Pakistan Journal of Hydrocarbon Research
Vol. 22 & 23, (June 2012 & 2013),p.25-40, 23 Figs. 01 Table.

3D Modeling of Subsurface Stratigraphy and Structural Evolution of Balkassar Area, Eastern Potwar, Pakistan.

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ABSTRACT

Balkassar area is located in the eastern part of Potwar sub-basin on the southern flank of Soan Syncline in Himalayan collisional regime. Borehole data obtained from wells drilled in Balkassar area indicate about 4km thick succession of Precambrian to Pliocene sedimentary rocks interrupted by four unconformities present at Precambrian-Eocambrian, Cambrian-Permian, Permian-Paleocene and Eocene-Miocene time. On the basis of information rendered by ten exploratory/development wells and eleven seismic lines, five distinct reflecting surfaces were marked. The Balkassar structure is a long, northeast southwest trending doubly plunging anticline that was created by north-south directed Himalayan forces with the inflow of evaporates form the sides thereby producing shortening in the overlying sedimentary sequence. Compression generated a Thrust 1 at the southeastern limb followed by Thrust 2 in NW direction to the earlier thrust. The structure is bounded by two thrusts at the SE side and a back thrust at the northwestern side of the anticline. At a later stage, a SE dipping back thrust at the northwestern side of the Balkassar anticline was created to merge the Thrust 1 and 2 over the décollement in the Salt Range Formation. Information from 3D models depicts steep limbs at the northwestern side whereas the flanks of anticline are gentle on the southeastern side, both truncated by faults. The Balkassar structure may have reservoirs of Chorgali, Sakesar and Khewra formations levels. At the level of Paleocene Lochkart limestone and Eocene Sakeasr limestone two fault bounded closures are observed which may act as possible prospects for Hydrocarbon exploration.

INTRODUCTION

Delineation of subsurface structural traps to explore hydrocarbon is a prime requisite of many geophysical studies. Analysis of seismic data of Balkassar area coupled with well information through present day software (Kingdom Suit 8.6) provides an insight into structural framework and architecture of a study area. Kohat-Potwar region situated in Sub-Himalayan domain contains significant quantity of hydrocarbons trapped in post Himalayan orogeny related compressional/transpressional subsurface structures (Jaume and Lillie, 1988; Pennock et al., 1989; Raza et al., 1989; Kadri, 1995; Khawaja and MonaLisa, 2005; Moghal et al., 2007). Since first discovery of oil in 1914 at Khaur, about 150 wells for exploration of hydrocarbons have been drilled in the Potwar sub-basin. Most of these wells were unsuccessful due to complex subsurface structuration, anomalous thickness of evaporates and huge succession of molasses that pose abnormal pressure during drilling in the area (Jaume and Lillie, 1988; Kadri, 1995; MonaLisa et al., 2005; Moghal et al., 2007). Balkassar area (32° 56' 23.16" N; 72° 40' 6.25" E) lies on southern flank of the Soan Syncline in Eastern Potwar (Figure 1). The present study works out the stratigraphic variation and structuration in the eastern Potwar sub-basin with special reference to Balkassar area. This 2D seismic interpretation has been completed with the help of 3D models to reveal the subsurface structure of Balkassar area and to infer the possibility of hydrocarbon occurrence and accumulation in deeper horizons of the sedimentary sequence i.e. Khewra Sandstone of Early Cambrian age.

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TECTONIC SETTING

The Himalayan collisional orogen started developing in Cretaceous as a result of continent-volcanic arc-continental collision (LeFort, 1975; Treloar et al., 1989; Kazmi and Jan, 1997). In the complex NW Himalayan tectonic domain, Main Mantle Thrust (MMT), Main Boundary Thrust (MBT) and Himalayan Frontal Thrust (HFT) demarcate major tectonic zones, Figure 1, Tahirkheli et al., 1979; Ghazanfar, 1993. The Potwar sub-basin is about 130-150km broad sheet of Precambrian to Recent rocks. The MBT (Main Boundary Thrust), active since 15 my, and the Salt Range bound the Potwar sub-basin on north and south, respectively. Left lateral Jhelum and right lateral Kala Bagh strike slip faults delineate the basin on east and west (Kadri, 1995; Jadoon et al., 2003), respectively.

