) and (5) below.

3) Geologic characterization of the high-resolution seismic reflection geometries (truncation patterns, sigmoidal reflections) seismic facies using the coarsening-up, fining-up and blocky GR log motifs from the offset wells or from the wells located on the seismic lines.

4) Seismic stratigraphic interpreted sections with Wheeler diagrams (relative time stratigraphic charts) to document the temporal and spatial

relationships of different sand bodies.

5) Gridding and mapping of the picked seismic horizons followed by isochore (or isopach) maps. Draw and annotate on these maps the critical depositional interfaces, i.e. shelf margin built by the Sembar and "A" lowstand, and subtle offlap breaks within the "A" to "D" sequences. These critical trend lines control the westward limit of medium to coarse-grained sands.

6) Seismic attribute maps (RMS and Min negative amplitudes) over different windows to visualize different shapes and linear to sub-linear trends indicative of the depositional trends and potential presence of sand. Compare these seismic attribute maps (and inversion anomalies) with the maps generated in (5) and with the correlations prepared in (2) above.

7) Integrate above to:

a) Identify below the flooding surfaces potentially sand-prone intervals represented by brightening and dimming (of amplitude) of the seismic events and by the coarsening-up, sharp-based fining-up, or blocky log motifs in the offset wells,

b) Compare with the local and worldwide modern and ancient analogues to predict the depositional environments and likely sand body geometries. Understand the depositional processes and controls on the size and shape of these sand bodies,

c) Reconstruct Gross Depositional Environment (GDE) maps and infer and plot on these maps the depositional geometries (e.g. deltaic distributary channels, lobe, shoreface barrier bars, etc.). The resulting maps show the areal extent of the sand bodies and both the depositional downdip (structurally updip) and lateral shale-out (seal) that provide seal with or without a fault related offset, and

d) Finally, use petrophysical evaluations and core analysis results from the offset wells and from the analogue producing sands to characterize the interpreted and mapped sand body for its reservoir attributes (net sand, N:G, porosity/permeability relationship, etc.).

8) Reservoir and lateral and updip seals in such plays carry significant uncertainty. These elements should, therefore, be adequately risk-evaluated by quantifying the relevant uncertainties such as seismic coverage, accurate log-to-seismic tie and geologic characterization.

Sand and Seal Prediction

The most critical challenge when dealing with the Lower Goru stratigraphic prospects is an accurate prediction of the presence of a medium-to coarse-grained sand body, its reservoir quality and the extent of its lateral and updip shale-out. An overall eastward tilt of the strata or a valid structural closure is the other prerequisite for such prospects. Therefore, in addition to the conventionally made depth structure and fault maps, seismic and well log sequence stratigraphic correlations and seismic attribute maps are essential parts of any Lower Goru Play or prospect evaluation workflow.

Seismic Sequence Stratigraphy

In order to reconstruct the depositional systems, and then the spatial distribution and geometry of the "A", "B" and "C" sands, a sequence stratigraphic framework is required within which sands can be differentiated and facies mapped. For this purpose, an integrated core-, log- and seismic-based sequence stratigraphic correlation has been attempted using the approach of hierarchical bundling of genetic stratigraphic packages and facies tracts (Ahmad, 2003; Ahmad et al., 2000). The sequence stratigraphy and play chart shown in Figure 5 summarizes the stratigraphic framework of the Sembar and Lower Goru sequences, the nomenclature used by others in the industry and the discoveries. Similar undrilled leads and prospects exist and maturing them to drillable state can significantly benefit from the application of sequence stratigraphy tools.

Sembar Shelf Margin and Lower Goru Ramp

Seismic stratigraphic interpretation is based on the regional E-W and NW-SE seismic lines flattened at the Late Jurassic drowning unconformity (near top Chiltan Limestone). The flattened seismic sections show characteristic seismic reflection geometries, truncation patterns, and hierarchy of major bounding surfaces indicative of a regionally widespread Intra-Sembar sequence boundary, a lowstand prograding wedge (LSW) or a base-of-slope prograding lobe (bfc), overlain by a thick abandonment shale apron. The whole Sembar Formation can, therefore, be subdivided into the following genetic stratigraphic units; Sembar-1 (lower sequence), Sembar-2 (the upper sequence), and slope to base-of-slope lowstand wedge referred to as "A" Sequence Lowstand, as shown in Figure 6 and Figure 8.

The maximum progradation of the Sembar-1 sequence is given by the Sembar-1 last offlap break. The Sembar- 2 SB is defined by a downward shift in the coastal onlap below the Sembar-1 shelf margin, by a downlap of the steep post-Sembar-1 reflections onto the low angle Sembar-1 toe and base-of-slope reflectors, and by the onlapping truncations against the slope of the Sembar-2 SB (Figure 6 and Figure 7). The Sembar-2 sequence is characterized by the chaotic to drape and mound like geometries stacked against the slope and base-of-slope of Sembar-1. These are interpreted as turbidite lobes that resulted from a major drop in relative sea level. These submarine fans are overlain by the progradational geometries indicative of shelf-edge deltas with characteristic topsets. The seismic reflections in this package (Sembar-2; Figure 7 and Figure 8) are relatively high angle (oblique) in shape and represent the clinoforms of a westward prograding system. The offlap break of this Sembar-2 wedge exhibit a subtle aggradational trend followed by sub-horizontal topsets (e.g. E-W lines P2091-11 and 92CO-101 through area near Miano- Rehmat fields) which can be interpreted as slight backstepping followed by highstand progradation forming the HST PS set of the Sembar-2 sequence (Figure 7 and Figure 8).

Another forced-regressive wedge of a seismic character similar to the Sembar-2 lowstand wedge is stacked against the Sembar-2 slope and base-of-slope. This wedge is interpreted as the lowstand part of the "A" Sequence (Figure 8). Conventionally, this wedge is mapped as a part of the Sembar Formation. This wedge defines the maximum westward shift of the Sembar shelf margin and acts as a critical interface to restrict the westward sand transport in the overlying sequences as discussed in the sections below.

It is evident from these regional seismic lines that the deposition of the Sembar-2 Sequence and "A" lowstand wedge extended the Sembar-1 shelf westwards and provided a wide regionally extensive ramp on which the Lower Goru deposition took place. On top of the lowstand wedge in the basinal part and on top of the Sembar-2 sequence boundary in the proximal areas towards the east, a regionally widespread positive reflectivity seismic event (toplap surface), is picked as the “A” Sequence flooding surface. On the logs from Miano field and other wells (Figure 11, Wells 5 and 6), this event correlates with the high GR log motif which on the cores can be identified as pyritic and glauconitic pelagic shales and interbedded mudstone-siltstone-sandstones deposited in a deeper water anoxic to anaerobic setting. These shales and basal ravinement erosion related lag can be interpreted as a transgressive surface formed during a major flooding and backstepping above the ramp formed by “A” lowstand wedge and Sembar-2 highstand. The nature of the Sembar-2 sequence (Type-I vs. Type-II) varies from one area to the other and is controlled by local uplift (e.g. thermal doming east of the line in Figure 7) and the magnitude of resulting base level fall (compare Figure 6 and Figure 7).

The Sembar-2 clinoforms toplap (upward) directly against the “A” mfs regional seismic event. Typical deltaic or shoreface topset facies (sorted shoreface or deltaic distributary channel sands) are also missing in the sections drilled/logged. It shows that the Sembar-2 section evident on the seismic lines is a depositional remnant of the fluvio-deltaic progradation from which the uppermost better reservoir quality sands were lost either during the subsequent regression or during transgressive ravinement erosion of the overlying “A” sequence. In view of that, the areas bearing higher accommodation space, such as the distal part of the ramp, should be explored for the shelf edge deltaic topsets and shoreface depositional remnants of the Sembar-2 Sequence.

Lower Goru Sequences

As evident from the regional seismic lines (Figure 6, Figure 7 and Figure 8), large proportion (thickness) of the “A”, “B” and “C” sequences laps out near the Sembar-2 last offlap break (Sembar-2 and “A” lowstand shelf margin). The wells drilled near or west of this shelf margin (e.g. logs from Kandra-1, Gajwaro-1, Khasarwari-1, Duljan- 1 and Shahdadpur-1; Figure 3) and the offlap-downlap geometries from within these Lower Goru sequences also show that the shoreface sands were always restricted to eastward of this shelf margin (Figure 11). The two major breaks in slope of the ramp can be documented near the Sembar-2 shelf margin and where seismic imaging quality allows, these can be mapped out from regional seismic lines throughout the Middle and Lower Indus Platform area. This segment of the ramp (outer ramp) is located between the Sembar-2 shelf margin and the margin built outwards by the “A” lowstand wedge, and can be interpreted as a distally steepened ramp. On the proximal ramp, the “A” and “B” sands deposited thick aggradational stacked parasequences with significant thinning over the distally steepened ramp. The “B” and early “C” regressions probably constitute stacked forced regressive sand wedges, bound by coalesced maximum flooding surfaces and correlative conformities to sequence boundaries. The fluvial tracts feeding into the subsequent “D” forced regressive systems are more likely to have incised much deeper into the underlying “B” highstand on the proximal ramp and thus led to the more focused, massive and prominent shelf edge delta and detached shoreface systems on the distally steepened part of the ramp above or near the Sembar-2 shelf margin.

The distally steepened part of the “A”, “B” and “C” time ramps is critical for accommodating and preserving the shoreface or strandplain sands. Sawan, Miano and recent basinward discoveries in the western parts of the Sinjhoro and Mirpur Khas blocks occur at or near the distally steepened ramp, and the respective Lower Goru discoveries appear on the Creaming Curve as rising limbs (Figure 2). Similarly, the

“A”, “B”, “C” and “D” sequences detached shorelines, forced-regressive shoreface bars, associated rip current and ebb (tidal current or storm) deltas, and forced-regressive deltaic distributary channels/lobes located in a basinward position on this steepened ramp, can deliver the unseen by-passed reserves as predictable from the creaming curve (Figure 2).

High-resolution Well Log Sequence Stratigraphy of the Lower Goru

Seismic stratigraphic implications shown above help document the large-scale controls on sand distribution. In order to resolve the small-scale post-Sembar individual sequences of the Lower Goru megasequence and identify prospective leads in the basin, core-based sedimentology and OH log-based high-resolution sequence stratigraphy is used by the explorationists at OMV (Pakistan). This enables geological (reservoir) characterization of the seismic progrades and associated brightening and dimming of the amplitudes for each sequence (or parasequence set).

