3D GEO-CELLULAR RESERVOIR MODELLING TO EVALUATE RESERVOIR PROPERTIES OF THE PALEOCENE AND CRETACEOUS FORMATIONS OF ZAMZAMA BLOCK, KIRTHAR FOLD BELT, PAKISTAN

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A thesis submitted to Quaid-i-Azam University, Islamabad in partial fulfillment of the requirement for the degree of MPhil in Geology

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ABSTRACT

This study has been carried out at the Zamzama Gas field, which is located at Kirthar Foredeep, Southern Indus Basin, Pakistan. In the Zamzama field, primary reservoir is the Pab Formation of Cretaceous age which is a fluvio-deltaic sandstone of about 220-meter thick overlain by a secondary 50-meter thinner reservoir section of Palaeocene Khadro Formation. Khadro Formation is heterogeneous reservoir compared to Pab Formation and represents the deposits of few supra-tidal mud-flats having poor to fair quality sands and tidal channels having fair to good quality sands. Static model was built to evaluate the remaining potential of above-mentioned Palaeocene and Cretaceous clastic reservoirs. 3D Geocellular model was built by using DSG Earth modelling (EM) software of Halliburton (version EP 10.4). Total 11 wells (Zamzama-1 to Zamzama-9, Zamzama- North-1 and Zamzama East-1) data which includes Formation tops, well logs, core analysis reports, production data and 3D seismic cube were used for static modelling. Structural interpretation for Khadro, Pab and Fort-munro formations were carried out. Structural framework was built by using all the same interpreted horizons and faults. Zamzama structure is elongated, north south, thrust bounded anticline with no surface expression. It is bounded to the east by a major thrust separating the main hanging wall from a smaller footwall structure. Petrophysical properties were estimated for each well which were further used for facies and petrophysical modelling. Four lithofacies (limestone, sandstone, shaly sand, and shale) were defined for Paleocene and three lithofacies (sandstone, shaly sand, and shale) were defined for Cretaceous reservoirs. Then well log, core and lithofacies data were incorporated in the model by using Sequential Indicator Simulation (SIS). Tight limestone at the top interval of Khadro Formation is acting as a seal for Khadro Sands in the model. Porosity and permeability were distributed in the model by constraining them with lithofacies. Saturation height modelling was carried out for water saturation distribution above free water level (FWL) from well log and core data. 2 TCF gas initially in-place (GIIP) has been estimated (recoverable ~1.8 TCF with 90% recovery factor) by using 3D Geocellular model in post processing module of the EM software. The cumulative production data confirms that 1.7 TCF gas has been produced from the field however ~0.1 TCF are the remaining gas reserves.

DEDICATION

I dedicate this research work to my brother Mr. Muhammad Safdar, who always appreciated me, provided me support and encouragement. I am grateful to my oil industry mentor Mr. Khalid Shoaib (Manager Exploration OPI) for guiding me throughout my research work.

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CHAPTER 1

INTRODUCTION

1.1. INTRODUCTION

Static modelling is a 3D mathematical representation of geological and geophysical data of a field. It integrates all the geological/geophysical attributes i.e., structure, sedimentology and petrophysics, etc. of a reservoir rock. It is reliable for the evaluation of the gross and net rock volumes, reservoir properties distribution and to estimate the static and dynamic hydrocarbons initial in place (GIIP).

3D Geo-cellular reservoir modelling approach is used by E&P companies to achieve following objectives:

1. Selecting the field development strategy
2. Reservoir properties distributions and reserves computations
3. To find out optimal locations for injector and producer wells
4. Computing the production profiles (oil, gas, and water)
5. Identifying and quantifying the key uncertainties

Zamzama is a mature gas field located in the southern Indus basin of Pakistan. Total 13 wells have been drilled in the field. Out of 13 wells, 11 wells discovered hydrocarbons from Cretaceous and Paleocene reservoirs. All producing wells have been used in thesis work. Zamzama static reservoir modelling has been carried out to estimate the gas initial in place (GIIP) of Palaeocene and Cretaceous reservoirs, and remaining hydrocarbon potential of the Zamzama field.

1.2. LOCATION AND PHYSIOGRAPHY

Zamzama gas field is in the Dadu concession, and it lies approximately 180 km North of Karachi and 10km west of Dadu city in Sindh province, Pakistan. Geologically it is located at the edge of Kirthar Fold Belt (KFB) of Pakistan constituting almost 3,648.73 square kilometers of area. Zamzama block is a producing field having coordinates 26˚ 57' 00.70" N and 67˚ 36' 00.57"E, 26˚ 57' 00.70"N and 67˚ 43' 00.52"E, 26˚ 32' 00.84"N and 67˚ 43' 00.51"E and 26 32 00.84" N and 67 36 00.57" E as shown in figure 1.2. Zamzama field is covering an area of around 110sq.km and was ranked as one of Pakistan's largest gas discoveries at the time of its initiation.

Figure 1.1. Location map of Zamzama gas field in Pakistan (OPPL).

1.3. EXPLORATION HISTORY OF STUDY AREA

The Zamzama gas field was discovered in 1998. Geologically, it is located at the western edge of Indus Basin on the leading edge of Kirthar fold and thrust belt as shown in figure 1.1. It is north-south trending, thrust bounded, anticlinal structure with no surface expression. Zamzama structure is bounded to the east by a major thrust, separating the main hanging-wall structure from a smaller footwall structure.

The main reservoir in Zamzama field is the upper Cretaceous Pab Formation sandstone with the lower Paleocene Khadro Formation sandstone as a secondary reservoir. The Pab Formation consists of three main depositional facies: shoreface, estuary, and braided fluvial-deltaic in vertical succession from oldest to youngest. The Pab Formation sands are well developed across the structure, have a high net to gross ratio. The average gross thickness is

220meters with an average net sand thickness of 135meters. The Khadro reservoirs are thin tidal/estuarine sands that are poorly to moderately developed across the structure. Its average gross thickness is 50-55meters with an average net sand thickness of 4-7meters.

The Sembar Formation is considered as the potential source rock of Zamzama gas field. However, no well has been penetrated in Sembar to prove the respective source rock for Pab and Khadro reservoirs. Other potential source rocks include Jurassic Chiltan & Anjira formations also have the potential to generate both oil and gas (Wandrey et al., 2004).

Commercial production in the Zamzama field began in the year 2001. Currently Orient Petroleum Pty. Ltd. (OPPL) is the operator with 38.05% working interest along with JV partners, GHPL (25%), Eni (17.75%), AEPL (9.375%), and KUFPEC (9.375%).

Total of 13 wells have been drilled in the field (Zamzama-1, Zamzama-2, Zamzama-3, Zamzama-4, Zamzama-5, Zamzama-6, Zamzama-7, Zamzama-8, Zamzama-9, Zamzama-East-1, Zamzama- North-1, Zamzama- North-2 and Zamzama Sub-1) 11 wells discovered hydrocarbons and 2 wells (Zamzama North-2 and Zamzama Sub-1) are abandoned. Cumulative production from the field till March 2021 is ~ 1.72 TCF gas and ~ 9.85mMBBL condensate.

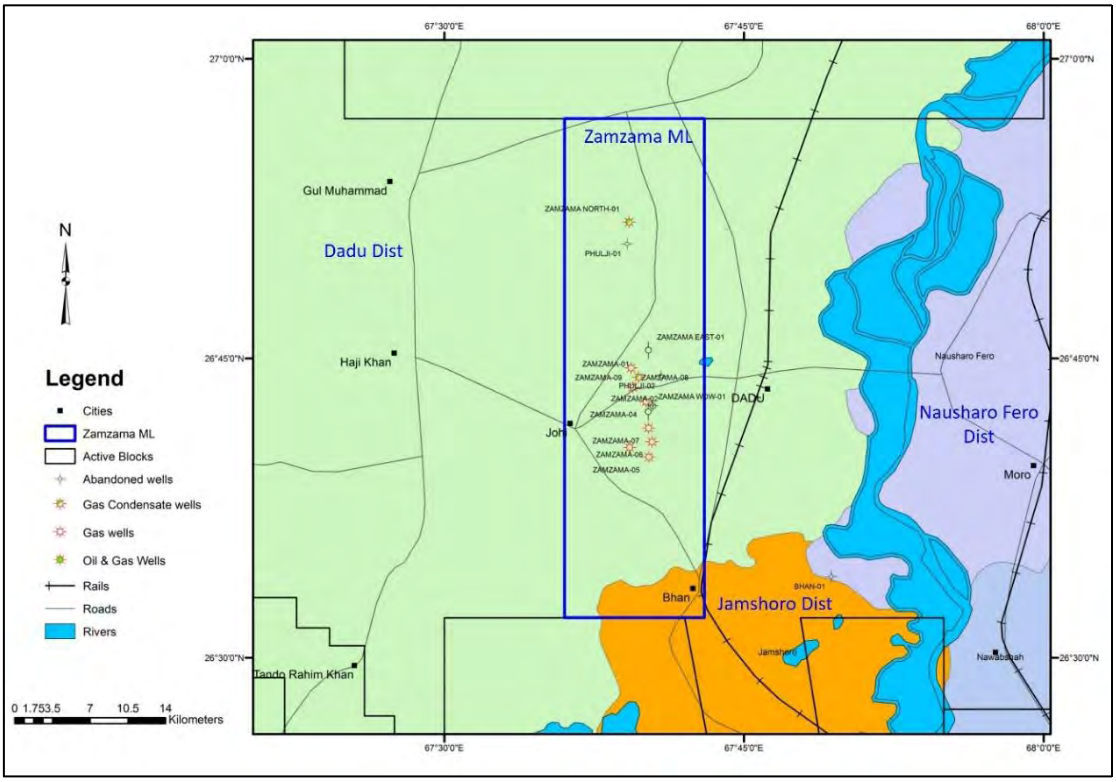


Figure 1.2. Map showing area of interest in Zamzama with surrounding fields in Southern Indus Basin (OPPL).

1.4. AVAILABLE DATA

Zamzama is a mature gas field with 13 drilled wells and 3D seismic. The following G&G dataset was provided by OPPL for preparing of model.

1. **Seismic data:**
   - 420 km^2 3D seismic cube (both PSDM and PSTM)
2. **Wells data:**
   - Formation tops
   - Wireline logs
   - Core data / Cores reports and Photographs
   - Perforation Intervals and production rates
   - Wells production data

1.5. METHODOLGY

Reservoir modelling is the process of building a three-dimensional representation of reservoirs based on its petrophysical, geological and geophysical properties. The main steps of static modelling workflow are shown in figure 1.3.

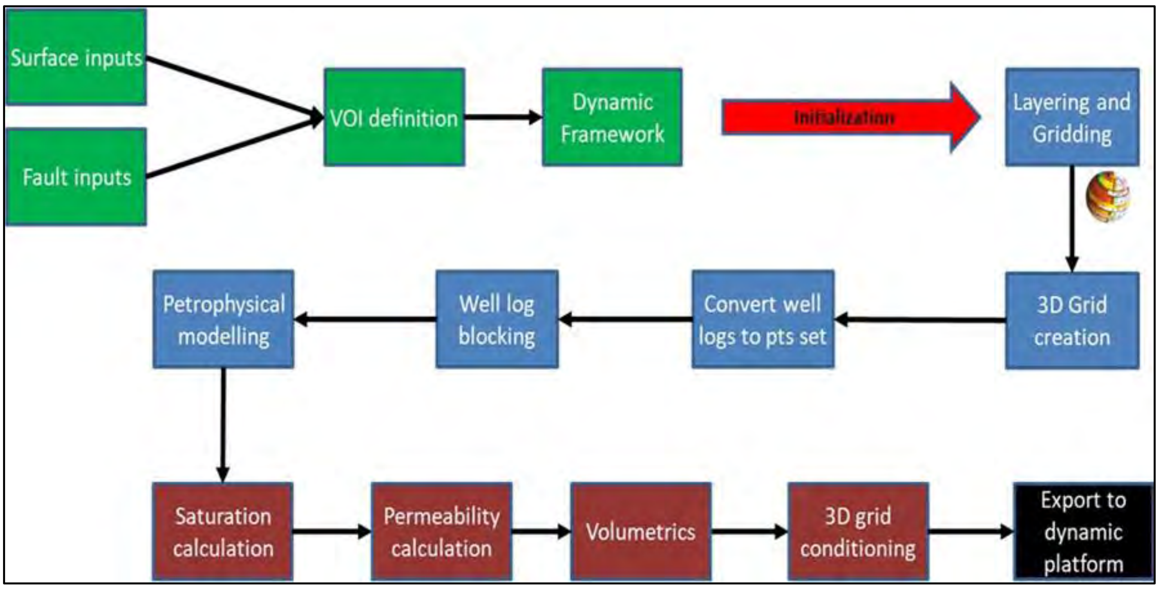


Figure1.3. Methodology followed for building static model.

Regarding Zamzama static modelling, a structural model having 11.5million cells of 50x50m with 2.9m vertical resolution was built for Khadro and Pab formations. A total of 17 and 70 layers were prepared for Khadro and Pab formations respectively for detailed evaluation of reservoir heterogeneity. Facies model was built using depositional environments. Property modeling was carried out by constraining facies data, furthermore static reserves volumes were calculated.

1.6. OBJECTIVE

The study was undertaken on the Zamzama field with the following objectives:

1. 3D Seismic data interpretation of Khadro, Pab and Fort-Munro formations to prepare 3D structural framework.
2. Advance petrophysical interpretation of wireline logs and use the interpretation for property modeling.
3. Prepare zonation's and sub-zonation's of both (Khadro and Pab) formations to evaluate the reservoir heterogeneity in detail.
4. Prepare facies model and use the same model for Porosity and SW modeling.
5. Calculate the reserves and remaining potential of the field.
6. Identify the location for new well or sidetrack potential of present well.

