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Hydrocarbon Reservoir Evaluation and Fault Seal Analysis of Balkassar Area, Potwar Sub Basin, Pakistan

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ABSTRACT

Balkassar oilfield is one of the major hydrocarbon producing field in Potwar Plateau, Upper Indus Basin, Pakistan. This field has been producing oil and gas from fractured carbonate deposits of Eocene and Paleocene age. In order to delineate the hydrocarbon potential of the Balkassar area, 2D seismic interpretation and petrophysical analysis has been carried out and is represented in the current study using five seismic lines and one well. Balkassar field is geographically located in central part of Potwar Sub-basin. Geologically it is located in Himalayan foreland fold and thrust belt, which is dominated by thrusting and folding features. The salt tectonics is responsible for the formation of structural traps in Balkassar area. The direction of deformation is in NW-SE direction. The main reservoir formations of Balkassar area are Chorgali Formation and Sakesar Limestone which are charged by shales of Patala Formation of Paleocene age. Formations were identified on the seismic section on the basis of time-depth chart and well tops. Petroleum trap is a structural trap where major thrust and back thrust bound the anticline, and sealing impact is provided by both clays of Murree Formation and faults which is further confirmed through fault seal analysis (Allan diagram). One reservoir zone has been identified in Chorgali Formation using petrophysical analysis, which indicates effective porosity of 3.08%, water saturation 40.5% and hydrocarbon saturation 59.5%. Based on the statistical analysis performed, it is concluded that the Chorgali Formation is more economically promising as compared to Sakesar Limestone. Volumetric reserves calculation is done to estimate the volume of original oil in place (OOIP) for the Chorgali Formation, which comes out to be 18.6 Million Barrels for P90 case.

1. Introduction

This study attempts to decipher the hydrocarbon reservoir evaluation of the Balkassar area using structural and petrophysical interpretation as well as fault seal analysis and volumetric reserves estimation. Interpretation of seismic image data involves a certain degree of knowledge in structural geology, stratigraphy and tectonic settings, as well as an understanding of the physics behind the creation of a seismic image. Interpreters must use knowledge and understanding to produce a consistent solution that satisfies not only all available data, but also confirms expected target in subsurface [1-3]. Interpretation of faults in seismic images are used for the creation of geological models of the subsurface. The Potwar sub-basin, one of the oldest hydrocarbon provinces, lies in the western foothills of the Himalayas in northern Pakistan. Geologically, it is a component of Upper Indus Basin, Pakistan. The study area lies in district Chakwal of Punjab Province (32° 56' 20" N, 72° 40' 5" E) as shown in Fig. 1. Balkassar is an exclusive Development and Production (D&P) lease of Pakistan Oilfields Limited (POL) located in Southern Potwar Plateau Zone (SPPZ). It was discovered in 1945 by Attock Oil Company. 2D seismic data was acquired in Balkassar field by Oil and Gas Development Company Limited (OGDCL) in 1980 and processed in 1981. Exploratory well, Balkassar-Oxy-01 drilled in 1981 was utilized in this study.

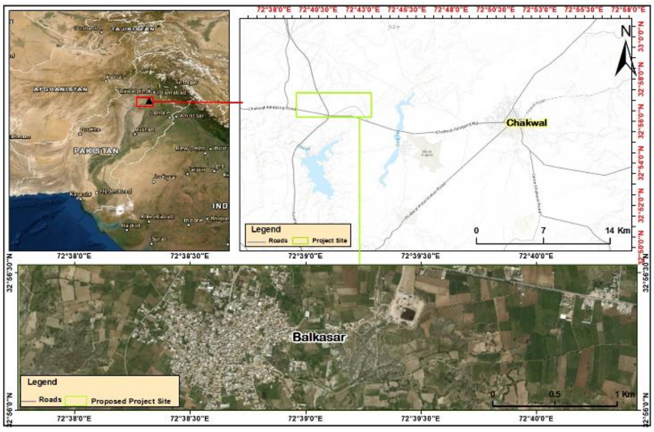

Fig. 1: Location map and satellite image of Balkassar area showing the location of Balkassar-Oxy-01 well (Generated in Arc GIS 10.4).

2. Geological and Tectonic Setting of the Study Area

Intense Himalayan collisional orogeny resulted in the formation of Potwar sub-basin. It represents the thrust sheets of Precambrian to recent rocks comprised of the Northern Potwar Deformed Zone (NPDZ) and the Southern Potwar Platform Zone (SPPZ) separated by the asymmetrical Soan Syncline. The Upper Indus Basin is located in northern Pakistan and Sargodha high separates it from the Central Indus Basin. The Potwar sub-basin lies in the western Sub-Himalayan tectonic zone. It is bounded in north by Main

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Boundary Thrust (MBT) and Salt Range in south while the left-lateral Jhelum strike-slip fault and the right-lateral Kalabagh strike-slip fault occurs in its east and west, respectively. The basin is covered by the molasse sediments ranging in age from Miocene to Pleistocene. Precambrian to Quaternary sequence is exposed along the ranges in south [4]. Balkassar is located in the northern Punjab consisted majorly of the anticline and thrust faults, indicating the compressional regime [5]. The EW trending Salt Range Thrust (SRT), which is a surface expression of the leading edge of a regional decollement, brought the entire sedimentary succession to the surface [6-8]. The southern part of the basin, Southern Potwar Deformed Zone (SPDZ), is relatively less deformed as compared to the Northern part (NPDZ). The non-deposition and/or erosion in the basin caused the absence of Ordovician to Carboniferous sediments. Lower Permian strata lie unconformably over the Cambrian strata. Late Permian and Mesozoic formations are interrupted due to disconformities in the fold belt. These unconformities are not easily recognizable in the seismic profiles because of intense thrusting [9]. The structural map of Potwar sub-basin is shown in Fig. 2 [10].

