Evaluation of a Distinct Sub-Play for Enhanced Exploration in an Emerging Petroleum Province, Bannu-Kohat Sub-Basin, Pakistan*

Nadeem Ahmad[1] and Moin Raza Khan[2]

Search and Discovery Article #10391 (2012)
Posted February 27, 2012

*Adapted from oral presentation at AAPG International Conference and Exhibition, Milan, Italy, October 23-26, 2011

[1]Pakistan Petroleum Ltd., Islamabad, Pakistan (AHNadeem@ppl.com.pk)
[2]Pakistan Petroleum Ltd., Karachi, Pakistan

Abstract

A prolific petroleum province, the Bannu-Kohat sub-basin, has recently emerged in the northwestern foreland basin of the Himalayan fold-and-thrust belt in Pakistan, since first discovery at Chanda only a decade ago. Gas and oil occur in multiple reservoirs. Although new prospective structures continue to emerge, ambiguity surrounds the definition of plays as distinct reservoir-seal pairs and geological inter-dependencies. Practical implications are: resources under-estimated, misleading success/failure analysis of wells, and ambiguous wellsite geology decisions. This is an attempt to define the key plays and document their sub-plays/part-plays within a sequence stratigraphic framework built through an integration of outcrop, wireline log and seismic data. Key risk elements have been assessed to draw Common Risk Segment (CRS) maps and prospectivity corridors.

The Jurassic-Eocene sedimentary succession of interest was deposited on the northwestern margin of the Indian plate in a restricted to shelfal marine setting in the form of six mega-sequences. The Lower Cretaceous Chichali-Lumshiwal sequence, Upper Cretaceous Kawagarh sequence, Paleocene Hangu-Lockhart sequence, and Paleocene-Eocene Patala-Panoba-MamiKhel mega-sequence contain the reservoirs and seals of the key play of interest, the Lumshiwal-Hangu-Lockhart play. Reservoirs are charged through juxtaposition against the prolific Upper Paleocene Patala marine shale source. Regionally extensive thick Panoba-Mamikhel shales and evaporites cap and laterally seal the reservoirs in highly tectonized structural culminations to make the play work. The Lumshiwal reservoir is a fluvio-deltaic to strandplain shoreface sandstone and correlates with the Lower Goru, a prolific play in the south. Stacked Lumshiwal-Hangu sandstones with dual porosity (matrix-fracture) provide key storage space. Overlying tight but fractured Lockhart Limestone serve to drain the hydrocarbons.

Regional correlation and a Wheeler diagram reveal a Shelf Margin Systems Tract in the form of calcareous shale and marly limestone deposited further basin-wards from the Lumshiwal coastal plains. Consequently, three stacked reservoir formations are split in the northwest to provide two sub-plays, Lumshiwal and Hangu-Lockhart, as also confirmed by the discoveries like Shekhan-1. Therefore, independent resource assessment of the two is essential. Wellsite decisions to drill deeper or abandon should also be made accordingly.

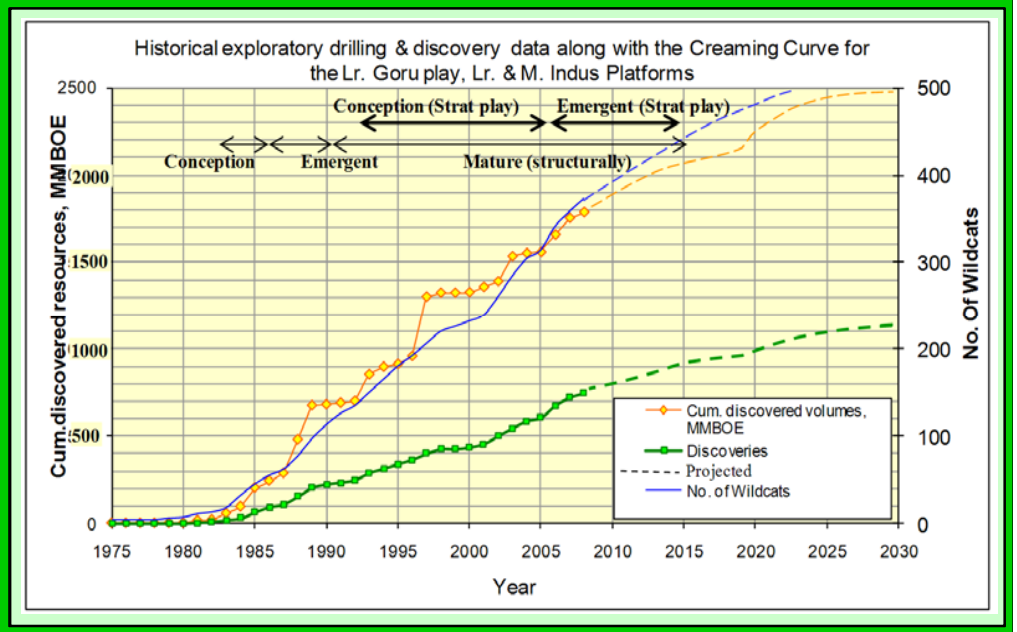
Evaluation of a Distinct Sub-Play for Enhanced Exploration in an Emerging Petroleum Province, Bannu-Kohat Sub-Basin of Upper Indus Basin, Pakistan

Nadeem Ahmad, Ph.D.
Senior Manager Exploration
(QA, Portfolio, Studies)

and

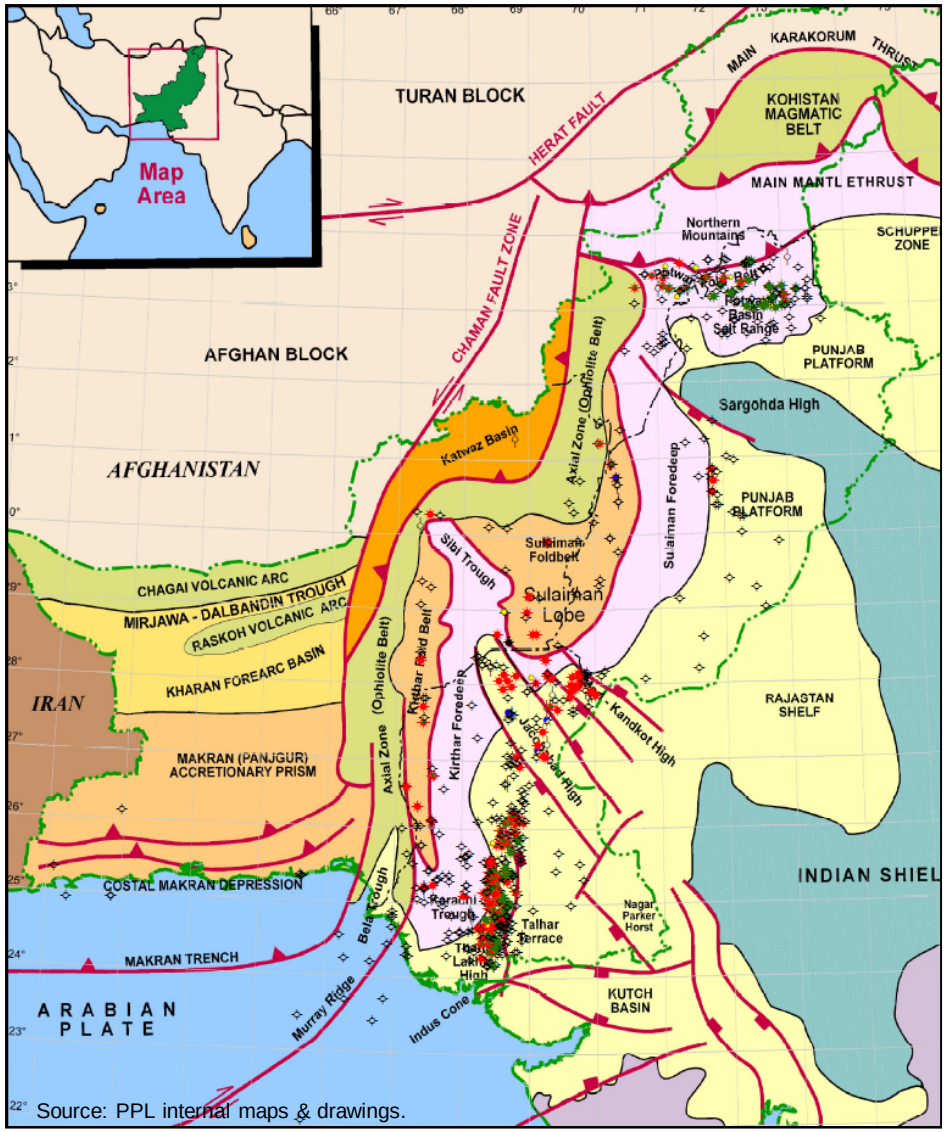
Moin Raza Khan
General Manager Exploration

Pakistan Petroleum Limited



Emerging Petroleum Province - Context

- Series of Fold & Thrust belts, Foredeeps. Bannu-Kohat sub-Basin, an emerging prolific petroleum province
- Gas, Condensate, oil at multiple levels
- Creaming curve exhibits bullish trend
- Although new prospective structures continue to emerge, yet ambiguity surrounds the definition of plays as distinct reservoir-seal pairs. Unclear geological inter-dependencies
- Implications for Operations decisions, capturing full-range of possibilities, inaccurate reserves estimates, misleading success/ failure analyses
- Exploration performance not optimized



Source: PPL internal maps & drawings.

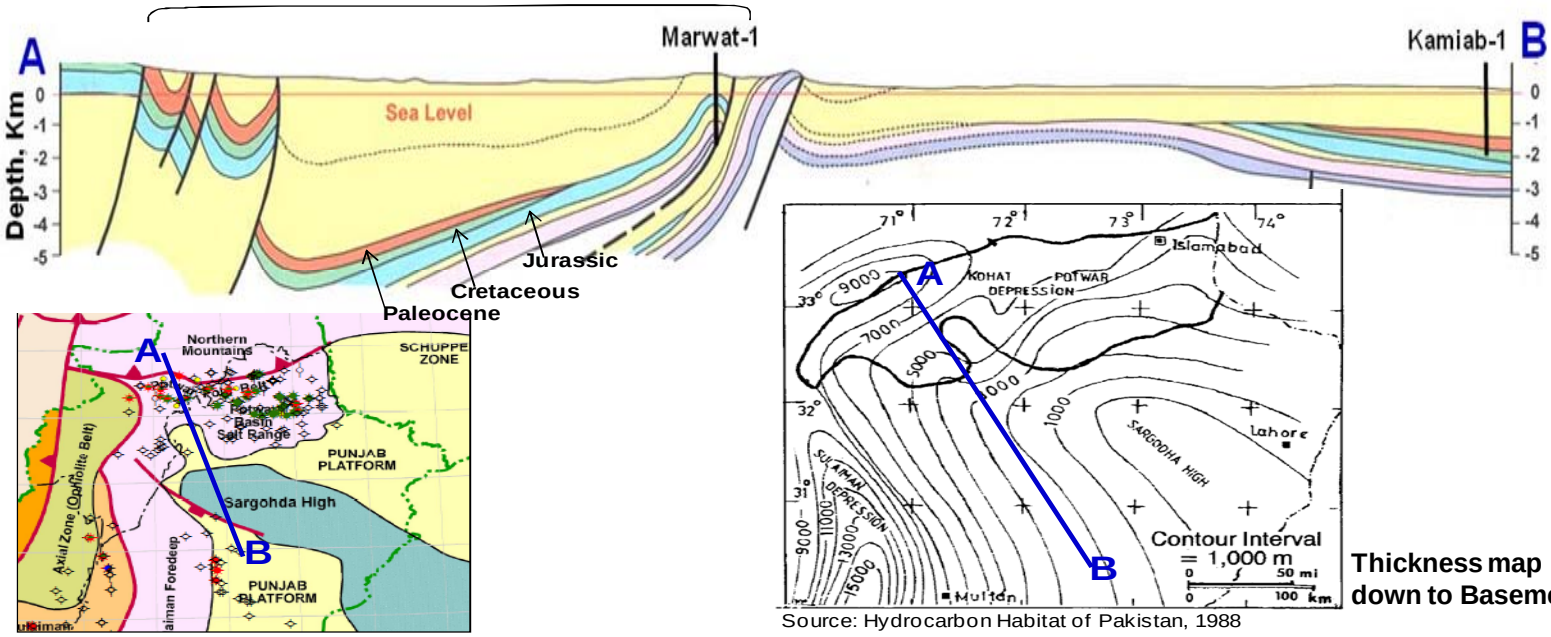
Emerging Petroleum Province – Introduction

OUTLINE

- New Petroleum Province – Introduction to the Region
- Context: Exploration Funnel. Basin- and Play-entry Decisions.
- Stratigraphic and Tectonic Framework
- Exploration History, Play and Field Statistics
- Dataset and Methodology, Scope of Work
- Sequence Stratigraphy as Predictive Tool to Identify and Define Plays
- Facies analysis, Integration of logs, outcrops, seismic. Facies maps, Gross Depositional Environment (GDE) maps of Reservoir & Seal
- Geoseismic sections and High-resolution Sequence Stratigraphy
- Learnings from the Lower & Middle Indus basin – extension of Lr. Goru play!
- Exploration Way forward and Potential

