



Study of Stratigraphy and Structural Styles in the Subsurface of Southern Sindh Monocline, Pakistan:
Using Seismic and Well Data.

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Abstract: The study area is the part of Southern Sindh Monocline. Sindh Monocline is an important hydrocarbon producing area of Pakistan from where a large number of hydrocarbon fields have been discovered in the tilted fault blocks. The area is highly deformed and is characterized by extensional tectonic activities which are related to rifting phases experienced by the Indo-Pakistan plate. Thus the study of structural styles formed due to these tectonic activities is much important as the cretaceous rifting episodes had a profound effect on the formation and occurrence of hydrocarbons in Sindh Monocline.

To solve structural problem twenty five seismic lines and well information has been used for the interpretation of stratigraphy and structural styles within the subsurface of study area. Total Eight reflectors have been marked and were named as R1 of Upper Ranikot Group (Lakhra Formation), R2 of Lower Ranikot Group (Khadro Formation), R3 of Parh Limestone, R4 of Upper Goru, R5 of Top Lower Goru Formation, R6 of Sand Below Badin Shale (C- Sand unit) of Lower Goru Formation, R7 of Sembar Formation and R8 of Chiltan Limestone respectively from top to bottom.

Ultimately the average depths were calculated as of Upper Ranikot Group at 355.05 meters, Lower Ranikot Group at 646.00 meters, Parh Limestone 690.21 meters, Upper Goru at 1434.26 meters, Top Lower Goru at 1937.66 meters, Sand Below Badin Shale (C- Sand unit) at 2075.45 meters, Sembar Formation at 2475.41 meters and Chiltan Limestone at 2932.00 meters.

Through this study faults have been also marked on seismic lines which are normal faults by nature; collectively form horsts and grabens which is the evidence of effect of extensional tectonics in the area. Faults showing the north-west to south-east trend in the studies area. Interpretation of seismic data reveals that as a result of major and minor tectonic events, the study area has gone through extensive structural as well as depositional changes forming horst and graben structures up to Paleocene (Khadro Fm) horizon while the top most Upper Ranikot Formation is unaffected. Structures in the area provide basic elements of petroleum system. Grabens play main role for producing of hydrocarbons while faults are providing migration pathway for hydrocarbons from source to reservoir rocks while the faults also providing the trapping mechanism for hydrocarbons. Other main constituents are also present in the studied area.

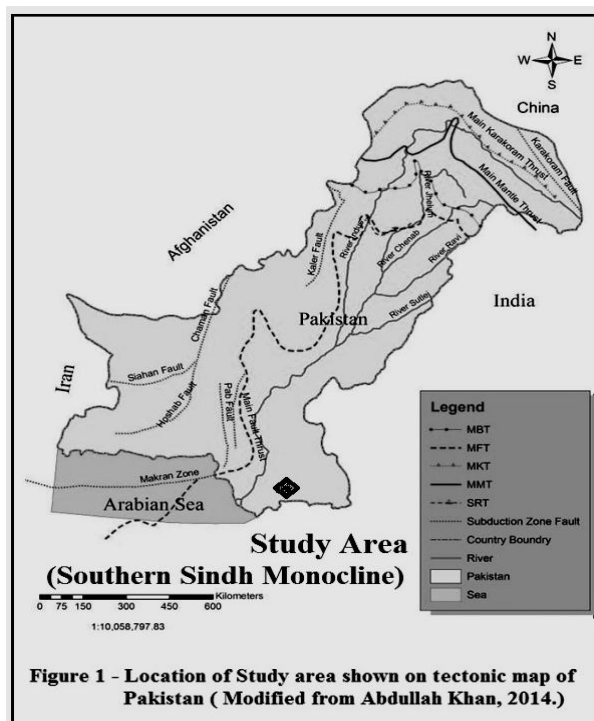
Keywords: Structural Styles, Horts, Grabens, Stratigraphy, Seismic Data Interpretation, Southern Sindh Monocline.

