Physico-Chemical Controls on Source Rock in Offshore Indus – Comparative Study of Some Major Tertiary Deltas of the World*

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Search and Discovery Article #50560 (2012)
Posted February 29, 2012

*Adapted from oral presentation at PAPG/SPE Annual Technical Conference 2011, Islamabad, Pakistan, November 22-23, 2011

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Abstract

Offshore Indus (Pakistan) contains one of the major Tertiary deltas of the world and is considered an attractive exploration frontier. The Indus Fan, the second largest submarine fan in the world after the Bengal Fan, started to develop since Late Oligocene and contains more than 10 km of Tertiary sediments over Deccan Volcanics. Exploration activities in Offshore Indus were initiated in 1961-62. A fair coverage of seismic data exists and 13 exploratory wells have been drilled with no commercial success. Only 1 well, PakCan-01, encountered non-commercial gas, with flow rate of 3.7 MMscfd composed of 97% CH_4 and 2.7% CO_2, from Middle Miocene sandstone.

Predominant lithologies of the drilled section indicate both lateral and vertical variations depending on depositional processes and position in the basin. Consequently, parts of the basin with low energy conditions, i.e., lagoons, outer shelf and the inter-volcanic seamounts depressions, received fine and shaly sediments in anoxic environment. Over-pressures have been encountered in the Miocene section in different wells drilled in Offshore Indus (e.g., Indus Marine A-1, B-1, and C-1). These over-pressured intervals, having huge thickness, might have retained the hydrocarbons beneath them or in potential stratigraphic traps in the area.

An integrated approach using basin modeling and seismic data is essentially required to minimize risks associated with: a) source presence/maturity; b) migration/HC charge; and c) reservoir-seal pair, before selecting a suitable candidate for drilling. A comparative study of some of the major Tertiary basins, including Offshore Indus, related to deltas has been carried out to understand similarities and differences in physico-chemical controls on source rock deposition, maturation, hydrocarbon generation and expulsion in Offshore Indus. 1D basin modeling was applied to three Offshore Indus wells to understand timing of maturation and expulsion of

hydrocarbons. The results of the study will potentially reveal the characteristics, presence, and effectiveness of a Tertiary Petroleum System in Offshore Indus Basin.

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ANNUAL TECHNICAL CONFERENCE
2011

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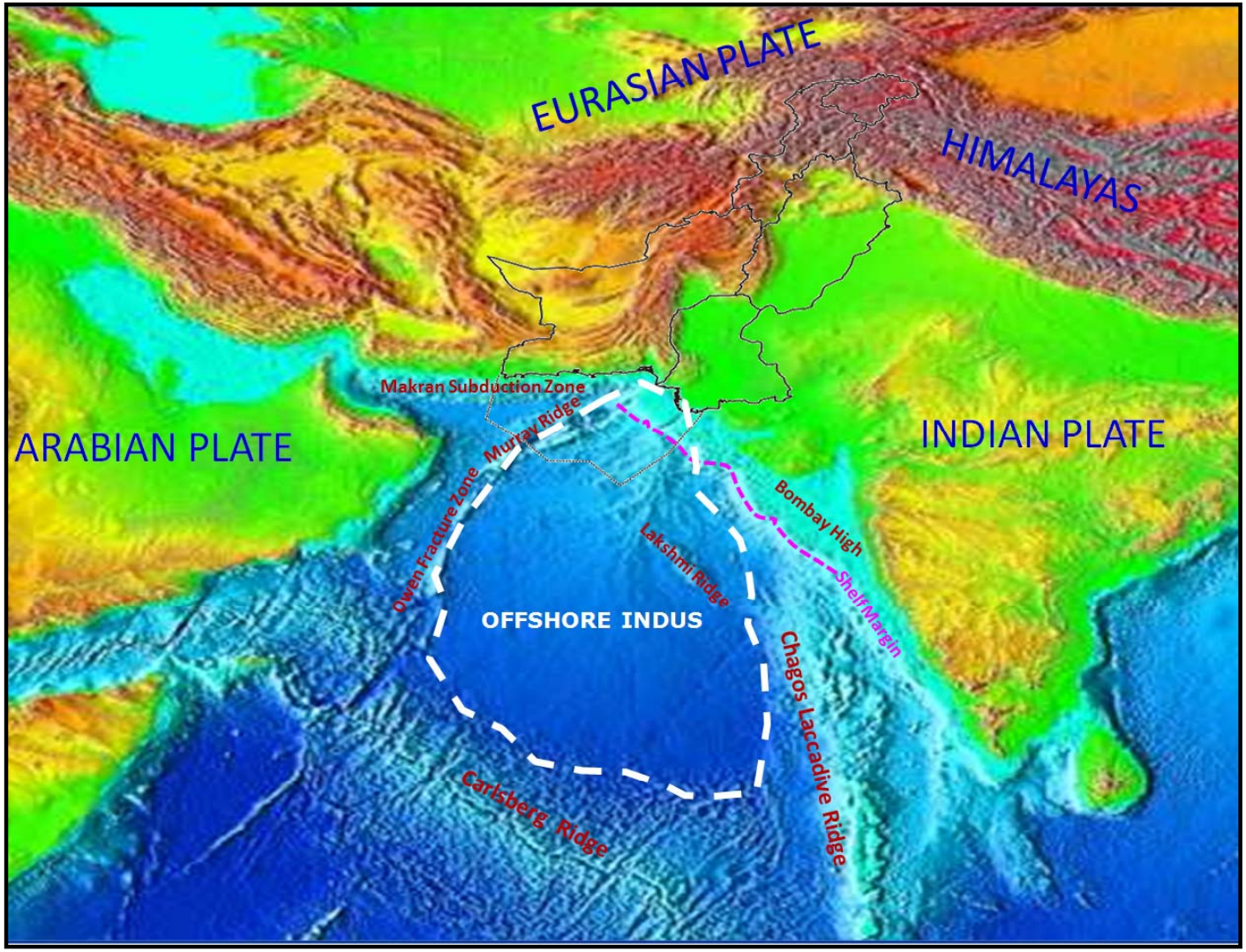
INTRODUCTION

- Offshore Indus - a passive continental margin basin with a major Tertiary Delta-Fan Complex
- Started building up in Late Oligocene to Early Miocene related to Himalayan Orogeny
- Second largest submarine fan in the world after the Bengal Fan
- Indus Fan contains around 10 km Tertiary sediments
- An under-explored basin - exploration concentrated on Miocene and younger section, mainly in the platform area
- No commercial oil / gas field discovered – Petroleum System not proven yet
- Exploration failures generally attributed to the absence of an effective source rock
- Basin Modelling performed on selected Offshore Indus wells and a comparitive study of various Tertiary Deltas carried out to understand hydrocarbon prospectivity