Tectonic Framework

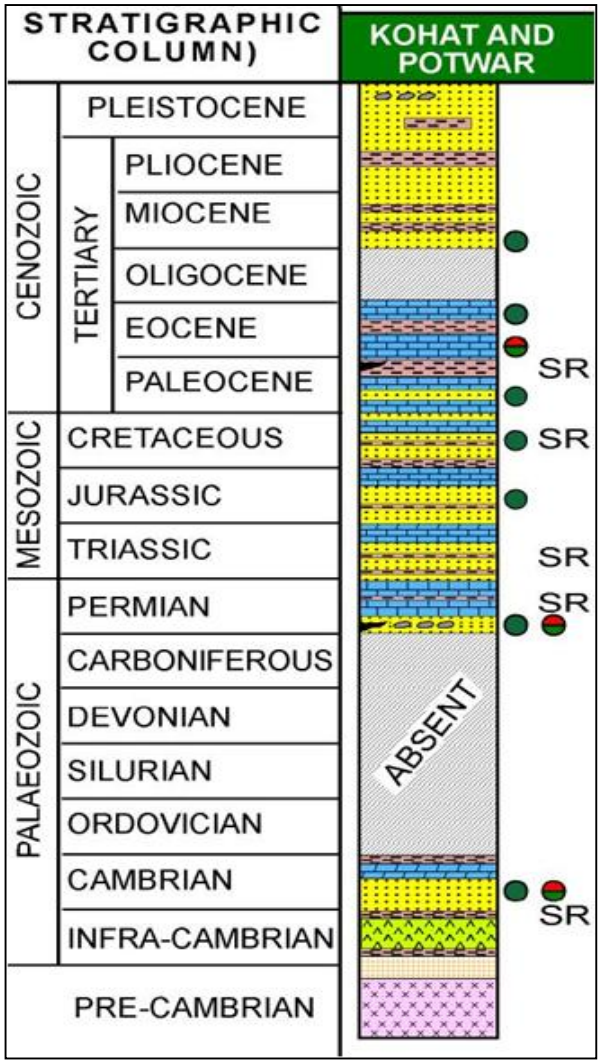
- Upper Indus Basin: Bannu-Kohat sub-Basin
  - Fold and Thrust Belt evolved as Indian plate docked into Eurasian plate.
  - South verging Frontal thrusts bounding the foredeep sub-basins in the south.
  - Regional detachments: Infra-Cambrian evaporites and Oligocene-Miocene mollase in Potwar, whereas in Bannu Kohat thick Eocene plastic shale and evaporites host key detachments in Bannu-Kohat
  - Docking initiated in Eocene, complete by Oligocene. Foredeep basin fill: Miocene-Pliocene

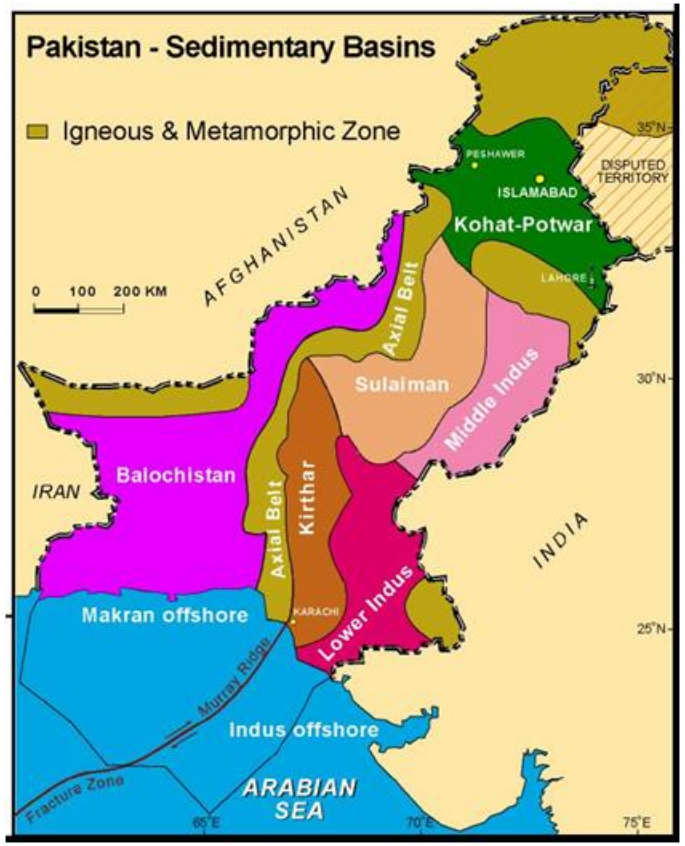


Thickness map down to Basement

Source: Hydrocarbon Habitat of Pakistan, 1988

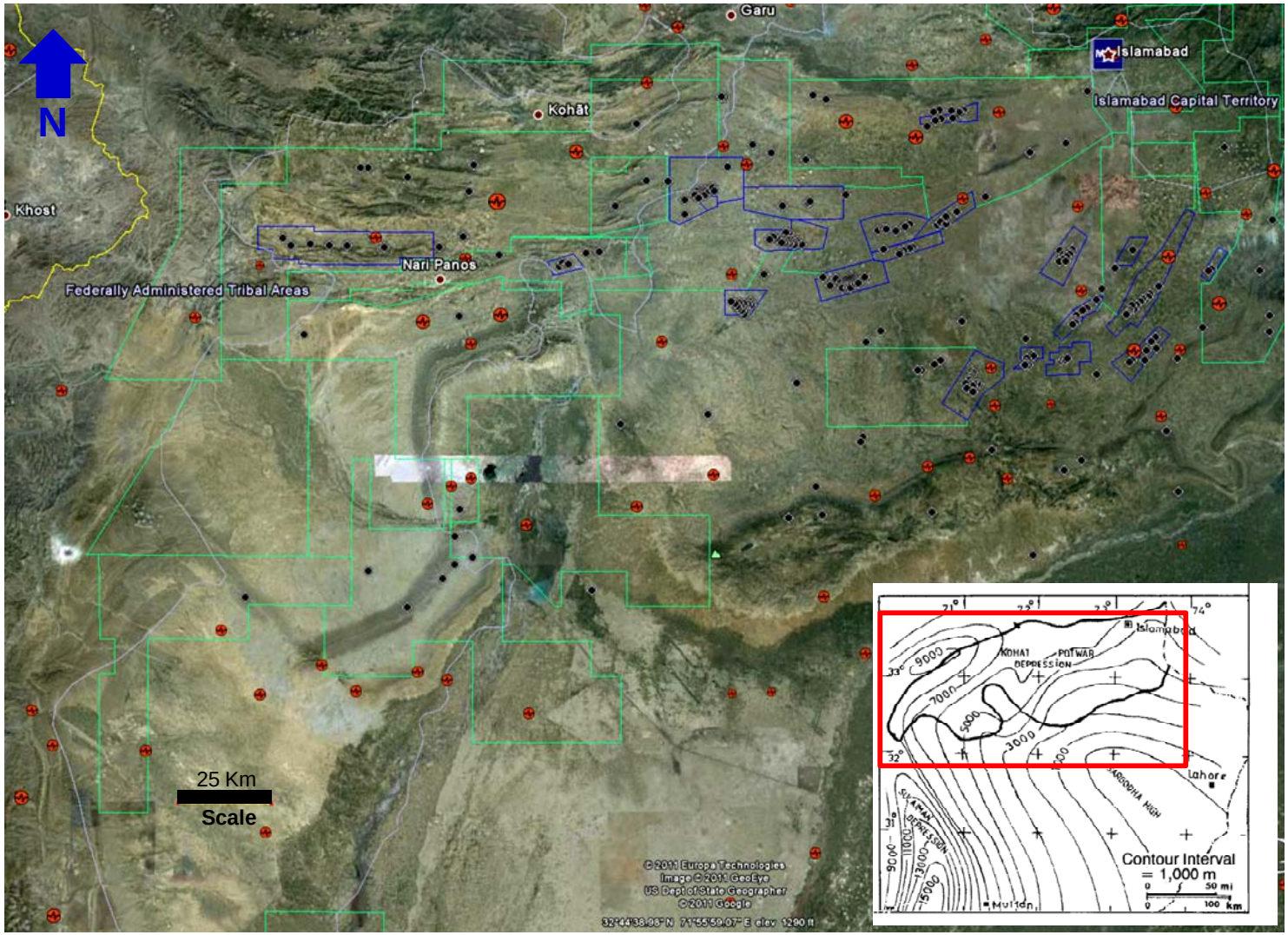
Stratigraphic Framework



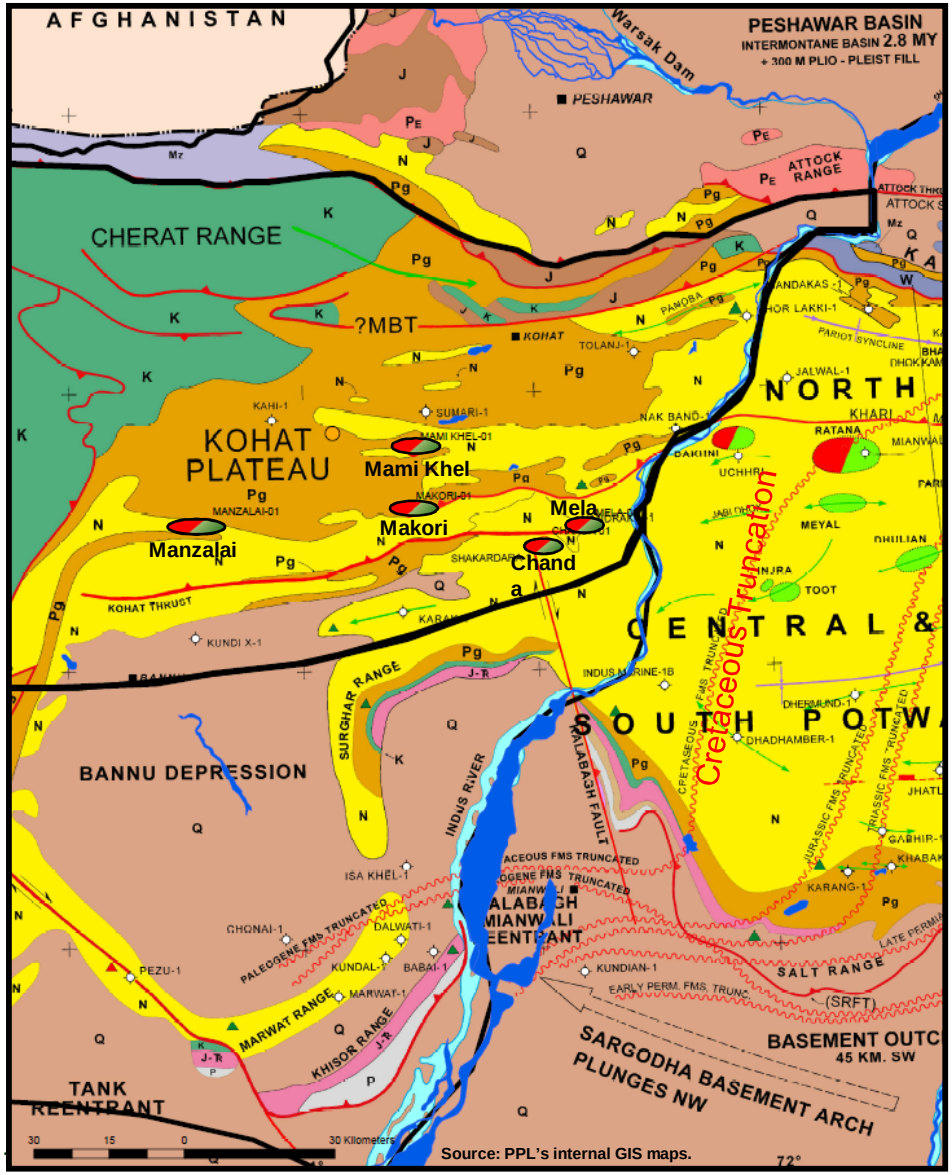


Source: PPL internal maps & drawings.

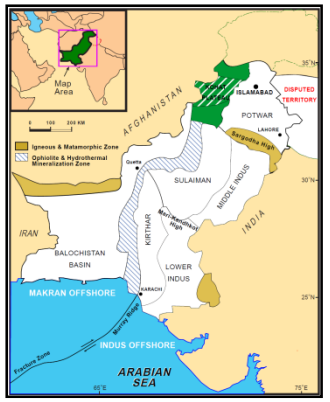
Database and Study Area



Database and Study Area



- Major structural and stratigraphic elements of the study area
- Erosional feather-edges (red wiggly lines) of different stratigraphic packages successively truncating towards southeast and east on to the Sargodha High Indo-Pak Plate's margin.