Depositional Facies and Characterization of Log Motifs

The lithologic information from mudlogs, petrophysical information from the wireline logs and facies information from cores have all been integrated to characterize the log response and assign log motifs to certain stratal stacking patterns (e.g. progradational, aggradational, etc.) and gross depositional systems (e.g. distributary channel fill sand, deltaic topsets, barrier bar sand, etc.). Facies analysis of the core cut in Lower Goru sequences show that only a limited number of depositional facies make up the reservoir sands. In general, the Lower Goru sequences are comprised of the following ten facies types: (1) Upper Shoreface barrier bar medium- to coarse-grained sands, Upper shoreface tidal channels, Upper shoreface rip current or ebb delta sands (Figure 9), (2) Coarse-grained Deltaic distributary channel and mouthbar sands, (3) Deltaic heterolithics fine- to medium-grained sands, (4) Transgressive tidal channel medium- to coarse-grained sands, (5) Middle Shoreface storm and/or longshore drift reworked fine-grained bioturbated or current-laminated sands, (6) Outer (lower) shoreface to offshore storm generated siltstone-mudstone, (7) Offshore mudstones and pelagic shales, (8) Slope and base-of-slope fine-grained turbidite lobe sandstone-siltstone, (9) Transgressive chamositic medium- to coarse-grained lithoclasts-bearing argillaceous sandstone (Figure 9), and (10) Tansgressive pyrite-glauconite rich dark mudstone. Out of these ten facies, only the Facies types 1, 2, and 4 are proved reservoir facies in the Lower Goru fields such as Kadanwari, Miano, Sawan, Rehmat, Mari Deep, and Sinjhoro and Mirpur Khas block discoveries.

The GR log motif, sedimentologically characterized based on core logs, explains the identification of sequence stratigraphic surfaces on well logs and interpretation of detached shoreface wedges (Figure 10) as seen on high-resolution seismic reflections of the “B” and “C” sand progrades. On the GR logs (and spectral GR logs K, Th and U) from widely separated wells, the transgressive shales (Facies type 10) described in previous section appear as regionally widespread stratigraphic markers of high GR character and relatively lower acoustic impedance (slow DT). These shales overlie reworked lithoclasts-bearing chamositic mudstone lag layer (Facies type 9) of high-GR and high acoustic impedance (fast DT) as shown in Figure 9 and Figure 10. A low-GR coarsening-upward, blocky or fining-upward sand-prone interval occurs further below representing the sands (Facies type 1 and 2). These transgressive events are picked on the seismic as “A”, “B” and “C” Sequence flooding surfaces that overlie the “A”, “B” and “C” sequence boundaries, respectively. The high-GR shales (and high U and Th on HNGS logs) thus define basin-wide genetic stratigraphic packages within the Lower Goru megasequence. Depending on the cemented (tight) or porous nature of the uppermost last regressive sand within each of the “A”, “B” and “C” sequence, the transgressive shale seismic event (mfs) overlies a positive or negative reflectivity event (peak or trough on zero phase seismic data) that on the proximal areas towards the east marks the sequence boundary in each case. In the distally steepened ramp setting, the sequence boundary is located on the bottom of the forced regressive sand which exhibits a sharp-based fining upward log motif. It is recommended to map the flooding surface on seismic and then extract amplitudes in a window below this surface in order to generate geologically meaningful attribute map. Within the sand fairway area, usually the Top “B” and “C” Intervals (Figure 5) are expressed as negative reflectivity event (trough). The seismic response is complicated where a thin transgressive lag of high AI is present above the equally thin porous sand (e.g. Miano and Rehmat fields; Figure 6).

Small-scale Sequences, Parasequences or PS Sets

The high-GR shales (Facies types 9 and 10) also occur at other stratigraphic levels within the “A”, “B” and “C” sequences and overlie fining-up, coarsening-up or blocky GR log motifs. These transgressive shales bound genetic stratigraphic packages comprised of further higher order, smaller scale, multiple coarsening- or fining-upward sequences representing the multiple regressive sand wedges within the “A”, “B” and “C” sequences (Figure 11). Each smaller scale sequence is comprised of the coarsening-upward or blocky sand capped by the ravinement erosion surface in the form of thinner high- GR high-AI litharenite lag layer (Facies type 9), followed by the high-GR transgressive mudstones (Facies type 10) and shaly bottom sets of the following prograding paralics (Facies types 5-7). These smaller scale sequences bounded by the regionally correlative transgressive shales belong to a higher hierarchical level and can be correlated by using the “pattern fitting” method, but more effectively by the facies tract mapping method (Ahmad, 2003; Ahmad et al., 2000) considering the lateral changes in facies, such as downdip shale-outs, lateral shale-out away from the feeder system, updip erosion of the topsets, or sandstone truncations through coastal onlap (Figure 11). These small sequences and sequence sets potentially represent the parasequences and PS sets. Regional seismic stratigraphic interpretations and high resolution correlations indicate a marine transgression occurred above the Sembar and “A” lowstand wedge followed by a regression within the “A” sand. Equilibrium between relative sea level rise and sediment supply produced an aggradational stack of shallow marine and costal plain deposits within the upper “A” sand. The “A” sequence highstand and subsequent “B” forced regressive sandy wedges are widespread and can be found all the way down to the Sembar-2 shelf margin (Figure 6, Figure 7 and Figure 11). Sedimentology of the cores shows wave and tide influence on the shoreface sands with bar and tidal channel sand facies developed throughout the deposition of Lower Goru sequences. Since the “A” sand deposystems are widespread and thick amalgamated sands are present all the way down to the Sembar-2 shelf margin, the lack of lateral seal through facies change and the likely presence of distal thin turbidite sands become a major risk during exploration of stratigraphic plays. On the other hand, the reservoir potential of “A” Sequence sands is highly under-explored in the structural traps.

The “B” Sequence is the time of maximum backstepping within the Lower Goru, with only thin sand-prone depositional systems making it all the way out to the distal ramp across the Sembar-2 shelf margin. In this distal setting, the thin forced regressive detached sand bodies are sandwiched between an overall mud-prone packages and N:G of the entire sequence is overall very low. As a result, the “B” detached sands, where present in basinward setting, are productive reservoirs because of an effective lateral seal due to facies change. The chances of a better fault seal are also higher in this setting due to the thin sand and lower N:G (higher clay smear probability). Strong wave action and longshore drift probably played a significant role in limiting the distribution of sands onto the ramp towards east. A strong fetch and longshore drift can be anticipated from the paleogeographic reconstruction of the Indian plate (Scotese, 2001) which had started to drift away from the Arabian and African plates, leaving an extensive seaway between.

The "C" PS sets show a relatively greater tendency of progradation and building fluvio-deltaic systems as indicated by the progradational seismic reflection geometries on the regional seismic lines (Figure 6 and Figure 7). Sands are relatively thicker (Figure 11) and relatively finer grained, except where the detached shorelines or forced regressive deltas exit. In the areas away from the fluvial input, the grain size is finer and the porosity preserving mechanism of early Fe-chlorite coating around the quartz grains (Figure 9ii) that could preserve porosity-permeability during deep burial is not available. Such Fe-chlorite coatings are only formed where a nearby fresh water input is available to mix fresh water with the marine waters (Krois et al., 1998). Such requirement is met where a detached shoreface or forced-regressive deltaic distributary channels/lobes can be mapped out, e.g. Figure 12 and Well 6 in Figure 11. In this example, the logs exhibit sharp-based fining upward motifs and are characterized as deltaic distributary channel-mouth bars overlain by the shoreface barrier bars.

In general, where present, the "C" detached shoreface systems are more focused and are fed by the feeders that incised deeper than the "B" systems. The main cause of this difference in behavior is the nature of ramp that aggraded preferentially in the eastern part to form a distally steepened ramp during the "B". A drop in the base level below the subtle offlap break led to incision which resulted in the transport of coarse sands onto the distal part of the ramp to build the "C" lowstand wedge (Figure 7 and Figure 12).

The post-"C" forced regressive systems, especially when they occur on the proximal part of the ramp in areas above (or east of) the Sembar-2 shelf margin, are prone to erosion unless concomitant subsidence (enhanced accommodation space) and a prompt subsequent transgression caps the upper shoreface coarse-grained sands with the transgressive shales. In the absence of subsidence and accommodation space, the transgressive ravinement erosion results in total or partial loss of porous-permeable upper shoreface (or topset) reservoir facies. The validity of this mechanism can be demonstrated in Gambat-1, Khushbakht-1, Rehan-1 and few other wells in the Middle Indus Basin where in spite of the presence of seismic progradational geometries, bright amplitudes and inversion anomalies, permeabilities were very low in the middle shoreface facies. Seismic reflections indicate truncation of the flat parts (topsets) of the progrades. Successfully predicting the depositional remnants of the post-"C" forced regressive wedges ("D" Sequence lowstand) poses a major reservoir risk in the area (Martinsen, 2003). The interpretation shown in the Figure 12 provides an example where such a detached shoreface sand wedge was preserved in a basinward position and contains porosities and permeabilities in the range of 20-25% and 100-1000 mD.

Sand Prediction at Prospect Scale

The above mentioned small-scale sequences and their respective log motifs can be related to subtle seismic reflection geometries and spatial variations in seismic attributes such as amplitude and frequency. An example of a forced-regressive deltaic distributary channel-lobe sands and detached upper shoreface sand reservoir from the Middle Indus Basin is given in Figure 12. The stratigraphic wedge shows a gentle rollover and eastward tilt caused by the younger structuring. Sigmoidal seismic reflectors, dimming of the amplitudes and frequency variations in either direction (towards east and west), subtle but clearly evident toplap towards the east (or northeast), offlap break towards the west and a downlap further westward all point to a pronounced downward (depositionally westward) shift in the coastal onlap which forced-out near-shore coarse-grained sands onto the distal shale-outs of the previous progradational systems tract of the “C” Sequence. Availability of ample accommodation space and prolific sand ponding built a pronounced forced-regressive sedimentary wedge (Figure 12). The above example shows that the mapping of coastal onlap and offlap break trend lines, when used in conjunction with the seismic attribute maps, 2D inversion and regional fairway maps based on well log sequence stratigraphic correlations, may help reconstruct the depositional systems and predict areas of sand distribution. A similar sequential reconstruction of the “B” highstand and “C” lowstand sands from the Middle Indus Platform (Figure 13) explains how the coarse-grained upper shoreface reservoir quality facies can downstep in a basinward direction and exhibit facies related lateral and downdip change in porosity which provides the seal. While such detached shoreface wedges offer excellent exploration opportunities, it is also clear how a well can easily miss the reservoir quality facies if an integrated workflow is not followed to predict and map the sand and characterize its reservoir quality.

