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Identification and Analogy of Carbonate Geometries Between Offshore Indus Basin in Pakistan and Proven Carbonate Play

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Abstract

This article investigates the seismic reflection geometries (possible reservoir) of Paleogene of Offshore Indus Basin Pakistan (shelf area) from 2D seismic and make an analogue with the proven carbonate reservoir geometries found in countries such as Canada and Middle East.

The 2D seismic data are used to interpret the possible carbonate features and methods to identify them and define its depositional setting on the carbonate platform.

The offshore Indus Basin is tectonically a rift and a passive continental margin basin, located in Offshore Pakistan and Northwest India where carbonates were deposited on the shelf and the deep offshore area during early post-rift phase. In the deep offshore area, carbonates were set on volcanic seamounts during the Paleogene age.

In Paleogene, the Indian Plate was passing through the equator in the conditions of warmer water with appropriate water salinity, where those conditions were suitable for the growth of organisms responsible to develop reefs in the Offshore Indus area. The available seismic data analysis has indicated the possible presence of different carbonate reefs on the shelf. The seismic data enabled to define the possible carbonate Rimmed shelf depositional model in the area.

The aim of this article is to highlight and analogue carbonate seismic geometries, their internal architecture in the Paleogene interval of the Offshore Indus Basin (shelf area) and how to identify them, which may help for further exploration in Offshore Indus Basin.

Introduction

The Offshore Indus Basin of Pakistan is an under-explored and potential hydrocarbon province. It is located in the eastern part of Arabian Sea. The Murray Ridge – Owen Fracture Zone is the western limit of the basin, and it extends in the east toward western coastline of the Indo-Pakistan subcontinent (Fig. 1). It may divide in to two parts (Fig. 1), shallow shelf area and deep offshore area. The shallow shelf area is from shore line to about 200 m water depth. The deep offshore having water depths ranging from 400 m to 2800

m. The deep offshore may further divide into two parts. Deep offshore parallel to Murray Ridge, and deep offshore Saurashtra volcanic platform (Fig. 2, Fig. 3).

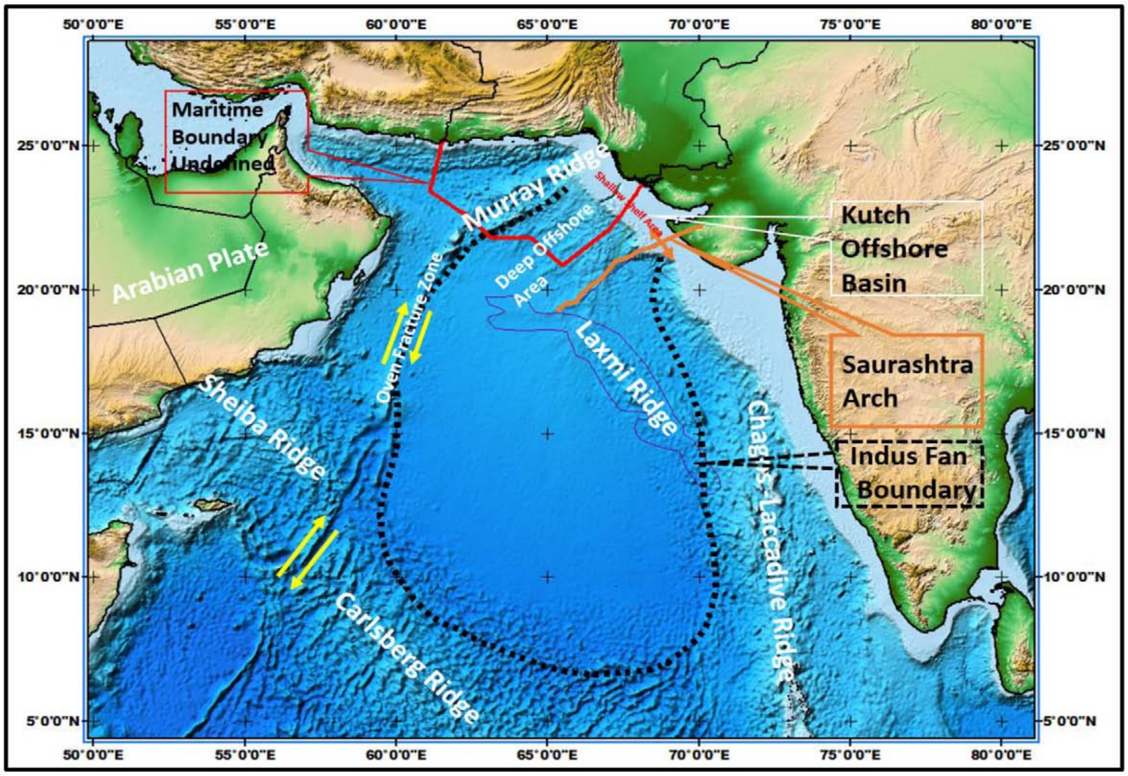


Figure 1—Color, shaded-relief image of the ETOPO1 ice surface global relief model (NOAA, USA). Indus fan boundary (after M.A. Prins, 2000). Saurashtra Arch (Madhu Bisen, 2010).

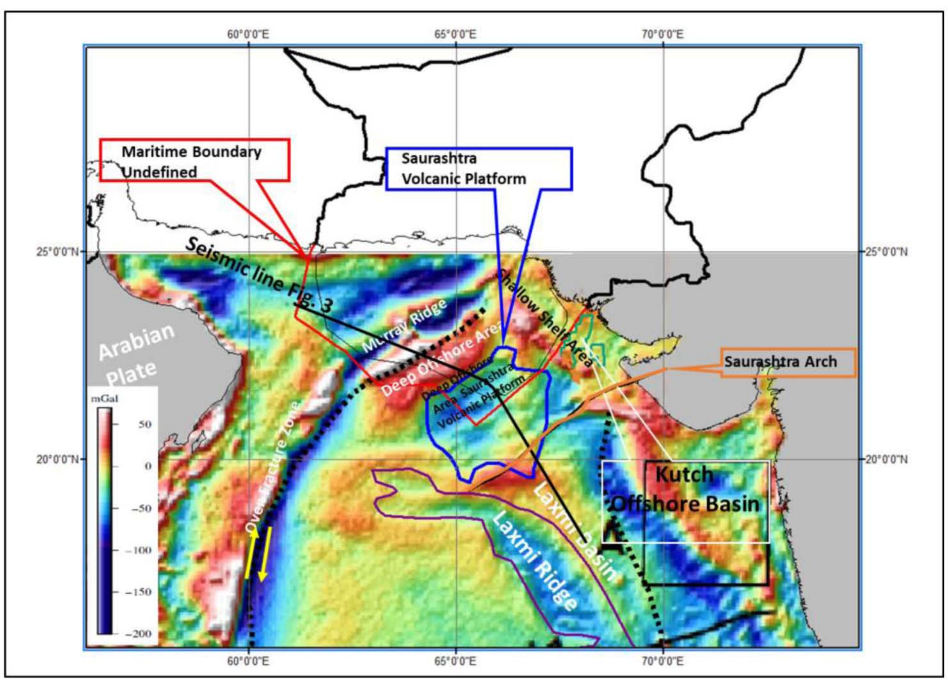


Figure 2—Free-air gravity anomaly Map (after K.M. Sreejith1, J. Asian Earth Sci., vol.62; 2013; 616-626). The Saurashtra volcanic platform outline (Richard I. Corfield, 2010, Petroleum Geoscience vol.16).

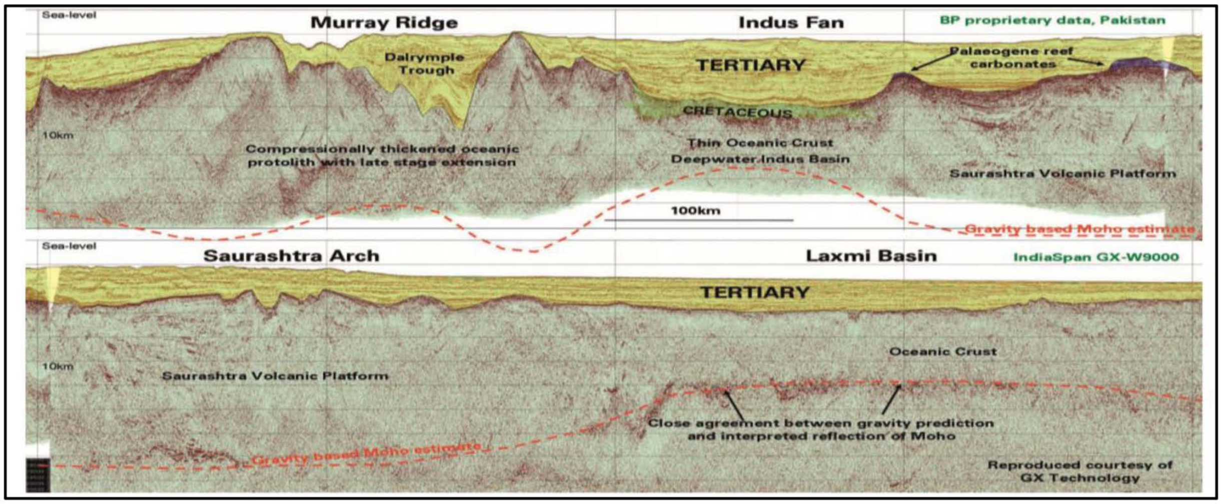


Figure 3—(R. I. Corfield et al). Regional strike seismic line across the distal continental margin in Pakistan and India. Cenozoic clastic sediment (yellow) and carbonate sediments (blue) are interpreted in addition to minor Mesozoic sediments (green). The Moho based on the gravity inversion carried out is marked as a dotted red line which coincides well with the interpreted Moho reflectivity where present. This profile emphasizes the considerable along-strike variation in the deep structure of the margin relative to only minor changes in present day bathymetry.