LEGEND

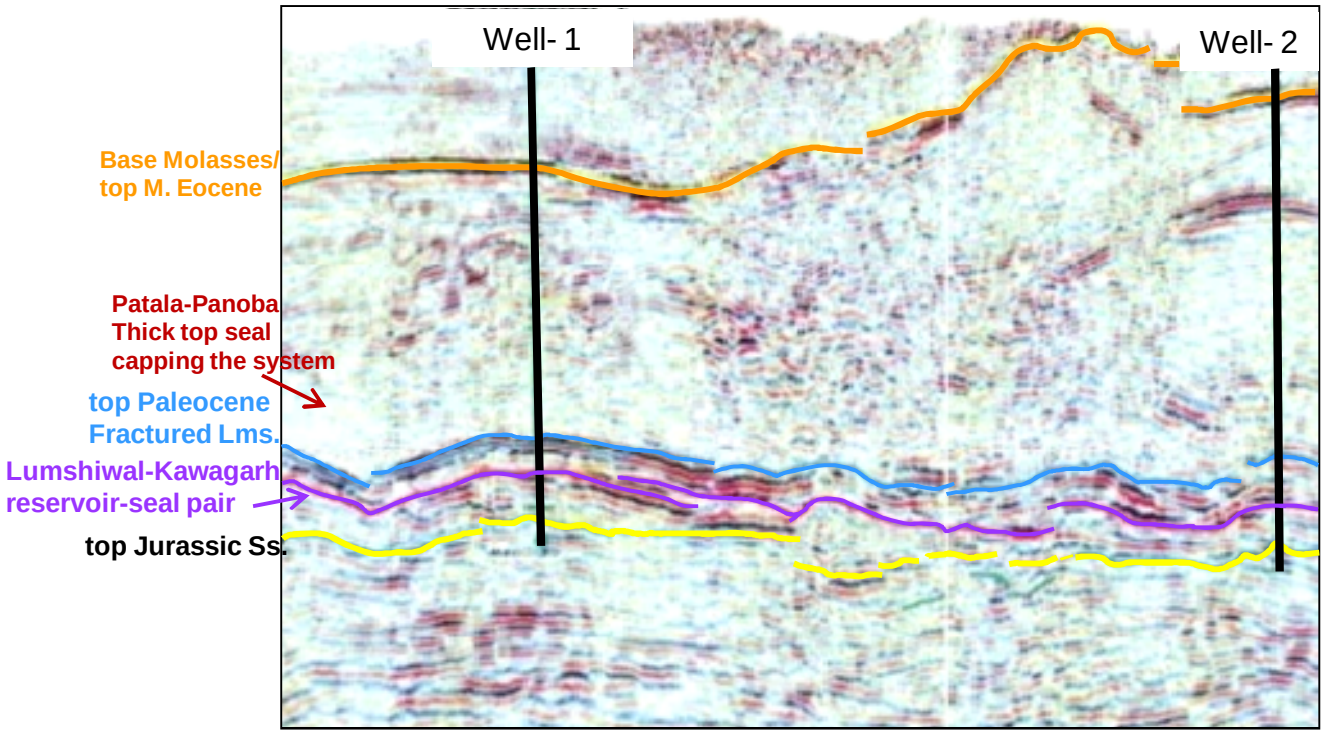
- Q QUATERNARY
- N NEOGENE
- E EOCENE
- Pg PALEOGENE
- K CRETACEOUS
- J JURASSIC
- J-R JURASSIC-TRIASSIC
- Mz MESOZOIC
- Op OPHIOLITES
- Mp EARLY MESOZOIC-LATE PALEOZOIC
- P EARLY PALEOZOIC
- Pc-Ic INFRACAMBRIAN
- PE PRE-CAMBRIAN

- ANTICLINAL AXIS
- SYNCLINAL AXIS
- OIL FIELD
- GAS/CONDENSATE FIELD
- OIL SEEP
- GAS SEEP

Nadeem Ahmad & M. R. Khan, 2011

Database and Study Area

- Structural style and trap configuration. Challenge is seismic imaging of complex structures below thick plastic shales & evaporites above the Paleocene Lokhart Lms.
- Implication: Very limited use of seismic is possible for Seismic stratigraphic interpretation and for the mapping of reservoir / seal pair using seismic attributes

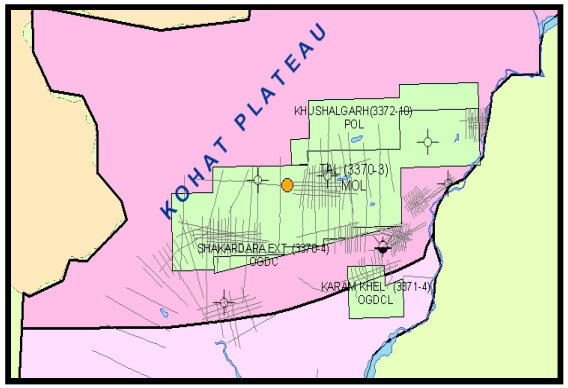


East-West Strike line along the south-verging thrust sheets

Exploration History, Exploration Performance

Three eras of exploration campaigns:

- Up to 1970
- Up to 1990
- Up to 1990's



- Advent of PSDM and PreSTM in early-mid 1990's, but a late start in Pakistan (in 2000s) leading to improved exploration performance!

Exploratory Wells Drilled

S. No.	NAME	YEAR	STATUS	COMPANY
1	NANDRAKHI-01	1957	ABD	POL
2	PEZU-01	1968	ABD	PPL
3	MARWAT-01	1970	ABD	PPL

SUMMARY OF SEISMIC ACTIVITY

Vintage	No. Of Lines	L. Km / Sq. Km	Company Name
1948-1970	4	60 L. Km	AMOCO

Exploratory Wells Drilled

S. No.	NAME	YEAR	STATUS	COMPANY
1	BABAI-01	1982	ABD	IBPC
2	SHAKARDARA-01	1989	ABD	OGDCL
3	CHONAI-01	1990	ABD	PCPI

SUMMARY OF SEISMIC ACTIVITY

Vintage	No. Of Lines	L. Km / Sq. Km	Company Name
1981-1990	220	4400 L. Km	OGDCL, AMOCO, OCCIDENTAL, CRECENT, POL, PETROCANADA

Exploratory Wells Drilled

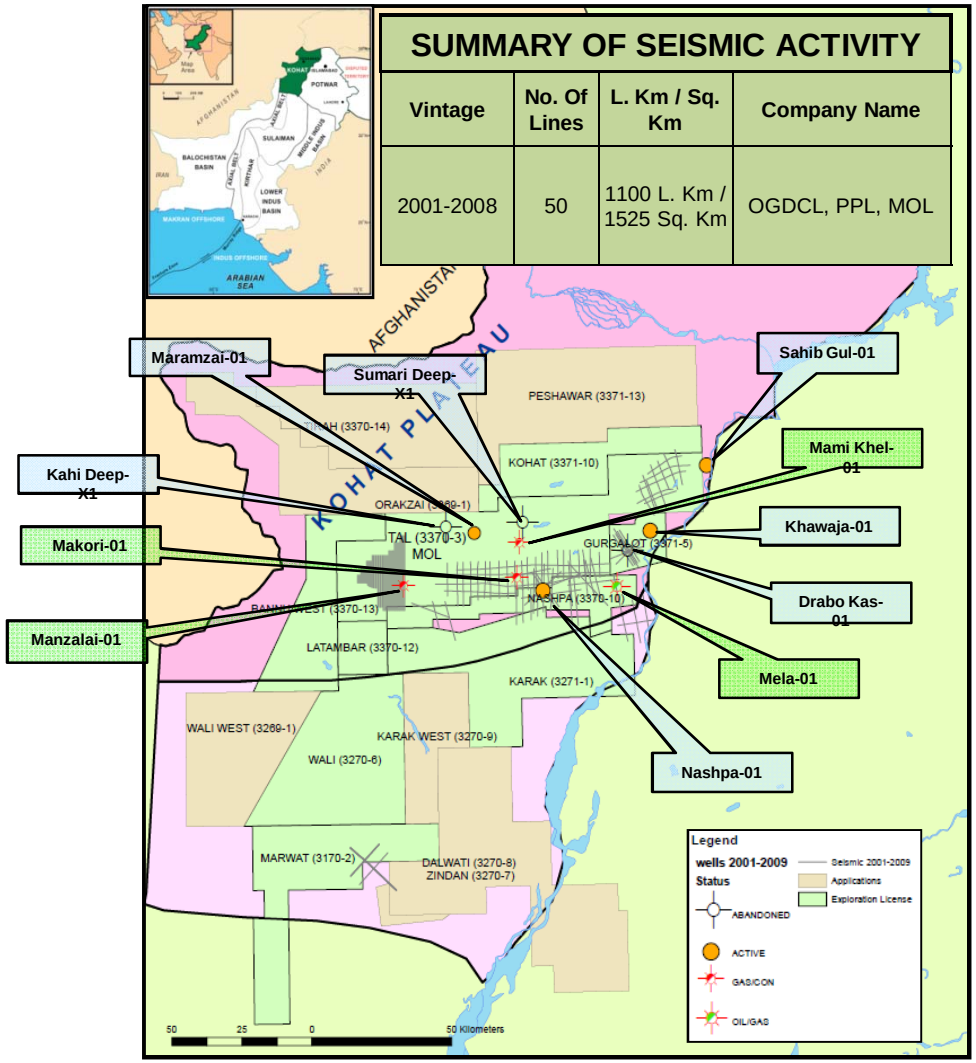
S. No.	NAME	YEAR	STATUS	COMPANY
1	TOLANJ-01	1991	ABD	AMOCO
2	NAK BAND-01	1992	ABD	OGDCL
3	KAHI-01	1992	ABD	AMOCO
4	SUMARI-01	1993	ABD	AMOCO
5	KUNDI-X1	1994	ABD	PPL

SUMMARY OF SEISMIC ACTIVITY

Vintage	No. Of Lines	L. Km / Sq. Km	Company Name
1991-2000	175	4000 L. Km	OGDCL, PPL, AMOCO

Exploration History, Exploration Performance

First Discovery after 50 years from first Seismic!



- Shakardara-01 on poorly imaged structure,
- Seismic reprocessing, further acquisition followed by combined processing – PreSTM and PSDM. Better depth imaging. Targets better defined.
- Chanda-1, Oil at Multiple levels!

Wells drilled in Kohat area since 2000

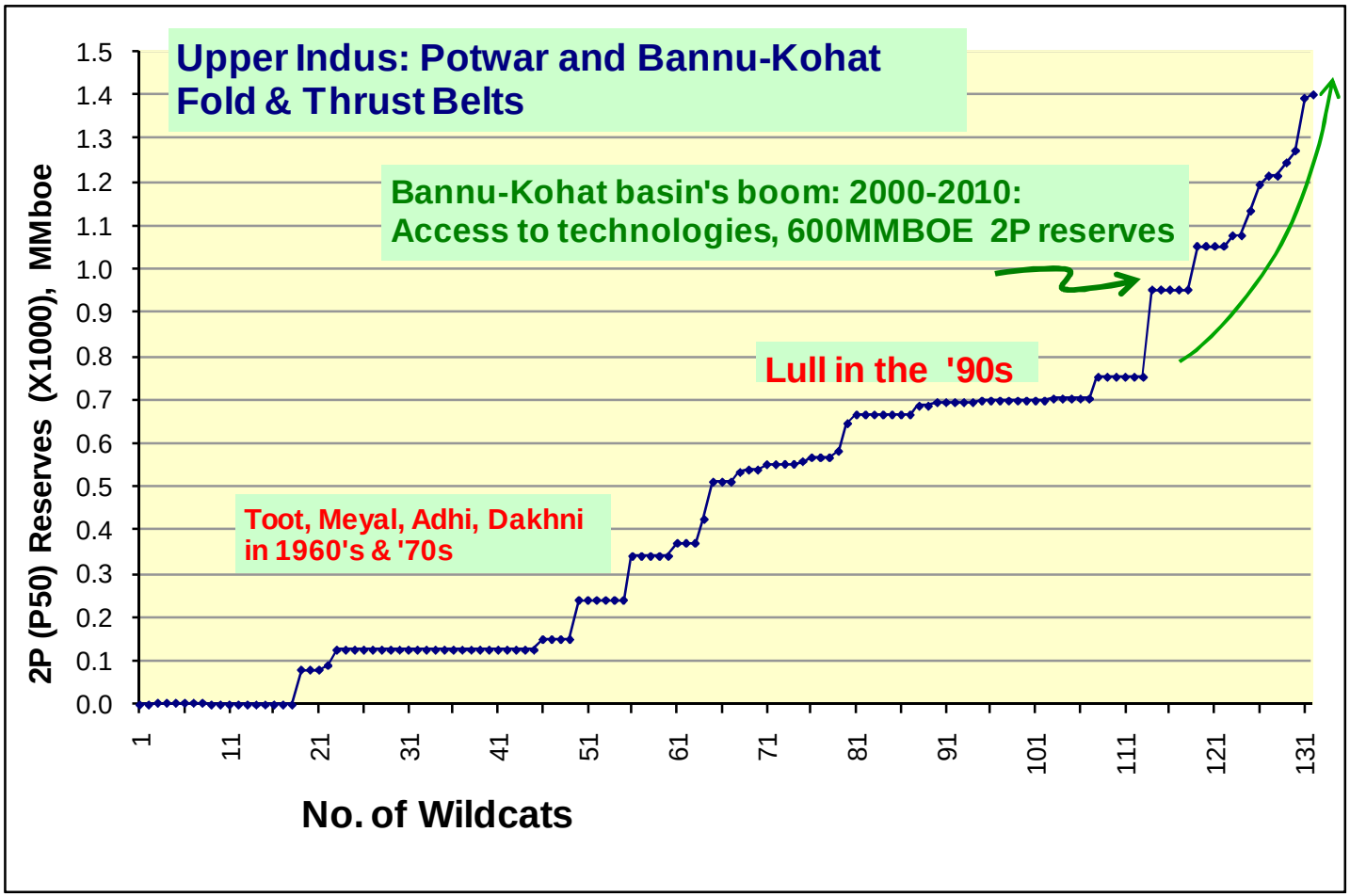
Well Name	Year of Drilling	Status	TD, m	TD Formation
Chanda-1	1/14/2000	Oil / Gas	4788.1	Datta Formation
Chanda Deep-1	21/12/2000	Oil	5100	Wargal Formation
Manzalai-1	10/31/2002	Gas / Cond	4575	Datta Formation
Makori-1	27/11/2004	Gas / Cond	4307	Tredian Formation
Summari Deep X-1	27/07/2006	Abandoned	2323	Datta Formation
Mela-1	17/05/2006	Oil / Gas	4951.7	Datta Formation
Kahi Deep-1	39053	Abandoned	2100	Samanasuk
Mamikhel-1	22/02/2008	Gas / Cond	4120	Kingrali (Triassic)
Maramzai-1	40112	Gas / Cond	3425	Kingrali
Nashpa-1	16/10/09	Gas / Cond	4375	Lockhart Limestone
Makori West-1	27/11/2009	Suspended	4360	Shinwari Formation
Shekhan-1	2/4/2010	Gas	2810	Shinwari Formation
Tolanj X-1	40761	Gas	5500	Shinawari
Makori East-1	21/06/11	Gas / Cond	4900	Datta Formation
Hilini-1	24/10/2011	Oil / Gas	5350	Datta Formation
Jabi-1	2011	Active	3000	Datta Formation

