Mud Diapirism Induced Structuration and Implications for the Definition and Mapping of Hydrocarbon Traps in Makran Accretionary Prism, Pakistan*

Moin Raza Khan[1], Abid Hussain[2], Muhammad Sajid[2], and Tahir Javed[2]

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[1]Exploration, Pakistan Petroleum Limited, Karachi, Sind, Pakistan (k_moin@ppl.com.pk)
[2]Exploration, Pakistan Petroleum Limited, Karachi, Sind, Pakistan

Abstract

The mobile mud coupled with tectonic forces has played an important role in shaping the structural styles as well as geomorphic features in the Makran Accretionary Prism. At surface, key structural elements associated with mud tectonics such as broad synclines, very tight anticlines, and mud volcanoes have been observed particularly in the southeastern part of the Makran Accretionary Prism. There are often associated emanating methane gas with mud volcanoes. In the subsurface, mud walls and mud diapirs have been envisaged in the cores of anticlines separated by less deformed broad synclines representing possible mud withdrawal areas. Occasionally, anticlines encircle the synclines and form dish like geomorphic feature, which appear like mini basins. The same as the ones associated with salt tectonics. These kinds of mini basins usually act as depocentres for the sediments eroded from adjacent growing anticlines as well as for pounded turbidites from regional sediment supply. It is also envisaged that the strata probably truncate against the mud walls as in analogous geological settings. Folding related fracture sets and strike slip faults have facilitated the extrusion of the mud at the surface. This phenomenon is characterized by occurrence of active as well as passive mud volcanoes in the study area. Results of the study suggest that potential hydrocarbon traps in the region of the Makran Accretionary Prism could be associated with the truncation of strata against "Mud walls" and around "Mud diapirs" with hydrocarbon accumulations at the limbs of anticlines. To date, a number of dry wells have been drilled in the Makran Accretionary Prism, mostly targeting the crests of these mud-cored anticlines, which could be one of the reasons of not finding the predicted reservoirs, let alone the hydrocarbons. Due to the same geological reason, drilling hazards while drilling through the over pressured mudstones have also led to mechanical failures in some of the wells, i.e. Dhak Anticline wells. The proposed paradigm shift in defining the hydrocarbon traps and locating the exploratory wells on these structures has significant implications for petroleum exploration in the region.

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PPL

September, 2015

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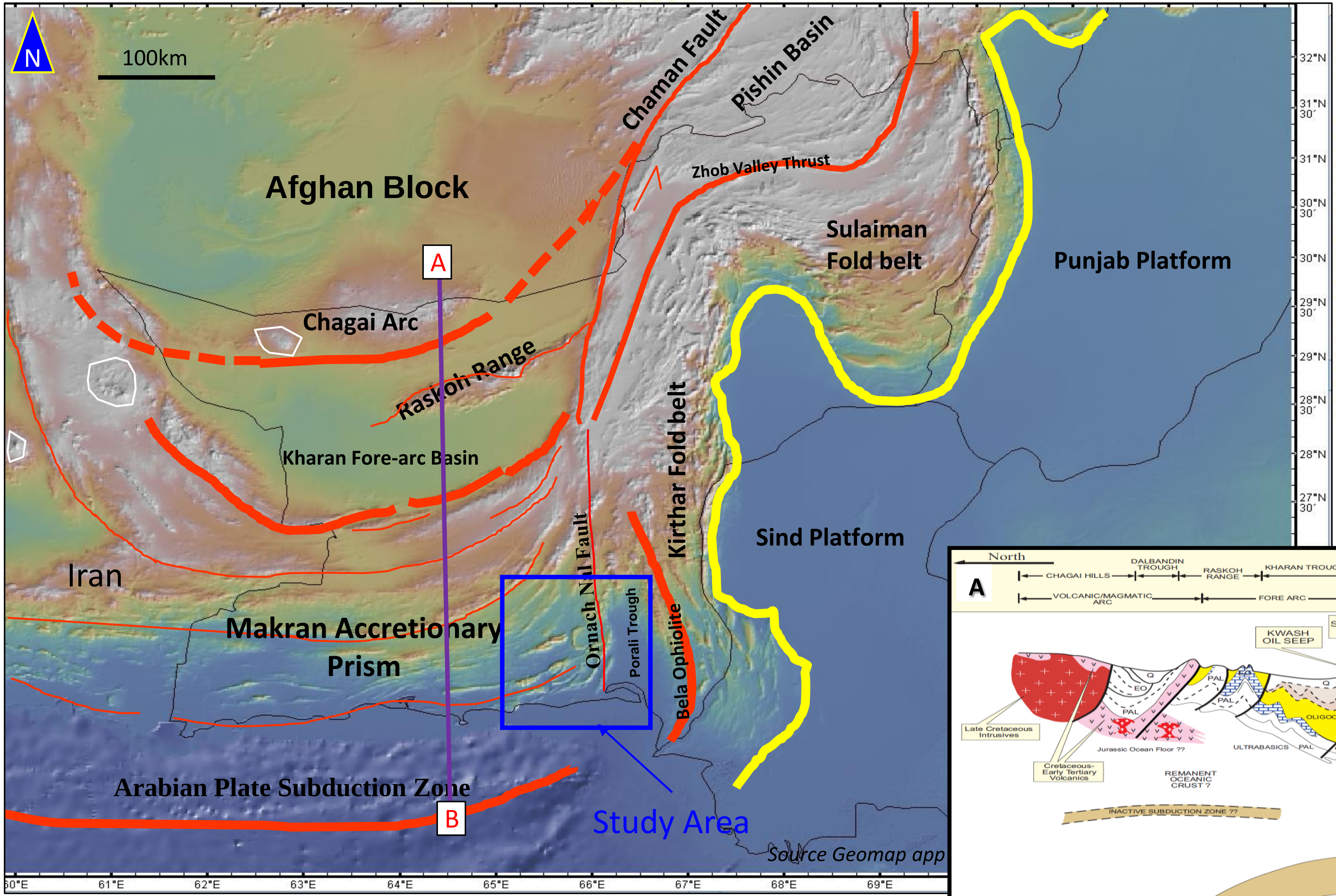
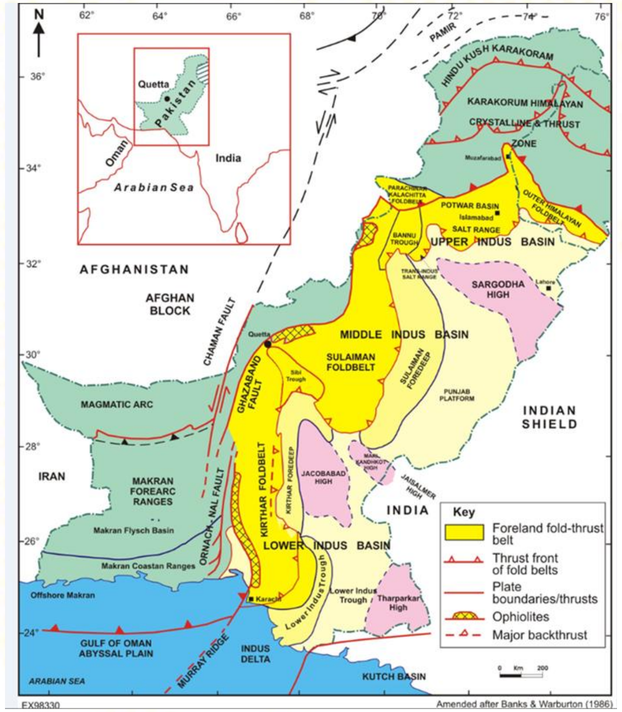
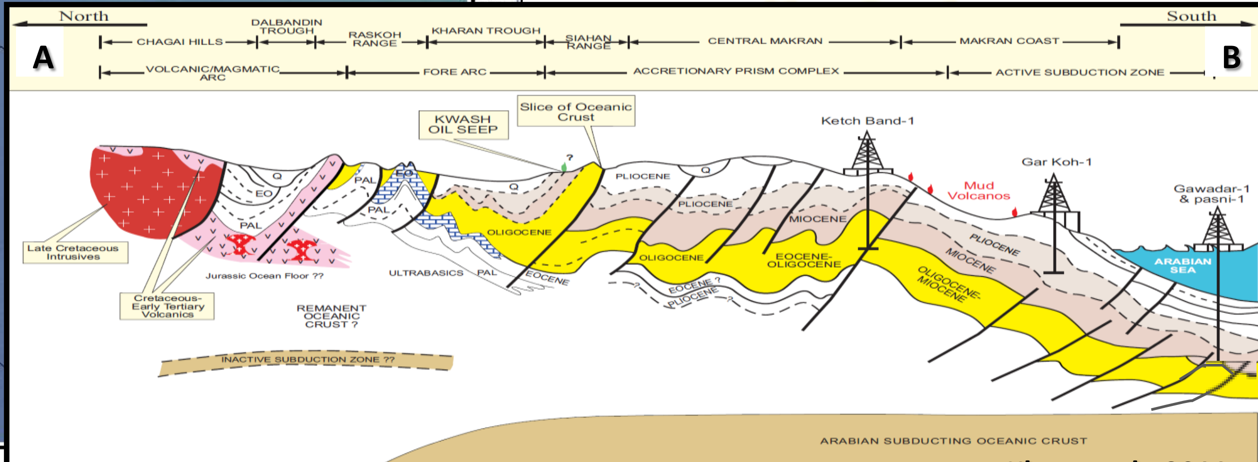
Objective

- **To share the possibility of Hydrocarbon entrapment mechanism associated with Mud-diaprism and spatial facies variations - not yet explored in Makran Accretionary Prism**

