Surface and Subsurface Expressions of Jacobabad Khairpur Highs, Southern Indus Basin Using Well Data: An Approach For Well Prognosis

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ABSTRACT

The study area lies in Rohri near Jacobabad-Khairpur High, which is the part of Sukkur rift zone. The High trends NNW-SSE that separates the Southern Indus Basin from the Middle Indus Basin. The Jacobabad High represents the horsts structure on the regional scale, coupled with Pano-Aqal Graben and Mari Kandhkot Highs these structures are collectively known as Sukkur Rift Zone. The research work is based on constructing the structural and stratigraphic correlations of the wells, depth contours and isopach maps to delineate subsurface structures. Using these depth contours and Isopach maps; constructing the Pseudo-well at the outcrop of Habib Rahi Formation, to examine the shape of Jacobabad Khairpur Highs across this well. Depositional history of Indus-01B and (Pseudo well). Reservoir characteristics of Kandra-01 are determined at Sui Main Limestone level to know the hydrocarbons values and suggestions for (Pseudo-well) with comparing results of Indus-01B.

Cretaceous rock sequence is absent on the North Western part of the High and Paleocene Dunghan Formation overlies the Middle Jurassic Chiltan Formation (Jhatpat-01), and the (Jacobabad-02) wells. On the Eastern part of the High at Rohri (Pseudo-Well), there is an evidence of complete petroleum system due to the presence of source rock Sembar Formation (Cretaceous), reservoir rock Lower Goru Formation and seal rock Upper Goru Formation and Sui Main Limestone as a main reservoir target. Petrophysical interpretations of Kandra-01 shows good reservoir characteristics for Sui Main Limestone. The reservoir parameters for Sui Main Limestone in Kandra-01 shows average porosity of 14.5% with water saturation 54.12% and hydrocarbons saturation of 45.88%. The Depositional model represents two major tectonic events, the Indian Plate rifting during the time of Middle Jurassic, and the Eocene time period indicated by sharp uplift feature in model which is Himalayan Orogeny. The Himalayan Orogeny results in the uplift of Rohri (Pseduo-well) in the subsurface.

Keywords

Jacobabad Khairpur Highs, Southern Indus Basin, Depth Contour Maps, Isopach Maps, Structural Correlations, Depositional Modelling, Petrophysical Interpretations, Well Prognosis.

1. Introduction

The study area Rohri with the exact co-ordinates 27° 67' 76''N 68° 91' 24''E; is on the eastern flank of Jacobabad Khairpur High, which is the part of Sukkur Rift Zone, Southern Indus basin. Sukkur Rift Zone comprises of normal faults associated Horsts and Graben Structures, which include Mari Kandhkot High, Panu Aqal Graben and Jacobabad Khairpur High (Farah et al, 1984). The study area is situated on the separating boundary between Central and Southern Indus Basin. The Central and Southern Indus Basin are separated by Jacobabad and Mari Kandhkot Highs (Figure 1), together termed as Sukkur Rift (Raza et al, 1989). The study area has a prominent position in hydrocarbon prospecting with Sargodha high, Indian Shield and marginal zone of Indian Plate in north, east and west respectively (Kazmi, A and Rana, 1982; Hussain et al, 2017). (Qayyum et al, 2016) said that "Different structural styles of Southern Indus Basin are the result of different tectonic events throughout its geological history (Ahmed and Ali 1991). There are three significant post-rifting tectonic events that can be distinguished in Southern Indus Basin, a Late Cretaceous uplift and inversion, a late Paleocene right-lateral wrenching, and a late Tertiary Holocene uplift of the Khairpur High" (Kazmi and Jan 1997; Hedley et al. 2005). Rocks of Eocene are well exposed on the surface across and along the Jacobabad High which is due to collision of Indian and Eurasian Plate. This piece of work is based on studying the subsurface and surface structural styles of Jacobabad Khairpur High at Rohri area and assigning new location for well prognosis. For new prospects in any area, seismic data interpretation for hydrocarbon traps is not sufficient, further detail study like Petro physical analysis, reservoir characterization, rock physics analysis and seismic modeling is required (Coffen, 1984). The work is done by using 12 wells data to construct structural well correlations and stratigraphic correlation to visualize the trends and variations in geological formations found in these wells, depth contour maps to determine the shape of the High at different formation levels, Isopach maps to examine the subsurface thickness of the formations, depositional or back-stripping model to understand the past geological depositional styles in different geological time periods, based on these structural and stratigraphic correlations, depth contours and Isopach maps, suggesting the new well at Rohri (Pseudo-Well) where the Eocene Habib Rahi Formation is exposed; name given on the basis of well correlations, to examine and determine the shape of the Jacobabad High at this location which is based on the actual and assumed thickness of formations found in the wells that are used in this research for future hydrocarbon explorations. Petrophysical interpretations and reservoir characteristics of Sui Main Limestone of Kandra-01 to suggest an idea of hydrocarbons prospects for Pseudo-Well by comparing values of Indus-01B previously done by (Shakir., et al, 2017).

2. Geology and Tectonic Settings

Pakistan lies on one of the most ubiquitous and active regions of the world. Its geographical position makes it most complex and active in terms of geology and tectonics, as it is almost wedged between Indian and Eurasian Plate coupled with Afghan Micro block. The zone of collision between Eurasian and Indian Plate is continuously in convergence that gives rise to mighty Himalayas, and adjacent mountain ranges with a rate of 3-5 cm/year. This collision is the main cause of the development of the sedimentary basins of Pakistan because the rate of uplift is balanced by the rate of erosion which causes sedimentary basins to develop. Based on the sedimentation history and structural style, the Indus Basin is divided into three segments namely Upper, Central and Southern Indus basins. (Ahmad, et al, 2012; Berger A., et al, 2009). Relatively high areas from shoreline of Jacobabad-Khairpur and Mari Kandhkot highs distributed the lower portion of Indus basin in central and southern basins mutually known as Sukkur Rift (Jadoon. S et al, 2016). From geological point of view, the study area lies in eastern part of Jacobabad Khairpur High which is the NNW-SSE trending High (Siddique, 2004). "The Southern Indus Basin is bounded by Indian Shield to the east, marginal zone of Indian Plate to the West. Its Southward extension is confined by Offshore Murray Ridge-Oven Fracture Plate boundary" (Jadoon. S et al. 2016). "The Murray Ridge is an offshore equivalent of Kirthar Fold Belt in Pakistan onshore" (Clift et al. 2002a; Edwards et al. 2000). "The stratigraphy in Kirthar Fold belt ranges from Triassic to Recent age" (Hasany et al. 2007; Qayyum et al. 2016). On the northern side the Jacobabad High delimits the Southern Indus Basin from the Middle Indus Basin. In the southeastern corner, Precambrian basement rocks are exposed at Nagar Parkar (Quadri and Shoaib 1986) (Figure 1). The Jacobabad, Mari-Kandh Kot and Lakhra highs all have the appearance of horst blocks and probably formed in response to the extensional tectonic style of Lower Indus Basin (Quadri and Quadri, 1996) which formed in response to the spreading axis between Madagascar and the Indo-Pakistan continental mass in the mid Cretaceous. Later transpression between the convergent Indo-Pakistan and Eurasian plates caused inversion and the superimposition of a transform style (Amjad, 2010). The Sibi lineament separates the Jacobabad high from its magnetic "paired" highs. This magnetic high was probably shifted because of inadequate identification of objects on maps (Kadri 1995). The geologic evolution of the area covered by Lower Indus Basin in context with regional geology is such that with the exception of a few Triassic outcrops. The Mesozoic rock succession of the Lower Indus Basin is represented several thousand-meter-thick Jurassic sequences. These are shallow water marine rocks consisting of limestone and shale with subordinate sandstone inter-beds in the lower part. The intra Jurassic unconformity at the close of Callovian time occurs throughout the Indus Basin (Zaigham et al., 2000). In the Rohri Sukkur area mostly Eocene rocks are exposed on the surface, but the oldest rocks found in the Southern Indus Basin is Wulgai Formation of (Triassic) Age (Jhatpat-01). On the northwestern part of Jacobabad Khairpur High there is absence of entire Cretaceous succession, based on subsurface well data from (Jhatpat-1) of (AMOCO) and (Jacobabad-2) of (PPL), and the Paleocene Dunghan Limestone is present directly above the Middle Jurassic Chiltan Formation, marking the well renowned unconformity K-T boundary (Siddiqui, 2004). The Dunghan Formation was deposited when the Indian Plate passes over the Kerguelen Hotspot, becoming the part of continental shelf and depositing Dunghan Limestone (Naveed Ahsan et al.

2018). While on southern side of this High significant succession of Upper Cretaceous is present indicating submerging of Jacobabad High allowing deposition of Cretaceous succession based on data from Kandra-04D and Kandra-01 (Figure 2). Whereas in the Pano Aqal Graben nearer to the Northeastern part of the High, an example from Sundrani-01 (Figure 2), and the oldest rock encountered during drilling is Chiltan Formation of (Middle-Jurassic), but the point to be noticed is that the (Sembar Formation) of (Early-Cretaceous) is present in a sufficient thickness, well enough to produce hydrocarbons. This is the only well nearer to the eastern side of Jacobabad Khairpur High, where the entire Cretaceous sequence is present over the Jurassic rocks, over the Cretaceous the Paleocene Ranikot Formation is present, above which the Dunghan Limestone was deposited and the sequence extends upto recent alluvium. The Indus-01B was drilled upto Cretaceous Pab sandstone. It means there should be existence of older Cretaceous and Middle Jurassic Chiltan Formation that we have shown in our correlations using assumed thickness (Figure 5.1). The Eocene strata is present within and on the surface with minor truncations and pinch outs in the subsurface. In the study area the Eocene Habib Rahi Formation Member of Kirthar Formation is exposed which was then uplifted by Himalayan Orogeny. In short, the geology of Southern Indus Basin ranges from Triassic to recent alluvium (Kadri 1995) based on well data (Figure 3).

3. Petroleum Activities of the Study Area

The first wells drilled in the vicinity of Jacobabad Khairpur High was Jacobabad-01 and Jhatpat-01 1958 and 1960. In 1989, LASMO (of U.K.) made a gas discovery in Lower Goru Sandstone (Cretaceous) at Kadanwari, south of Khairpur Jacobabad High (Young, H., 1992). Three gas discoveries have been made so far including (Khairpur, Jacobabad and Kadanwari). The Khairpur and Jacobabad discoveries are from Early Eocene carbonate (Sui Main Limestone) with a (porosity about 12%). The Kadanwari discovery is from Goru Sandstone (Cretaceous), which is a continuation of Badin's Goru reservoir and is sourced by Sembar Formation of (Early Cretaceous) (Riaz Ahmed and Jalil Ahmed 1991). The Jhatpat-01 of AMOCO was drilled upto the maximum level of (Triassic) Wulgai Formation. Kandra-04D is drilled upto Chiltan (Jurassic) level with missing of source rock Sembar Formation for most prolific Goru Formation, whereas in Kandra-01 Upper Cretaceous Goru Formation is encountered during drilling with no source Sembar Formation (Cretaceous). According to (Riaz Ahmed and Jalil Ahmed 1991), it is possible and expected that a commercial gas discovery can be made by drilling southern culmination, where Habib Rahi and Pirkoh Limestone are present with effective seal provided by the increased shale content towards South. The Jacobabad-Khairpur horst contains gas in Eocene carbonates and in Jurassic and Triassic sandstones, and in Badin region of Sindh oil and gas occur in sandstones of Cretaceous Goru Formation in structural traps (Malik et a1. 1988, Raza et a1. 1989b).

Previously the similar work was done by (Shakir et al. 2017), that work was to some extent is based on seismic interpretations, attribute analysis and petrophysical interpretations of Badar South-01 and Indus-01b of Pano Aqal Graben. They have had suggested location for new well at seismic line GHA94-16 shot point 75. The work is based only on Pano Aqal Graben, but our research is more than this because in a sense we used 12 wells data and we have adopted new technique; like, structural and stratigraphic correlations using well tops, depth contours with Isopach maps, with detailed subsurface depositional modelling of Pseudo-Well with an ideal condition for the presence of hydrocarbons. They have concluded that the new well total depth should be up to Cretaceous Pab Sandstone with Sui Upper and Sui Main Limestone as a potential target. Our work shows that there is possibility for the presence of Cretaceous Sembar Formation which is the potential source rock based on assumed thickness and correlations starting in the North from Sundrani-01 to Indus-01b up to Sagyun-01 in the South.

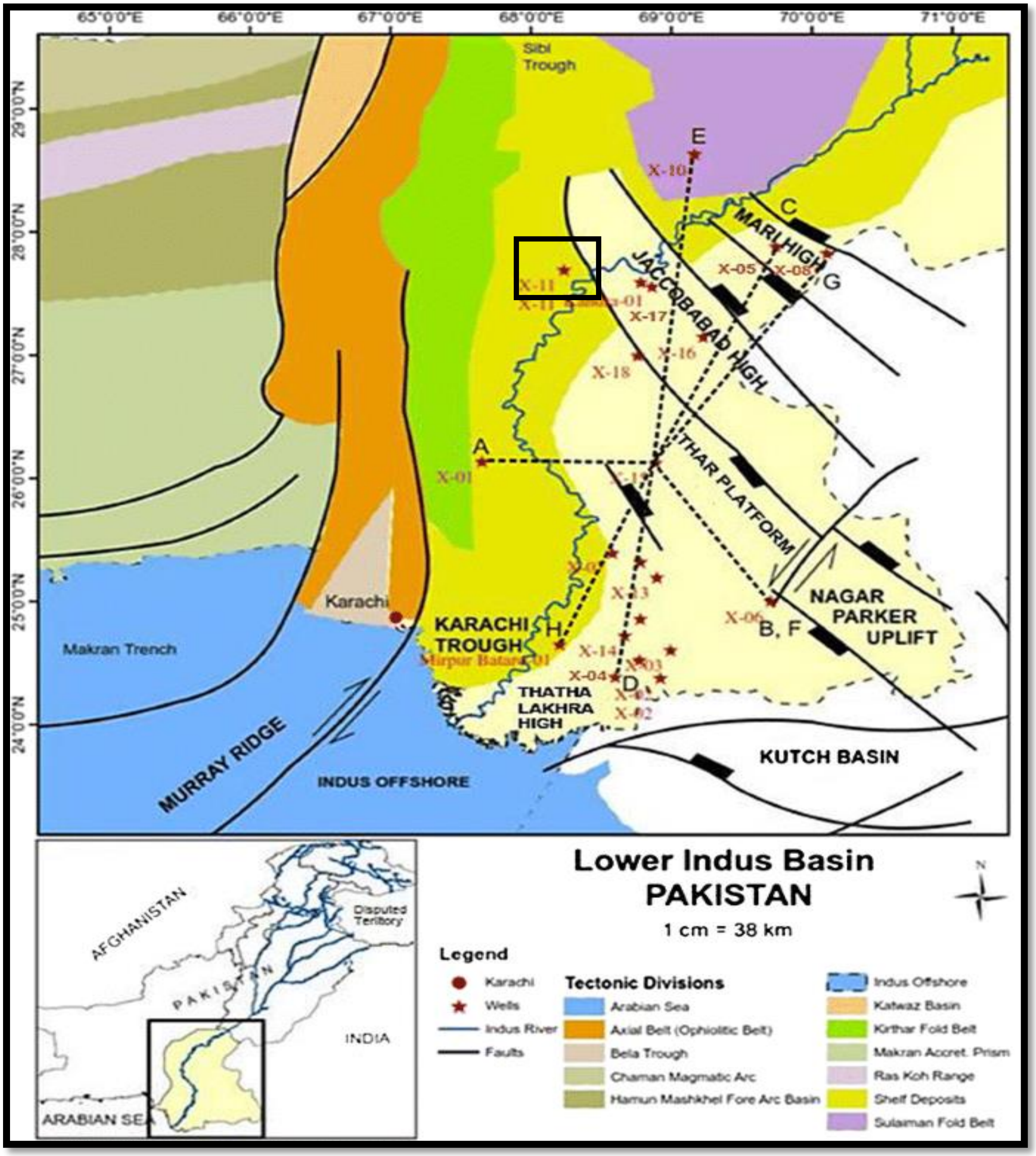

Figure 1. Map showing the study area (i.e., Southern Indus Basin) (modified after Kazmi and Rana 1982; Quadri and Quadri 1996; Raza et al, 1990)