Summary – Sand and Seal Prediction Criteria

Based on the discussion given above, the prediction criteria should be based on the following attributes and uncertainties (risks) for successful sand and seal prediction at prospect scale within the Lower Goru “A”, “B”, “C” and “D” sequences:

1) The presence of detached shoreline or shoreface indicated by an abrupt west/northwestward shift of coastal onlap and offlap-break on the seismic and by the presence of sharp-based sandy log motifs in laterally correlative offset wells.

2) The seismic amplitude and inversion anomaly, potentially indicative of porous reservoir, must be located near or eastward of the shelf margin built by the Sembar-2 and “A” lowstand wedge. The shelf morphology can be best inferred by flattening the seismic lines on the top Chiltan drowning unconformity.

3) Subtle thickness anomaly eastward of the offlap break of a seismic event within the individual PS sets of “A”, “B”, “C” and “D” sequences indicates the presence of reservoir quality sand.

4) Proximity to the feeder (fluvial input) allowing coarse sand emplacement and fresh-to-saline water mixing to form Fe-Chlorite coatings around the quartz grains is a necessity for the presence of porosity and permeability in the sand. This early cement preserves the porosity during deep burial.

5) Depositional remnants of the “D” and “C” sequence sands should be documented by locating areas where the combination of accommodation space and transgressive erosional processes (immediately after the shoreface sand deposition) are such that the minimal shoreface erosion and shoreface reworking of the upper shoreface sands takes place.

6) The chance of lateral seal is greater when the anomaly is located in a relatively basinward position on the distally steepened part of the ramp over the Sembar-2 shelf margin. In this distally steepened ramp setting, the individual PS sets of the sequences “C” and “D” (“B” and

"C" intervals, respectively) are more likely to have lower N:G, with the detached shoreface sandwiched between the thicker mud-prone offshore facies. In this distal ramp setting, the risk of fault-related breaching and uncertain lateral entrapment due to laterally coalescing sand bodies from neighboring feeder systems is also minimal.

7) The presence of depositionally distal thin turbidite or storm sands toward the west (structurally updip), especially in the case of "A" Sequence prospects, should be carefully documented. These sands may act as thief sand and add to the trap breaching risk. In westward tilted blocks, the thief sand risk is even greater due to the likely presence of feeder system related thin sands in depositionally proximal direction (toward the east).

These criteria of predicting seal, trap and reservoir sands have helped in the past and can help in the future to tap the remaining hydrocarbon potential associated with the detached regressive and forced-regressive strandplain, shoreface barrier bar and deltaic distributary channel/lobe reservoirs as indicated by the Creaming Curve of the Lower Goru Play.

Eastward tilt, eastward onlap against the fines, and westward and lateral facies changes form subtle stratigraphic traps that offer high-risk high-reward exploration opportunities. The sealing risks are mitigated by documenting the presence of sand-prone facies in a relatively basinward (westernmost) position over the Sembar-2 shelf margin and "A" lowstand wedge where the individual sequences "A", "B", "C" and "D" more likely exhibit low N:G with detached shoreface sandwiched between thick shales. In this scenario, the risk of fault-related breaching and lateral entrapment risk due to laterally coalescing sand bodies from the neighboring feeder systems is minimal. In structural traps, precise sand prediction can help find an enormous upside through successful sand and reservoir quality prediction.

Acknowledgements

We acknowledge the permission granted by OMV (Pakistan) management and JV partners to publish this paper. We also acknowledge the discussions and feedback received from our JV partners ENI-Pakistan, PPL, OGDCL and GHPL during our technical workshops. Mr. Nusrat Kamal Siddiqui reviewed the paper and we are grateful to him for his comments and suggestions.

References

Ahmad, N., 2003, Facies tract mapping technique, a sequence stratigraphic tool: Case study of lowstand Carper Sandstone Play, Lower Carboniferous of Eastern Illinois Basin, North America: ATC 2003 Conference Proceedings, p. 47-66.

Ahmad, N., B.D. Keith, and P.R. Vail, 2000, Deposition, sequence stratigraphy and hydrocarbon potential of a sandy debris flow and turbidite in an interior cratonic ramp setting, Middle Mississippian Borden Group, eastern Illinois Basin, USA: AAPG Bulletin, v. 84/13.

DGPC, 2003, Energy YearBook 2003, Ministry of Petroleum and Natural Resources, Pakistan.

Dominguez, J.M.L., L. Martin, and A.P. Bittencourt, 1987, Sea-level history and Quaternary evolution of beach-ridge plains, ESE Brazilian coast: SEPM Special Pub 41, p.115-127.

I.E.D.S., 1995, A sequence stratigraphic study of the Lower Goru – Sembar Formations of Lower and Middle Indus Basins of Pakistan and Rajasthan: Multiclient study.

Khan, J.M., M.A. Moghal, and M.A. Jamil, 1999, Evolution of shelf margin and distribution of reservoir facies in Early Cretaceous of Central Indus Basin – Pakistan: PAPG-SPE ATC 1999, p. 1-23.

Krois, P., T. Mahmood, and G. Milan, 1998, Miano Field: A case history of model driven exploration: Pakistan Petroleum Convention 98, Islamabad, Pakistan.

Martinsen, R.S., 2003, Depositional remnants: Examples from the Western Interior Cretaceous basin of North America: AAPG Bulletin, v. 87/12, p. 1883-1909.

Milan, G., and M. Rodgers, 1993, Stratigraphic evolution and play possibilities in the Middle Indus Area, Pakistan: Presented at SPE Pakistan Seminar, Islamabad, January 19, 1993.

Scotese, C.R., 2001, Atlas of Earth History, PALEOMAP Project, Arlington, Texas, 52 p.

Snedden, J.W., J.F. Sarg, and X. Ying, 2003, Exploration play analysis from a sequence stratigraphic perspective: AAPG Search and Discovery Article #40079. Web accessed 9 April 2012.
http://www.searchanddiscovery.com/documents/snedden/index.htm

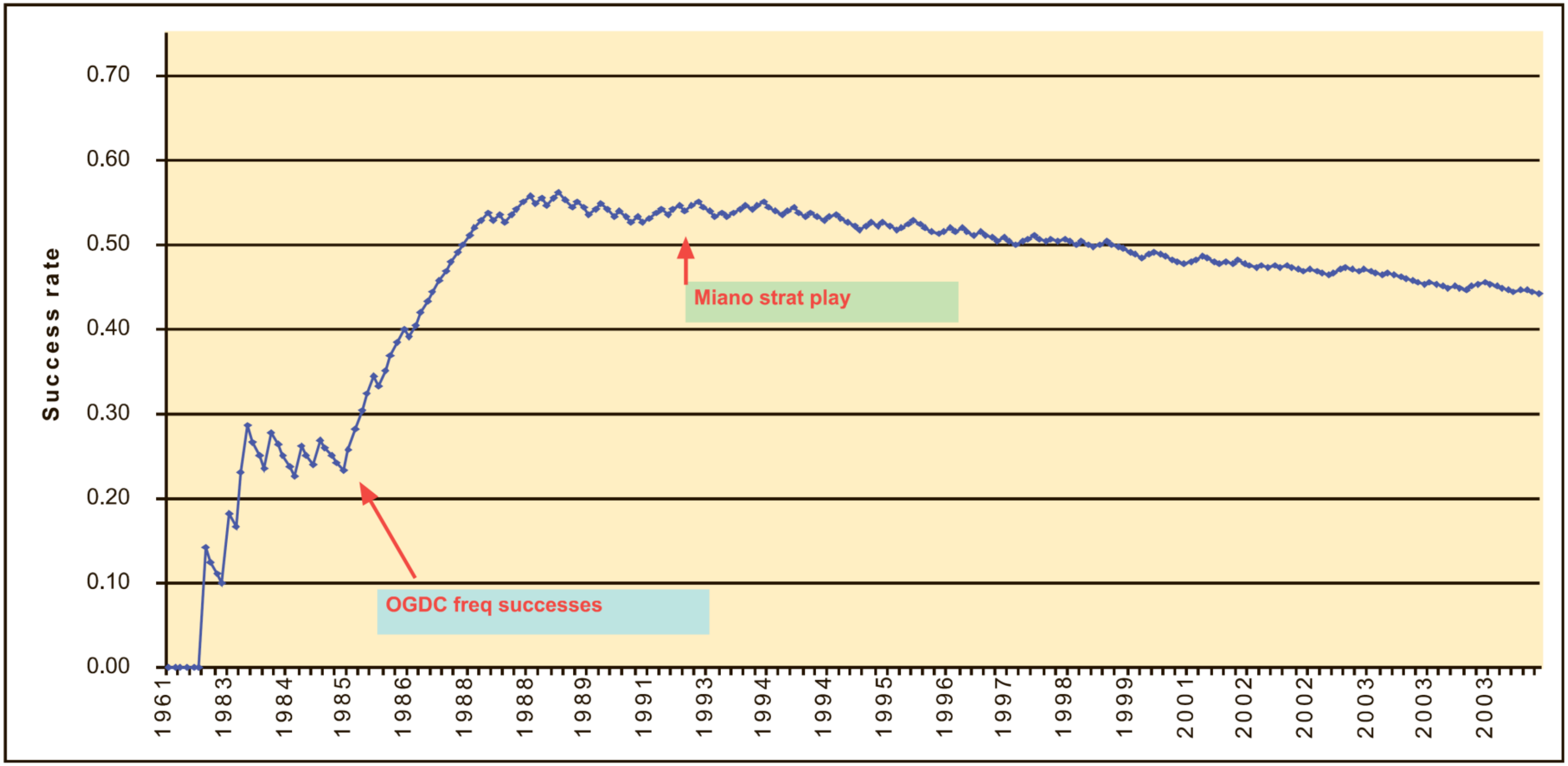

Figure 1. History of exploration success in Lower Goru Play (indicative of Pg).