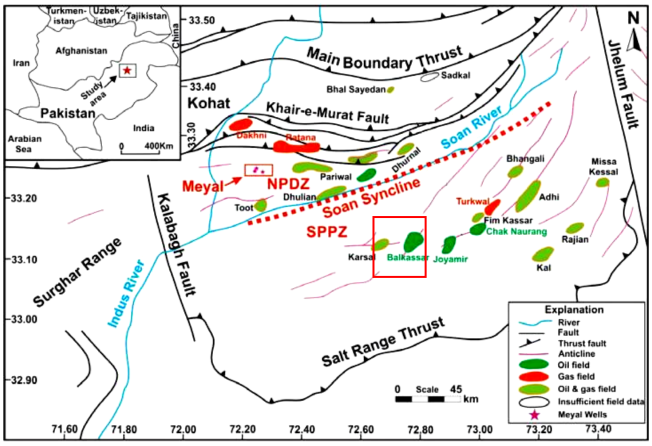

Fig. 2: Structural map of Potwar Sub-basin, depicting the oil and gas fields. Balkassar Oilfield is highlighted with red square [10].

The basement in Potwar sub-basin is composed of hard rocks (slates and phyllites) overlain by oldest Precambrian sedimentary strata of Salt Range Formation. The Salt Range Formation consists of rock salt, gypsum and marl with some dolomite and minor oil shale [11]. Younger than this is Jhelum Group of Cambrian age that consists of Khewra Sandstone, Kussak Formation (sandstones and shale), Juttana Formation (dolomite) and Baghanwala Formation (sandstone, siltstone and shale). This is unconformably overlain by the early Permian continental Nilawahan Group [12] and late Permian marine carbonates of the Zaluch Group [13]. The sediments of Mesozoic age are eroded/not deposited in the eastern and central parts of the Salt Range due to early Jurassic rifting [14, 15]. During middle to late Eocene time, a regional withdrawal of the sea occurred. There is an unconformity in Oligocene time due to orogeny building and sediments of this age have not been found in the region. From the Miocene onward, only fluvial sediments were deposited [16]. A complete petroleum system is present in the study area in which reservoirs are the carbonates of Eocene age recharged by the Patala shales of Paleocene age. Lateral and vertical seal is provided by clays of Murree Formation.

3. Methodology

Structural analysis methodology is used for seismic interpretation in this work. Five migrated seismic lines including four of dip and one strike, provided by Directorate General of Petroleum Concession (DGPC), used to delineate the Balkassar anticline. The migrated line PBJ-04 was taken as control line, as the Balkassar-Oxy-01 well is located on this line, therefore, the reflectors were identified and marked on it. The correlation of data was done using time-depth chart manipulation technique as shown in Fig. 3. Four prominent horizons have been identified while faults have been marked, based on the lateral amplitude discontinuity in the strata. The last continuous prominent reflector was of Salt Range Formation. The sedimentary strata which is resting above Salt Range Formation is involved in the petroleum system of Balkassar field. The base map was generated as shown in Fig. 4.

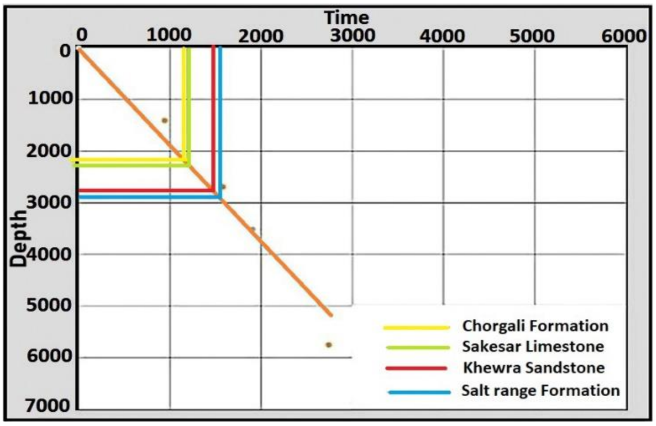

Fig. 3: Time depth chart showing time and depth of targeted formations after datum equivalent. Time values are in milliseconds and depth values in meters.

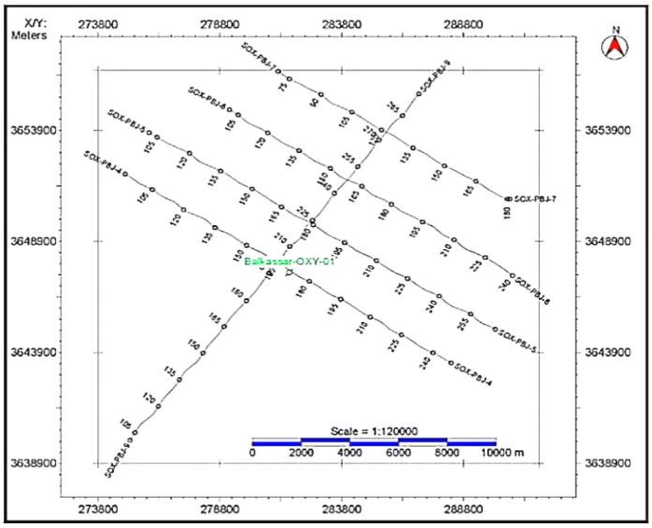

Fig. 4: Base map of study area showing seismic lines and well location. Balkassar-Oxy-01 well is located on strike line (Generated in Kingdom Software).