The Kutch basin is in the south of lower Indus basin and the offshore extension of Kutch basin is parallel to the offshore Indus Pakistan. It covers at least the lower half of the Indus offshore basin of Pakistan (Viqar-un-Nisa Quadri, 1996). The Kutch deep-water area has a bathymetry range of 400m – 3000 m and is located to the west of the present day shelf break (Madhu Bisen, 2010). The Kutch offshore deep-water area is a part of Saurashtra volcanic platform which is part of Indus offshore, Pakistan (Fig. 2).

Viqar-un-Nisa Quadri in 1996, reported the possibility of reefs in shallow offshore area and Kolla and Coumes 1987; Clift et al. 2002a, b, reported the deposition of shallow water carbonates along a chain of northeast-southwest trending volcanic seamounts during the Paleocene-Eocene.

Since 1960, 13 exploratory wells have been drilled in offshore Indus basin. 11 wells are drilled in shallow shelf area up to 200m water depth, well Pak G2-1 is drilled in deep offshore on the Saurashtra volcanic platform and well Anne-1 is drilled in deep offshore parallel to Murray Ridge.

The oil & gas discovery in Kutch Offshore, India, blocks KD-GKH and Block-I Ext represented by K-1 and K-4 (Fig. 4), increases the prospectivity of offshore Indus basin in Pakistan. KD-1 well was drilled in Kutch offshore close to the Mari time undefined boundary found oil at 1095-1097m in relatively tight Early-Middle Eocene limestone tested 173 b/d of oil. Well GK-28-1 drilled in Block- I Extension PEL, Western Offshore Kutch Basin to a depth of 1,550 m, flowed gas.

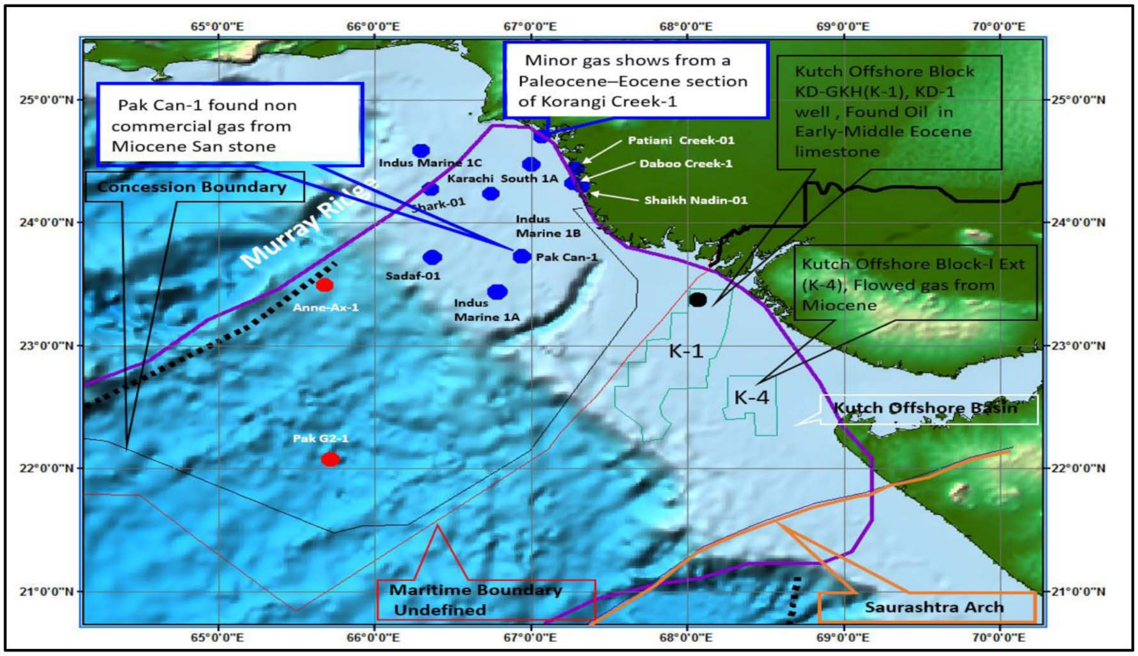


Figure 4—Map showing information compiled from different sources. Well information inside Pakistan (Syed Asif Ahsan, 2011, PAPG/SPE Annual Technical Conference). Indian concession boundaries (Petroleum exploration and production activities, India, 2008-09). K-4 Block well information (announced in news by ONGC, Dec 18, 2009 01:00 AM). K-1 Block well, KD-1 information (Viqar-un-Nisa Quadri, 1996).

Geological setting

"During the early post-rift phase of the Indian plate, attached carbonate platforms of Paleocene and early Eocene age formed along the continental margin and detached platforms or carbonate banks on volcanic seamounts within the basin. Between the carbonate banks, coeval pelagic sediments were deposited in the intervening structural lows. The detached reefs and coeval pelagic sediments correspond respectively to the basement cover sequence and ponded sequence recognized by Clift et al. (2002). The Paleogene sequence also comprises horizons of carbonate banks and occasional patches of reefal build-ups over the shelf area as identified from the seismic data", (Tariq Jaswal, Tahir Maqsood, 2003).

"During the TA2 super cycle between the Intra Thanetian/Late Paleocene, 58.5 million years ago, and Base Lutetian/early Eocene, 49.5 million years ago, there was a wide transgression and a sharp decrease in the supply of elastic material into marine basins surrounding the Pak-Indian shield. Accumulation of carbonate and pelagic shale predominated, and favorable conditions were created for development of organic buildups. TA2 is a second order global cycle of relative change of sea level, incorporating an assemblage of rocks with distinctive stratigraphic and structural attributes. The same super cycle witnessed the formation of Australian reef systems and the Laccadive Islands along India's western margin. Globally, the distribution of Cenozoic reefs in time and space is a direct result of changes in oceanic circulation patterns brought about by the progressive blockage of the Tethyan seaway by plate interaction. Although there are reefs of Paleocene age, most of the corals in them are survivors from the Cretaceous. Within South Asia in general and Pakistan in particular, Paleogene reefs are mainly algae-foraminiferal and to a lesser extent formed by hermatypic coral general", (Viqar-un-Nisa Quadri, 1996).

Dataset and Interpretation

In this article twenty-three (23) scanned and one (1) digital (SEGY, seismic line 9124-86) 2D seismic lines (Fig. 5) and one well Karachi south A-1 was available and used to highlight stratigraphic and paleogeographic variations across study area to identify the possible reefs. The seismic data set, is a 2D multi-channel post stack time migrated data, acquired by Petro Canada during 1986 and processed in the same year. The seismic stratigraphic interpretation was carried out marking the horizon tops in the zone of interest by using Karachi south A-1 well data. The stratigraphic features, such as buildups, carbonate banks, toplaps, downlaps and onlaps were identified with confidence. The near base middle Eocene reflector was interpreted with confidence (green reflector) and all the reef are identified below middle Eocene and one possible reef in cretaceous.

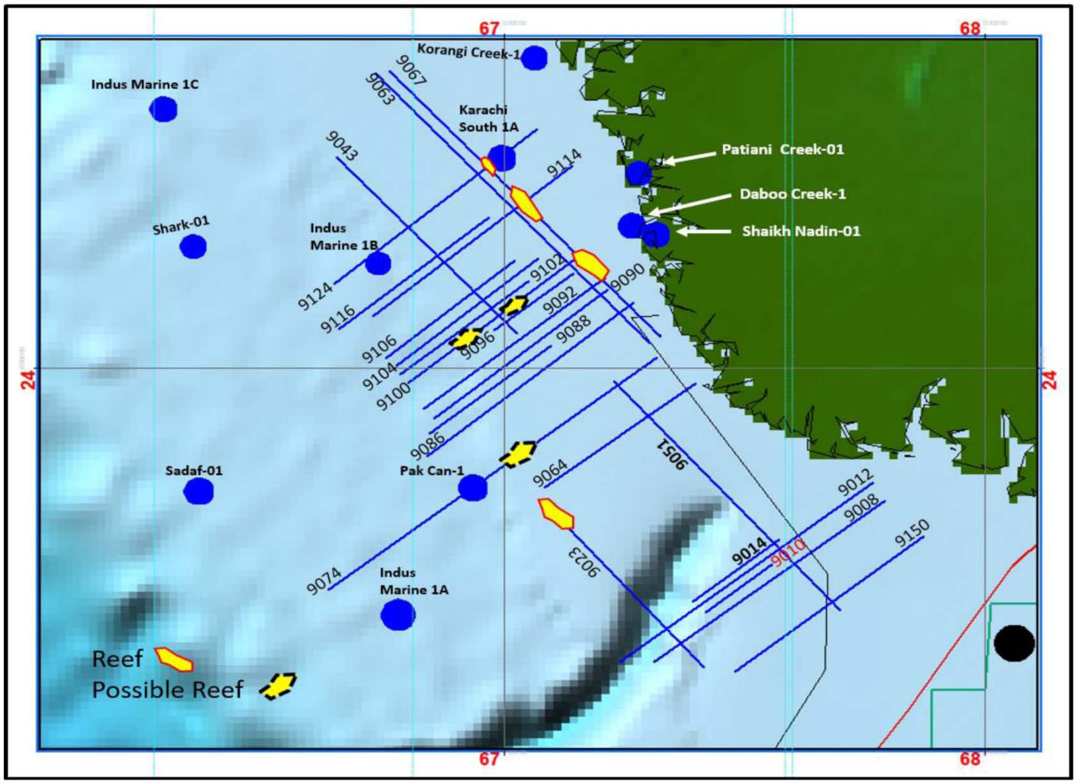


Figure 5—Reef distribution map. Seismic Base Map digitized from the printed base map. Well information (Syed Asif Ahsan, 2011, PAPG/SPE Annual Technical Conference).