CHAPTER 2

TECTONIC SETTING AND GENERAL GEOLOGY

2.1. TECTONIC SETTING

Along with smaller/sub-basins, two major sedimentary basins i.e., Baluchistan and Indus Basin are marked in Pakistan. Both basins under-went entirely different geological events and settings before joining together along the Ornach-Nal/Chaman Strike Slip fault during Cretaceous/Paleocene age. Covering a large extend of the eastern side of Pakistan, Indus Basin also stretches into India with an aerial extent of about 8,73,000 sq.km, making it the largest onshore basin of Pakistan. In our region, based on structural regime and the petroleum prospects, Indus Basin is subdivided into Upper, Central and Southern Indus Basin (Naeem et al., 2016).

Based on tectonic setting, Southern Indus Basin is further divided into the Thar Platform, Karachi Trough, Kirthar Foredeep, Kirthar Foldbelt and Offshore Indus. The north-south (N-S) oriented tectonic feature and subsidence zone are marked as Kirthar Foldbelt and Kirthar Foredeep respectively in Southern Indus Basin (Kadri, 1995).

Oblique collision between north moving Indian Plate and the Helmand Block of the Eurasian Plate; through Mio-Pliocene to recent times, resulted in the formation of Kirthar Foldbelt Basin and Kirthar Foredeep. This sub-basin is bounded by Sulaiman Foldbelt, Offshore Indus Basin and the Kachchh Basin, and Southern Indus Basin, Bela-Waziristan Ophiolite and the Baluchistan-Pishin province from north, south, east, and west respectively (Kadri,1995). Major part of Kirthar Foldbelt lies on the Khuzdar Block; a semi-detached part of the Indian Plate, splitting from the Indian Block along a N-S striking major oblique crustal fault, the Kirthar Basement Fault (Bannert et al., 1992).

Kirthar Foredeep is a depression zone having a thick sediment succession of ~15,000meters. It was subducted by the developing Kirthar fold and thrust belt. This zone has great potential for the development of hydrocarbon kitchen. Kirthar Foredeep is separated from Thar Platform by a fault in the east (Kadri,1995).

The Zamzama gas field lies in the foreland of Kirthar Foldbelt and Kirthar Foredeep corresponds to western part of Kirthar mari Kandhkot High and eastward limited by Nabisar Slope and Thar-Parkar High.

The Zamzama structure lies in the foreland of the Kirthar Foldbelt and Kirthar Foredeep as shown in figure 2.1. In Kirthar Foldbelt, a carbonate dominated Tertiary sequence is overlayed by >1399m sediment sequence of miocene to Recent fluvial sediments (Siwalik Group) and underlain by Late Cretaceous Pab Sandstone reservoir. Following the tectonic activity in the last several million years, this sediment sequence has been folded to form the Phulji Anticline.

2.2. GENERAL GEOLOGY

Chiltan Formation, which consists of carbonate rocks, was deposited during the middle Jurassic time period in a stable shelf platform setting. This was followed by extension and consequent fault block rotation in the late Jurassic causing development of good reservoir within shoals/ karstified area (Kemal 1991; Kadri 1995).

Gondwana land continued to split from Jurassic to early Cretaceous time period which caused the interior of the Indian Plate to be uplifted gently and ultimately the carbonate platform of the middle Jurassic was replaced by shale and sandstone of shallow marine to deltaic setting. Indo-Pak Plate separated from Madagascar during the Late Cretaceous, and north-western part of the Indian Plate passed over the Reunion hotspot which result in eruption of the Deccan Trap (Khadro Formation) (Powell 1979). The said events are once again responsible for uplifting of the interior of the Indian plate and then replacement of the carbonate platform by clastic sediments (Kazmi and Abbasi 2008; Shah (1988, 2009).

Sinistral transpression established during the Paleocene age near the western edge of the Indus Basin that reacted at a point where inversion of the previously deposited sequence took place. On the passive margin setting at the northern edge of the Indus Basin, carbonates were deposited (Meissner and Rahman 1973; Shah 1977, 2009).

Extensively perceived strata of the Eocene are present, but the majority of Oligocene sediments are missing. A thick sediment succession of Miocene to recent deposits is also observed in the area.

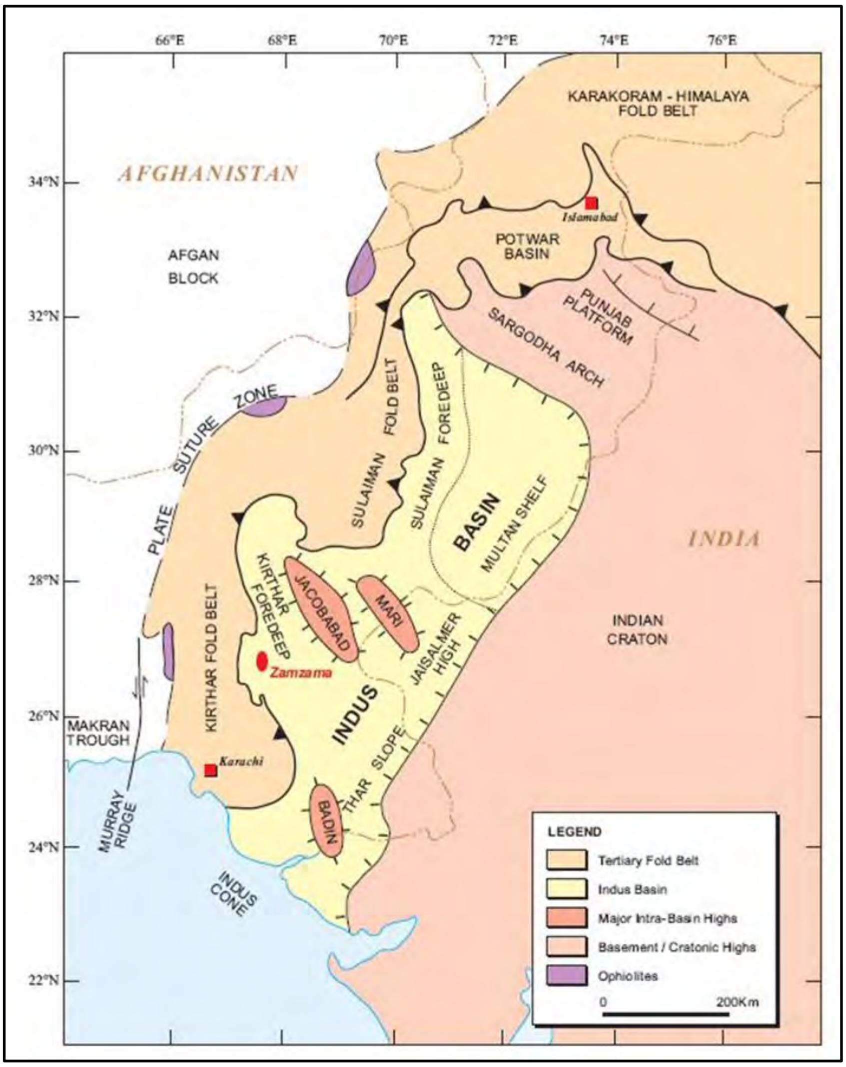


Figure 2.1. Tectonic map of Southern Indus Basin highlighting the study area along with surrounding fields (OPPL).

2.3. STRATIGRAPHY

Detailed stratigraphy of Zamzama block is shown in table 2.1.

Table 2.1. Detailed stratigraphy of the Zamzama field (OPPL).

Age	Formation	LITHOLOGY
MIOCENE to PLIOCENE	Siwalik Group	The Siwalik Group is a thick sequence of interbedded sandstone and claystone with minor calcareous sandstone and coal. The sandstones are variable in colour, ranging from yellow to light olive brown to light grey and are generally fine to medium grained

		and variably calcite and silica cemented. Lithic fragments and micas are common, with minor argillaceous sandstone near the base. The clay stones are generally dusky yellow to light olive brown and very dispersive and sticky in part, becoming greyish green in the lower part of the section. Thin limestone beds are present in the top half of the section down to approximately 750m with rare coal beds throughout the middle of the section.
	Gaj Formation	The Gaj Formation consists of more compact sub-fissile to sub-blocky clay stones with minor sandstones & siltstones. The Gaj clay stones are characteristically pale red purple at the top but varicoloured (pale to olive brown and greyish green) and grade to argillaceous siltstones in part. The sandstones are very fine to fine grained and are described as glauconitic towards the base, but this may also be fine grained chlorite grains. Careful observation and description are required (ideally supported binocular microscope photographs) of all green coloured minerals in this section.
OLIGOCENE	Nari Formation	The top of the Nari Formation is a gradational contact with overlying Gaj Formation and consists of light brown to olive grey claystone and fine to medium grained sandstones. Thin limestones may occur in the top 50m to 70m and contain bivalve and foram fragments and are variably dolomitised. The section becomes dominated by sandstone and siltstone towards the base. Quartz grains are commonly stained olive brown in the upper part of the Nari Formation but become clear to translucent towards the base. The lower part of the Nari Formation consists of interbedded hard, white to grey limestones with siltstone and fine sandstone.
MIDDLE EOCENE	Kirthar Formation	The Kirthar Formation is a white to yellowish-grey coloured limestone. It is massive micro-crystalline to cryptocrystalline and contains traces of fossil fragments. The upper part of the Kirthar Formation contains minor but common interbedded claystone and fine-grained sandstone.

	Ghazij Formation	The top of the Ghazij Formation is characterised by greyish green, hard, micro-crystalline to cryptocrystalline limestone with common patchy greyish green argillaceous matrix. In the lower part of the Ghazij section, this limestone is interbedded with pale olive to greyish-olive calcareous claystone, grading with depth to claystone.
EARLY EOCENE	Laki Formation	The Laki Formation is predominantly massive, light olive-grey to pale yellowish-brown, microcrystalline to cryptocrystalline limestone, hard to very hard. The limestone is interbedded with minor greyish olive claystone at the top. The basal 30-40m is marked by a series of limestone, argillaceous siltstone, carbonaceous claystone, and very fine sandstone interbeds.
PALAEOCENE	Dunghan Formation	The Dunghan Formation is a massive, homogeneous pale yellowish-brown to yellowish-grey, microcrystalline to crypto-crystalline medium hard to hard limestone. It contains trace to common microfossils, particularly forams, and algal remains. The basal 25m grades into a dark grey argillaceous limestone.
	Girdo Formation	The top 60m of the Girdo Formation consists of hard, greenish black to greyish black claystone with occasional thin argillaceous limestones grading downwards to argillaceous siltstone with subordinate tight, very fine sandstone. The basal 50m to 70m of the Girdo Formation is characterised by moderately hard to hard medium grey to greenish-black claystone
	Khadro Formation	A 3-4m thick, very hard, tight limestone marks the top of the Khadro Formation. This limestone is grey to yellow-brown, micro to cryptocrystalline, and gives a very distinct reverse drilling break. This is underlain by an interbedded sequence of very fine to medium occasionally coarse-grained sandstones containing volcaniclastic detritus and often cemented with chlorite, which imparts a greenish colour to the sandstones. These sandstones are interbedded with medium dark grey to brownish-grey and

		reddish-brown claystone up to approximately 30m in thickness. The sandstone contains a framework of well sorted quartz and altered feldspar grains and greyish black and white (reworked) lithic fragments, quartz cement with lesser calcareous cement and minor grey to greenish-grey tuffaceous argillaceous matrix. The remainder of the Khadro Formation is dominated by reddish brown to greyish brown claystone with minor interbedded sandstone and thin calcareous limestones.
CRETACEOUS	Pab Sandstone	The Pab Formation is composed of sandstone with minor claystone. A sharp reverse drilling break generally marks the top of the formation. The sandstones are hard, clean quartz arenites and are fine to medium grained with minor coarse to granule grain size, especially towards the base. The sandstones contain common to abundant quartz cement, as well as minor to common calcite cement and minor argillaceous matrix in part. The clay stones are varicoloured, generally moderate brown to greyish brown becoming greyish green with depth. minor lithologies within the Pab include thin coaly beds at the base.
	Fort-munro	Fort-munro Formation is consisting of Limestone with streak of siltstone. Limestone is pale yellowish brown to yellowish brown, cream, hard, sub blocky to blocky, massive, and cryptocrystalline to relic sandstone texture, dominantly sparite, rarely micritic, commonly occurs as rock flour, intercalated with grey / black very carbonaceous siltstone.
	Parh	Parh limestone is mainly consists of thick and massive limestone with streaks of claystone. Limestone is off white to dirty white, light to dark brownish grey, in parts grey, firm to moderately hard, soft in parts, occasionally hard to very hard, sub blocky to amorphous, occasionally blocky, dominant amorphous, crypto to micro-crystalline, chalky in parts, highly argillaceous, in parts grading to marl, dolomitic, no visual porosity and no shows. claystone is light to medium grey, dark grey, in parts light greenish grey, olive grey, light brownish grey in parts, firm to soft,

		occasionally moderately hard to hard, sub-blocky to amorphous, in parts sub fissile grading to shale, highly silty, in parts grading to siltstone, slightly to moderately calcareous, occasionally highly calcareous grading to marl, in parts non calcareous, micaceous, traces of carbonaceous inclusions
	Sembar/ Goru (Undifferentiated)	Goru Formation is mainly consisting of marl in upper part, shale in the middle and limestone in the basal part. Marl is light to medium grey, light greenish grey, occasionally olive grey, firm to soft, dominant soft, in parts very soft, rare moderately hard, sub blocky, slightly washable, in parts grading to (limestone)mudstone. claystone is light grey to dark grey, light greenish grey, olive grey, firm to soft, dominant soft, occasionally moderately hard, amorphous to sub-blocky, dominant amorphous, slightly sticky, silty in parts, slightly to moderately calcareous.
Jurassic	Chiltan	The Chiltan limestones is mostly peloidal/ooidal pack-stone to grain-stone texture containing predominantly ooids and peloids, as well as significant amounts of skeletal debris with minor intra-clasts, large benthonic foraminifera and intra-clasts. Locally, the intra-clasts may be slightly algal in nature suggesting a high energy and shallow water setting.