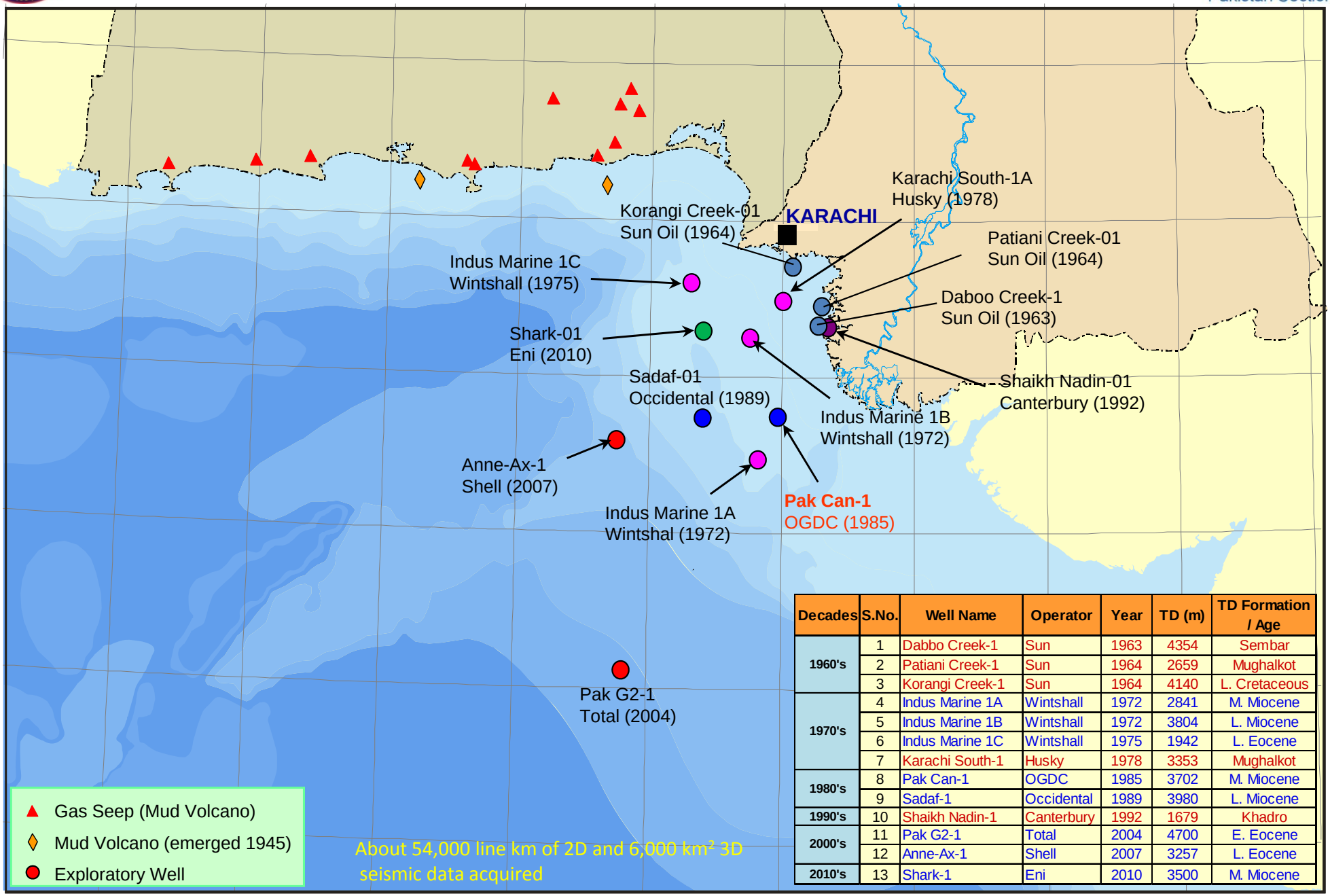
LOCATION MAP

- Murray Ridge-Owen Fracture Zone to the west and Bombay High to the east
- Two tectonic units with the dividing hinge line/shelf break :
  - Platform to NE, and
  - Deep offshore to SW



EXPLORATION HISTORY

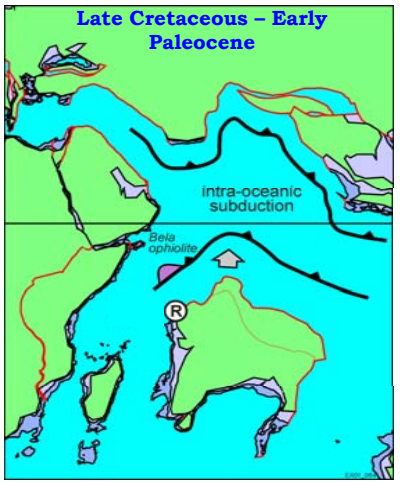
Pakistan Section

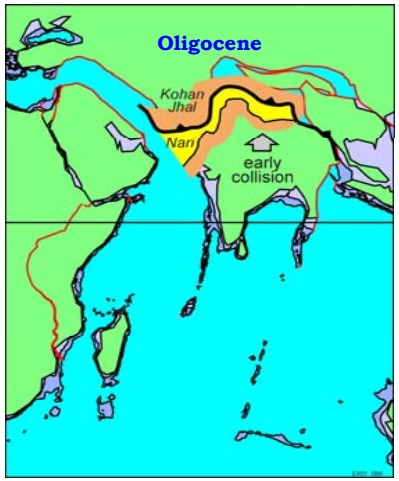


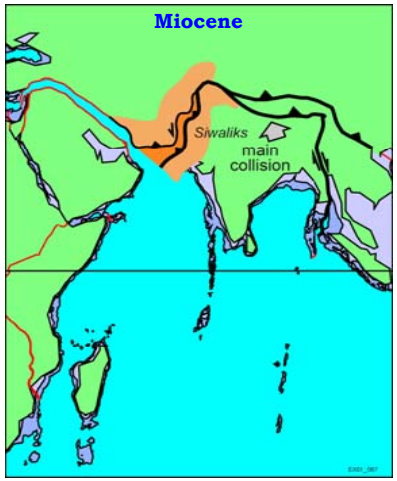
Decades	S.No.	Well Name	Operator	Year	TD (m)	TD Formation / Age
1960's	1	Dabbo Creek-1	Sun	1963	4354	Sembar
	2	Patiani Creek-1	Sun	1964	2659	Mughalkot
	3	Korangi Creek-1	Sun	1964	4140	L. Cretaceous
1970's	4	Indus Marine 1A	Wintshall	1972	2841	M. Miocene
	5	Indus Marine 1B	Wintshall	1972	3804	L. Miocene
	6	Indus Marine 1C	Wintshall	1975	1942	L. Eocene
	7	Karachi South-1	Husky	1978	3353	Mughalkot
1980's	8	Pak Can-1	OGDC	1985	3702	M. Miocene
	9	Sadaf-1	Occidental	1989	3980	L. Miocene
1990's	10	Shaikh Nadin-1	Canterbury	1992	1679	Khadro
2000's	11	Pak G2-1	Total	2004	4700	E. Eocene
	12	Anne-Ax-1	Shell	2007	3257	L. Eocene
2010's	13	Shark-1	Eni	2010	3500	M. Miocene

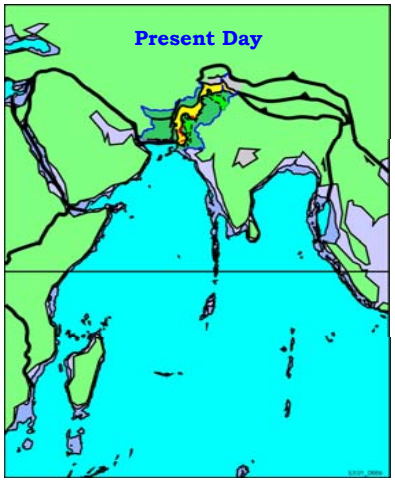
GEOLOGICAL HISTORY

- **Late Cretaceous – Early Paleocene:**
  - Rapid northward movement of Indian Plate after separation from Madagascar
  - Bela ophiolites obduction
  - Extrusion of Deccan Volcanics
- **Paleocene - Eocene:**
  - Deposition of limestone on seamounts and shales in lows / depressions
- **Oligo-Miocene:**
  - Himalayan orogeny
  - Indus Delta-Fan deposition