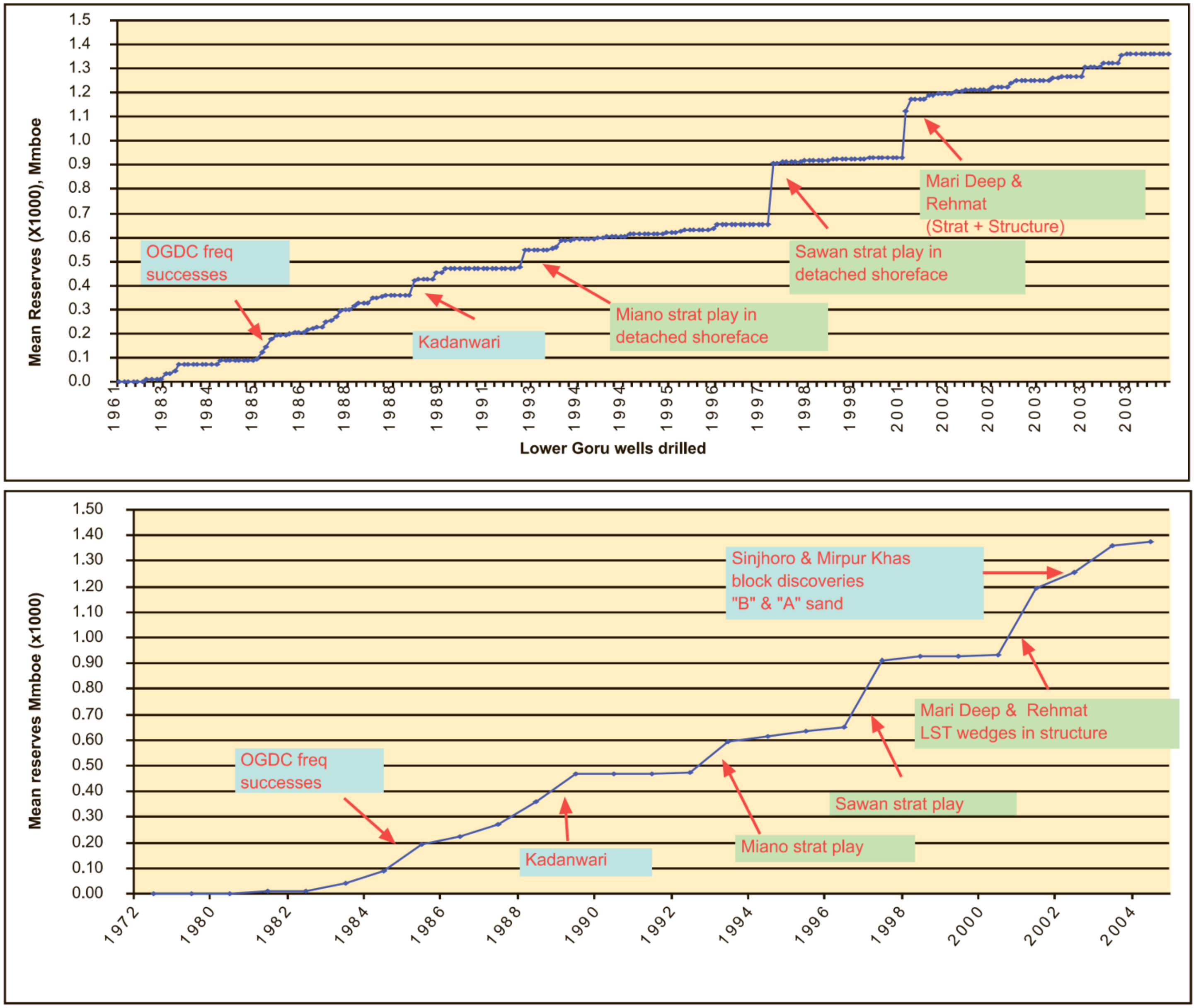

Figure 2. Creaming curve of the Lower Goru Play in Middle and Lower Indus Platform. Top: Each exploratory well plotted as a dot with year on x-axis. Bottom: Cumulative reserves added by exploratory wells each year. Source: DGPC Energy Yearbook 2000, 2002, 2003, and authors' own estimates of the 2003-2004 discoveries.

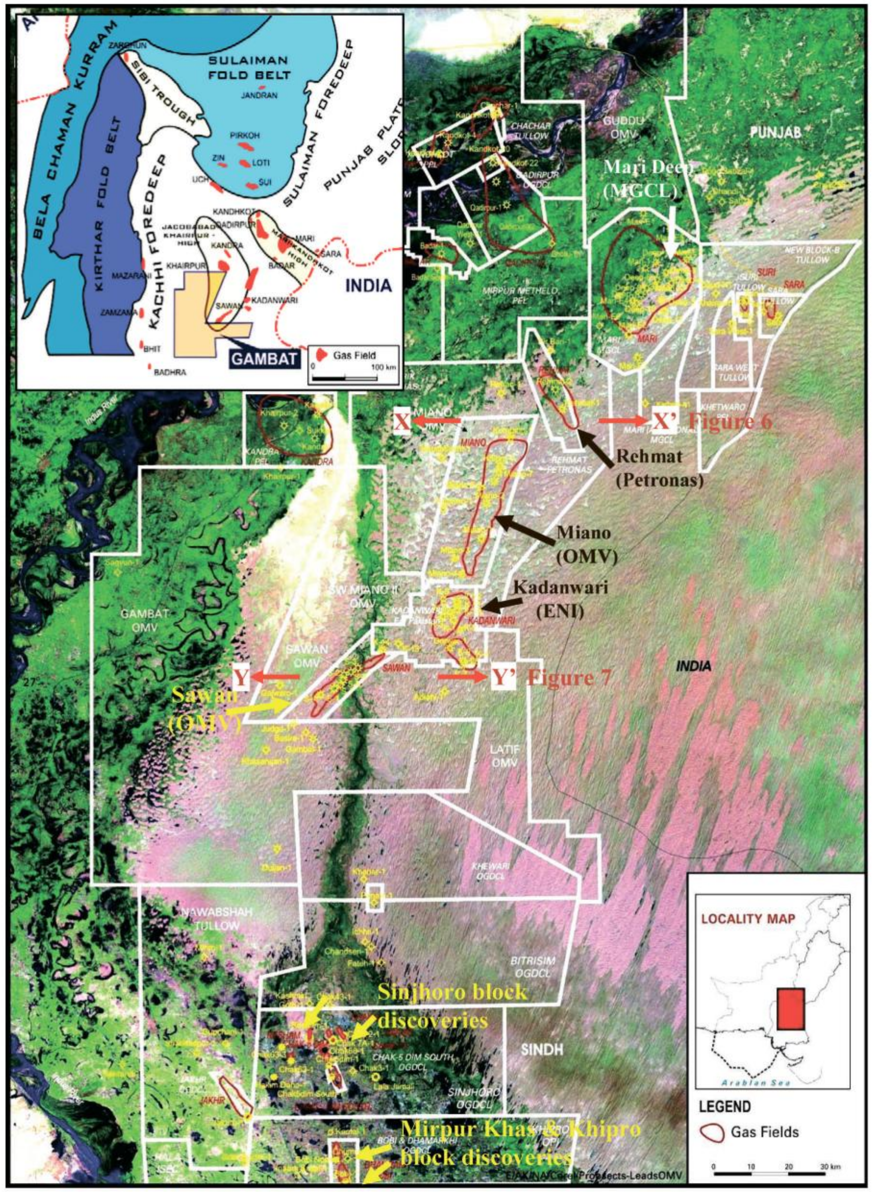

Figure 3. Map of the study area showing the exploration blocks, fields and exploratory wells in the area.