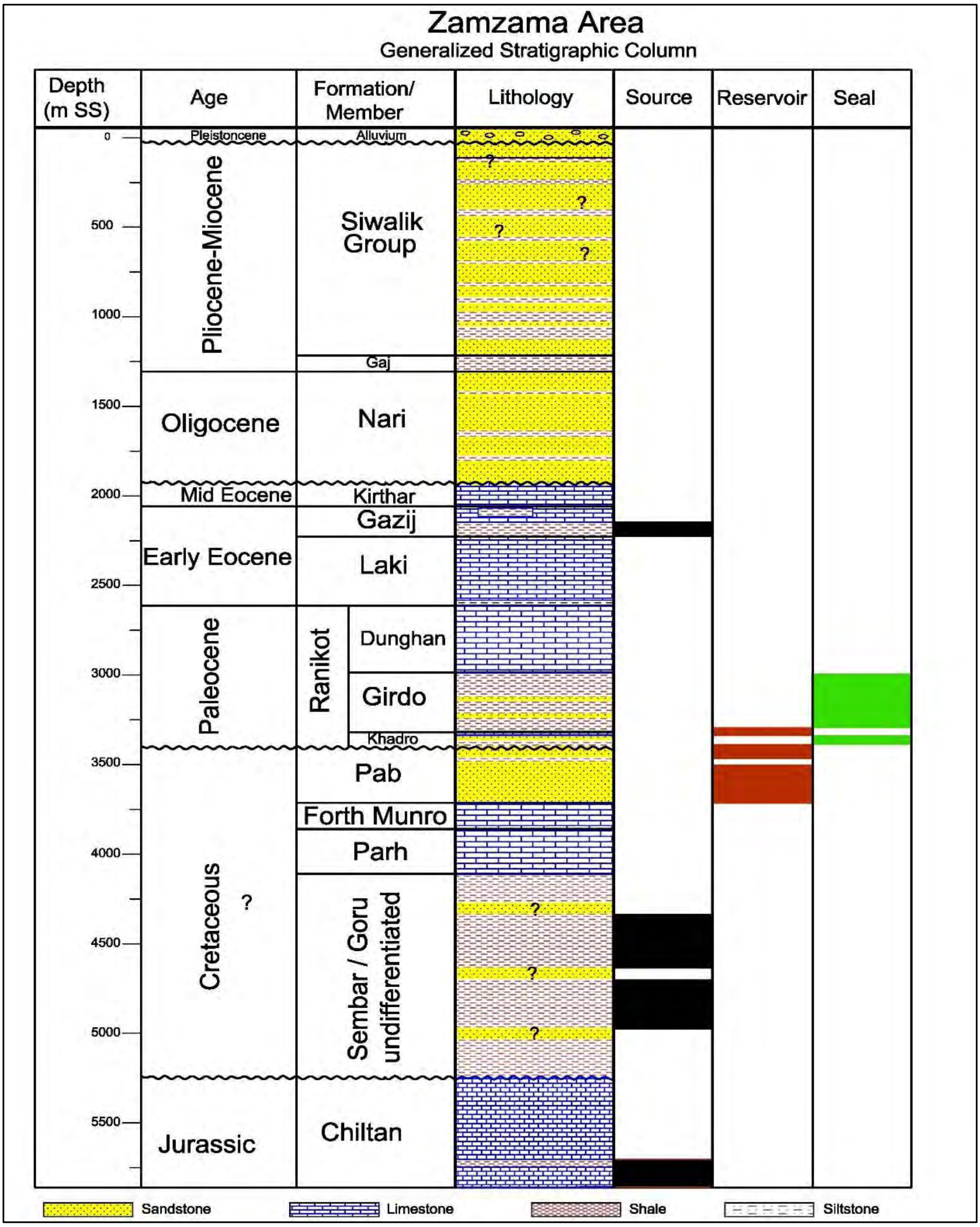


Figure 2.2. Stratigraphic column indicating the petroleum systems present in Zamzama field (OPPL).

CHAPTER 3

PETROLEUM SYSTEM

3.1. PETROLEUM SYSTEM OF ZAMZAMA GAS FIELD

North to South extends of field is filled with approximately 15000m thick molasses of Miocene to Pliocene age. These Siwaliks are gently dipping and thickening toward the axis of foredeep which is in western direction. The Eocene strata is pinching out towards the Jacobabad –Khairpur High, whereas Oligocene strata is missing in the area. The wells in the Mari, Khairpur and Mazarani fields are indicating that Paleocene sequence also dip and thicken in the same direction as the foreland basin sequence. Quaternary alluvium covers the central part of foredeep. The thick deposition of the sediments in the depression may also provide greater influence on the maturation of younger shales especially the Eocene oil shale.

The oldest formation encountered in Zamzama gas field is Parh Formation of Cretaceous age to the youngest formation being Alluvium of Pleistocene as shown in figure 3.1. A major unconformity is also marked between Jurassic carbonates and lower most Cretaceous clastic sediments (Sembar Formation) (Kadri, 1995).

3.1.1. Source

The source of gas in the Zamzama Field is not known but it is thought to be the basinal marine shales of the Lower Cretaceous Sembar and Goru Formations (Wandrey et al., 2004). Reported TOC values from the Sembar Formation in Badin area wells in the foreland portion of the Lower Indus Basin have values ranging from 0.5 to 3.5 percent and averaging about 1.4 percent. A Van-Krevelen cross-plot of pyrolysis data indicates that the organic matter in the Sembar Formation is mainly type-III kerogen, and therefore gas prone; however, additional Wandrey et al. (2004) also indicate the presence of type-II kerogen suggesting that there may be oil generation potential in the Sembar Formation shale.

3.1.2. Generation and migration

Present day the Sembar Formation shales range from thermally immature to over mature depending on location in the source kitchen (Qayyam et al., 2016). Simple 1D maturity plots (Nazir et al., 2012) document that the Sembar Formation shales in the Lower Indus Basin entered gas generation window from the late Miocene to early Pliocene. Hence migration of hydrocarbon in the Zamzama Field is developed post-structuring.

3.1.3. Reservoir

The Pab Formation sandstone is the primary target in the Zamzama wells and in the Kirthar Foldbelt (Eschard et al.,2003; Eschard et al.,2004; Fitzsimmons et al., 2005; Smewing et al., 2002). The Pab Formation sandstone of Late Cretaceous age (Maastrichtian) is overlain by a marked regional unconformity, a response to extensional tectonics associated with the Deccan volcanism. The formation is ~220m in total thickness with an average net to gross of ~60% and is dominated by a stacked sequence of clean quartz-rich sandstones and shale interbeds which record deposition in a prograding fluvial to shore face depositional sequence. Reservoir quality is generally poor to fair, with compaction and quartz cementation reducing intergranular porosities to typically <7%, although local grain coating chlorite cements in the more estuarine-influenced sandstones reduces the effect of both compaction and quartz cementation, locally preserving higher intergranular porosities. In any case, the Pab Formation sandstones are hard and typically result in low drilling RoPs.

The secondary target in the Zamzama field is Khadro sandstone of Paleocene age which are separated from the Pab Formation by variable thicknesses of coastal plain shales and mudstones, often containing soil and calcrete profiles. The Khadro Formation is generally around 50m thick and has an overall low net to gross of 10% to 15%. Khadro Formation sandstones comprise estuarine to shoreface deposits with the shoreface units being cut by tidal channels and therefore are highly discontinuous and variable in distribution. Khadro Formation clastics are resulting from the erosion of Deccan volcanics. During early diagenesis volcaniclastic detritus are highly reactive which resulted in significant grain coating chlorite cements which preserves greater intergranular porosity in the detrital clay-free shoreface and estuarine clastics. Although heterogeneous distribution, these chlorites cemented sandstones can be good quality reservoirs.

3.1.4. Seal

Girdo Formation shales of Paleocene age act as top seal for the Khadro Formation channelized sand bodies. The 2-4m thick top limestone layer of Khadro Formation is very tight; having no porosity and permeability also acts as a intraformational seal for Khadro Sands.

Shales in the basal part of Khadro Formation are acting as seal for underlying Pab Formation (Ahmad et al., 2015).

3.1.5. Trapping Mechanism

Southern Indus Basin was formed as a part of large-scale extensional regime hence normal faults and related horst and graben structures are widely distributed which were mostly formed during Cretaceous age, at the time of deposition of main source and reservoir rocks of Southern Indus Basin. Later the anticlockwise rotation of Indian plate further complexed the already existing extensional structures. This region is characterized by both structural, stratigraphic and their combinational traps (Ahmed et al., 2010).

3.2. STRUCTURAL SETTING OF ZAMZAMA GAS FIELD

The Zamzama field is an elongated, north-south, thrust bounded, anticlinal structure with no surface expression. It is bounded to the east by a major thrust, separating the main hanging wall structure from a smaller footwall structure. It is located on the western edge of the Indus basin, exactly on the leading edge of Kirthar folds and thrust belt. The main reservoir is the Upper Cretaceous Pab sandstones with the lower Paleocene Khadro Formation sandstone as a secondary reservoir.

Seismic data indicate that the thrusted anticline is a relatively simple structure with concentric harmonic folding, which incorporates litho-stratigraphic units from Cretaceous to Pleistocene age.

The newly acquired 3D seismic data clearly reveals the structure of the thrusted anticline at the top Pab level in Zamzama Far North Compartment (ZFNC) illustrates the three-way dip closure bounded by N-S trending thrust fault as shown in figure 3.2. Mapping of the whole field structure indicates that the Zamzama field was originally filled with a spill.

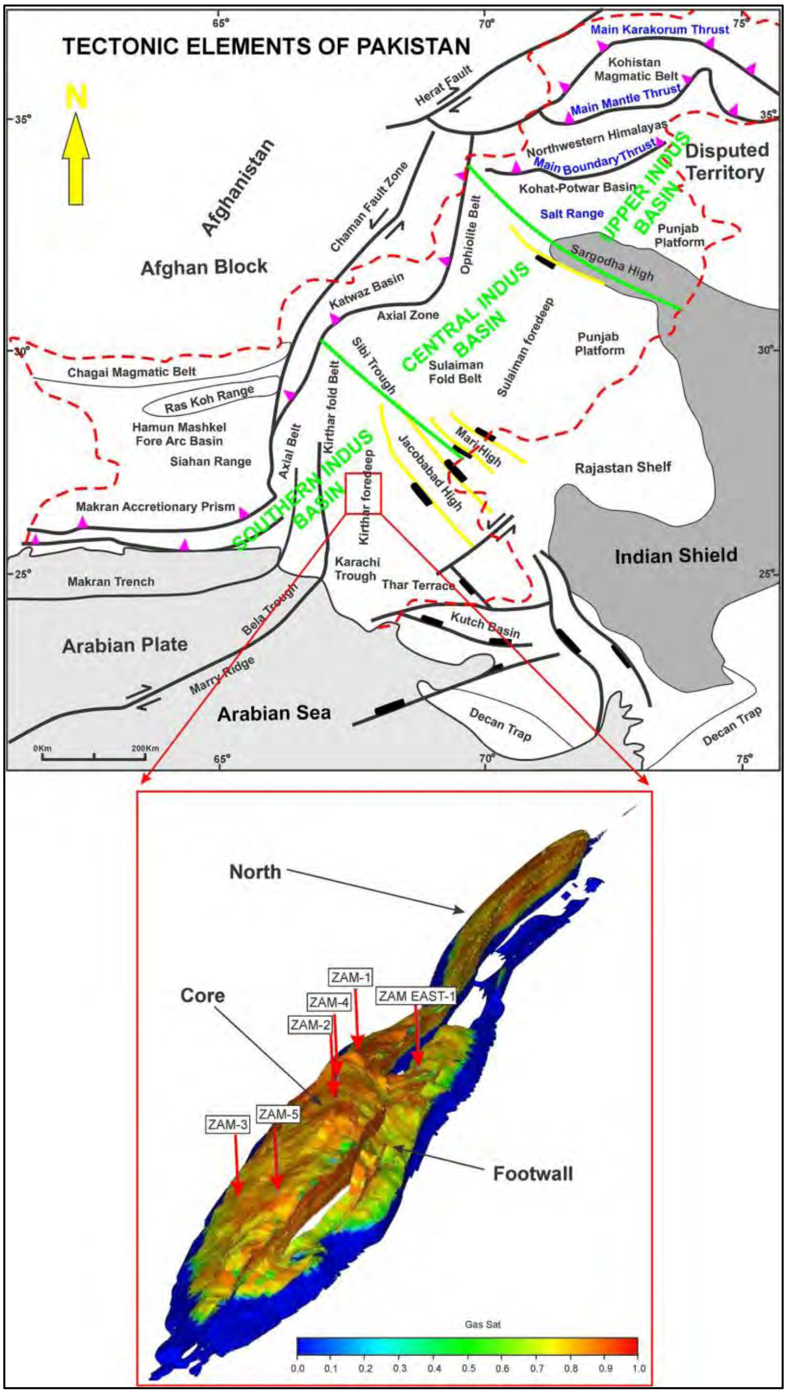


Figure 3.2. Tectonic map of Pakistan and the divisions of Indus Basin (modified after Kadri 1995). The indicated part is showing the Zamzama field along with the structural model (Qureshi,2021).