The Potwar sub-basin represents a deformed thrust sheet comprised of Northern Potwar Deformed Zone (NPDZ) and Southern Potwar Platform Zone (SPPZ) separated by asymmetrical Soan syncline (Jaswal et al,. 1997; Jadoon et al., 2003). The complexity in the structures located to the north (NPDZ) is higher as manifested by occurrence of tight folds and complex faults as compared to isoclinal fold and thrusts present in the south. In a study by Aamir and Siddiqui (2006) and Jadoon et al., (2003) shows popup structures in the eastern Potwar sub-basin. In most cases the detachment plain as a décollement is in the Salt Range Formation. Moreover, perusal of geophysical data along various transects indicate that the structural elements of Potwar sub-basin exhibit wide variation from east to west (Aamir and Siddiqui, 2006). These structural complications are attributed to a different mechanical behaviour during detachment and propagation between Jhelum and Kala Bagh strike slip faults in addition to occurrence of salt. In the eastern Potwar sub-basin, the structures are left stepping whereas right stepping structures in en-echelon pattern are present in the east of Kala Bagh fault. Due to the combined effect of these faults and associated splays the overall migration of the basin is to the south where along HFT it is thrusting over Punjab Plain.

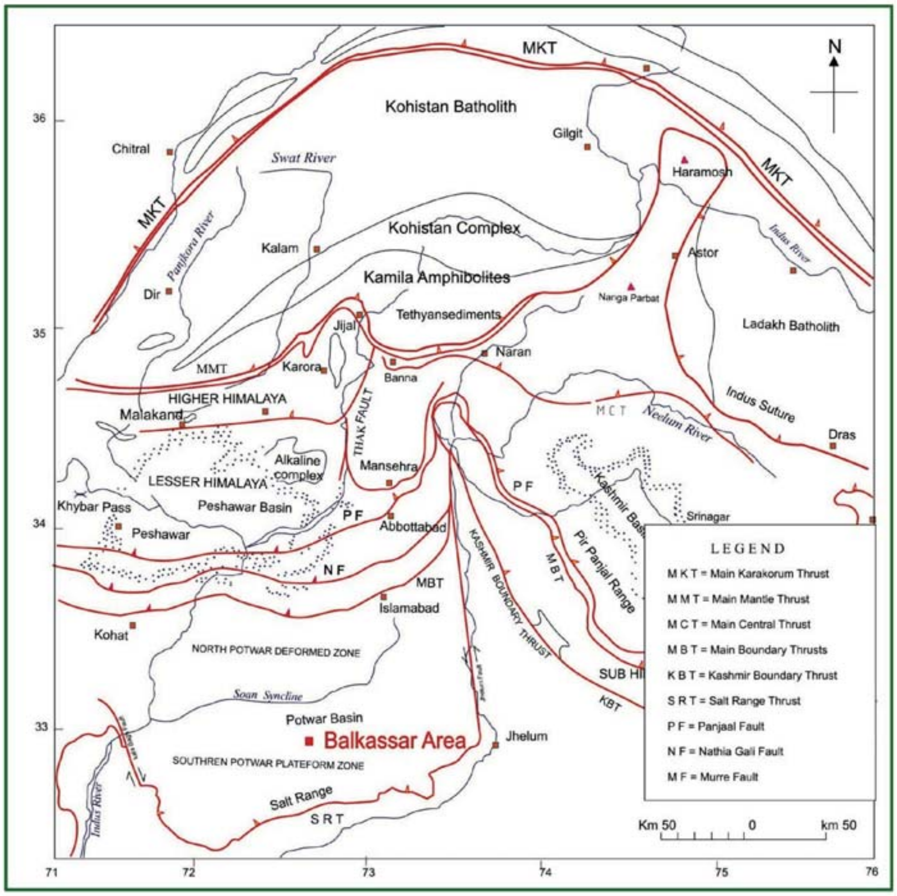

Figure 1 - Tectonic map of Pakistan (Modified after Ghazanfar, 1993) .