Geological Introduction to Study Area

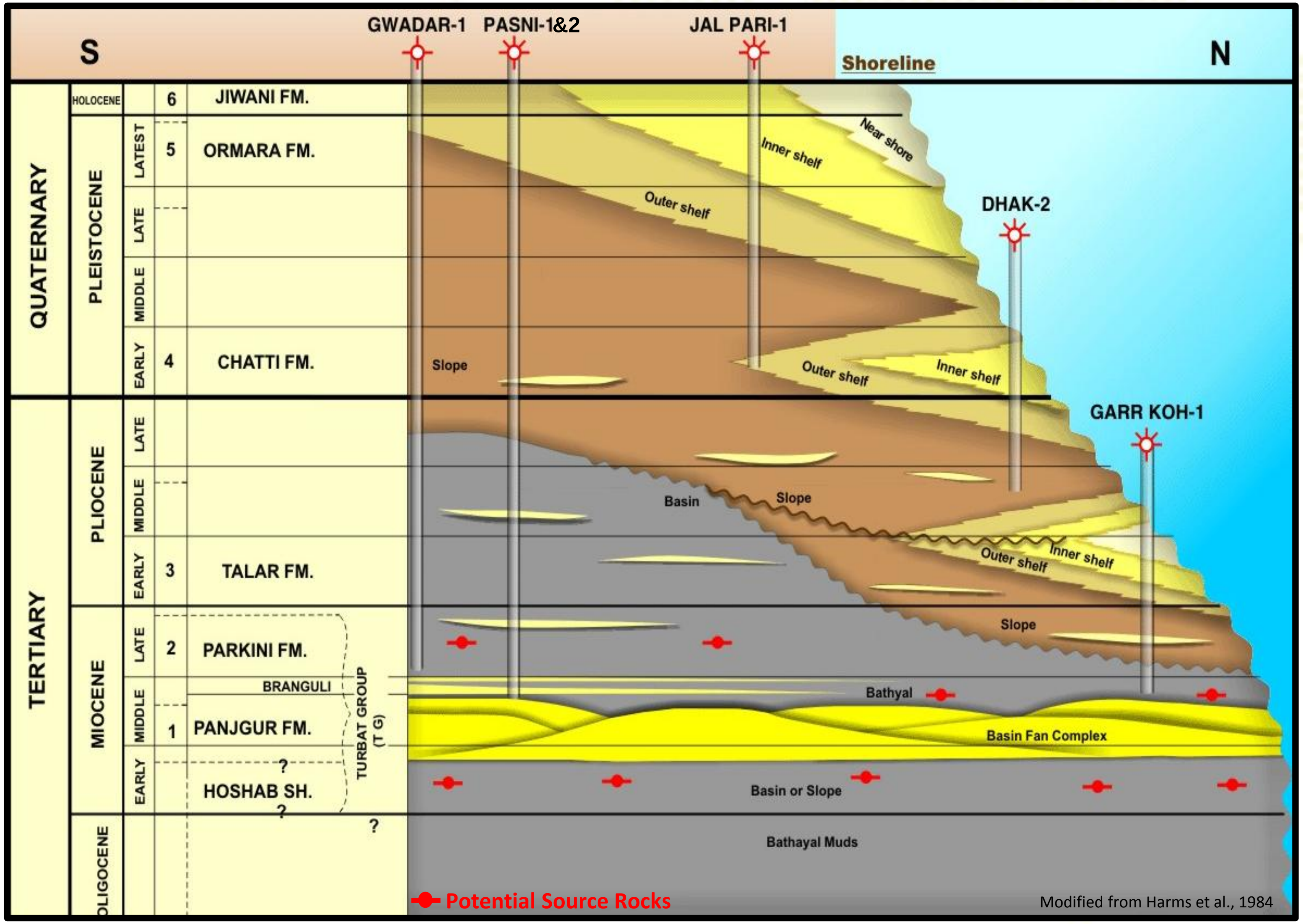


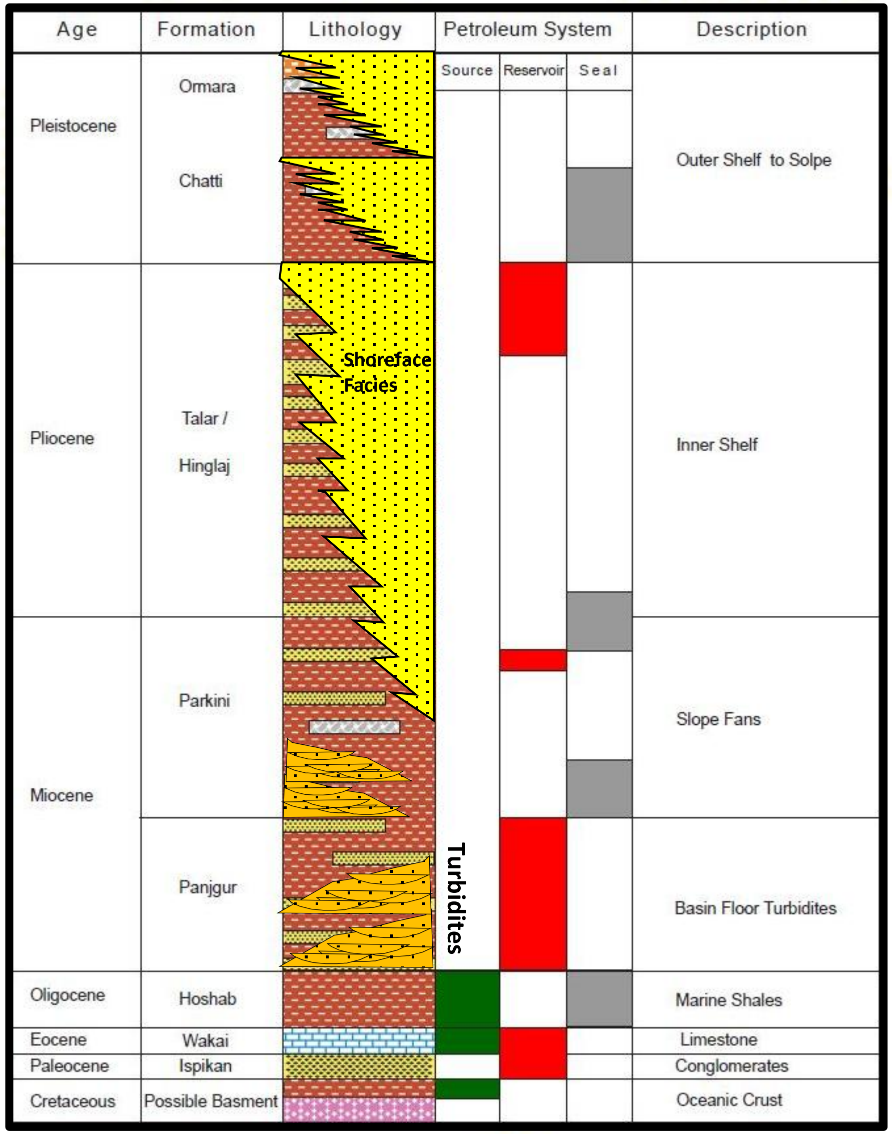




Khan et al,. 2011

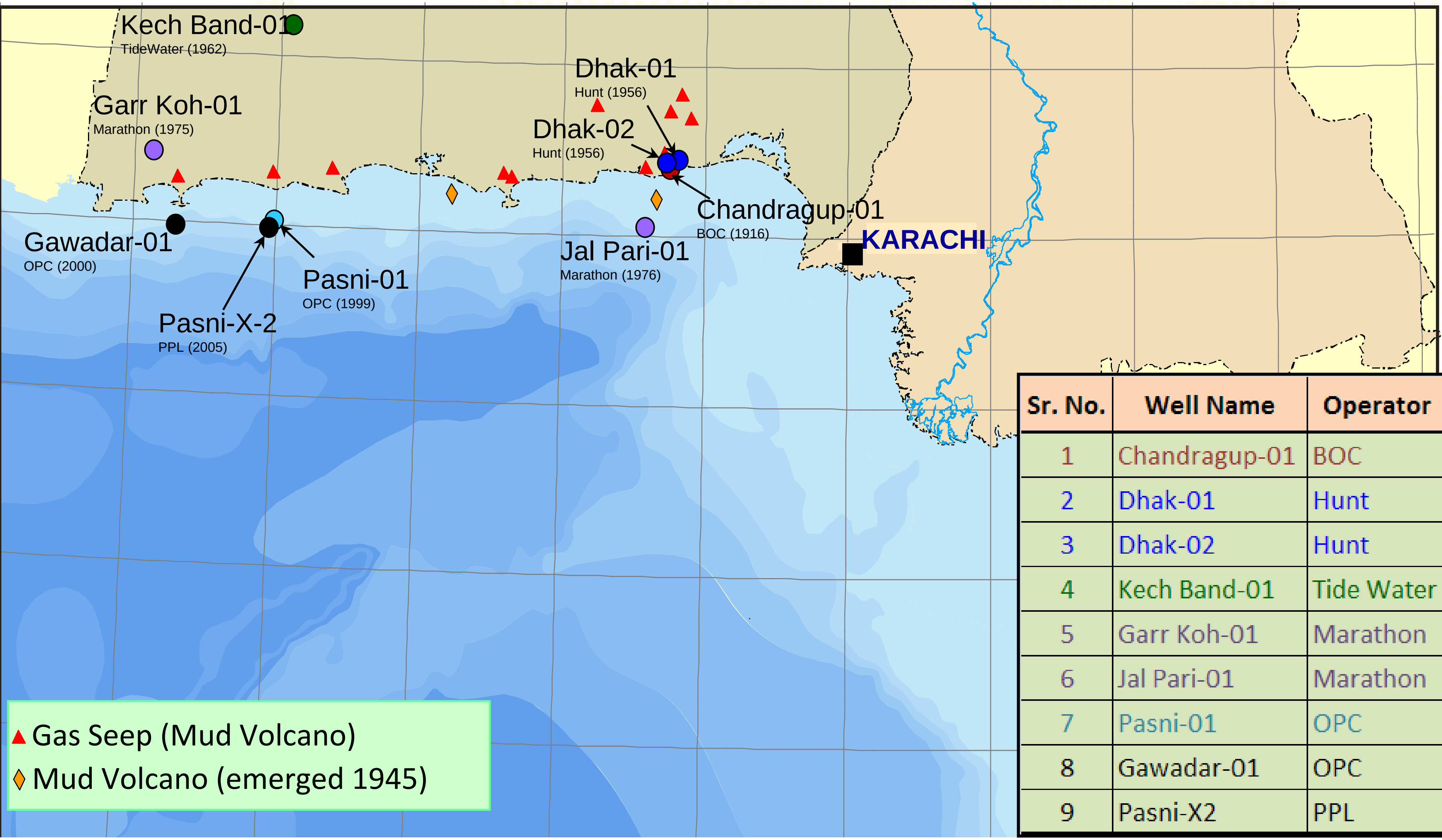
Startigraphy and Petroleum System

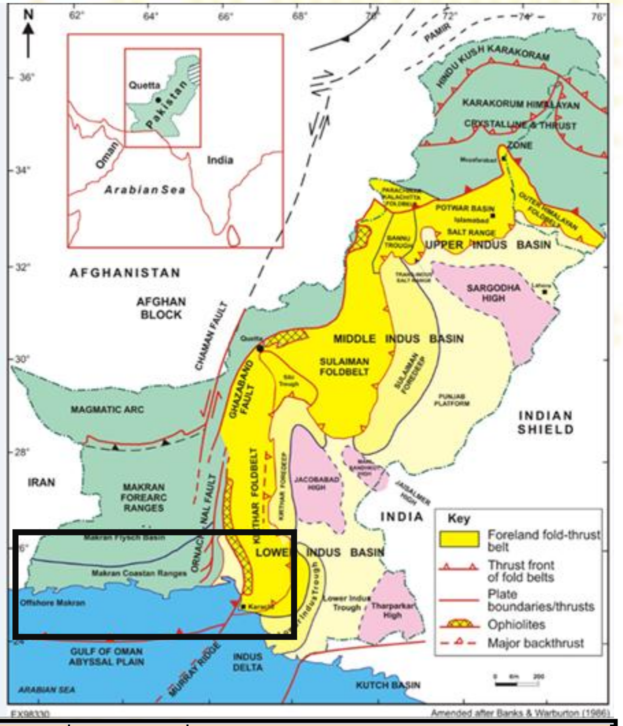




Exploration History

- Total nine wells drilled in the Makran Accretionary Prism area targeting the turbidites
- Well mostly failed due to absence of reservoir or mechanically failed



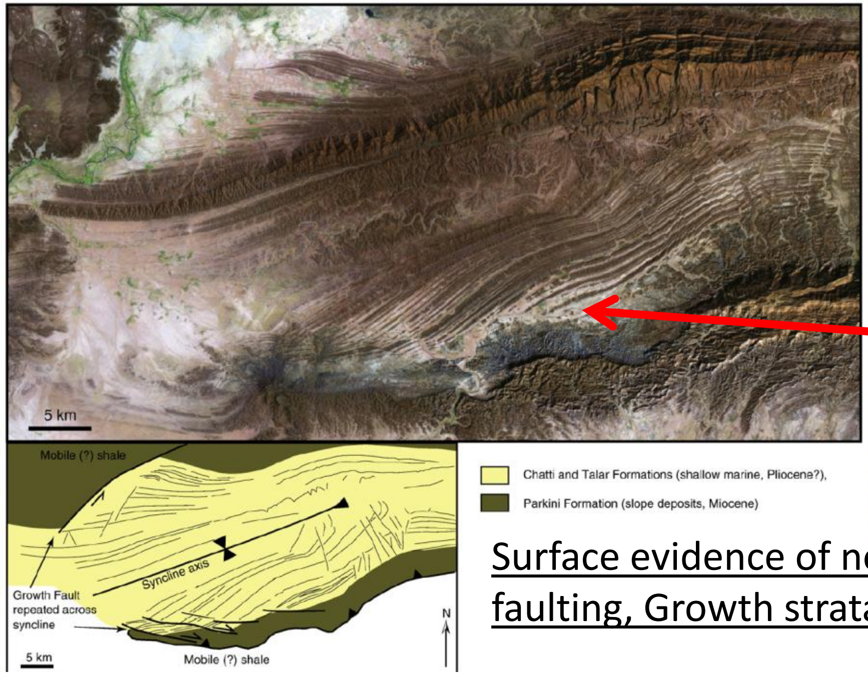


Sr. No.	Well Name	Operator	Year	TD (m)	Results (All wells P&A)
1	Chandragup-01	BOC	1916	810	Mechanical Failure
2	Dhak-01	Hunt	1956	2561	Reservoir not encountered
3	Dhak-02	Hunt	1956	4454	Mechanical Failure
4	Kech Band-01	Tide Water	1962	3348	Reservoir not encountered
5	Garr Koh-01	Marathon	1975	3622	Reservoir not encountered
6	Jal Pari-01	Marathon	1976	2007	High formation pressures
7	Pasni-01	OPC	1999	3368	Reservoir not encountered
8	Gawadar-01	OPC	2000	3810	Reservoir not encountered
9	Pasni-X2	PPL	2005	4000	Reservoir not encountered