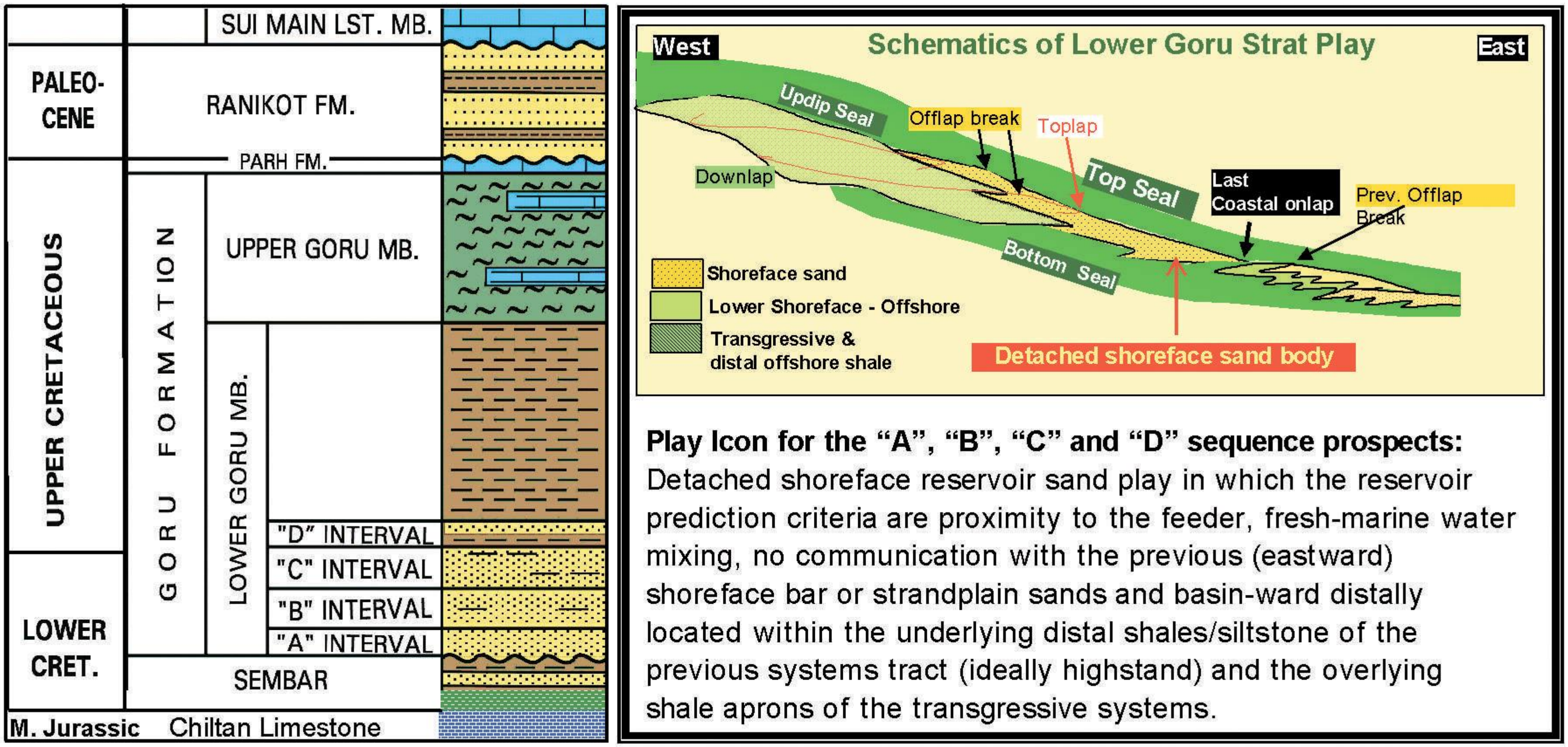

Figure 4. Stratigraphic column on the left showing position of the Lower Goru prospective sands within the regional stratigraphic framework. Play icon on the right showing how the prospects generally work in this play.

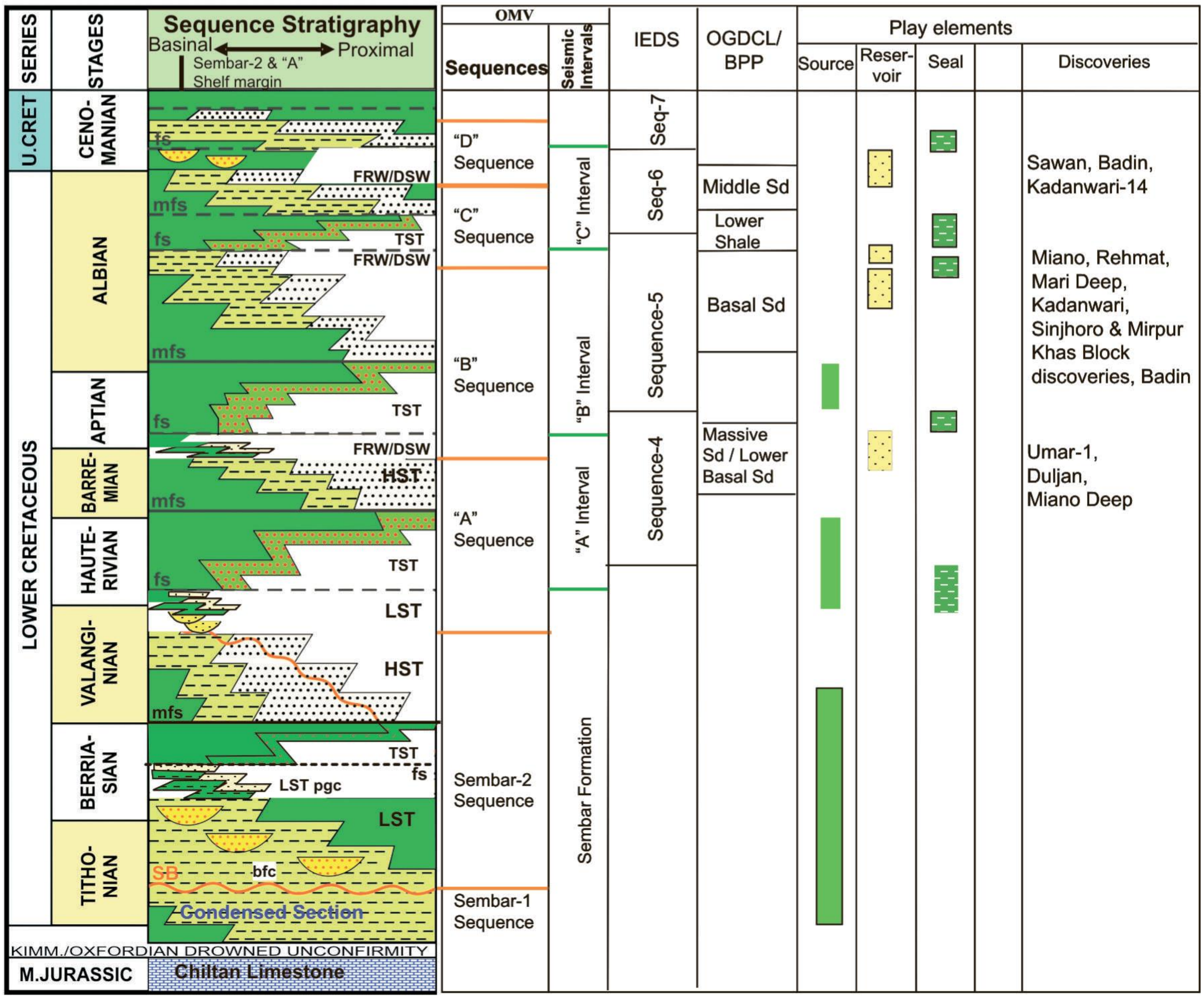

Figure 5. Sequence stratigraphy and play summary chart of the Sembar and Lower Goru sequences, along with the stratigraphic nomenclature used in the industry. For explanation of abbreviations, refer to Figure 8.

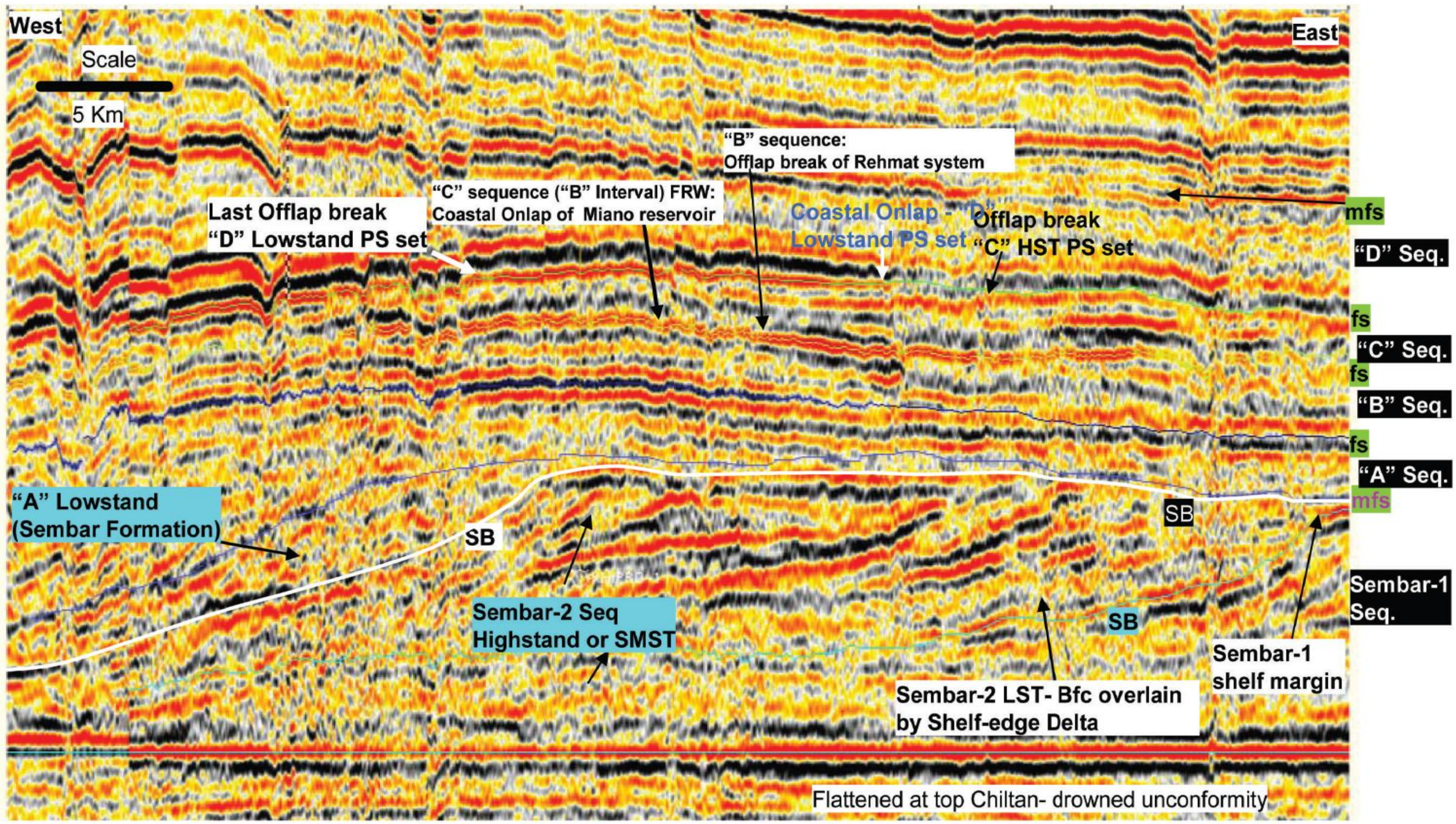

Figure 6. Seismic stratigraphic interpretation of a nearly E-W regional seismic line from the area near Miano and Rehmat fields (see Figure 3 for approximate location).