STRATIGRAPHY

Subsurface geological data from wells drilled in Balkassar area indicates presence of Precambrian-Eo-Cambrian, Cambrian-Permian, Permian-Paleocene and Eocene-Miocene breaks in deposition (Table 1). Eo-Cambrian Salt Range Formation unconformably overlies the basement rocks, composed of metamorphic and volcanic rocks of Indian Shield (Yeats and Lawrence, 1984), and is overlain unconformably by Early Cambrian Khewra Sandstone. Contrary to well data obtained in Rajian, Missa Keswal and Adhi (Moghal et al., 2007) Kussak, Jutana and Baghanwala formations were not encountered in Balkassar Oxy-01-Well. Tobra Formation (conglomerates) of lower Permian age unconformably overlies the Khewra Sandstone. Dandot, Warchha and Sardhai formations of lower Permian age mainly composed of sandstone (Dandot and Warchha formations) and shales (Sardhi Formation) successively overly Tobra Formation. The area remains exposed from upper Permian through lower Paleocene. In Danian, Tertiary sequence with Hangu Formation at the base was deposited over Sardhi Formation. In the central and northern Salt Range, like Karsal, Dhurnal, Meyal and Dakhni wells (Moghal et al., 2007), a Permian, Triassic, Jurassic and Cretaceous sequence is present (Shah, 2009). In Balkassar area, Permo-Triassic (between Chhidru and Mianwali formations) and Triassic-Jurassic (between Kingriali and Datta formations) unconformities overstep a Permian-Tertiary (between Sardhi and Hangu formations) composite unconformity. Paleocene sequence comprising of Lockhart and Patala formations is well developed. Nammal, Sakesar and Chorgali formations of lower and middle Eocene in age conformably overlies Paleocene strata. Rawalpindi Group (Murree and Kamlial formations) with Himalayan provenance (Chaudhry et al., 1998) was deposited unconformably over middle Eocene Chorgali Formation. Chinji and Nagri formations are present at the top of Miocene molasses sequence in Balkassar area.

SUBSURFACE STRUCTURAL ANALYSES

Data and methodology

Analyses of subsurface geology are usually carried out utilizing well logs, cores and variety of seismic data (Telford et al., 1990). Subsurface structural analyses in the present work were worked out through lithological information provided by borehole data and 2D seismic data. Borehole lithological data obtained from (N-S) oriented wells (Balkassar 1A, Balkassar 4A, Balkassar OXY 01, Balkassar 4B and OXY 02) and (E-W)

Table 1 - The stratigraphic section of Balkassar OXY-01 well .

FORMATION	AGE	LITHOLOGY	TOP (M)	Thickness (m)
Nagri	Pliocene	Sandstone	0.00	478.82
Chinji	Miocene	Clay, sandstone	78.27	929.29
Kamlial	Miocene	Sandstone	1408.11	106.68
Murree	Miocene	Sandstone	1514.78	906.74
UNCONFORMITY				
Chorgali	Eocene	Limestone, shale	2421.52	45.72
Sakesar	Eocene		2467.24	135.63
Patala	Paleocene	Shale	2602.87	21.34
Lockhart	Paleocene	Limestone	2624.20	35.05
Hangu	Paleocene	Sandstone	2659.25	27.34
UNCONFORMITY				
Sardhi	Early Permian	Clays	2686.68	109.72
Warchha	Early Permian	Sandstone	2796.40	143.73
Dandot	Early Permian	Sandstone	2938.13	60.96
Tobra	Early Permian	Conglomerate	2999.09	51.80
UNCONFORMITY				
Khewra	Early Cambrian	Sandstone	3050.90	78.33
Salt Range	Pre-cambrian	Evaporates, marl	3129.23	o.77