1. INTRODUCTION

The study area is the part of southern Sindh Monocline, Southern Indus Basin of Pakistan (**Fig. 1**). Geological boundaries of the area are: Indian shield in the east ; Kirthar Ranges in the West, to the north it is bounded by the Sukkur Rift Zone and with the Indus Offshore platform being the southern extension. Sindh Monocline is an important hydrocarbon producing basin of Pakistan contributing 50% of the country's oil, mostly discovered from structural traps. Khaskheli field discovery was the first big discovery by Union Texas Pakistan (UTP) in 1981 near by the study area. South Mazari Field was discovered in 1985 by British Petroleum (Pakistan) Exploration & Production Inc. from a large Crotch trap, a trap formed by two faults culminating at one point. Zaur field discovery was found in 1993 by B. P (Pakistan) Exploration and Production Inc. on a structural closure on a narrow

horst block, later on more wells were discovered on nearby fault blocks of the Horst structure. Later on many other major fields like Jabo, Zaur Ghunghro and many other Exploration and Production Companies have discovered hydrocarbons from and nearby study area. Recently in 2013 more discoveries have been successful from the fault closures of Jabo as well as Nur and Bagla fields. Thus the study of structural styles formed due to extensional tectonic activities and stratigraphic horizons is of vital importance. This research work is based on the study of structural styles and stratigraphic horizons within the subsurface of study area based on seismic data interpretation. The seismic data and well logs were collected from LMKR for research as well as for publication purpose with the permission of Directorate General of Petroleum Concessions, Ministry of Petroleum and Natural Resources, Islamabad.

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Alam *et al*, (2003) worked on Zaur field lies in the north of study area and interpreted Horst bounded by two faults by using Seismic and well log data. The difficulty of their work was due to the fault shadow effects and that the small width of the horst caused poor quality seismic imaging on the 2D seismic data. Further 3D seismic data was acquired over the Zaur field in 1998 with an objective to understand and interpret the Zaur field structural styles. The interpretation of 3D seismic data suggested that the Zaur field is a very complex structure.

Ahmad (2002) carried out the work on structure of South Mazari field of Badin Block and interpreted that a number of small normal faults are present in the field that divided the field into several compartments.

Ebdon *et al*, (2004), carried out work on Sequence Stratigraphy of the B Sand (Upper Sand, Lower Goru Formation) in the Badin area and concluded that over 60% of found reserves are from the Lower Goru Formation, and thus is the most important reservoir unit. Reservoir quality with in B Sand is primarily controlled by the depositional facies.

Syed *et al*, (2010) worked on the diagenesis of Basal sands of the Lower Goru Formation of the Badin Area, Sindh, Pakistan and concluded that the Basal Sands of Lower Goru Formation were deposited in marginal marine to shallow marine environment.

Khan (2012) worked on the impact of Indo-Pakistan and Eurasian Plates collision in the Sulaiman Fold Belt, Pakistan using seismic data and suggested that the Himalayan chain is primarily resulting from North-South collision between Indo-Pakistan and Eurasian plates and during the collision, the sedimentary overload separated from the basement of Indian Shield.

Brohi. *et al*, (2013) worked on joint analysis and economic importance of Lakhra Formation of Lower Indus Basin in which joints were analyzed by using the structural techniques and rose diagrams for the purpose to determine the maximum force direction exerted in the formation of joints. The application of structural data through rose diagrams in the studied area shows that the maximum force for the development of the major structures and joints has been generated from the NW direction.

Munir, *et al*, (2014) carried out the work on seismic interpretation and fault mapping in Badin area and he concluded that structuring in the area provides basic elements of petroleum system. Grabens are main areas for generation of hydrocarbons while faults are providing migration pathway for hydrocarbons from source rocks to reservoir rocks.

The above discussed literature is related to this research work but still there is a strong need to understand the sequence of the tectonic evolution of the area which will help in resolving the subsurface structure related problems which ultimately will be very helpful in formulating future exploration strategies in the area. Preparation of geophysical models using seismic reflection profiles will definitely increase the certainty of the subsurface structural behavior in the study area.