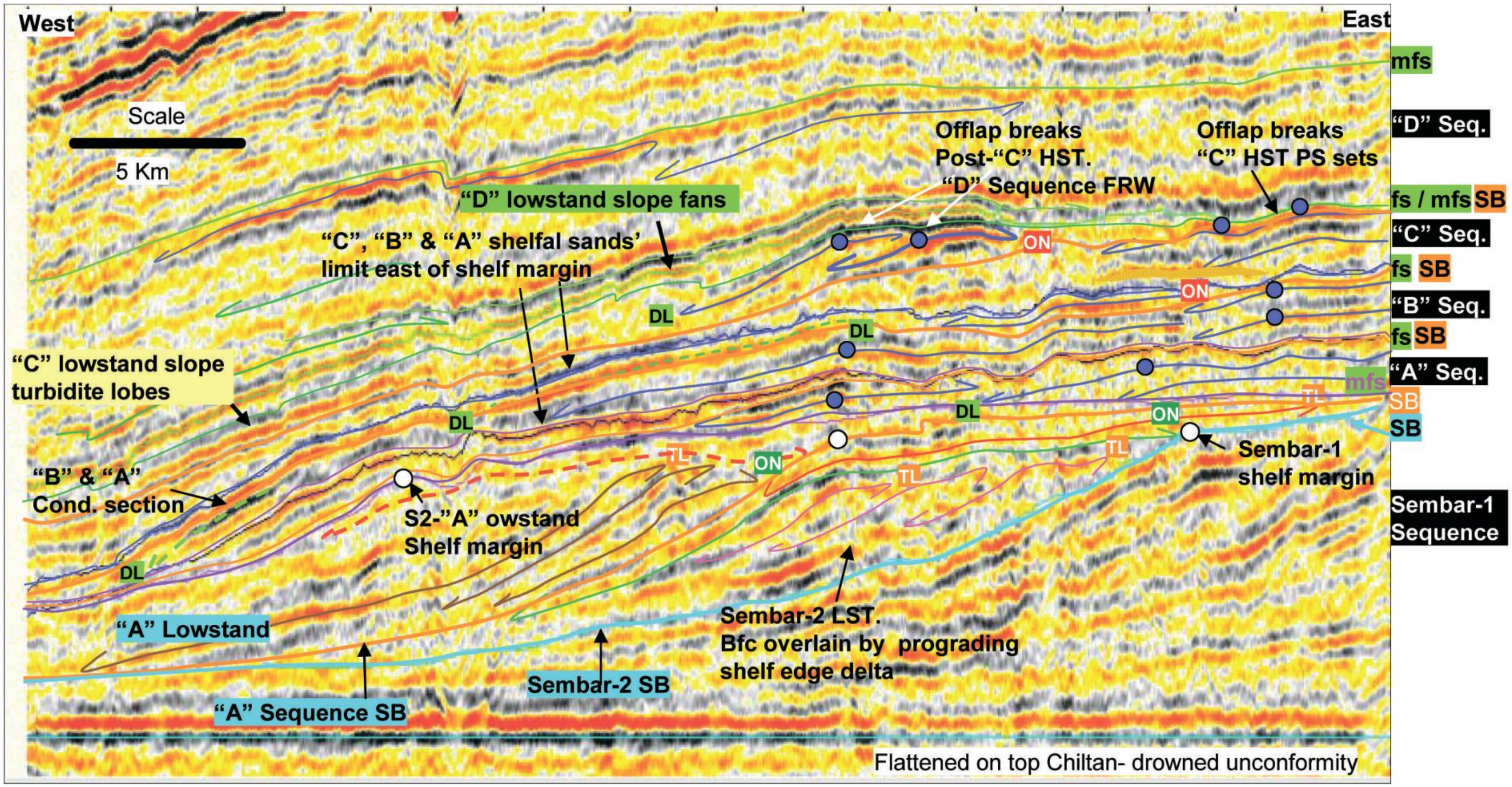

Figure 7. Seismic stratigraphic interpretation of a nearly E-W regional seismic line from the area near Sawan and Kadanwari fields (see Figure 3 for approximate location). In this case, the base level fall is greater than in the north (Miano-Rehmat area) and south (Khewari-Gambat block area), probably due to uplift in the east. As a result, pronounced shelf edge delta and slope and basin floor fans/lobes are developed during Sembar-2 and "A" lowstand times with "A" sequence flooding marking a major post-Sembar backstepping. For abbreviations, refer to Figure 8.

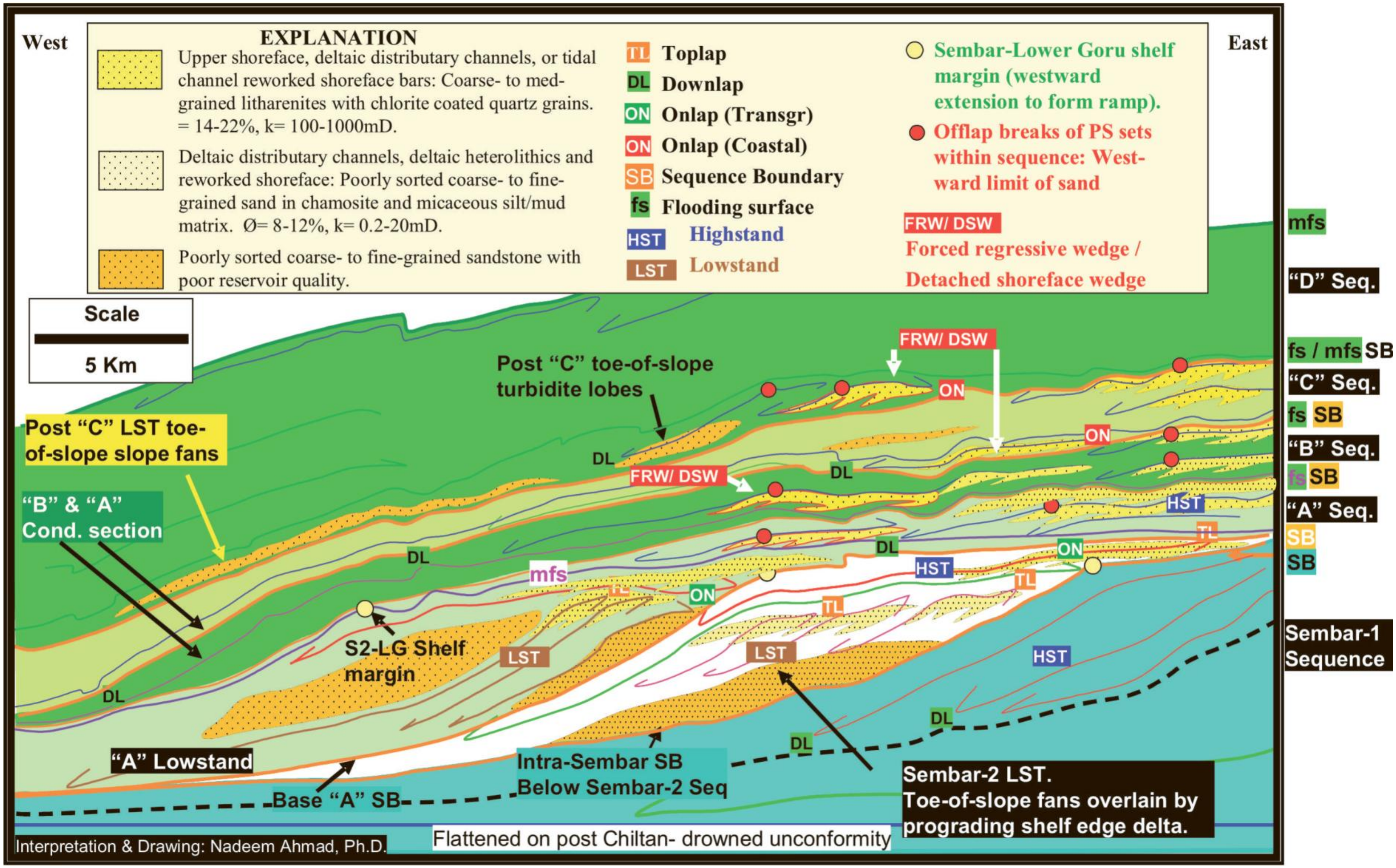

Figure 8a. Sequence stratigraphic framework and temporal and spatial relationships of the interpreted sand bodies based on Figure 7 seismic reflection geometries, truncation patterns, seismic amplitudes as integrated with the well log correlations (Figure 11) and comparisons with the modern and ancient depositional analogues. An alternate interpretation of the Sembar-2 and "A" lowstand wedges is given in Figure 8b.

