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Integration of seismic and well data for a 3D model of the Balkassar anticline (Potwar sub-basin, Pakistan)

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Abstract: The Potwar sub-basin is an important hydrocarbon producing zone of the Upper Indus basin and has significant oil and gas potential. The Balkassar area is the main oil field of the Potwar sub-basin and oil is mainly produced from Eocene carbonates. The Chorgali Formation is of Eocene age and is the main reservoir rock in this area. Structurally, the Potwar sub-basin is complicated, and surface features often do not reflect subsurface structures. This is due to the presence of detachments at different levels. In such cases, it is necessary to integrate seismic data with geological information for an accurate delineation of subsurface structures. Eleven seismic profiles were interpreted to understand subsurface structural style. To correlate well data with seismic data, a synthetic seismogram has been generated. Time, velocity and depth contour maps have been prepared. A 3D model for the Chorgali Formation has been prepared which confirms that this is a four-way anticlinal structure bounded by faults. It makes this structure more favorable for hydrocarbon accumulation. Moreover, a cross section has been prepared for five wells to show that the Chorgali Formation is spreading. Based on it, to show the relationship between compressional tectonics and basement slope, a 3D structural model has been prepared. In this case study, the Balkassar anticline was interpreted as a four-way closure pop-up structure which provides a structural trap for the accumulation of hydrocarbons. This study will help us understand the accumulation of hydrocarbons in the same type of structural traps in the Potwar sub-basin and in similar kinds of basins. It is also relevant to oil exploration within Pakistan.

Keywords: 2D-seismic interpretation, well correlation, 3D modelling, Potwar sub-basin, Balkassar anticline, Pakistan

INTRODUCTION

Pakistan is comprised of three main sedimentary basins: Indus, Balochistan and Pishin (also known as Kakar Khorasan basin) (Fig. 1). The Indus basin is the largest basin of Pakistan which is part of the northwestern Indian Plate and covers an area of about 533,500 km^2. It has great potential for hydrocarbon exploitation, and more than 90% of the total wells in Pakistan have been drilled in this basin and number of successful discoveries have been made (Khan et al. 1986). Based on structural and sedimentological characteristics, the Indus basin is subdivided into three segments: Upper, Central and Southern Indus basins (Fig. 1).

The study area is located in the Upper Indus basin, 105 km SW of Islamabad (Fig. 1). In detailed geological descriptions, the study area is distinguished as the Potwar sub-basin.

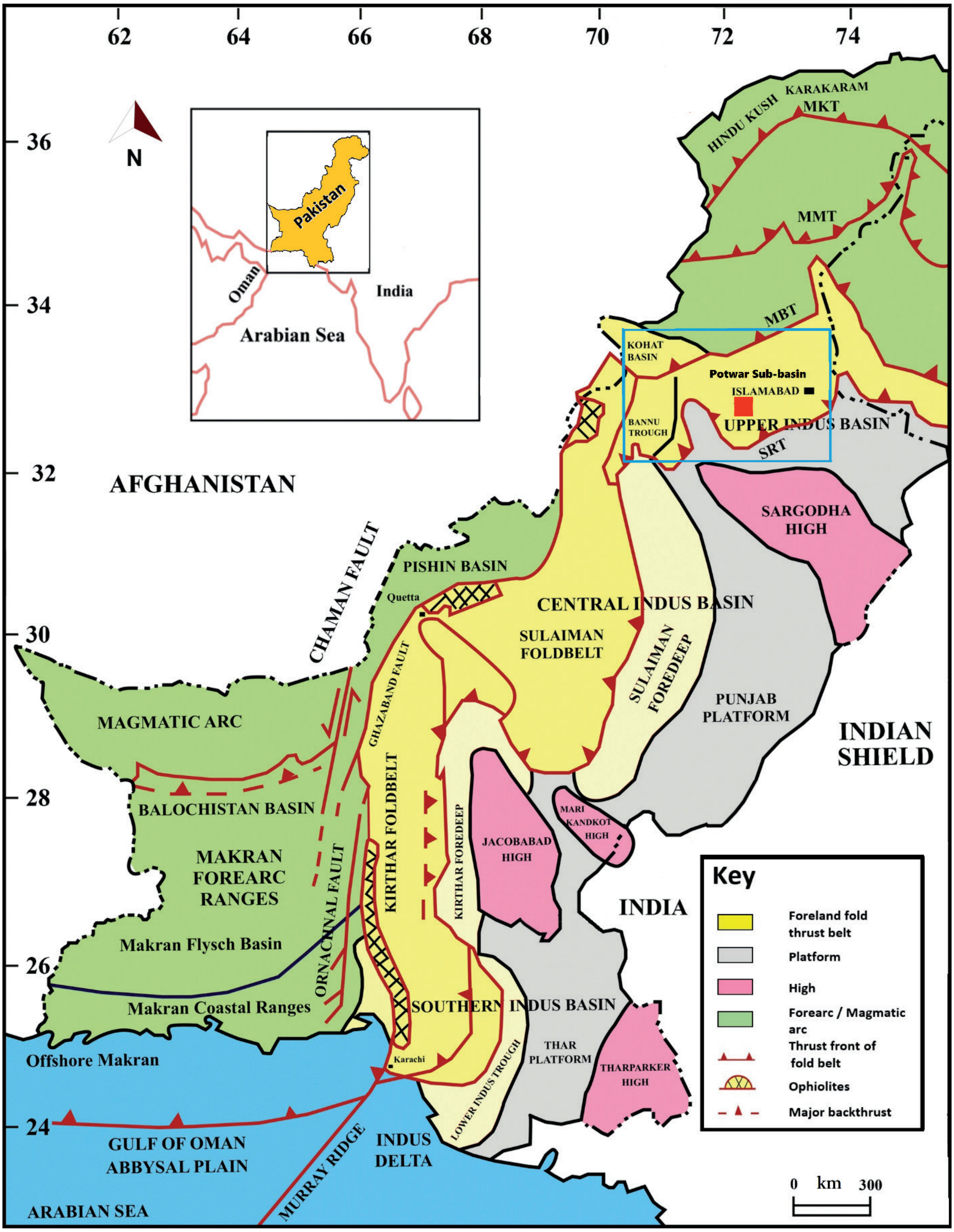

Fig. 1. *Sedimentary basins of Pakistan. Upper Indus basin, Central Indus basin and Southern Indus basin are collectively also known as the Indus basin (modified after Ahmed et al. 2020); the red box shows the study area, the blue box represents Figure 2*

The Potwar sub-basin is one of the oldest oil provinces in the world, where the first commercial discovery was made in 1914 at Khaur Oil Field (Moghal et al. 2003). Since then, many hydrocarbon fields have been discovered in different parts of the Upper Indus basin (Khan et al. 1986).