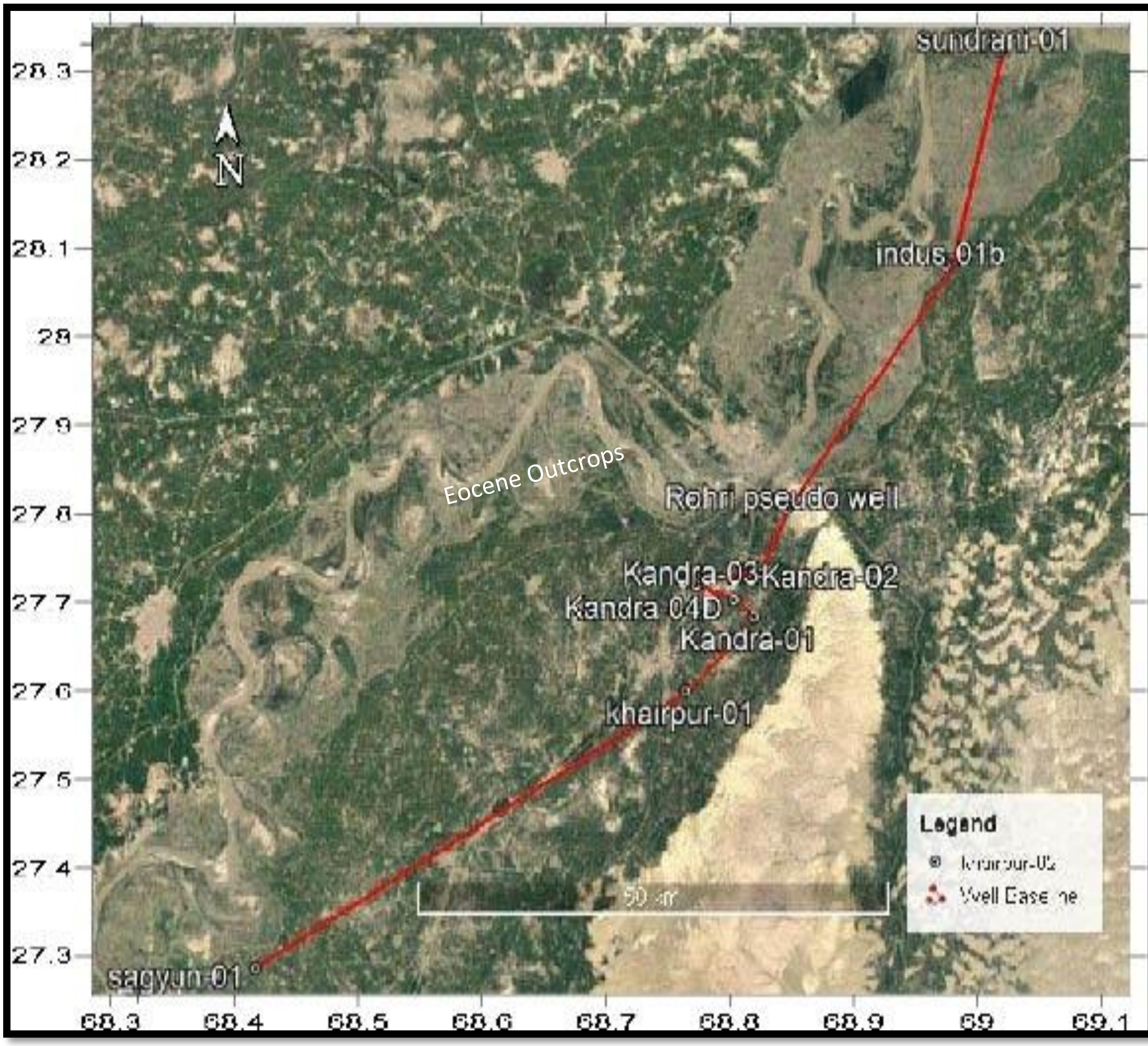

Figure 2. l Google Earth map of study Area with well location and names.

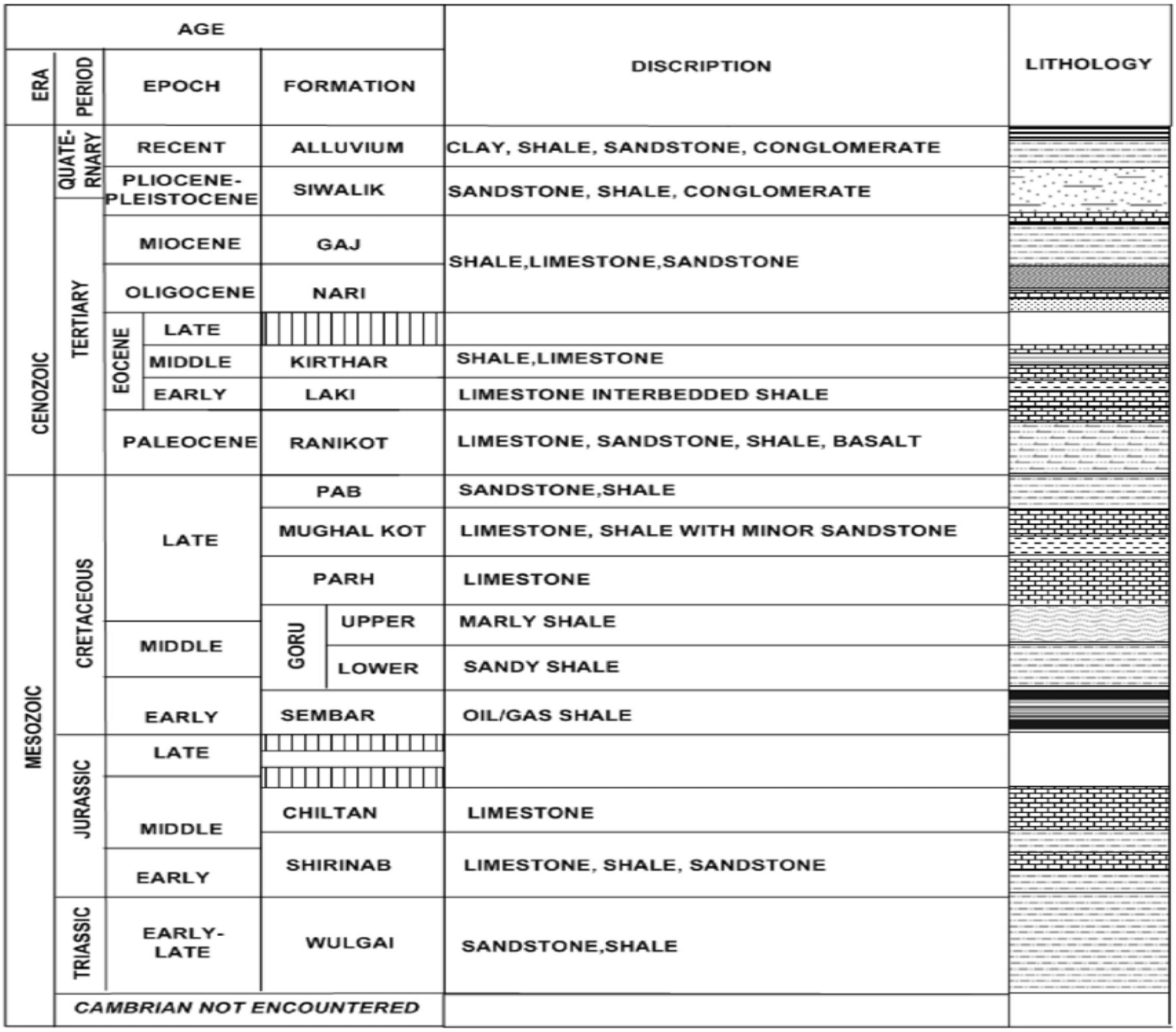

Figure 3. Generalized Stratigraphy of the Southern Indus Basin (after Raza et al, 1990).

4. Material and Methods

For this research work 12 wells data were acquired from Directorate General of Petroleum Concession. The data include well tops acquired by different companies during drilling of these wells and LAS file of Kandra-01. Different techniques (Figure 4) have been used in the research work to obtain the desired results. Due to confidentiality of seismic data that are not in public domain, we can't get the seismic lines data to use it in this research. Therefore, an exceptional and extraordinary methodology was opted to use only well tops data for subsurface mapping including depth contour maps and Isopach maps, structural and stratigraphic correlations using actual well tops and assumed data to better understand the subsurface structural variations and trends in geologic formations found in the respective wells to create an ideal approach for Well-Prognosis, past depositional models were also constructed using the well tops data for examining the past depositional settings of formations during different geological time periods (Aziz et al. 2018) for (Pseudo-well). Petro-physical interpretations are done on different formations to calculate volume of shale, water saturation and hydrocarbons saturation. "The geological data is collected from previous work of (Ahmed and Ashten 1982; Quadri and Quadri 1996; Raza et al. 1990; Ahmed and Ali 1991; Kadri 1995; Ahmed and Chaudhry 2002; Khan et al. 2002; Shah 2009 and Nazir et al. 2012; Qayyum et al, 2016)".

First, we have constructed structural correlations of 12 wells namely Kandra-01, Kandra-02, 03 and 04D, Khairpur-01, 02 and 03, Sagyun-0, these wells are drilled on the southern side of the Jacobabad Khairpur High, whereas Jacobababad-02, 03 and Jhatpat-01 which are drilled on the Northwestern side of the High are used. In addition to this 2 wells data namely Sundrani-01 and Indus-01B which are penetrated in the vicinity of Pano Aqal Graben are also used. Three structural correlations were constructed from North to South on a regional scale. This approach was opted to examine the shape of Jacobabad Khairpur High using all wells in one correlation, while the second correlation is constructed using selective wells to better understand the trend and shape of this High, an ideal case was generated which will later be described in the results and discussion section. The third correlation was constructed from Pano Aqal Graben to Northwestern side of the High in an East-West direction. The technique used to construct the correlation is very simple; first, we have drawn the correlation using actual well tops data on a simple graph paper, after which the shape of Jacobabad High was determined and then the assumed or prognosed thickness technique is opted which is actually taking the thickness half of the original thickness of different formations found in the above mentioned wells, this gives us the ideal shape of the Jacobabad High and provided an insight to construct and assign a new well (Pseudo-Well) based on the trends and variations of these formations. After doing all this on the graph paper, the structural correlations were created on Corel-Draw software. The stratigraphic correlation was constructed by taking Paleocene (unconformity) as a base level to better understand the shape and trends dynamic during Paleocene time period.

After constructing the structural and stratigraphic correlations next step was to create the depth contour and Isopach maps using the well tops data on Surfer software by Golden Software Company. As Surfer is used for surface mapping, we have assigned negative well tops values to visualize the subsurface depth contours and Isopach maps. The technique was very easy and simple; the negative values of all well tops of formations are pasted on the Surfer sheet along with coordinates to create a dat. file, which was then converted to a grid file using Grid menu, after which the grid file was used to create a 3D depth contour map. The Isopach maps were developed using the Math option after which, we have used an equation;

$$\mathbf{Z = A - B;} \qquad \mathbf{(4.1)}$$

Where Z is the resultant surface,

A is the upper surface or Formation top,

And B is the lower surface or Formation bottom.

This equation gives us the Isopach maps of the desired formations. It must be kept in mind that we have to create another dat. files for the desired formation thickness map with equal number of lines so that x, y and z layers of upper surface is equal to the lower surface and vice versa. Depositional models of Pseudo-well and Indus-01B were constructed on Petro Mod (Schlumberger), using the well tops we have got after the structural correlations and depth contour maps. The data was entered to software using 1D modelling menu along with formation names, depth, ages and petroleum system data which means that whether the formation is source, reservoir, and seal, under burden or over burden. Furthermore, the temperature curve was taken on a regional scale (South Asia) already present in the software. This technique gives us the unique models of the Pseudo-well. These models include depth, facies, and temperature and porosity curves. Petrophysical interpretations were done using Interactive Petrophysics software by (Schlumberger). The LAS file of Kandra-01 was interpreted. The interpretations were done to calculate the volume of shale (Vsh), Porosity (ϕ), water saturation (Sw), and hydrocarbon saturation (Shc) (Qadri, S.M et al, 2019). First, we have loaded the data into the software then, selected the triple combo to view the logs in the form of curve. After which, the zoning is done, by splitting the first zone into the respective ones, then the porosity (ϕ) and water saturation calculations were done using the interpretations options and choosing the mentioned step. After all of this the cross plots were interpreted, matrix density, log calibrations were adjusted. As a result, the lithology log was prepared with respective logs interpretation and hydrocarbons signs. Cut-off and summation option was selected and the report was generated.

4.1. Determination of Shale Volume

The shale is more radioactive than non-shale, the gamma ray log (GR) is used to measure shale volume in porous reservoirs. (Asquith and Krygowski, 2004). The volume of shale can then be applied for analysis of shaly sands.

The first step in determining the shale volume from a GR log is to estimate the gamma ray index (IGR). I_{GR} is calculated with the help of Schlumberger Empirical Relation equation (4.2)

$$\boldsymbol{IGR} = \frac{\boldsymbol{GRlog - GRclean}}{\boldsymbol{GRshale - GRclean}} \qquad \mathbf{(4.2)}$$

Where,

V_{shale} = Volume of shale

I_{GR} = Gamma ray index

GR_{log} = Gamma ray log value

GR_{clean} = Gamma Ray reading in a adjacent clean zone

GR_{shale} = Gamma Ray reading in a adjacent shale

Shale volume is then calculated by using the Steiber equation 4.3.

$$\boldsymbol{Vsh} = \frac{\boldsymbol{IGR}}{\mathbf{3.23.0 - 2.0} \times \boldsymbol{IGR}} \quad \textbf{(4.3)}$$

4.2. Determination of porosity (ϕ)

The pore volume per unit volume of the formation is known as its porosity. Porosity is denoted by the ϕ. From density, sonic, and neutron logs, porosity is measured.

The sonic log is used to determine the sonic porosity of a formation by determining the time it takes for a sound wave to pass through it. Raymer-Hunt-Gardner (Schlumberger Empirical Relation) is used to measure sonic porosity. Equation 4.4.

$$\boldsymbol{SPHI} = \boldsymbol{\phi s} = \frac{\mathbf{5}}{\mathbf{8}} \times \frac{\boldsymbol{DT} - \boldsymbol{DTMa}}{\boldsymbol{DT}} \quad \textbf{(4.4)}$$

Where,

SPHI = Sonic (acoustic) porosity

DT = Δt = Sonic travel time

DTMa = Δt_{ma} = Matrix travel time

Density porosity is calculated from density log with the help of Equation 4.5.

$$\boldsymbol{DPHI} = \frac{\boldsymbol{RhoMa} - \boldsymbol{RHOB}}{\boldsymbol{RhoMa} - \boldsymbol{RhoFl}} \quad \textbf{(4.5)}$$

Where,

DPHI = Density porosity

RhoMa = Matrix density

RHOB = Bulk density

RhoFl = Fluid density

Total porosity is estimated by using Schlumberger (1974) equation 4.6..

$$\boldsymbol{\phi T} = \frac{\boldsymbol{\phi D} + \boldsymbol{\phi N}}{\mathbf{2}} \quad \textbf{(4.6)}$$

Where,

ϕ_T = Total Porosity

ϕ_D = Density Porosity

ϕ_N = Neutron Porosity

Effective porosity is calculated with the help of the Hilchie (1978) equation 4.7.

$$\boldsymbol{\phi e} = \boldsymbol{\phi t} - (\boldsymbol{\phi shale} \times \boldsymbol{Vsh}) \qquad \textbf{(4.7)}$$

Where

ϕ_e= Effective porosity

ϕ_T = Total porosity

ϕ_{shale} = Value of the porosity measured in a nearby shale

V_{sh} = Volume of shale

4.3. Determination of water saturation (S_w)

The Archie's (1942) equation (4.8) is used to measure the water saturation of a reservoir's uninvaded zone.