oriented wells (Balkassar 06, Balkassar OXY 01, Balkassar 07, Balkassar 05 and Balkassar 09 (Figure 2, 3 and 4). The seismic survey of the project area was conducted by Occidental Petroleum Corporation (OXY) in 1981, a California-based oil and gas exploration and production company. The survey was conducted for subsurface interpretation in the Eastern Potwar Area (Balkassar) which lies in the UTM Zone 43N. For seismic interpretation of Balkassar area four seismic lines along the strike (NE- SW oriented) and seven seismic lines along the dip (NW-SE oriented) were interpreted (Figure 5).

The borehole data for subsurface lithological logs and correlation was plotted with the help of Log plot and Power-Point and seismic interpretation was carried out in geophysical software Kingdom Suit 8.6, Seismic Micro Technology (SMT). On seismic lines, as a first step reflectors were identified on the basis of prominent coherency of reflectors visible on the lines from the subsurface interfaces. For further refinement information of subsurface depths was utilized from well data to pick five prominent reflectors. This process was followed by correlation of the reflectors, marking fault locations, carrying out velocity analysis, digitization and time to depth conversion of the seismic data, construction of geo-seismic cross-sections and making of structural contour maps for subsurface seismic analysis.

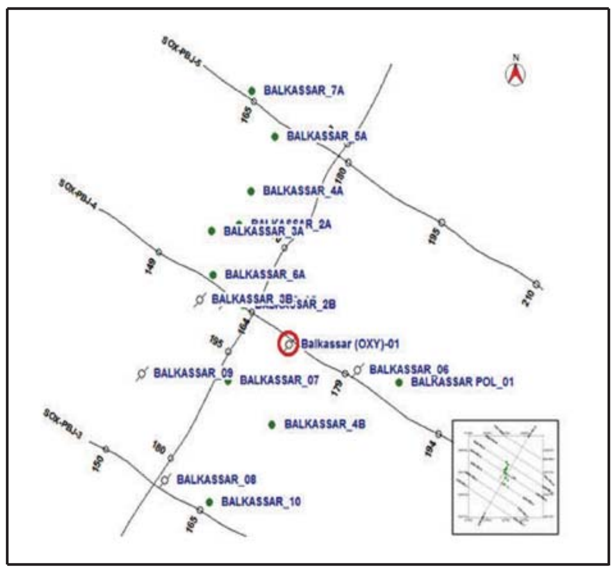

Figure 2 - Location of different Wells on the Balkassar Anticline .

RESULTS AND DISCUSSION

The overall aim of seismic interpretation is to aid in constructing the most accurate sub surface structural modal and to know the exact timing of the structural pattern development through 3D models. This model is helpful to understand the compartmentalization of the structure for hydrocarbon production.

In Balkassar OXY-01-Well, Salt Range Formation is present at a depth of about 3125m and three unconformities at the base and top of Cambrian and top of Permian are present (Figure 3 and 4). Other four wells were drilled up to base of Hangu Formation and abandoned. Thickness of Hangu Formation in the south is more as compared to thickness in the well logs towards south (Figure 3). Well data along general strike of Balkassar area shows that well Balkassar OXY-01 is towards the paleo-high as compared to well Balkassar OXY-02. Similarly, a monoclinal structure is present at Balkassar well 4A. A dip oriented correlation of Balkassar wells 09, 05, 07, Oxy-01 and 06 shows minor changes in thickness from east toward west (Figure 4).