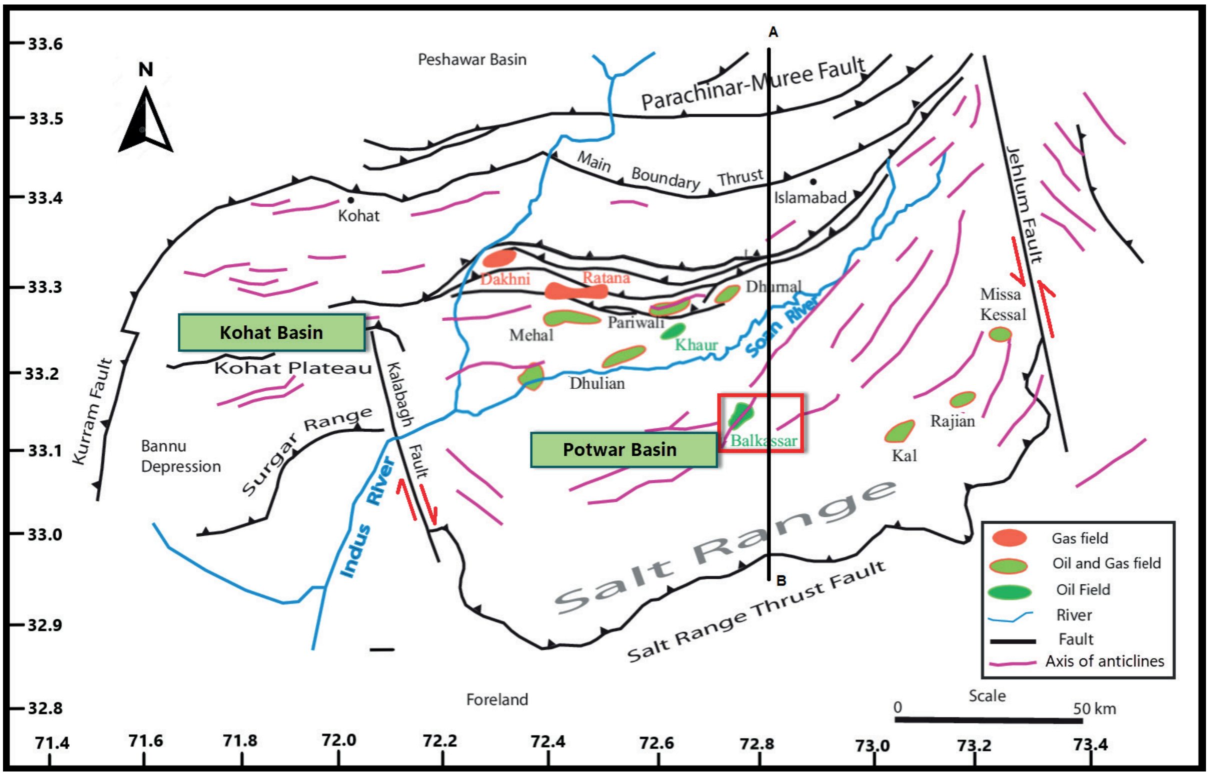

Fig. 2. Generalized structure of the Upper Indus basin (Kazmi & Rana 1982, Kadri 1995, Shah 2009 – modified); red box – the Balkassar Oil Field of the Potwar sub-basin

Most of these discoveries are associated with subsurface reverse faults, duplexes and associated anticlines (mostly salt-cored). About 150 exploratory wells have been drilled so far in the area; many of these were prematurely abandoned, as they could not reach their target depths due to structural complexities and associated technical drilling problems. Structurally, the Potwar sub-basin is complicated, and surface features often do not reflect subsurface structures (Jadoon et al. 1999). This is due to the presence of detachments at different stratigraphic levels (Jadoon et al. 1999). Therefore, for an accurate delineation of the subsurface structure, the true integration of subsurface geological information with the seismic data is necessary through well to seismic ties (Moghal et al. 2003).

This study attempts to develop a 3D structural model of a thrusted anticline through 2D seismic interpretation and the incorporation of log motifs, and to delineate the possible structural traps bounded by the thrust and reverse faults. The present study will help us to untangle the complexity of a proven anticlinal reservoir of the Potwar sub-basin. It will also allow us to better understand the hydrocarbon trapping mechanism in the foreland basins (Fig. 2).

GEOLOGICAL SETTING

The Potwar sub-basin extends about 130 km from the Main Boundary Thrust in the north and is bounded in the east by Jhelum Fault, in the west by Kalabagh Fault, and in the south by the Salt Range Thrust (Kadri 1995, Jadoon et al. 2003) (Fig. 2). This basin is filled with a thick series of Pre-Cambrian evaporites that are overlain by relatively thinner molasses deposits of Miocene age. The thickness of these molasses deposits varies within the basin and provide excessive burial for the source rock maturation (Shakir et al. 2021). This whole area has been severely deformed by the extremely intensive Himalayan orogeny (Kazmi & Jan 1997).

The Himalayan collisional orogeny started developing in the Cretaceous as a result of a continent-volcanic arc-continental collision (LeFort 1975, Treloar et al. 1992, Kazmi & Jan 1997). In the complex NW Himalayan tectonic domain, Main Mantle Thrust (MMT), Main Boundary Thrust (MBT) demarcate major tectonic zones (Tahirkheli 1979, Jadoon et al. 2003) (Fig. 1).

Structurally, the Potwar sub-basin is subdivided into the northern Potwar deformation zone (NPDZ) and the southern Potwar platform zone (Khan et al. 1986, Kadri 1995, Jadoon et al. 1999). Mainly contractional folds and faults occur in the area; however, preexisting normal faults also occur in the crystalline basement (Pennock et al. 1989). Normally, duplexes and thrusts occur in the NPDZ (Jadoon et al. 1999), and the southern part of the Potwar sub-basin is relatively less deformed (Jaswal et al. 1997). Cross-sectional balancing studies (e.g., Leathers 1987, Baker et al. 1988, Hanif et al. 2014) show that the central and western parts of the area have south-verging reverse faults, whereas, in the eastern part, NE–SW trending tight and occasionally overturned anticlines separated by broad synclines occur (Fig. 3). Paleomagnetic studies have shown that the structural trends originally developed perpendicular to the transport direction and subsequently acquired their present alignment because of the left lateral Jhelum strike-slip fault (Baker et al. 1988, Iqbal et al. 2014) (Fig. 2).

The Kalabagh Fault was formed by a transpressive right lateral strike-slip movement along the western Salt Range – Potwar sub-basin (Iqbal et al. 2014). Lateral ramping from a decollement thrust along the Pre-Cambrian evaporites produced folds and thrust faults (Iqbal et al. 2014). The Kalabagh Fault terminates northward (Iqbal et al. 2014).

The Potwar sub-basin is about 130–150 km broad sheet of Pre-Cambrian to recent sediments preserving the sedimentation, paleoenvironments, paleogeography and tectonic history of the plateau in them (e.g., Tahirkheli 1979, Gee 1980, Kazmi & Jan 1997, Kazmi & Abbasi 2008, Shah 2009, Iqbal et al. 2014). The area is known as a field museum of dynamic geology due to its spectacular structures, strata exposures and the occurrence of fossils along the Salt Range Thrust, the southern boundary of the Potwar sub-basin (Tahirkheli 1979).

The entire sedimentary succession is severely disturbed by the Himalayan orogeny between the northern margin of the Indian Plate and Eurasian Plate since about 55 Ma (Tahirkheli 1979, Khan et al. 1986, Baker et al. 1988, Kazmi & Jan 1997, Jadoon et al. 1999, Kazmi & Abbasi 2008, Shah 2009, Hanif et al. 2014, Iqbal et al. 2014). Furthermore, the orogeny in Pakistan has been the subject of many studies (e.g., Baker et al. 1988, Jaumé & Lillie 1988, Jaswal et al. 1997, Greland et al. 2002).

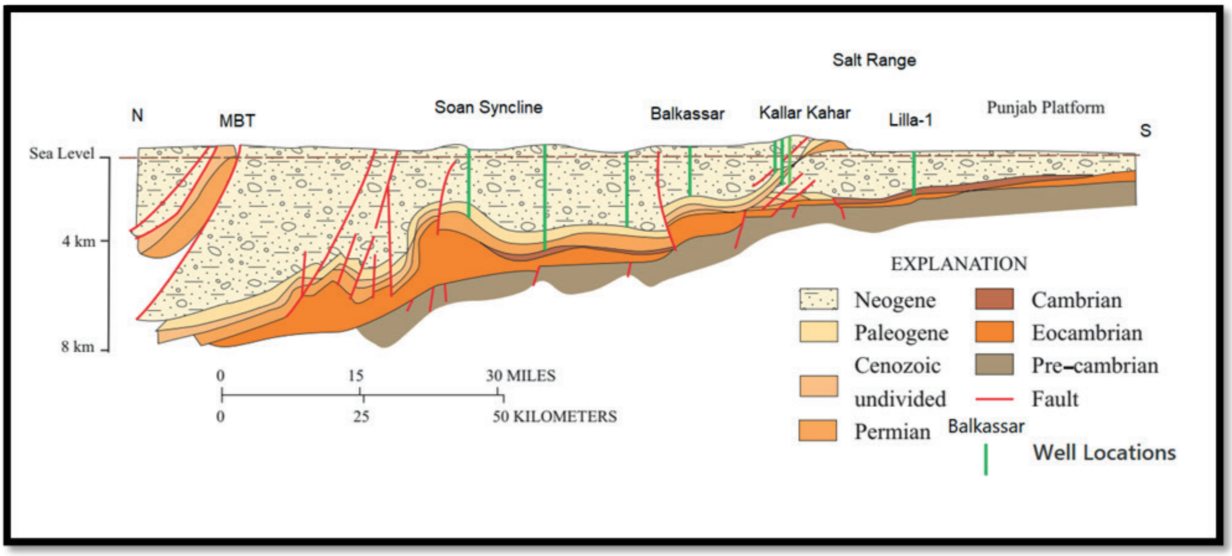

Fig. 3. *Generalized cross section showing structure through the Potwar sub-basin (modified from Shah 2009); for location see Figure 2*