The value of Rw used is 0.072 Ωm.

$$\mathbf{Sw} = (\boldsymbol{a}.\frac{\boldsymbol{Rw}}{\boldsymbol{Rt}}.\phi)\mathbf{1}/\boldsymbol{n} \qquad \textbf{(4.8)}$$

Where,

S_w = Water saturation of the uninvaded zone

R_w = Resistivity of water

R_t = True resistivity

ϕ = Porosity

a = Tortuosity factor

m = Cementation exponent

n = Saturation exponent

4.4. Determination of hydrocarbon saturation (HCS)

The Schlumberger (1974) equation (4.9) is used to determine hydrocarbon saturation.

$$\boldsymbol{Hydrocarbon\ saturation\ =\ 1 - Sw} \qquad \textbf{(4.9)}$$

Where,

S_w = Saturation of *water*

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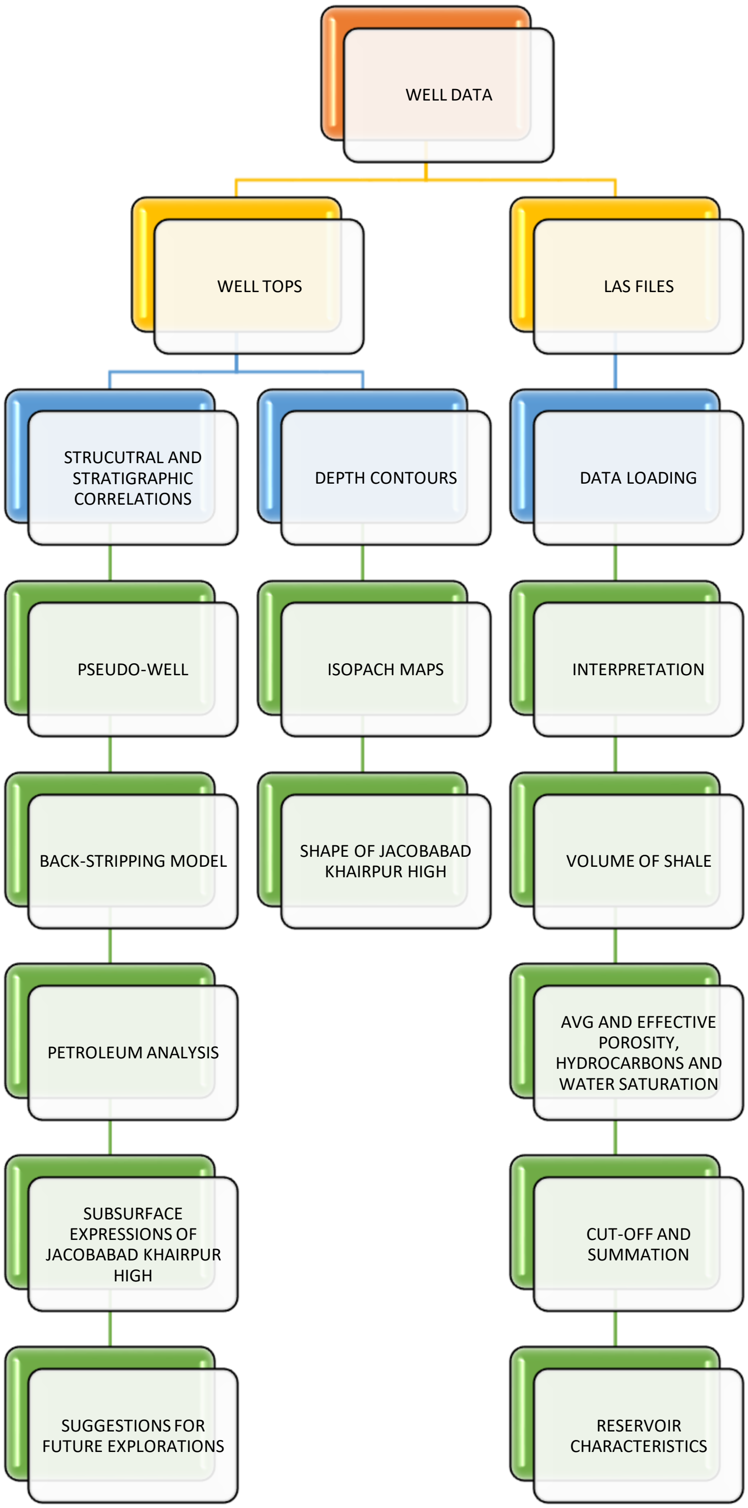

Figure 4. Methodology work flow of the research work.

5. Results and Discussions

This section deals with results and discussions about well data used in this research for understanding the surface and subsurface expressions of Jacobabad Khairpur High. The subsurface mapping, structural interpretations, reservoir modelling and petro-physical analysis can be used to locate the hydrocarbons. The Middle to Late Eocene Habib Rahi Formation outcrops are exposed in the Rohri, Sukkur area (Figure 2). The story begins why it is present on the surface? After interpreting well data by constructing the structural correlations of wells drilled across the Jacobabad Khairpur High, it is obvious that due to the Himalayan Orogeny which is the final time when Jacobabad High reactivated causes the subsurface strata to be uplifted onto the surface, which is evident by the presence of bulge in the depth contour maps of the different formation levels and are discussed in this section is divided into various sub-sections based on the data used in this research work. Let's discuss the first section:

5.1. Well Structural Correlation Case 1:

The Regional Northeast to Southwest structural correlation of wells drilled across Khairpur-Jacobabad High were constructed in details and on large scale by (Siddiqui, 2004) . These structural correlations are constructed in different cases to better understand the trends of geologic formations and the structure they have been making in the subsurface and to construct the geology of the Rohri from these correlations to assign new location for Pseudo-Well. The first structural correlation (Figure 5.1 a) shows that starting from Northeast direction i.e. from Sundrani-01 well drilled in the Pano Aqal Graben, the oldest rock encountered is Middle Jurassic Chiltan Formation with a thickness of 187m and is found from the depth of 3823m. Above the Chiltan Formation there is an unconformity and the Sembar Formation of (Early-Cretaceous) unconformably overlies the Middle Jurassic Chiltan Formation (Qayyum et al, 2016). Thickness of Sembar Formation is 145m, this well contains complete package of Cretaceous rock indicating uniform deposition during Cretaceous time period. The K-T boundary is present between Cretaceous Pab Formation and Paleocene Ranikot Formation. Thickness of Ranikot Formation is 132m and the sequence gets normal upto Alluvium. The Indus-01B is drilled upto Cretaceous Pab Formation upto the depth of 1364m but based on the regional correlation and assumed thickness there is a chance for the presence of the Cretaceous source Sembar Formation and reservoir and seal rock Upper and Lower Goru Formation. The estimated thickness is equals to the half of the original thickness found across wells in which they are present. Using assumed thickness, the Indus-01b could be penetrated upto the Middle Jurassic Chiltan Formation. The assumed thickness of Chiltan Formation is 750m, Sembar 30m, Lower Goru 700m, Upper Goru 250m. The most important thing to be noticed is that the Cretaceous sequence becomes thinner towards Sindh Platform (Sagyun-01) well based on the research of (Khan and Raza 1986; Raza et al. 1990; Quadri and Quadri 1996; Shah 2009; Qayyum et al. 2016). The Habib Rahi Formation was our main target because it was exposed on the surface at Rohri (Figure), and its thickness remains consistent from Sundrani-01 to Indus-01B. There is no such existence of Habib Rahi Formation in the Khairpur-01, it means that from Indus-01B the Habib Rahi Formation was uplifted to the surface (Figure 5.3 f), where we have placed the Pseudo-well. The correlation shows an uplift feature at the Pseudo-well location which is the result of Jacobabad Khairpur High development and the Eocene Himalyan Orogeny (see figure 5.3 a) with the Habib Rahi Formation of 100m (assumed thickness) at the surface, below which, the Ghazij Formation starting from Sundrani-01 to Indus-01b to Rohri (Pseudo-well), the assumed thickness of the Ghazij Formation is 250m. Sui Upper Limestone is present below the Ghazij Formation with the assumed thickness of the 30m, Sui Shale with 60m, Sui Main Limestone with 70m, Upper Paleocene Dunghan Formation with 40m, Ranikot 20m, unconformity between Ranikot and Middle Cretaceous Upper Goru Formation. "The basal Eocene carbonate platform extends into the Jaisalmer basin, India, where it is correlative with the Khuiala Formation" (Kalinin, 1964) mentioned by (Siddiqui, 2004). It is important to keep in mind that the Upper Cretaceous sequence is absent based on our regional correlations. The Goru Formation thickness is estimated to be about 250m (assumed thickness), Lower Goru 700m and Sembar Formation (Cretaceous) 20m. Below Sembar there is possibility for the presence of Jurassic Chiltan Formation with the thickness of 750m. The Pseudo-well gives an idea for the presence of Hydrocarbon system based on the presence of source, reservoir, and seal rock. In the Khairpur-01 and Sagyun-01 the Eocene strata become more pronounced, whereas, the Paleocene strata become thinner. The Chiltan Formation reaches the maximum thickness towards South of Jacobabad Khairpur High. Jacobabad Khairpur High starts to developed after the deposition of (Middle Jurassic) Chiltan Formation and remains uplifted till (Middle Cretaceous) time in the South allowing deposition of Middle Cretaceous rocks

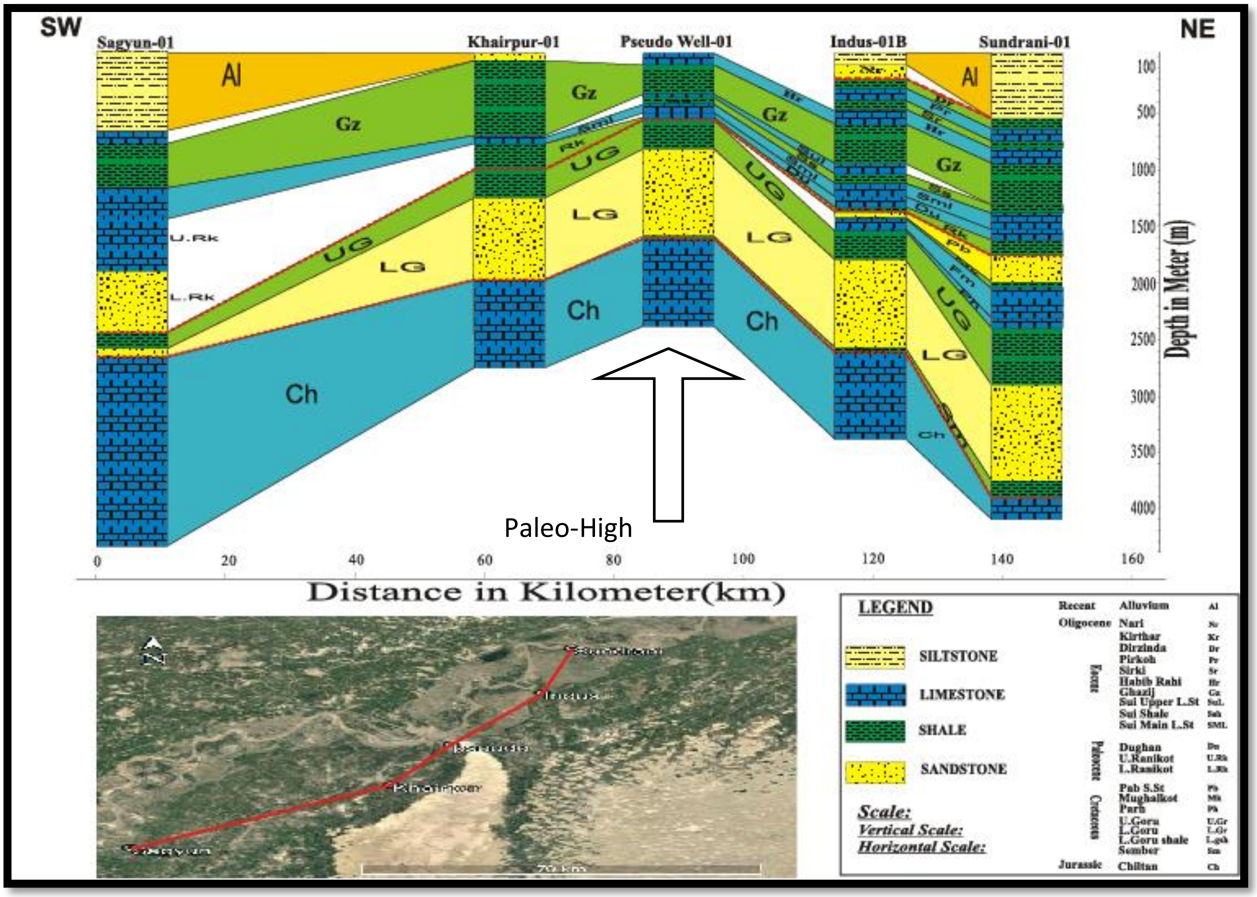

Figure 5.1 (a). The Northeast to Southwest correlation of wells drilled across the Jacobabad Paleo-High.

5.1.1. Case 2

(Figure 5.2 b) shows Regional Northeast to Southwest structural well correlation. This correlation is constructed using 9 wells data to view the subsurface trends and variations on the regional scale and to determine the behavior of geologic formations at the (Pseudo-Well) location. Starting from Northeast i.e. Sundrani-01 the same patterns and trends as discussed in the previous case till to Indus-01b and Pseudo-Well. From (Pseudo-well) to Kandra-02 which is originally drilled upto 591m at the Sui Main Limestone as a target, using prognosed thickness, we have extended it upto the Chiltan level as Kandra-01 was penetrated upto the Chiltan level, so if the Kandra-02 was drilled further, then the subsurface scenario be like, the Habib Rahi Formation pinchout in the subsurface (Figure 5.2), Ghazij Formation thickness increases consistently from Northeast towards the Southwest, Sui Main Limestone is present with Sui Shale and Sui Upper Limestone pinchout from the (Pseudo-Well) to Kandra-02, the thickness of the Sui Main Limestone is 68.5m at the depth of 591m, below the Sui Main Limestone based on assumed thickness from the correlations there is presence of Ranikot Formation with 20m thickness and the thickness remains consistent throughout to the South marking the so called unconformity with the underlying Cretaceous Upper Goru Formation. The prognosed thickness of the Upper Goru is 250m, Lower Goru is 700 there is a chance from our correlation that 20m of Sembar Formation (Figure 5.2) might be present in this well if drilled to the Jurassic level also there is unconformity between Middle Jurassic Chiltan and Cretaceous Sembar Formation. Khairpur-02 well is drilled upto the depth of 3557m, with the Chiltan Formation at the bottom. From Kandra-02 to Khairpur-02, the alluvium is at the top with the same thickness as of Kandra-02, the Ghazij Formation with increased thickness, below which the Sui Main Limestone with the highest encountered thickness of 122m. It is interesting to notice that only in Khairpur-02 (Paleocene) Dunghan Formation is found, it was deposited when the Indian Plate crossed over the Kerguelen Hotspot and then became part of the continental shelf to deposit this Limestone of Dunghan Formation with a thickness of 30m. The Ranikot Formation below Dunghan was drilled with a maximum thickness here of 56m, below which the (Cretaceous) Upper Goru with the actual thickness of 413m and Lower Goru with 900m thickness with missing of major source rock Sembar Shale. This increased in thickness of (Middle-Cretaceous) rocks indicate that the Jacobabad Khairpur High was uplifted after the deposition of Middle Jurassic till Middle Cretaceous, an evidence based on the correlation (Figure 5.2), suggesting that during the time of (Mid-Cretaceous) Jacobabad Khairpur High submerged in the Southeastern crest, allowing the considerable thickness of (Middle Cretaceous) rock but then after the deposition of Upper Goru of (Middle Cretaceous) level it was again uplifted, based on the absence of (Upper Cretaceous) rocks. The Kandra-03 was drilled upto the (Early Eocene) Sui Main Limestone as a target Formation. After assigning prognosed thickness the well hits the depth of 2300m approximately. With Alluvium at the top followed by Lower Alabaster Shale also known as Ghazij Formation, Sui Upper Limestone below which Sui Main Limestone with thickness of 60m.

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After assigning the assumed thickness below the Sui Main Limestone is Ranikot with 20m thickness with the same K-T boundary between (Middle Cretaceous) and (Upper Paleocene) i.e. Upper Goru and Ranikot Formation. Below the (Middle Cretaceous) there is also an unconformity with Chiltan Formation of (Middle Jurassic). Kandra-04D and Kandra-01 are the only wells in the vicinity of Jacobabad Khairpur High with maximum actual thickness of 1055m and 1125m(Middle Cretaceous) Lower Goru Formation which may be due to submerge of High at the time of Middle Cretaceous depositing maximum amount of Lower Goru reservoir sands and shale. These two wells were drilled upto the Chiltan Limestone. From Kandra-01 to Khairpur-01 which is drilled up to Upper Goru of Middle Cretaceous age at the total depth of 1375m, ranging from Alluvium to Ghazij with the maximum thickness in this well throughout the Jacobabad Khairpur High to Sui Main Limestone below which the Ranikot Formation marking K-T boundary. Below this the assumed thickness were used till Chiltan Limestone. Farther to the South towards the Sindh Platform, from Khairpur-01 to Sagyun-01, Alluvium attains maximum thickness of 668m, the Kirthar Formation of (Eocene) is present, the sequence remains the same till Ghazij to Sui Main Limestone, below which the Ranikot Group; Upper Ranikot and Lower Ranikot attains the maximum thickness then the sequence extends from Upper Goru to Lower Goru with considerable actual amount of thickness to Chiltan Formation. It is important to keep in mind that Sagyun-01 is the only well where (Middle Jurassic) Chiltan Formation attains the maximum thickness of 1634m.