Flow Potential of Lumshiwal reservoir (Target Play)

	Perforation Intervals (MD)	Choke, inch	Gas MMscfd	Oil Bbl/d	Condensate Bbl/d	Water Bbl/d
Well No. 1	3454-3458, 3464-3475, 3478-3499m	32/64"	13.22	-	239.8	11
Well No. 2	4110-4118m	-	No influx			-
Well No. 3	4086-4098m	128/64"	Weak gas flare			-
Well No. 4	3849-3859, 3872-3881m	36/64"	14.03	-	123	252
Well No. 5	3586-3608m 3610-3626m	32/64"	24		489	
		40/64"	29.9		525	17
Well No. 6	3895-3909m 3925.5-3945m	32/64"	18		225	--
		36/64"	19.4		229	1.2
Well No. 7	3166-3178m	32/64"	2.33	1680		--
	3129-3133, 3135-3152m	32/64"	5.13	2979		--
	3101-3121	32/64"	0.9	151		--
	3074-3090	32/64"	6.43		470	--
Well No. 8	4663-4670, 4674-4690, 4702-4711	32/64"	2.2	620	-	-

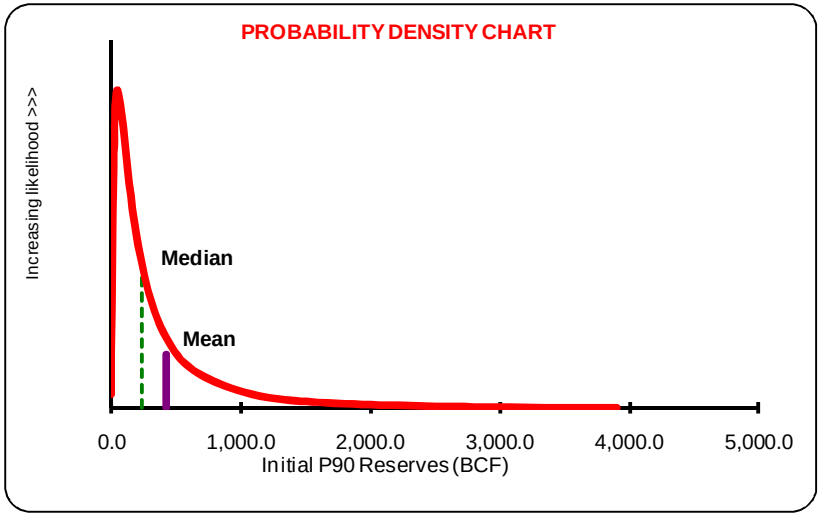
Exploration History

- Creaming curve exhibits a bullish trend since the first discovery at Chanda only a decade ago



Exploration History of Lr. Goru Play – Analogue statistical assessment

- Future direction of exploration in Lower Goru: Stratigraphic traps and combination traps
  - Extensive 3D coverage in next 10 years
  - Extensive use of seismic attribute maps and rock physics for reconstructing depo-systems & reservoir prediction
- Estimates of remaining potential in stratigraphic traps using statistical approach
  - FSD using Traps w/ strong stratigraphic element: Saqib, Kadanwari-14, Tajjal, Latif, Miano, Sawan
- Validate with play fairway & CRS mapping to show under-explored areas with under-utilized methods & technologies



Classes, MMBOE	1 - 10	10 - 50	50 - 100	100 - 200
Actual found	0	57.25	159.80	250.00
Modelled, MMBOE	7.22	280.18	283.00	575.59
# of Finds, actual	0	3	2	1
# of Finds, Modelled	1	10	4	4
YTF, MMBOE		222.93	123.20	325.59
New Pot. Finds	1	7	2	3

Emerging Petroleum Province – Exploration Drilling Results

Lessons Learned

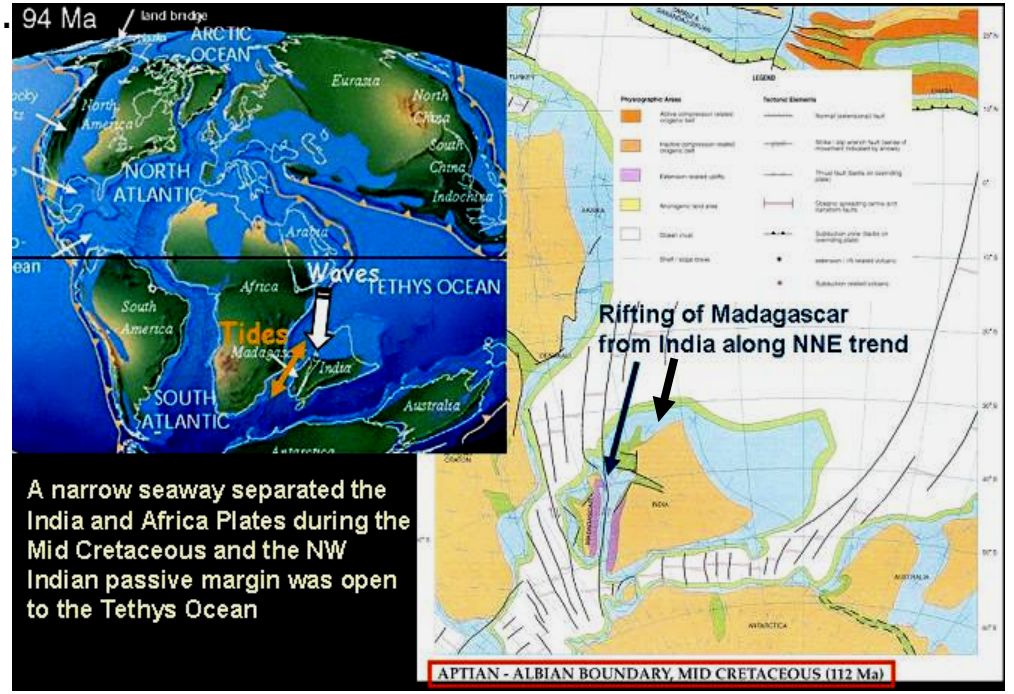
- Reservoir – Seal pair perspective had been missing.
  - Failure of shallow reservoir and/or entrapment was taken to condemn the deeper possibilities!
  - No charge or lack of seal assumed for the entire section
- Role of anomalously thick plastic shales (Panoba Shale) in a basinward outer shelf setting was under-estimated. And thus a late awareness of the existence of a play deeper than usual Middle Eocene upper targets,
- Resource potential under-estimated (or incorrectly estimated). Risking not implemented appropriately at the play or prospect level

Implementing the Lessons Learned for improved exploration performance

- Distinct reservoir-seal pair at deeper level
- Lateral change in facies, or basinward (or even lateral) occurrence of an additional stratigraphic package – new play due to a previously unknown reservoir or seal (or both)

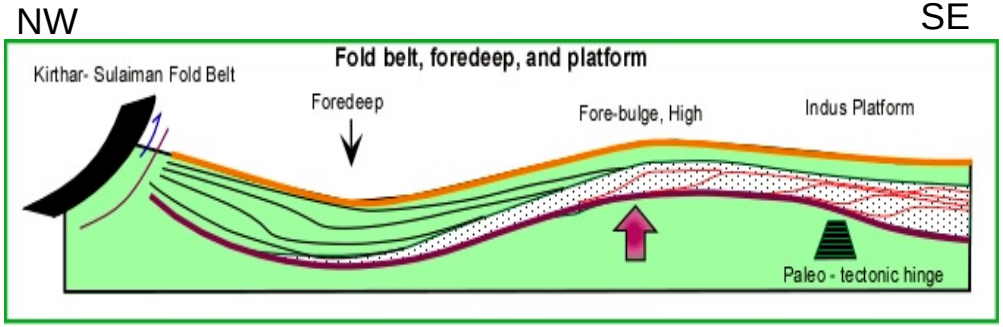
Stratigraphic Framework - Deposition

- Chichali-Lumshiwal sedimentation took place in Lower Cretaceous (Kimmeridgian– Albian) times
  - Early Cretaceous rifting on northwestern margin of Indian Plate
  - Accommodation Space created to accommodate abundant sediment supply from the east under relative sea level fluctuations
  - Causes: eustasy, uplift due to thermal doming and sagging due to reactivation of older rift related gravity faults.

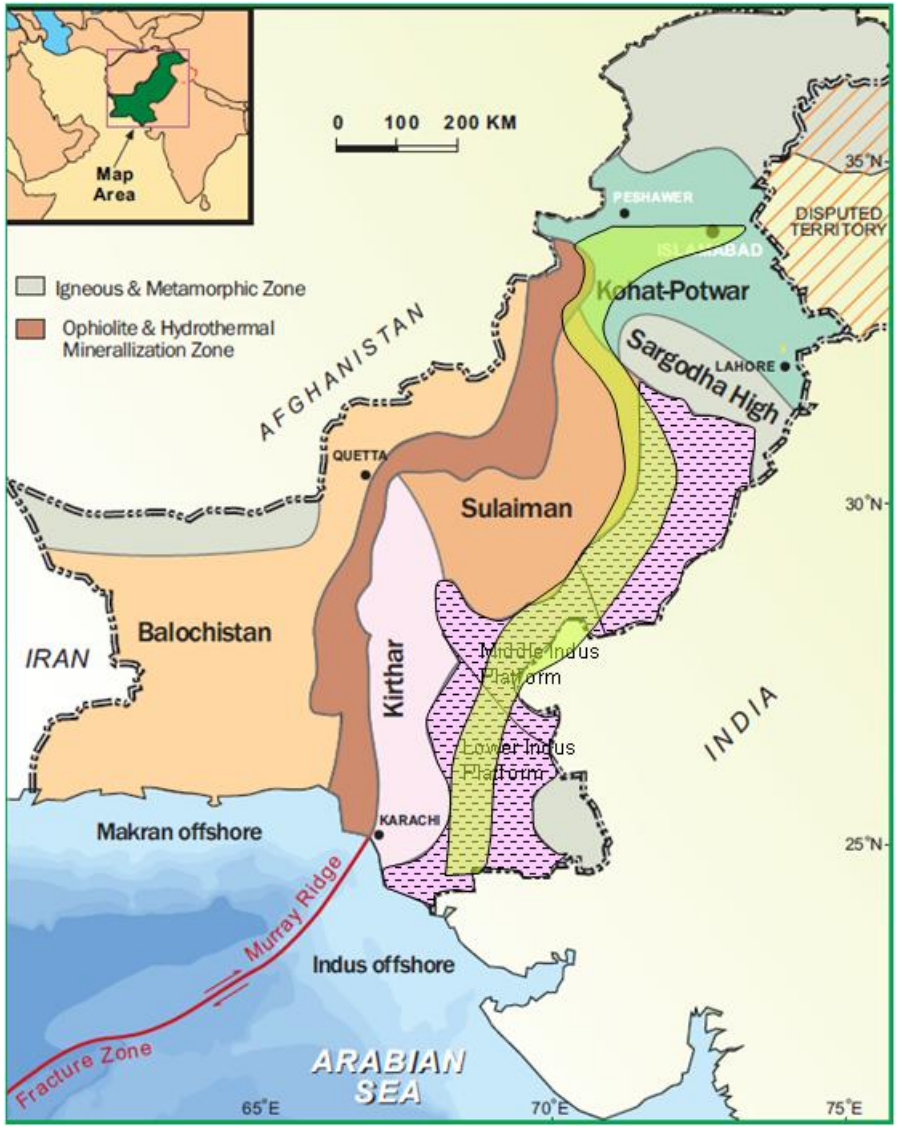


Regional Set-up of the Lower Cretaceous Play Fairway

- Lower Cretaceous, Lumshiwal paralic sands form prolific reservoirs (also proven in Lr & Middle Indus as Lower Goru play).
- Wrench and compressional tectonics modified Jurassic sag and rift (fault blocks) in which anoxic to anaerobic conditions were set up
- Horst & graben morphology still prevalent.
- Role of paleo-highs