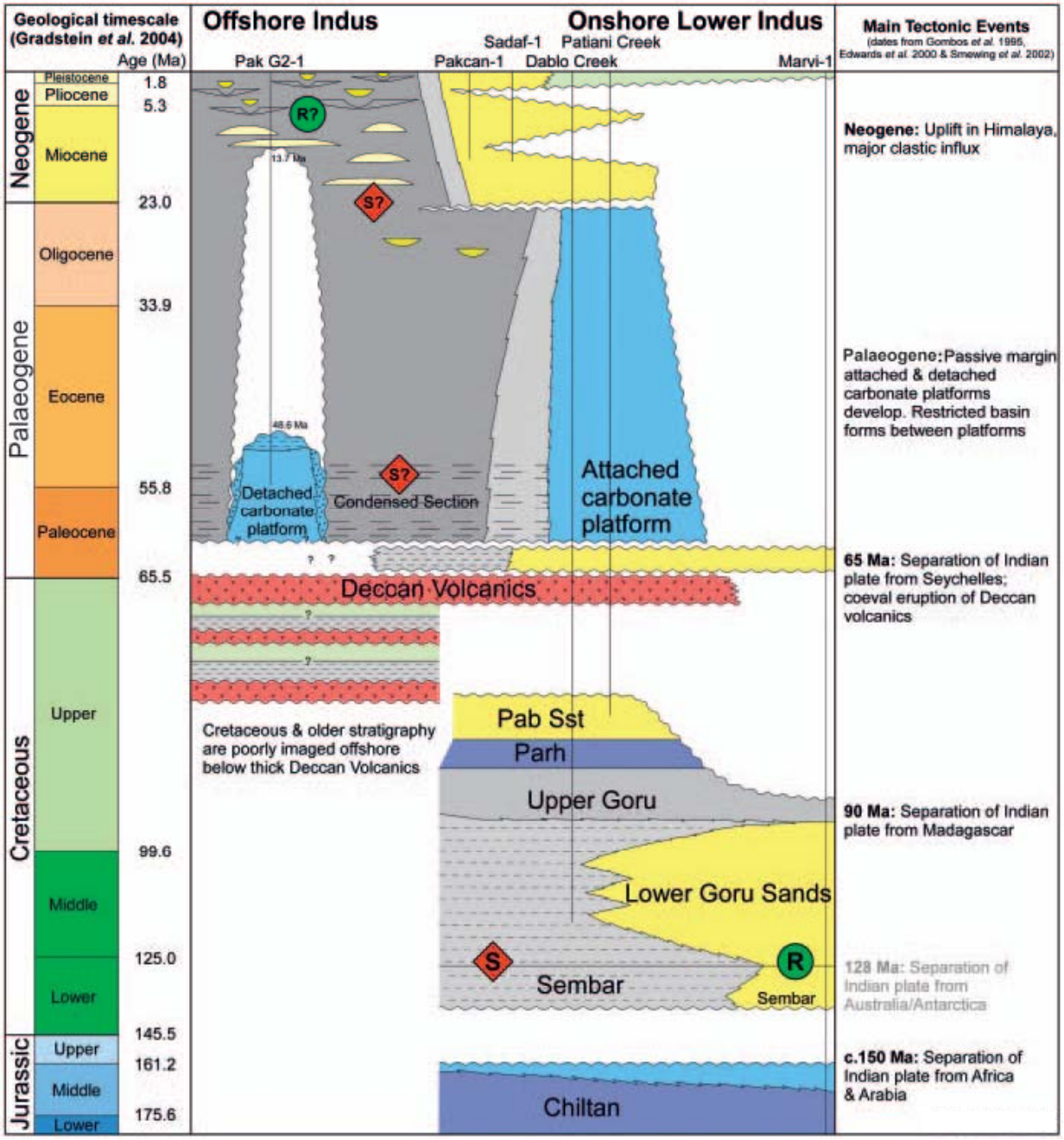








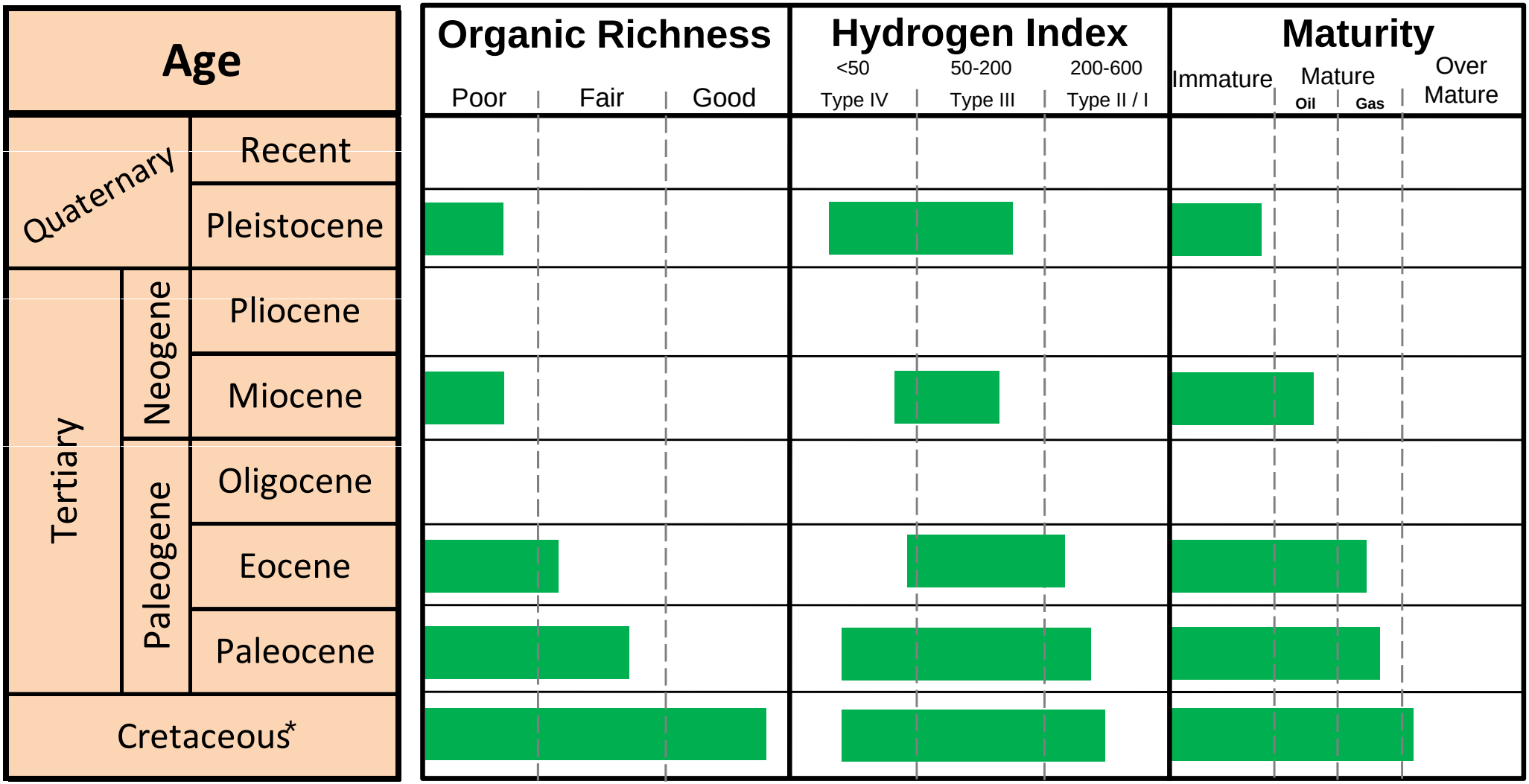
STRATIGRAPHY & PETROLEUM SYSTEM



After Carmichael, 2009

STRATIGRAPHY & PETROLEUM SYSTEM

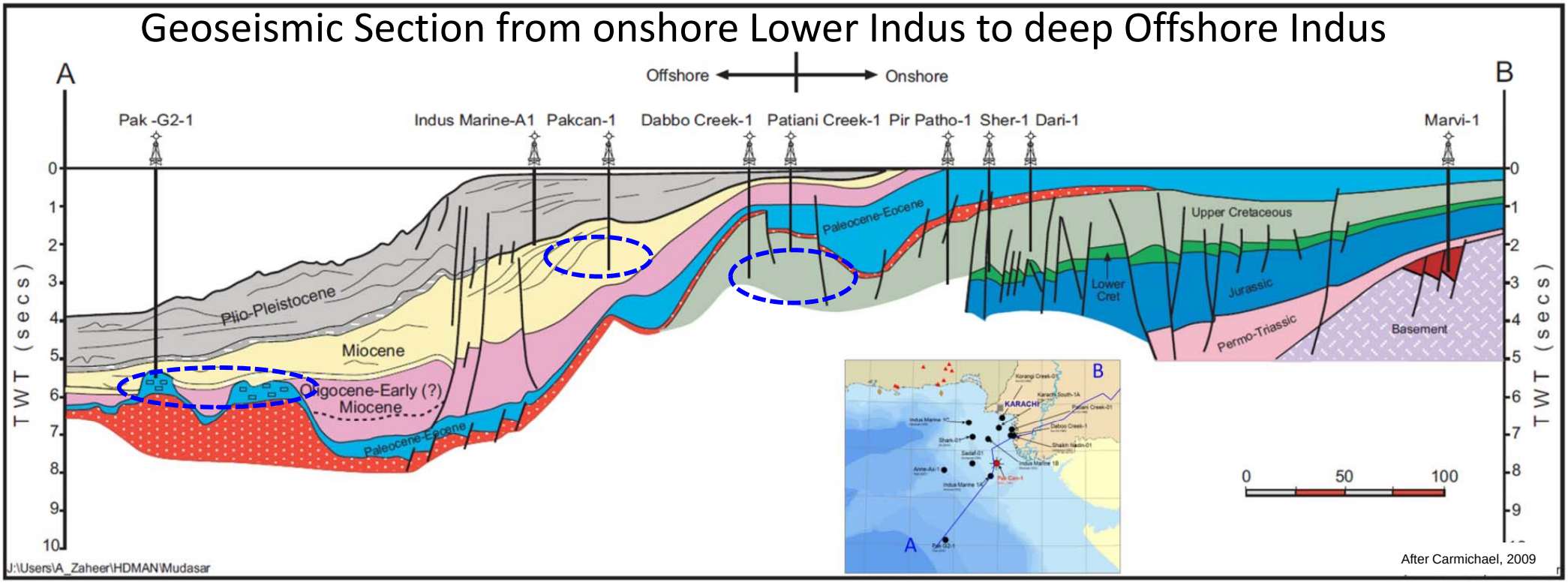
SOURCE ROCK PARAMETERS FROM WELLS



Offshore / Nearshore Karachi South-1A, Sadaf-01, Indus Marine-1A and PakCan-01 wells data used

* Includes data from onshore Lower Indus

STRATIGRAPHY & PETROLEUM SYSTEM



Reservoirs

- Miocene sandstones are proven reservoir (PakCan-1); Individual sandstone units vary in thickness from 2-50 m with porosity ranging between 15-20%
- In deep offshore, reefal or shoal limestone of Eocene-Oligocene age with more than 20% porosity (Pak G-2-1)
- Upper Cretaceous Pab/Mughal Kot and Paleocene Ranikot formations may be secondary reservoir targets in near-shore areas