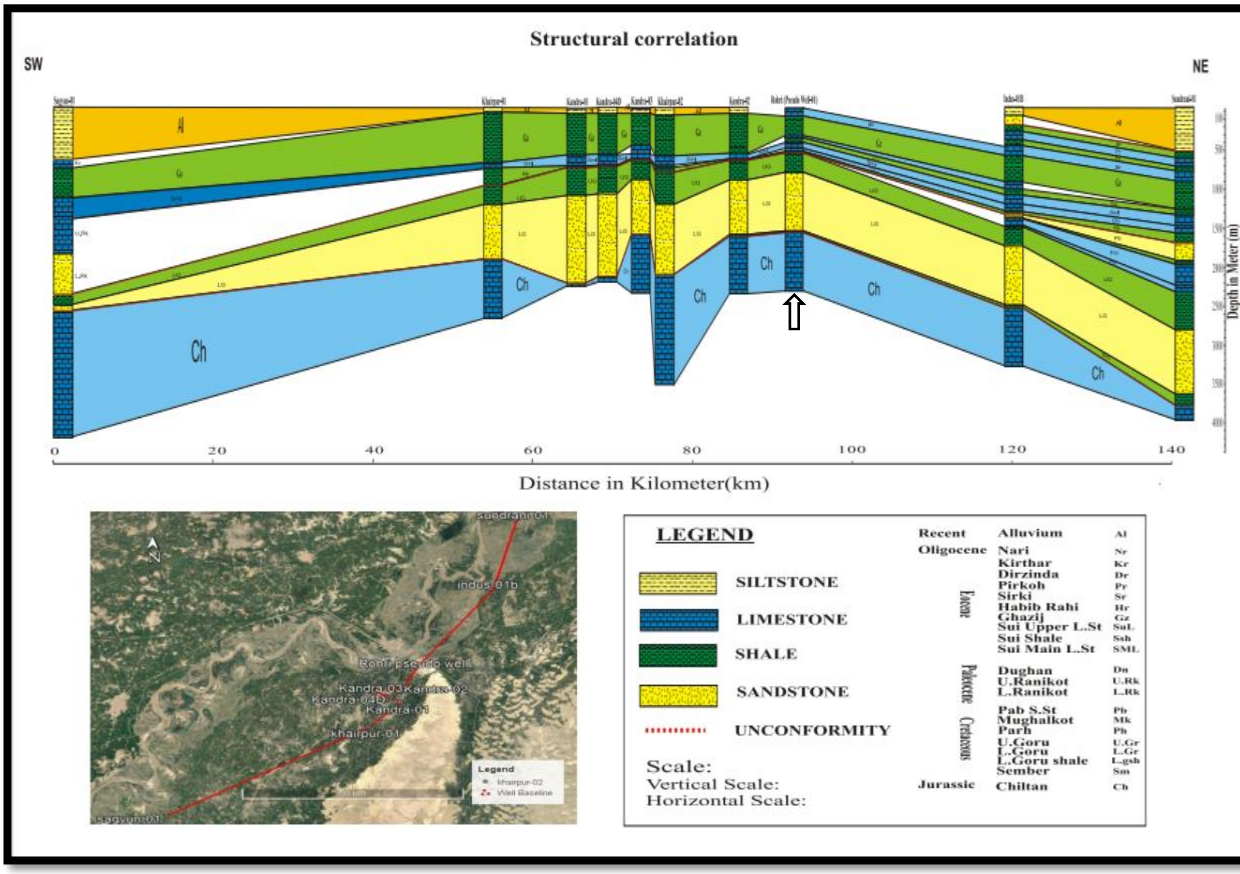

Figure 5.2. Regional Northeast to Southwest correlation on wells drilled across the Jacobabad Paleo-High, where the Lower-Mid-Cretaceous rocks overlies the Mid-Jurassic Chiltan Formation marking an unconformity, while the Upper Paleocene rocks overlies the Mid-Upper Cretaceous rocks demarcating the K/T boundary.

5.1.2. Case 3:

The third regional Northeast to Northwest correlation (Figure 5.1 c) shows the structural and stratigraphic configuration from Sundrani-01 to Jhatpat-01 to understand the subsurface trends and variations from Pano Aqal Graben to Northwestern most part of Jacobabad Khairpur High. Cretaceous and Tertiary rocks are absent on the Northwestern part of the High (Jhatpat-01), where the (Paleocene) Dunghan Formation directly overlies the (Mid-Jurassic) Chiltan Formation, indicating the uplift of the High right after the deposition of Chiltan Formation, the High remains uplifted till the deposition of (Mid-Paleocene) Dunghan Formation. In the Northern part of the High the Ghazij Shale is ineffective as a seal rock for the Sui Main Limestone due to an increased calcareous content (Siddiqui 2004). The Cretaceous and Tertiary sediments are comparatively thin in the top most portion of the Jacobabad Khairpur High. Wulgai Formation of (Triassic) age is only found in the Jhatpat-01 well throughout the Jacobabad High.

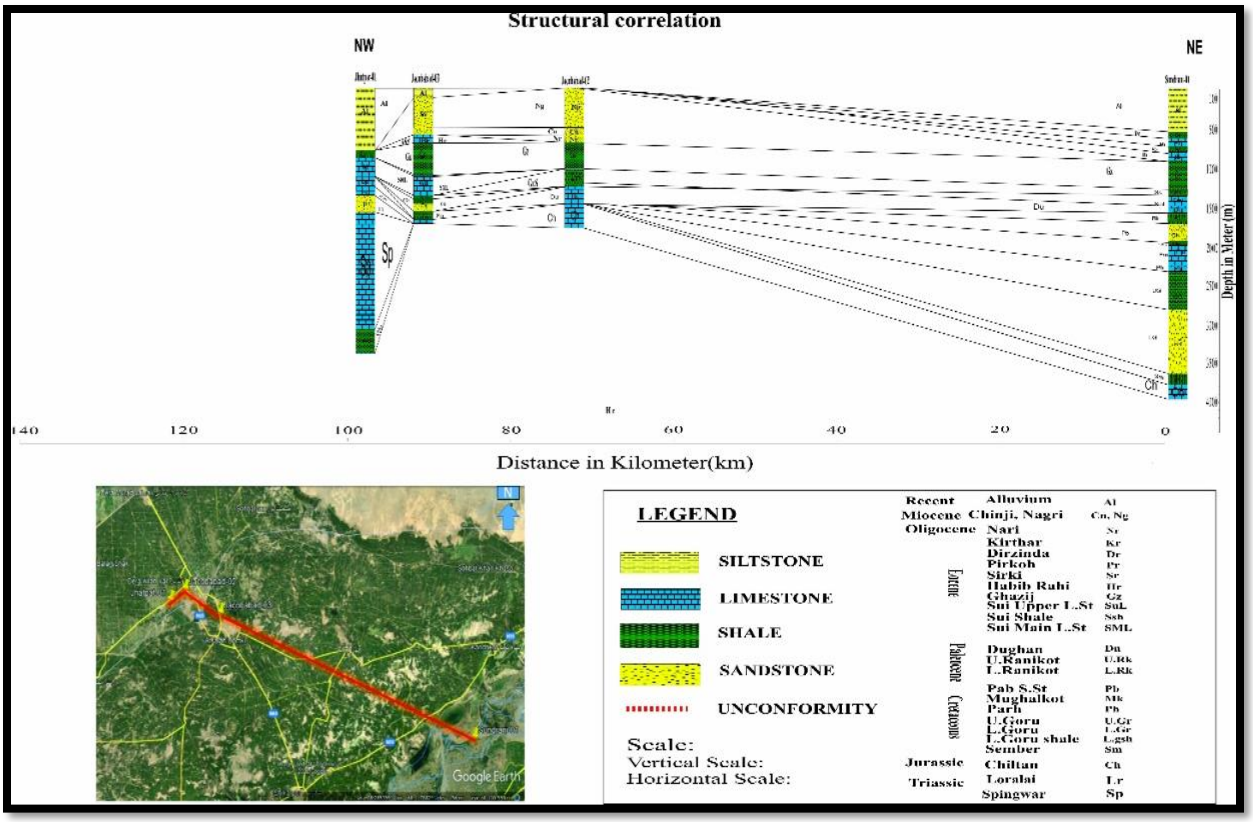

Figure 5.1c: Regional Northeast to Northwest structural correlation across Panu Aqal Graben and Northwestern part of Jacobabad High. Cretaceous sequence is absent in the Northwestern side of the High and Paleocene Dunghan Limestone overlies the Jurassic Chiltan Limestone.

5.2. Stratigraphic Correlation

The stratigraphic correlation of the 4 wells (Figure 5.2) from Northeast to Southwest was created to examine and visualize the subsurface variations and trends of Mid-Jurassic to Cretaceous rock sequence at the base Paleocene (unconformity) of Pseudo-well (Rohri).

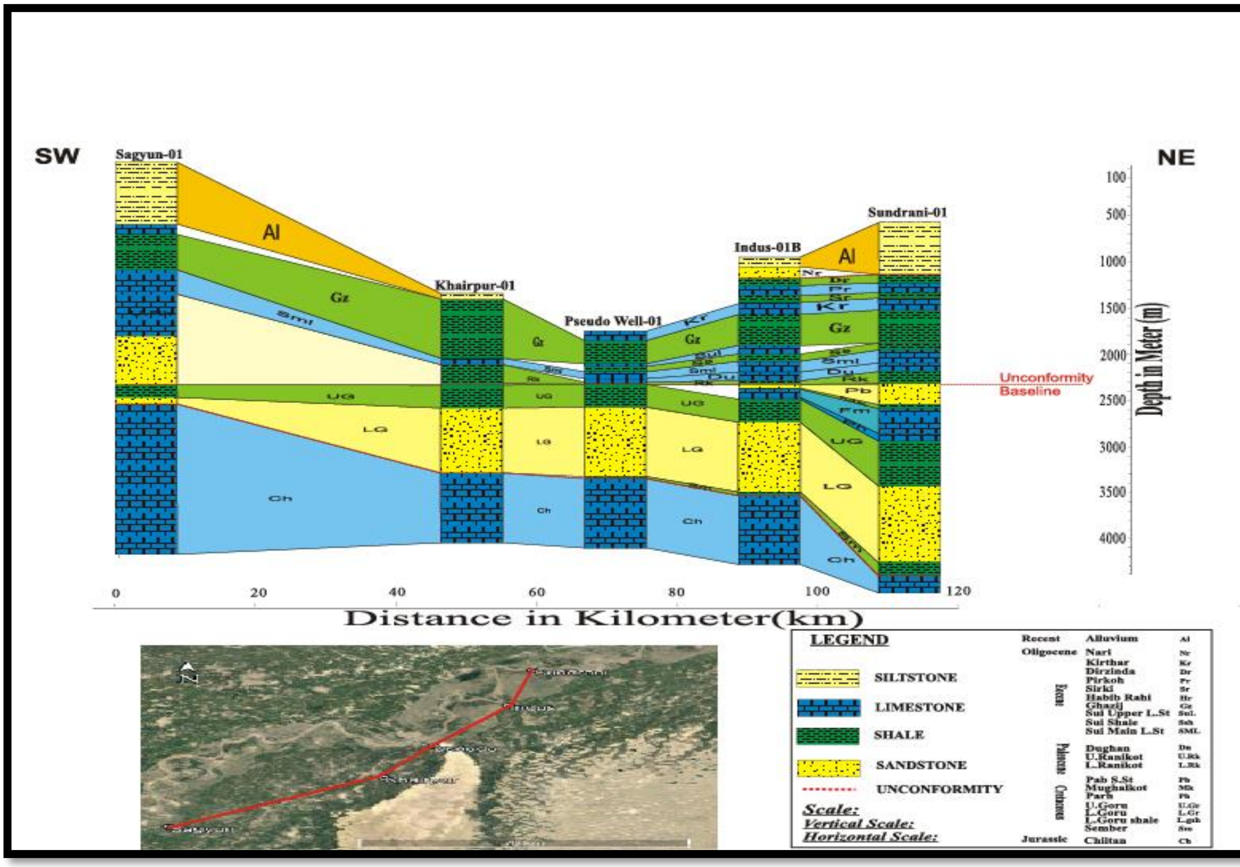

Figure 5.2. Northeast to Southwest Stratigraphic correlation with Paleocene as a base, Cretaceous sediments are comparatively thinner to the South and Jurassic Chiltan Formation thickness increases towards South and gets thinner towards Northeast.

5.3. Subsurface Evolution of Jacobabad Khairpur High

5.3.1. Depth Contour Maps

For subsurface mapping, as discussed earlier that Surfer was used, at first the excel sheet was prepared using well tops of the respective wells and assigning negative values for subsurface mapping. The excel sheet in Surfer was prepared in such a way; that the Longitude, Latitude of wells and well tops were written on that sheet. The process followed for all the desired Formations to construct their depth contour maps. After which the data file was prepared and then converted it into the grid file to use the 3D surface option. It must be kept in mind that for depth contour construction assumed well tops were also used to check out the (Pseudo-Well) characteristics in the subsurface.

5.3.1.1. Depth Contour Map of Chiltan Formation

Figure 5.3(a, b) represents the Depth Contour Map of Chiltan Formation. The maximum depth of the Chiltan Formation was encountered in the Sundrani-01 with a depth of 3823m, while the shortest depth was found in the Jhatpat-01 of 1335m, it is important to notice that around the Northwestern margin of Jacobabad Paleo-Highs the Cretaceous Sequence is totally missing due to the exposure. There is an obvious bulge feature observed at the Chiltan Formation exactly at our (Pseudo-Well) location. That bulge is an explanation to the uplift of the Rohri area during Jacobabad Khairpur High development. It is important to note that there is no convergence of contours near the bulge but a smaller convergence can be seen near Kandra-01 and all other wells on the South. The Jacobabad High orientation can be easily seen in the (figure 5.3 a) which is NNW-SSE. In figure (5.3 a) Northwestern side wells are just represented but data of Jhatpat-01, Jacobabad-02 and 3 were not used. (Figure 5.3 b) represents the Jacobabad Khairpur High with Northwestern part included with contour interval of 500.

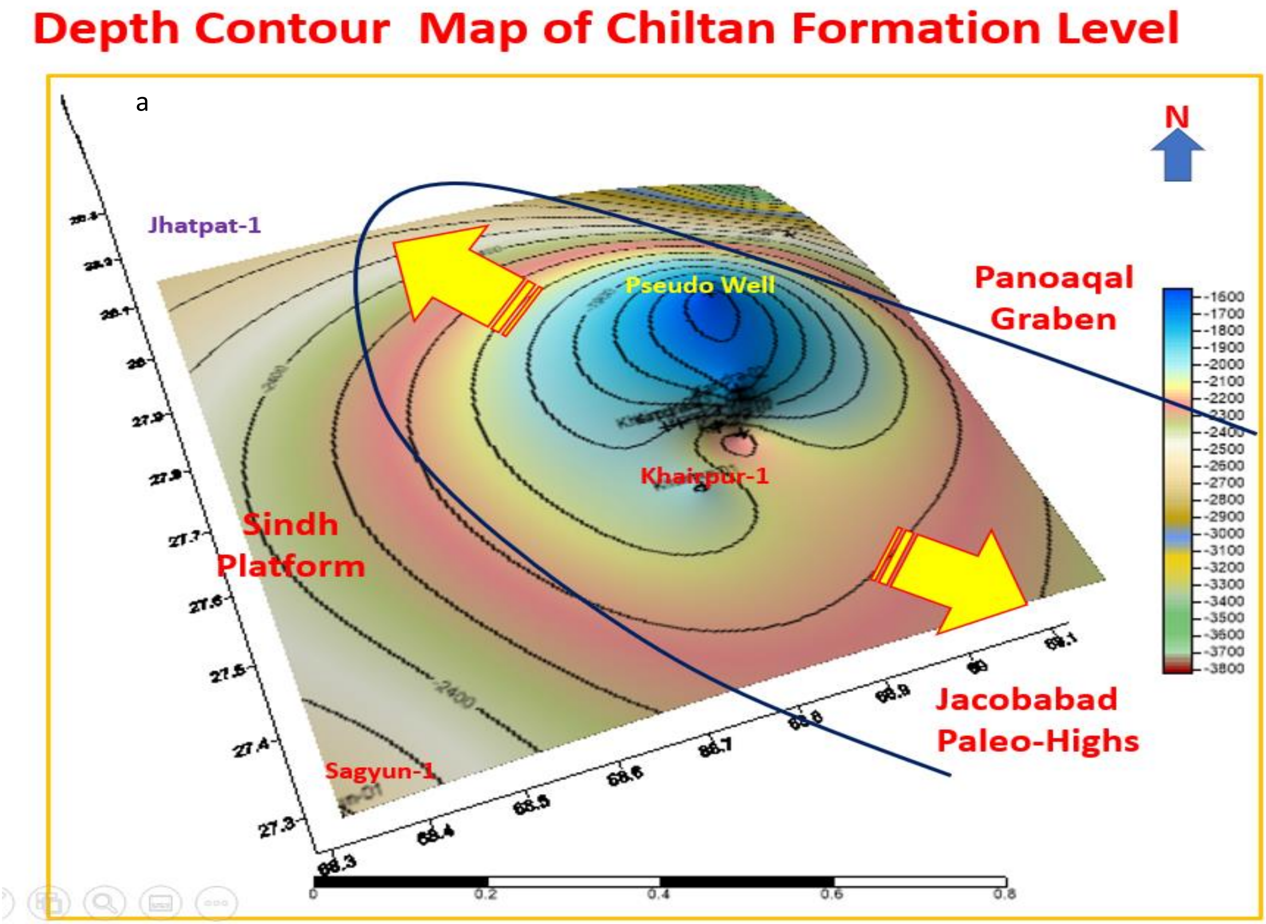

Figure 5.3 a. shows Bulge around the Khairpur-Jacobabad Highs flattened over the Middle Jurassic Chiltan Formation.