The stratigraphy of the Potwar sub-basin is well established along the Salt Range (Kazmi & Abbasi 2008, Shah 2009, Iqbal et al. 2014). The Pre-Cambrian basement is composed of slates and phyllites (Hanif et al. 2014). The oldest strata are the Pre-Cambrian Salt Range Formation that consists of evaporites dominated by rock salt, gypsum and marl with some dolomite and minor oil shale (Gee 1980). It is overlain by the Cambrian Jhelum Group that consists of Khewra Sandstone, Kussak Formation (sandstones and shale), Jutana Formation (dolomite) and Baghanwala Formation (sandstone, siltstone and shale) (Shah 2009) (Fig. 4).

AGE			FORMATIONS	LITHOLOGY	Tectonic events
ERA	PERIOD	EPOCH	Potwar Sub-basin		
CENOZOIC	TERTIARY	PLIESTOCENE	Lie Soan	Conglomerate Siltstone, sandstone	Himalayan-Tibet orogeny
		PLIOCENE	Dhok Pathan Nagri Formation Chingi Formation	Claystone & siltstone Claystone & sandstone Claystone & siltstone	
		MIOCENE	Kamlial Formation	Sandstone & siltstone	
		OLIGOCENE	Murree Formation	Sandstone & claystone	
		UNCONFORMITY			
		EOCENE	Chorgali Formation * Sakesar Formation * Nammal Formation	Limestone, dolomite & shale Limestone Shale, limestone	Initial collision of Indian plate with Eurasian
		PALEOCENE	Pata Formation Lokhart Formation Hungu Formation	Shale Limestone Shale & sandstone	Rifting b/w Indian plates and Seychelles
		UNCONFORMITY			
MESOZOIC	CRETACEOUS		Chichali Formation	Sandstone, silty shale	Collision of Indian with Ladakh Island arc
	JURRASIC		Samanasuk Shinwari Datta	Limestone, marl Limestone, calcareous shale Sandstone & shale	Rifting from Gondwanaland
	TRIASSIC		Kingriali Tridian Mianwali	Dolomite Sandstone Dolomite, shale & limestone	
		UNCONFORMITY			
PALEOZOIC	PERMIAN		Chiddru Wargal Amb Sardhai Warcha Dandot Tobra	Shale & dolomitic limestone Limestone Shale & sandstone Shale Sandstone, shale Sandstone, shale Sandstone, siltstone	
	CARBONIFEROUS | ORDOVICIAN	UNCONFORMITY			
	CAMBRIAN		Baghanwala Juttana Kussak Khewra *	Sandstone, siltstone, shale Dolomite Sandstone, shale Sandstone, siltstone, shale	
	PRE-CAMBRIAN		Saltrange	Evaporites, halite, marl, gypsum, dolomite, anhydrite	

Basement not exposed

Fig. 4. *Lithostratigraphy of the Upper Indus basin (Meissner et al. 1974, Gee 1980, Qayyum et al. 2015 – modified); asterisks – main reservoirs*

The Mesozoic sediments were eroded/ not deposited in the eastern and central parts of the Salt Range due to Early Jurassic rifting (Kadri 1995, Iqbal et al. 2014). Shallow marine foraminiferal limestone and dark-grey shale dominate the Paleocene-Eocene succession (Hanif et al. 2014). During the Middle to Late Eocene period, a regional emergence resulted in the complete and permanent withdrawal of the sea. From the Miocene onward, only fluvial sediments were deposited (Khan et al. 1986).

The sedimentary succession of the Potwar sub-basin is divided into four unconformity-bounded sequences. These unconformities in the study area are Ordovician to Carboniferous, Late Triassic to Early Permian, Late Paleocene to Early Cretaceous and Late Oligocene in age (Fig. 4). These unconformities are not easily identified in the seismic profiles due to complex thrusting. The oldest sedimentary formation is the Pre-Cambrian Salt Range Formation. The Salt Range Formation lies unconformably on the Pre-Cambrian basement. In the Balkassar Oil Field, the Nammal, Sakesar and Chorgali formations, which are of Middle and Late Eocene age, conformably overlie Paleocene strata (Fig. 4). The Rawalpindi Group (Murree and Kamlial formations) with a Himalayan provenance (Khan et al. 1986) was deposited unconformable over the Early Eocene Chorgali Formation (Fig. 4).

The Chorgali Formation (Eocene) is the main reservoir in the study area. Moreover, Khewra Sandstone (Cambrian) and Sakesar Limestone (Eocene) are proven reservoirs in the study area as well (Khan et al. 1986).

The Chorgali Formation rests conformably over the Sakesar Formation (type locality Chorgali Pass) (Pascoe 1920). It consists largely, in the lower part, of thin-bedded grey, partly dolomitized and argillaceous limestone with bituminous odor, and in the upper part, of greenish, soft calcareous shale with interbeds of limestone. Its thickness ranges from 30 m to 140 m. The age of the Chorgali Formation is Early Eocene (Pascoe 1920).

DATA AND METHODOLOGY

By using a standard industry software suite, the seismic interpretation was carried by means of the integration of well information with seismic data. The seismic data utilized for this study was acquired by the Occidental Petroleum Corporation (OXY). For the seismic interpretation of the Balkassar Oil Field, eleven seismic profiles have been interpreted. Of these seismic profiles, seven are dip lines and four are strike lines. The parameters for the acquisition of seismic surveys are listed in Table 1. The seismic data processing comprised involves deconvolution, velocity analysis, normal moveout correction, common mid point (CMP) stacking, band pass filtering, and final migration (Iqbal et al. 2018).

Table 1
Acquisition parameters for seismic lines under study (adopted from seismic section)

Source parameters	Energy source	Vibroseis system
	Sweep frequency	7–42 Hz
	Sweep length	20 sec
	No. of sweeps	14
	Vibroseis point V.P. interval	100 m
	Group interval	100 m
Recording parameters	Instruments	R-10, COBA-2
	Tape format	SEG-C
	Record length	25.0 msec
	Notch filter	Out
	Sample interval	4 msec
	Number of channels	48
	Natural frequency	10 Hz

Well data for twelve wells has been used in this research (Fig. 5). These data include the formation tops encountered in the wells, and digital log motives (density, sonic, gamma ray and neutron porosity log).

An accurate representation of the subsurface geological horizons and structures for hydrocarbon exploration requires the close framework and structural styles of a basin. To correlate well data with seismic data, a synthetic seismogram (Fig. 6) was generated to mark the five horizons on the time section. For this purpose, seismic line OX_PBJ_04 has been selected as the reference line and the BLK_OXY_01 well was chosen because this well has DT (sonic log). Velocities were calculated from this log. After that acoustic impedance (a product of density and velocity) has been calculated by taking density values from the density logs. The RC series is calculated in the next step, which is convolved with wavelet. This wavelet could be Ricker wavelet, Klauder wavelet etc. (Sengbush et al. 1961). But in this research wavelet was extracted from seismic trace by using Wiener-Levinson extraction method. This method compares the reflection coefficients from the well log with the sample values in the extracted seismic trace and computes a filter (wavelet) that, when convolved with an extracted seismic trace, will closely reproduce the reflection coefficient series. The resulting reflection coefficient seems similar to the seismic traces (Sheriff & Geldart 1995). After matching the synthetic seismogram with seismic traces, it is displayed on seismic line OX-PBJ-04 (Fig. 7).