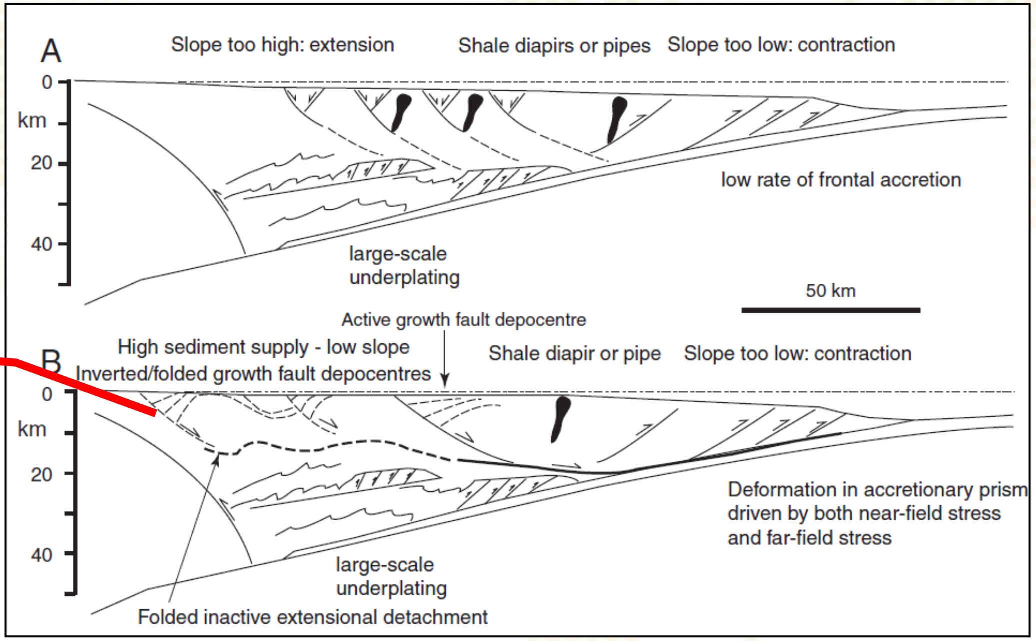
Challenges in drilling the Mud Volcanos

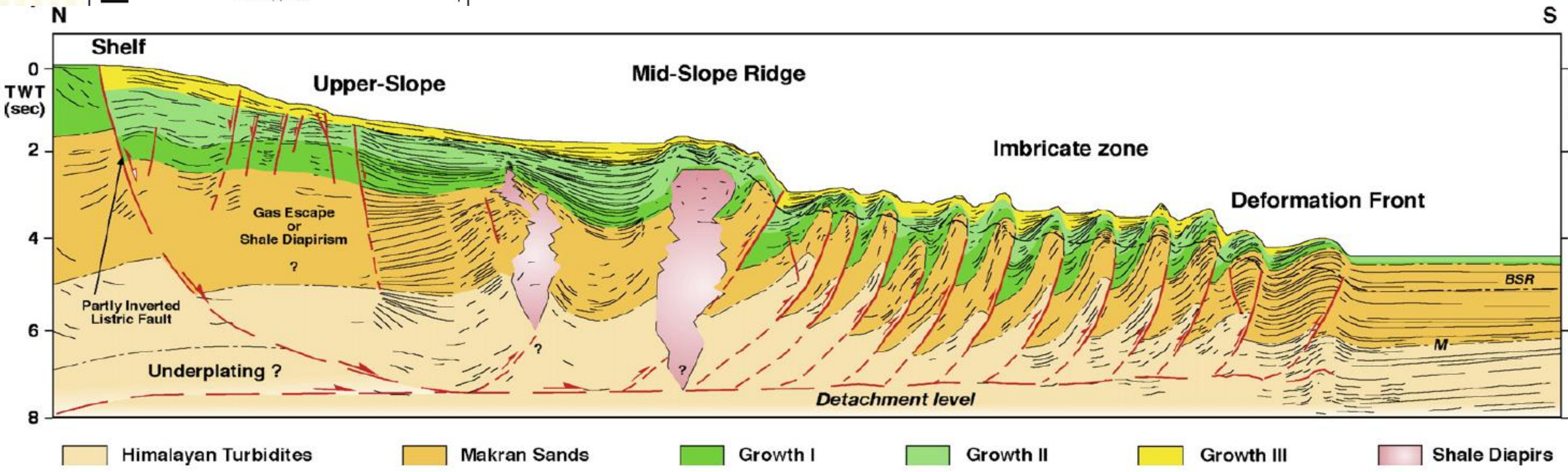
- **Sidoarjo mud flow** or Lapiindo mud (informally Lusi a contraction of Lumper Sidoarjo wherein lumper is the Indonesian word for mud)
  - On May 28, 2006, Banjar-Panji 1 exploration well in Indonesia triggered the mud eruption at Lusi.
  - It started with eruption of water, steam and a small amount of gas at a location about 200 m southwest of the well
  - Two further eruptions occurred on following days about 800–1000m northwest of the well, but these stopped shortly. During these eruptions, local villagers observed hot mud, thought to be at a temperature of around 60 °C (140 °F).
  - At its peak, Lusi spewed up to 180,000 m³ of mud per day
  - To explain what triggered the mud volcano, three hypotheses have been suggested, though none has won universal support:
    - ✓ Hydro-fracturing of the formation (reflecting a drilling problem)
    - ✓ Fault reactivation (reflecting a natural event)
    - ✓ Geothermal process (reflecting geothermal heating)
- Out of the three hypotheses the hydro fracturing hypothesis is appeared to be the one most debated

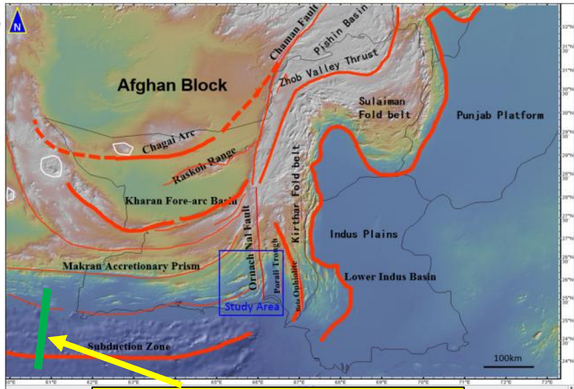
Evolution of Makran Accretionary Prism – Offshore Western part



Surface evidence of normal faulting, Growth strata



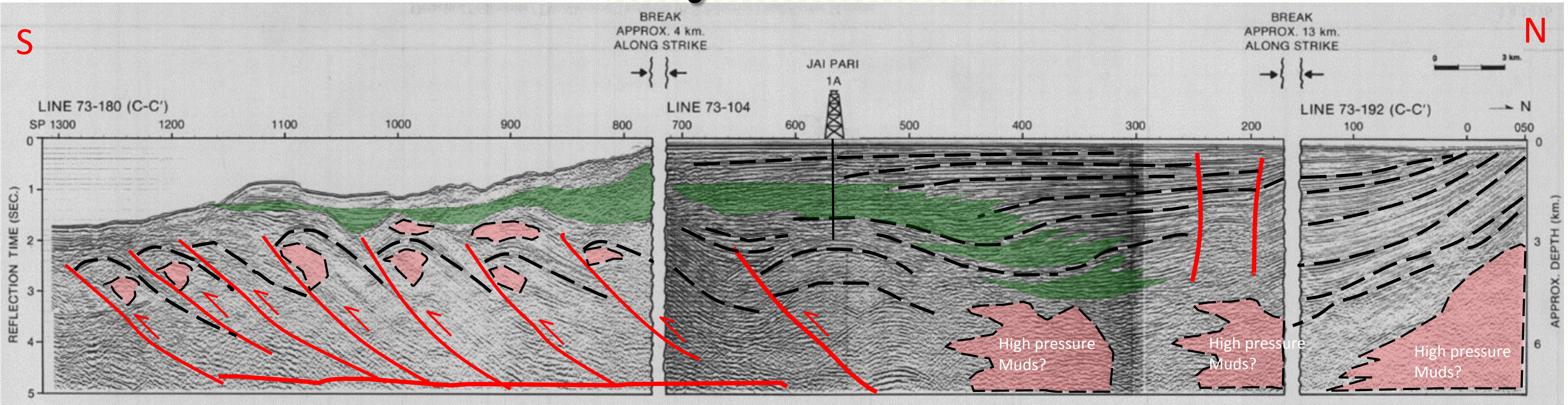




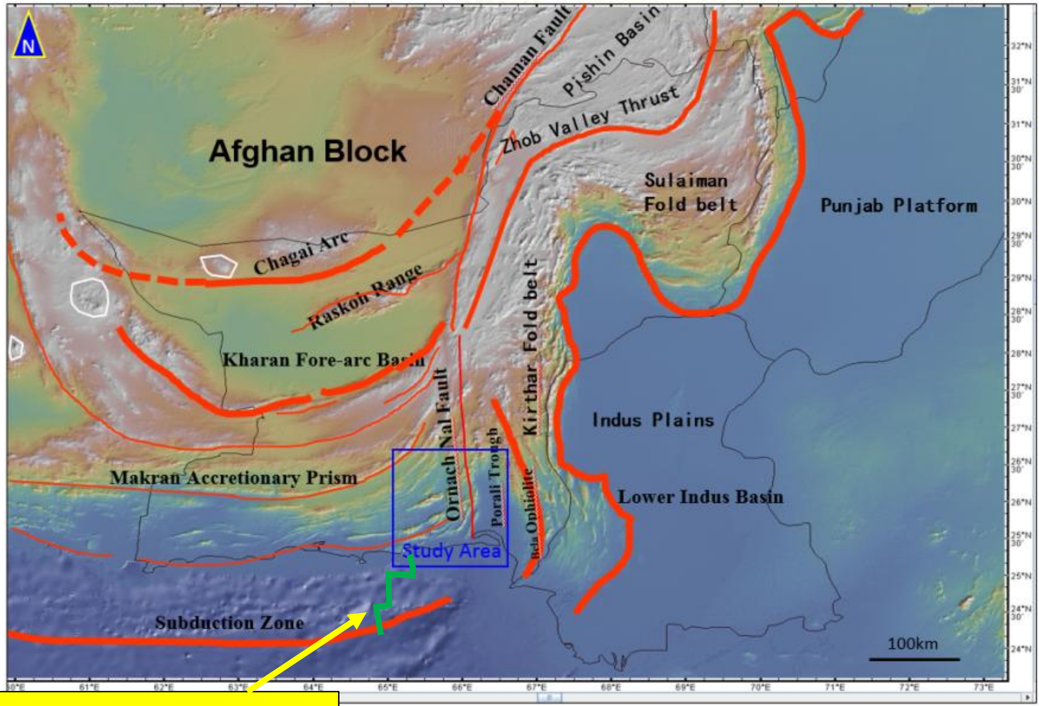
Location of Seismic Section

(Platt et al., 1985; Grando and McClay, 2007)