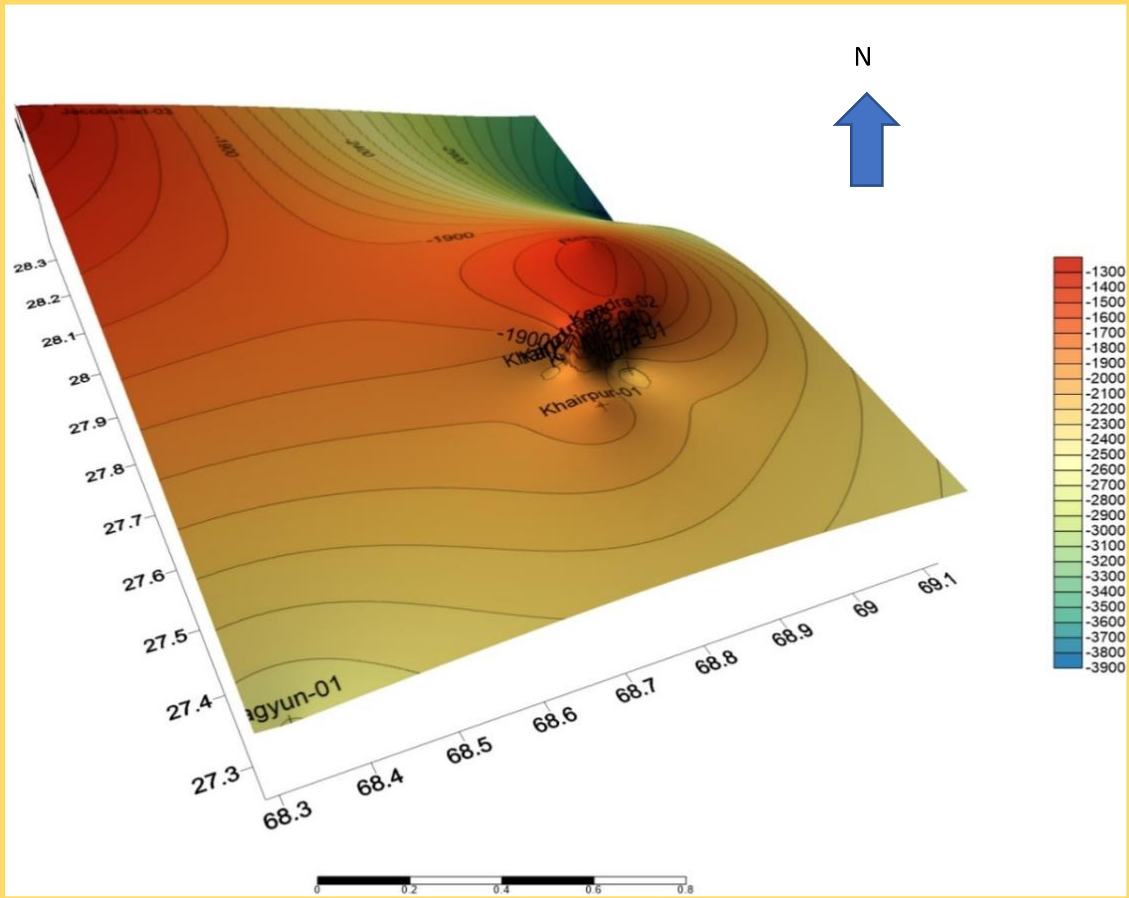

Figure 5.3 b. Shows Bulge across the Pseudo well, with Northwestern side wells included.

5.3.1.2. Depth Contour Map of Lower Goru Formation

Lower Goru, as encountered in wells, shows maximum depth in Sundrani-01 2850m, while the minimum depth was 1102m in Kandra-04D. The (figure 5.3 c) shows the bulge at Rohri Jacobabad Paleo-High when flattened over the Lower Goru Formation at the time of Middle Cretaceous. On the Northwestern side of the High there is absence of entire Cretaceous succession. Contour interval is 500.

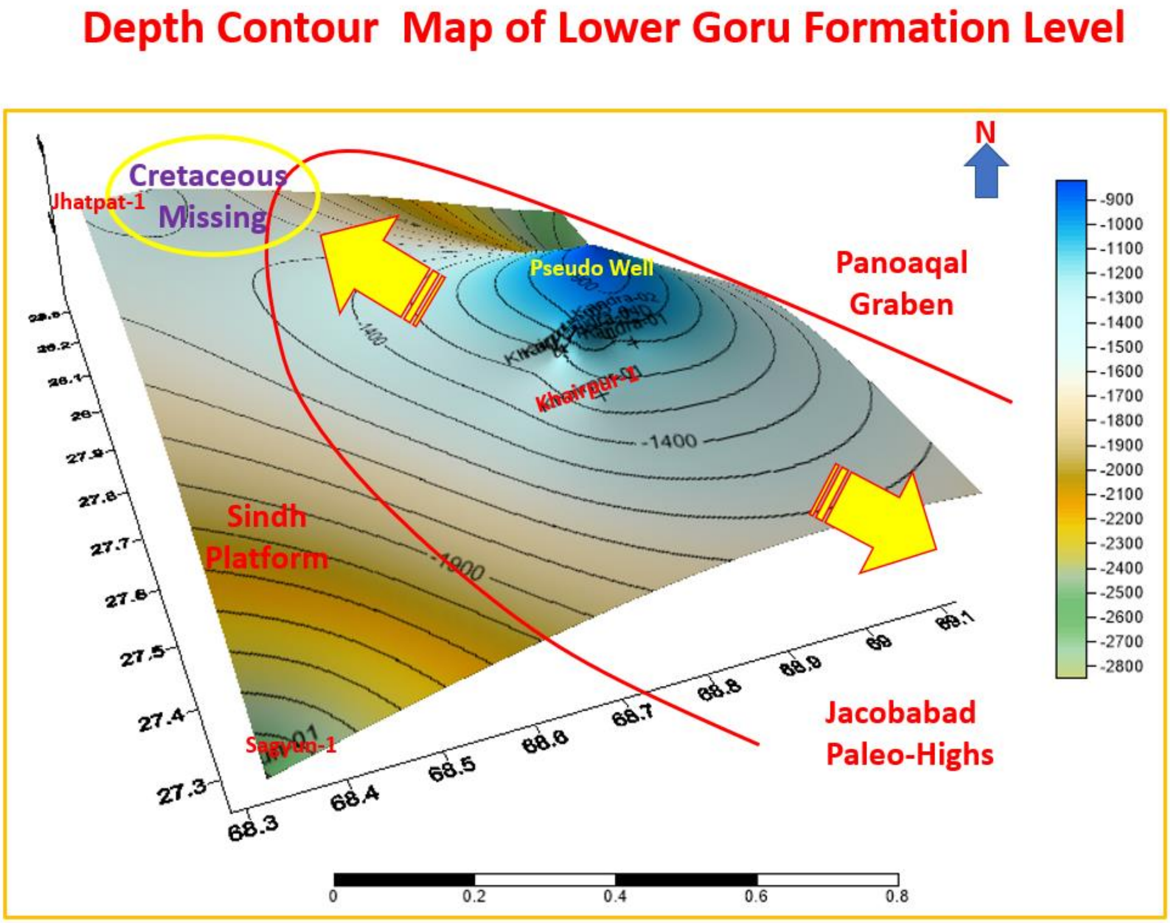

Figure 5.3 (c). Depth Contour map of Chiltan Formation, bulge can easily be seen near the eastern side of Jacobabad High at (Pseudo-Well).

5.3.1.3. Depth Contour Map of Upper Goru Formation

The Upper Goru Formation of Middle Jurassic encountered during drilling shows maximum depth in Sagyun-01 with a depth of 2402m, while the minimum depth was found in 748m in Kandra-04D. (Figure 5.3 d) shows bulge around the Jacobabad Paleo-Highs flattened over the Upper Goru Formation. Contour level is 500.

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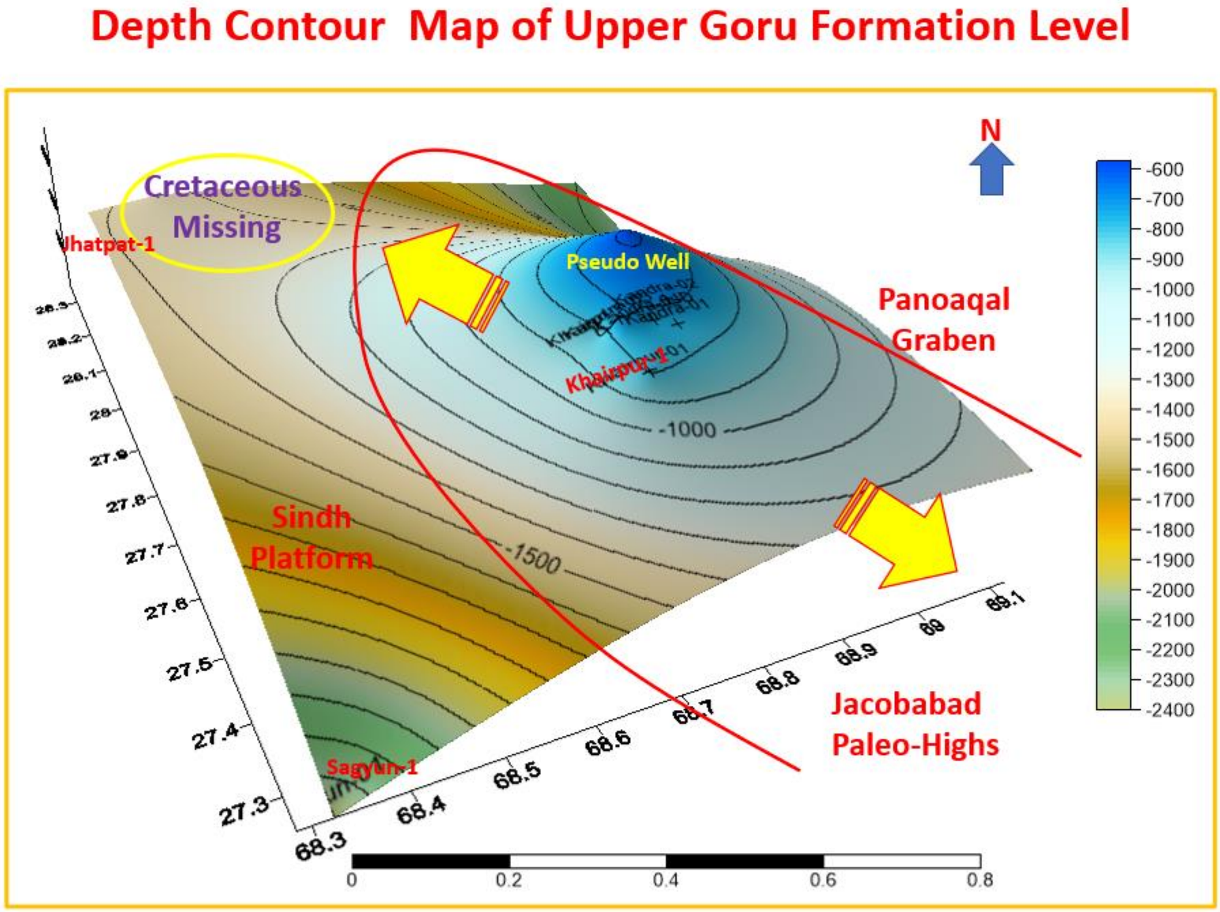

Figure 5.3 (d). Depth Contour Map of Upper Goru Formation, Bulge is also present at the Upper Goru level on (Pseudo-Well).

5.3.1.4. Depth Contour Map of Ghazij Formation

The Ghazij Formation of Late Paleocene encountered during drilling attains the maximum depth in Sundrani-01, while the minimum depth was found in Khairpur-01 about 61m. The figure below shows the Jacobabad Paleo-Highs flattened over the Ghazij Formation level (Figure 5.3 e). Contours are smooth and there is no convergence or sharpness in the contours at the Ghazij Formation level, contour interval is 500.

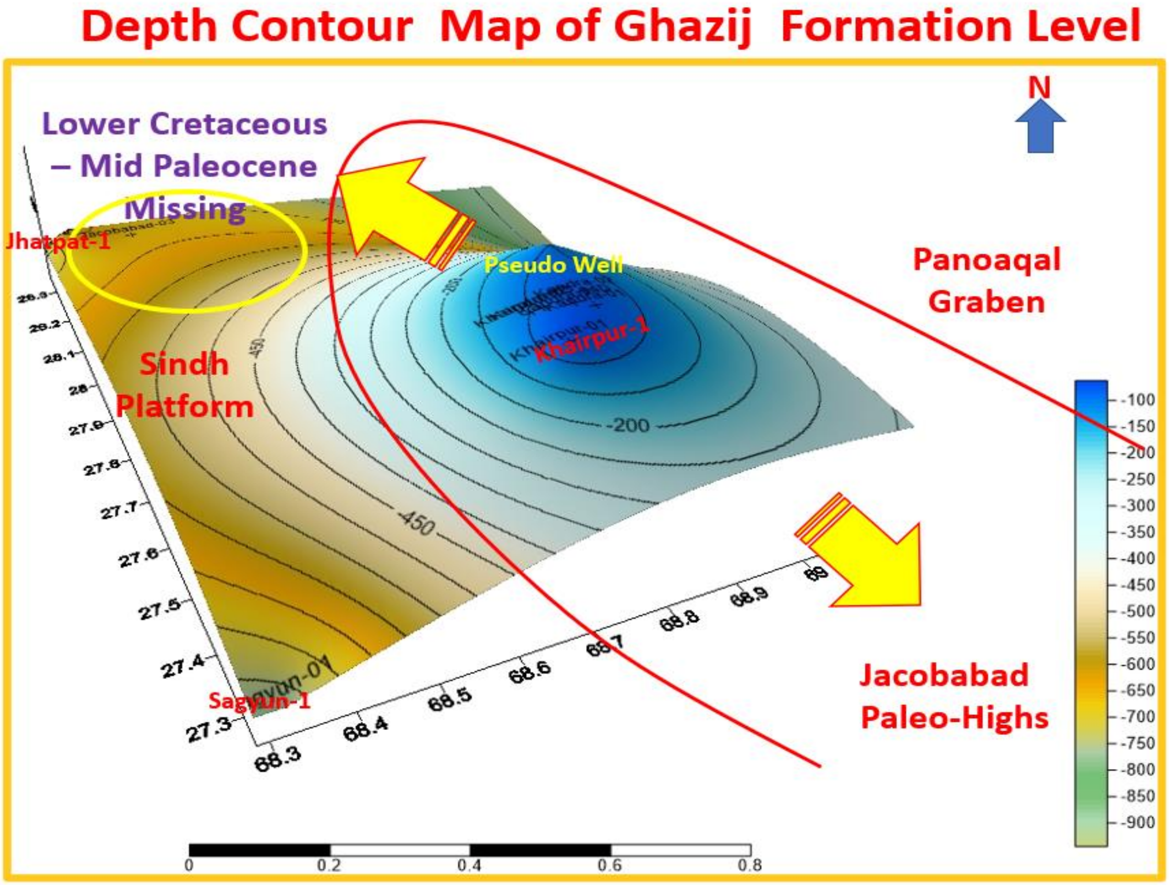

Figure 5.3 (e). Depth Contour Map of Ghazij Formation level showing the subsurface expressions of Jacobabad High, the bulge at (Pseudo-Well) location can easily be seen.

5.3.1.5. Depth Contour Map of Sui Main Limestone

Sui Main Limestone attains maximum depth of 1375m in the Sundrani-01 well of Panu Aqal Graben whereas in the vicinity of Jacobabad High is in Jacobabad-03 drilled at the Northwestern portion of the High of 1091m, and minimum depth is found in the Kandra-04D of 587m. (Figure 5.3 f) shows the depth Contour map of Sui Main Limestone with bulge present at the Rohri (Pseudo-Well) location. While the 1d depth contour map of Sui Main Limestone shows sharpening or closure of contour from Indus-01B to (Pseudo-Well), this feature may be an illustration of normal fault associated Horst and Graben structure (Figure 5.3 g). Contour interval is 250.

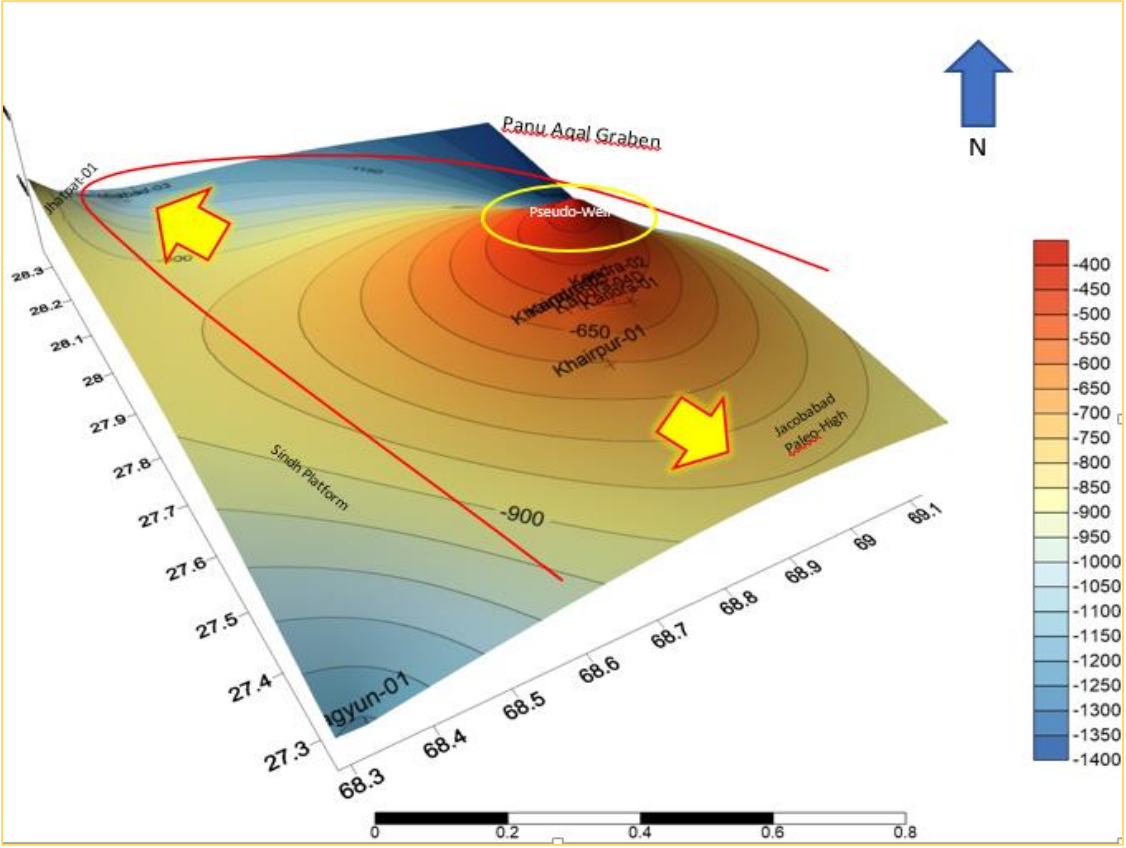

Figure 5.3 (f). 3D Depth Contour Map of Early Eocene Sui Main Limestone level with Bulge at (Pseudo-well) location in the subsurface.