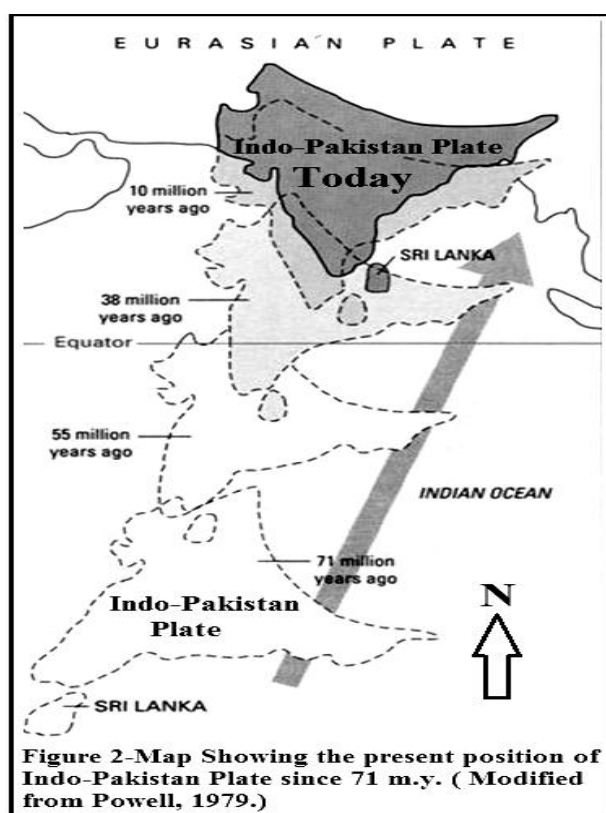
2. OBJECTIVES OF STUDY

Main objectives of this research are as under: The basic objective of this research work is to interpret and identify the horizons of different formations using surface seismic and well information, to interpret the structural styles within the subsurface of study area and to carry Seismic data Interpretation, geophysical modeling and inversion by using a world's leading Petrel Software created by Schlumberger.

3. TECTONIC SETTING OF THE AREA

Pakistan is located at the colligation of three lithospheric plates, the Indo-Pakistan, Arabian and Eurasian Plates. Indo-Pakistan plate was the part of Gondwanaland until Early Mesozoic (Before 200 Ma), started drifting during Jurassic to Early Cretaceous. Tectonics of Indo-Pakistan plate of which study area (Southern Sindh Monocline) forms a part have been discussed by many authors but Biswas S.K., (1982) comprehensively divided the history of drifting of Indo-Pakistan plate in to five stages as (1) Rifting of Gondwanaland took place in Late Triassic to early Jurassic with moderate sinistral rotation. (2) Drifting of plate independently from the rest of Gondwanaland in mid-Jurassic time with a speed of 3 to 5 cm/year. (3) Spreading speed reached its maximum 15 to 20 cm/year in Late Cretaceous time and during Late-Cretaceous to Paleocene, the western margin of the Indo-Pakistan Plate crossed the equator and passed over mantle thermal centre at latitude 70° S and Longitude 72° E, continuing counter clock wise rotation. (4) Collision with South margin of Eurasian Plate occurred in Late-Paleocene to Eocene time, while the spreading motion slowed down to 4 to 6 cm/ year. (5) The Final Welding of Indo-Pakistan Plate and Eurasian Plate occurred in Eocene-Oligocene time, which resulted the formation of Himalayan Mountains. The event of beginning of this continent-continent collision is known as Maastrichtian. As the Study area is the part of Southern Sindh Monocline, Southern Indus Basin of Pakistan, is the divergent boundary of Indo-Pakistan plate formed during Early to Middle Cretaceous (130-110 Ma) and resulted rifting. Due to this rifting the study area was deformed in a number of horst and graben structures. The cause of the formation of these structures was the northwest movement of Indian plate generated compression while the accompanying anticlockwise rotation produced tension. As a result of tension, the platform was split into horst and graben structures. The concentration of older reservoirs is more towards the east and northeast and the younger mature source rocks are to the west of the study area. The hydrocarbons in the grabens in the north-east (NE) and south-west (SW) of the monocline were subjected to higher temperatures due to deeper burial. Hence, extensional tectonics plays an important role in the

occurrence and maturation of hydrocarbons in the study and nearby areas. Structuring and widespread deposition of sedimentary facies including organic rich source rock (Sembar Shale) and highly porous and permeable reservoir rock (Lower Goru) in the area provides the basic elements of the petroleum system. Grabens are main areas for the generation of hydrocarbons while faults are providing migration pathway for hydrocarbons from source to reservoir rocks. Faults are also providing the trapping mechanism for hydrocarbons. The tilted fault block traps were in existence at the time of hydrocarbon generation. Fault associated with the structural closures are responsible for trapping oil and gas in lower Goru sand stones in the study and nearby areas.