Evolution of Makran Accretionary Prism – Offshore Eastern Part



- Thrust planes terminate along main decollement
- Since internal folding and thrusting increases to the north, it seems likely that lower sequence imbricate and shale of this sequence reached higher levels by deformation (high pressure mud)
- Each thrust slice terminates at depths of the decollement from which over-pressured muds easily may have entered the fault planes giving rise to diapirism along the faults
- Under-plated material is likely to include petroleum source rocks

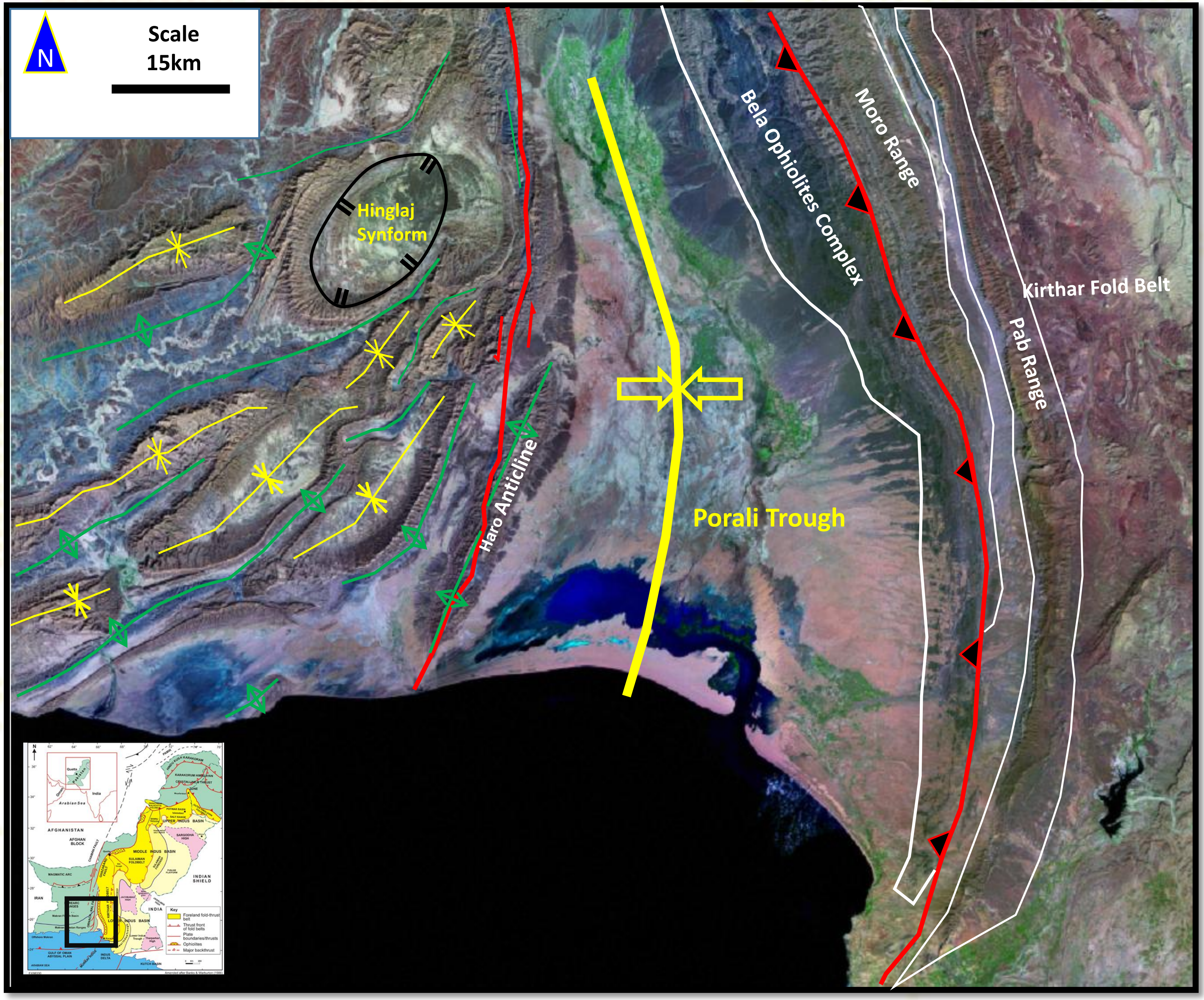


Location of Seismic Section

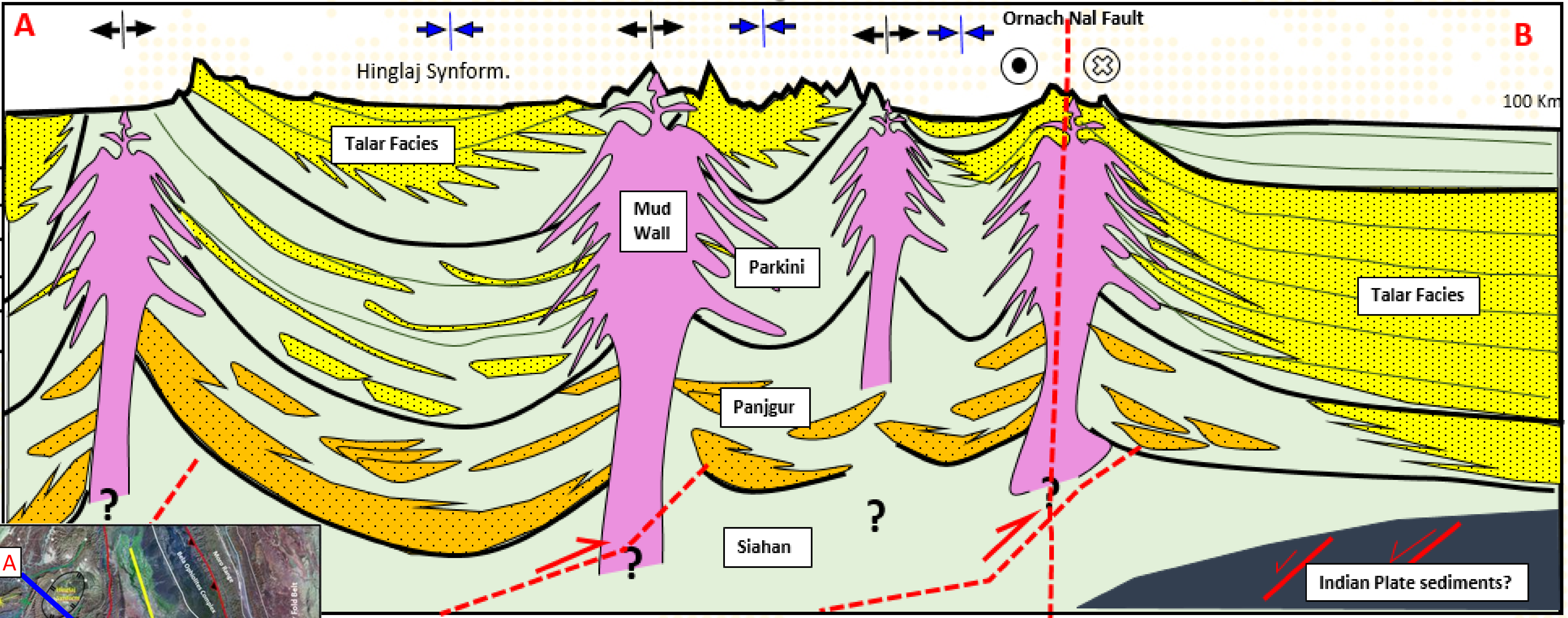
Structural Setting – Study Area

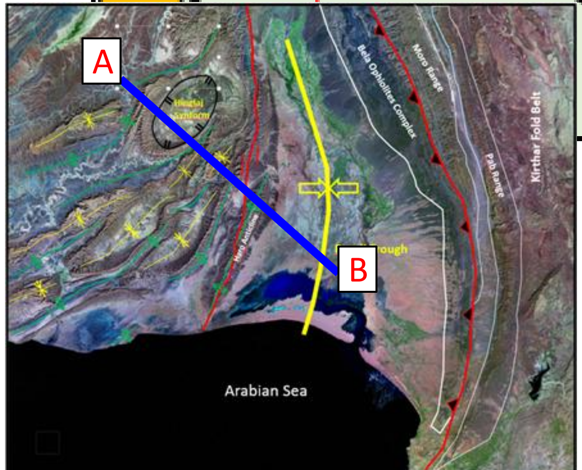
Major Structural features of the Study area are:

- Bela Ophiolite Complex emplaced during Late Cretaceous-Early Paleocene
- In addition to igneous part of oceanic crust, Jurassic-Cretaceous sediments of Indian plate were emplaced and exposed in Moro Range
- Pab Range contains Cretaceous to Paleogene sediments deformed during Kirthar Foldbelt development
- Porali trough - more than 10,000m deep, separated the Makran Accretionary Prism to Bela Ophiolite Complex
- Eastern part of Makran Accretionary Prism takes swing from NS to EW
- Haro anticline represents the first line of folding at eastern margin of Makran Accretionary Prism
- Dish like synclines (e.g. Hinglaj), elongated anticlines and synclines are the main structure features



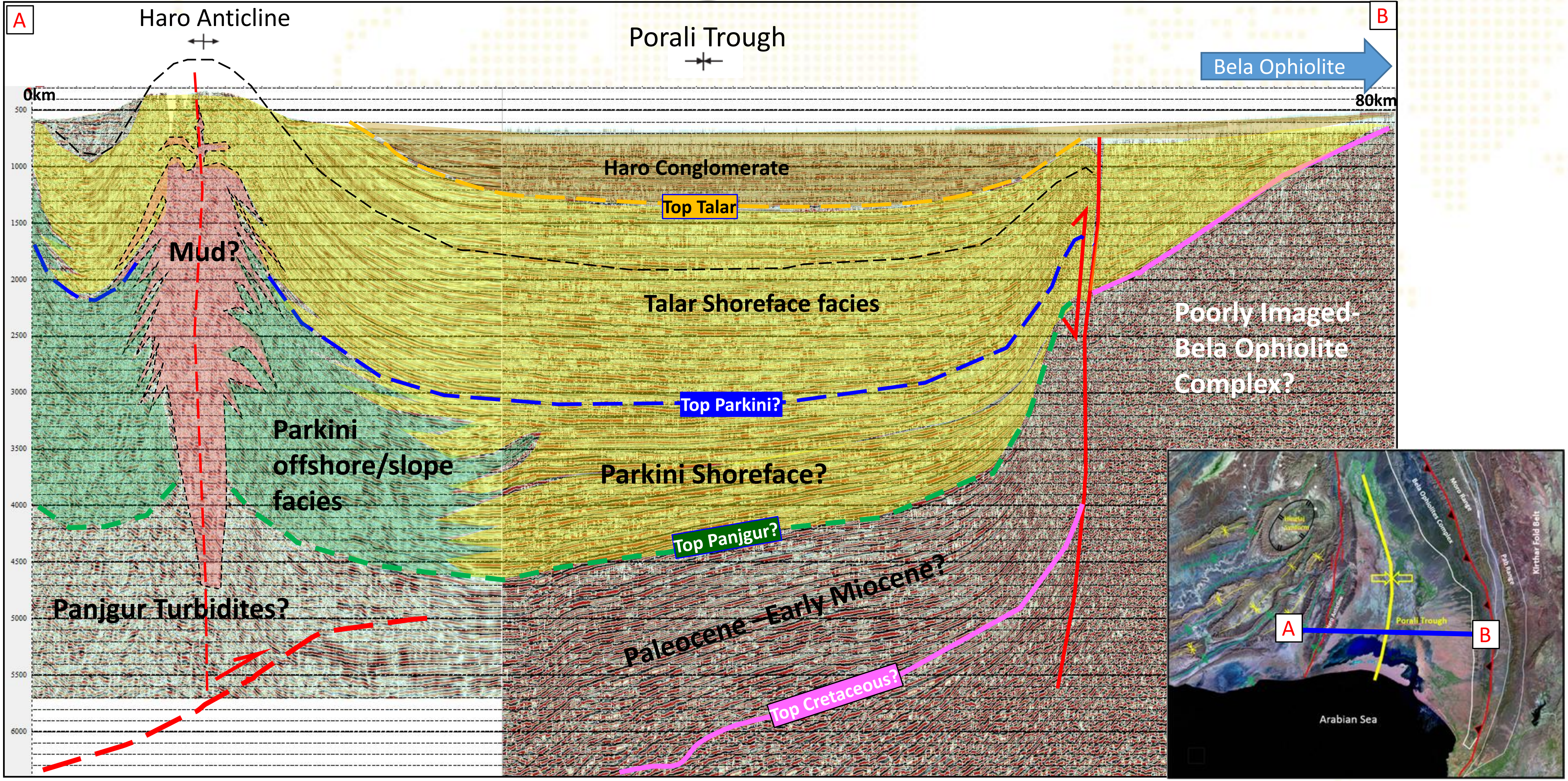
Schematics Cross-section Across Study Area