These five horizons were the tops of the Basement, Khewra, Lockhart Limestone, Sakesar and Chorgali formations. This horizon interpretation was done on all other seismic lines by tying to this seismic line (OX-PBJ-04). After that, three reverse faults and one normal fault in the basement were interpreted on all of seismic lines. On the base map, fault polygons were prepared by connecting each fault on all dip seismic lines. Once all of the seismic lines have been interpreted, the next step was to prepare time contour maps. An average velocity map was prepared and used to convert the time sections into depth sections. A 3D module of industrial seismic interpretation software was used to prepare the 3D model of the Chorgali Formation top surface along with the fault model. Well correlation was made using the lithological data obtained from five wells (BLK-1A, BLK-4A, BLK_OXY_01, BLK-4B and BLK_OXY_02 – for locations see Fig. 5).

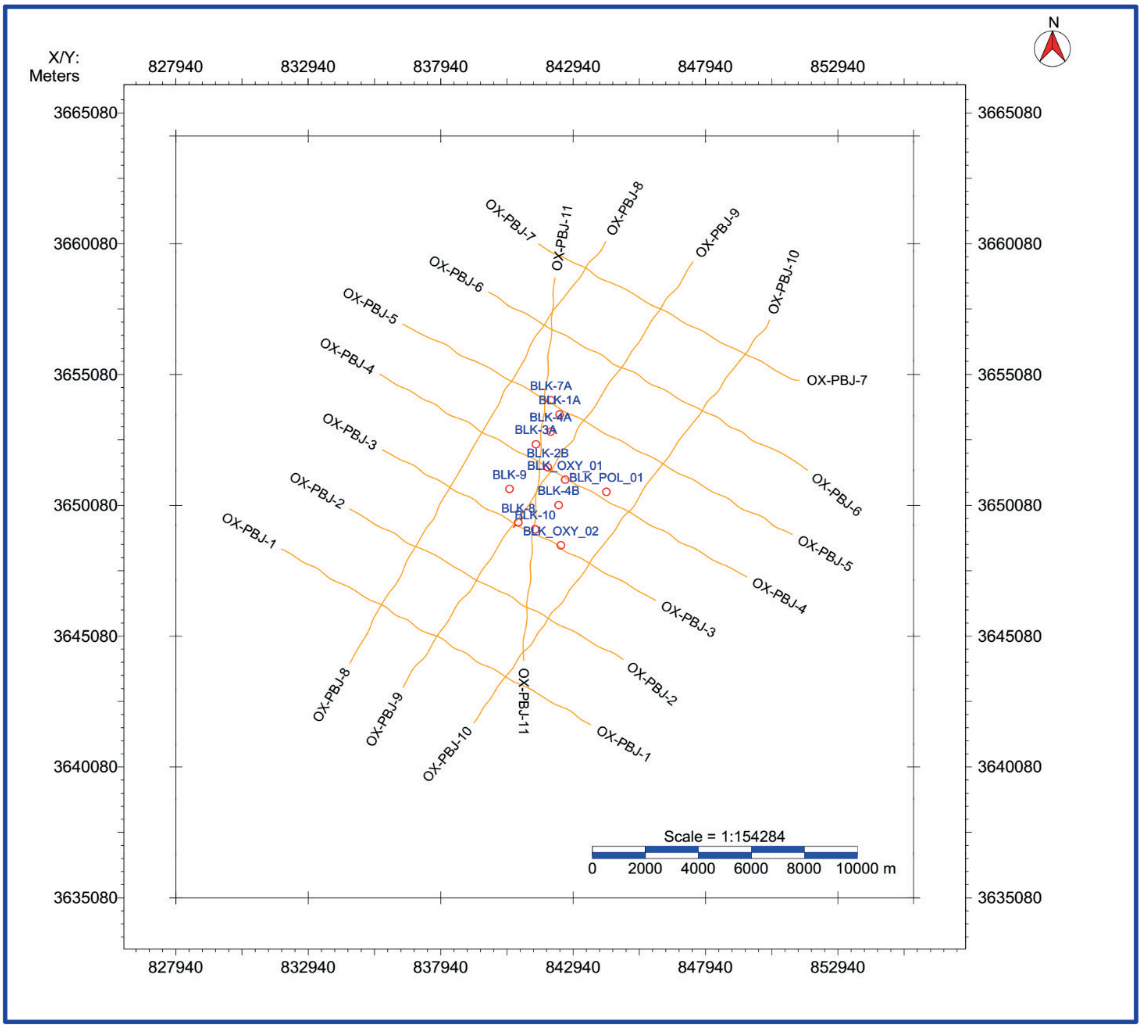

Fig. 5. *Base map representing 2D seismic lines and well locations for study area*