CHAPTER 4

INTERPRETATION OF 3D SEISMIC DATA

The primary goal of seismic interpretation is to identify horizons and reflectors of various geological formations. Seismic interpretation can provide structural and stratigraphic information. Horizons and faults can be marked for better results during seismic interpretation. The goal of seismic interpretation is to recognize the formation of structures (Naveed et al., 2021). The good seismic interpretation is depended on the quality of acquired seismic data. A clear data with great resolution is condition for the achievement of good results without any inaccuracy. The quality of data determines whether a proper interpretation is possible. The production of satisfying outcomes with no error requires clear data with high resolution. Whether a good interpretation is feasible is determined on the quality of the evidence. To achieve good results with no mistakes, you need clear data with high resolution. The next step is interpretation, the subsurface lithology (Formation) and faults that are formed due to sequence stratigraphy and tectonic forces are interpreted. This leads to marking zones of interest for hydrocarbon potential. These potential zones are marked on the bases of age, formation, and structures such as anticlines and faults which can accumulate and preserve the hydrocarbons over millions of years (Coffeen, 1986). Faults are discontinuities in the rocks that are formed due to compressional and extensional forces produced as result of tectonic plate movements and collisions. To mark faults and to be able to continue a horizon over a fault; along with knowing the type of faults in the region, the interpreter needs to identify the amount of vertical displacement of horizons along the faults. It may be possible that one reflector seamlessly continues over a fault into a different reflector (Bakker, 2002). All Seismic interpretation has been carried out using DSG Geosciences by Halliburton.

4.1. BASIC WORKFLOW OF SEISMIC INTERPRETATION

Following are the major interpretation steps that are taken to interpret the seismic date:

1. Area base map preparation by applying proper projection system.
2. Well-to-seismic tie
3. Horizon and fault Interpretation
4. Creation of structural maps

4.1.1 Area Base Map Preparation

Base map for Zamzama field is prepared with the geographic coordinates of study area along with wells and 3-D seismic data as shown in figure 4.1.

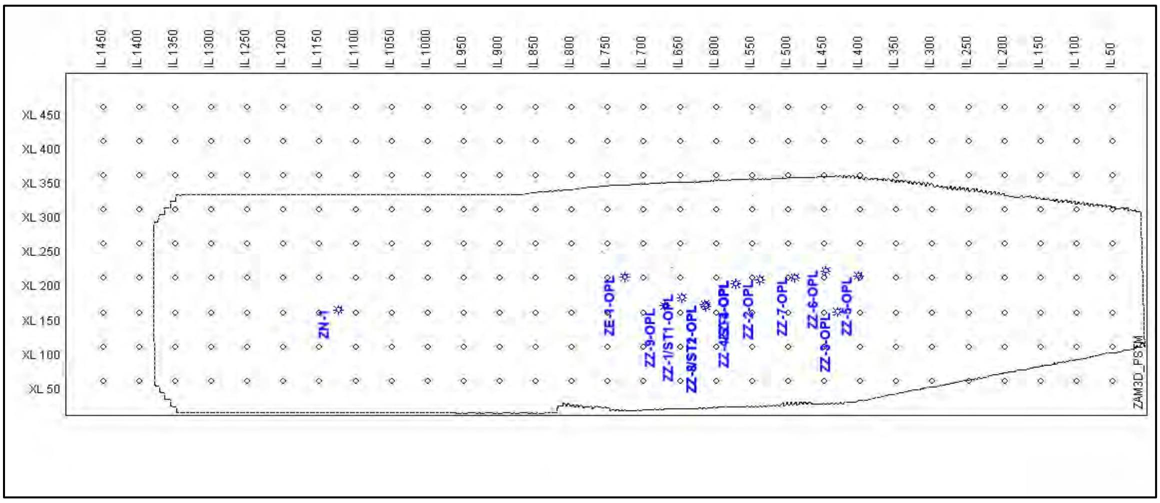


Figure 4.1. Base map of Zamzama Block presenting 3-D geometry of in-lines and crosslines along with eleven wells.

4.1.2 Well-to-seismic tie

Well to seismic tie is an important step in the seismic interpretation. It basically relates subsurface measurements obtained at a wellbore level, measured in depth and seismic data measured in time (David Cho and David Nordin, 2014). In Zamzama PSDM data, well tops data are matching with seismic reflectors to interpret horizons and we used same formation tops for seismic interpretation.

4.1.3 Horizon and Fault Interpretation

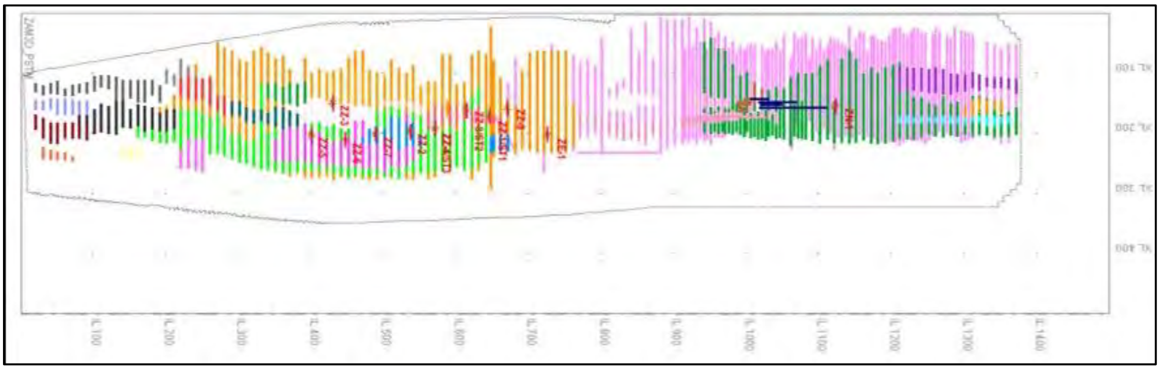


Figure 4.2. Base map showing faults marked in study area.

The main step of interpretation is marking horizons correctly on seismic data. For correct interpretation, it is necessary to have prior knowledge about stratigraphic and tectonic history of an area. Seismic data is correlated to the surface of outcrops and well data. After correlation, reflectors are observed and selected on seismic data. Hydrocarbons are generally present in good reservoirs having higher porosity and permeability. Such horizons generally show good character, continuity and sharp acoustic impedance contrast that can be followed throughout the area. Continuity is good where there is a sharp velocity-density contrast, thus representing a compact lithology.

Faults are interpreted on seismic data where discontinuity or significant displacement are observed in the seismic reflectors. The pattern of the faults is identified by the prior knowledge of the stress regime i.e., compressional, and extensional. Mostly in compressional regime reverse faults are dominant with minor normal faults but in extensional regime we observe normal faulting. Also, previous knowledge of study area helps about the age of the faults so primary and secondary features are easy to understand. Most hydrocarbon fields in Kirthar Foldbelt along with Zamzama block are in periclinal structures that appear to be fault propagation folds or thrust bend folds, modified as flower structures.

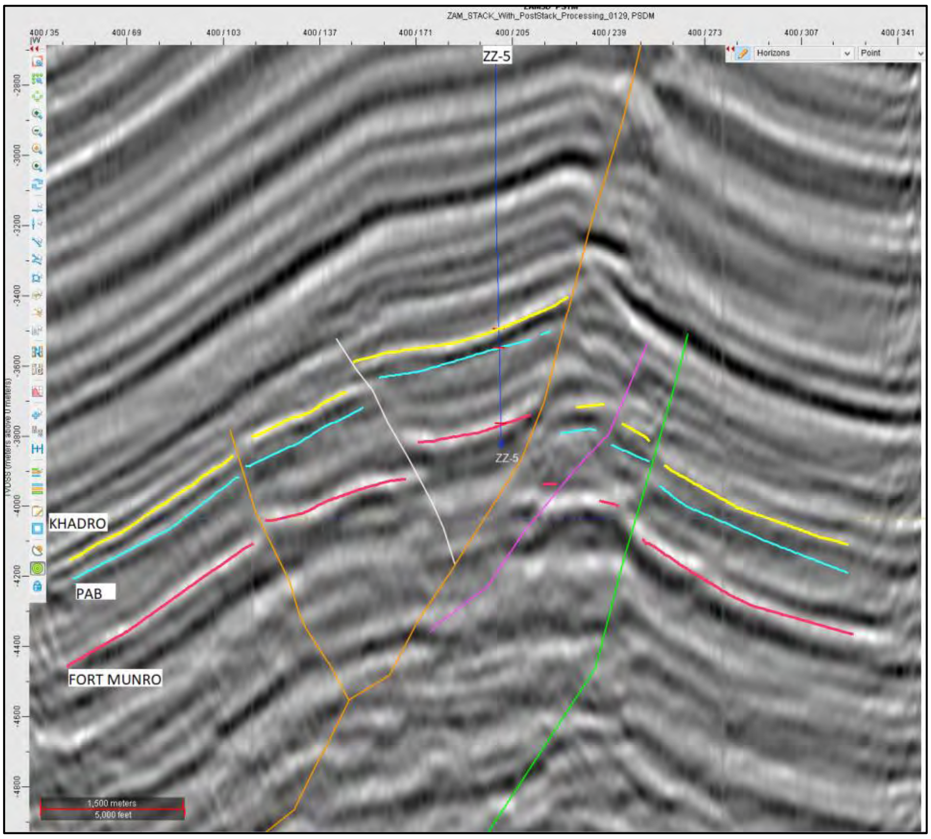


Figure 4.3. Inline 400 is interpreted for targeted horizons using wells tops data of Zamzama-5.

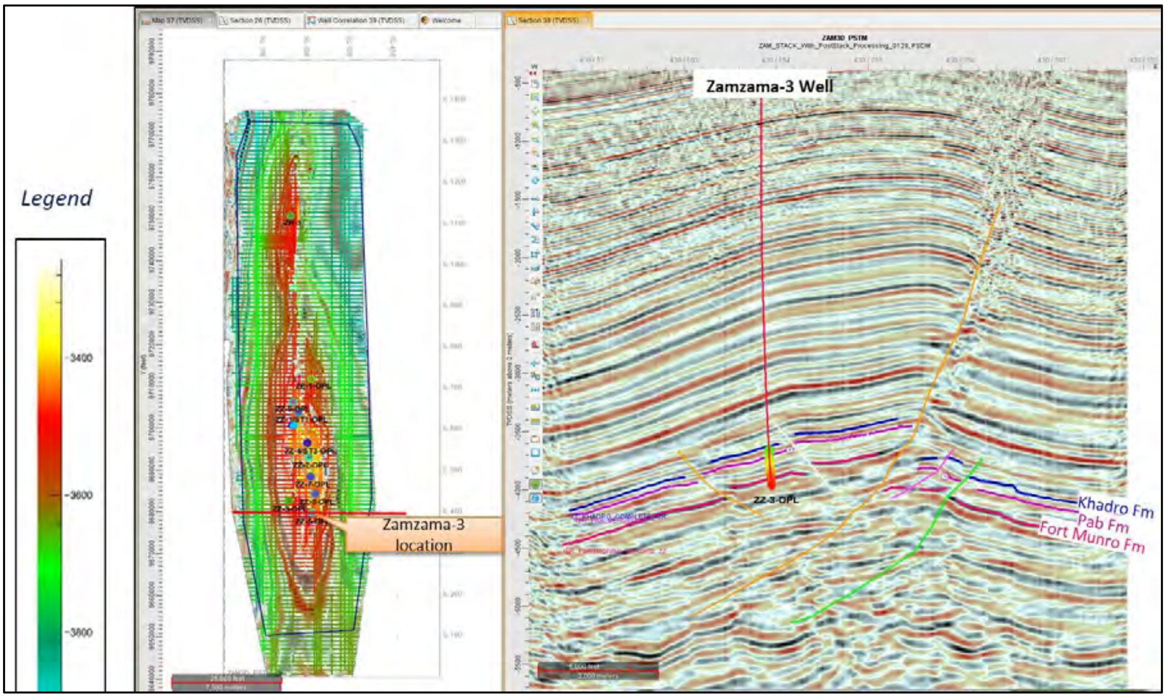


Figure 4.4. Inline is interpreted for targeted horizons using well tops of Zamzama-3 well on seismic section along with interpreted horizon displayed on base map.

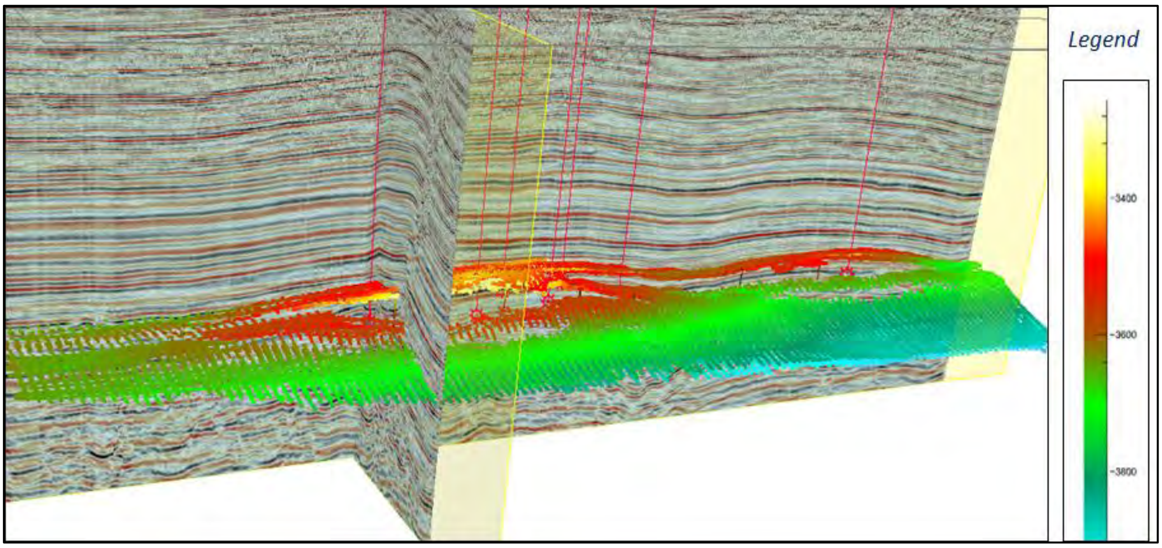


Figure 4.5. 3D view of interpretation of Khadro, Pab and Fort Munro formations.