STRATIGRAPHY & PETROLEUM SYSTEM

Seals

- Mud-dominated sediment packages will provide seals for potential reservoirs
- Transgressive mudstone and marls provide seals for Eocene-Oligocene reservoirs
- Intra-formational shales of Miocene would provide seal for the Miocene sands

Traps

- Both structural and stratigraphic traps
- Eocene carbonates build ups over seamounts, growth faults, roll-over anticlines and stratigraphic traps within deltaic fan system (e.g., bars, barrier islands and pinch-out / facies change etc.) are likely trapping mechanisms

EXPLORATION RISKS

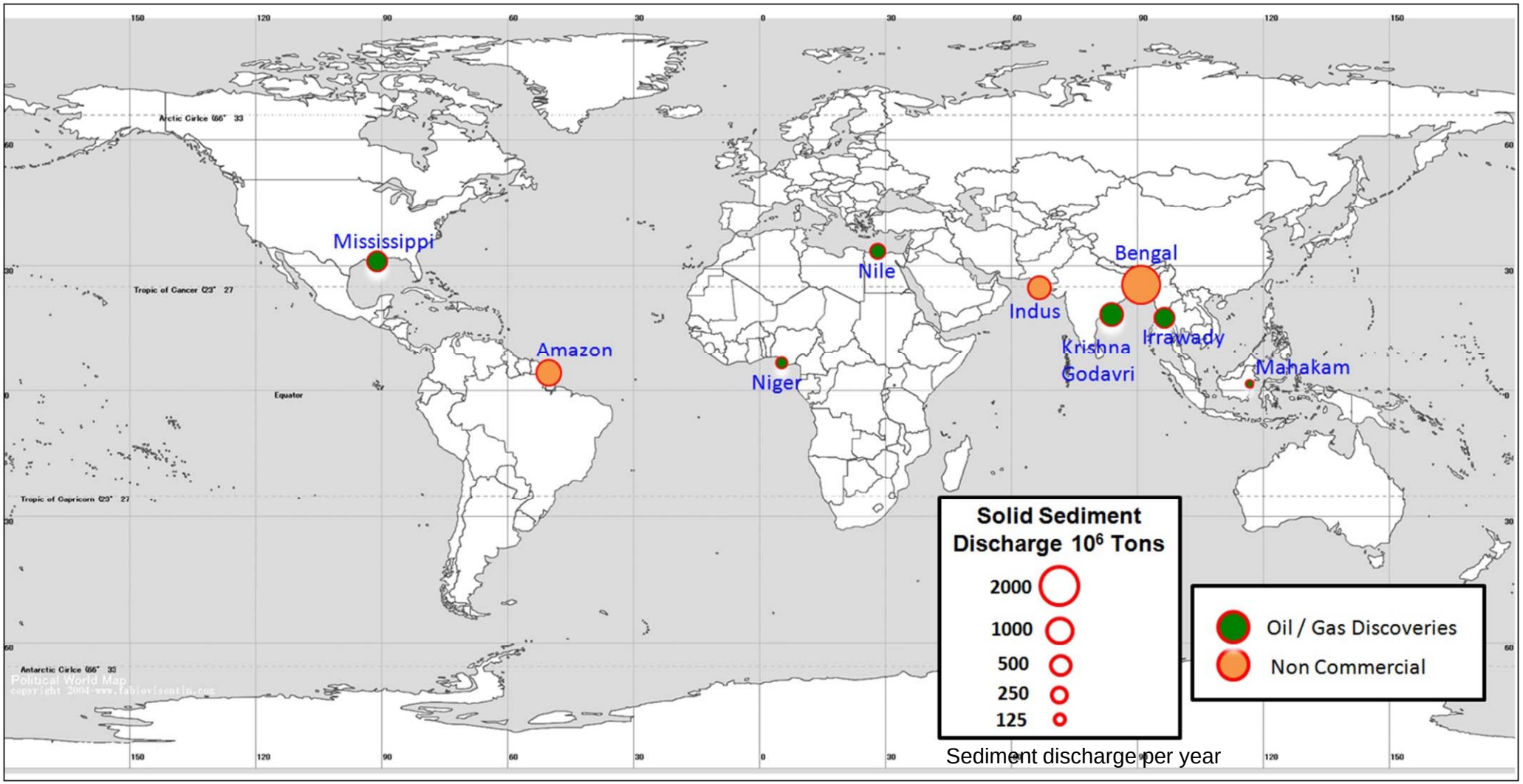
- **Source & Charge:** Medium to High risk
- **Reservoir:** Low to Medium risk
- **Seal:** Low to Medium risk
- **Trap:** Low to Medium risk