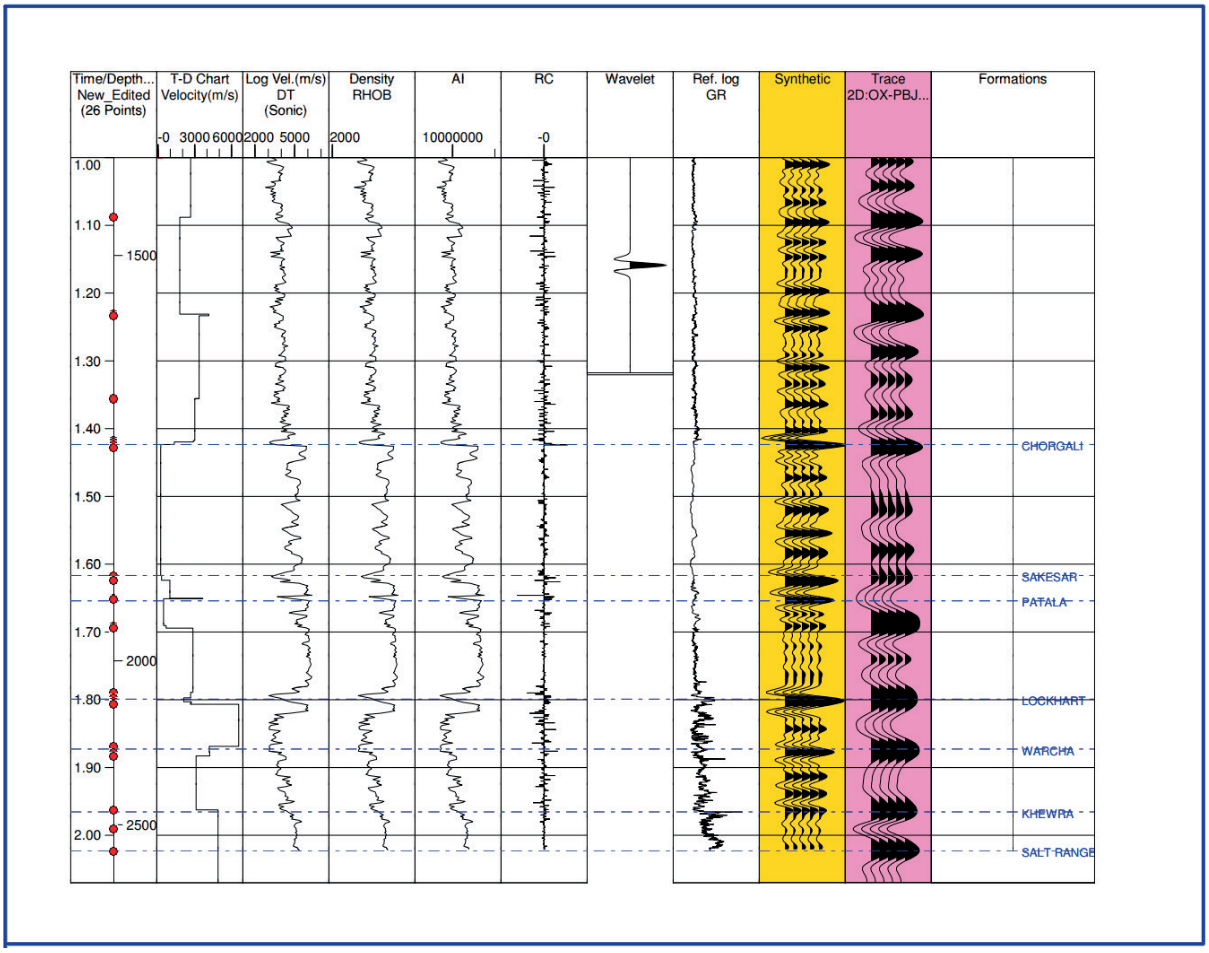

Fig. 6. Synthetic seismogram generated for BLK_OXY_01 well

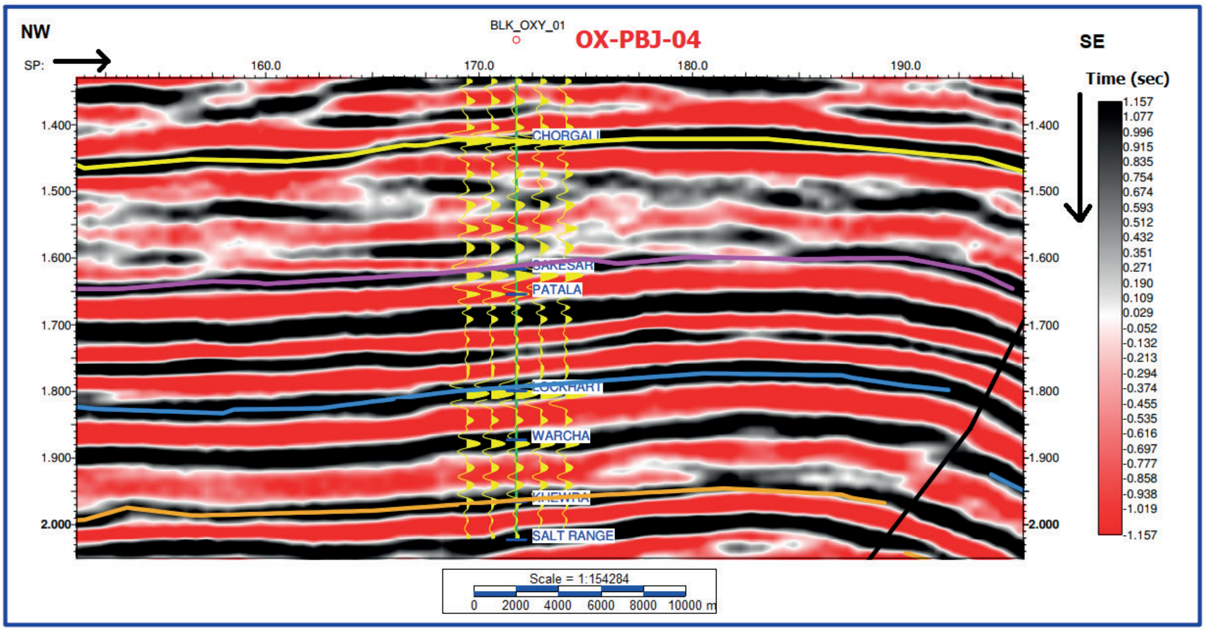

Fig. 7. Synthetic seismogram display of BLK_OXY_01 well on seismic line OX-PBJ-04 with horizons marked

RESULTS AND DISCUSSION

Seismic interpretation

On the NW-SE dip oriented seismic line OX-PBJ-01, five horizons have been marked (Fig. 8). The Basement is the oldest succession in the following interpretation and the Chorgali Formation is the youngest formation. The Basement reflector/formation is the most prominent reflector because of its continuity and is relatively straight. At shot point 145 to 165, another four reflectors i.e., Khewra, Lokhart, Sakesar and Chorgali are clearly show uplifting at around a time of 2.0 sec. In the central portion of this line, a pronounced bulge developed in the post Pre-Cambrian basement strata. This interpretation is in line with previous regional studies that indicate the post-Tertiary Himalayan compression produced an anticlinal structure (Lillie et al. 1987, Baker et al. 1988, Jaumé & Lillie 1988, Pennock et al. 1989, Jaswal et al. 1997).

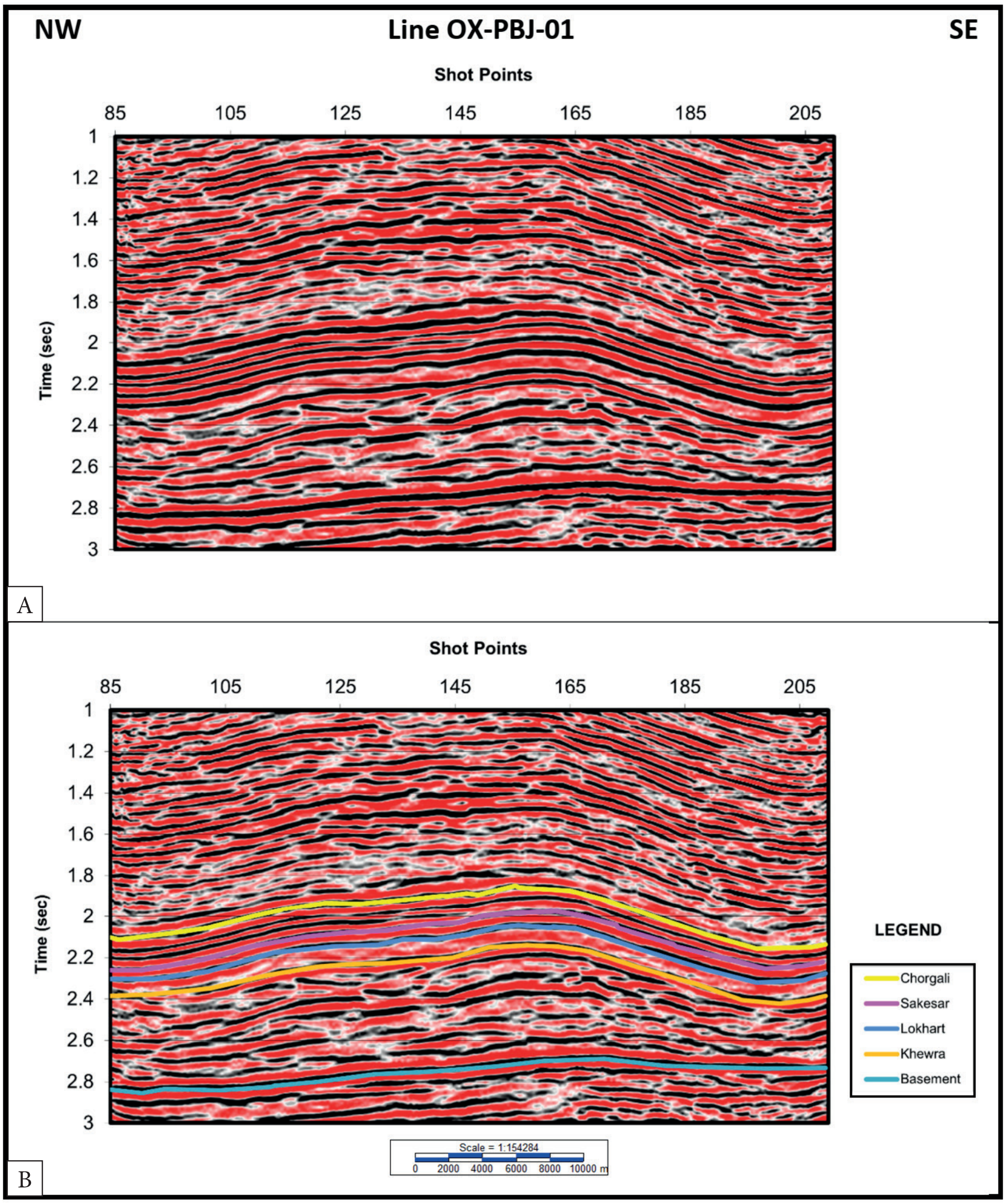

Fig. 8. *Uninterpreted seismic line (OX-PBJ-01) (A) and interpreted seismic line (OX-PBJ-01) (B) showing the anticlinal structure*

Furthermore, working on the interpretation towards north on the dip line OX-PBJ-04, a pop-up structure has been identified which is bounded by two reverse faults (Fig. 9). On the SE direction of this anticline, a major reverse fault, fault 1, is identified. It is curved in a concave style (antithetic to fault 3) and it extends towards the basement through the entire sedimentary succession. Fault 2 is on the same flank of the anticline and is probably decoupling the basement along the Salt Range Formation. On the north western flank of this pop-up structure, another thrust, probably of Pre-Cambrian rocks, extends downwards in Salt Range Formation. Fault 2 is present in the south eastern part of the structure and it disappears in the middle of the structure. The structure is becoming more complex because of the high tectonic activity in the eastern side, probably because of the presence of fault 1 (Fig. 9). In addition to these reverse faults, a normal fault is also present in the basement rocks. Due to the poor resolution of the seismic data along the apered zone, a confirmed interpretation is not possible. However, it has been shon with dotted lines.