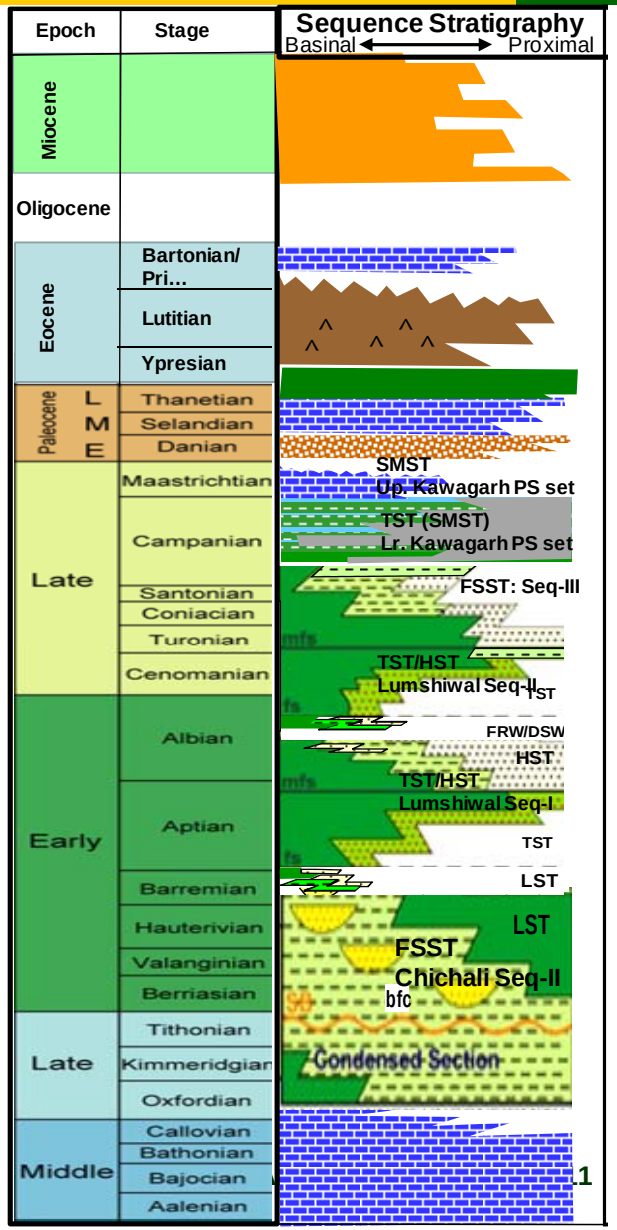


Regional setup of the Lower Cretaceous play fairway

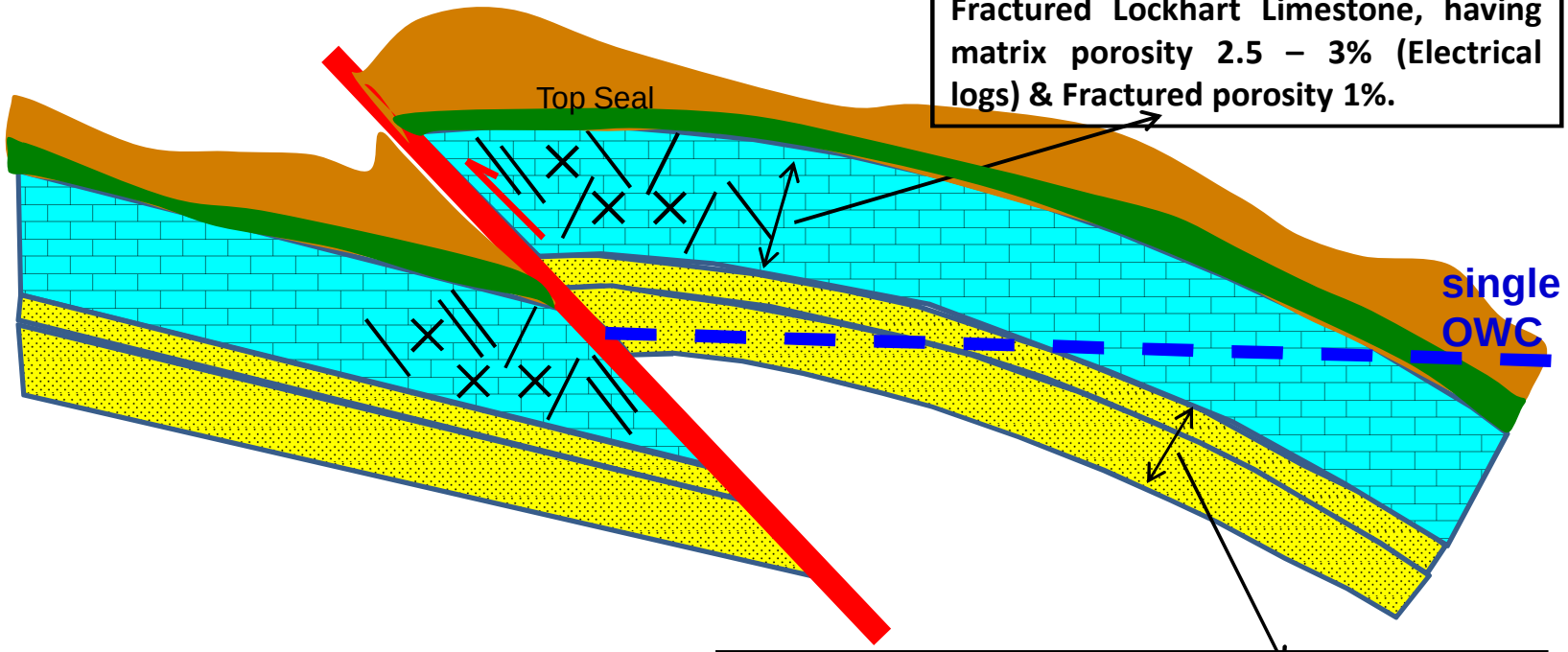


Reservoir – Seal Pairs: Defining the Distinct Plays

- Lumshiwal-Hangu-Lockhart and Patala Stacked Reservoirs play
  - Three reservoir formations are stacked . Matrix porosity of sandstones provides key storage space (for GIIP, OIIP) and the fractured carbonates provide means of efficient draining
- Lumshiwal - Kawagarh distinct play
  - Occurrence of additional shale to marl prone sequence (Kawagarh Limestone) to provide a distinct regional seal above the delatic to shoreface sandstone package
- Different entrapment styles making regional trends ask for the definition of Part-Plays for the above reservoir-seal pairs



Play Schematic: Fold & Thrust Belt setting
Play Schematics

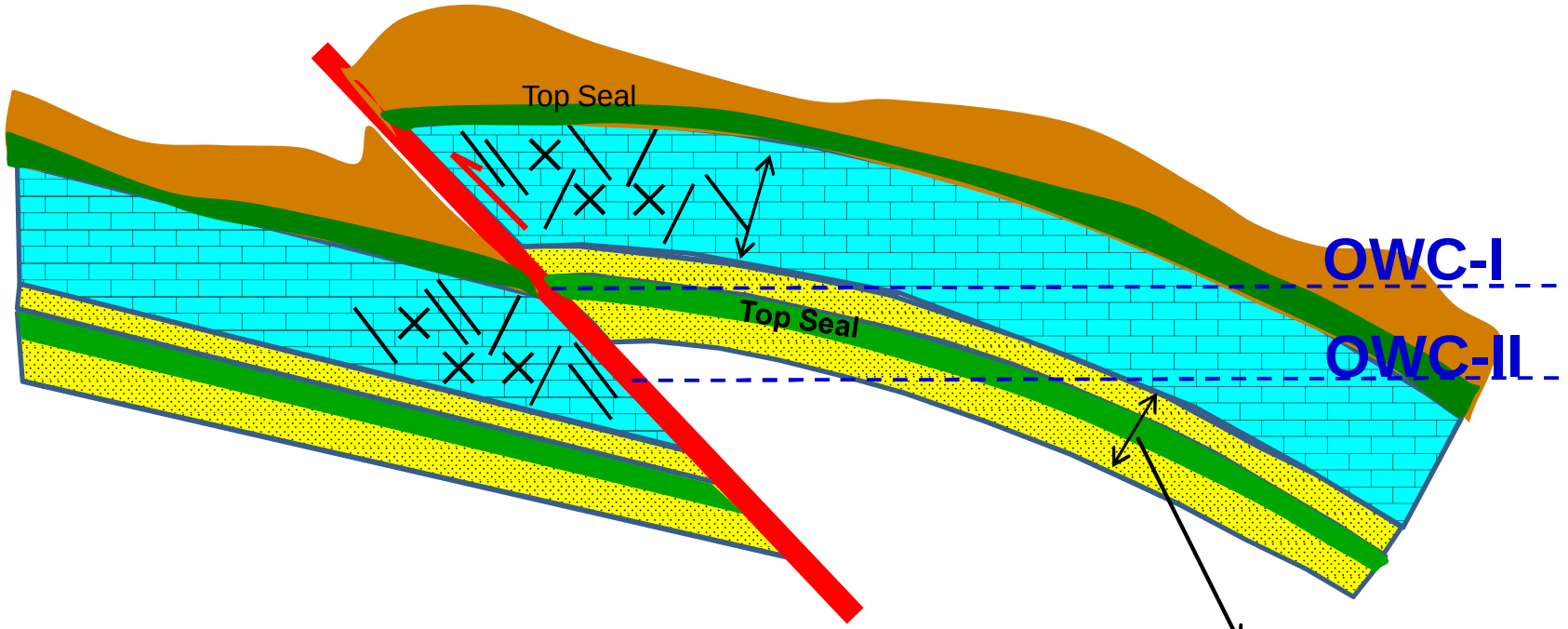


Fractured Lockhart Limestone, having matrix porosity 2.5 – 3% (Electrical logs) & Fractured porosity 1%.

Lockhart : Gross thickness 200m, Porosity 2.5 -3%
Lumshiwal : Gross thickness 45m, Porosity 7 - 9%
Hangu : Gross thickness 45m, Porosity 6 - 7%

- **Main HC storage tank in matrix porosity reservoirs (Hangu & Lumshiwal), while fractured Lockhart carbonates serve to drain this oil through pressure support provided by Hangu/Lumshiwal.**
- **Where top seal Kawagarh present, the storage capacity is limited, e.g., Shekhan-01**

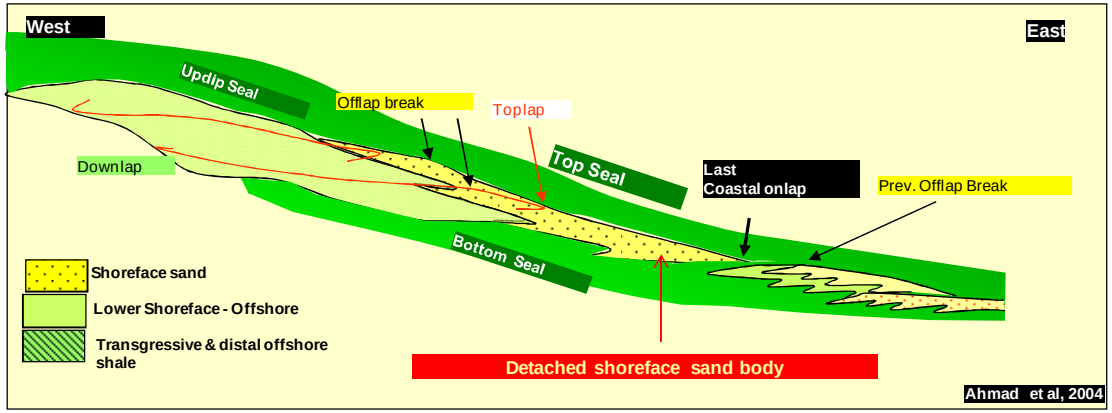
Play Schematic: Fold & Thrust Belt setting
Play Schematics



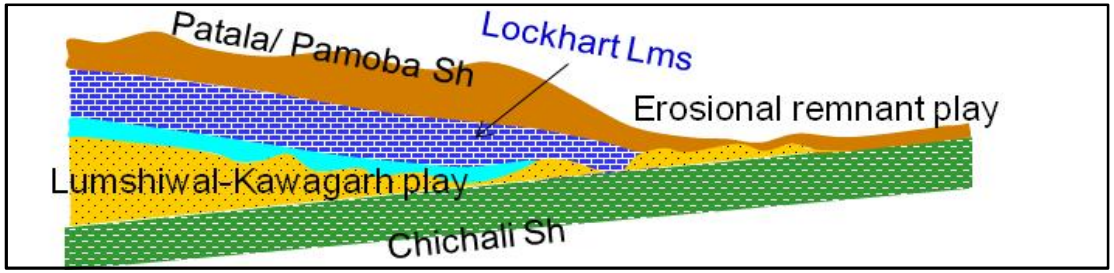
- Hangu & Lumshiwal) reservoirs split by the introduction of a new seal (SMST Kawagarh shales/marls and limestone).
- Dependency between this and the shallow Paleocene target no more exists
- Must be drilled and tested as an independent play in this case.

Play Schematic: Foredeep to Frontal Thrust setting

Strat-traps:
Counter-regional Dip Setting



1. Erosional remnants in SE,
2. Shoreface, Progradational wedges to the West & NW.

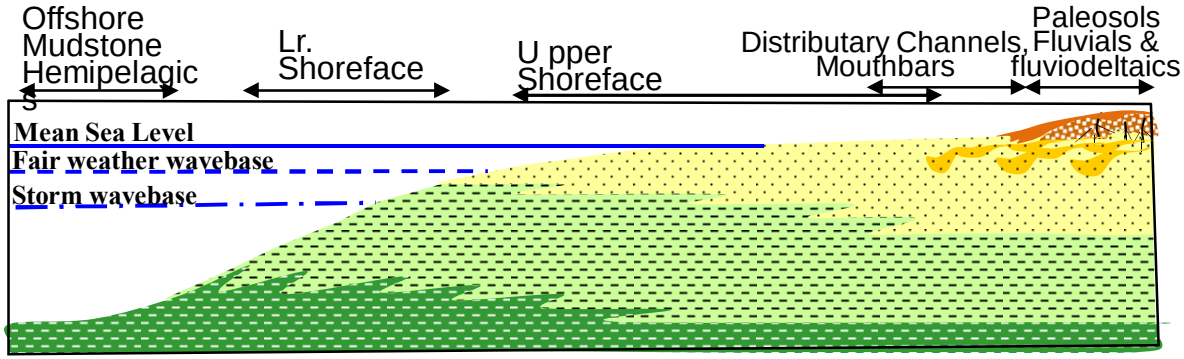


Lumshiwal –Patala play with Erosional Remnants Strat-traps

- Key reservoir: Deltaic to Shoreface sandstones on the flanks of paleohighs (Sargodha High, Jaisalmer High)
- Top Seal: Transgressive Shales of Patala Formation,
- Trap: Erosional remnants that survived erosion at K-T boundary due to thermal bulging or the early upheavals as the Plate approached Eurasian landmass,
- Onlapping shoreface sandstone bodies and erosional shoreface sand on the flank of Highs.