- Key challenges for future exploration in Tertiary Petroleum System are to establish:
  - Distribution and timing of effective source intervals' development within the drainage area of prospect
  - Timing of over-pressuring (up to 7000 psi at 2800m in Indus Marine-1A well) within Miocene section (for Miocene and younger targets) with respect to source rock maturation and expulsion

COMPARISON WITH OTHER TERTIARY DELTAS OF THE WORLD

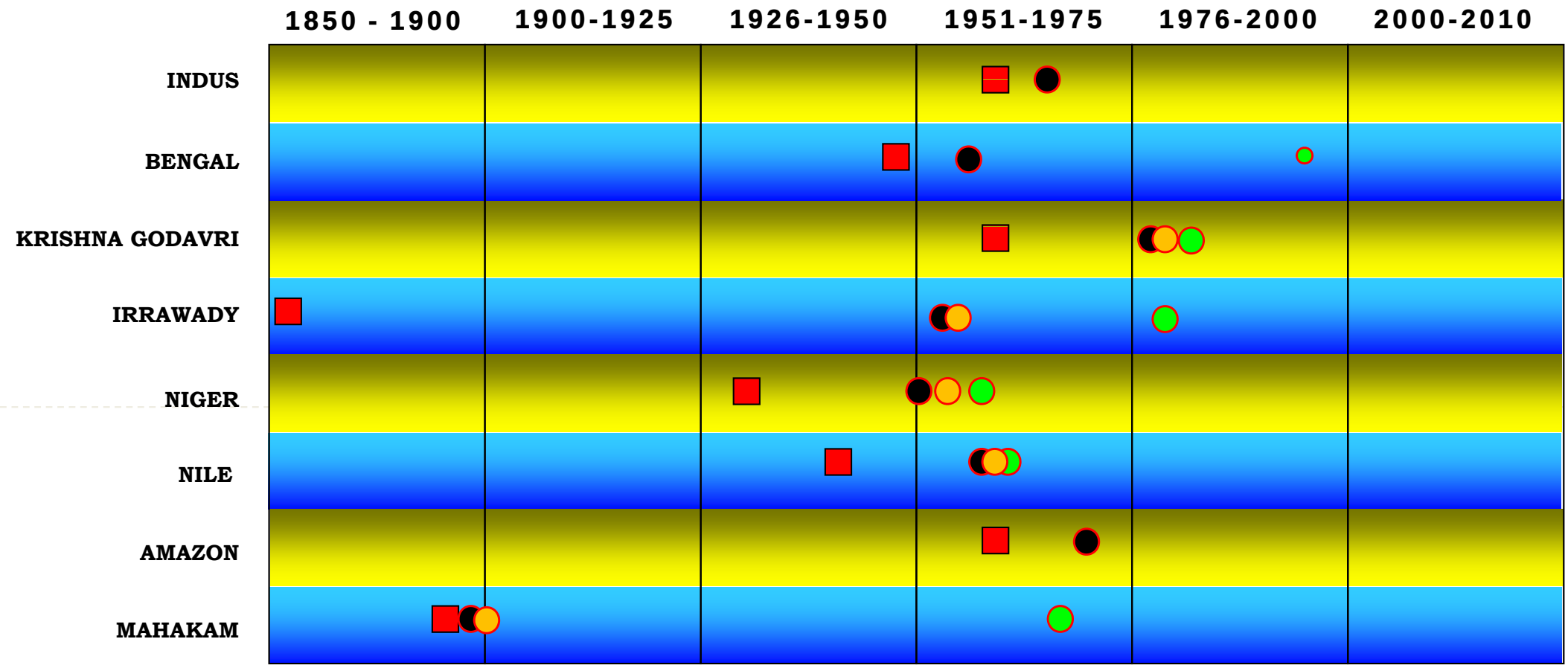
- A comparative study of Indus Delta petroleum system carried out with following deltas of the world :
  - Bengal Delta (Bangladesh and India)
  - Krishna-Godavari Delta (India)
  - Irrawaddy Delta (Myanmar)
  - Niger Delta (Nigeria)
  - Nile Delta (Egypt)
  - Amazon Delta (Brazil)
  - Mahakam Delta (Indonesia)