In this project, three horizons have been interpreted i.e., Khadro Formation, Pab Sandstone and Fort Munro Formation respectively. Horizons are interpreted along an anticline using seismic data. In addition, twenty-eight reverse faults are also interpreted on the seismic data, as shown in figure 4.2. Faults type indicate compressional regime that can be related to the collision of Indian Plate with Eurasian Plate along the Ornach-Nal/ Chaman Transform Fault. Figures 4.3 and 4.4 show interpreted horizons along Zamzama-3 and Zamzama-5.

3-D view of seismic interpreted horizons helps the interpreters get a more accurate view of subsurface which is helpful in identifying zones of interest or to QC the interpreted horizons as shown in figure 4.5.

4.1.4. Creation of Depth Structural Maps

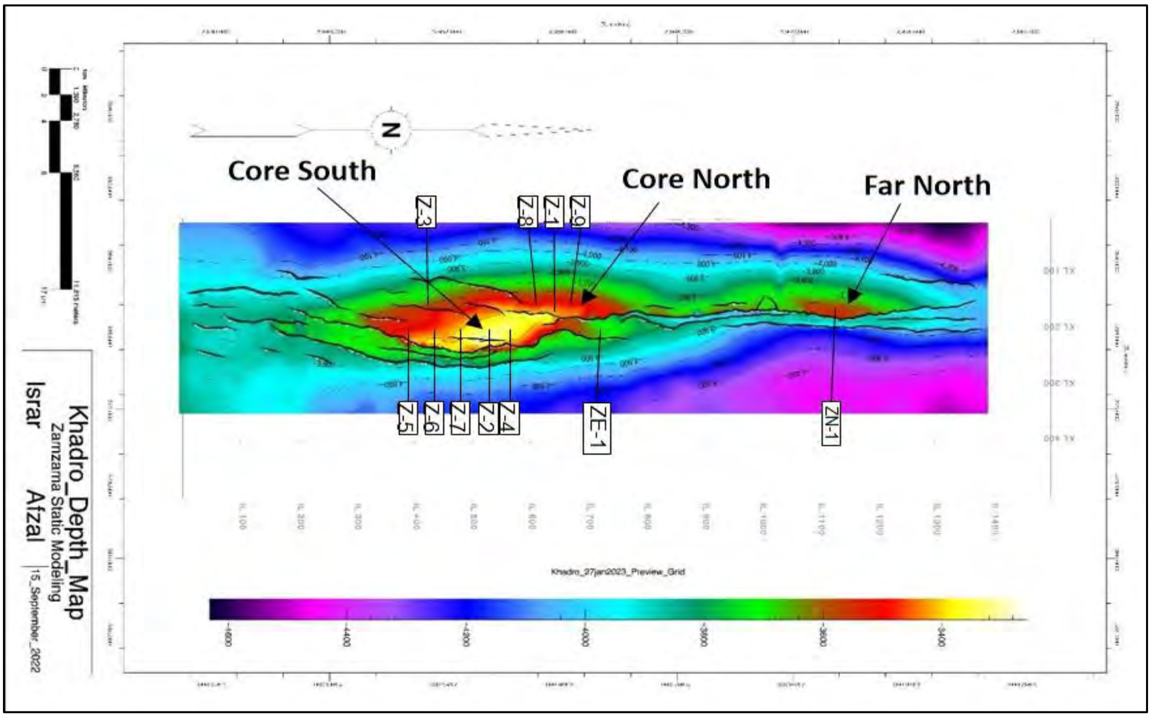


Figure 4.6. Depth structural map of Khadro Formation showing anticlinal structure along with faults.

The final stage of Interpretation is the contour map generation. Contours are lines that join the points of equal time, elevation, or depth. Contour maps are also known as seismic maps and are the final product of seismic interpretation, which is essential to make decisions about where and whether to drill well for oil (Coffeen, 1986).

Three horizons were marked on provided seismic sections that were lying in a depth range of 3000m to 4600m. Color variation in depth grids provided an initial idea about the structural variation along the study area. The low and high depth grid values show structurally shallow and deeper zones as shown in figures 4.6 and 4.7 respectively.

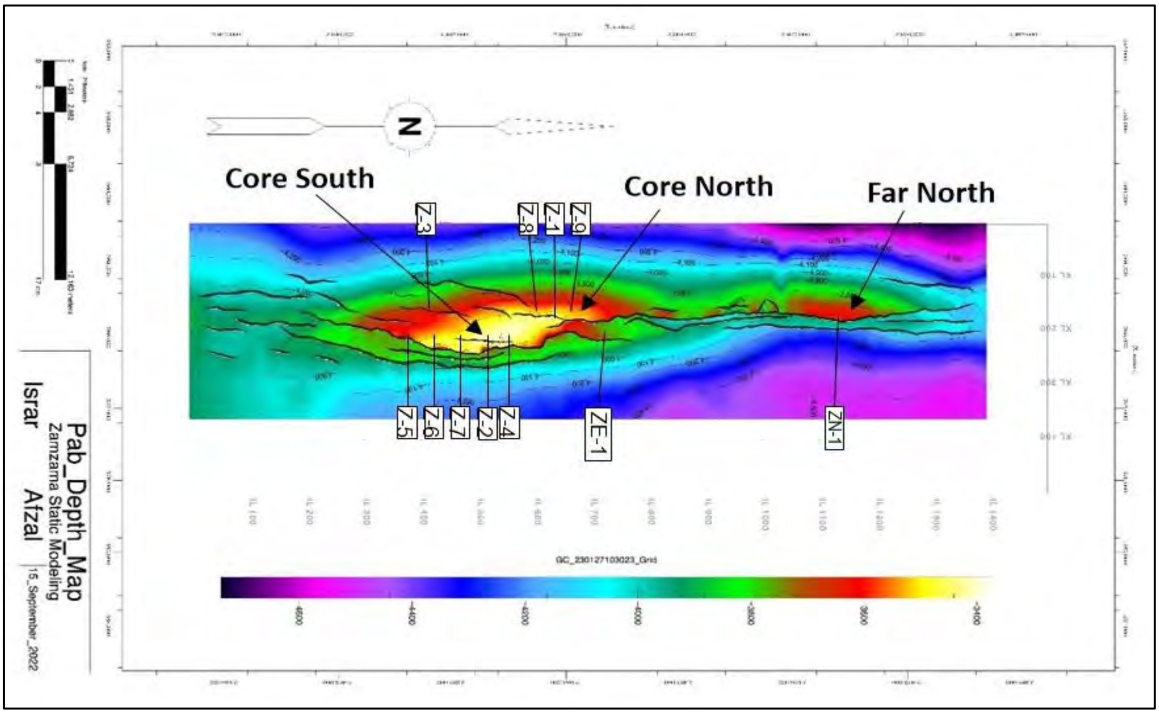


Figure 4.7. Pab Sandstone depth structural maps showing anticlinal structure along with faults.

CHAPTER 5

STRUCTURAL FRAMEWORK AND 3D MODEL BUILDING

The 3D structural framework of the Zamzama block was built using interpreted horizon and faults data. In the framework horizons were used to prepare the seismic surfaces on each line with negligible smoothing. The framework model provides a structural description of the Paleocene Khadro and Cretaceous Pab Formation intervals.

The following steps were used within Zamzama framework for building 3D model.

1. Created fault plane grids from seismic fault sticks.
2. Created top Khadro, top Pab and top Fort Munro surfaces using seismic depth horizon points.
3. Created Khadro and Fort Munro surface intersection lines with fault plane surfaces.
4. Generated Khadro, Pab and Fort Munro fault polygons from surface – fault intersection lines
5. Created top Khadro, top Pab and top Fort Munro surfaces using seismic depth horizon points, well tops and fault polygons.
6. Created Pab intra-reservoir zones using correlation/ sub-zonation's.
7. Created isochore maps between Pab intra-reservoir structure maps.
8. Built Parent Child faults relationship model.
9. Built Structural model.
10. Structural models are used to prepare cellular static model grid, which consists of total 11.5 million cells.

The input data for the framework modeling consisted of 3 primary seismic depth maps (Top Khadro, Top Pab and Top Fort Munro), well tops from 11 wells, and seismic fault polygons and fault sticks for each depth map. The Khadro and Fort Munro seismic surfaces serve as the top and bottom of the model interval. The seismic depth surfaces were constructed individually by major thrust block area (i.e., Hanging wall or Foot wall) to properly grid areas of overlap along the main thrust fault that subdivides the structure.

5.1. Framework Surface Building

The first step in the framework building process was to delineate the model area of interest (AOI) polygon. The AOI polygon serves as the model boundary and was drawn to capture the maximum edge of the reservoir limits possible during structural uncertainty modeling and allow for aquifer cells as shown in figure 5.1.

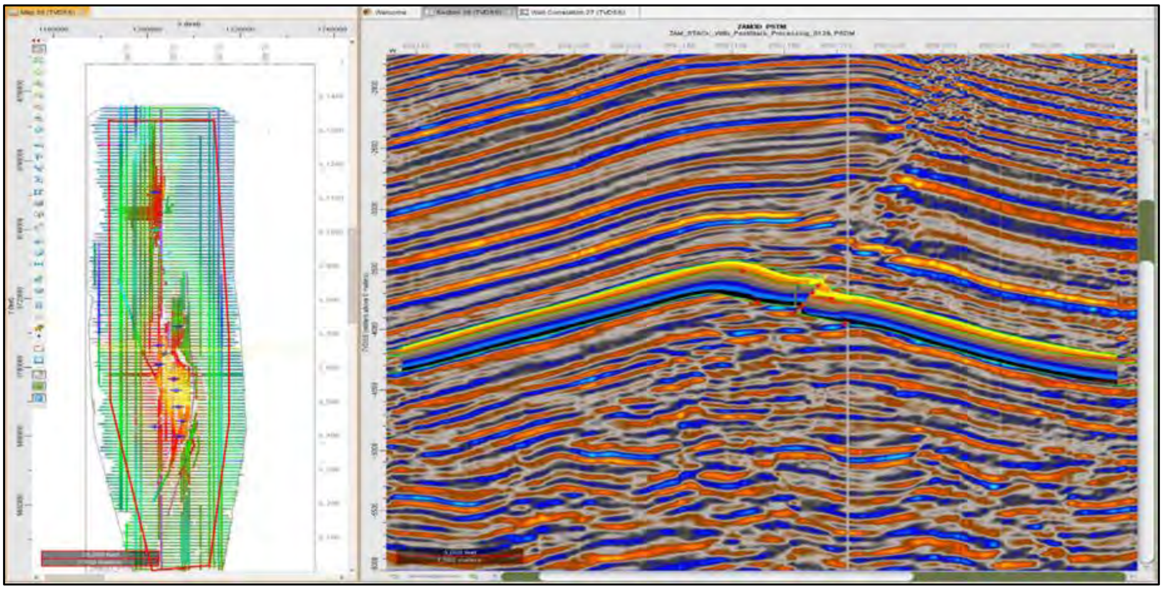


Figure 5.1. Seismic horizons used to prepare structure model along with AOI map.

5.2. Depth Map Construction

The final Khadro, Pab and Fort Munro horizons are used in modeling to build structure model. The seismic horizons data is further integrated with formation tops to make sure that surfaces are at exact depth. The goal of this process is to:

1. Create final seismic structure surfaces that tie to all wells.
2. Create residual depth tie data per well

5.3. Conformable Mapping and Sub-zonation's

The final step in the structure surface building process involved conformable mapping in DSG to prepare zones using well-tied structure maps. The conformable mapping process uses the overall gross isochore between the seismic depth maps and the individual subzone grid thickness values as a guide to proportion the seismic map defined intervals into subzones.

5.4. Fault Model

The faults model shown in figure 5.2 was built with the following workflows:

1. Imported seismic interpretation data of all three horizons and 28 faults into Structural Framework Builder module.
2. Prepared faults parent child relationship model
3. Faults relationship QC
4. Prepared final corrected relationship and used same to build 3D static model.

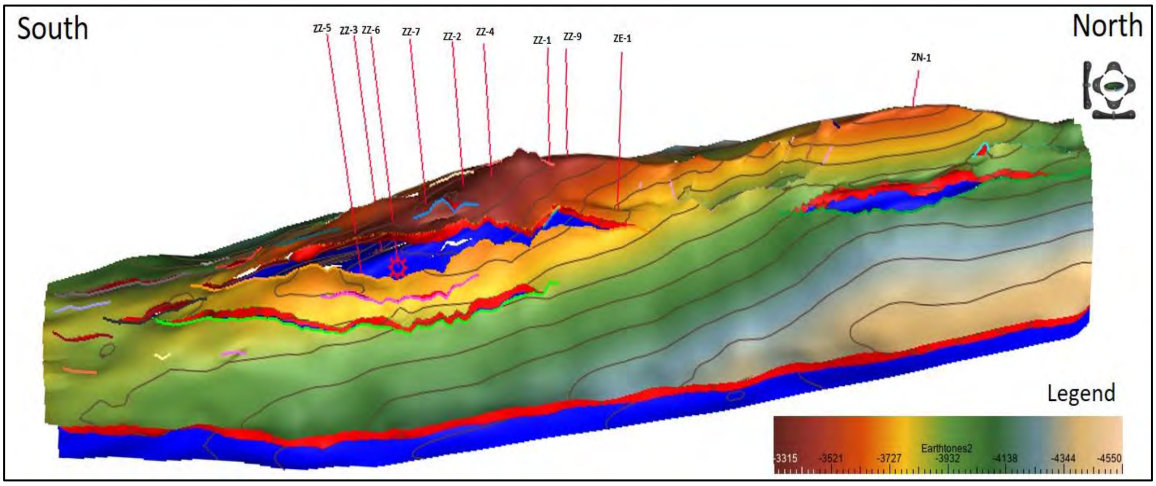


Figure 5.2. The Zamzama structural model from west showing faults modelled.