4. GENERALIZED STRATIGRAPHY

Study area is covered by thick alluvium deposits of Indus River, below alluvium the Laki, Ranikot and Khadro (Deccan Volcanics) rocks of Tertiary age composed of sandstones and shale with minor interjection of limestone are encountered. Eocene age Laki/ Kirthar limestone possibly indicate the last marine sedimentation during the development of Himalayan tectonic event. Deccan volcanics (Khadro) of Early Paleocene age unconformably overlies the Upper Goru Member and the Parh Limestone which is overlain by Khadro Formation followed by Ranikot

Formation. The Upper Goru Member unconformably overlies the Lower Goru Member, consisting of marl, shale, calcareous claystone and interbeds of silt and limestone. Upper Goru shale provides an excellent seal.

Lower Goru sequence of Cretaceous age plays as a main reservoir rock with in Badin Block for over twenty fields. The Sequence has five general subdivisions based on prevalent lithologies, as (i) Upper Sands, (ii) Upper Shale, (iii) Middle Sands, (iv) Lower shale and (v) Basal Sands. Basal Sands are the major hydrocarbon producing reservoir in and near the Badin Block. The higher porosity in the Basal Sand at a greater depth suggests that the oil primarily migrated to the Basal Sand through carrier beds from the Sembar source rock and preserved the porosity present at the time of migration. Basal Sands are divided in to upper and the Lower Basal Sands. The upper sands are further subdivided into four sands A, B, C and D sands, interbedded with shale and mudstone, which also provide bottom seal. The Early Cretaceous Sembar Formation lies below the Lower Goru Member. Detailed geochemical studies of the Sembar Formation indicate that / portions of Sembar Formation contains up to 3.5% thermally mature organic content. Sembar Formation is believed to be the primary source for Hydrocarbons found in the Lower Goru Sands. Chiltan Limestone of Jurassic age is directly overlain by the Cretaceous Sembar Formation. The Limestone is a dense micrite and is devoid of any porosity development within the Badin Block. All the information related to stratigraphy is revealed by geophysical and drilling data of different fields with in Badin block. (Fig. 3) shows the generalized stratigraphic column of Badin block.

ERA	SYSTEM	SERIES	FORMATION	LITHOLOGY	HYDROCARBON SIGNIFICANCE		
					NOMENCLATURE	RESERVOIR	SEAL
MESOZOIC	TERTIARY	HOLOCENE	ALLUVIUM		ALLUVIUM		
			GAJ / NARI		GAJ / NARI (sand) / SHALE		
			KIRTHAR		KIRTHAR LIMESTONE		
		EOCENE	LAKI		LAKI SHALE		
			RANIKOT		RANIKOT SAND		
	CRETACEOUS	PALEOCENE	KHADRO		VOLCANIC / BASALT		
					KHADRO SAND		
		UPPER	UPPER GORU MEMBER		UPPER GORU SHALE		
					UPPER SANDS		
		LOWER	LOWER GORU FORMATION		UPPER SHALE		
JURASSIC					MIDDLE SANDS		
					LOWER SHALE		
					BASAL SANDS		
	UPPER	SEMBAR			SEMBAR SANDS AND SHALE		
	MIDDLE	CHILTAN			CHILTAN LIME STONE		

Figure 3 - Generalized Stratigraphic Column of the Study Area.