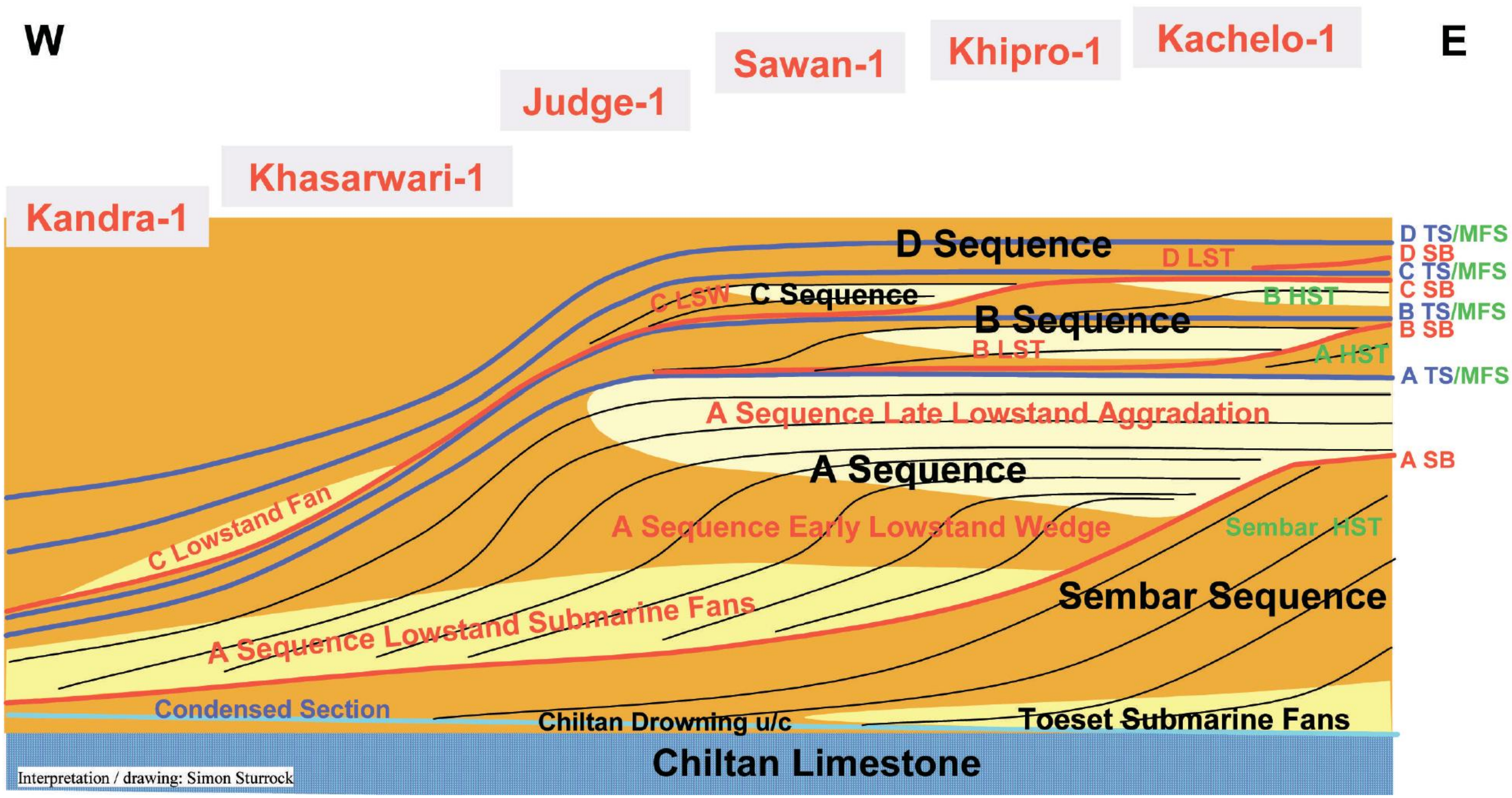

Figure 8b. An alternate sequence stratigraphic framework for the Sembar-Lower Goru formations to that given in Figure 8a, with the Sembar-2 and "A" progradational shelf margin wedges interpreted as "A" Sequence early lowstand wedge and "A" Sequence late lowstand aggradation.

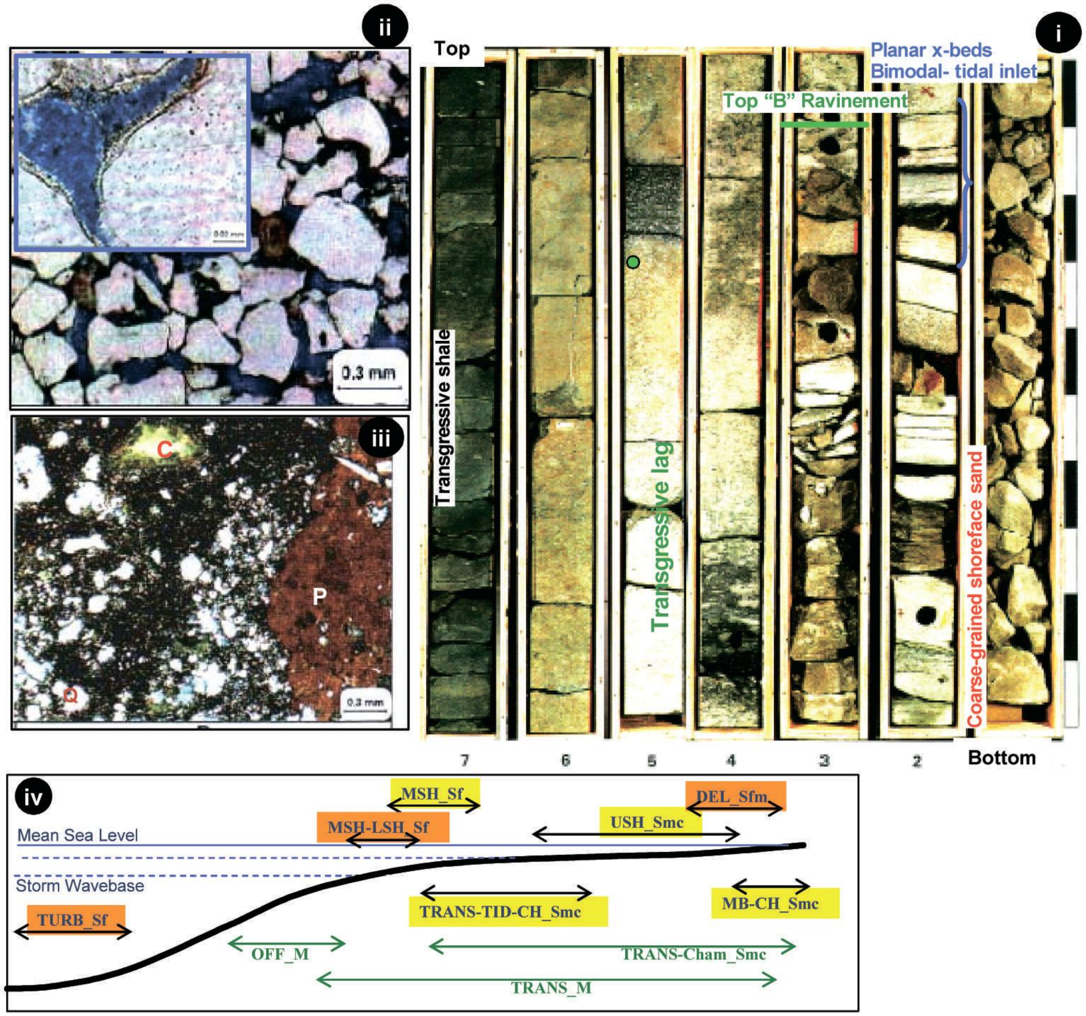

Figure 9. (i) Core photos showing a coarse-grained cross-bedded shoreface sandstone in wave-dominated tidal inlet/ barrier bar setting overlain by the transgressive lag through a ravinement surface (example from a "B" reservoir sand). Scale bar = 1m.
(ii) Thin-section of the shoreface sand showing quartz grains (grey) and pore-filling chamosite (brown) and pore lining. Fe-chlorite which preserves porosity during late burial.
(iii) Thin-section from transgressive lag showing medium-grained, strongly Fe-carbonate cemented chamositic lag formed by ravinement erosion during transgression above the shoreface sand. Phosphate concretions (P), Chamosite (C) and Quartz grains (Q).
(iv) Facies types generally encountered within the Lower Goru and schematic sketch of their depositional position.

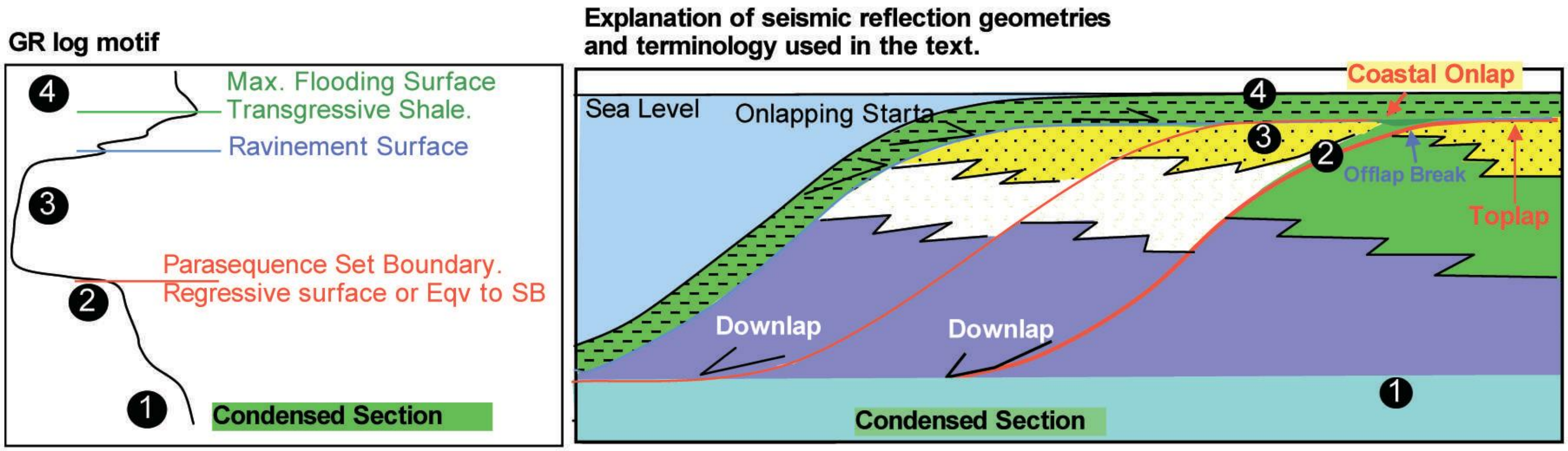

Figure 10. Interpreted Gamma Ray log motif after being calibrated with the core-based sedimentology log. Unit 3 is the sharp-based detached shoreface (probably the tidal channel reworked shoreface barrier bar). For details, refer to Figure 8 and Figure 12.