5.3.1.6. Depth Contour Map of Middle Eocene Level

The Middle Eocene Formations encountered during drilling attained the maximum depth in Sundrani-01 about 1335m in Sundrani-01, whereas the minimum depth was 587m in Kandra-04D. (Figure 5.3 h) below shows the depth contour map of Middle Eocene level with an ideal picture of Jacobabad Khairpur-Highs, flattened over the Middle Eocene Sequence, at the time of Middle Eocene. It must be kept in mind that at Rohri where (Pseudo-Well) is suggested and placed the Middle Eocene Habib Rahi Formation is exposed at the surface.

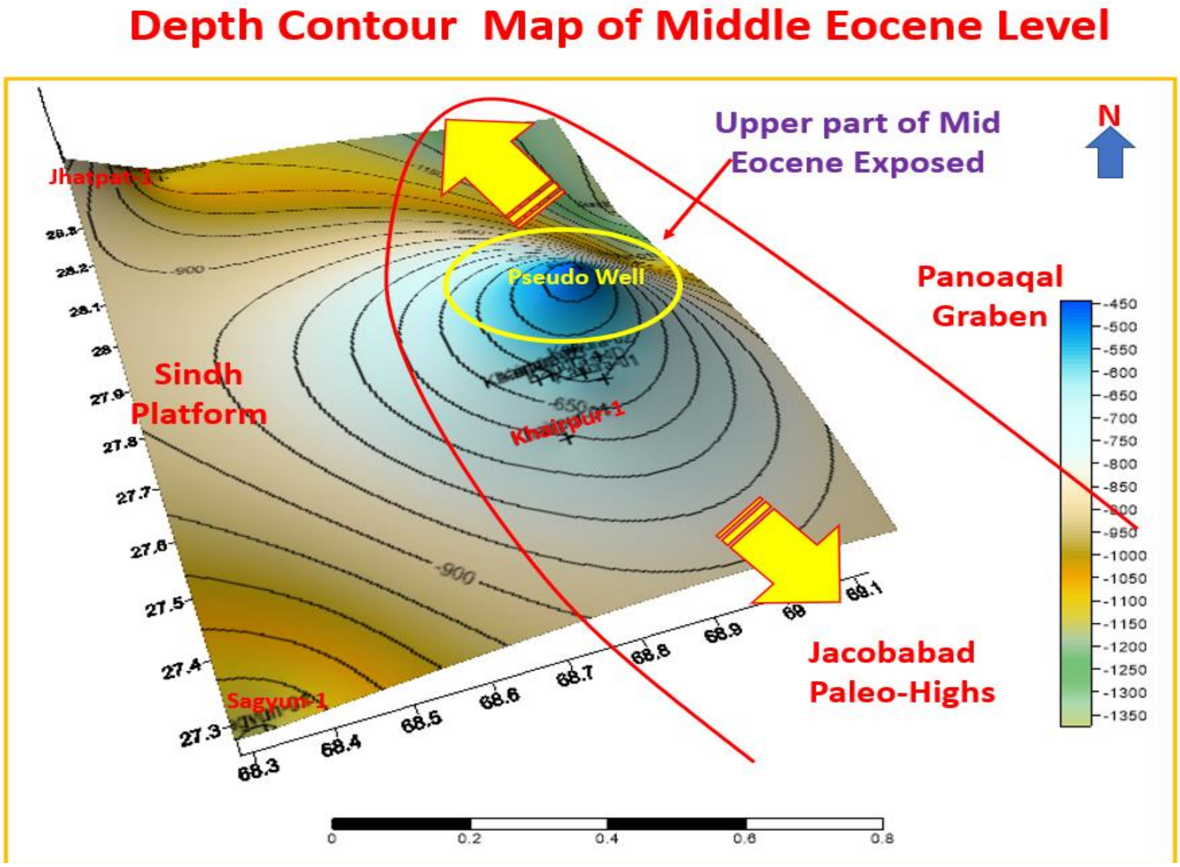

Figure 5.3 (g). Depth Contour Map of Eocene level representing the NNW-SSE oriented Jacobabad Khairpur High with bulge at the (Pseudo-Well). Closure of contours from Indus-01B to (Pseudo-Well) can be seen easily.

5.3.1.7. Digital Elevation Model on Alluvium

The (Figure 5.3 h) shows the Surface elevation of Jacobabad-Khairpur Highs flattened over the Alluvium. The minimum elevation is about 45m in Sindh Platform areas, whereas the maximum elevation is around the Rohri area.

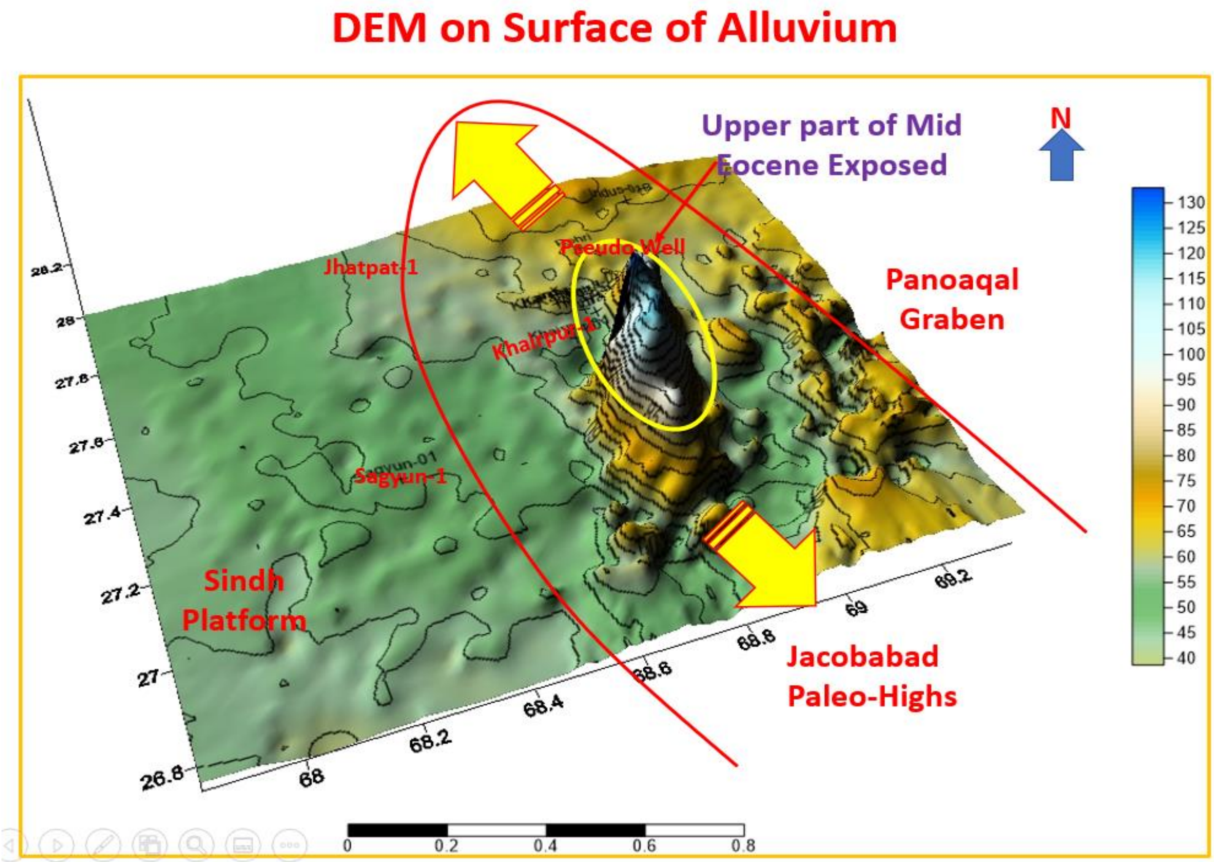

Figure 5.3 (h). Digital Elevation Model on Surface of Alluvium showing the surface orientation of Jacobabad Khairpur High.

5.3.2. Isopach Maps

Isopach maps were constructed on Surfer software in such a way that the upper part of the Formation was subtracted from lower part of the Formation using Math option in the grid menu. The Isopach maps were developed to determine the thickness of the formations and to analyze and disclose the 3D subsurface model of the study area (Pseudo-Well). The 3D surface was created for Chiltan Formations, Lower and Upper Goru Formation and Sui Main Limestone respectively.

5.3.2.1. Isopach Map of Chiltan Formation

The Chiltan Formation has maximum deposition towards South and Northwest of Jacobabad High. The maximum thickness of 1731m was encountered in Jhatpat-01 drilled at the Northwestern part of the High. At the Rohri area (Pseudo-well) the contours get wider like a flat surface. Below which there is slope towards the Kandra wells after which towards Khairpur field contour shows depression (Figure 5.3 i). The contour interval is 500.

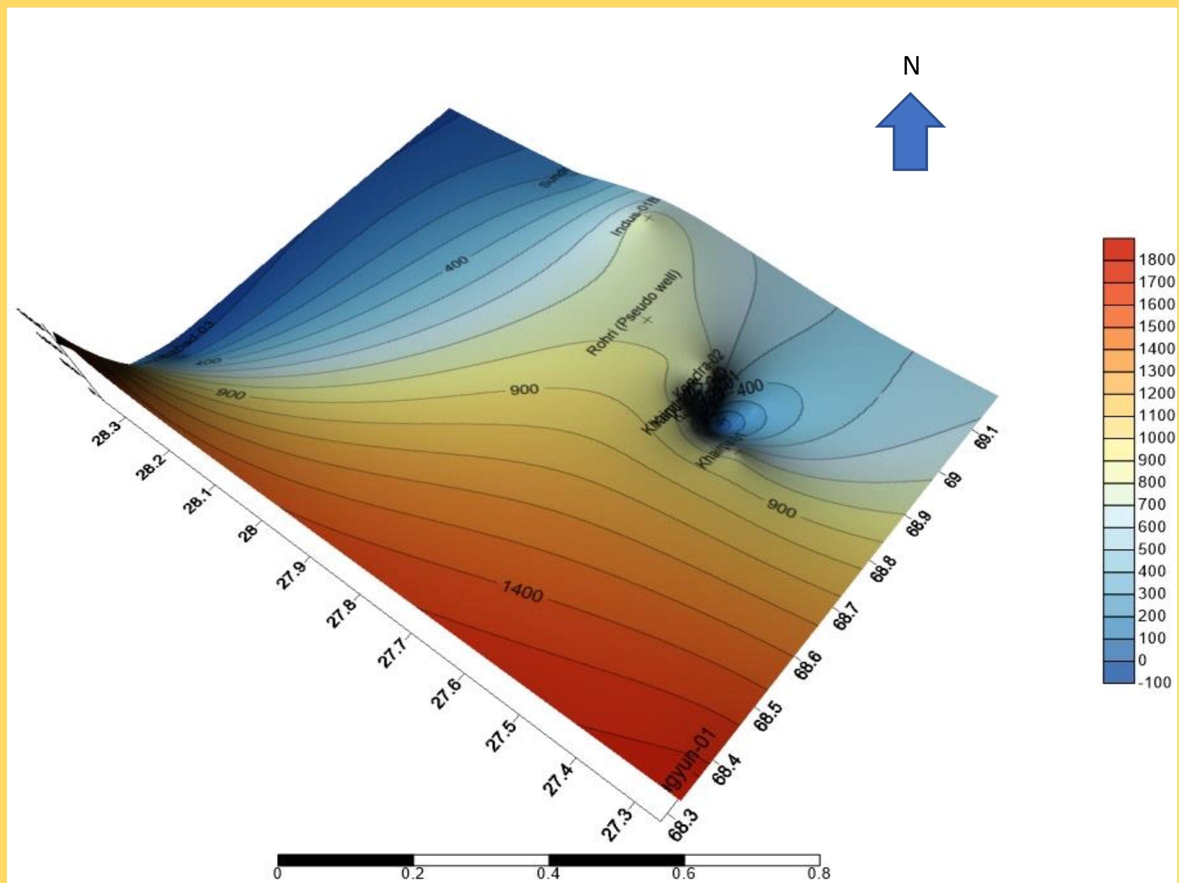

Figure 5.3 (i). 3D Isopach map of Chiltan Formation level

5.3.2.2. Isopach Map of Lower and Upper Goru

The maximum thickness of Lower Goru is 1125m in Kandra-01 making it the main depo-center of Lower Goru Formation (Figure 5.3 j). Whereas, the maximum thickness of Upper Goru Formation in Sundrani-01 of Pano Aqal Graben is 490m and in the vicinity of Jacobabad High maximum thickness is in Kandra-01 of 366m (Figure 5.3 k).

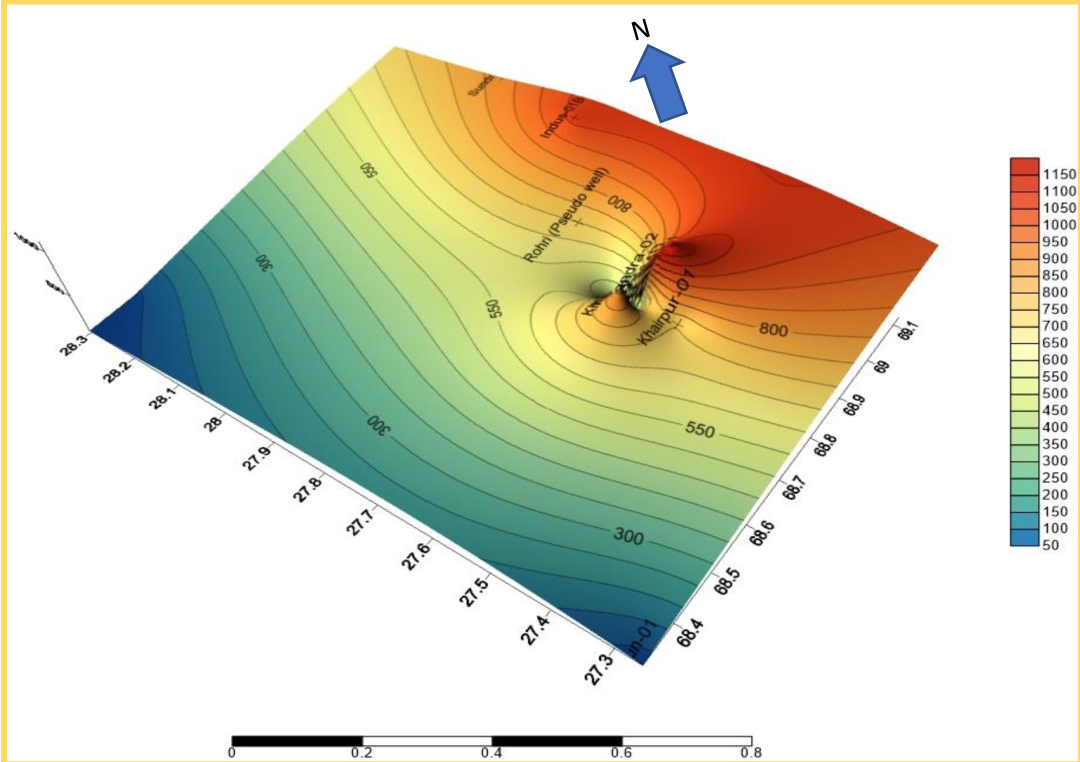

Figure 5.3 (j). Isopach map of Lower Goru Formation, with maximum thickness in Kandra-01.