5. MATERIALS AND METHODS

Seismic method is one of the direct Geophysical methods which give the least ambiguous information of the subsurface. Seismic method is the process in which generated travel times and amplitudes of seismic waves propagating through a specified subsurface, start travelling within the earth and ultimately after bouncing from different interfaces of horizons the travel time of these waves is recorded by the sensors laid out on the surface of earth. Interpretation of seismic data usually consists in calculating the depth positions and identifying geologically concealed interfaces from seismic pulses returned to the ground surface by reflection. Two main approaches for the interpretation of seismic data are adopted; first one is stratigraphic analysis while the other is structural analysis. Stratigraphic analysis involves the subdivision of seismic sections into sequence of reflections that are interpreted as seismic expression of genetically related sedimentary sequences. Application of structural analysis is the search for different structural styles within the subsurface. Seismic stratigraphic analysis is the delineation of individual seismic facies units. These seismic facies units are based on reflection configuration, continuity, amplitude and frequency.

A. SEISMIC DATA: Seismic data comprises of following twenty one lines have been used: 1. PK85-KH-01, 2. PK85-KH-04, 3. PK85-KH-06, 4. PK85-935, 5. PK85-937, 6. PK85-958, 7. PK85-960, 8. PK85-962, 9. PK85-964, 10. PK85-966, 11. PK86-1051, 12. PK86-1200, 13. PK86-1202, 14. PK92-1678, 15. PK92-1680, 16. PK92-1682, 17. PK92-1685, 18. PK92-1686, 19. PK92-1687, 20. PK94-1800, 21. PK95-1804.

B. WELL DATA: Well information of following well has been used for this study: 1. Jabo-01, 2. Jabo-05, 3. Pirshah-01, 4. Doti-01, 5. Beghari-01, 6. Zaur-01 and Zaur-03.

6. SEISMIC DATA INTERPRETATION

One of the initial important things for an interpreter of seismic data is the picking of or interpretation of reflectors of horizons because it involves the decision making of what wiggles from trace to trace are from the same reflection. But if most nearest well control is available, the interpretation of seismic data will be more accurate.

Interpretation of seismic data started was started by the picking of reflectors of different formations on line No. PK86-1202 with the help of well information of Jabo-05 well and on the basis of prominent reflection continuity and regional geological information. Mostly normal faults have been interpreted on seismic data which collectively form the Horst and Graben type structures.

7.

VELOCITY ANALYSIS

Velocity analysis has been carried out through using K-Tron Velocity Analysis Software. Velocity values were calculated from the interval velocity values given on the velocity windows on hard copies of seismic sections. Root Mean Square velocity values were calculated from the interval velocity values where as average velocity was calculated from interval velocity values. Average velocity values have been calculated as for Upper Ranikot 1893.65 m/sec, Khadro Formation 1987.71 m/sec, Parh Limestone 2000.62 m/sec, Upper Goru Member 2441.30 m/sec, Top Lower Goru 2645.28 m/sec, Sand Below Badin Shale (C- Sand unit) 2695.39 m/sec, Sembar Formation 2829.04 m/sec and Chiltan Limestone 2969.11 m/sec (**Fig. 3A**).