3.1 Seismic Data Interpretation

Seismic section is usually in time (seconds) units, the interpretation has been carried out in units of two-way travel time. The interpreted seismic lines are shown in Figs. 5, 6 and 7. PBJ-04 (Fig. 5) is taken as a control line because the well Balkassar Oxy-01 is located on it which is confirmed by the base map. Following the interpretation on the line PBJ-04, other seismic lines have been delineated. The well lies at the vibroseis point: 173 on PBJ-04 line. After the selection of control line and relevant well point, the closest velocity function was solved. The RMS velocity was then multiplied with two-way travel time in order to get the depth values using the formula:

$$s = (v * t)/2000$$

Where, s = Depth in meters, v = Velocity in meter/seconds and t = Time in milliseconds.

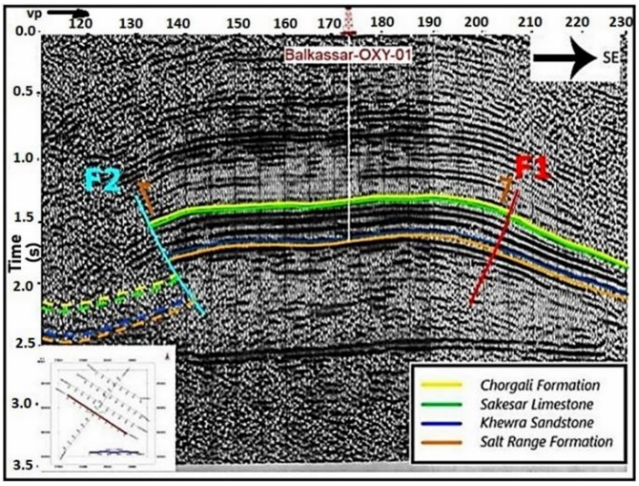

Fig. 5: Interpreted seismic section PBJ-04 which is a control line, where Balkassar-Oxy-01 well is present. The faults are marked as F1 and F2.

The Balkassar is an "anticlinal pop-up" structure created by both compressional and shears stress regimes. Compressional phenomenon is increasing while moving from south to north, as more faults have been observed on PBJ-05 (Fig. 6) and PBJ-06 (Fig. 7). The eastern flank is bound by a regional reverse fault, that regionally trends NE-SW along one complex of fault-bend folds as displayed in Fig. 5. It is becoming narrow towards north, where a fault bound syncline plunges into the middle of the anticline. The resultant geometry is shown in Fig. 6 where compartmentalization is clearly evident. The anticline has two culminations separated by a small saddle. Mapping of the structure showed that western compartment is structurally lower than eastern one as displayed in Fig. 7. The tectonic forces are intense in north as compared to south as seismic correlation shows that the throw of faults gradually dies out as we move from north to south as displayed in the interpreted seismic sections. These pop-up structures have a large thickness of evaporates below the crestal region, while the flanks which are typically reverse bound fault exhibit salt withdrawal. This is quite evident on the seismic profiles.

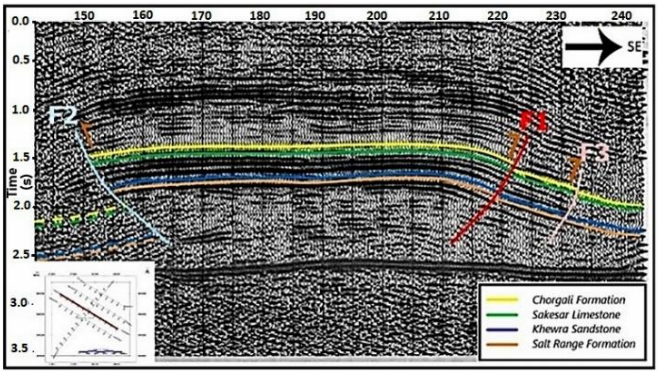

Fig. 6: Interpreted seismic section PBJ-05 showing the pop-up anticline dissected by three faults, marked as F1, F2 and F3.

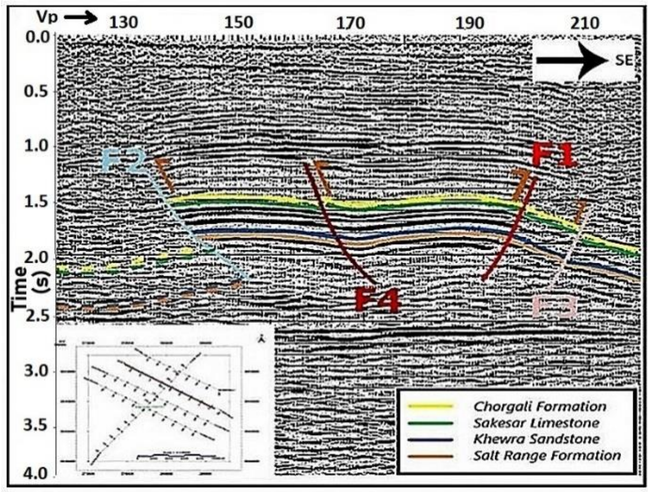

Fig. 7: Interpreted seismic section PBJ-06 showing pop-up anticline with a saddle and dissected by four faults marked as F1, F2, F3 and F4.

By contouring points of equal time value, time contour maps of the targeted horizons were prepared. Taking the root mean square velocities and the time with the depths encountered in Balkassar-Oxy-01, the depth structure maps were generated. Fig. 8 shows the depth contour map of Chorgali Formation; whereas Fig. 9 illustrates the depth contour map of Sakesar Limestone. The depth contour maps are generated to find out the target depth of reservoir. The values of depths calculated from depth contour map and the depths of the formation top from wells are matching accurately. In order to confirm the structure interpreted on the seismic data, the time and depth values were plotted against the latitudes/longitudes and then mapped.