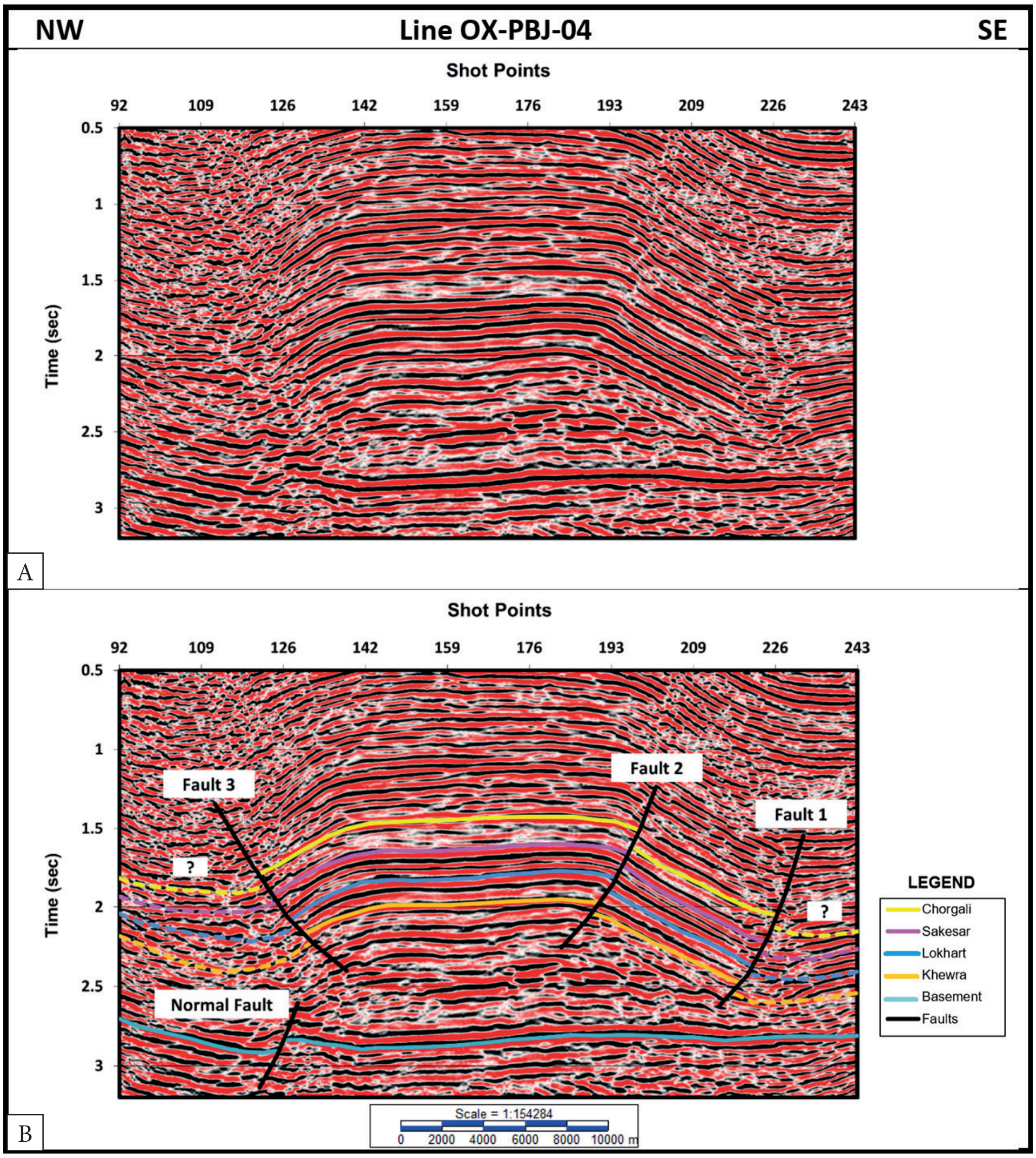

Fig. 9. *NW-SE dip oriented uninterpreted seismic line (OX-PBJ-04) (A) and interpreted seismic line (OX-PBJ-04) (B) showing the pop-up structure bounded by reverse faults*

Time, velocity and depth contour maps of the Chorgali Formation

To prepare the time contour map of the Chorgali Formation, the time values of the horizons were plotted on the base map and then these values were contoured using gridding algorithms. The contours of the same values have been joined. Flex gridding algorithms in SMT Kingdom Software was used for the preparation of the time contour maps. The fault polygons prepared can be seen in the time contour map of the Chorgali Formation (Fig. 10).

Time values for the Chorgali horizon surface ranges between 1.6 to 2.15 sec (Fig. 10). The structure between faults (Fig. 10), marked in a yellow colour, can be interpreted as an anticlinal structure and is known as the Balkassar anticline. This structure is bounded by faults from two sides which makes it more favourable for hydrocarbon accumulation.

To convert the time structure map to a depth structure, the average velocities were used to prepare a depth contour map. The top of the Chorgali Formation has a depth of 2421 m in the Balkassar_OXY_01 well. In this well location, the same contour passes through the well (Fig. 11). This confirms the depth map accuracy and structure is almost identical to that of the time contour map and is proof of the anticlinal geometry of the studied structure.