MAJOR DELTAS - PRESENT DAY SEDIMENTATION RATE

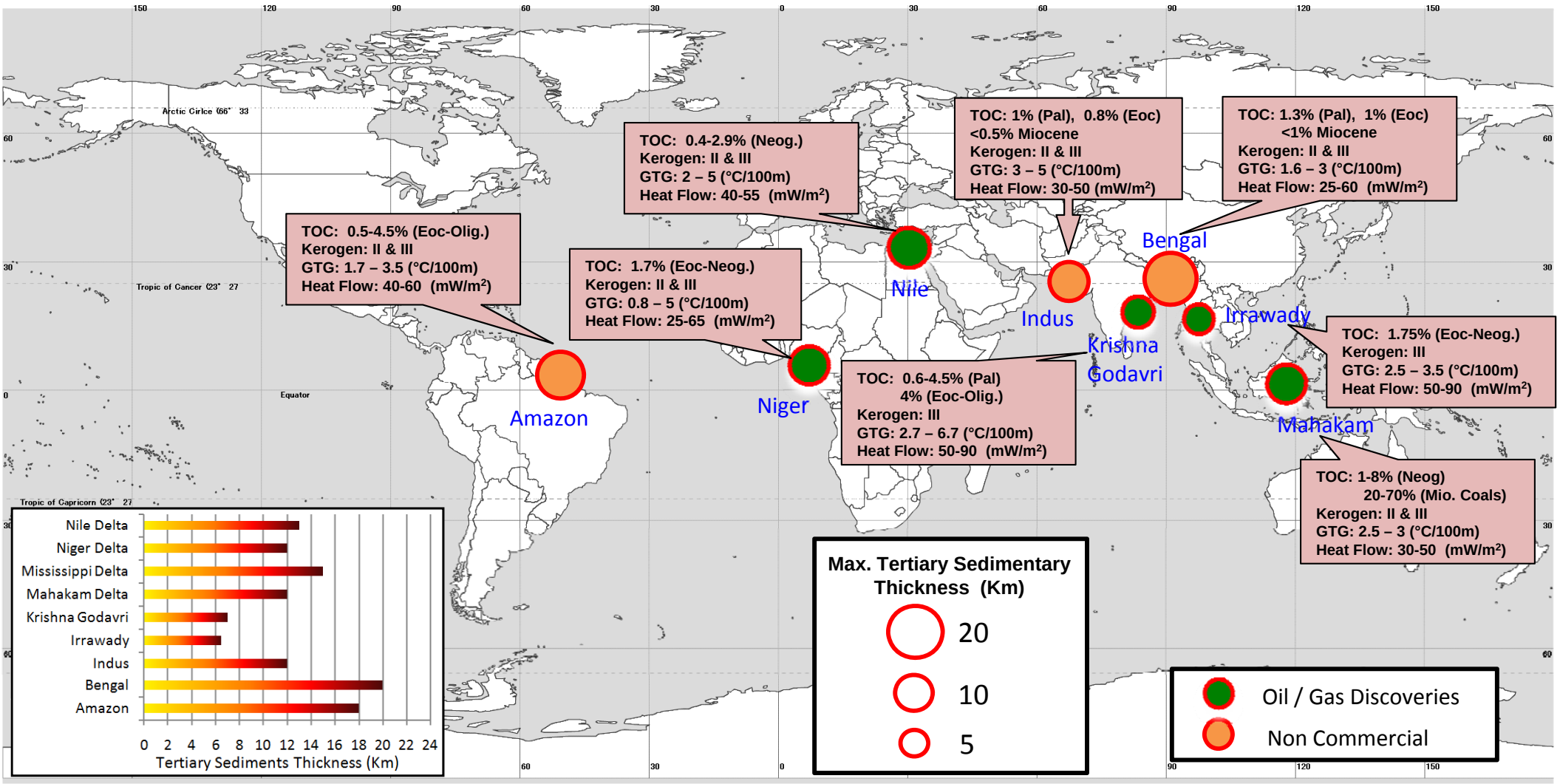


Sediment discharge per year

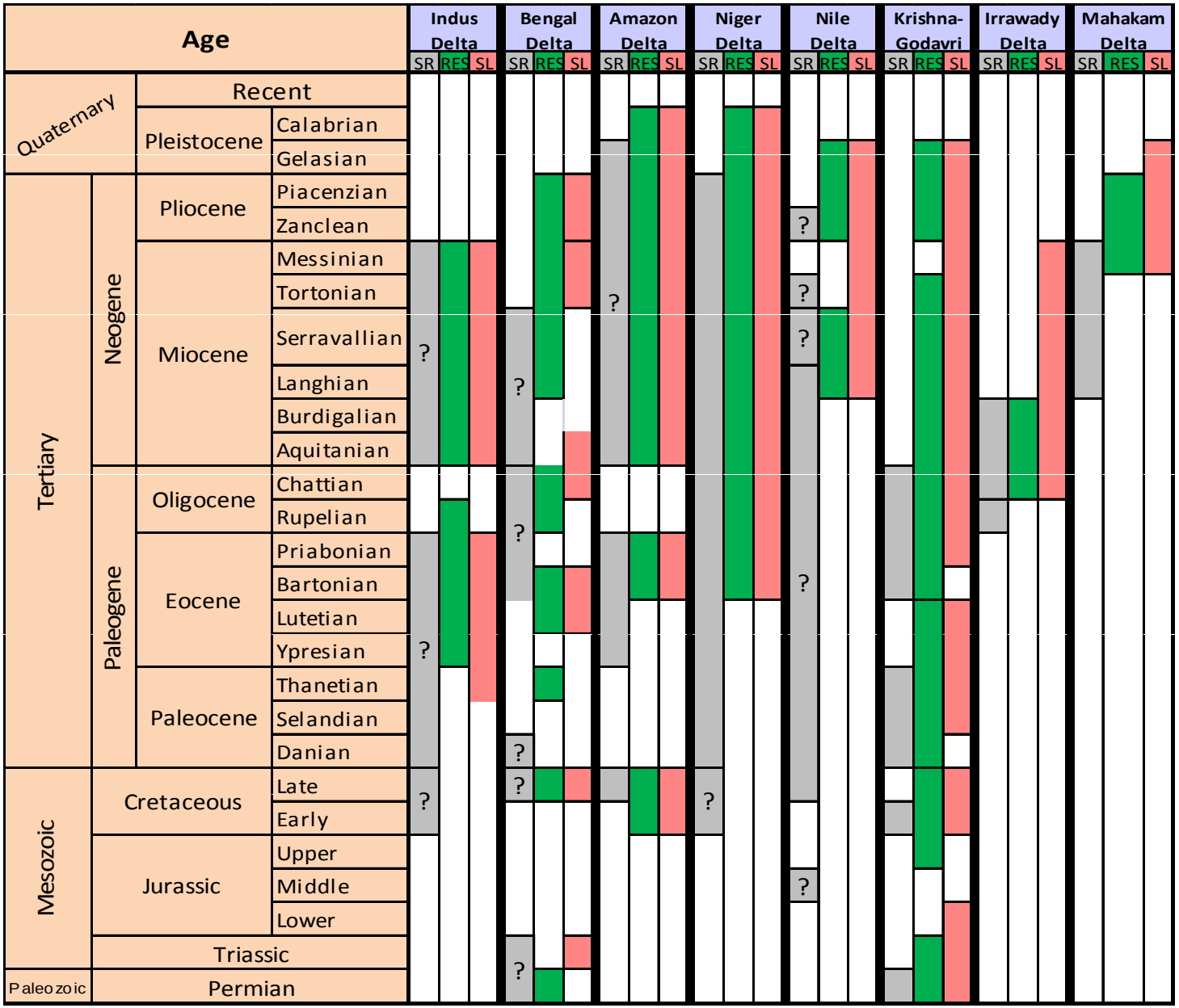
MAJOR DELTAS – EXPLORATION HISTORY



MAJOR DELTAS - TERTIARY THICKNESS AND SOURCE ROCKS



MAJOR DELTAS - PETROLEUM SYSTEM



COMPARISON RESULTS

- Comparison suggests that discoveries in offshore deltas have been made in:
  - Extension of proven onshore petroleum system to offshore at drillable depth (e.g. Niger, Nile, Irrawady & Mahakam deltas)
  - Reservoir –Seal pairs associated with good quality but less mature source rock drilled onshore (at shallow depths) progressively mature in offshore (e.g. Krishna-Godavri and Nile deltas)
  - Biogenic gas found in shallow younger Tertiary section (e.g. Krishna-Godavri and Nile deltas)

BASIN MODELING

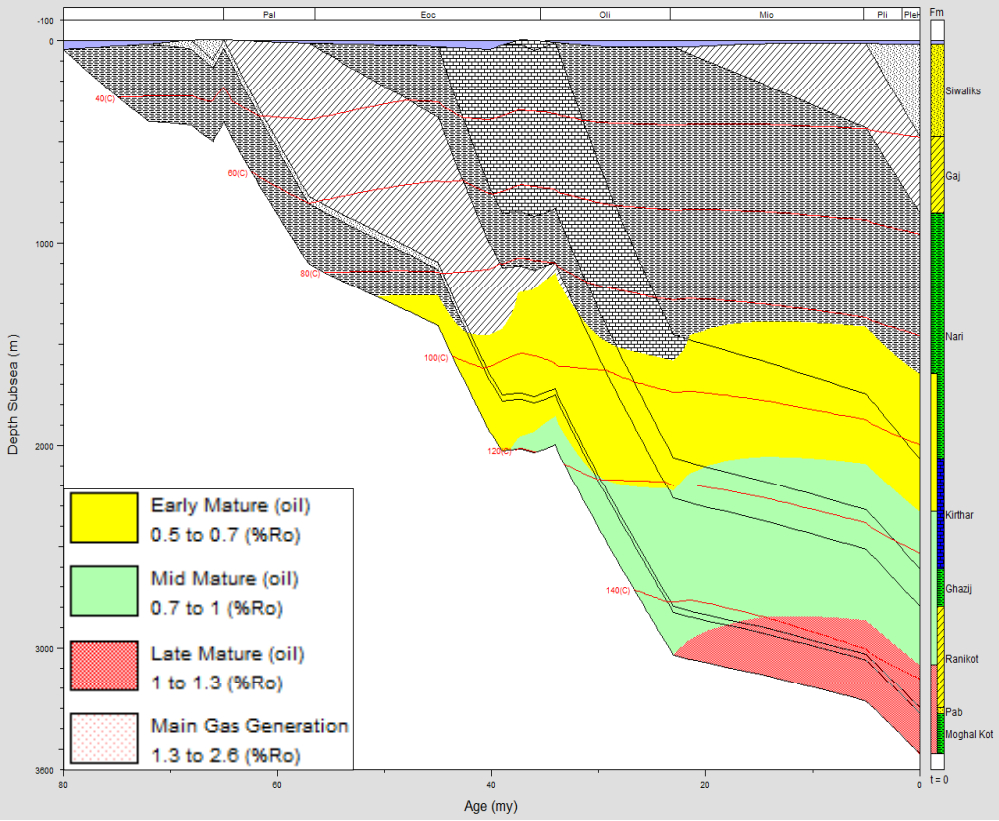
- 1D Basin Modeling carried out on 3 wells' location:
  - Karachi South-1A (Near-shore)
  - PakCan-1 (Shelf)
  - Pak G2-1 (Deep offshore seamount)

- Vitrinite reflectance of Karachi South-1A and PakCan-1, and BHTs in Pak G2-1 used for maturity calibration