Stratigraphy

The stratal hierarchy and nomenclature used in the present article is shown in (Fig. 6) and Fig. 7 is showing the general stratigraphic column of offshore indus. The seismic stratigraphic sequence of Bilal Haq and Vail et al and the bio stratigraphy of Karachi south A-1 well are used to pick the super cycles on the key seismic line 9124-86 passing through the well Karachi south A-1(Fig. 8). In late Paleocene, a Paleo high was developed in the north-west of Karachi south A-1 well because of the growth fault and created an ideal place to grow the reef. The shelf edge in cretaceous was in the north-east of Karachi south A-1 well which was shifted to north-west during Paleocene (Fig. 8). Based on interpretation of super cycles TA1, TA2 and their stacking patterns of HST, LST and TST, development of reef is marked on the key seismic line during TA2. We also observed a possible reef in cretaceous, north-east of Karachi south A-1 well. The depositional pattern supports that the cretaceous reef was developed as a shelf edge reef (Fig. A1).

seismic stratigraphic sequence of Bilal Haq and Vail et al.	
Mega Sequence Boundaries	**Geochronologic unit**
TB2	Early and Middle Miocene
TB1	Late Oligocene and early Miocene
TA4	Late Eocene and early Oligocene
TA3	Middle Eocene
TA2	late Paleocene and early Eocene
TA 1	early Paleocene

Biostratigraphy of Karachi south A1			Karachi South A1 Well synthetic
Sequence Boundaries	**Geochronological unit**	**Depth Interval**	**TWT msec**
Lower-upper Tf	Middle? - upper Miocene	900' - 2780'	
Lower Tf	Middle Miocene	2780' - 3760'	
upper Te	Lower Miocene	3760' - 5000'	
Tcd Lower Te	Oligocene Upper Eocene unconfirmity	5000' - 7940'	980-1320
Ta3 - Tb	Middle -Upper Eocene	7940' - 8520'	1320-1400
TA2	Lower Eocene Upper Paleocene unconfirmity	8520' - 9400'	1400-1600
TA 1	Lower Paleocene?????	9400' - 10830'	1600-1860
	Upper cretaceous	10830' - 11002'	

Figure 6—Table showing information compiled from Biostratigraphy, Synthetic, Interpreted stratigraphy from Karachi south A-1 well and seismic stratigraphic sequence of Bilal Haq 1987.

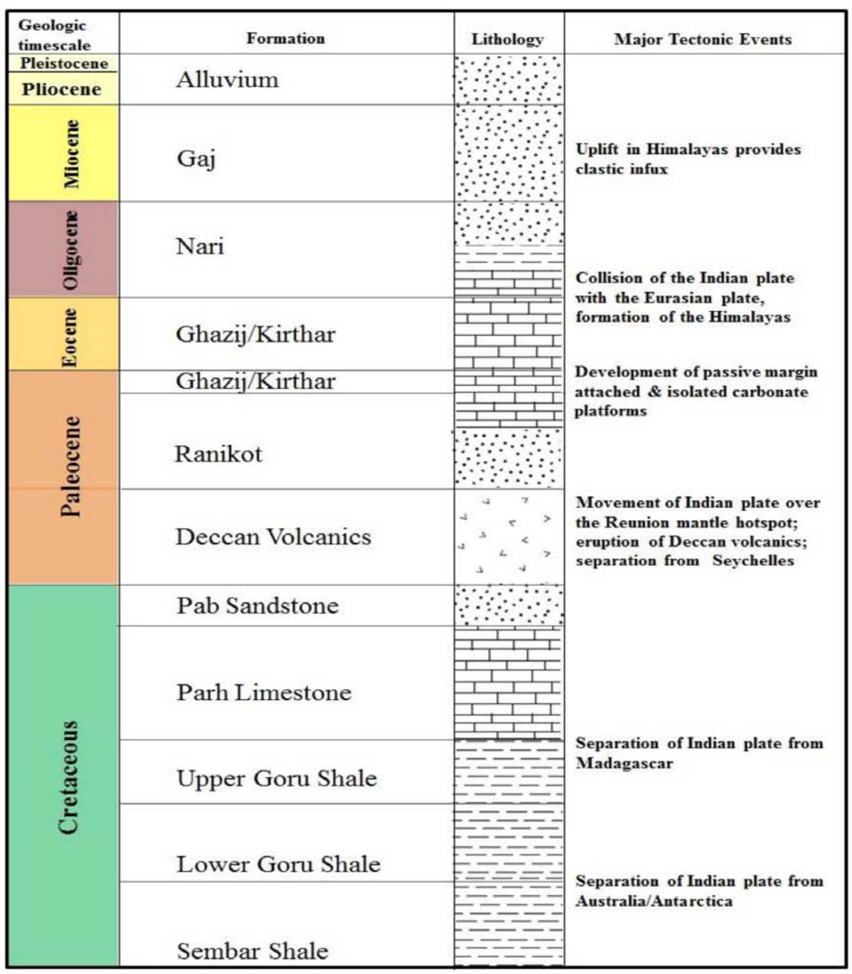


Figure 7—General Stratigraphic column of offshore indus basin (https://en.wikipedia.org/wiki/Offshore_Indus_Basin)

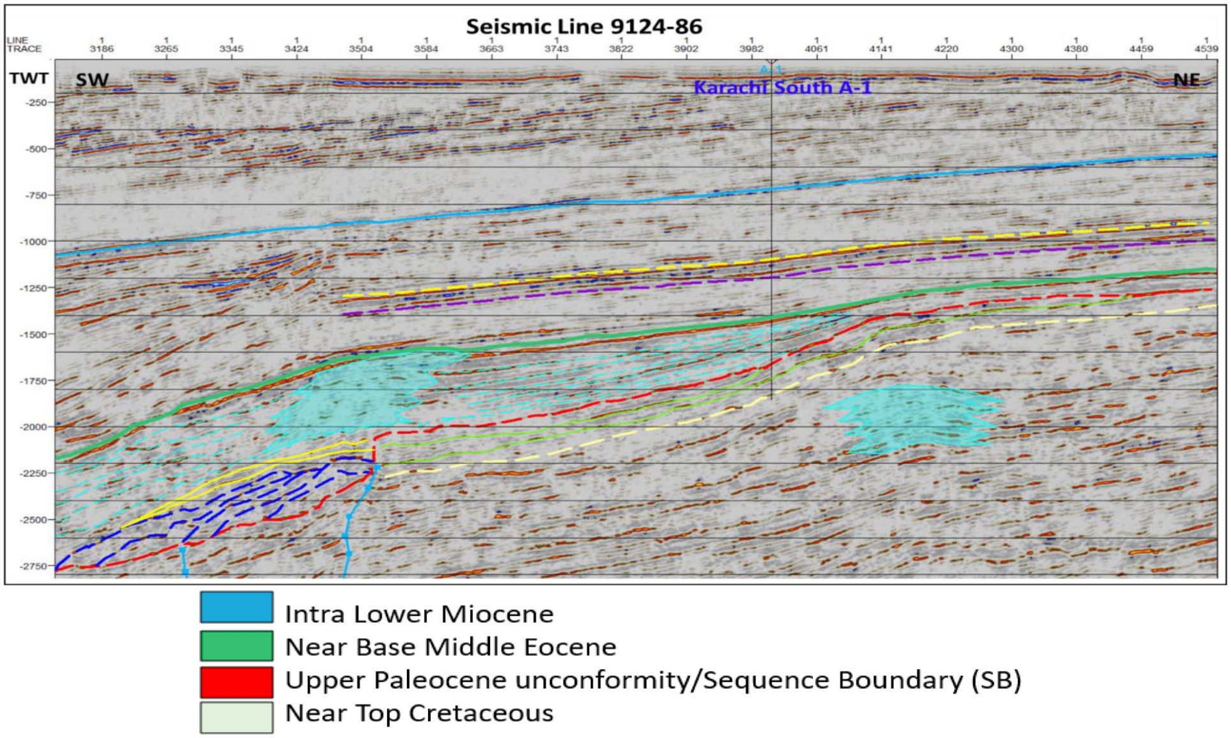


Figure 8—NE – SW 2D seismic line 9124-86 (location is shown in Fig. 5) passing through well Karachi south A-1 with Interpreted geological markers.