3.2 Time and Depth Contour Maps

The contours that are placed in between the two reverse faults (F1 and F2) show lower time and depth values thus representing a pop-up structure formed because of the uplifting due to compressional tectonics. The contours in the central region with lesser values can be indicative of the presence of hydrocarbons trapped by the structure. The time contour maps are generated using a contour interval of 0.06 sec. Chorgali Formation time map, shown in Fig. 10, depicts a broad-flat anticline showing low values of time at the center.

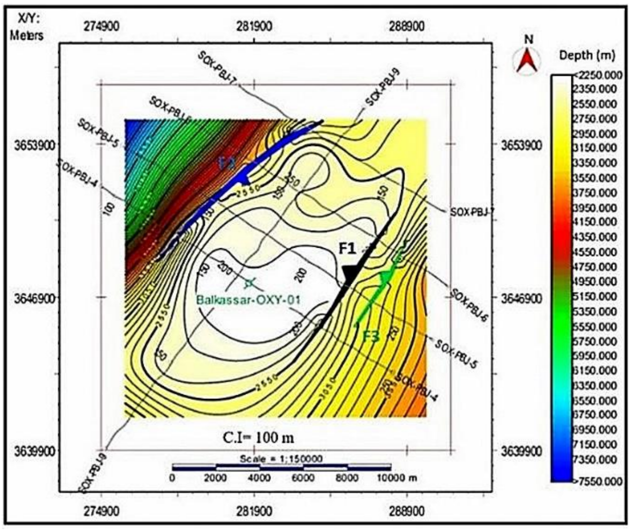

Fig. 8: Depth contour map of Chorgali formation showing popup anticlinal structure in the center of the map.

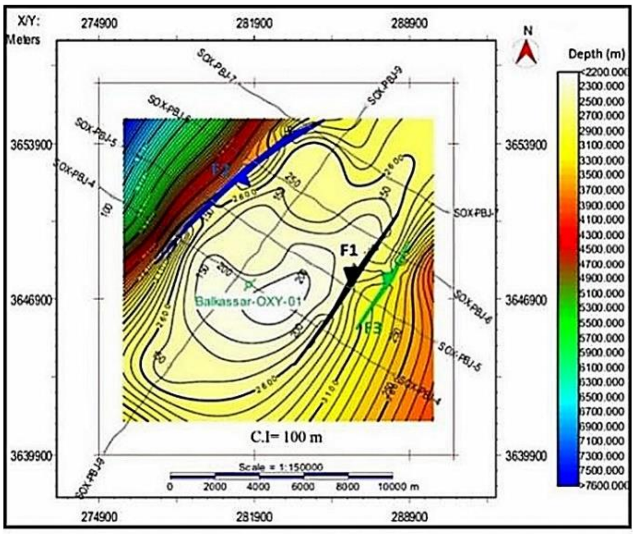

Fig. 9: Depth contour map of Sakesar limestone depicting pop-up structure with white and yellow color.

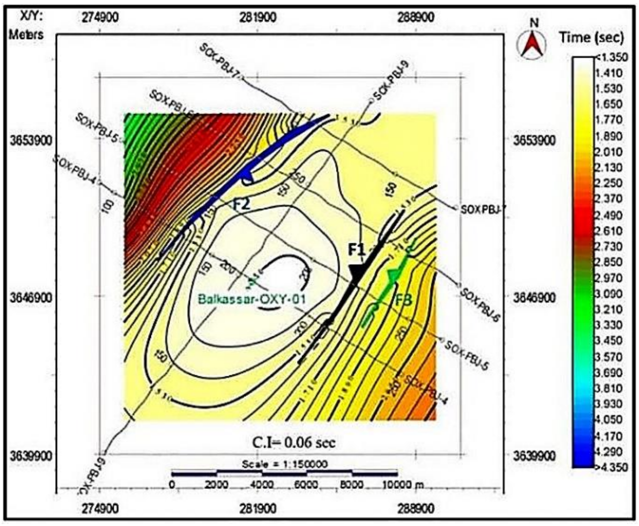

Fig. 10: Time contour map of Chorgali formation.

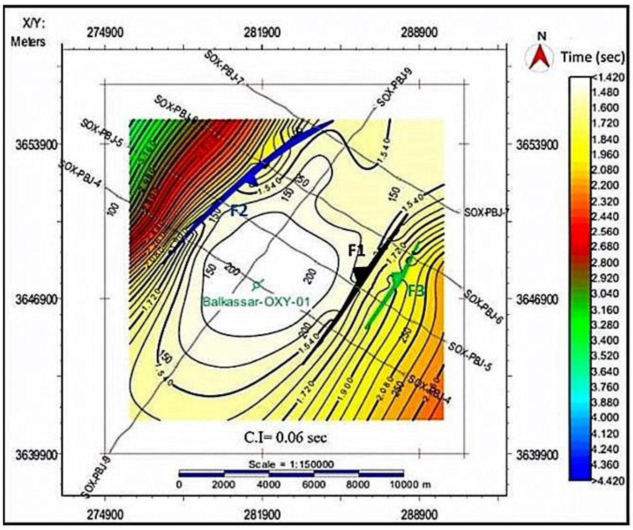

Fig. 11: Time contour map of Sakesar limestone.