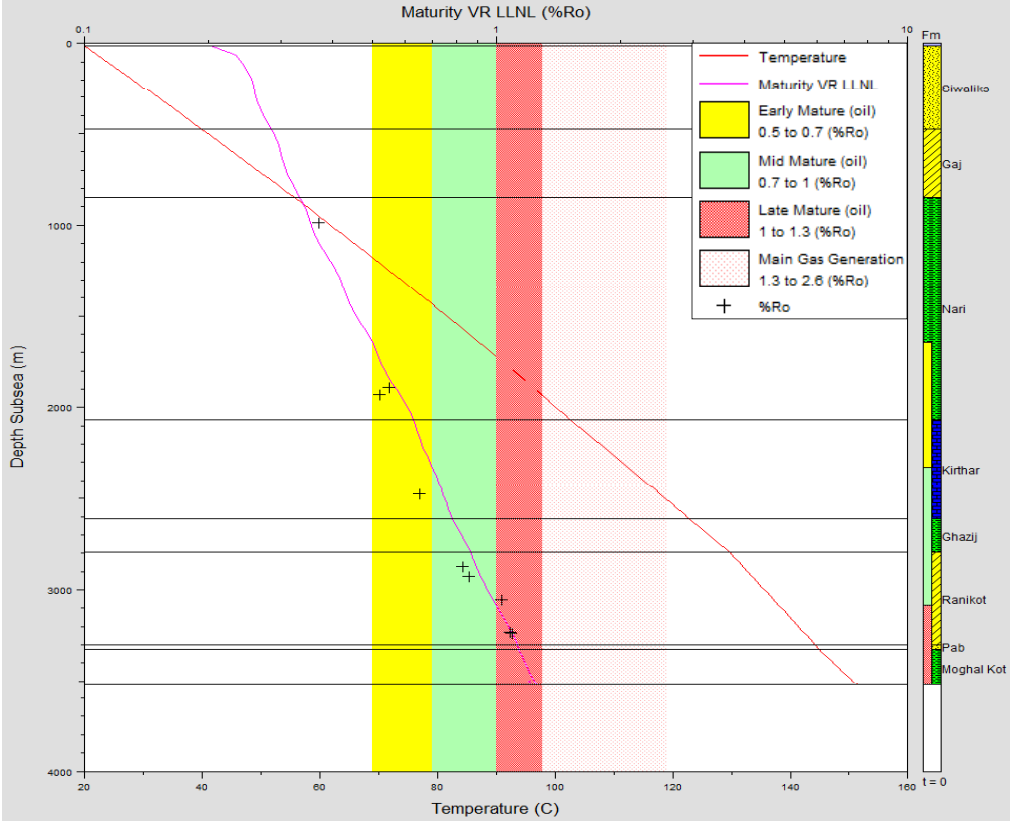
BASIN MODELING – Karachi South-1A

- Ranikot sequences entered in Mid Mature Oil window in Middle Oligocene
- Presently lower part of Ranikot is in Late Mature Oil window

Burial History Curve



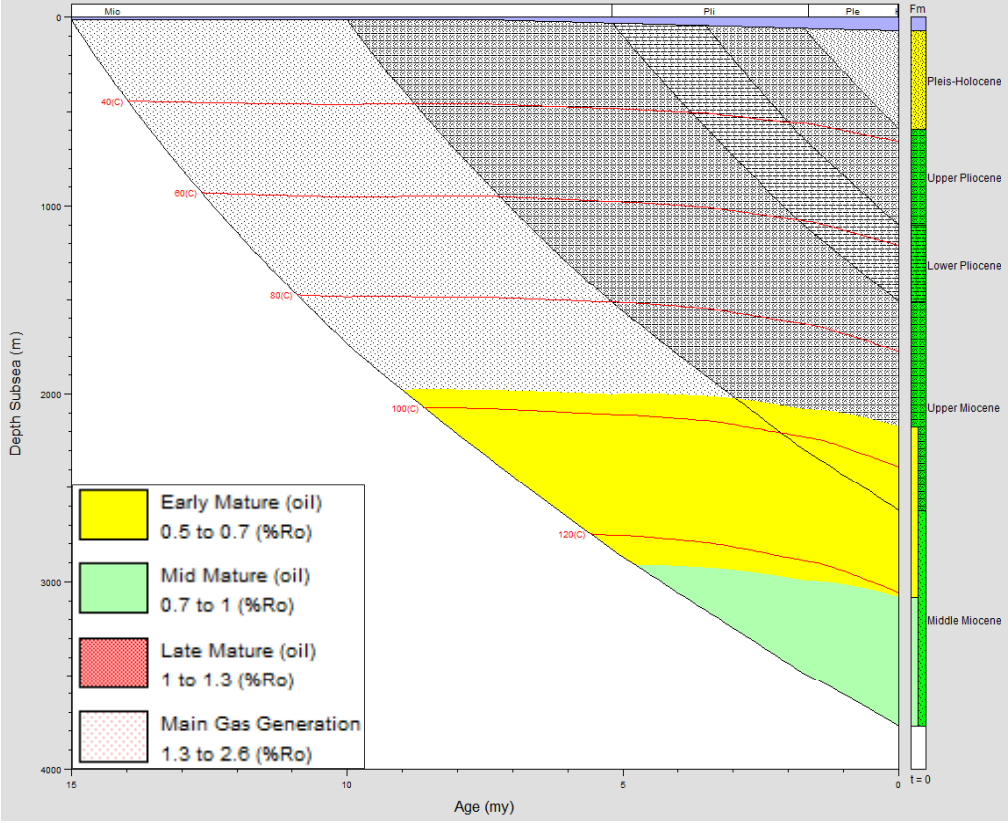
Calculated Temperature and Maturity VR



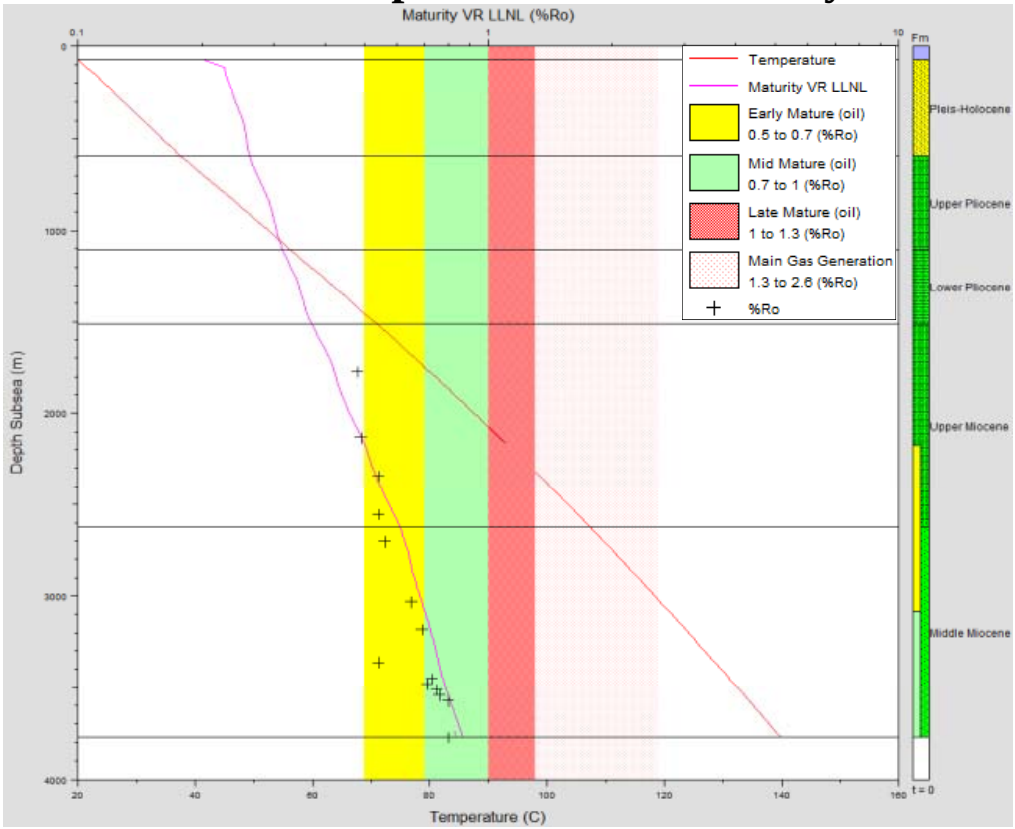
BASIN MODELING – PakCan-1

- Lower part of Middle Miocene entered in mid mature oil window in Pliocene time
- Maturity profile indicates that Paleocene and Eocene section will be in main gas generation window and might have charged the Miocene sands