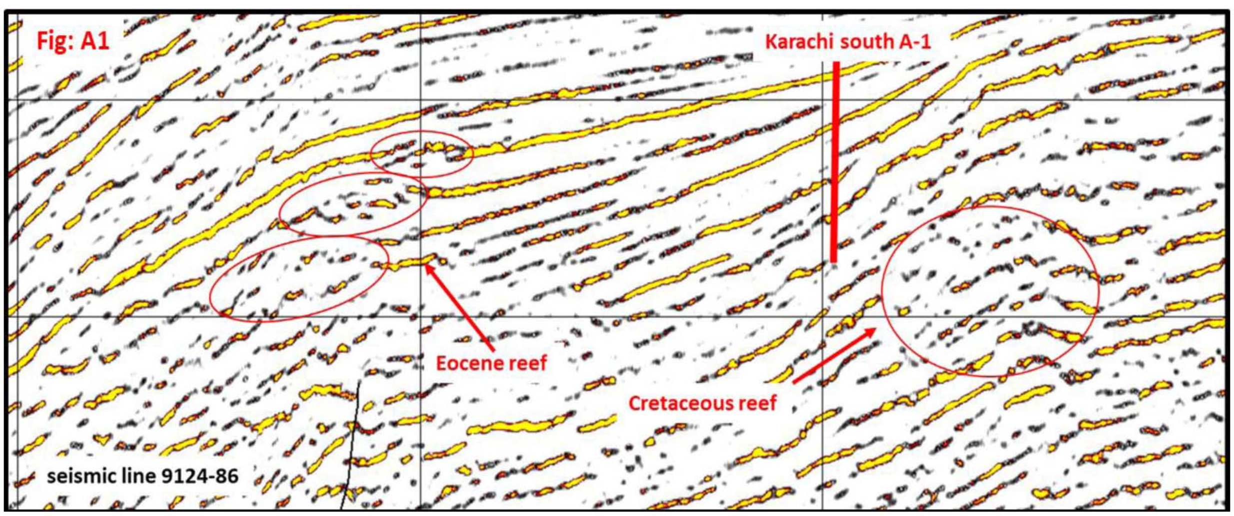


Figure A1—showing northeast – southwest seismic line marked with Eocene and Cretaceous reefs.

Stratal Hierarchy and seismic sequence stratigraphy

A hierarchy of stratigraphic cyclicity is developed within the super cycle TA2 that has a pronounced influence on reef development. Stratal geometries developed within the upper Paleocene unconformity to early Eocene record a complete regressive-transgressive cycle developed in response to a fall and rise in sea level. The TA2 super cycle is subdivided into different major phases of deposition, corresponding to the regressive, early low stand, late low stand and transgressive phases of the sea level cycle (Fig. 8). A subsequent regression phase marks the base of the overlying system tracts. Stratal geometry and stacking patterns vary systematically between each phase of deposition (Fig. 8). The sequences identified in TA2 are well-developed regressive, low stand and transgressive system tracts.

Upper Paleocene Unconformity/Sequence Boundary

The super cycle TA1 sequence boundary that developed on the top of the upper Paleocene unconformity resulted in long term exposure of the Paleocene platform, providing an opportunity to identify the clear impact of long-term exposure of the shelf. The exposed surface is because of regression and becomes progressively younger towards the basin due to progressive downslope shift of the sea level and more erosion to the landward. Near top TA1 is marked by following the upper Paleocene unconformity in the well and identified by top laps on seismic at the sequence boundary (Fig. 9). The sequence boundary is the highlighted red dashed line and equivalent surface in the slope is interpreted with the continuous red line.

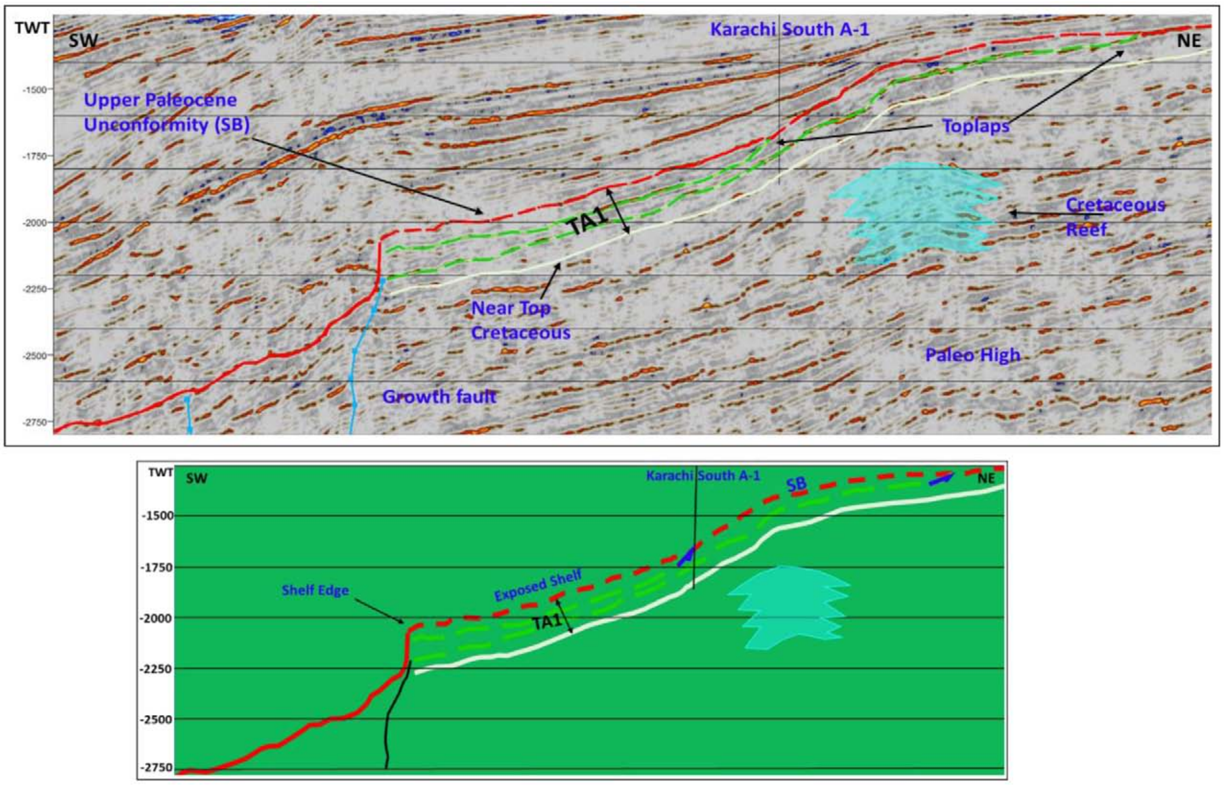


Figure 9—Seismic section and line drawing illustrating the sequence boundary at the end of super cycle TA1 with toplaps at SB.

Early Lowstand Phase/Falling stage system tract

The super cycle TA2 started from early low stand after upper Paleocene unconformity because of the sea level falling (regression). Below the shelf edge, prograding basinward clinoforms represents the continuous falling sea level. A series of clinoforms observed downlapping at the correlatable conformity highlighted blue (Fig. 10).

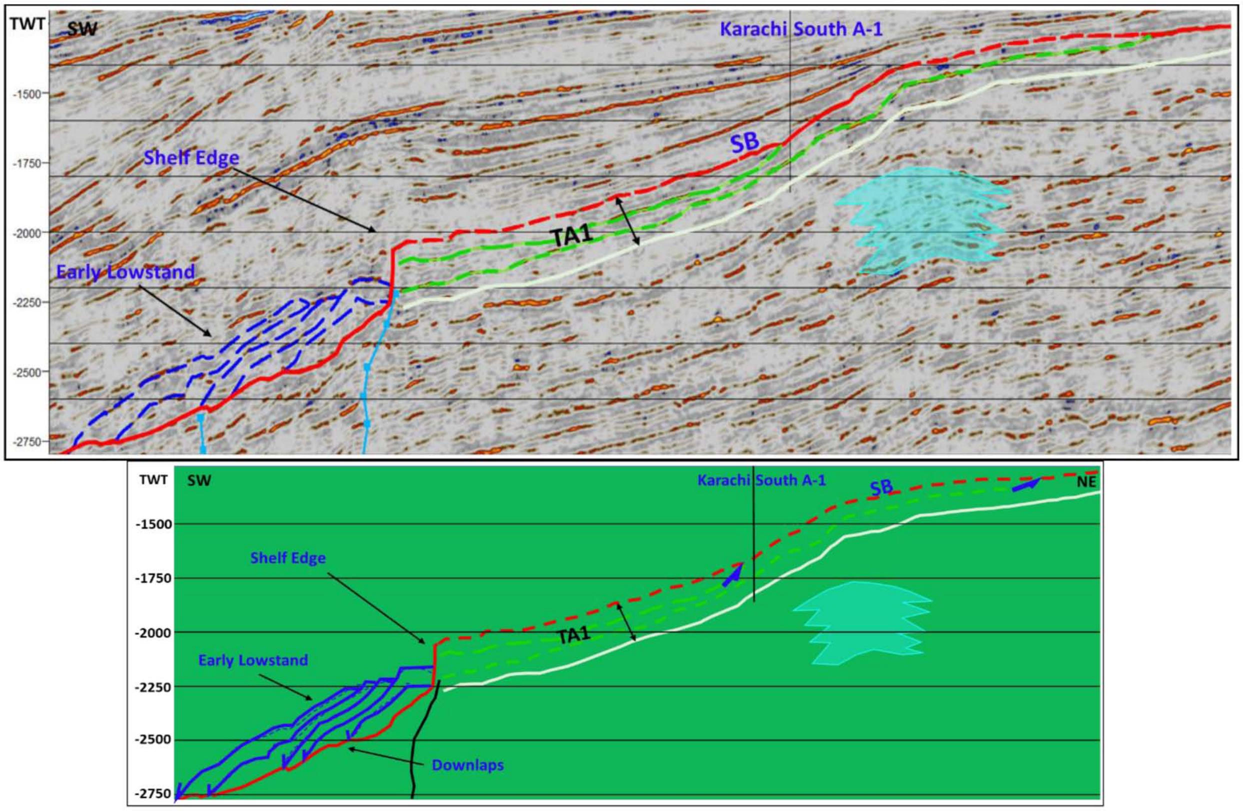


Figure 10—Seismic section and line drawing illustrating the geometry of early lowstand in blue downlapping at SB surface.