Sakesar Limestone time map in Fig. 11 also depicts a heart shapes structure. The presence of low values of time at the center of Fig. 11 prove it an anticlinal structure. The depth contour maps are generated using a contour interval of 100 meters. In Fig. 8 depth map of Chorgali Formation is shown which clearly unfolds an anticline structure. Depth contour map of Sakesar Limestone (Fig. 9) recounts the same anticlinal structure. The map view of the Balkassar structure typically looks “heart-shaped” which is structurally high, flanked by reverse faults on both the east and the west sides. As mentioned above, Eastern fault is the major reverse fault of regional significance. The Western Fault although having substantial throw is a subsidiary fault. Two fault bend folds appear as the two lobes of the “heart shaped” Balkassar structure as displayed in time and depth contour maps. The mapping revealed that the eastern compartment is structurally higher than the western compartment. The shallow part is present in the middle while the deeper part is present at the flanks. The closeness of the contours shows steep slopes at the flanks while widely spaced contours show a gentle slope. The upthrown block is enclosed by major and minor reverse faults. The crestal location of the Chorgali Formation and Sakesar Limestone is around 2200 and 2250 meters respectively. Depth maps clearly show, in between the two thrust faults (F1 and F2), an up-thrown block with a two-way dip closure. The contours widen in the NW direction of pop-up anticline are representing the gentler flanks of the anticline. The flanks between F1 and F2 have steeper dip in the SE direction, most likely due to the compressional tectonic regime.

3.3 *Petrophysical Analysis*

The Balkassar-Oxy-01 well was spudded by POL to the total depth of 3130 m. The status of the well is abandoned. The aim of petrophysical analysis is to transform well log measurements into reservoir properties like porosity, permeability, volume of shale, oil saturation and water saturation etc. The objective of petrophysical analysis is to attain information from Balkassar-Oxy-01 well. The logs

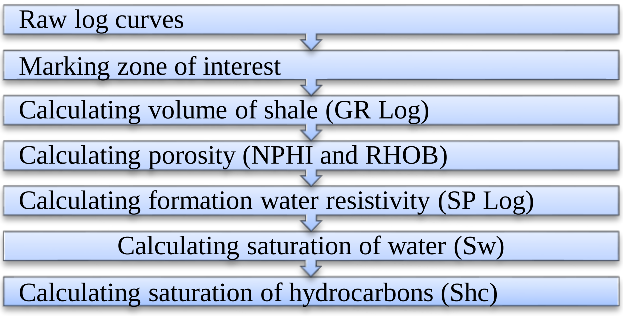

Fig. 12: Step by step work flow adapted for Petrophysical analysis.

used are Caliper Log, Gamma Ray Log, SP Log, Density Log, Neutron Log and Resistivity Log. Work flow adapted for petrophysical analysis is shown in Fig. 12 which is followed for the zones demarcation.

Figs. 13 and 14 show the log curves with marked zone of interest of Balkassar-Oxy-01 from Chorgali Formation and Sakesar Limestone, respectively. Zones of interest were marked where caliper log is stable, low gamma ray values, neutron density shows cross over, resistivity is high and separation between micro spherical focus log (MSFL) and deep lateral log (LLD). The starting and ending depth of zones of interests are given in Table 1.

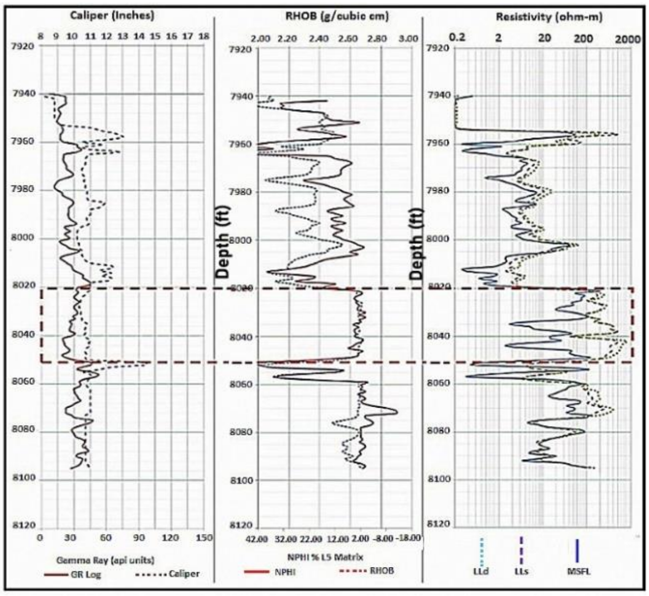

Fig. 13: Well logs of Chorgali formation with marked zone of interest.

Physical Parameters are calculated using different formulae of well log interpretation. The average volume of shale in Chorgali Formation and Sakesar Limestone calculated is 25% and 23.7% (Fig. 15), respectively. Fig. 16 shows the Effective Porosity in Chorgali Formation is 3.08% and Sakesar Limestone is 1.92%. Fig. 17 shows the Average Water Saturation in these two sections, which is 40.5% and 79.5%, while Average Hydrocarbon Saturation is 59.5% and 20.5%, respectively. It is concluded from petrophysical analysis that Chorgali Formation acts as a potential reservoir in the area as compared to Sakesar Limestone.

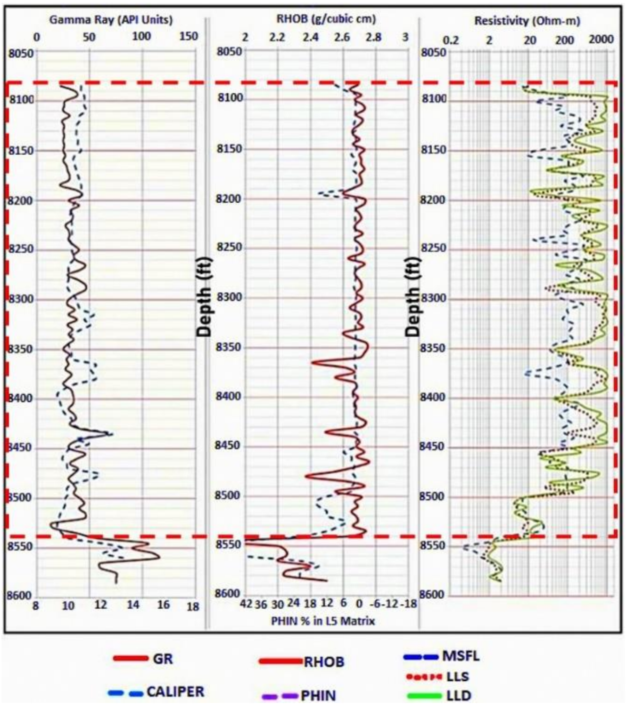

Fig. 14: Well logs of Sakesar limestone with marked zone of interest.