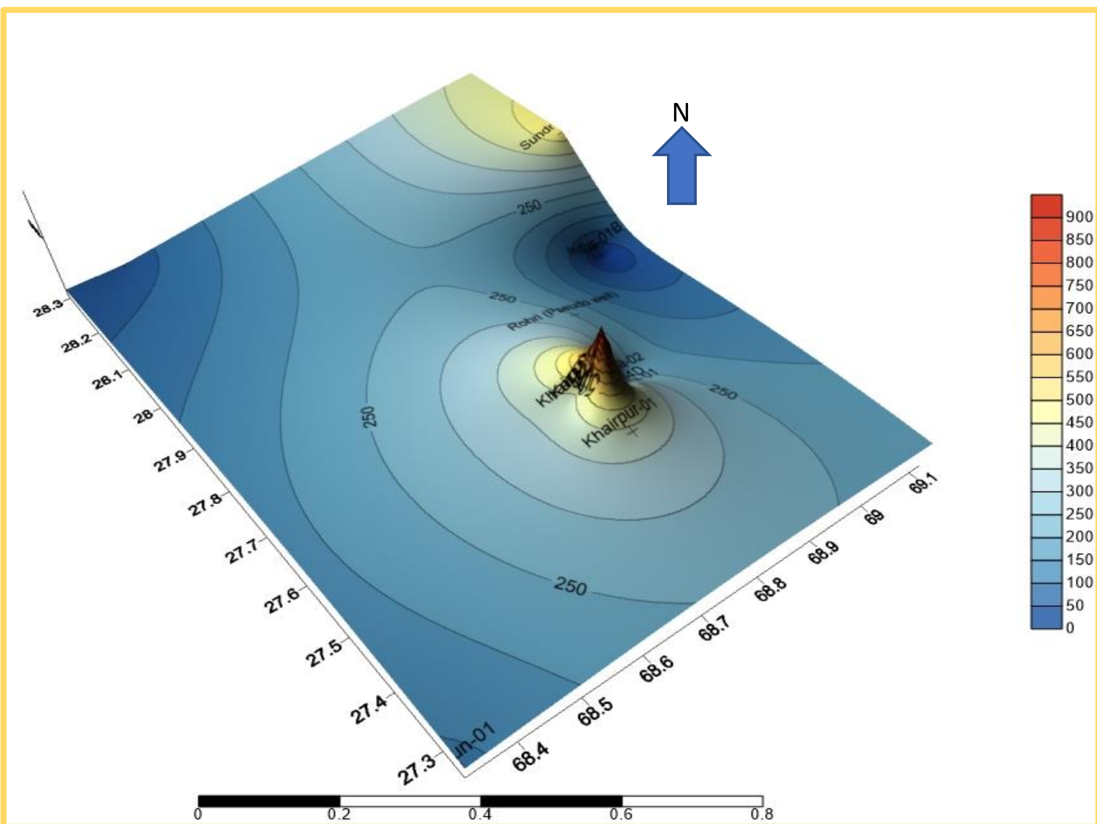

Figure 5.3 (k). Isopach map of Upper Goru Formation, with maximum thickness in Kandra-01

5.3.2.3. Isopach Map of Sui Main Limestone

The Sui Main Limestone one of the most prolific reservoirs of Southern Indus Basin (Siddiqui, 2004). The Sui Main Limestone attains a maximum thickness in the Northwestern part of Jacobabad Khairpur High of 270m (Figure 5.3 l), although across the other wells drilled in the Jacobabad Khairpur area, Sui Main Limestone is relatively thinner. The reason of the maximum thickness at Northwestern part is its continuation from the Sui area towards east.

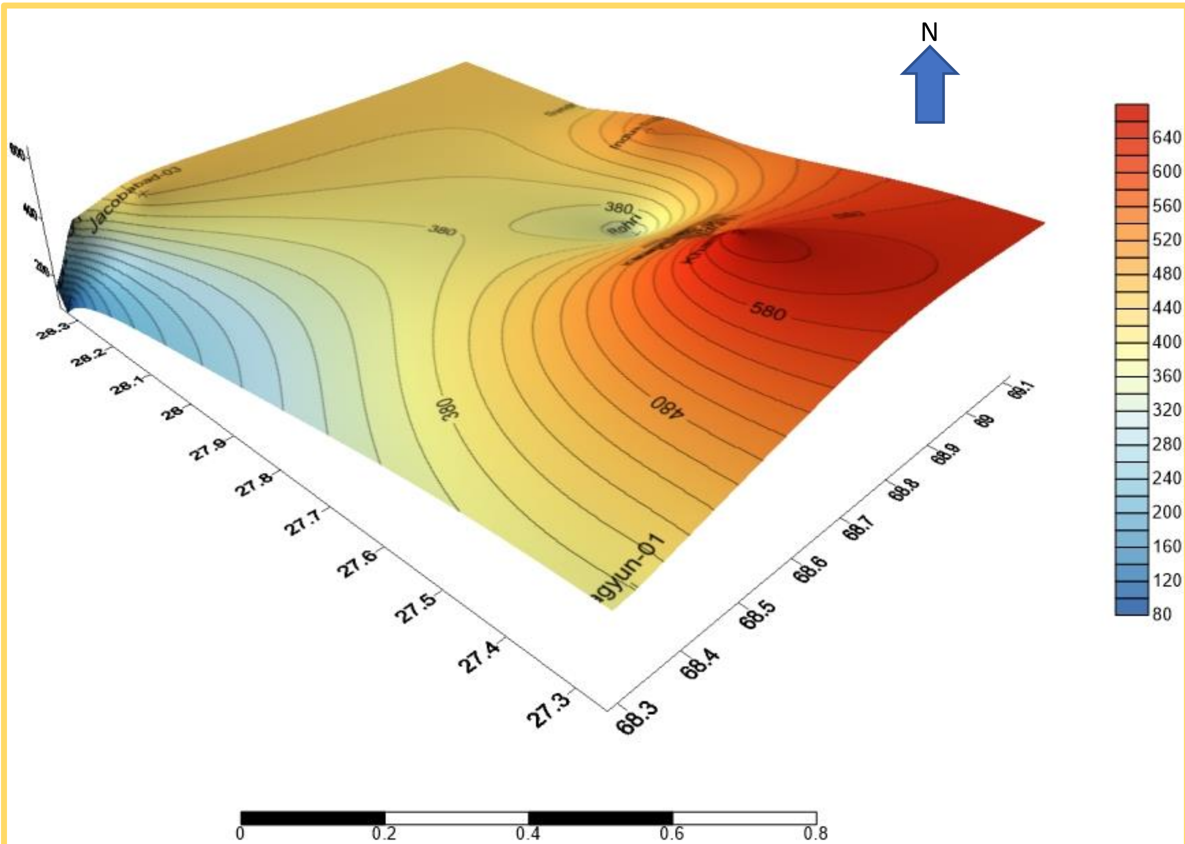

Figure 5.3 (l). 3D visualization of Sui Main Limestone Grid.

5.4. Petrophysial Interpretations

(Senosy, A.H., Ewida, H.F., Solaiman, A.H, et al. 2020) mentioned that “One of the most useful and crucial tools for reservoir rock characterization is petrophysical examination of well logs. Petrophysical parameters like as lithology, porosity, water saturation, permeability, and saturation affect well productivity in hydrocarbon-bearing reservoir” (Lyaka Al & Mulibo GD, 2018;). The petrophysics framework here is known as formation evaluation, which is the process of evaluating the features of subterranean formations using borehole measurements (Helander 1983). The Petrophysical interpretations and anlaysis was conducted for Sui Main Limestone of Eocene age. “The first paper on the Sui Main was presented in 1992 and was later partly published” (Siddiqui, 1993, 2004). (Tainsh et al. 1959) mentioned ‘‘The Sui Main Limestone provided a major surprise when it was first met in Sui well-1” (Siddiqui, 2004). Indus-01B well data analysis results for reservoir characteristics of Sui Main Limestone were taken from (Shakir et al, 2017) for comparing the impact result of Jacobabad High on Sui Main Limestone versus Sui Main Limestone of Pano Aqal Graben. The Volume of shale (Vsh), Porosity (ϕ), water saturation (Sw) and Hydrocarbon saturation (Shc) were calculated based on petrophysical analysis using technique previously done by (Qadri, S.M et al, 2019). The Gamma ray log is the record of formations’s radioactivity and measure the amount of shale as a function of depth (Zia et al, 2016). The lithologies like Shale contains high GR values API (>75) and Limestone contains probably low GR log values API (<45) (Rider, 1996). In Kandra-01 the volume of shale in the upper part of the reservoir starting from 600m to 700m is decreasing, while below the depth of 714m the volume of shale is increasing consistently till the depth of 2000m, right after this depth there is decrease in the volume of shale due to the presence of Chiltan

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Limestone at the depth of 2242m (Figure 5.4 a). The Sui Main Limestone shows good reservoir characteristics values while permeable and impermeable zones were marked by GR log (Figure 5.4 b). Also, the Lower Goru Formation shows good reservoir characteristics. The GR log values were not so high and remains low throughout the Sui Main Limestone. Below the Sui Main Limestone, the GR log response increased and generally reached the maximum value above the Base line in Lower Goru zone. According to (Shakir et al, 2017), in Indus-01B the volume of shale values in the upper reservoir part of reservoir are increasing, but after the depth of 1190m decreasing trend started in shale volume till 1235m. Sui Main Limestone interval shows good reservoir characteristics. The permeable and impermeable zones were identified using SP and GR log. The values of shale are 29%, average porosity 15.45%, Effective porosity 13.19%, average water saturation 90% and hydrocarbon saturations are 10% (Table 5.2). Due to higher water saturation at Sui Main Limestone reservoir level Indus-01B is abandoned well. In Kandra-01 volume of shale values from 600 to 743m for Sui Main Limestone are 20.9%, average porosity 14.5%, Effective Porosity 14.43%, average water saturation 54.12% and hydrocarbon saturation 45.88% (Table 5.3). The Kandra-01 was drilled for Chiltan Formation as a target which has a gas potential. According to (Qasim, 2017) he conluded that Sui Main Limestone of Kandra-01 has 49% hydrocarbon saturation. The suggestions for reservoir characteristics of (Pseudo-well) will be in between Indus-01B and Kandra-01 with the assumed success rate of 20% due to unavailability of Seismic data and well data for other wells for large scale assumptions and interpretations for the end result for (Pseudo-Well).

Table 5.2. Petrophysical Analysis Results of Indus-01B (after Shakir et al, 2017)

Indus-01B					
Interval		Shale Volume %	Average Porosity %		Saturation
Formation Top (m) and Base (m)		29	Total (ϕ)	Effective (ϕ)	Water Saturation
1120	1240		15.45	13.19	90 (water wet)

Table 5.3. Petrophysical Analysis Results of Kandra-01

Kandra-01					
Interval		Shale Volume %	Average Porosity %		Saturation
Formation Top (m) and Base (m)		13.8	Total (ϕ)	Effective (ϕ)	Water Saturation and HC Saturation
600	743		14.5	13.04	54.12% and 45.88%

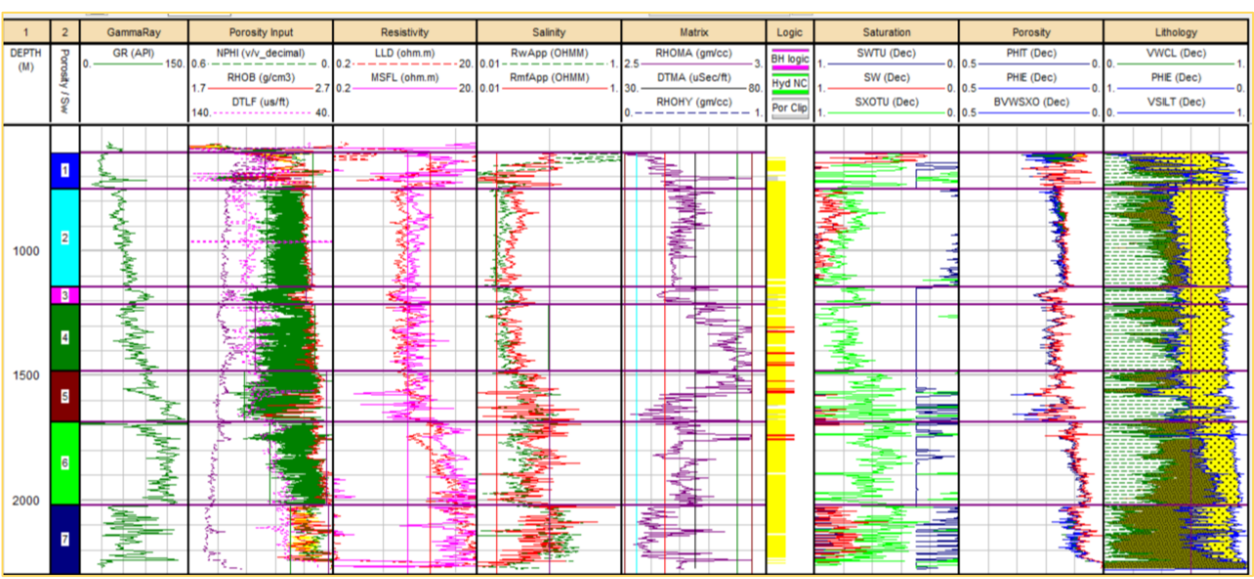

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Figure 5.4 (a). Petrophysical interpretations of Kandra-01. For Formations see Table 4.2

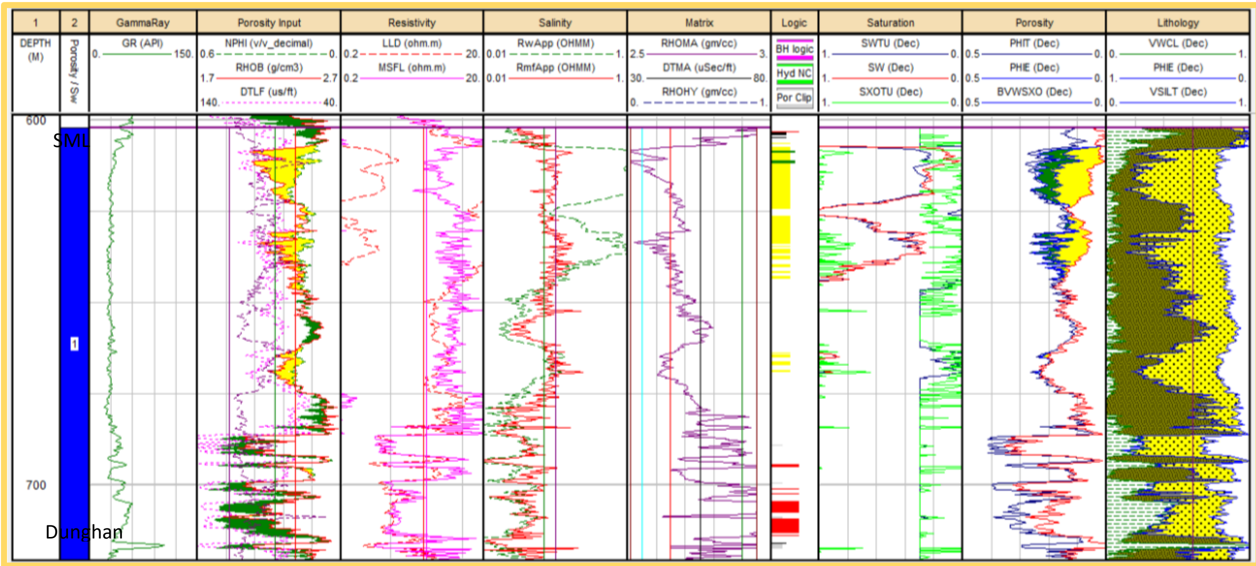


Figure 5.4 (b). Petrophyscial interpretations of Sui Main Limestone Zone of Kandra-01.

5.5. Depositional Modelling

Backstripping is a powerful tool for quantifying the tectonic subsidence and uplift history of a sedimentary basin (Watts & Ryan 1976). This depositional model of Indus-01B is constructed based on well tops provided by the Directorate General of Petroleum Concession of Pakistan (DGPC), and (Pseudo-Well) placed at the Rohri based assumed thickness derived from structural and stratigraphic correlation. The main purpose as mentioned earlier is to construct the ideal depositional model of the well understanding the lithologic trends, variations in lithologies, porosity trends. While the temperature is based on the regional scale due to confidentiality of the data that is not given to us, the temperature trends are just ideally been taken to simple correlate it with the depth to reach up to the conclusion. The method to construct the models was very simple by taking the wells tops values and giving age values to the respective Formations given by the Stratigraphic Committee of Pakistan, and producing the simple burial history of the wells, understanding the burial history of the Formations, the decrease in porosity, temperature variations and idealizing the past geological conditions to examine the subsurface expressions around the Jacobabad Paleo-Highs.