Late Lowstand Phase/Rising stage system tract

A complete cycle of low stand identified when the sea level was continuously falling and rising below the shelf edge, which includes early low stand and late low stand (yellow) (Fig. 11). At the end of the low stand, TST were identified on the shelf.

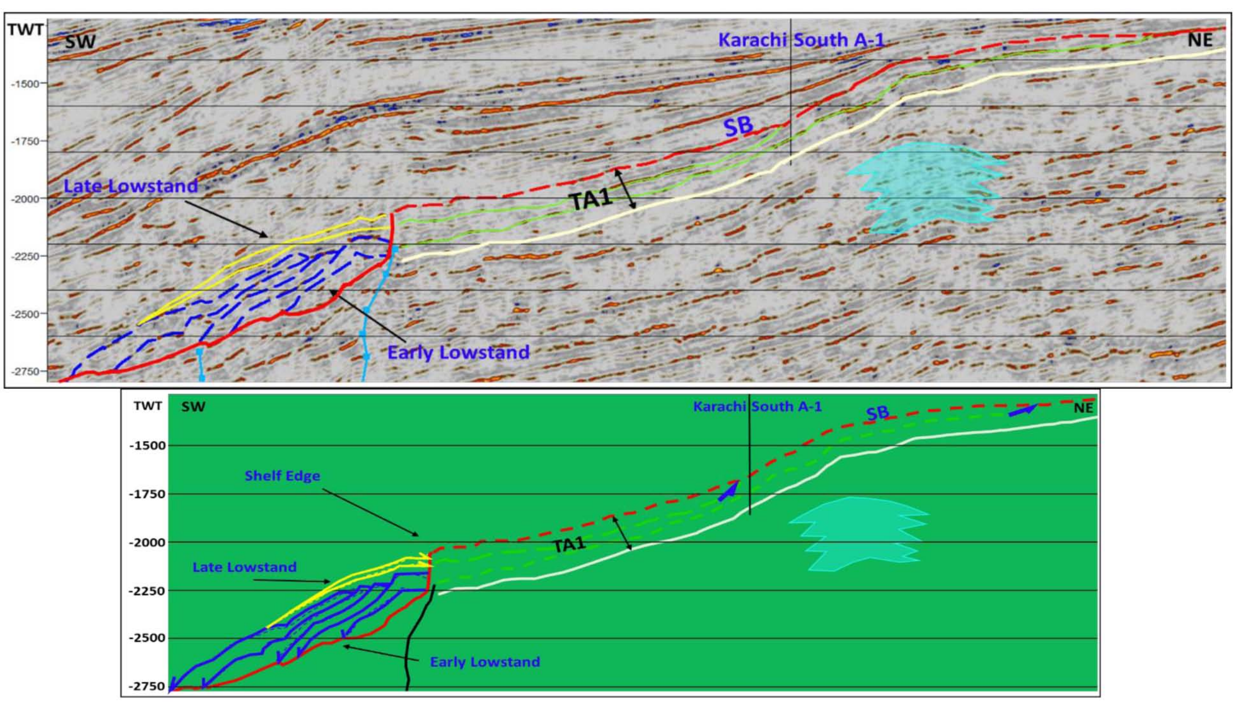


Figure 11—Seismic section and line drawing showing the complete cycle of early lowstand(blue) and late lowstand(yellow).

Transgressive System Tract

TA2 transgressive phase records the deposition during the rising limb of the long-term sea level cycle and includes many small cycles of transgression and regression. This was stated by Bilal Haq and Vail et al in 1987 and is supported by Karachi south A-1 well data. The transgressive system tract onlapping on the upper Paleocene sequence boundary (SB) on the shelf (highlighted with cyan color), until the time of maximum transgression of the coast, just prior to enter into the high stand system tract marked by the maximum flooding surface(MSF) highlighted green. The start of the reef development is marked at the shelf edge from start of TST and up to the near base middle Eocene (Fig. 12).

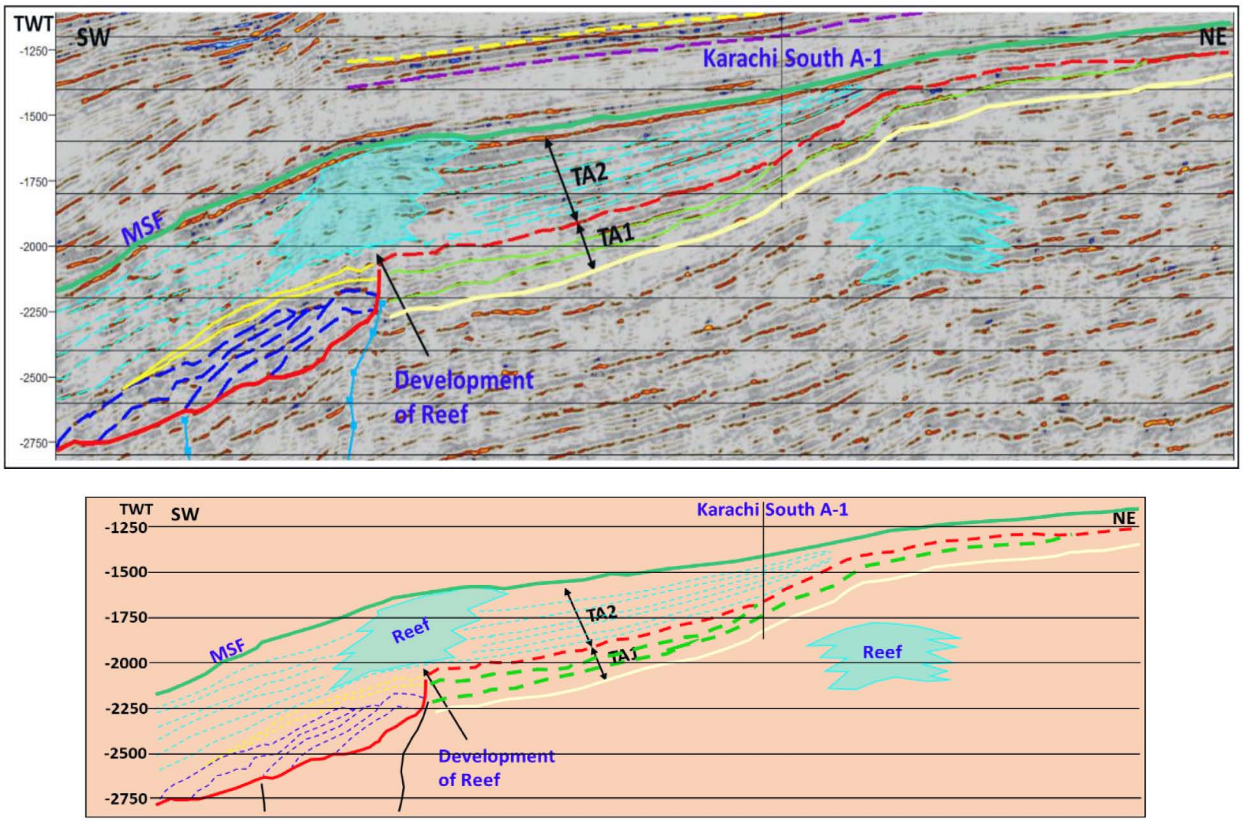


Figure 12—Seismic section and line drawing illustrating the complete TA1, TA2 and development of reef.

Carbonate platforms

The Carbonate platform is a general term. It is used to refer to a depositional surface upon which shallow-water carbonate facies are deposited. There is a plethora of geoscientists (Tucker in 1990, Tucker and Wright, 1990; Burchette and Wright, 1992) who classify the variety of platform types according to depositional profile and distribution of carbonate facies; as well as their evolution in both passive and convergent margin settings as in Fig. 13.