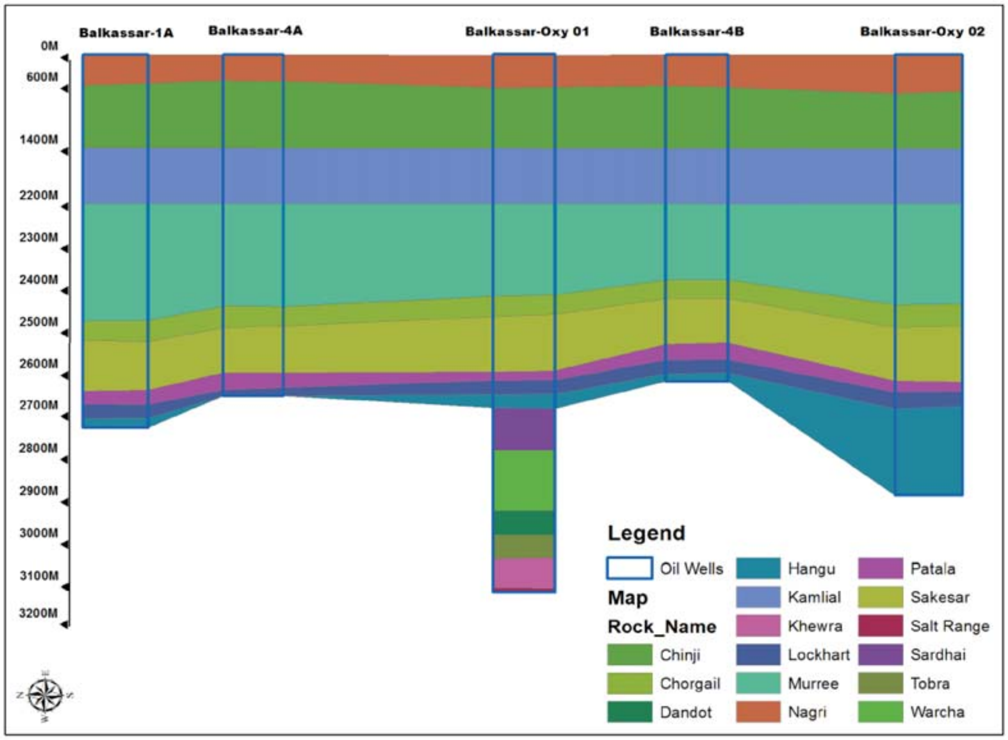

Figure 3 - TStrike oriented stratigraphic correlation of different wells.