5.5. 3D Grid

A total of 17 and 70 layers were prepared for Khadro and Pab formations respectively. The layers in the stratigraphic model were prepared using a proportional method for maintaining equal thicknesses. The purpose of small layers for Khadro Formation was to incorporate 3/4 meters small productive sand channel in the model.

Zamzama 3D grid as shown in figure 5.3, was built by using above mentioned structural framework. Zamzama 3D grid is consist of X:50m Y:5m and Z:2.96m length cells. Total number of the cells are 11.5m in the 3D grid. The same grid was later used for the post processing.

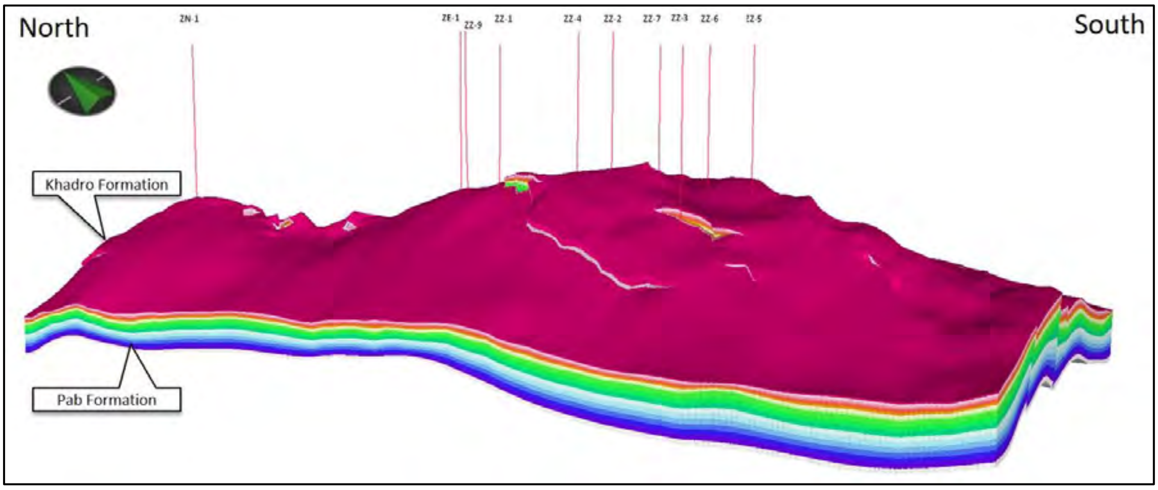


Figure 5.3. 3D grid of Zamzama block from west.

CHAPTER 6

WELL CORRELATION AND PETROPHYSICAL ANALYSIS

The main producing formation in Zamzama Field is Cretaceous Pab Formation which is primary objective of all 13 drilled wells. Later Khadro also tested which proved to be secondary target in Zamzama Field. Out of these 13 wells, 11 wells (Zamzama-1, Zamzama-2, Zamzama-3, Zamzama-4, Zamzama-5, Zamzama-6, Zamzama-7, Zamzama-8, Zamzama-9, Zamzama-North-1 and Zamzama East-1) have been incorporated in the study. Substantial pressure difference of Pab and Khadro leads to complete both formations to be completed separately. Simultaneous mineral model approach was used for petrophysical interpretation of all wells shown in table 6.1.

6.1. WELL CORRELATION

Wells correlation was carried out for detailed evaluation of facies trends and production behaviours of wells. Both Khadro and Pab formations were further subdivided into 6 zones. Figure 6.1 is showing stratigraphic representation of all Zamzama wells hanged on top Pab Formation and figure 6.2 showing the structural correlation of wells indicating the upward water movement with the life of the field.

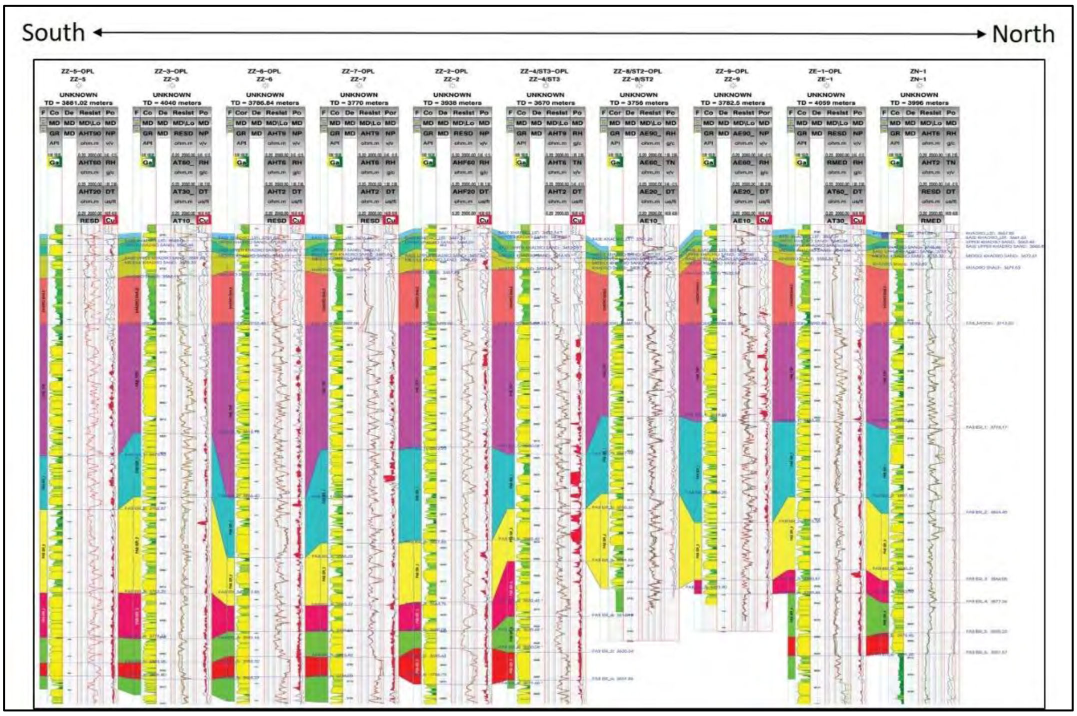


Figure 6.1. Wells correlation showing trends of lithofacies from South to North.

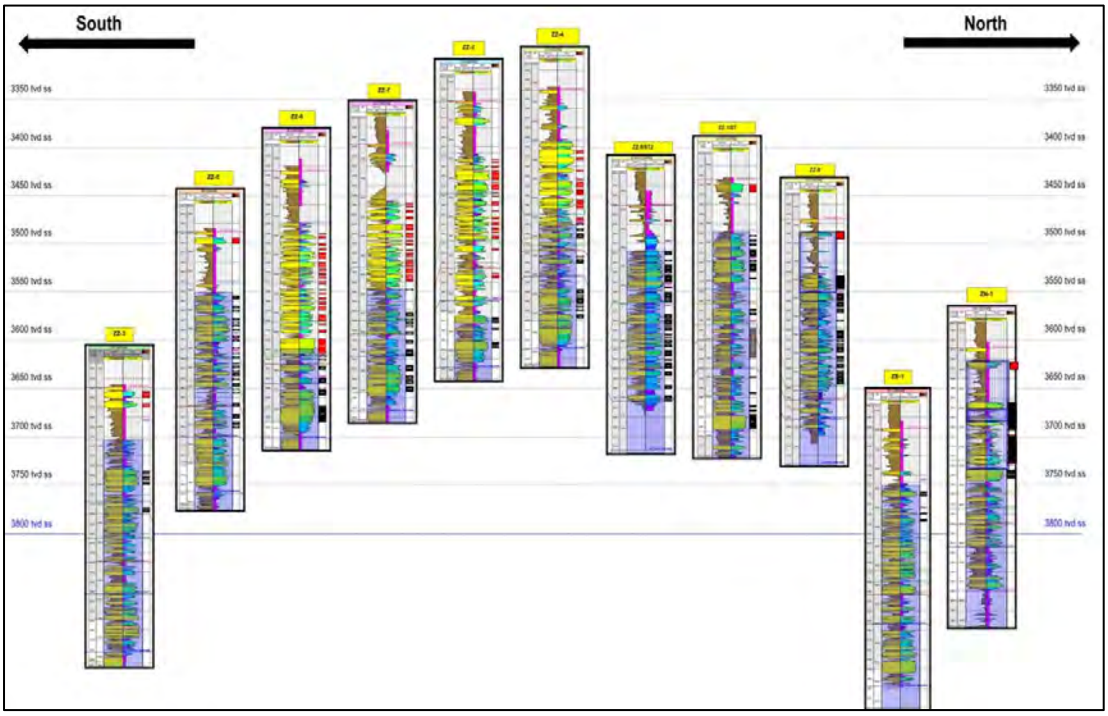


Figure 6.2. Highlighted blue area is showing water producing zones in each well at later stages.

6.2. INTERPRETATION MODEL

Sandstones of the Khadro Formation are described as shallow marine to shoreface, mineralogically immature, lithic arenites. They are fine to occasionally medium grain and moderate to well sorted. Sandstones of the Pab Sandstone are described as alluvial to coastal plain, mineralogically mature, quartz arenites with minor amounts of feldspar. Grain size varies from silty to very coarse. Compaction is high with the main diagenetic features being quartz overgrowths, weakly replacive ankerite (ferroan dolomite) cements and pore plugging iron-rich kaolinite.

6.3. FORMATION WATER SALINITY

Around 23.00 ppm water salinity was analysed from produced water of Pab Formation and almost ~17ppk water salinity was analysed from produced water of Khadro Formation. A strongly positive SP over the Khadro Sand in Zamzama-1 well which was drilled with Water Based Mud, supports the use of this value as rest of the wells have been drilled with Oil Based Mud due to borehole stability issues in overlying Girdo Shale.

6.4. PERMEABILITY ESTIMATION

Permeability was estimated using the Herron equation (Herron, 1987). The Herron equation for estimating intrinsic permeability relies on predetermined assumptions concerning the relationship between permeability, porosity. Porosity, textural maturity and framework grain abundances define a maximum permeability curve as a function of porosity. The clay mineral abundances act to reduce the observed permeability from this maximum permeability curve.

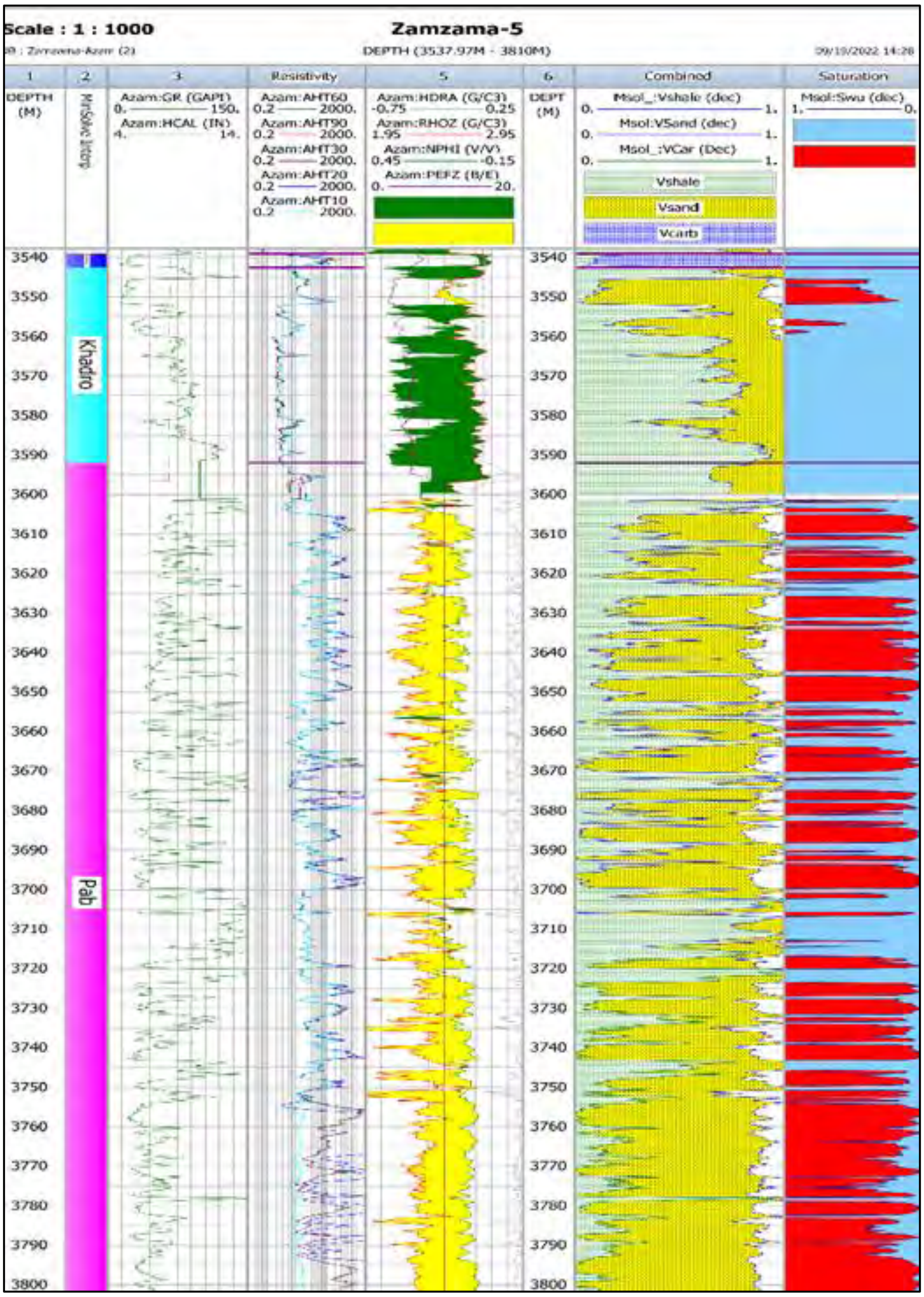


Figure 6.3. The petrophysical Interpretation of Zam-5 well.