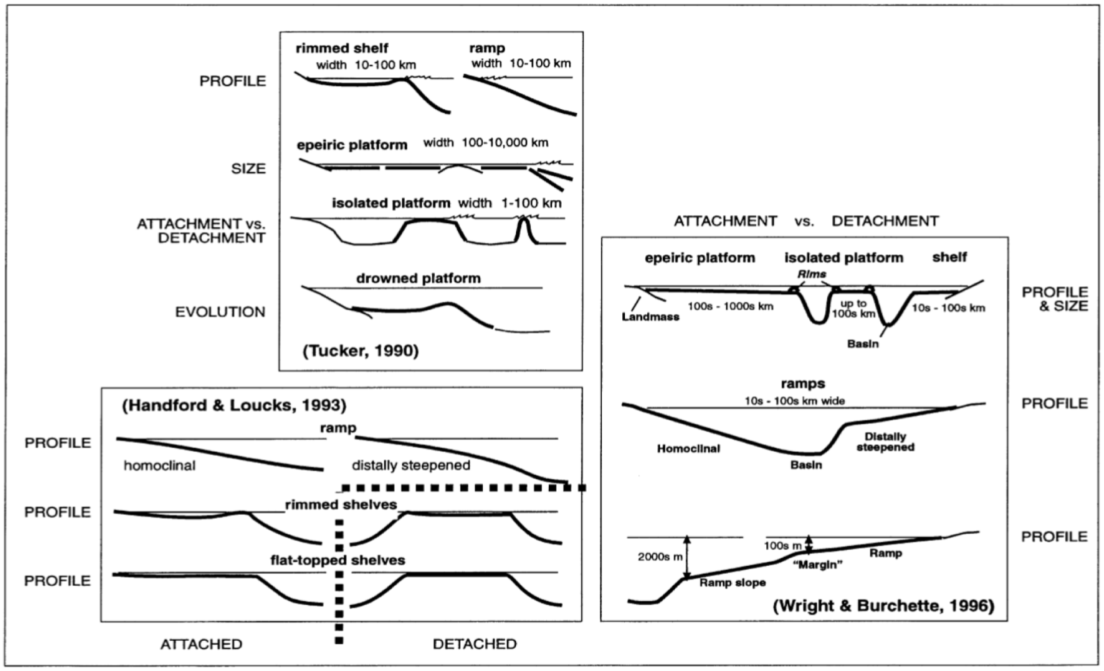


Figure 13—The different types of carbonate platform.

Rimmed shelf platform depositional model

From the seismic sequence stratigraphy of seismic line 9124-86, we noticed the presence of the carbonate platform where possibly the reef was growing at the shelf margin (Fig. 8). The platform reflections can be traced with confidence except for below the reef where it is not very clear. This is a typical example of the rimmed shelf carbonate depositional model. Fig. 14 shows the rimmed shelf platform derived from the seismic line 9124-86 and Fig. 14.a exhibits the 3D depositional model of the reef in the shelf area of offshore indus. Rimmed shelf are shallow marine platforms that have pronounced slope breaks some distance from the shore. The slope break is marked by rim forming reefs. The rim was developed at the paleo high. In the proximal side of the shoal (rim) there is a lagoonal area and in distal side there is a slope and then basin. The back reef/patch reef can be seen in the proximal area Fig. 14.a.

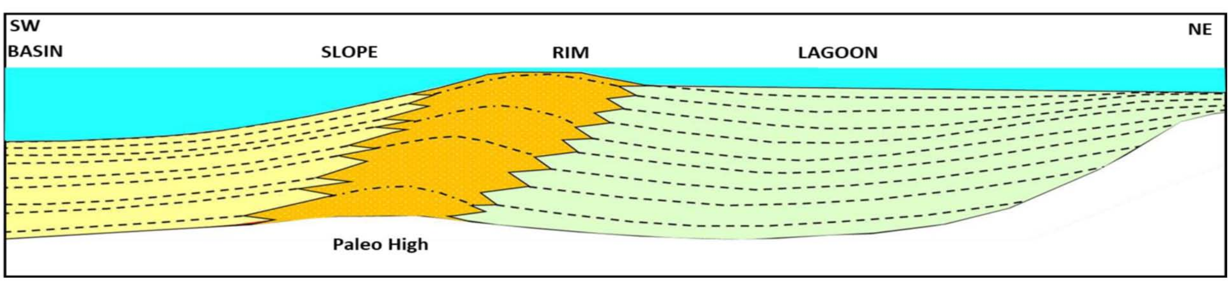


Figure 14—Rimmed shelf Conceptual model of Reef development from seismic line 9124-86.

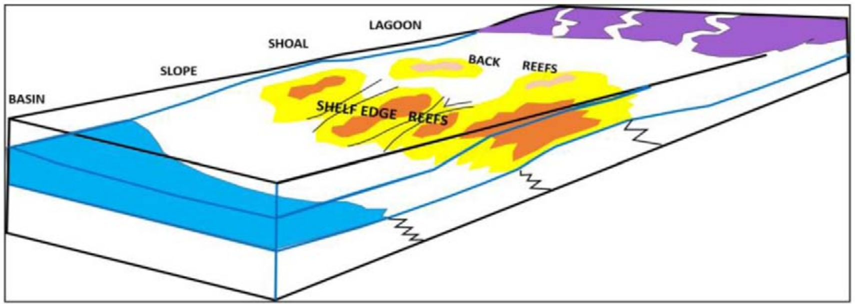


Figure 14.a—3D Depositional model of Reef in offshore indus shelf area.

Methodology to identify Carbonate geometries

To identify the reefs/buildups on seismic section after knowing the geology of the area and interpretation of the geological markers on seismic section, the most important is the prior Knowledge of geological geometry (analogue) of reefs in order to be able to localize them by identifying their reflection characteristics. Based on the experience of reef/buildup identification in Africa and Middle east, following characteristic of reefs identification are summarized in the offshore indus area. These seismic reflection characteristics are important to pinpoint through analogue or by using different techniques.

1. Plat form, a depositional surface where the reef grew.
2. The external appearance, the envelope which covers the reef main body.
3. The draping structure of overlying stratum.
4. The internal structure.
5. Thickening of layers on both sides of the buildup.
6. Onlaps, Downlaps and Toplaps associated with the reef.
7. Abnormal landform area.
8. Change in lateral velocity (Interval velocity) across the reef.
9. Stretch and squeeze of the seismic section horizontally and vertically.
10. Flatten the seismic horizon at the base of the reef/buildup to see the overall geometry.
11. Test different color schemes to highlight the internal/external geometry.
12. Change in seismic character showing lateral change in facies.

The above reflection criteria vary case to case and it is not necessary that we can see all the above features in one case. Each of above principles and geological elements give a specific seismic reflection response and can be witnessed qualitatively and quantitatively. The qualitative methodology includes points 1-12. The quantitative methodology which includes Porosity distribution (Out of scope of this article due to lack of seismic data) through amplitude and Inversion. All the reef characteristics from the available seismic data have been observed carefully and the reef distribution map of the area of interest was prepared. Fig. 5 shows the reef distribution map of the area of interest. Three seismic lines (Fig. 15, Fig. 16 & Fig. 17) were selected to explain the reef/buildup features by identifying their reflection characteristics.

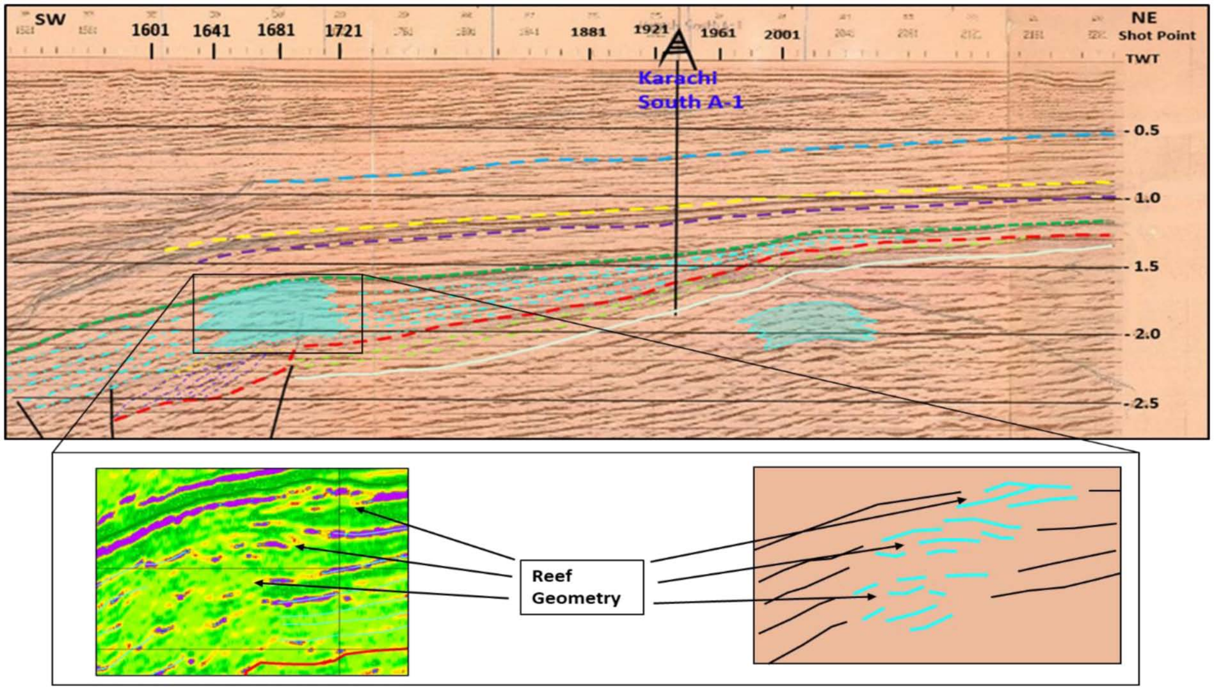


Figure 15—NE – SW 2D seismic line 9124-86 (location is shown in Fig. 5) passing through well Karachi south A-1 with Interpreted geological markers and reef geometry. The colored reef geometry is from the SEGY version of the same seismic line 9124-86.