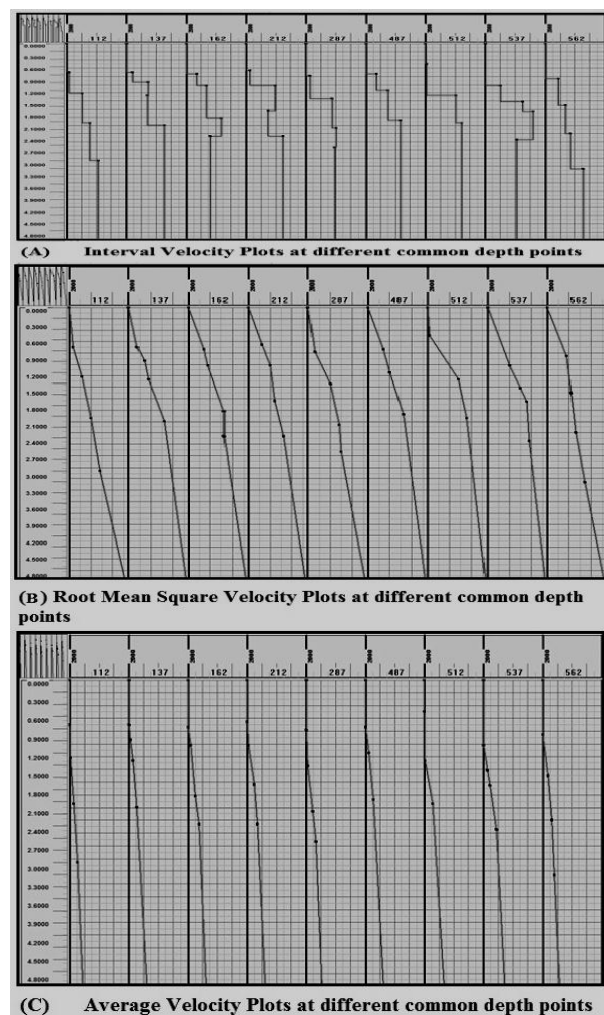


Fig.3A: (A) Interval Velocity Plots at different common depth points (B) Root Mean Square Velocity Plots at different common depth points (C) Average Velocity Plots at different common depth points & (D) Mean Average Velocity graph

8.

RESULTS AND DISCUSSION

In this study well tops and velocity information of Jabo-05 well which is nearest well have been used as

a control for marking of reflectors of different formations.

Eight reflectors has been marked and were named as 1. Upper Ranikot Group (Lakhra Formation), 2. Lower Ranikot Group (Khadro Formation), 3. Parh Limestone, 4. Upper Goru member, 5. Lower Goru Formation, 6. Sand Below Badin Shale (C- Sand unit) of Lower Goru Formation, 7. Sembar Formation and 8. Chiltan Limestone from top to bottom respectively (**Fig. 4**). The two way reflection time of was interpreted as Upper Ranikot Group (Lakhra Formation) at 0.375 sec, Lower Ranikot Group (Khadro Formation) at 0.650 sec, Parh Limestone 0.690 sec, Upper Goru at 1.175 sec, Top Lower Goru at 1.465 sec, Sand Below Badin Shale (C- Sand unit) at 1.540 sec, Sembar Formation at 1.750 sec and Chiltan Limestone at 1.975 sec (**Fig. 5**).

The velocity analysis has been carried out using K-tron VAS software and average velocity values have been calculated as for Upper Ranikot Group (Lakhra formation) 1893.62 m/ sec, Lower Ranikot Group (Khadro Formation) 1987.71 m/sec, Parh Limestone 2000.62 m/sec, Upper Goru 2441.30 m/sec, Top Lower Goru Formation 2645.28 m/sec, Sand Below Badin Shale (C- Sand unit) 2695.39 m/sec, Sembar Formation 2829.04 m/ sec and Chiltan Limestone 2969.121 m/sec. Ultimately the average depths have been calculated as of Upper Ranikot Group (Lakhra Formation) at 355.05 meters, Lower Ranikot Group (Khadro Formation) at 646.00 meters, Parh Limestone at 690.21 meters, Upper Goru at 1434.26 meters, Top Lower Goru Formation at 2645.28 meters, Sand Below Badin Shale (C- Sand unit) at 2075.45 meters, Sembar Formation at 2475.41 meters and Chiltan Limestone at 2932.00 meters.

Faults have been also marked on seismic lines which are normal faults; collectively form horsts and grabens which is the evidence of extensional tectonic in the area during.

Interpretation of seismic data reveals that as a result of major and minor tectonic events, the study area has gone through extensive structural as well as depositional changes forming horst and graben structures up to lo Upper Goru (Cretaceous) horizon while the top most Upper Ranikot (Paleocene) and Khadro (Paleocene) formations are unaffected.

Structures in the area provides basic elements of petroleum system. Grabens play main role for generation of hydrocarbons while faults are providing migration pathway for hydrocarbons from source to reservoir rocks while the faults also providing the trapping mechanism for hydrocarbons.

9.