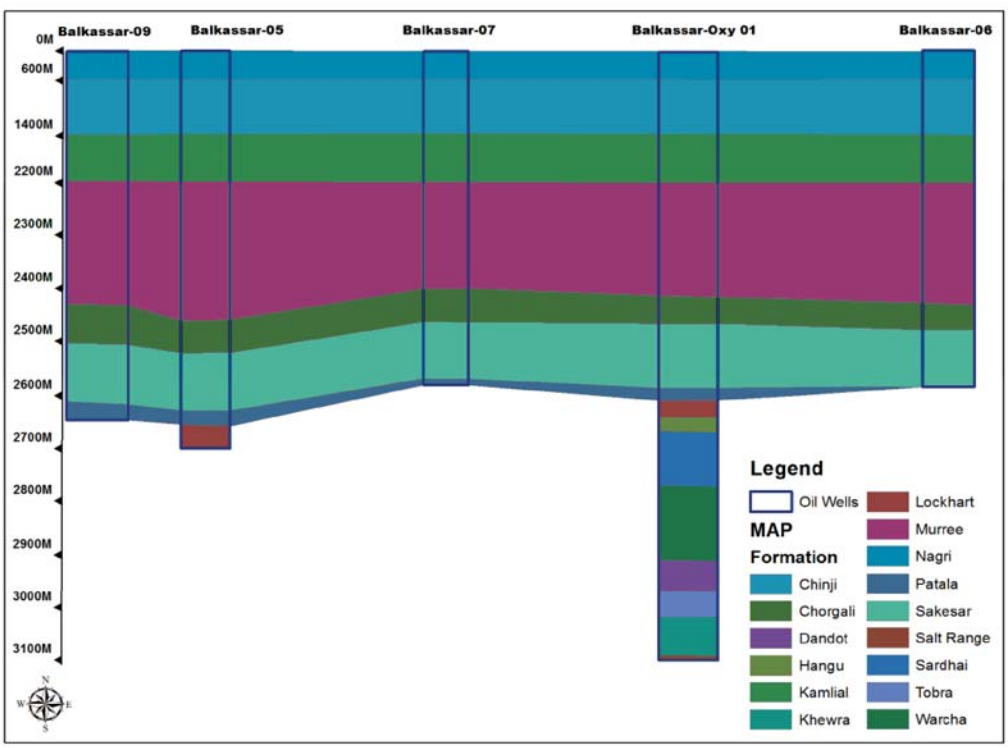

Figure 4 - Dip oriented stratigraphic correlation of different wells.

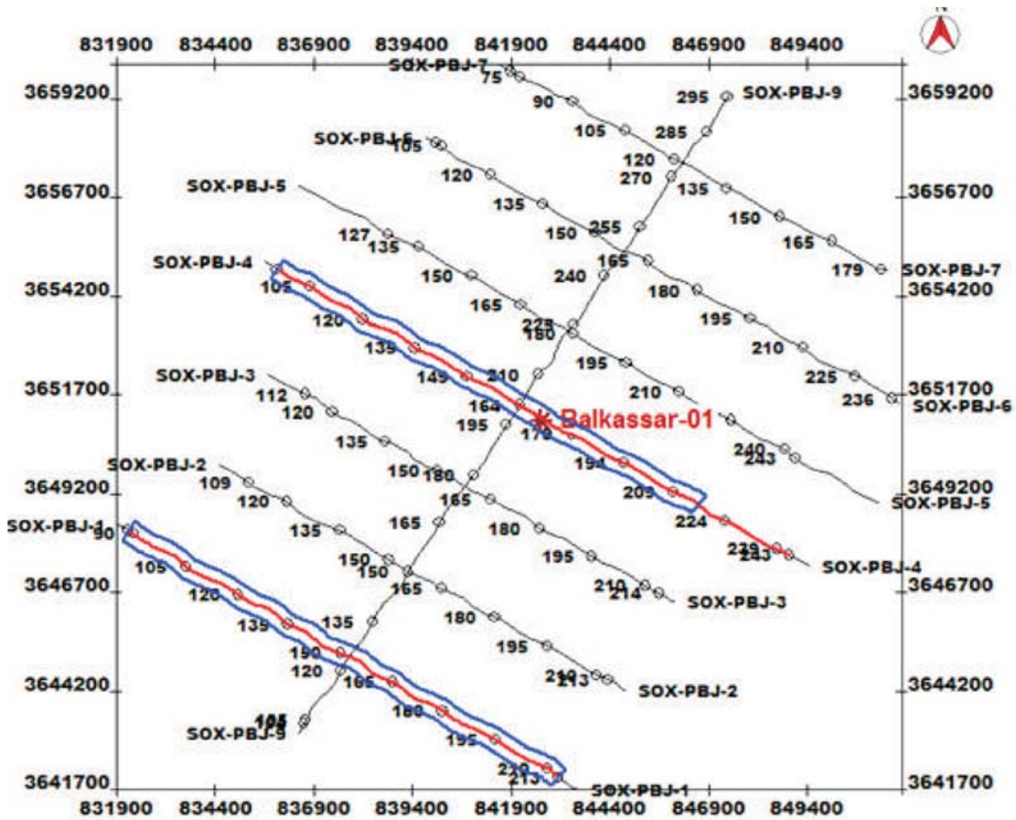

Figure 5 - Orientation of seismic lines of project area.