6.5. NET PAY CUTOFFS

The most realistic cut-offs approach was used to compute the reservoir properties of both Khadro and Pab formations. Net reservoirs are consisting of <55% SW, <30% VCL and >4% effective porosity.

Using above mentioned cut-off parameters, detailed petrophysical interpretation was carried out for all wells. An exemplary Figure 6.3 showing the petrophysical interpretation of Khadro and Pab formations for Zamzama-5 well.

Table 6.1. Reservoir parameters of each well calculated using simultaneous mineral model.

Well	Zone	Interval	Gross (m)	Net Pay (m)	N/G (%)	Porosity (%)	S_w (%)
ZZ-1	Khadro	3470-3530	60	8	13	6	48
	Pab	3530-3850	320	178	0.55625	8	49
ZZ-2	Zone	Interval	Gross (m)	Net Pay (m)	N/G (%)	Porosity (%)	S_w (%)
	Khadro	3400.0-3454.0	54	6.4	12	9	27
	Pab	3454.5-3678.0	223.5	121.7	55	9	20
ZZ-3	Zone	Interval	Gross (m)	Net Pay (m)	N/G (%)	Porosity (%)	S_w (%)
	Khadro	3701-3754	53	10.8	20	7	20
	Pab	3754-3973	219	153.2	70	7.2	43
ZZ-4	Zone	Interval	Gross (m)	Net Pay (m)	N/G (%)	Porosity (%)	S_w (%)
	Khadro	3391-3441	50	5.9	12	5	49
	Pab	3441-3652	211	149	70	7.3	30
ZZ-5	Zone	Interval	Gross (m)	Net Pay (m)	N/G (%)	Porosity (%)	S_w (%)
	Khadro	3539-3592	53	7.9	15	8.4	18
	Pab	3592-3810	217	139	64	7	151

ZZ-6	Zone	Interval	Gross (m)	Net Pay (m)	N/G (%)	Porosity (%)	S_w (%)
	Khadro	3473-3527	54	n/a	n/a	n/a	n/a
	Pab	3527.3 - 749.1	221.8	165.9	74	8.6	35.3
ZZ-7	Zone	Interval	Gross (m)	Net Pay (m)	N/G (%)	Porosity (%)	S_w (%)
	Khadro	3444.4-3503	59	n/a	n/a	n/a	n/a
	Pab	3503.1 - 715.6	212.5	159	74	7.5	43.1
ZZ-8	Zone	Interval	Gross (m)	Net Pay (m)	N/G (%)	Porosity (%)	S_w (%)
	Khadro	3515.4 – 3560	53.6	n/a	n/a	n/a	n/a
	Pab	3560 -3730	170	135	77	8.8	52.9
ZZ-9	Zone	Interval	Gross (m)	Net Pay (m)	N/G (%)	Porosity (%)	S_w (%)
	Khadro	3533.6 – 3560	55	n/a	n/a	n/a	n/a
	Pab	3588 -3768	180	119.6	64	7.5	42.4
ZZ East-1	Zone	Interval	Gross (m)	Net Pay (m)	N/G (%)	Porosity (%)	S_w (%)
	Khadro	3738.4-3794.9	56	6.6	12	5.4	65
	Pab	3794.9-4005.1	212	148	70	7	34
ZZ North -1	Zone	Interval	Gross (m)	Net Pay (m)	N/G (%)	Porosity (%)	S_w (%)
	Khadro	3657.8-3712	54.2	4.8	8	6	74
	Pab	3712-3908	196	120	60	6	32

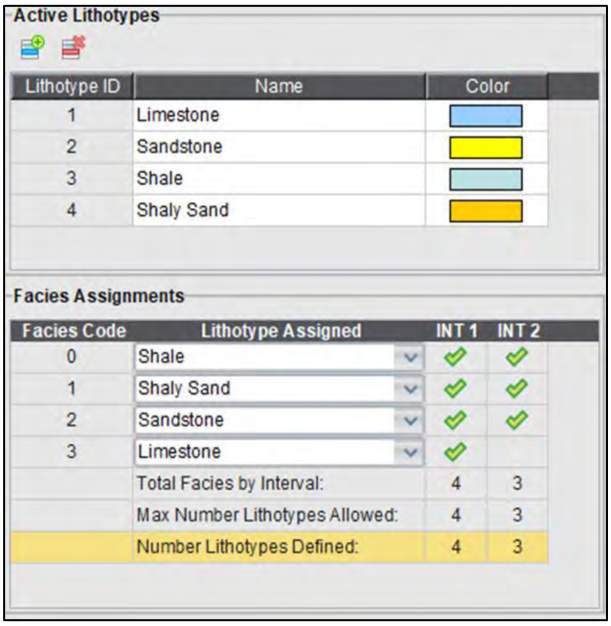
CHAPTER 7

FACIES MODELLING

Four lithofacies (limestone, sandstone, shaly sand, and shale) are defined for Paleocene Khadro Formation and three lithofacies (sandstone, shaly sand, and shale) are defined for Cretaceous Pab reservoir. Tight limestone at the top interval of Khadro Formation is acting as a seal for Khadro Sands in the model. All lithofacies distributed in the layered grid and QCed with wireline and core data. The facies model used as template for population of petrophysical properties as shown in figures 7.1 and 7.2.

Following are the input data used for facies modelling.

1. A 3D structural framework.
2. Stratigraphic layering for each reservoir interval.
3. 3D geocellular stratigraphic grid.
4. A blocked well log data based on the geocellular grid.
5. Proportion map for each interval.



Active Lithotypes

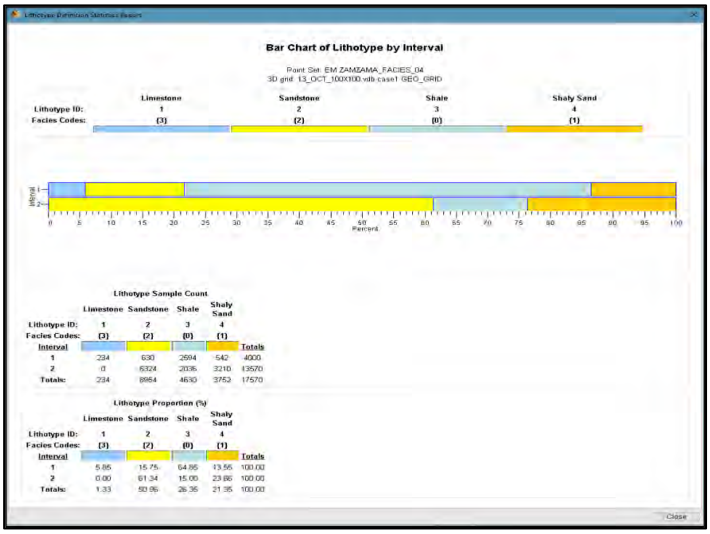
Lithotype ID	Name	Color
1	Limestone	
2	Sandstone	
3	Shale	
4	Shaly Sand	

Facies Assignments

Facies Code	Lithotype Assigned	INT 1	INT 2
0	Shale	✓	✓
1	Shaly Sand	✓	✓
2	Sandstone	✓	✓
3	Limestone	✓	
	Total Facies by Interval:	4	3
	Max Number Lithotypes Allowed:	4	3
	Number Lithotypes Defined:	4	3

Figure 7.1. Four different facies are assigned to Zamzama static model based on lithologies.

Facies were distributed in the grid using Sequential Indicator Simulation Methodology. SIS requires to describe the spatial continuity in terms of a variogram. These methods are very flexible and can also accommodate secondary data but require a variogram of the secondary data and its relationship to the primary data. Figure 6.3 shows the channel sand facies in Khadro Formation based on assigned facies. Facies model generated are shown in figures 7.4 and 7.5.



Lithotype Sample Count

	Limestone	Sandstone	Shale	Shaly Sand	
Lithotype ID:	1	2	3	4	
Facies Codes:	(3)	(2)	(0)	(1)	
Interval					Totals
1	234	630	2594	542	4000
2	0	6324	2036	3210	13570
Totals:	234	8954	4630	3752	17570

Lithotype Proportion (%)

	Limestone	Sandstone	Shale	Shaly Sand	
Lithotype ID:	1	2	3	4	
Facies Codes:	(3)	(2)	(0)	(1)	
Interval					Totals
1	5.85	15.75	64.85	13.55	100.00
2	0.00	61.34	15.00	23.66	100.00
Totals:	1.33	50.96	26.35	21.35	100.00

Figure 7.2. Bar chart of lithotype used for facies modelling.

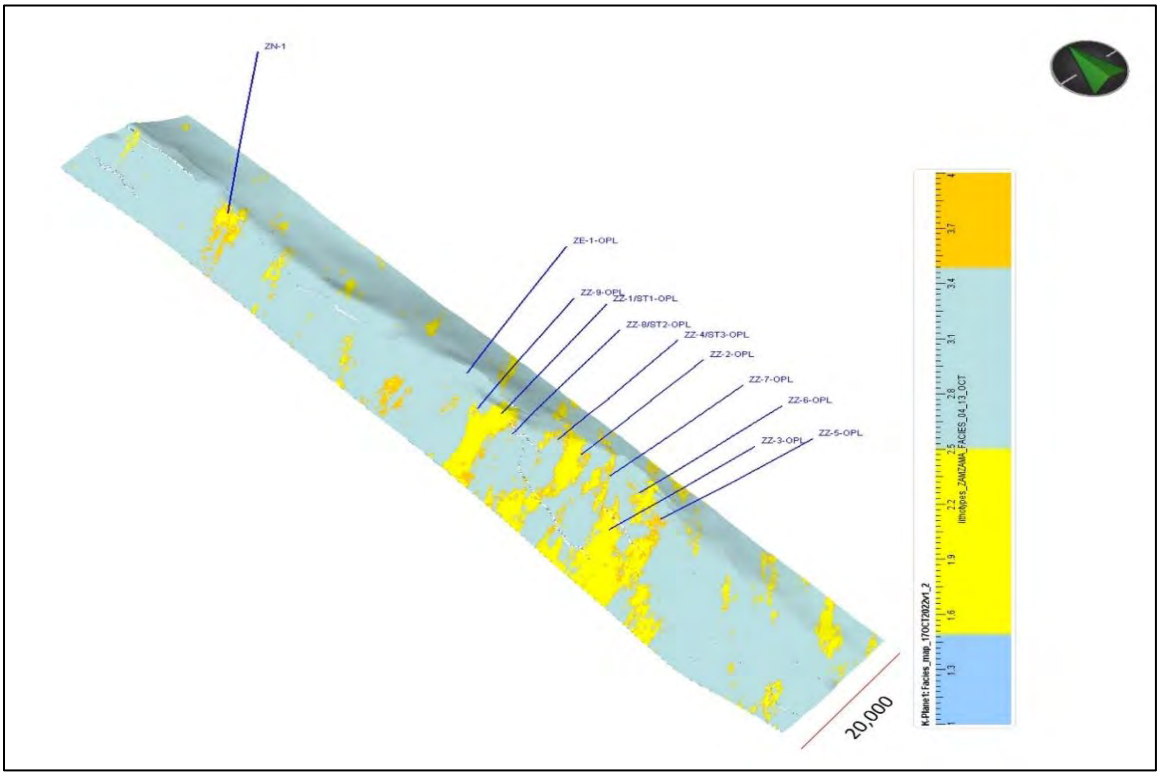


Figure 7.3. The channelized sand bodies inside the Khadro shales based on facies defined.

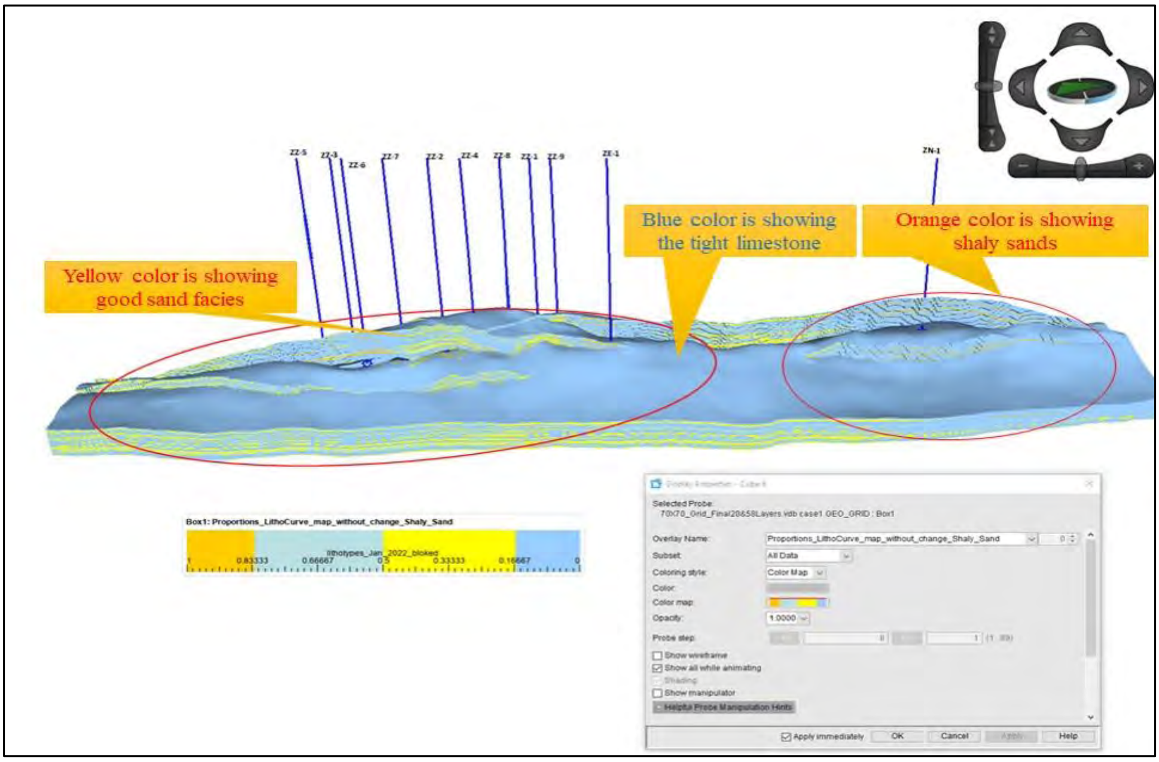


Figure 7.4. The Facies model of Zamzama block from East.