Table 1: Depth and thickness of zones of interest.

Zones	Zone of Chorgali formation	Zone of Sakesar limestone
Starting Depth	8020 ft (2444.49 m)	8095 ft (2467.35 m)
End Depth	8050 ft (2453.63 m)	8540 ft (2602.99 m)
Net Thickness	30 ft (9.144 m)	445 ft (135.63 m)
Gross Thickness	150 ft (45.72 m)	445 ft (135.63 m)

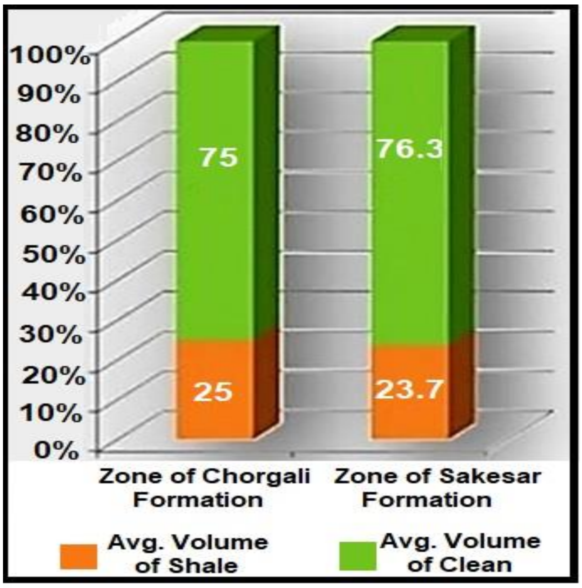

Fig. 15: Calculated average volume of shale and volume of clean for Chorgali formation and Sakesar limestone.

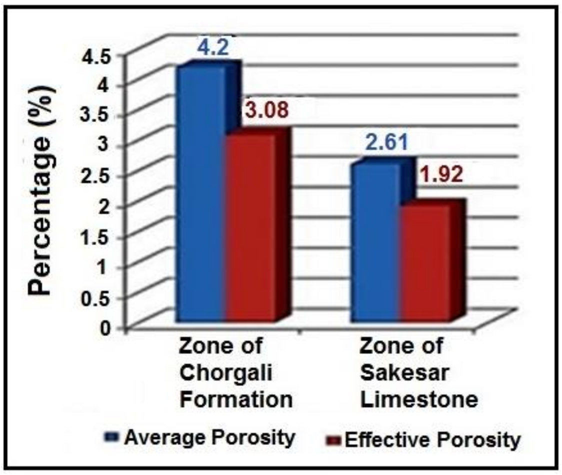

Fig. 16: Calculated average porosity and effective porosity for Chorgali formation and Sakesar limestone.

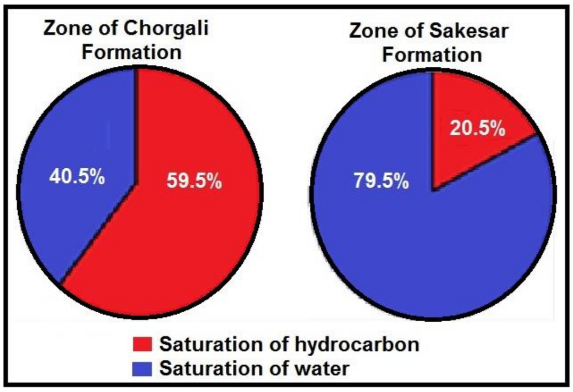

Fig. 17: Calculated average saturation of hydrocarbon and saturation of water for Chorgali formation and Sakesar limestone.

4. Fault Seal Analysis

In hydrocarbon exploration and production, evaluating fault seal risk is an important factor. A fault can be a transmitter and barrier to fluid flow and pressure communication. Faults that do not form seal prevent oil and gas from accumulating as hydrocarbons and migrate through structures in the sub surface. Open and permeable faults within an established reservoir may cause serious lost circulation during drilling operations [17].

One of the studies that involves in fault seal analysis is juxtaposition. It tells us about the lithological juxtapositions of foot wall and hanging wall along the fault. In the present study area, Balkassar field, two main faults were observed in the seismic section. Based on seismic data and wellbore information, Allan diagram demonstrates the juxtaposition relationships across a fault plane. Both seismic and well data are utilized to develop Allan diagram. In order to define hanging wall and footwall offset across the fault, interpreted horizons were used, and to define the stratigraphic changes between the seismic horizons, the well data was used.

The depth contour map of Chorgali Formation was used. Precise contour maps were generated using an interval of 100 meters. The values of contours cutting the fault were noted. The procedure was implemented both for upthrown and downthrown portions of fault F1 and F2. The values were measured in centimeters by taking a reference point and then multiplied by the scale of the plotted contour map. By taking these points of Chorgali Formation as a reference, the depth of all other formations were calculated. At the end, these values of depth were plotted against distance on a graph to get Allan diagram as shown in Fig. 18. Same procedure was repeated for the second fault on the Chorgali Formation depth contour map, as shown in Fig. 19.