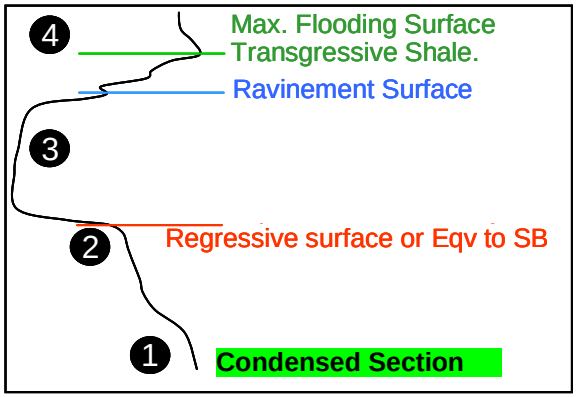
Mapping for Play Fairway Evaluation: Lithofacies & Depositional Environments

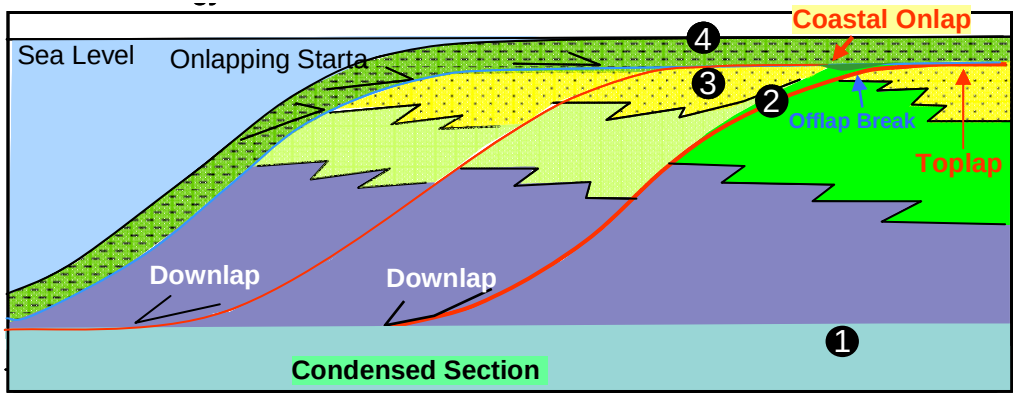
Facies model for the Facies logs reconstructed



TL Toplap
DL Downlap
ON Onlap (Transgr)
ON Onlap (Coastal)
MR S Max. Reg. Surface
SB Sequence Boundary
fs Flooding surface
HST Highstand
LST Lowstand
FRW/ DSW
Forced regressive wedge / Detached shoreface wedge

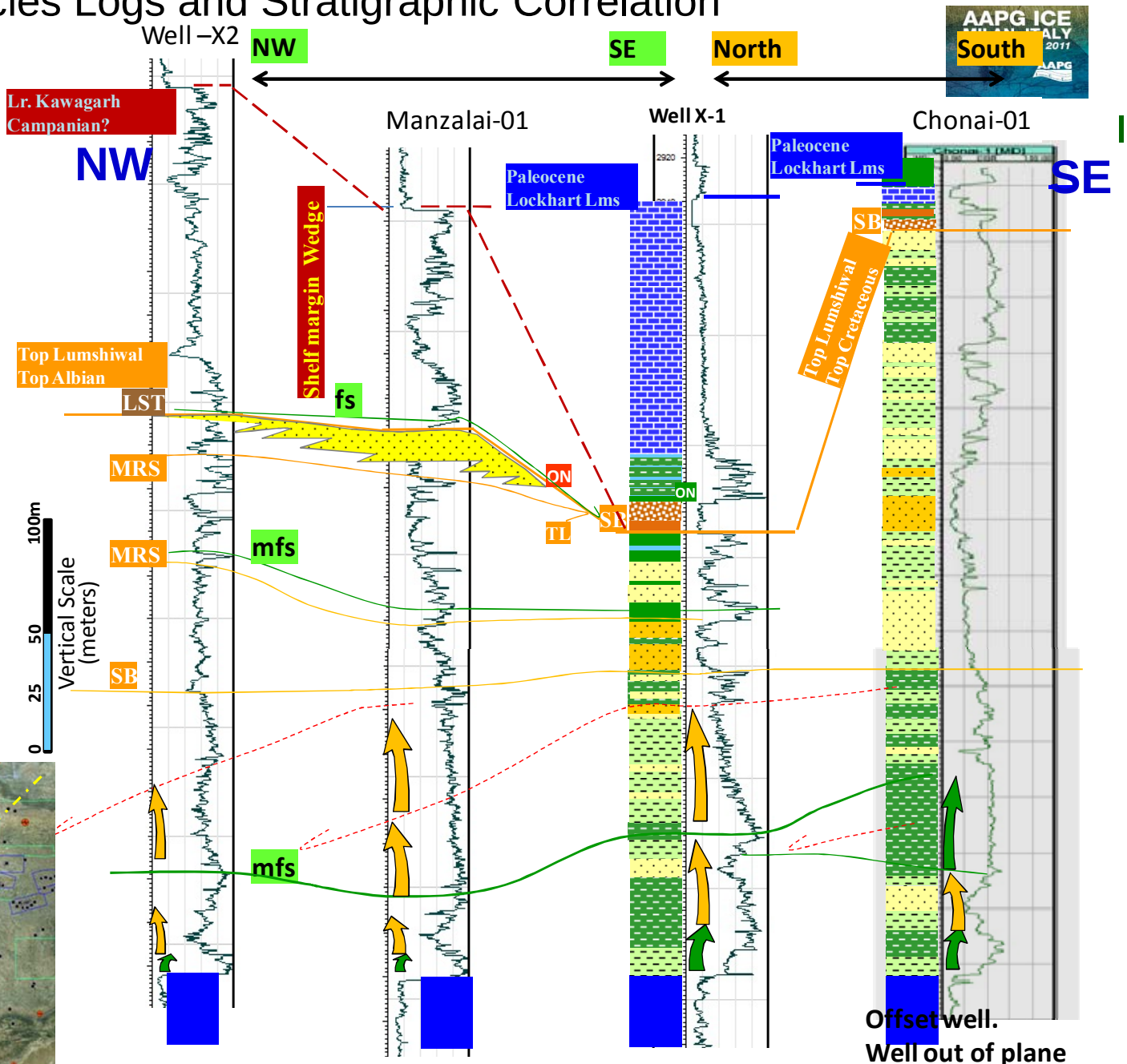
Model of the depositional and stratal geometries for interpretation of the Cretaceous succession using log motifs and seismic

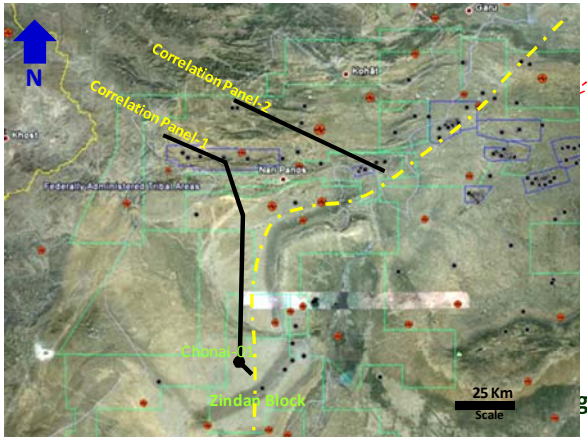




Facies Logs and Stratigraphic Correlation

Panel - I





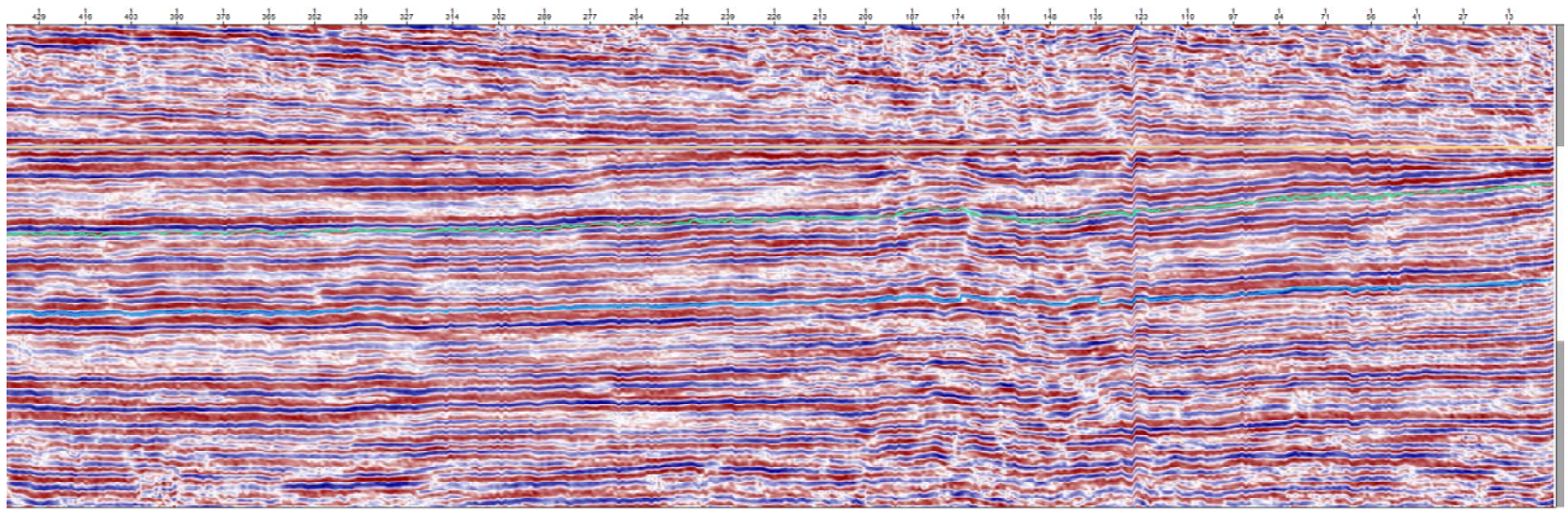
ging Petroleum Province - Bannu-Kohat, Pakistan