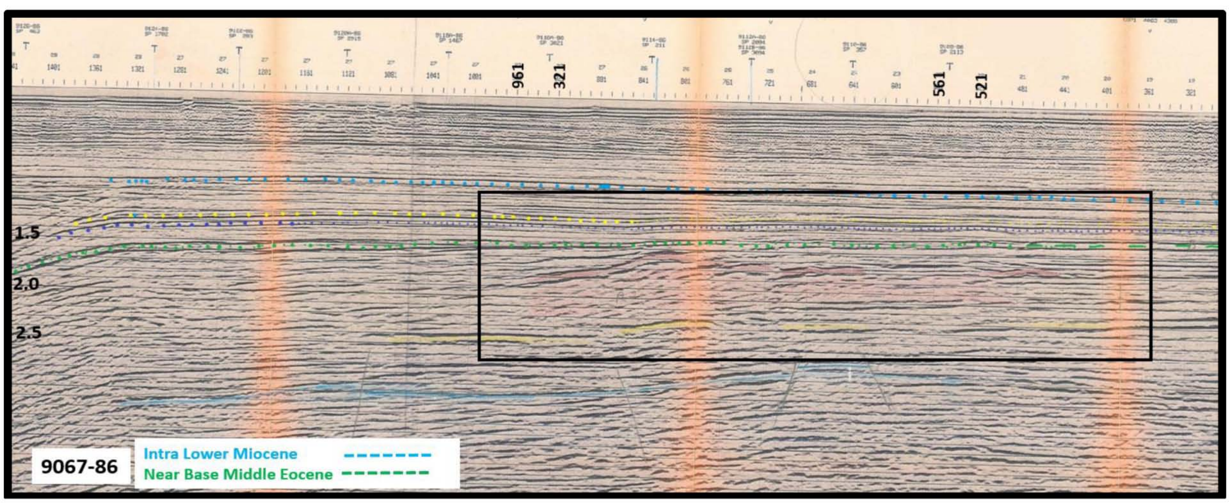


Figure 16—NW – SE 2D seismic line 9067-86 (location is shown in Fig. 5) is showing the reef inside black box at paleo high.

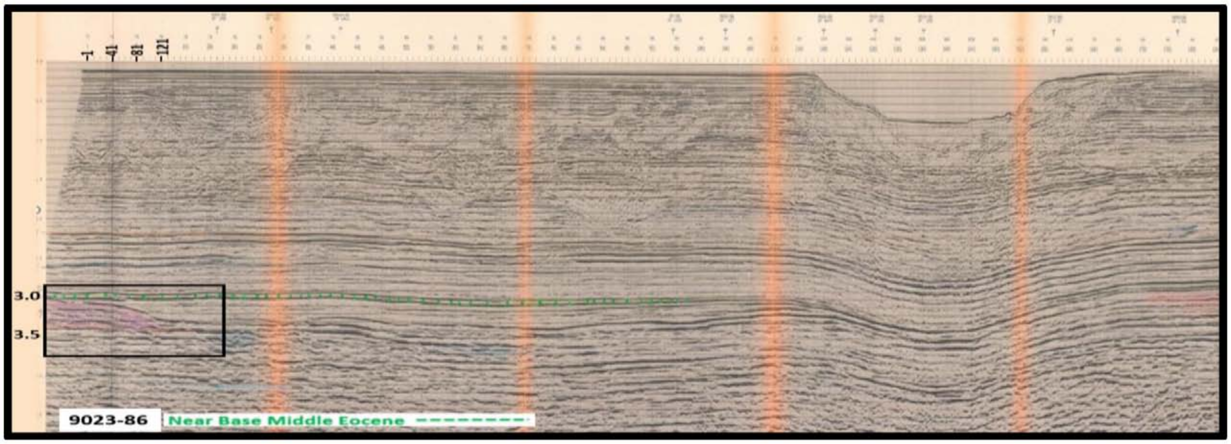


Figure 17—NW-SE 2D seismic line 9023-86 (location is shown in Fig. 5) showing seismic reflection characteristics with reef inside the black box.

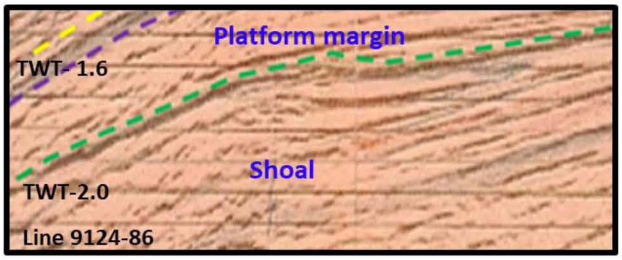
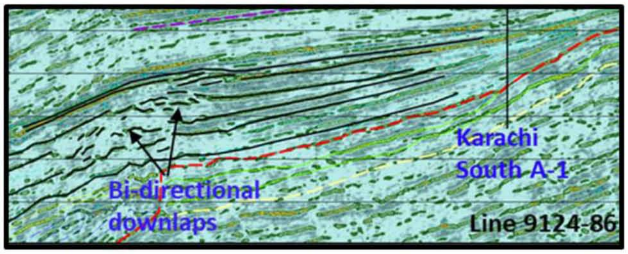
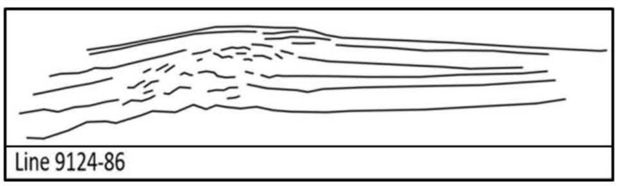
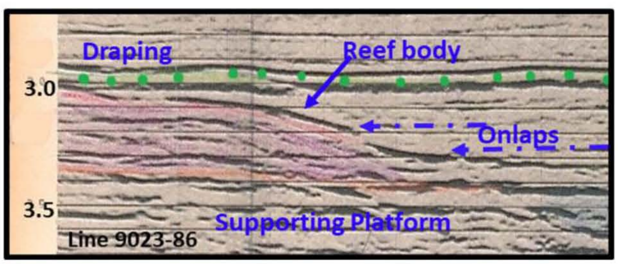
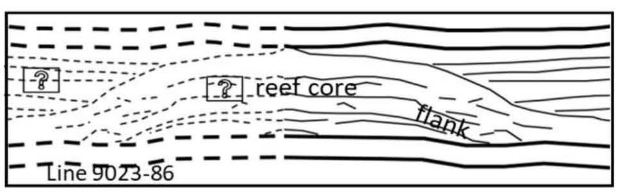
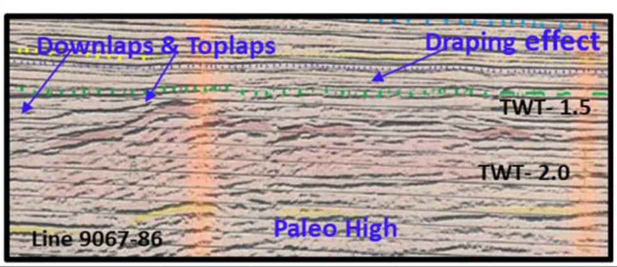
Based on the above described seismic reflection characteristics for reefs, reef indication was observed in seismic line 9124-86 between 1600-1800 msec. and between SP.1601 -SP.1721 (Fig. 15). The top of the reef is about 2880 m by using average velocity of 3600 m/sec. The reef characteristics are: External appearance rim (Shoal), platform, internal structure, change in seismic character, Change in lateral velocity (Interval velocity). Although lateral velocity change was witnessed from the velocity panel but the confidence level is low and we decided not to display. We believe that the latest processing sequence can give more confidence on lateral interval velocity change.

In seismic line 9067-86 reef indication was observed between 1500-1800 msec. and between SP.961 -SP.521 (Fig. 16). The top of the reef is about 2700 m by using average velocity of 3600 m/sec. The top of the reef is marked below the continuous reflector Near Base Middle Eocene. The reef characteristics are: Plat form, external appearance, draping structure of overlying stratum, internal structure, thickening of layers across the reef, onlaps & toplaps, Abnormal landform area.