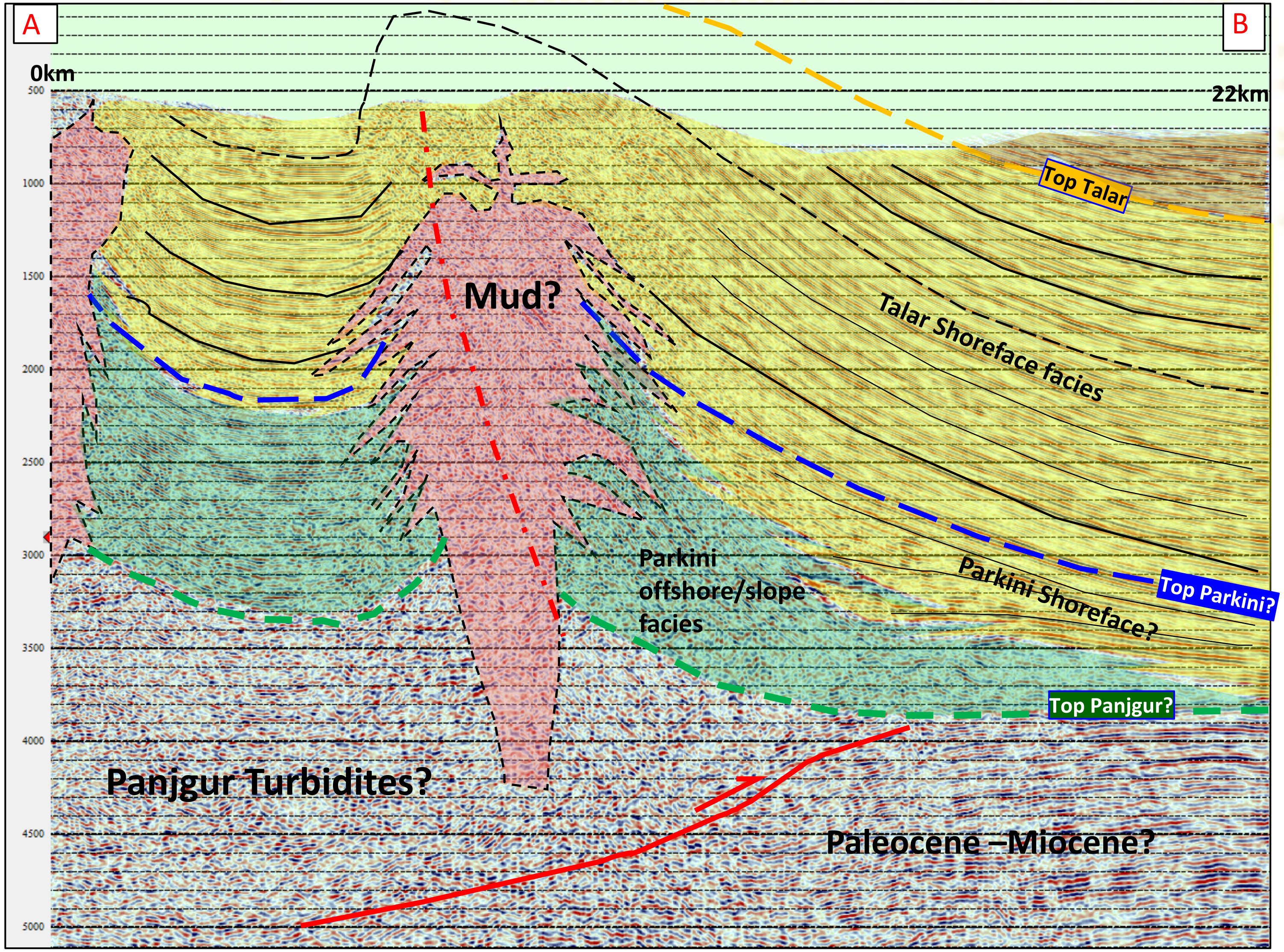


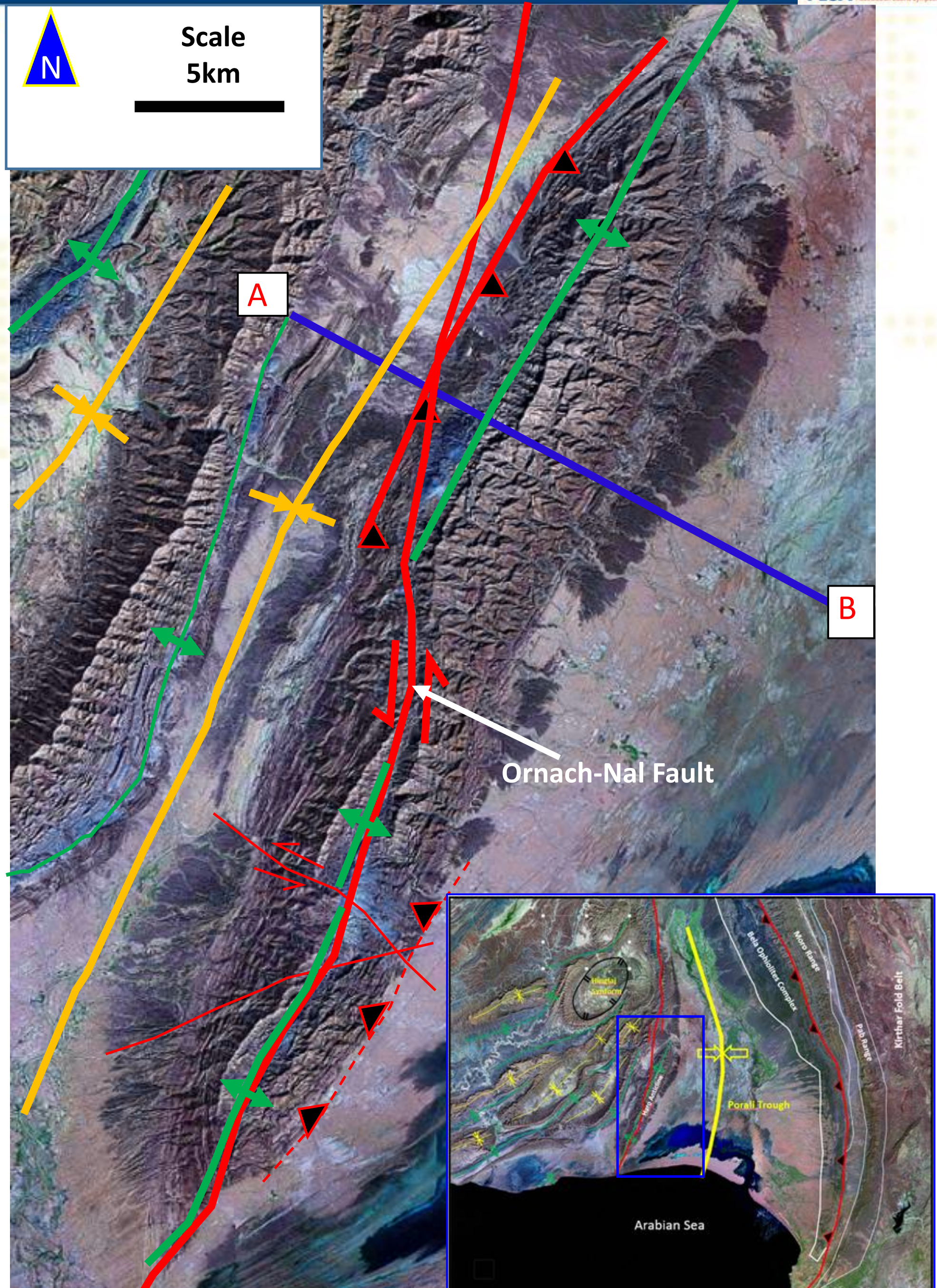
- Showing variations in facies and possible mud walls in the area
- Anticlines are tight and filled with high pressure mud