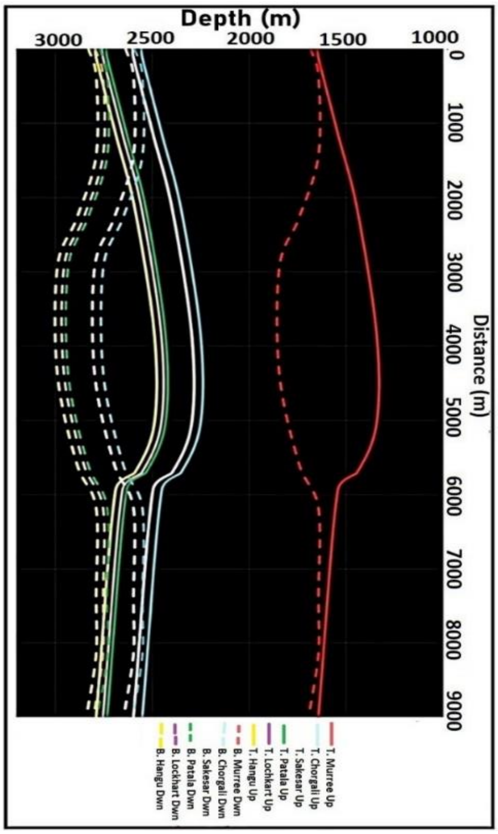

Fig. 18: Allan diagram of fault 1.

In order to have proper sealing fault, there must not be any overlapping between the upthrown strata and downthrown of same formations to prevent hydrocarbons to migrate at any other place. The upthrown of Chorgali Formation and Sakesar Limestone juxtaposes with downthrown of Murree formation. Clays of Murree Formation providing seal to the reservoir, hence it is suitable for the entrapment of hydrocarbons.

5. Volumetric Reserve Estimation

The integration of well and seismic data provide an insight to reservoir hydrocarbon volume which refers as volumetric estimation of reservoir. Original oil in place (OOIP) and original gas in place (OGIP) are the total volume of hydrocarbon stored in a reservoir prior to production. Reserves are the volume of hydrocarbons that can be profitably extracted from a reservoir using existing technology. Estimating hydrocarbon reserves is a complex process that involves integrating geological and engineering data [18].

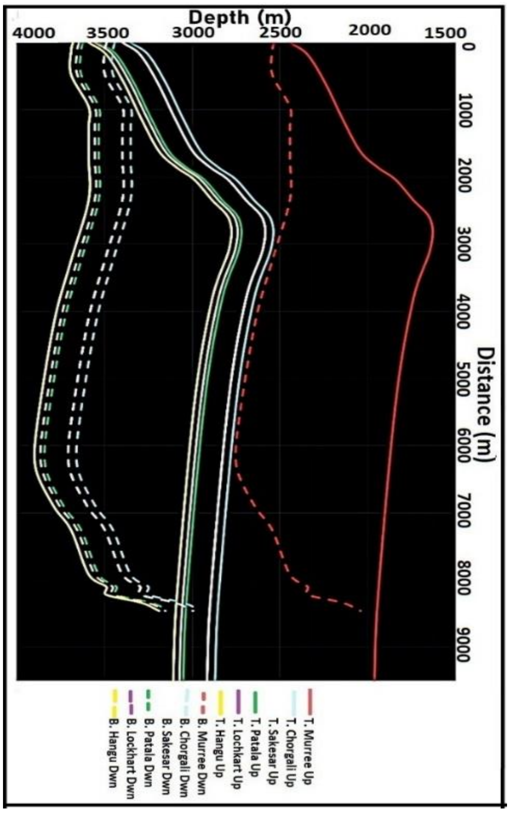

Fig. 19: Allan diagram of fault 2.

5.1 *Volumetric Analysis*

Estimated values were calculated manually out of the reserves. This procedure was adapted taking the area of the concerned formation on well or the zone of interest in the well data which in this case is Chorgali Formation. Values of depth were taken from the depth contouring of the Chorgali Formation. From the depth map, the area of Chorgali Formation was taken and calculated in acres on graph paper. The values were then multiplied by the vertical closure and derived values were then used in the formula for the reservoir estimation.

5.2 *Volume in-place Calculations*

The unit of oil used in the oil industry is barrel; one barrel is equal to 42 US gallons, which is about 159 liters or 35 imperial gallons [18]. The volume of oil and gas in-place depends on a number of parameters: The aerial coverage of the reservoir (A), the thickness of the reservoir rock contributing to the hydrocarbon volume (h_o), the pore volume, as expressed by the porosity ($\emptyset_E$), the reservoir quality rock and the proportion of pore space occupied by the hydrocarbon (S_o). The formula used to calculate the "originally oil in place (OOIP)" is mentioned below:

$$OOIP = [7758 * A * h * \emptyset_E * (1 - S_w)/B_0]$$

B_o= Oil formation volume factor [Barrel (bbl)/Stock Tank Barrel (STB)]

Petrophysical properties of zone of interest in Chorgali Formation are calculated and are given in Table 2.

Table 2: Calculated variables for Chorgali formation.

Formation	Chorgali Formation
Depth (ft)/(m)	7944.5ft/2421.5m
Total thickness (ft)	149
Net pay thickness (ft)	30
Lithology	Limestone, Sand and Shale
Average volume of shale %	25
Average porosity %	4.20
Effective porosity %	3.08
Average saturation of water %	40.52
Average saturation of hydrocarbon %	59.48

Table 3 shows the calculated factors of P90, P50 and P10. The total area enclosed between main and back thrust of Chorgali Formation calculated for P90 is 5,232.98 Acres, P50 is 12,132.317 Acres and P10 is 19,119.98 Acres, shown in Figs. 20, 21 and 22, respectively. The estimated value of original oil in place (OOIP) for P90 is 18.6 million barrels in the selected reservoir and there is 90% probability that this quantity of hydrocarbon is present in this area. The estimated value of original oil in place for P50 is 43.13 million barrels in the selected reservoir. The estimated value of OOIP for P10 is 67.97 million barrels in the selected reservoir.