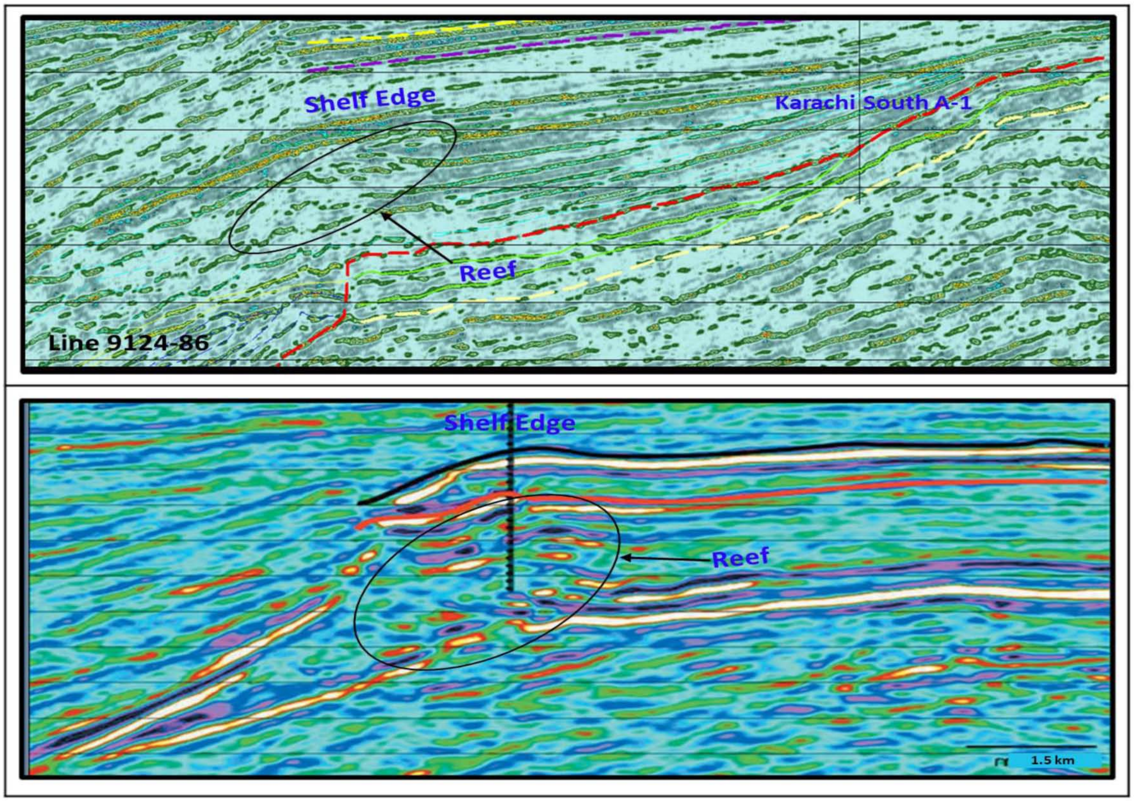
In seismic line 9023-86, Near Base Middle Eocene (green reflector) is a continuous reflector marking the top of the reef below TWT 3.0 msec on the left. A reef indication was observed between 3000-3300 msec. and between SP.1 -SP.121 (Fig. 17). The top of the reef is about 5400 m by using average velocity of 3600 m/sec. The identified reef characteristics are: Plat form, external appearance, draping structure of overlying stratum, internal structure, thickening of layers across the reef, Onlaps, Abnormal landform area. The observed reef is at the end of the seismic line and we can see only part of the reef.

Table - 1—Main seismic features identified on the 2D seismic data with their reflection characteristics (internal geometries, continuity, shape). Their identification and interpretation is based on a criteria described above.

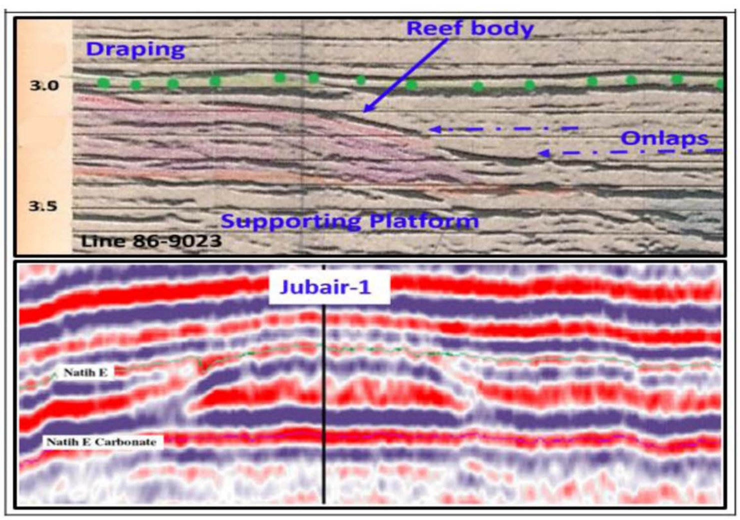
Reflection Characteristic & Interpretation

	Mound shape(shoal). Discontinuous to semi continuous Barrier reef below Platform margin/shelf margin.
	Seismic line is showing Rimmed shelf platform. Bi-directional downlaps & distorted reflections inside the reef body.
	Schematic cross section of seismic line 9124-86 flattened at base of reef showing reef geometry.
	Reef geometry with curved reflections below the green reflector and distorted reflections inside the body of the reef. Blue reflectors on lapping at the reef body.
	Schematic model of seismic line 9023-86 showing reef geometry.
	Downlap and toplap terminations on the left and onlap terminations on the right. The draping effect can be seen at the top of the Reef.

Carbonate geometries Analogue



Analogue – 1—Top seismic line is from study area and bottom seismic line is an analogue from deep Panuke gas field showing reefal buildup at the edge of Abenaki platform, Atlantic Canada (from Hogg and Enachescu, 2003). The deep Panuke is a shallow water discovery. This reef play was also tested in offshore Morocco and got success (Harland et al, 2002; Wierbicki et al, 2002; Tonn et at 2004).



Analogue – 2—The bottom seismic line is a reef analogue from a published paper "New Exploration Opportunities Associated with the Natih E Intra-Shelf Basin (Hisham A. Al-Siyabi, Omar S. Al-Ja'aidi, Hilal H. Al-Rashdi and Yaqoob M. Al-Sa'adi, PDO, Oman). The Jubair-1 well was drilled and proved good reservoir quality in the reef. The well was unsuccessful due to the lack of charge. Both of the reef geometries are look-alike but the vertical relief of line 9023-86 (top seismic line) is higher and overall size of the reef is bigger. The same reef geometry was also tested in Offshore Qatar and got success.

Conclusion

Based on the appearances criteria of reflection response, the presence of reef could be spotted by careful observation of seismic sections. Although the quality of the seismic sections is not good, the reef can still be identified with confidence.

A high resolution 2D seismic data can help to validate and identify more possible reefs in the area and to prepare a reef distribution map by using qualitative methodology as described in this article.

A high resolution 3D seismic data can help to see the areal extent of the reef and to apply quantitative methodology for further investigation.

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References

Tariq Jaswal, Tahir Maqsood, Structural geometry of the offshore indus basin, Pakistan.

Viqar-un-Nisa Quadri, S.M.G.J. Quadri, 1996. EXPLORATION Reefal petroleum prospects possible in Pakistan.

Richard I. Corfield, Scott Carmichael, John Bennett, Shakeel Akhter, Mansoor Fatimi & Tim Craig, 2010. Variability in the crustal structure of the West Indian Continental Margin in the Northern Arabian Sea. *Petroleum Geoscience* July 2010.

S. M. Carmichael, S. Akhter, J. K. Bennett, M. A. Fatimi, K. Hosein, R. W. Jones, M. B. Longacre, M. J. Osborne and R. S. J. Tozer, 2009. Geology and hydrocarbon potential of the offshore Indus Basin, Pakistan.

Gerome Calves, Mads Huuse, Anne Schwab, and Peter Clift, 2008. Three-dimensional seismic analysis of high-amplitude anomalies in the shallow subsurface of the Northern Indus Fan: Sedimentary and/or fluid origin. *Journal of Geophysical Research*, VOL. **113**.

M.A. Prins, G. Postma, J. Cleveringa, A. Cram, and N.H. Kenyon, 2000. Controls on terrigenous sediment supply to the Arabian Sea during the late Quaternary: *The Indus Fan*.

Tim Daley and Zaheer Alam. Seismic stratigraphy of the offshore Indus Basin.

Pioneer Global Geohistory Chart Waite 2002.

Luis Pomar. Departament de Cie Áncies de la Terra, Universitat de les Illes Balears, E-07071 Palma de Mallorca, Spain, 2001. *Types of carbonate platforms: a genetic approach*

Christopher George St. Cleme, William Full and Gregory L. Whittle. Article in Developments in Petroleum Science, December 1996. Chapter 2 *Seismic expression of carbonate reservoir systems*.

Syed Asif Ahsan, Rizwan Khan, Yasir Naveed & Mudasar M. Saqab, 2012.

M.A. Prins et al. 2002. Controls on terrigenous sediment supply to the Arabian Sea during the late Quaternary: The Indus Fan, *Marine Geology* **169** (2000) 327–349.

M.V. Ramana, Maria Ana Desa and T. Ramprasad 2015. Re-examination of geophysical data off Northwest India: Implications to the Late Cretaceous plate tectonics between India and Africa.

Dragana Todorovic-Marinic, Satinder Chopra and Mark Edmonds, 2011. Advanced seismic techniques help in characterizing a challenging Jean Marie carbonate play, *NE British Columbia, Canada – a Case Study*

Wayne M. Ahr, Texas A&M University. *Geology of carbonate reservoirs*