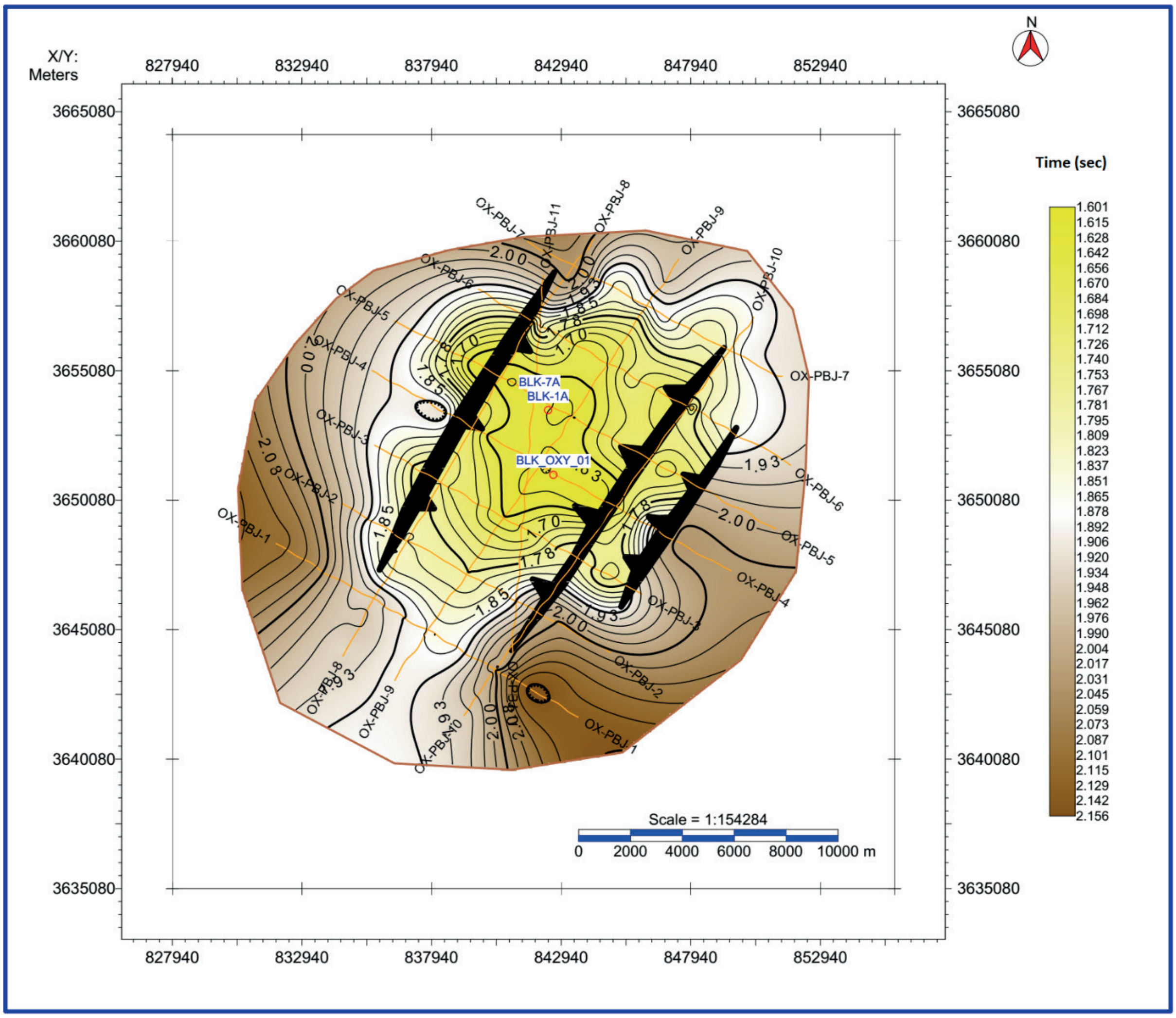

Fig. 10. *Time contour map of the Chorgali Formation. Contour interval is 12 m/sec*

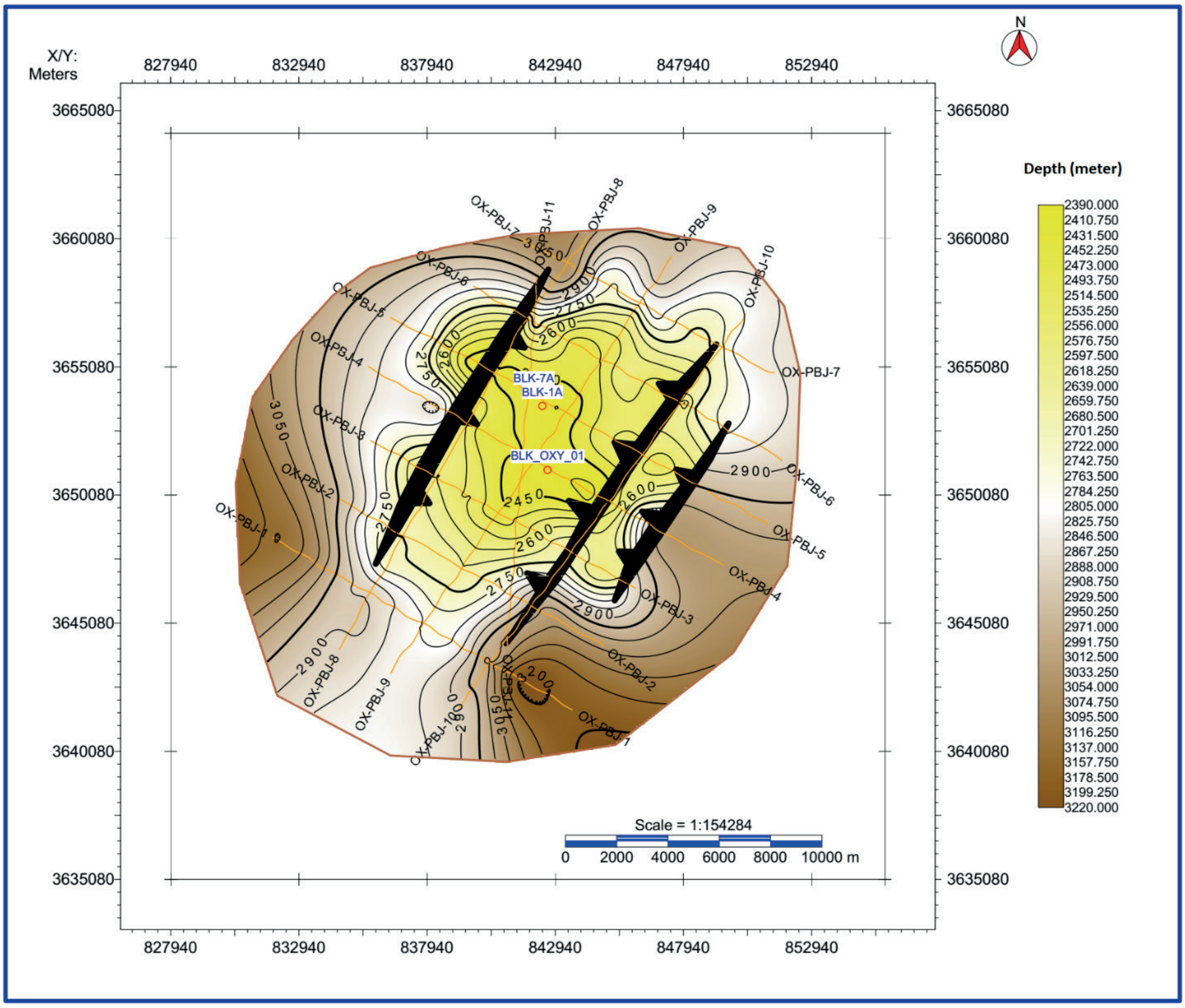

Fig. 11. Depth contour map of the Chorgali Formation

3D model of the Chorgali Formation

Based on the seismic analyses, a 3D model of the Chorgali Formation has been generated to show the subsurface picture of the study area (Fig. 12). This model shows that fault 1 and fault 2 are dipping towards the NW while fault 3 is dipping in opposite direction (Fig. 12). This structure is asymmetrical and dips steeply in a NW direction and gently in a SE direction. This model for the Balkassar anticline proposes a four-way closure for hydrocarbon accumulation. The four-way closure has the same dip as the Indian Plate in the NW direction and therefore it acts as a perfect hydrocarbon trap for oil and gas accumulation in the anticline.

Well correlation

Five wells were correlated (Fig. 13). Chorgali, Sakesar, Lokhart and Khewra formations were marked on the seismic profiles. These wells are not drilled upto the basement. Gamma ray (GR) log is also plotted for each well (Fig. 13). In BLK_OXY_02 well at the level of Chorgali Formation, value of GR log decreases from about 100 API units to around 60 API units because it contains less clay content.

At BLK-4B well, anticlinal structure (which can be clearly seen) confirms the Balkassar anticline which has been interpreted on the time contour map of Chorgali Formation (Fig. 10).