Nadeem Ahmad & M. R. Khan, 2011

Facies Logs and Stratigraphic Correlation

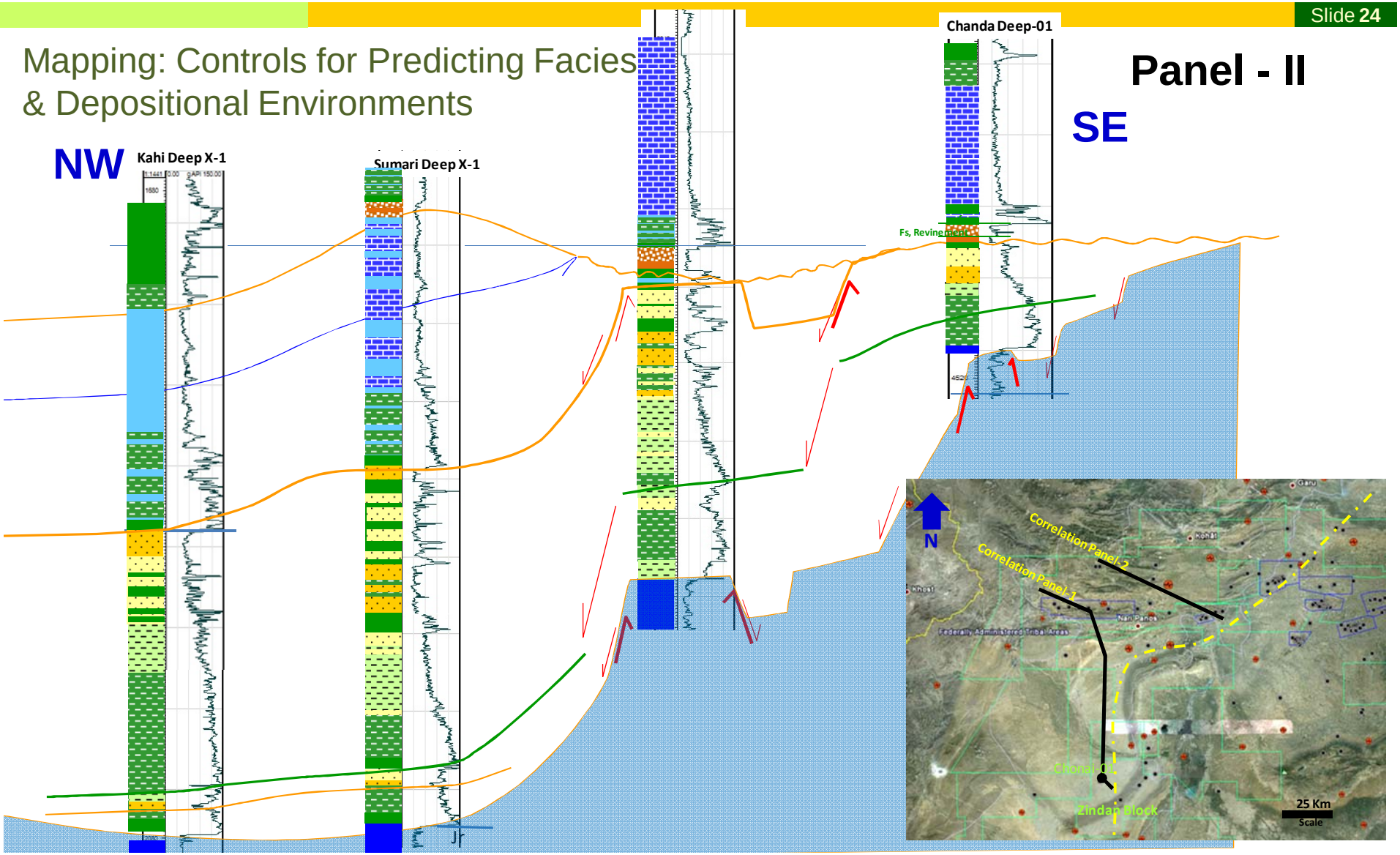
Chonai-1

SE

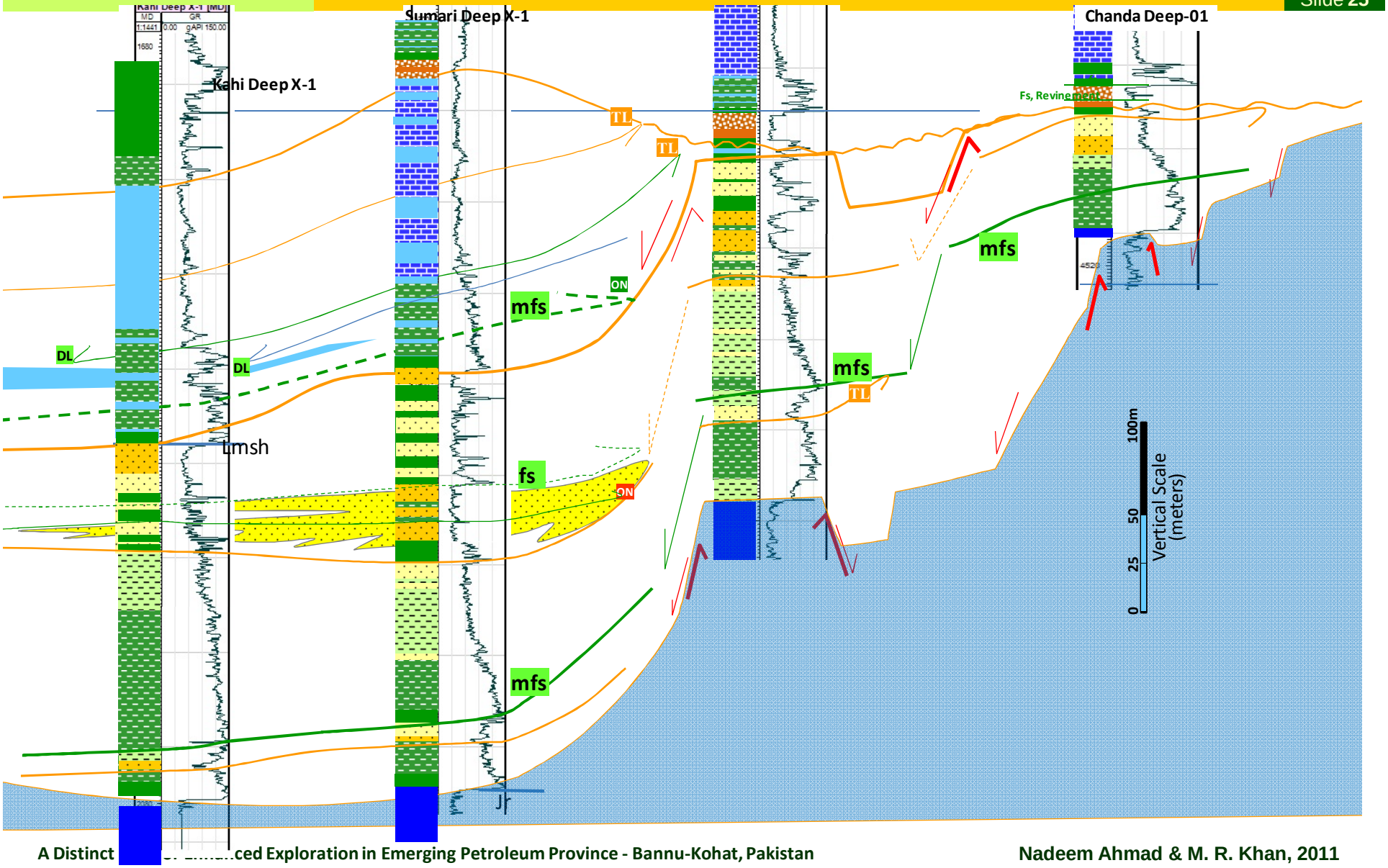


Facies Logs and Stratigraphic Correlation

Mapping: Controls for Predicting Facies & Depositional Environments



Mapping: Controls for Predicting Facies & Depositional Environments



A Distinct [illegible]ced Exploration in Emerging Petroleum Province - Bannu-Kohat, Pakistan

Nadeem Ahmad & M. R. Khan, 2011

Modern Analogues: Controls for Predicting Facies & Depositional Environments

- Modern analogues. Strandplains & barrier-bars come in sizes: 5-30Km long, 2-5Km wide.

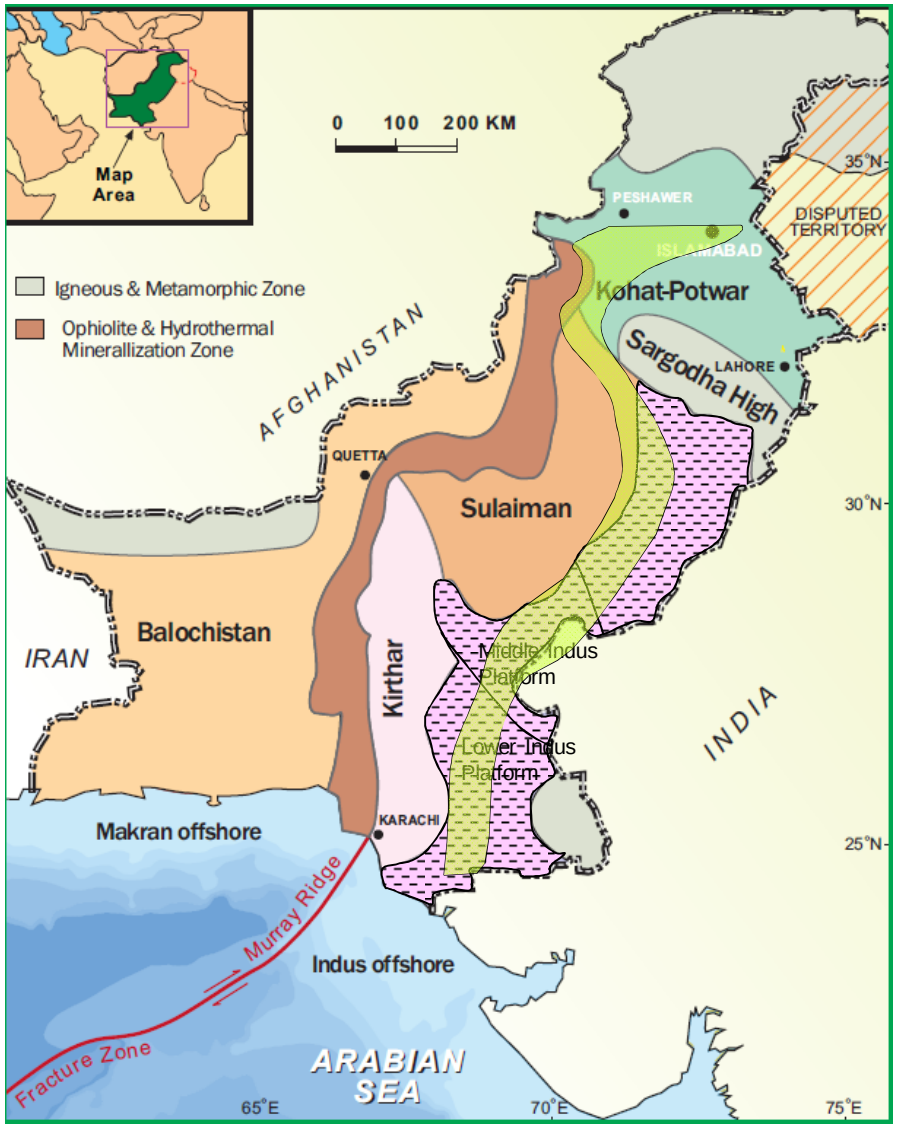
Lumshiwal - Kawagarh reservoir / seal rock facies in the outcrops

Marls and cleaved limestone in Kawagarh Shelf Margin systems tract (top Seal)

Marl and and medium bedded limestone in Kawagarh (top Seal)

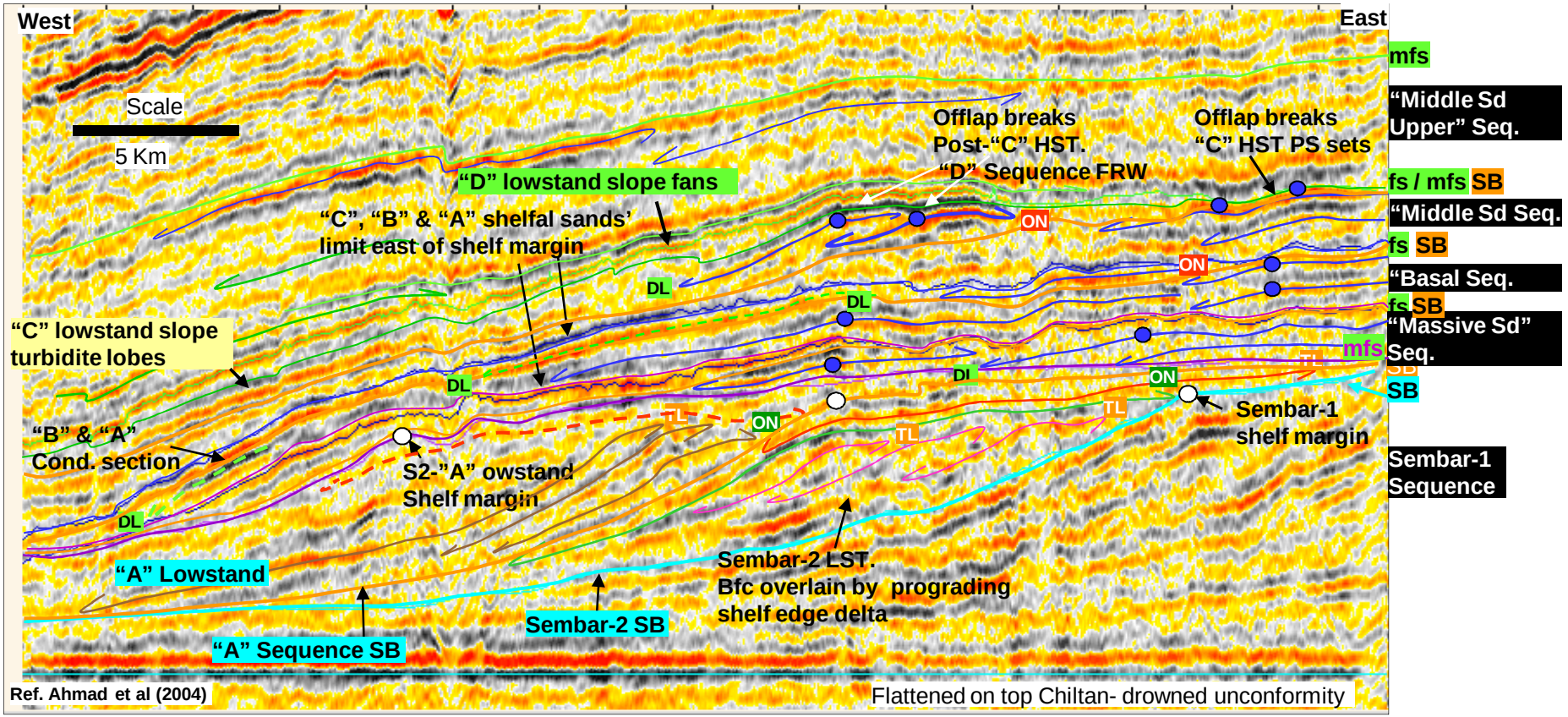
Direct Analogue: Predicting Reservoir Facies Distribution

- Time-equivalent of the Lumshiwal works as an excellent reservoir in structural and stratigraphic traps in the Lower/ Middle Indus Basin
- Sargodha high (a paleo-high) seperates the two corridors as shown
- Stratigraphic traps have been successfully explored in this play based on integrated workflows using 3D seismic and Seismic Geomorphology



Direct Analogue: Predicting Reservoir Facies Distribution

- Seismic stratigraphic interpretation of E-W regional seismic line from across the Sawan area
- Subtle seismic reflection geometries, truncation patterns and dimming & brightening of amplitudes help infer coastal onlaps and offlap breaks -> sand bodies' proximal and distal extents



Direct Analogue: Reservoir Prediction from Seismic Stratigraphy

AAPG ICE MILAN, ITALY 23-26 October 2011

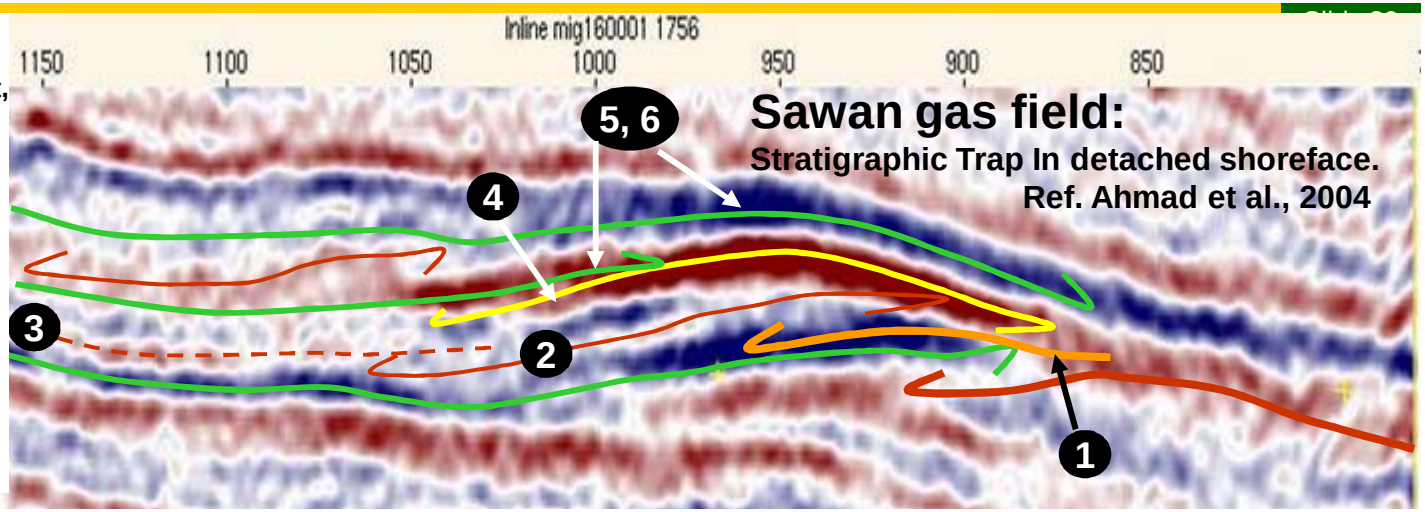
Upper Shoreface Sd (Excellent poro-perm in east, good to fair in the west)

M. To Lower Shoreface Fine Sd to siltstone

Offshore siltstone & Mudst.