Burial History Curve



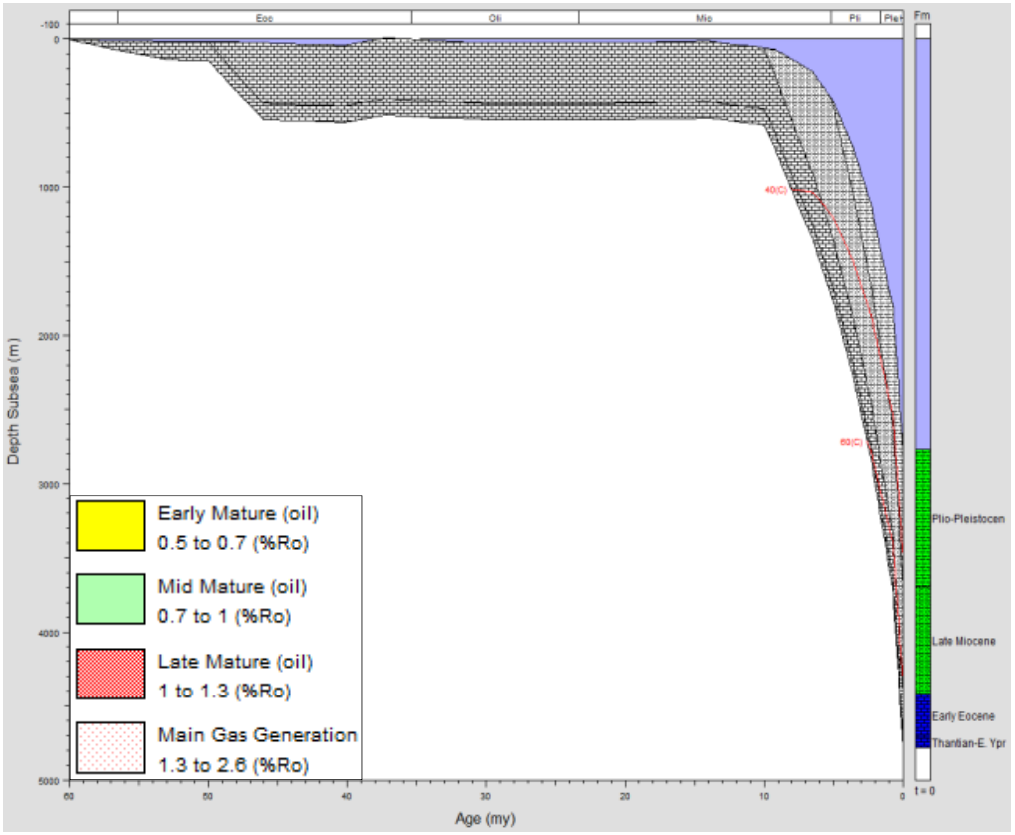
Calculated Temperature and Maturity VR



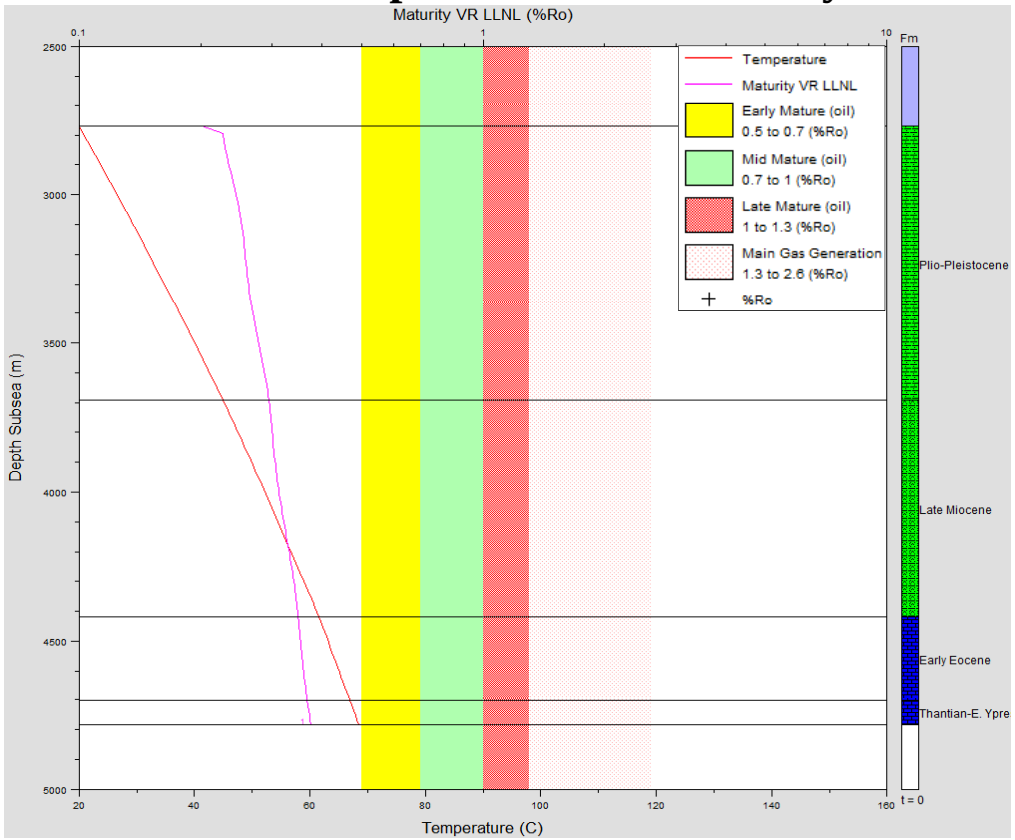
BASIN MODELING – Pak G2-1

- Immature Paleocene rocks
- Gas shows indicate thermogenic gas generation where the Paleogene section is deeply buried

Burial History Curve



Calculated Temperature and Maturity VR



CONCLUSIONS

- International offshore exploration efforts in delta areas have generally been successful due to:
  - Extension of established onshore petroleum system to offshore at drillable depths
  - Good quality less mature source rock drilled onshore progressively mature in offshore
  - Gas discoveries of biogenic origin

- In Indus Offshore:
  - Onshore proven Cretaceous petroleum system (Sembar, Goru, Mughalkot & Pab) is generally at significant depths in the offshore part due to presence of very thick Deccan Volcanics
  - Miocene and younger section drilled onshore is less likely to have encouraging play attributes
  - Miocene section which has lean gas generation potential is generally not in gas window
  - Exploration focus should be in areas with mature / access to mature Paleocene-Eocene source rock
  - Regionally mature kitchens (especially in Paleocene – Eocene section) should be located first, which will eventually reduce the area of search

Acknowledgement

- We are thankful to the management of PPL for granting permission to present this paper
- We are indebted to Jerome Kelly (Global Geological Advisor, Tullow Oil) and Syed Manshoor Ali (GM Exploration, Spud Energy) for their review and constructive input
- We also thank our colleagues for their support and help

Thank You . . .