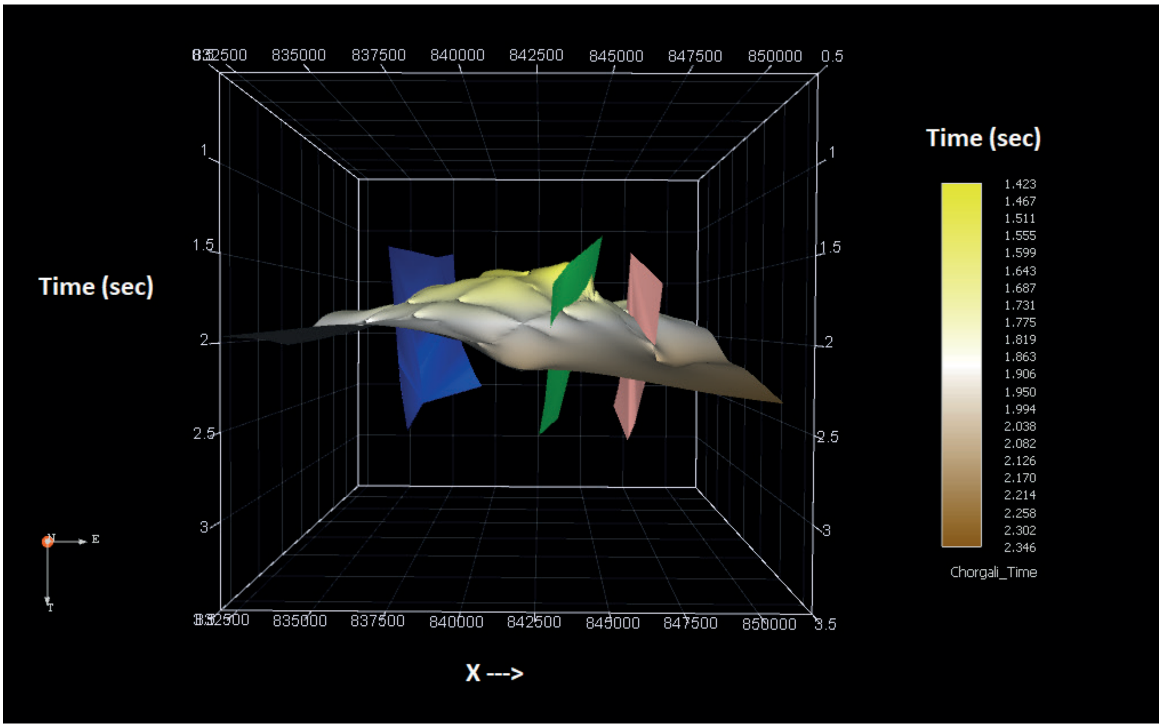

Fig. 12. 3D model of the Chorgali Formation

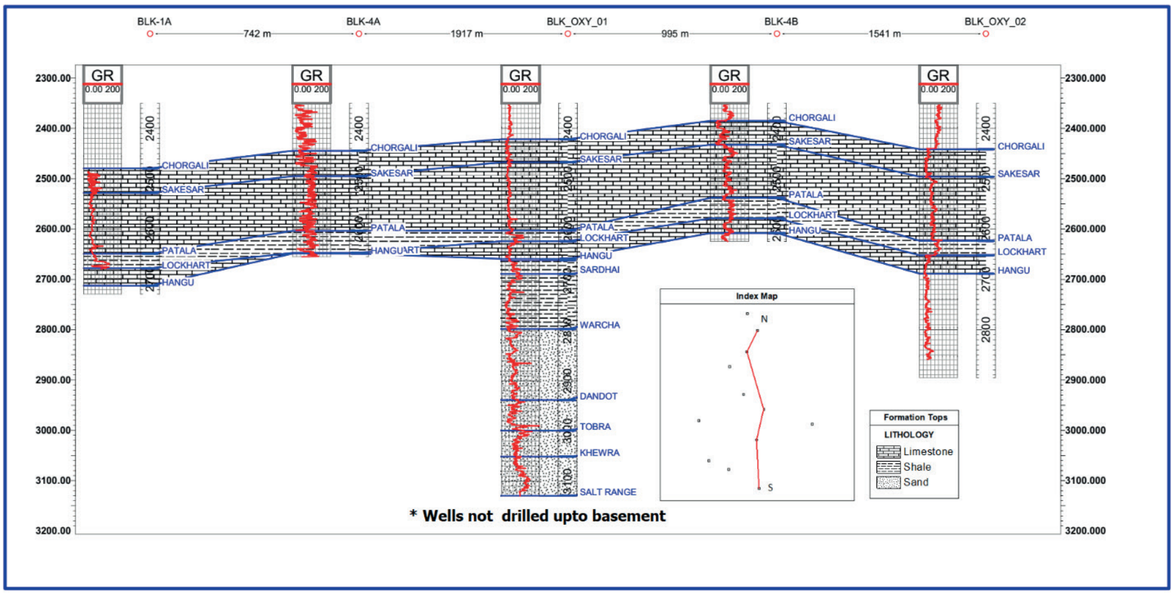

Fig. 13. Correlation of the well data, organized along the NS direction

Structural model of the Balkassar anticline

The seismic profile OX-PBJ-04 was used to prepare the structural mode of the Balkassar anticline. To prepare this model, a code has been written in C# language. Each horizon was divided into four polygons (Fig. 14). Polygon 1 to the left of fault 3, polygon 2 between fault 3 and fault 2, polygon 3 between fault 2 and fault 1, and polygon 4 to the right of fault 1.

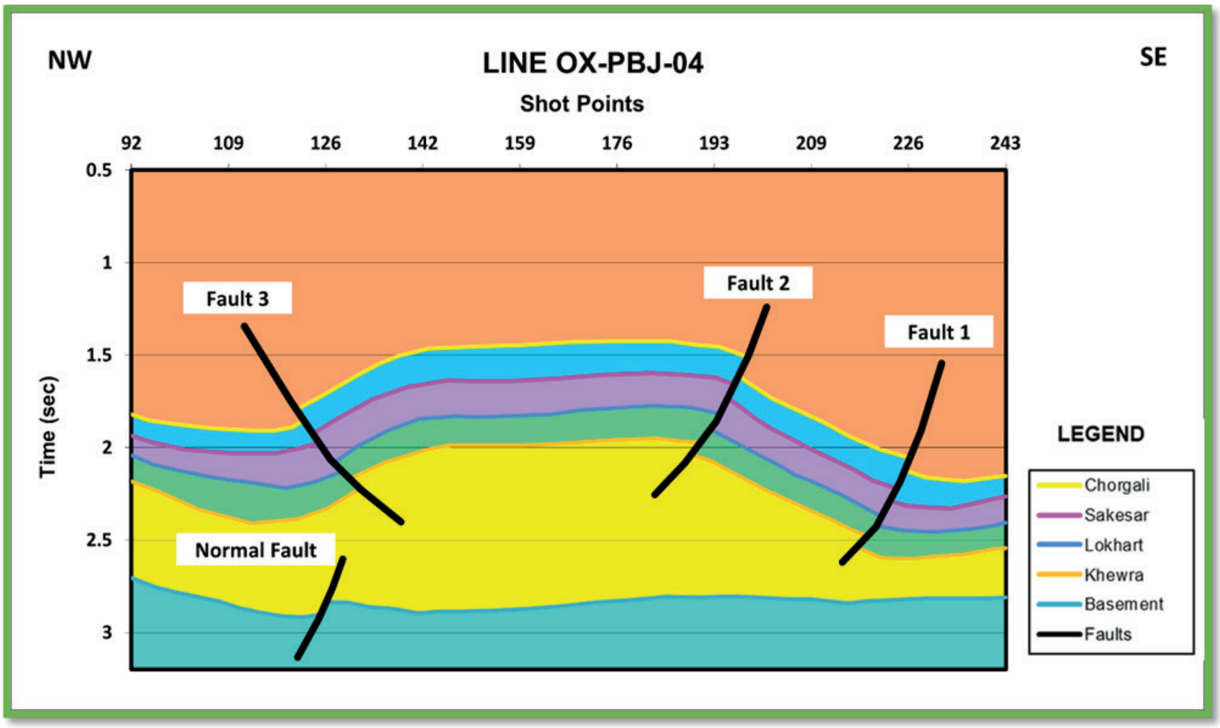

Fig. 14. *Structural model of the Balkassar anticline*

These polygons were filled with different colour for each horizon (Fig. 14). The final model is now giving clearer picture of subsurface layers. The Balkassar anticlinal structure is now more enhanced (Fig. 14).

This research is the first step towards the development of basin analysis (structural deformation, crustal shortening, and tectonic basin subsidence). This tool will be an open-source tool through computer programming and mathematical approach.

The anticline is in fact a four-way closure pop-up structure in which the uneven thickness of Pre-Cambrian evaporites produced a salt-cored anticline. Moreover, it may be a structural trap for hydrocarbon accumulations.

CONCLUSIONS

– The studied Balkassar anticline is asymmetrical and is dipping steeply in NW direction and dipping gentle in SW direction.
– 3D model indicates that fault 1 and fault 2 are dipping towards NW and fault 3 is dipping in opposite direction.
– Well correlation confirms the anticlinal structure interpreted on seismic data as the Balkassar anticline.
– The Balkassar anticline is a four-way closure pop-up anticlinal structure and is a structural trap for the accumulation of hydrocarbons.

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