Seismic Profile across Porali Trough and Haro Anticline

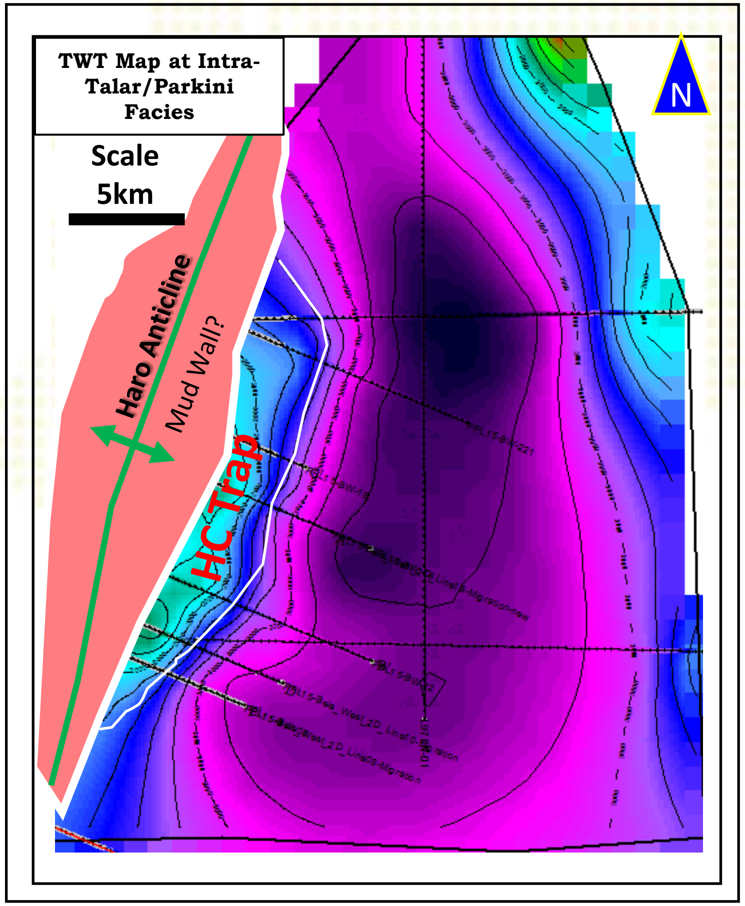


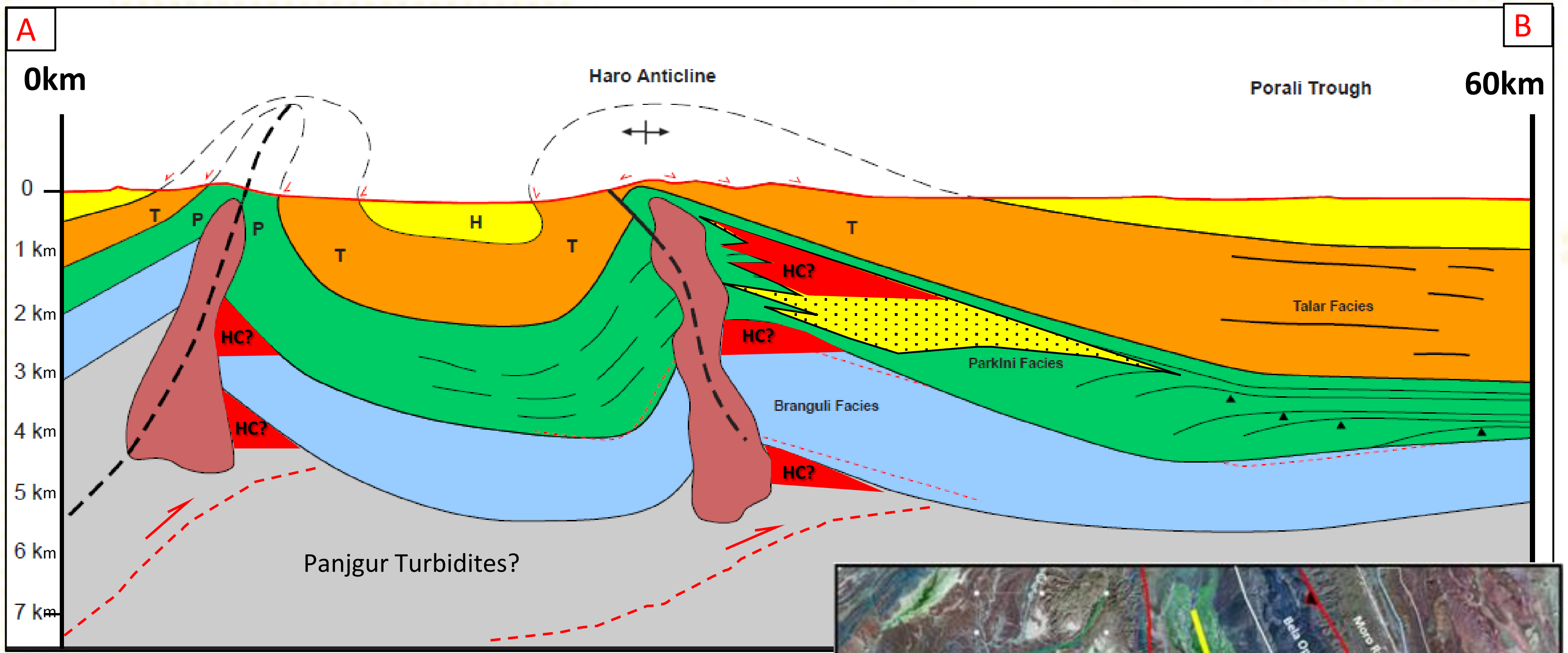
Seismic Profile over Haro Anticline with Structural Features on Satellite Image

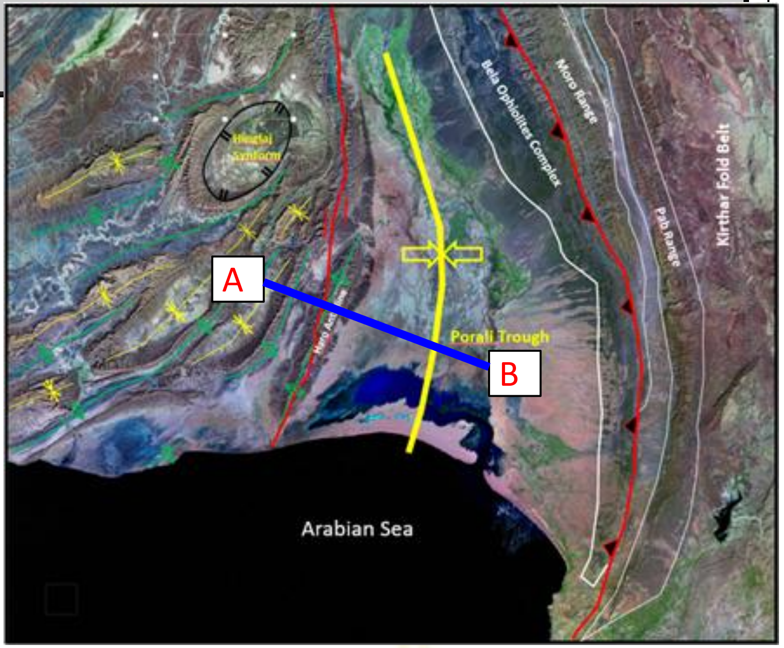




Structural Styles around Haro Anticline – Possible HC Traps



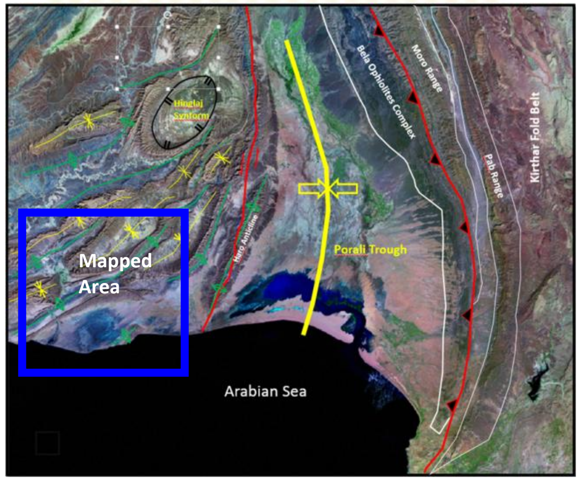




- Two possibilities of trap formation:
  - Truncation of reservoir facies against mud wall
  - Facies variation at the limb of large anticlines

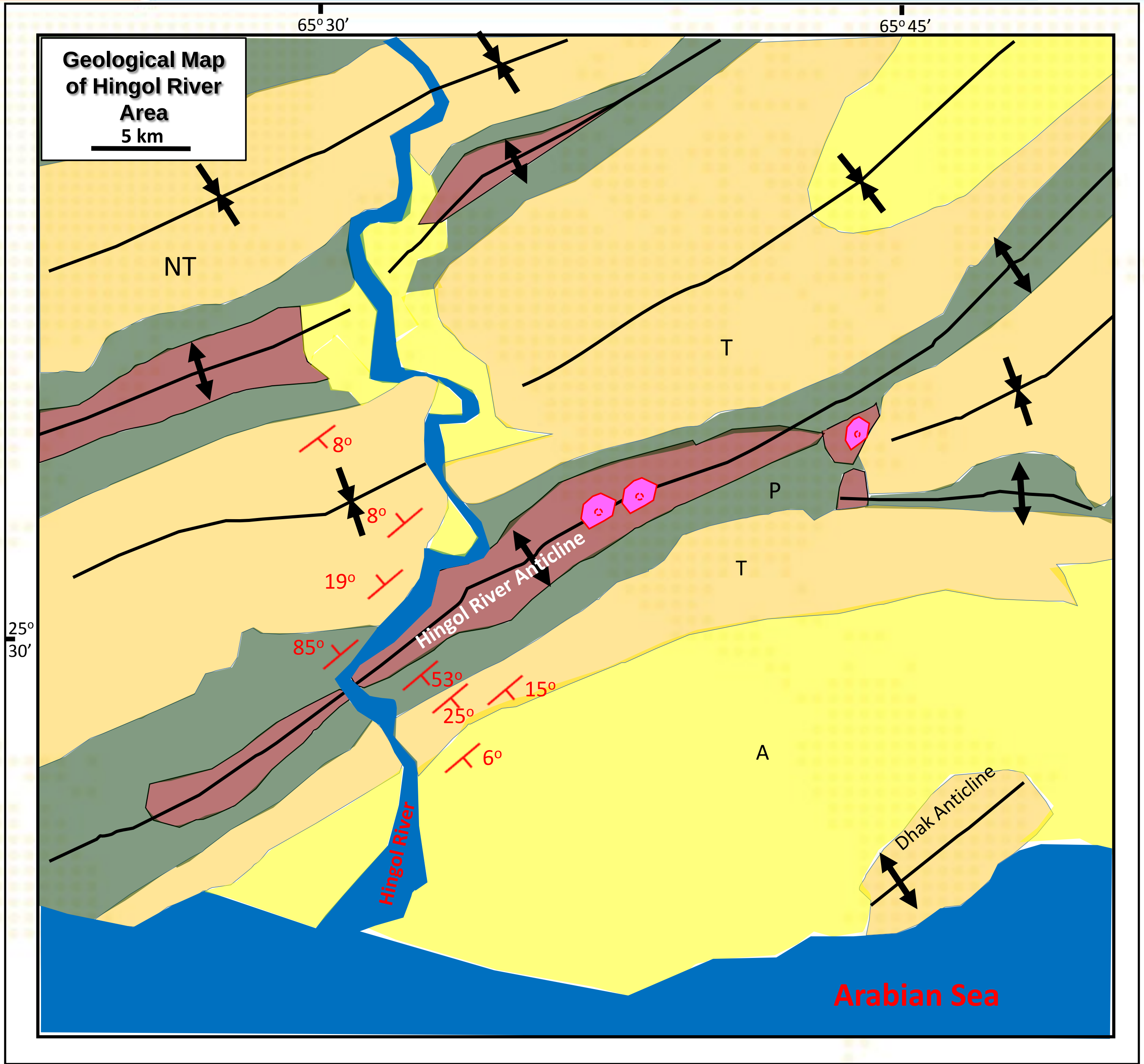
Structural Styles around Hingol River Section

- Elongated and narrow anticlines with steep limbs (85º near the axial zone)
- Wide syncline with flat crest
- Mud extruded along the axis of the anticlines
- Talar facies prograding from NE to SW
- Extruded mud have same lithology as of Parkini facies (field evidence)