The main key point was to analyze the subsurface tectonic and geological history of the Rohri area where we have placed the (Pseudo-Well) for future exploration activities, based on the depth contours, structural, and stratigraphic correlations, variations in the trends of Formations encountered during drilling, the results were up to some level like the adjacent wells as drilled by the specific companies. We have used the stratigraphy, formations and lithologies data from (Shah, 2009).The depositional model shows that the well Indus-01B (Fig 5.5 a) which is located in the Pano Aqal Graben was drilled to the Upper Cretaceous Pab Sandstone, based on the structural and stratigraphic correlations, and depth contours of the 09 wells around the vicinity of Jacobabad Paleo Highs, the prognosed thicknesses were used to look up to the Middle Jurassic Chiltan Formation, most of the wells were drilled to the Middle Jurassic Formations, this idealized concept led us to the conclusion that during the Middle Jurassic Time period, the Chiltan Formation, which is mostly Limestone and act as a reservoir in some parts of Lower Indus Basin, was deposited in the Shallow marine environment, above which there is a major unconformity between Chiltan Formation of Middle Jurassic and Early Cretaceous Sembar Formation deposited in deep marine environment during rifting of Indian Plate from Gondwanian domain, which then lead the way for the deposition of 1080m complete Cretaceous rocks. This exceptional theory is based on the prognosed thickness used in the depositional model of the Indus-01B; that if it was drilled further below the Pab Sandstone, the situation will be much similar to our model that represents an ideal case. The Upper Paleocene Ranikot Formation overlies the Pab Sandstone of Upper Cretaceous marking the K/T boundary and then sequence get normal above the Ranikot Formation, due to the presence of entire Eocene Rocks, up to the recent alluvium. The reason of this well not producing hydrocarbons is due to high water saturation reservoir zone. Our aim was just to know about the ideal burial history of this well, based on well tops data.

The Rohri (Pseudo well) (Figure 5.) which is the prognosed well based on following the regional structural correlation of the Formations, encountered during the drilling in the wells around the Jacobabad Paleo-Highs, and depth contours of the respective Formations, which leads to develop the ideal well by assuming the thicknesses of the Formations, that were correlating with others while some Formations were pinching out. The well then shows that at the bottom the Middle Jurassic Chiltan Formation is present in subsurface, indicating shallow marine environment based on the Limestone lithology, trending across the respective wells, above which the small bed of Sembar Formation of Lower Cretaceous age lies. Mentioned by (Qayyum et al. 2016) “Sembar Formation has fair to good hydrocarbon source potential (Wandrey et al. 2004; Hasany et al. 2007; Nazir et al. 2012). The formation consists of black shale with interbedded silt-stone and argillaceous limestone (Raza et al. 1990; Kadri 1993; Khan et al. 2002 and Shah 2009). The thickness in the type section is 133 m but the formation thickens to 262 m in the Mughal-Kot Section of the Sulaiman Range (Shah, 2009)". In Kandra-01 according to (Qayyum et al. 2016) Sembar Formation is present based on prognosed thickness about 11m, our results suggest based on correlations thickness of Sembar Formation (Cretaceous) is around 20m in (Pseudo-Well) and Kandra-02 not in Kandra-01 because it is nearer to our (Pseudo-Well) and Kandra-01 is located east of Southeast of Kandra-02. An unconformity occurs due to gap in deposition from Middle Jurassic to Lower Cretaceous (Williams, 1959); that depicts an interpretation for the deposition of Early to Middle Cretaceous rocks, based on the correlations from Northeast to South West starting from Sundrani-01 to Indus-01B up to Rohri and so on. The Sembar Formation indicated the deep marine environment due to its marine Shale source rock, marking the transgression of the regional sea level (Ahmed et al. 2011); while the sequence is followed by the Mid-Cretaceous Lower Goru Sandstone that represents the marine regression for the non-marine reservoir of Lower Goru to be deposited. (Fatmi, 1977) described that the Goru formation consists of inter bedded limestone, shale and siltstone. Above the Lower Goru the Upper Goru Shale and marl deposited, representing the transgression of the sea level to deposit the regional seal to cap the Lower Goru, The Ranikot Formation then mark the unconformity between Mid-Cretaceous to Upper Paleocene, known as K/T boundary. The sequence then gets normal due to the presence of the Dungan Formation of Paleocene age and above that the Sui Main Limestone of Early Eocene get deposited, the sequence then get similar to Khairpur-01 that the Sui Shale, Sui Upper Limestone, Ghazij Shale, and Kirthar Formation deposited marking several changes in the environment of deposition, from shallow marine to deep marine and vice versa. The Habib Rahi Formation is exposed due to some tectonic activity, we may not know the exact case what were the reasons that causes it to expose to the surface. In other wells all the members of Kirthar Formations are exposed like in Sundrani-01 and Indus-01B but at the surface the Habib Rahi Formation is only exposed, after the Indian Eurasian Plate collision and uplifting of Himalayas. (Qureshi et al. 2020) mentioned that "The Himalayan Orogeny, which has been active since Tertiary, represents collision between Indian and Eurasian Plates" (Molnar and Tapponnier, 1977). Himalaya is divided into four tectonic elements. A northward dipping normal fault known as the Trans- Himadri Fault has bounded the high Himalayas from the central crystalline complex (Valdiya, 1989). It is a late tertiary gravity collapse structure with the movement of several kilometers (Burchfield et al., 1985). But in the other wells like Kandra-01, Kandra-04D, Khairpur-01 etc. wells there is no such record for the presence of Habib Rahi Formation, trending from Northeast to Southwest, the Kirthar Formation whose member is Habib Rahi Formation, was then encountered in the Sagyun-01 well located in the Sindh Platform, creating the mystery that has yet to be resolved. Maybe it is due to regional scale normal faulting that results into the Horsts and Graben structures causes the erosion of Habib Rahi Formation beyond the Rohri area towards Sindh Platform. The model history of (Pseudo-well) suggest an existence of petroleum system and can be used for future exploration activities by considering Lower Goru (700m) of Cretaceous based on the presence of source Sembar Formation(20m) and Sui Main Limestone (Eocene) as reservoir rock. Sui Main Limestone has no surface exposure in Pakistan (Kadri 1995). The porosity and temperature curves also suggest the sufficient temperature nearly up to 100 C.

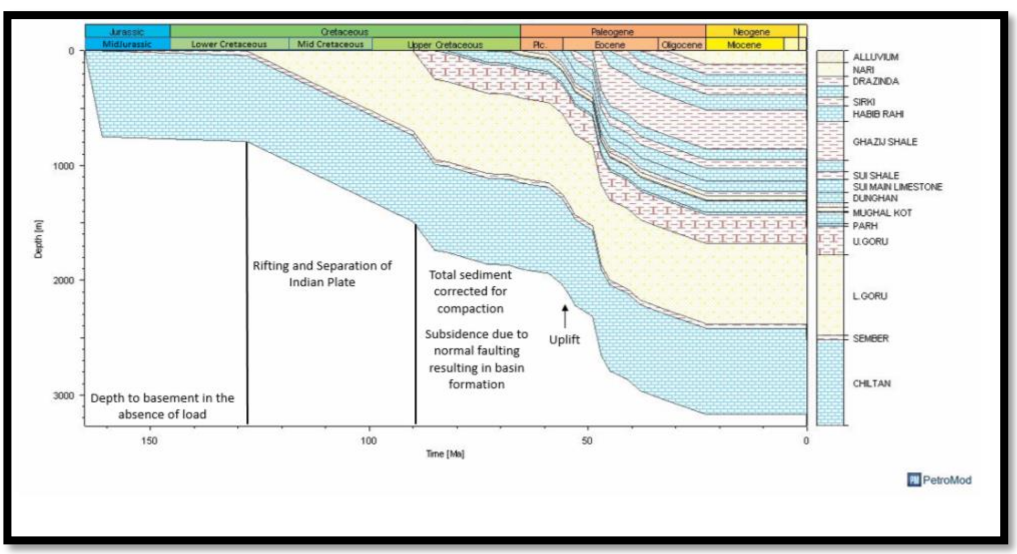


Figure 5.5 a. Depositional Model of Indus-01B, from Chiltan to Mughal Kot are prognosed thickness.

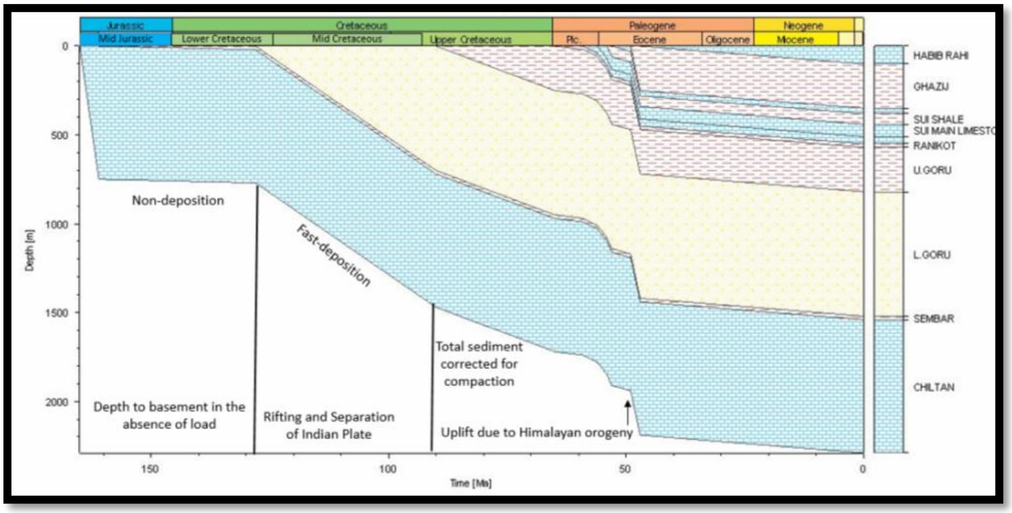
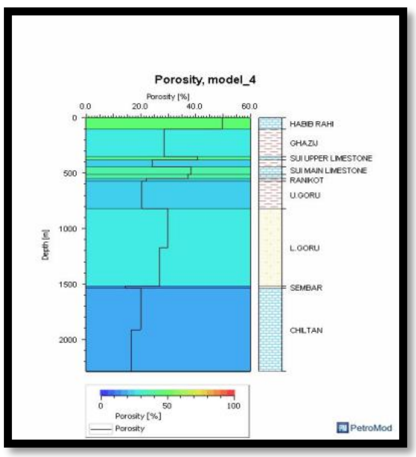


Figure 5.5 b. Probable Depositional Model of Rohri (Pseduo-Well) based om Assumed Thickness



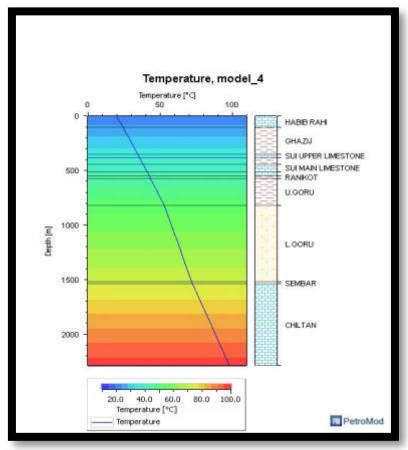


Figure 5.5. c. Possible Porosity Curve Model of Rohri (Pseudo-Well), porosity vs depth relationship as porosity is decreasing with depth.

Figure 5.5. d. Possible Temperature vs depth relationships of Rohri (Pseudo-well), as temperature is increasing with depth.

5.6. Well Prognosis (Pseudo-Well)

The Probable Rohri (Pseudo-Well) is placed at the section of Habib Rahi Formation exposed in the Rohri area at Latitude 27°39’52.0” N and Longitude 68°89’33.9” E. The (Pseudo-Well) is prognosed based on the depth contour maps as well structural and stratigraphic correlations of 9 wells starting from Pano Aqal Graben to South of Jacobabad Khairpur Highs. The location is marked on the top or apex of bulge as shown in depth contour maps (fig. 5.3 h). The total depth of the prognosed well will be 2290m. The Sui Main Limestone with probable depth of 440m, Upper Goru Formation at 570m, Lower Goru Formation at 820m, Sembar Formation at 1520m and Chiltan Formation at 1540m possibly (fig. 5.6). The petroleum prospect for the prognosed will be like Indus-01B. Sembar Formation as source for Lower Goru Formation and Upper Goru as seal for Lower Goru and Ranikot Formation as source for Sui Main Limestone with Sui Shale and Ghazij Formation as double seal for Sui Main Limestone. Chiltan Formation can also be drilled and test for reservoir. The details of the of the (Pseudo-Well) are given in Table 5.6 (a). The prognosed formations thickness that will be encountered in the new (Pseudo-Well) are calculated by developing depth contour maps and correlations of the desired formations and adding average values of other formations found in the other wells. The success ratio for the hydrocarbons prospect of the prognosed well is almost about 30%.

Table 5.6 (a). Detail Analysis of Prognosed (Pseudo-Well)

Well Name	Rohri (Pseudo-Well)
Location	Rohri
Co-ordinates	Latitude 27°39’52.0” N and Longitude 68°89’33.9”E
Target Formations	Sui Main Limestone and Upper Goru
Total Depth	2290m
Formation at the bottom (Total Depth)	Chiltan Formation
Type of Well	Exploratory
Area	Jacobabad Khairpur High

Table 5.6 (b). Petroleum Play and Prospect of Prognosed (Pseudo-Well)

Source	02
Reservoir	02
Seal	03
Trap	Normal Faulting (Horst and Graben)
Success ratio	20%

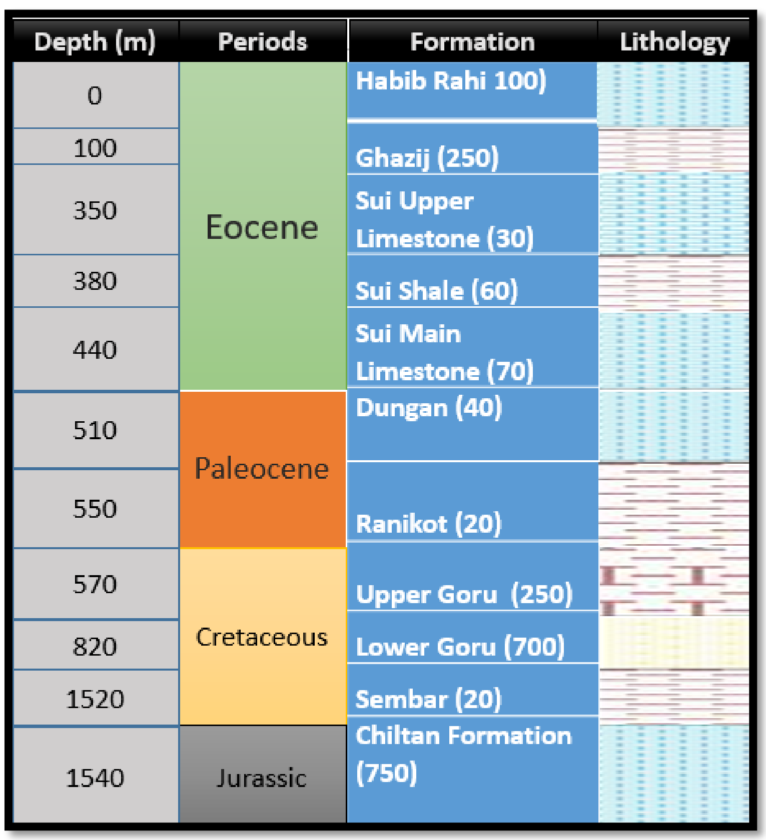


Figure 5.6. Well Prognosis of Rohri (Pseudo-Well).

6. Conclusions

Jacobababd Khaipur High is an extensional rifting associated feature formed from Jurassic to Paleocene. It is characterized as a regional Horst structure. The orientation is NNW-SSE. It has impacted the petroleum system of the area. On Northwestern side Cretaceous rocks are entirely absent and there is an unconformable contact between Jurassic and Paleocene rock. The Southernmost region of the High has considerable thickness of Middle Cretaceous above Jurassic formation, with the absence of Early Cretaceous. The Eastern side particularly Rohri where Middle Eocene Habib Rahi Formation is exposed shows tectonic uplift associated feature as a bulge like structure both on the surface and in the subsurface that was uplifted as a result of Himalayan Orogeny, based on depth contour maps and structural correlations. The correlations depth contour maps are constructed using assumed thicknesses, visualizing an ideal condition of the subsurface as most of the wells were drllled at very shorter depth due to non-reservoir conditions. Petrophysical interpretation analysis of Kandra-suggests that Sui Main Limestone has good reservoir characteristics but. The (Pseudo-Well) is prognosed at the outcrop of Habib Rahi Formation Rohri area East of Sukkur and North of Kandra-01 based on different well correlations and depth contour maps. Depositional model of the Indus-01B and (Pseudo-Well) shows two major tectonic events first one during Cretaceous (130 m/y) right after the deposition of Middle Jurassic Chiltan Formation and the second one Himalyan Orogeny during Early Eocene (50 m/y) ago indicated by sharp uplift feature. The (Pseudo-Well) shows an ideal locaton for future hydrocarbons exploraton. There is presence of main reservoir Sui Main Limestone with source Ranikot Formation and seal Sui Shale and Ghazij Shale in the (Pseudo-Well). There is also presence of Sembar Formation with 20m thickness as a source for Lower Goru as a reservoir and Upper Goru Formation. Sui Main Limestone shows good reservoir characteristics in Indus-01B and Kandra-01. The reservoir value for hydrocarbon saturations in Kandra-01 and Indus-01B are 45.88% and 10%. The future chances for hydrocarbon saturation would be around 20%. In short, the (Pseudo-Well) reservoir conditions must be in between Indus-01B and Kandra-01.

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Conflict of Interests

The authors have no conflict over this research.

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