Fair to good quality med-grained sands

Chamositic sands



Sawan gas field:
Stratigraphic Trap In detached shoreface.
Ref. Ahmad et al., 2004

Relative time-stratigraphy (Wheeler-like diagram)

Stratal relationships, Timing of sand bodies

Stratigraphic Time (relative)

mfs 6

Ravinement erosion as the base level rises. Possible erosion of most proximal Sawan sands especially where accommodation space limited on elevated locations (seismic expression of coastal onlap enhanced).
Chamosite-rich sands in prograding wedge (b/w 5 & 6)

First fs 5

Possibly adds to Michko sands

4

Switching of sand input towards NE. Sand bar development under shelfal processes with sands being transported southwestwards

3 **Turbidite lobe deposited**

2

Deltaic incursion under the base-level fall. Seismic expression of coastal onlap enhanced by possible post-Sawan ravinement erosion

1

Previous TST shales and HST fines eroded by first incision of Sawan sands and post-Sawan mfs ravinement erosion

Interpretation/ drawing: Nadeem Ahmad

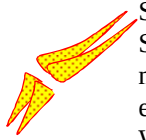
Direct Analogue: Reservoir Prediction from Seismic Stratigraphy

- Gross Depositional Environments map (GDE) based on depo-systems reconstruction for key geomorphic elements - PS Sets-3 and -4 Basal Ss Seq.
- Three phases of strandplain-barrier bar down-stepping towards west and sand emplacement on to the lower shoreface to offshore siltstone-shale.

Reservoir Quality Map

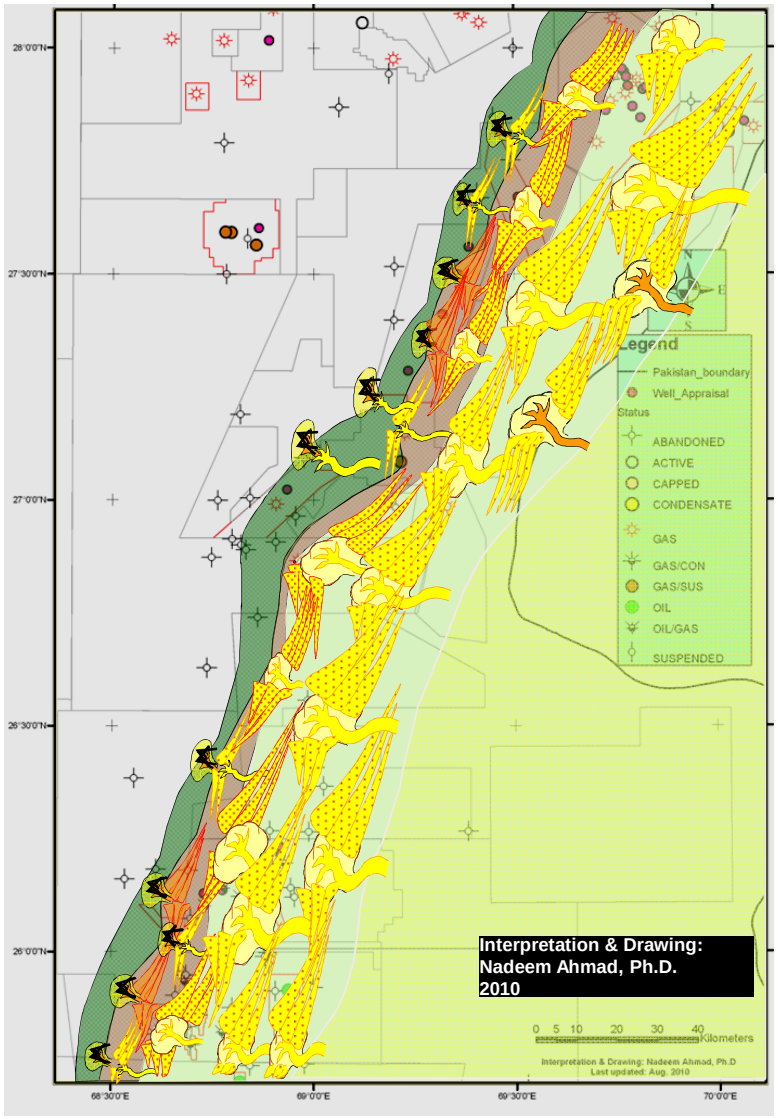
Feeders: Delta plane distributary channels, mouth bars & heterolithics

Longshore drift.



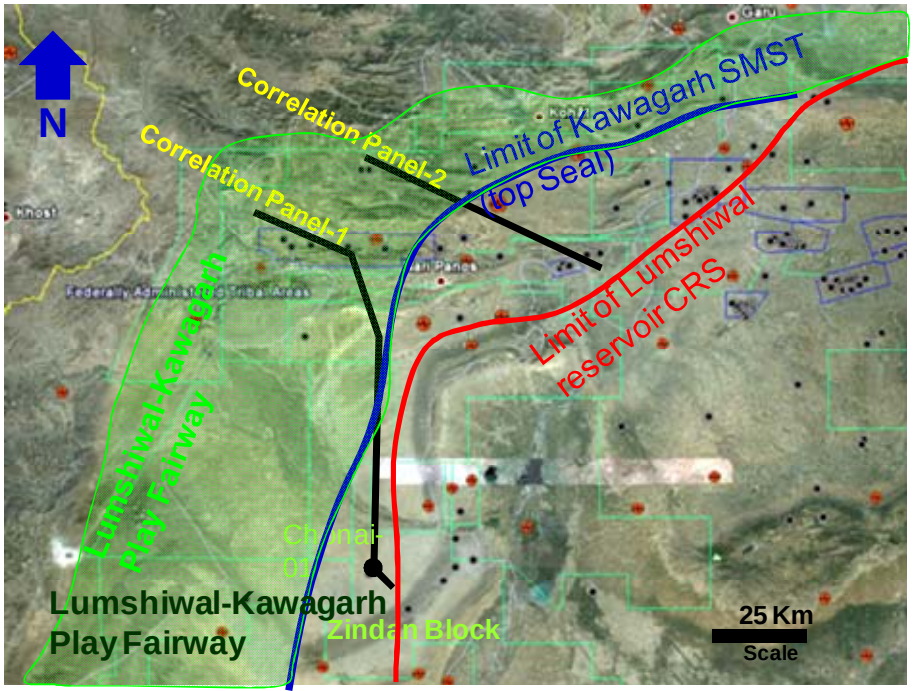
Strandplains & Shoreface bars under mixed wave & tide effect.
Waves actively back-piling sands. Tides spreading fines around and laying sand onto the back-barrier lagoons.

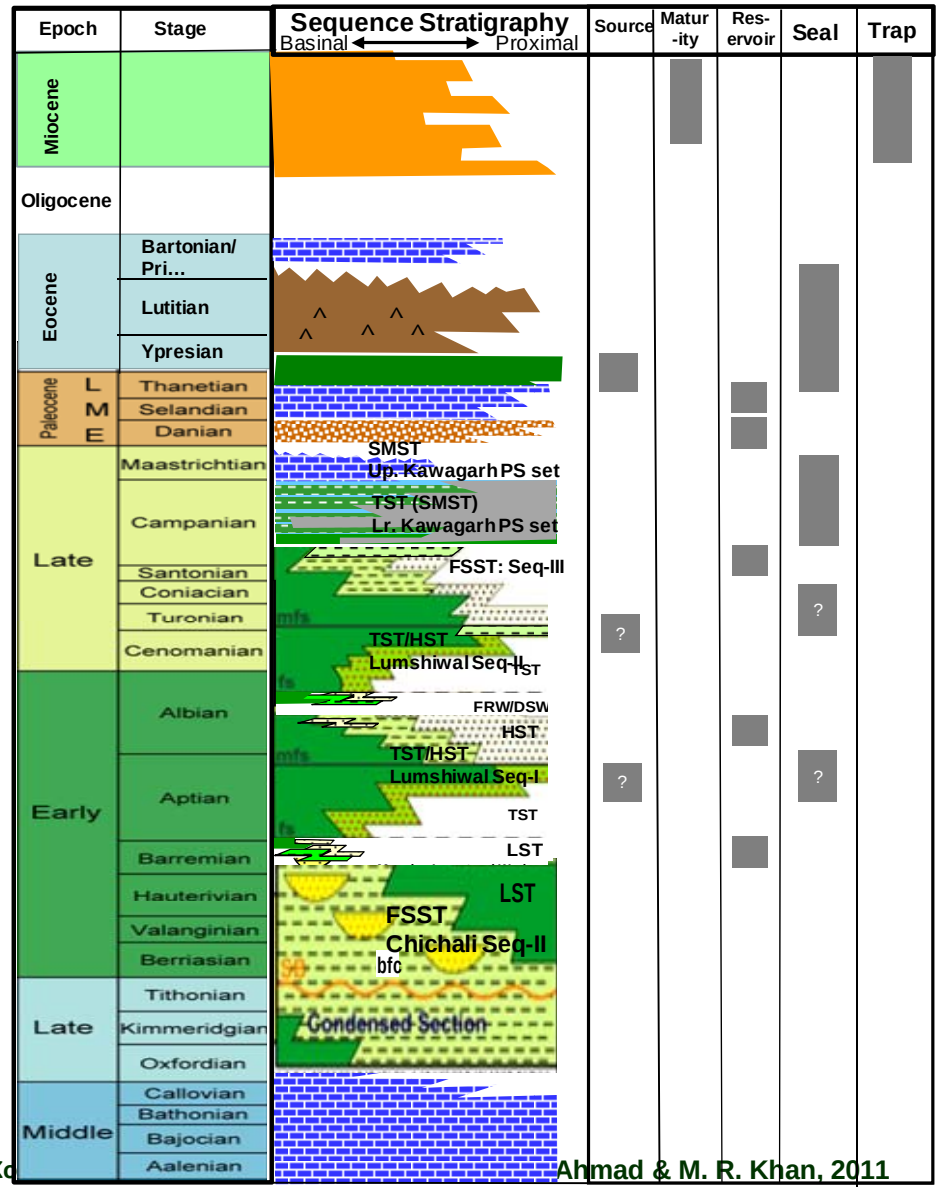
Rip current or Ebb flood deltas attached to the Tidal inlets cutting across the shoreface bars and even strandplains



Mapping of reservoir-seal pair: Facies & GDE outlines

- Petroleum System diagram along with the sequence stratigraphic framework
- Limits of the Reservoir and Top Seal GDE of the Lumshiwal-Kawagarh play.
- Play fairway based on the overlay of Reservoir CRS and Seal CRS (common risk segment) .





A Distinct Play for Enhanced Exploration in Emerging Petroleum Province - Bannu-Ko

Ahmad & M. R. Khan, 2011

CONCLUSIONS

- Regional sequence stratigraphic correlations and overview of tectonic elements and sedimentary systems forming the source, reservoir and seal rocks has allowed to document a Reservoir-Seal pair as a **distinct** play,
- Because of the consistency of structural and stratigraphic framework at a regional scale, the success and failure analysis addresses only the rightly correlative reservoir & seal intervals. Comparison of timings of charge and structuration possible.
- Improved seismic imaging techniques allowed the mapping of multiple thrust sheets and traps using the 1990s' developments of PreSTM/PSDM
- Discoveries in the last decade, though late in basin's exploration history, show a bullish trend on the Creaming curve; Strat-traps yet to be mapped
- Prospectivity corridor/ region highlighted where HC charge & entrapment studies are required to materialize structural & Strat traps

CONCLUSIONS (contin...)

- Inherent issues of diachronous Formations resolved through the sequency stratigraphic correlations prepared,
- Discoveries demonstrate that the Lockhart – Patala play works through regionally extensive thick Panoba-Mamikhel shales / evaporites that cap and laterally seal the reservoirs in highly tectonized structural culminations. Deeper plays' potential is high-graded due to this efficient 'retention' of hydrocarbon.
- Deposition of the Kawagarh's shale/marl-pronefacies and Chichali's organic-rich anoxic facies controlled by the reactivated paleo-high/ thermal bulge. Implications for targeting Cretaceous source kitchens!
- Key geological uncertainties: 1) Mapping of top Seal, 2) Reservoir quality,
- Independent resource/risk assessment of this plays is essential. Make decisions to drill deeper or abandon independent of the 'Shallow' results!
- For Strat-traps, Seismic and facies modeling needs to be focused on the flanks of regional synclines.

Acknowledgement

Authors acknowledge:

- Management of Pakistan Petroleum Limited for its support and encouragement to present this work
- Contributions of the companies chasing the stratigraphic traps including PPL and using sequence stratigraphy extensively
- Play Fairway and CRS mapping work presented here is part of the ongoing processes and workflows that the first author together with his team is developing at PPL for effective targeting of Stratigraphic Traps and enhanced exploration in Indus Basin. Author particularly acknowledges the support provided by Habib S. Shah (Asst. Geologist) in compiling the Tables and Log displays (used in Correlation panels).