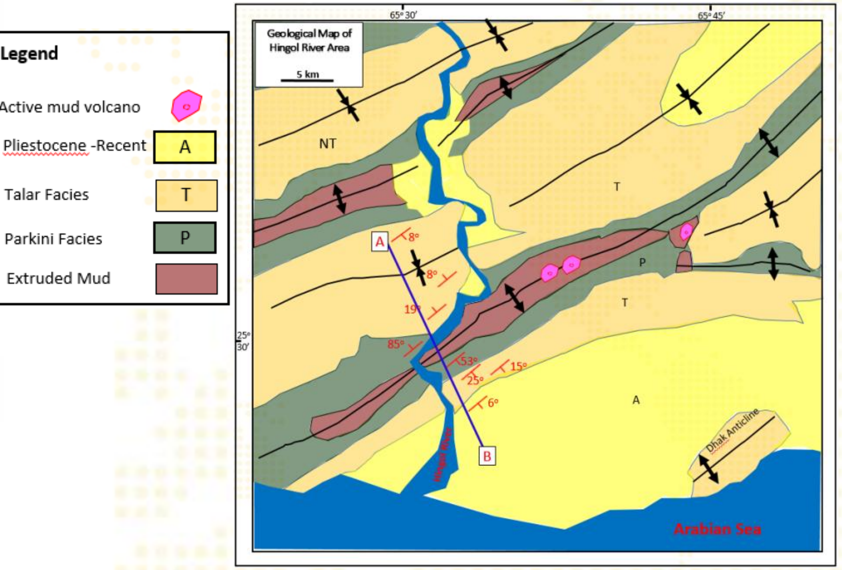


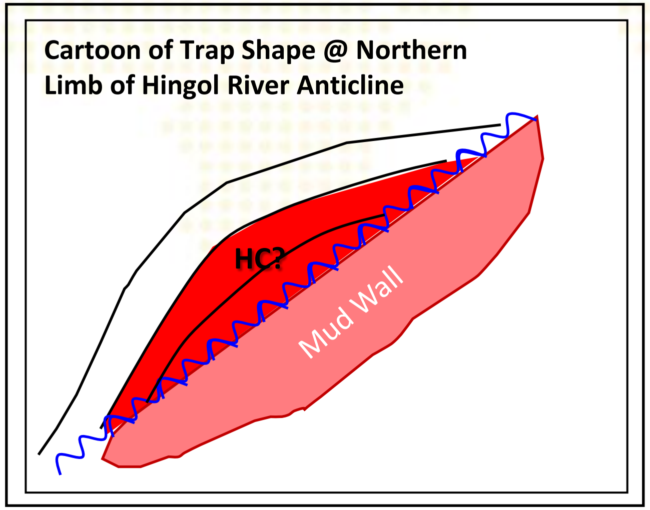
Legend

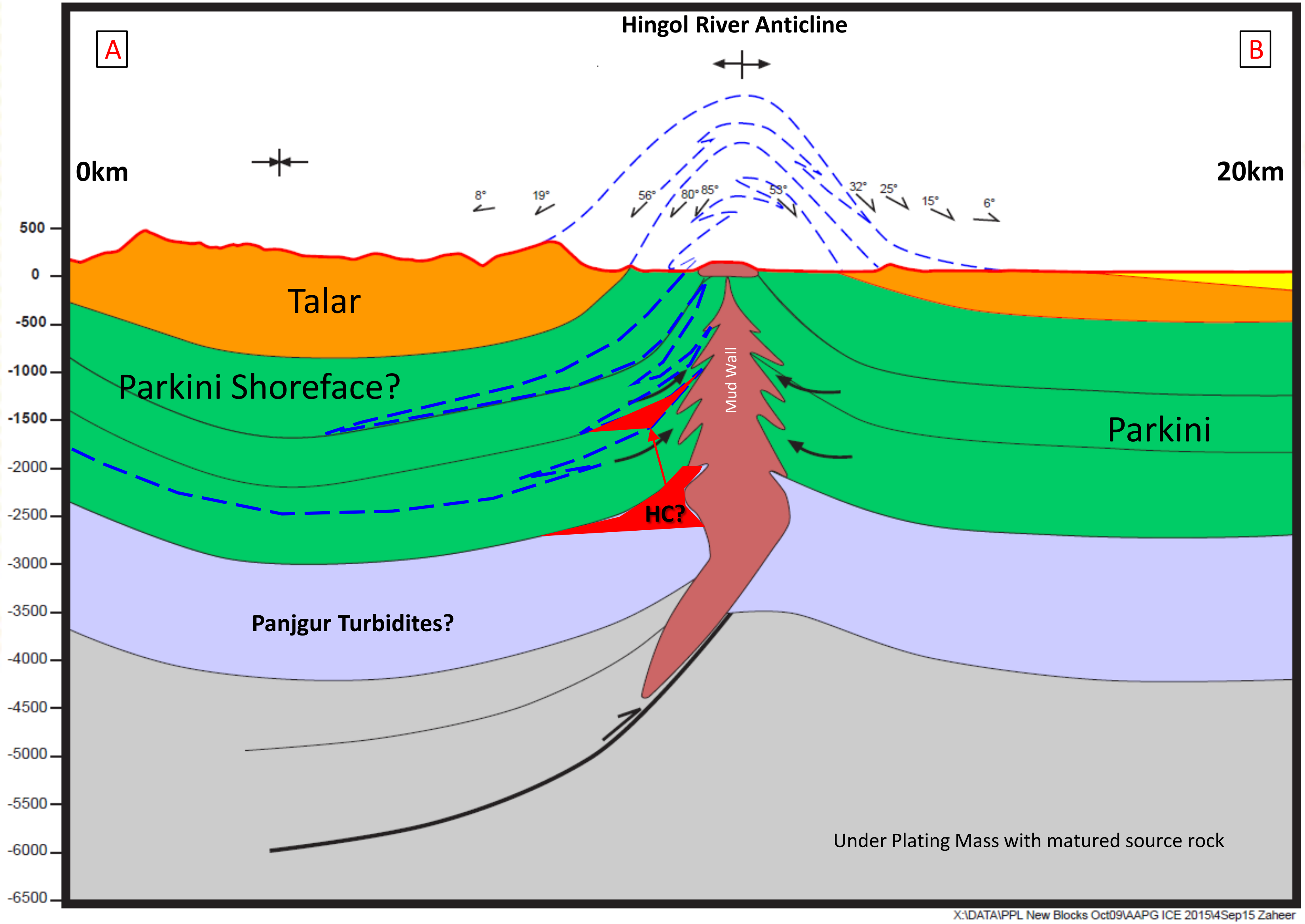
Active mud volcano	
Pliestocene -Recent	A
Talar Facies	T
Parkini Facies	P
Extruded Mud	



Structural Styles around Hingol River Section – Possible HC Traps

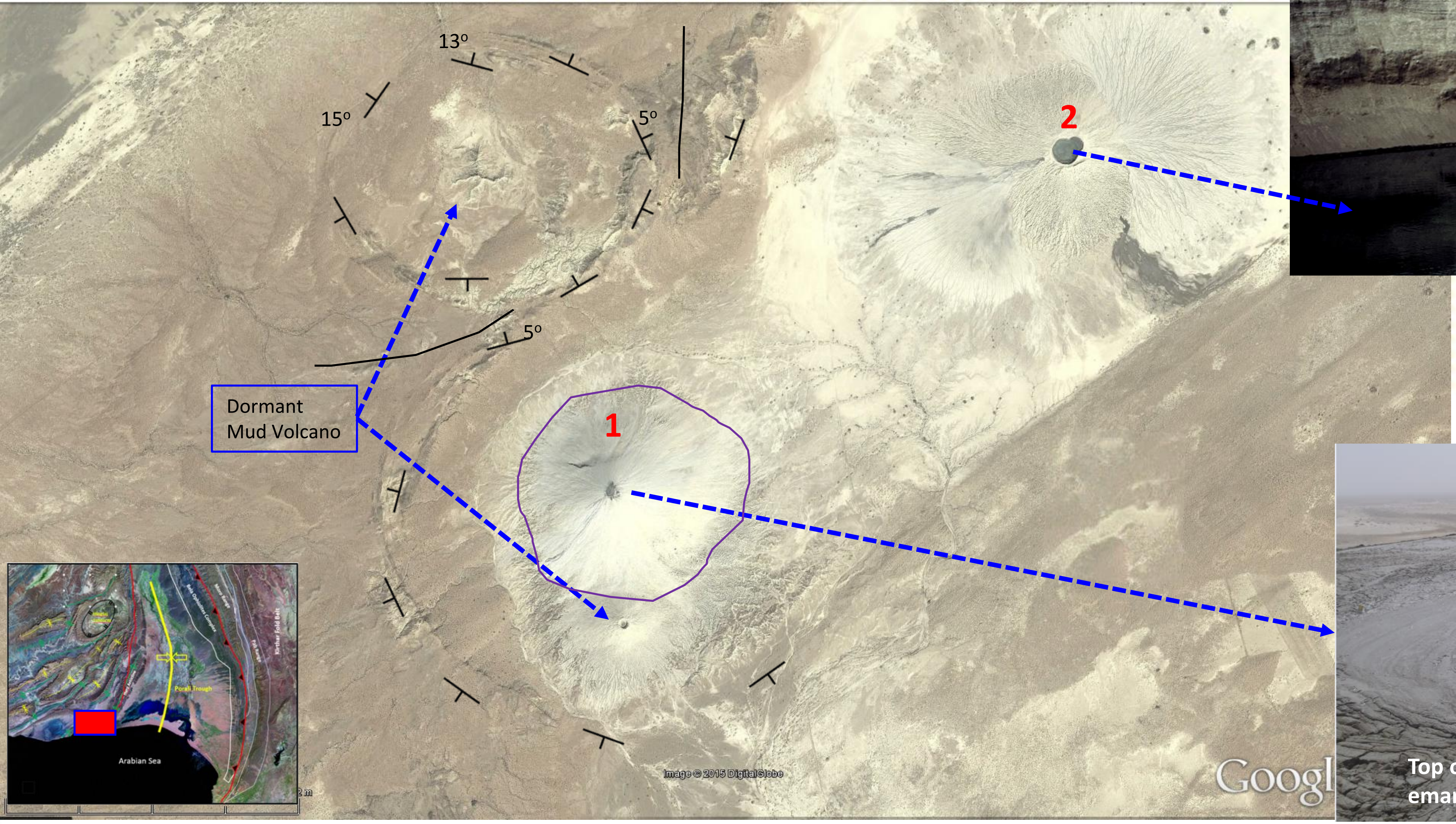


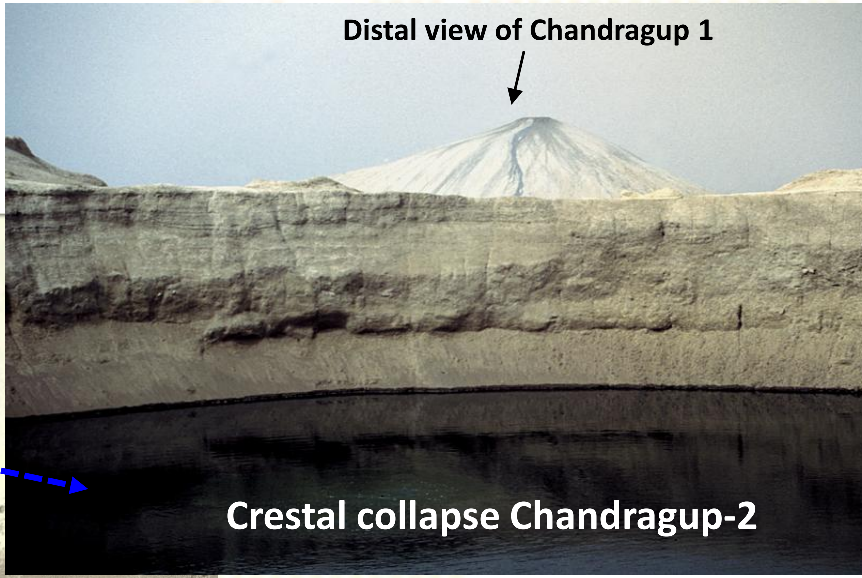




Active Mud Volcano in Study Area - Chandragup

- Thermogenic gas is emanating from the active mud volcanoes
- Dipping away strata around the mud volcanos show the structural control



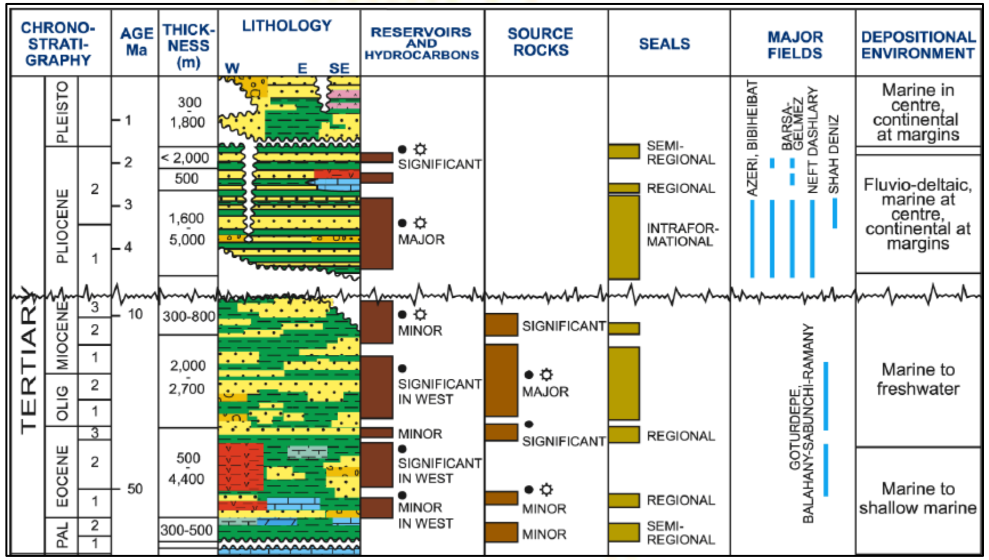


Analogy – Gas Seepage/Mud Volcano

- Azerbaijan and the Caspian Sea are home to nearly four hundred mud volcanoes - more than half the total throughout the world
- These small cones emit cold mud, water and gas almost continually
- Every twenty years or so, a mud volcano may explode with great force, shooting flames hundreds of meters into the sky
- Mud volcanoes are one of the visible signs of the presence of oil and gas reserves under the land and sea in the Caspian region