Interpretation of Seismic Lines

On NW-SE dip oriented seismic line SOX-PBJ-01 five reflectors representing Basement, Khewra Formation, Lockhart Limestone, Sakesar/Nammal formations and Chorgali Formation have been marked (Figure 6). In the central portion of the Figure 6, a pronounced bulge has developed in the post Precambrian Basement strata. Many studies exist (Lillie et al., 1987; Baker et al., 1988; Jaume´ and Lillie, 1988; Pennock et al., 1988; Jaswal, 1997) to demonstrate that post Tertiary Himalayan compression from NW direction produced a bulge/anticlinal structure. In such cases, a thick sequence of evaporates of the Salt Range Formation act as a basal décollement surface (Jaume´ and Lillie, 1988; Smit et al., 2003). Further towards north on the dip line SOX-PBJ-04, a pop-up structure (Balkassar anticline) bounded by two thrusts is identified (Figure 7). On the SE direction of the Balkassar anticline, a major thrust, Thrust 1, is curved in concave style (extending) towards the basement offsetting the whole sedimentary succession. The SE directed Thrust-1 has its imbricate thrust, Thrust-2, on the same flank of the anticline, decoupling the basement probably along Salt Range Formation. On the northwestern flank of the pop-up structure, a back thrust, in post Eo-Precambrian rocks extends downward in Salt Range Formation as fault plains of Thrust 1 and 2. Whereas, Thrust 2 is present in the south eastern part of the structure and it disappears in the middle of the structure. The intensity of the structuration is higher in the east towards the Jehlum Fault (Figure 7). In addition to these thrusts, a normal fault is also present in the Basement rocks that represent tectonic loading of the Indian plate in the north (Pennock et al., 1988) at about 6 to 5 my ago (Blisniuk et al., 1998).

3D Structural Model

A total 6 models have been generated at different levels (Permian - Eocene) to know the clear subsurface picture of the study area. With the help of 3D structural models, subsurface structural trend, its closure and reservoir area can easily be interpreted.

A composite 3D model for faults and folds present in Balkassar anticline at the level of Chorgali horizon depicts that the Thrust 1 and its imbricate Thrust-2 , as described earlier, is dipping towards NW and the back-thrust is dipping in the opposite direction (Figure 8 and 9). The asymmetric anticlinal structures steeply dipping to NW side and its dip is gentle in the SE limb. Similarly, the behavior of the Balkassar structure at Sakesar Limestone of Eocene age (Figure 10 and 11), Paleocene Lockhart Limestone (Figure 12 and 13) and Cambrian Khewra Sandstone level (Figure 14 and 15) is the