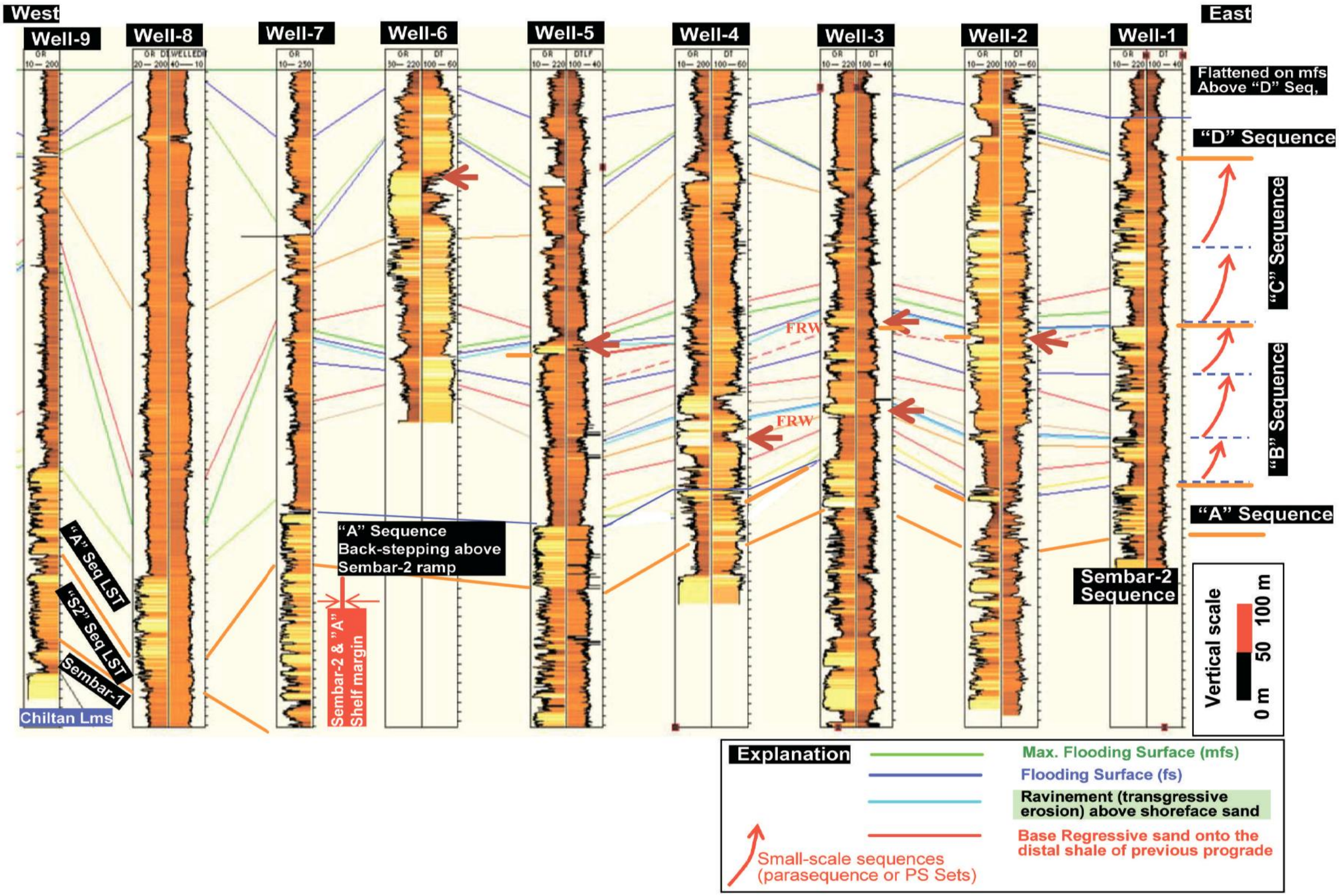

Figure 11. High-resolution well-log correlation showing the Lower Goru sequences and the stratigraphic position of detached shoreface sand wedges (red arrows) comprised of coarse-grained porous (on DT log) sands. Location of wells: Well-1 and -2 fall in purple fairway in Figure 13, Wells-3 and -4 fall in blue fairway, Wells-5 and -6 fall in green fairway, whereas the Wells-7 to -9 occur on the slope and base-of-slope of the Sembar-2 and "A" shelf. For comparison with regional seismic sequence stratigraphic framework, refer to Figure 8.

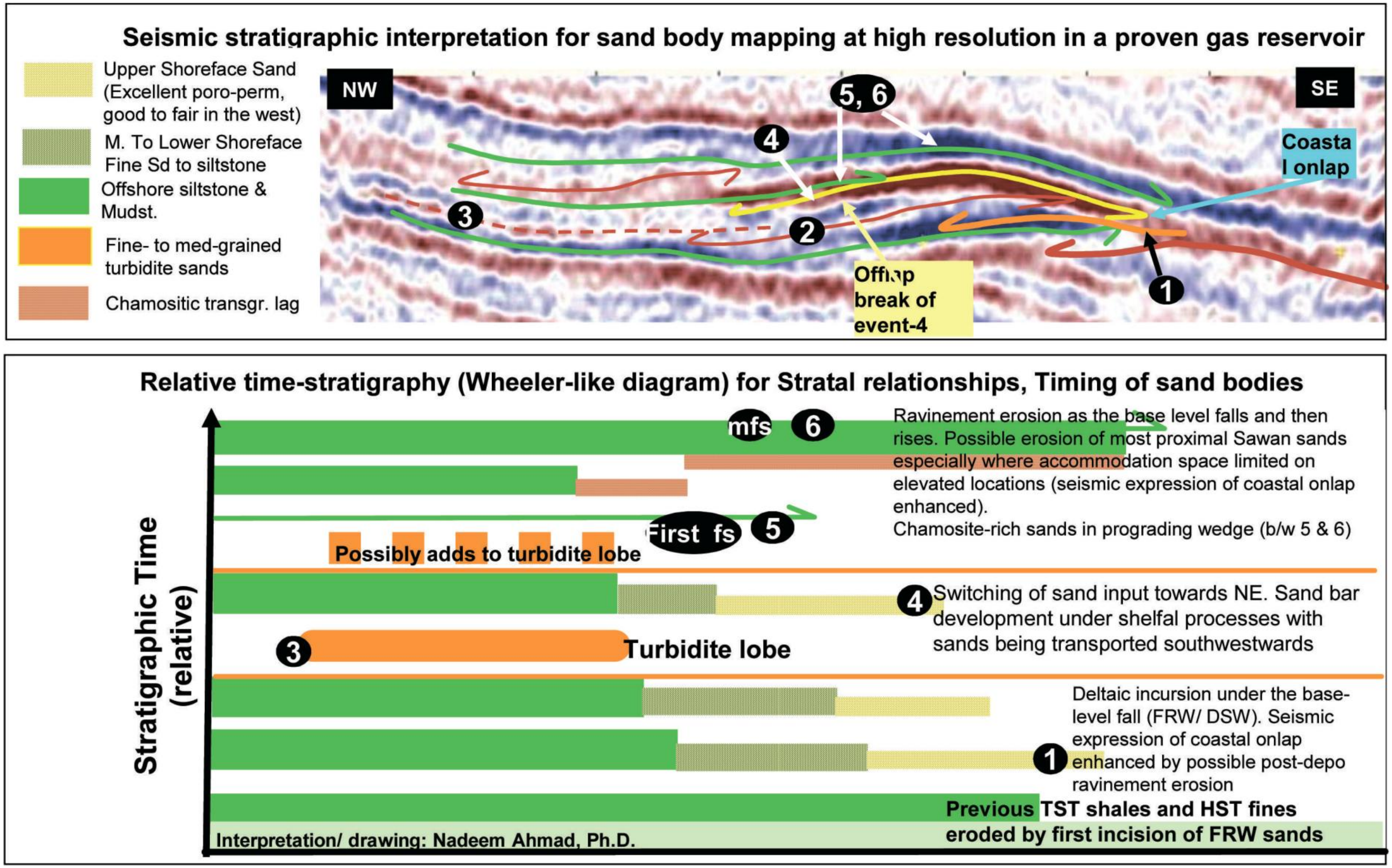

Figure 12. Example of sand prediction and prediction of stratigraphic continuity using high-resolution seismic stratigraphy.

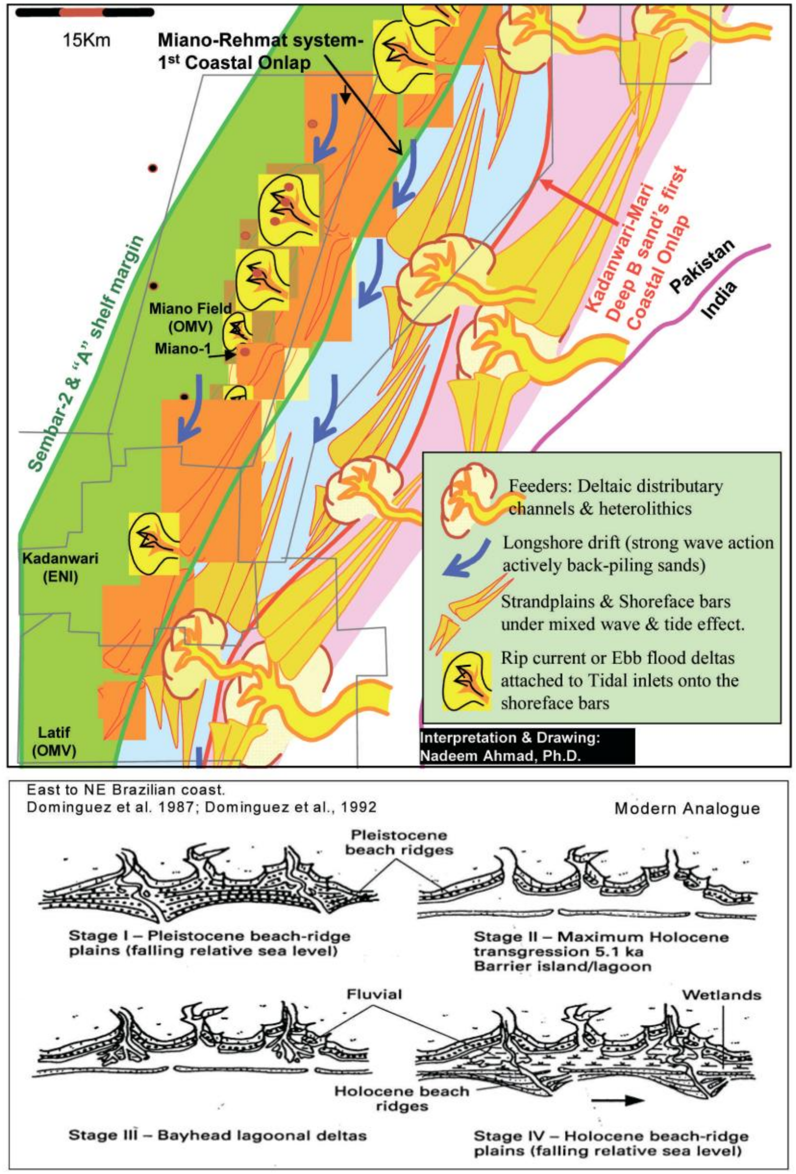

Figure 13. "B" sand fairway map along with the architectural elements of the depositional systems predicted by using the integrated workflow as discussed in the text. Westward down-stepping shoreface facies belts and their shifting coastal onlaps are also evident on the logs shown in Figure 11 modern analogue (Dominguez et al., 1987).