6. Results and Discussions

The Balkassar Oil field, situated in the Central Potwar Sub-basin, lies on the southern flank of Soan Syncline in Himalayan collisional or compressional regime. Thrusting and folding of Himalayan orogeny, Indo-Pak plate movement and Salt Range uplift, resulted in forming the structural trap in lkassar sub-surface (Balkassar anticline). The anticline has NE–SW-oriented axis, and both the SE and NW limbs are bound by thrust faults. Eastern compartment is structurally higher than western side. Seismic interpretation and contour maps confirm the presence of pop-up, salt-cored, anticline in the subsurface.

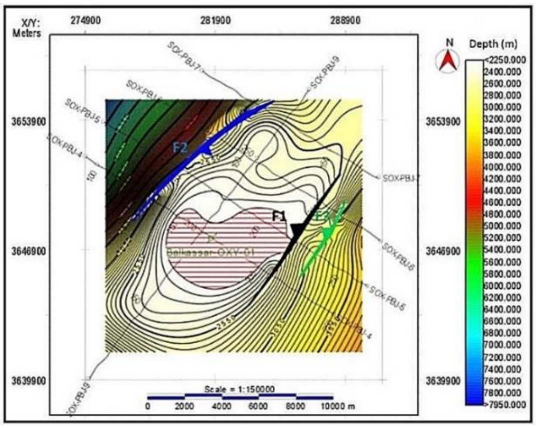

Fig. 20: Enclosed reservoir area for P90 estimation.

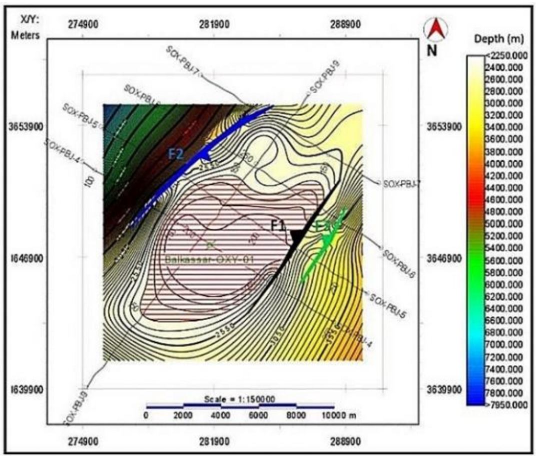

Fig. 21: Enclosed reservoir area for P50 estimation.

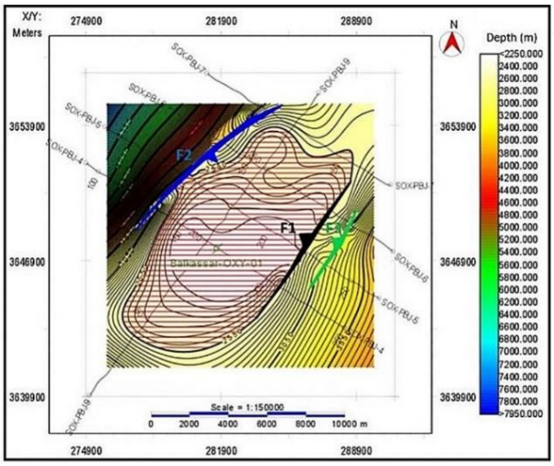

Fig. 22: Enclosed reservoir area for P10 estimation.

Table 3: Calculated factors for P90, P50 and P10.

Calculated Factors	P90	P50	P10
Area (Acres)	5,232.98	12,132.32	19,119.98
Net pay Thickness (ft)	30	30	30
Effective porosity	0.031	0.031	0.031
Hydrocarbon saturation	0.595	0.595	0.595
Oil formation volume factor	1.2 bbl/STB	1.2 bbl/STB	1.2 bbl/STB

The petrophysical analysis for Chorgali Formation and Sakesar Limestone of Eocene age in Balkassar-Oxy-1 well was conducted. The analysis was performed to calculate the shale volume, porosity, water saturation, water resistivity and hydrocarbon saturation. The average volume of shale in Chorgali Formation and Sakesar Limestone is calculated as 25% and 23.7%, effective porosity is 3.08% and 1.92%, average water saturation is 40.5% and 79.5%, while average hydrocarbon saturation is 59.5% and 20.5%, respectively. Chorgali Formation is proved to be better reservoir as compared to Sakesar Limestone as effective porosity, hydrocarbon saturation and volume of shale turned out to be more favorable for Chorgali Formation.

Fault seal analysis confirmed that downthrown of Murree Formation of Miocene age juxtaposes with the upthrown of Chorgali Formation of Eocene age. Therefore, it is inferred that clays of Murree Formation provide seal to the Chorgali Formation.

Volumetric estimates of original oil in place (OOIP) are based on a geological model that geometrically describes the volume of hydrocarbon reserves. The total area of Chorgali Formation for P90 is 5,232.98 acres which is present in the enclosure between Main Frontal Thrust and Back Thrust, which shows that there is 90% probability that high quantity of hydrocarbon is present in this area.

7. Conclusions

The study area lies in compressional tectonic regime which is further confirmed by seismic structural interpretation. Balkassar structure proved to be a thrusted pop-up anticline, comprised of two (northern and southern) compartments. South eastern compartment is shallower and more suitable for hydrocarbon entrapment which is evident through the fault seal analysis and structural mapping. Petrophysical interpretation proved that the Chorgali Formation is more economically and potentially viable as compared to Sakesar Limestone based on high percentage of effective porosity and saturation of hydrocarbon. Volumetric estimation done on the Chorgali Formation also provided aid to the physical properties calculated through petrophysics.

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