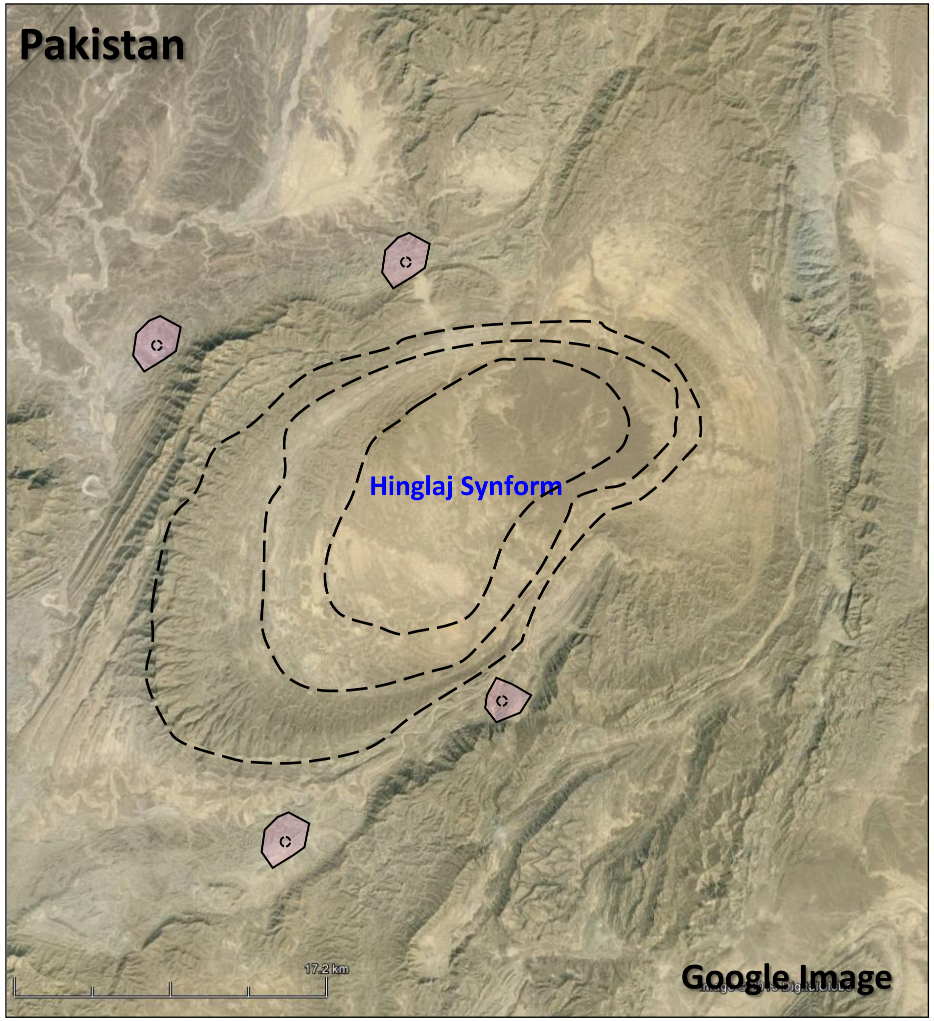
Fired mud volcano, Azerbaijan

Tertiary Stratigraphy and Petroleum System, Azerbaijan

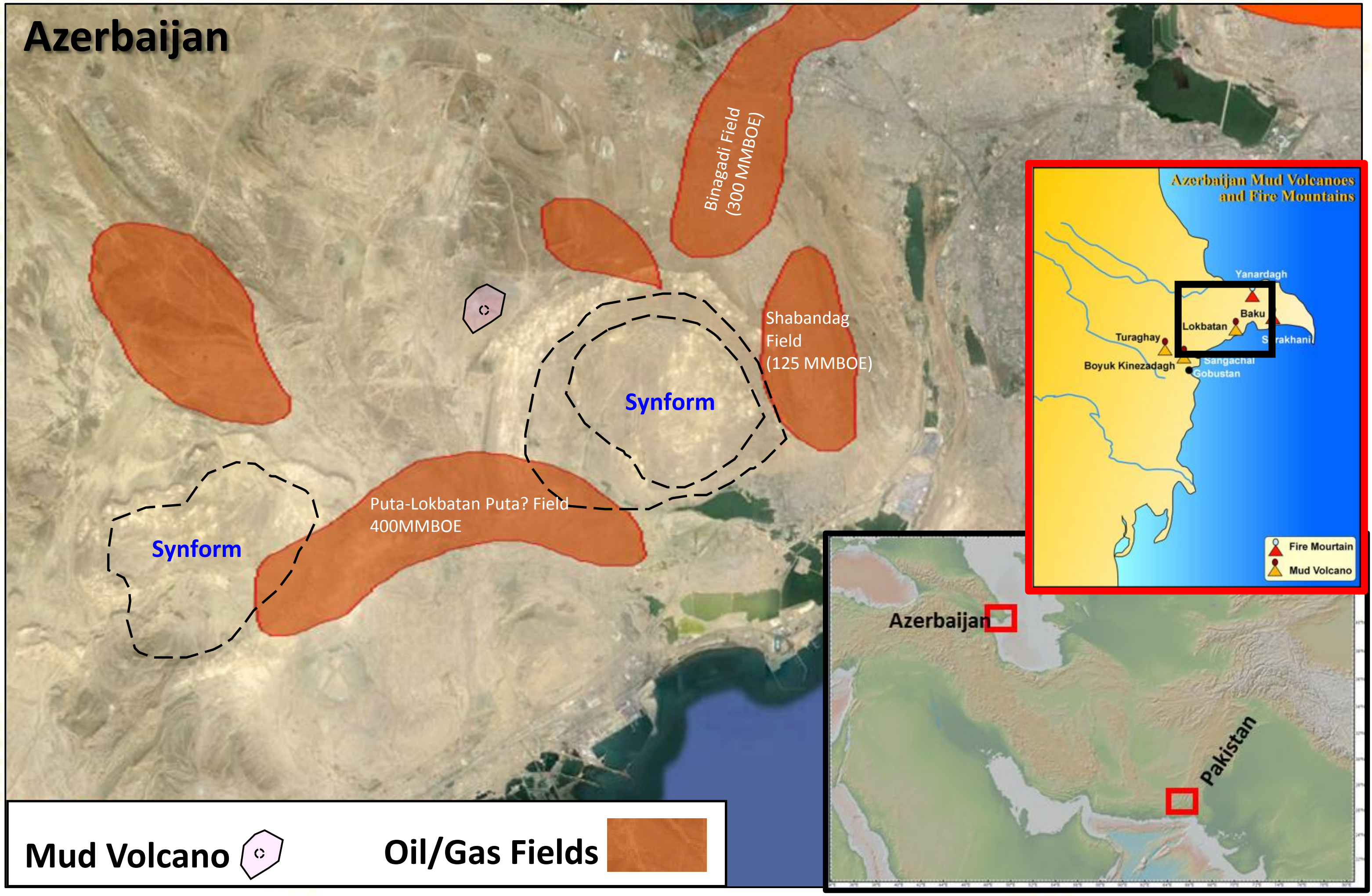


Analogy - Structural Features Onshore South Caspian Basin

Higlaj Synform - Dish Like Structures surrounded by mud volcanos



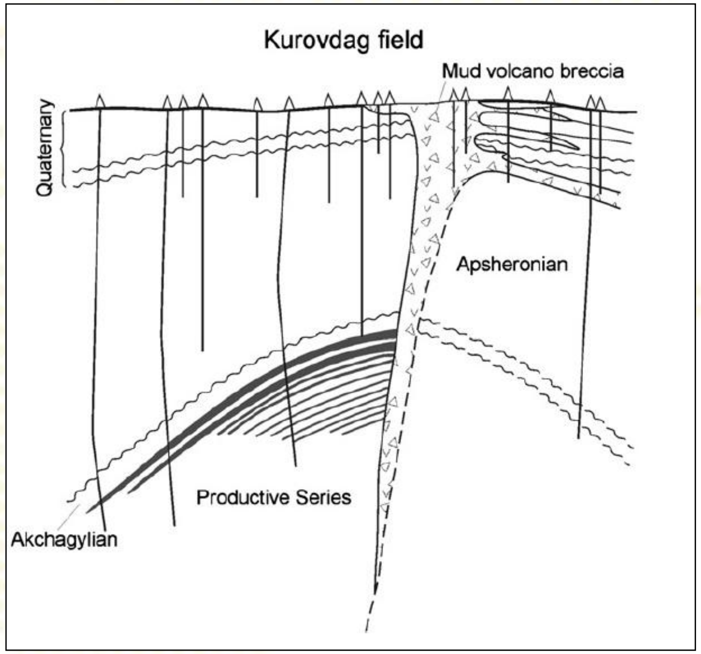
Dish Like Structures at onshore Azerbaijan surrounded by Oil/Gas Fields and mud volcanos.



Analogue Traps (Onshore South Caspian Basin)

Kurovdag Field (~500 MMBOE or ~2.8 Tcfe reserves at multiple levels–source IHS monitors)

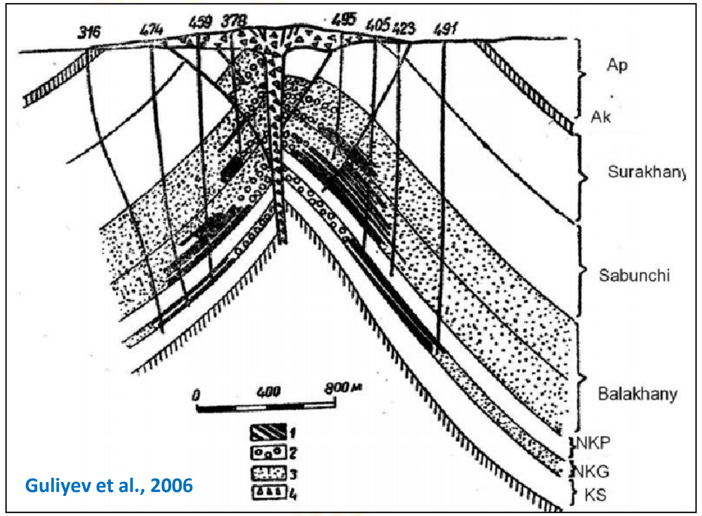
- Elongated and faulted asymmetrical anticline (SW flank dips by 45-50^o and NE flank dips by 20-25^o)
- This anticline is cut by a major longitudinal normal wrench fault extending along the axis
- The trapping mechanism is related to fault closures/fault blocks as well as to lateral facies changes (shale-outs), depositional pinch-outs and lenticular development of sand/sandstone bodies



Geological section across the Lokbatan oil field

Lokbatan Field (~400 MMBOE or 2.2 Tcfe reserves at multiple levels - source IHS monitors)

- located in the Lower Kura Depression belongs to a classical area of mud diapirism with multiple trapping mechanisms due to the combination of mud tectonics with folding
- This Group of Fields represent a major W-E trending reverse faulted mud diapiric anticline related to a regional longitudinal thrust fault along
- Thrust fault zone extending along the crest of this anticline is associated with three mud-volcanoes and the mud volcano breccia originating in the deeper-seated overpressure
- The trapping mechanism in the Pliocene section (Productive Series) is also subordinately related to lateral facies changes (shales-outs), depositional wedge-outs



Guliyev et al., 2006

Conclusions

- Presence of mud volcanoes along the hinges of the anticlines shows that mud walls/chambers could be present in the cores of these anticlines in subsurface
- All the wells in Offshore and Onshore Makran were drilled on the crests of anticlines and failed either due to operational issues or absence of expected reservoir facies
- Multiple reservoirs (Oligocene to Pliocene) with possibilities of truncation against mud or shale out against limbs of the anticlines could be present. This concept not yet been tested in Makran
- A perfect analogue of producing onshore South Caspian Basin, Azerbaijan - combination traps against mud walls and facies variations at the limbs of the anticlines

Acknowledgement

- We thank Management of Pakistan Petroleum Limited for allowing to present this paper
- We are also indebted to our co-workers who reviewed this work critically and provided useful input to improve it