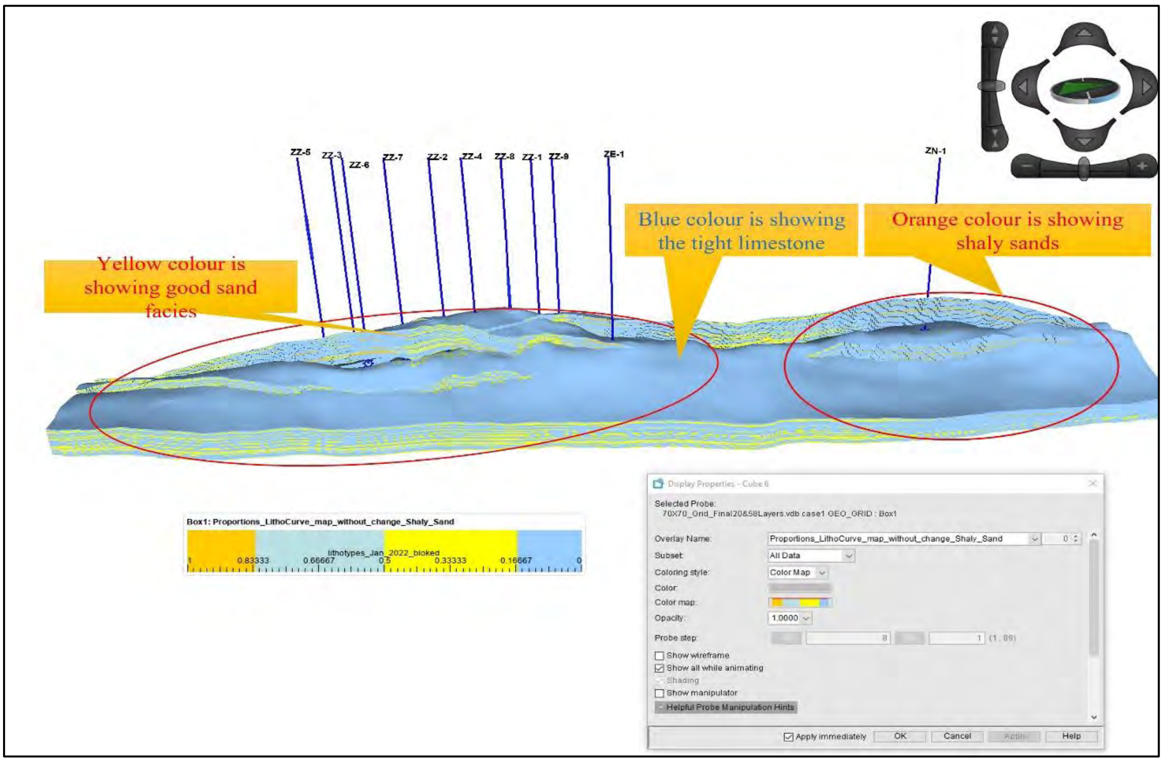


Figure 7.5. The facies model of Zamzama block from West.

CHAPTER 8

PETROPHYSICAL PROPERTY MODELLING

After facies modelling and simulation, a petrophysical property modelling was carried out to populate petrophysical properties (porosity, permeability, water saturation, etc.) using a blocked point set that resides on the 3D grid. Petrophysical modelling is constraining the facies modelling.

8.1 POROSITY AND PERMEABILITY MODELLING

The effective porosity in the Zamzama well are rages from 0% to 17%. Prepared blocked point set for porosity along with the association of permeability as a secondary pointset for residing in the 3D grid. Previously prepared facies model was used for populating the porosity in the 3D- Grid. 5 different realizations were run for the porosity distribution for each interval by using kriging method.

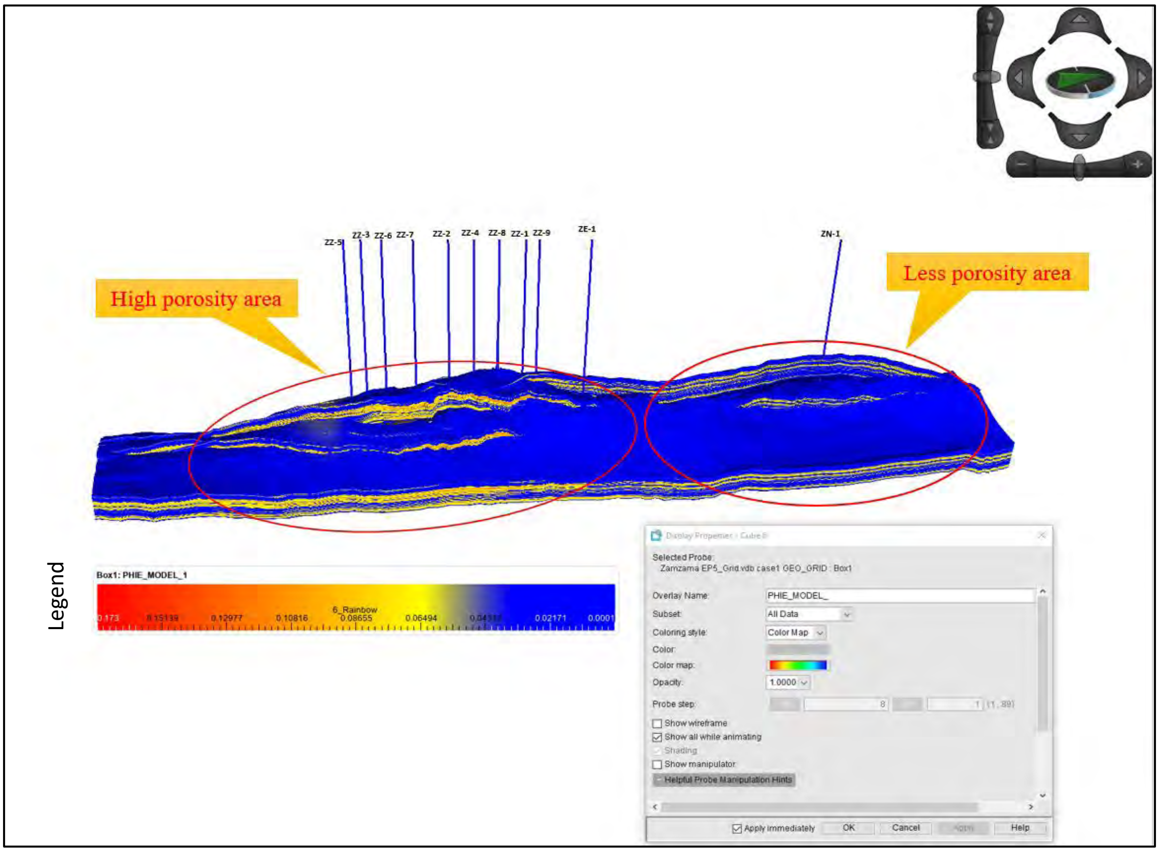


Figure 8.1. 3D porosity model of Zamzama block.

The porosity model in figure 8.1 shows that porosities are improving from north to south in the Zamzama block due to decrease in the clay content with in Khadro and Pab formations from north to south. Hence our well data is also indicating that facies of Pab Formation in the Zamzama North-1 well are less productive compared to Zamzama main compartmental wells. The producing channelized sand of Khadro Formation is also not present in the Zamzama North-1 well.

8.2 SW MODELLING

SW modelling performed using Sw curve pointset. Sw distributed in the model from free water level. The last closing contour -3800m is taken as initial gas water contact for hydrocarbon saturation modelling as shown in figure 8.2. The software default SHF equation used to carry out this step.

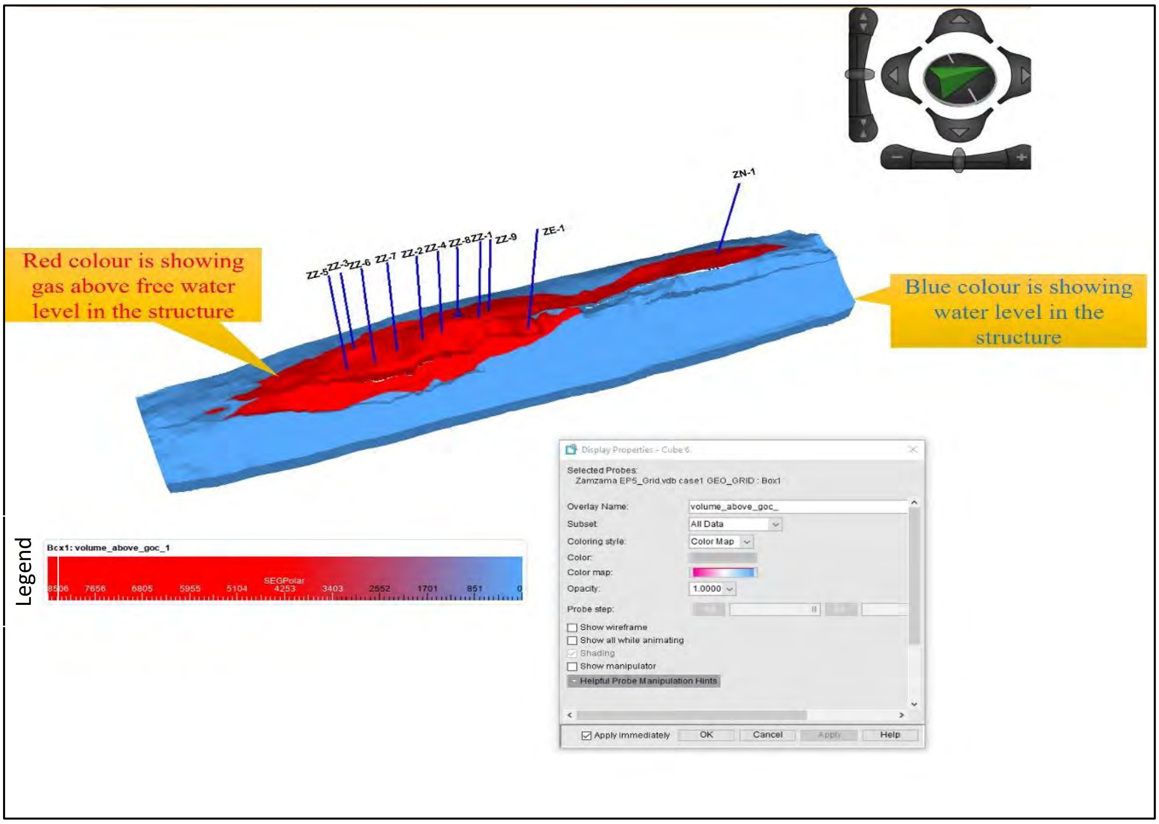


Figure 8.2. The volume above GWC in Khadro Formation.

The above figure 8.2. is clearly indicating that the volume of gas in the main compartment is much higher than the northern compartment. Hence wells in the main compartment also produced higher than Northern compartment.

8.3 POST PROCESSING

Zamzama static model post processing shows that total 2 TCF GIIP are present in the field. Due to higher porosity and permeability in the field, the recovery is ~90 percent. As per ~90 percent recovery factor, 1.8 TCF recoverable gas volume are present in the structure and so far, OPPL has produced around 1.7 TCF gas from the Zamzama field.

The current Zamzama production is ~10 MMSCFD which is at tail end and less than 0.1 TCF recoverable gas is remaining in the field.

CONCLUSION

Following are the conclusion of the study.

1. 3D Static model of Zamzama field is built using geological, geophysical and petrophysical data.
2. Facies and petrophysical properties are distributed to model using kriging method.
3. In the Zamzama block facies are changing toward the South i.e., Porosity and hydrocarbon saturation in main/southern compartment is much higher than northern compartment.
4. No significant thick shale bed is present within the Pab Formation which can act as seal barrier within the Pab sands.
5. No isolated compartment is present in the field.
6. Khadro Formation is producing from shoreface/channelized sand bodies, these shoreface/channelized sands are present in Zam-1, Zam-3 and Zam-5 wells; and in the remaining wells these facies of Khadro Formation are not promising.
7. More than 2 TCF GIIP with 1.8 TCF recoverable gas volumes are calculated from Geocellular model. So far, OPPL has produced around 1.7 TCF gas from the Zamzama field and 0.1 TCF gas is remaining in the field. The gas recovery of Zamzama Field is ~90%.

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All the geological (well locations, Formation tops, wireline logs) & geophysical (3D seismic cube) data along with the location maps, stratigraphy and tectonic history was provided by the OPPL.