CONCLUSIONS

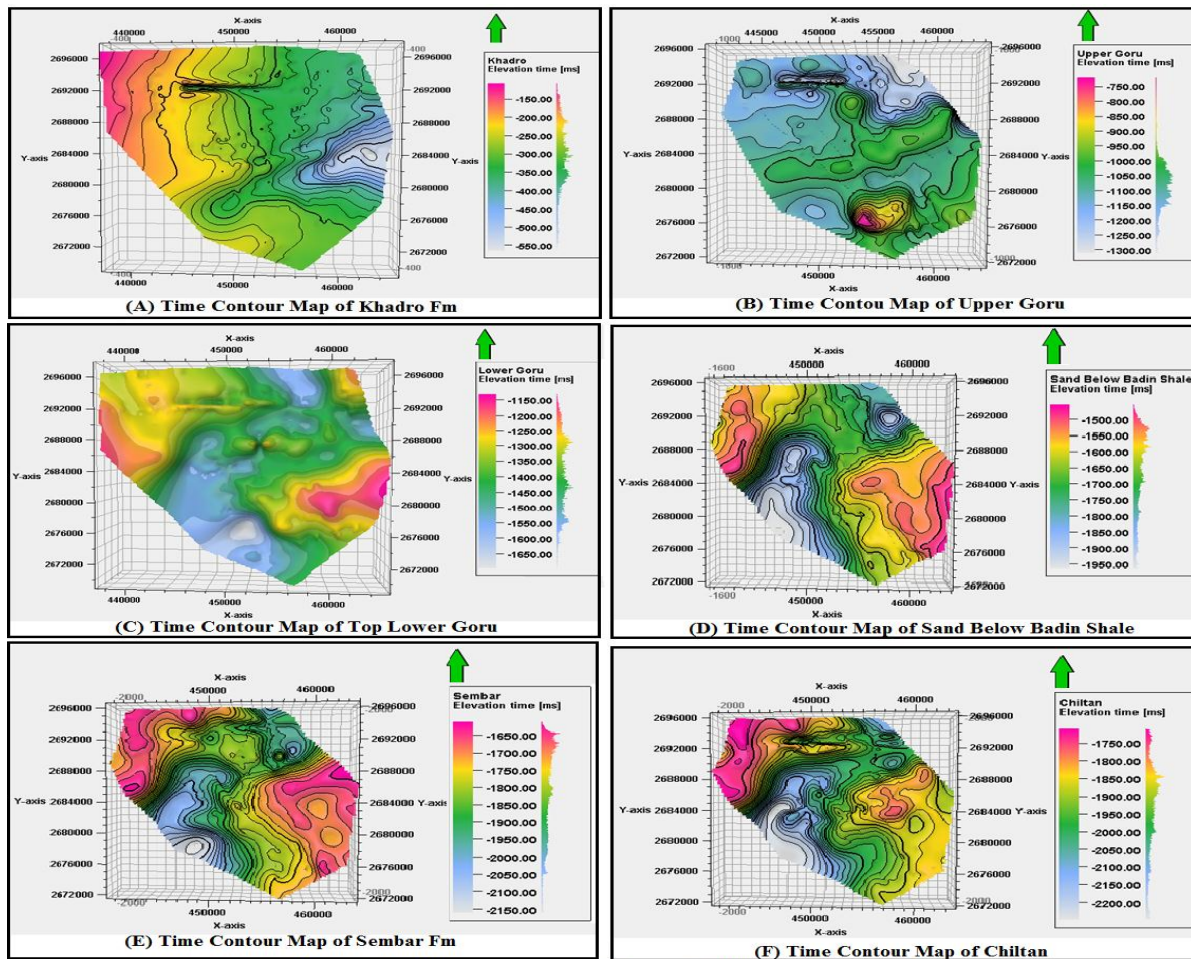
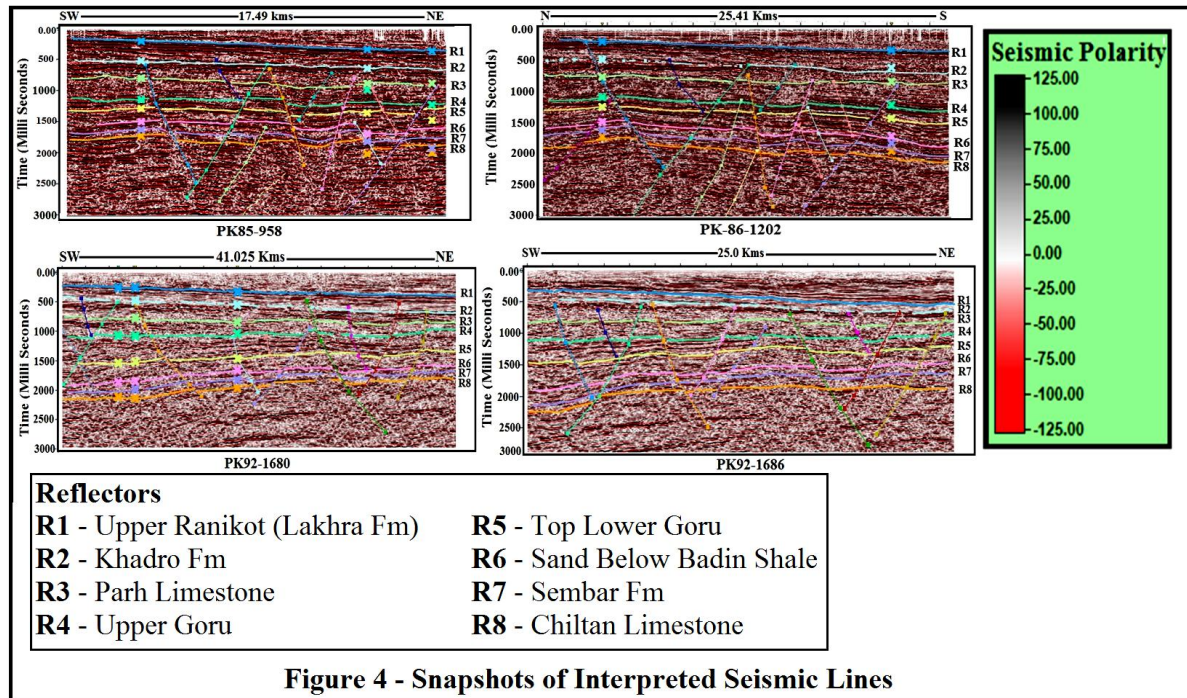
Total Eight reflectors have been marked and were named as R1 of Upper Ranikot Group (Lakhra Formation), R2 of Lower Ranikot Group (Khadro Formation), R3 of Parh Limestone, R4 of Upper Goru, R5 of Top Lower Goru Formation, R6 of Sand Below Badin Shale (C- Sand unit) of Lower Goru Formation, R7 of Sembar Formation and R8 of Chiltan Limestone respectively from top to bottom. Average time of reflectors were interpreted as for R1 at 0.375 sec, R2 at 0.650 sec, R3 at 0.690 sec, R4 at 1.175 sec, R5 at 1.465, R6 at 1.540 sec, R7 at 1.750 sec and R8 at 1.975 sec. The average depths of reflectors of different geological horizons have been calculated as of Upper Ranikot Group (Lakhra Formation) at 355.05 meters, Lower Ranikot Group (Khadro Formation) at 646.00 meters, Parh Limestone at 690.21 meters, Upper Goru Member at 1434.26 meters, Top Lower Goru Formation at 2645.28 meters, Sand Below Badin Shale (C- Sand unit) at 2075.45 meters, Sembar Formation at 2475.41 meters and Chiltan Limestone at 2932.00 meters.

Faults were marked on seismic sections which collectively form horsts and grabens which is the evidence of extensional tectonic in the area. Faults showing the north-west to south-east trend in the studies area. Interpretation of seismic data reveals that as a result of major and minor tectonic events. The area is highly deformed and characterized by extensional tectonic activities which are related to rifting phases experienced by the Indo-Pakistan plate. The study area has gone through extensive structural as well as depositional changes forming horst and graben structures up to Paleocene (Khadro Fm) horizon while the top most Upper Ranikot formation is unaffected. Structures in the area provides basic elements of petroleum system. Grabens play main role for generation of hydrocarbons while faults are providing migration pathway for hydrocarbons from source to reservoir rocks while the faults also providing the trapping mechanism for hydrocarbons. Other main constituents are also present in the studied area.

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