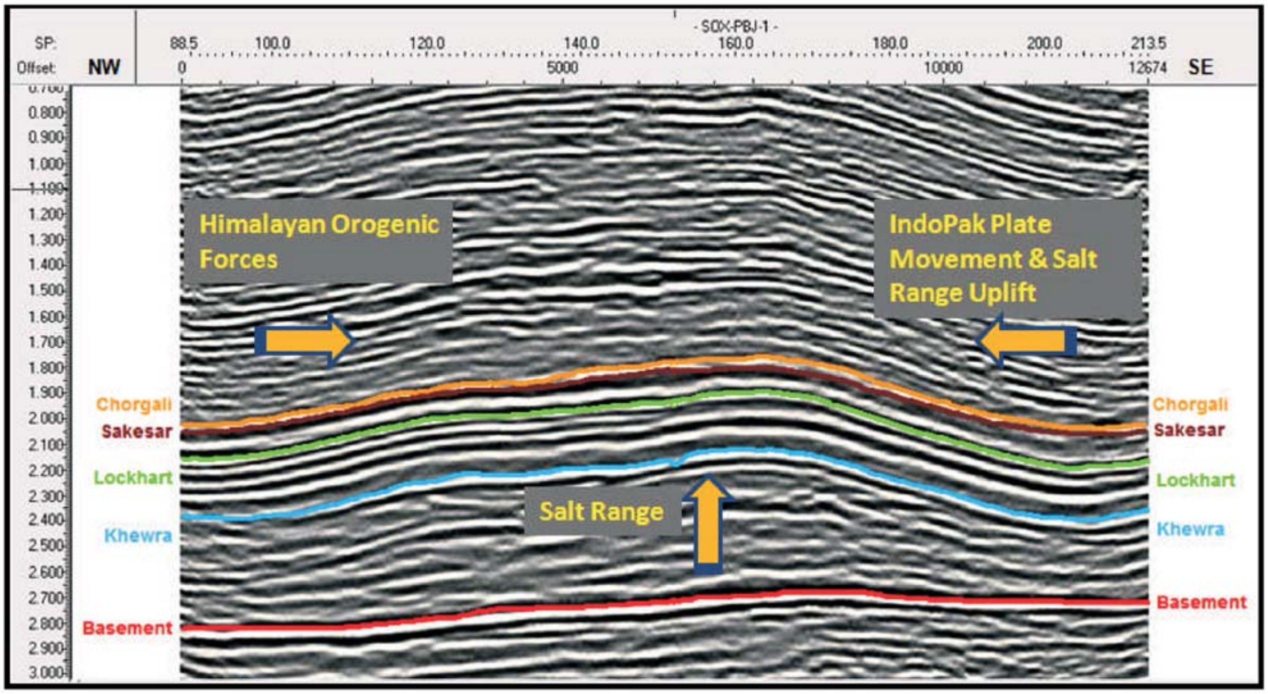

Figure 6 - NW-SE dip oriented seismic line (SOX-PBJ-01).

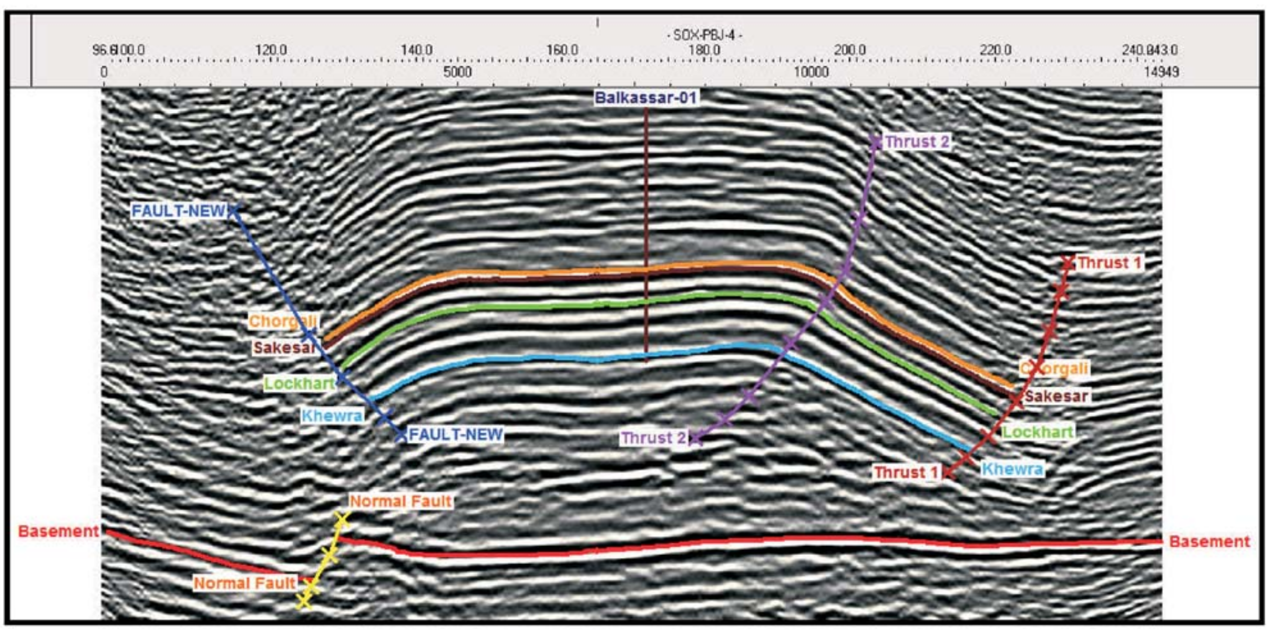

Figure 7 - NW-SE dip oriented seismic line (SOX-PBJ-04), showing different horizons and interpreted structures.

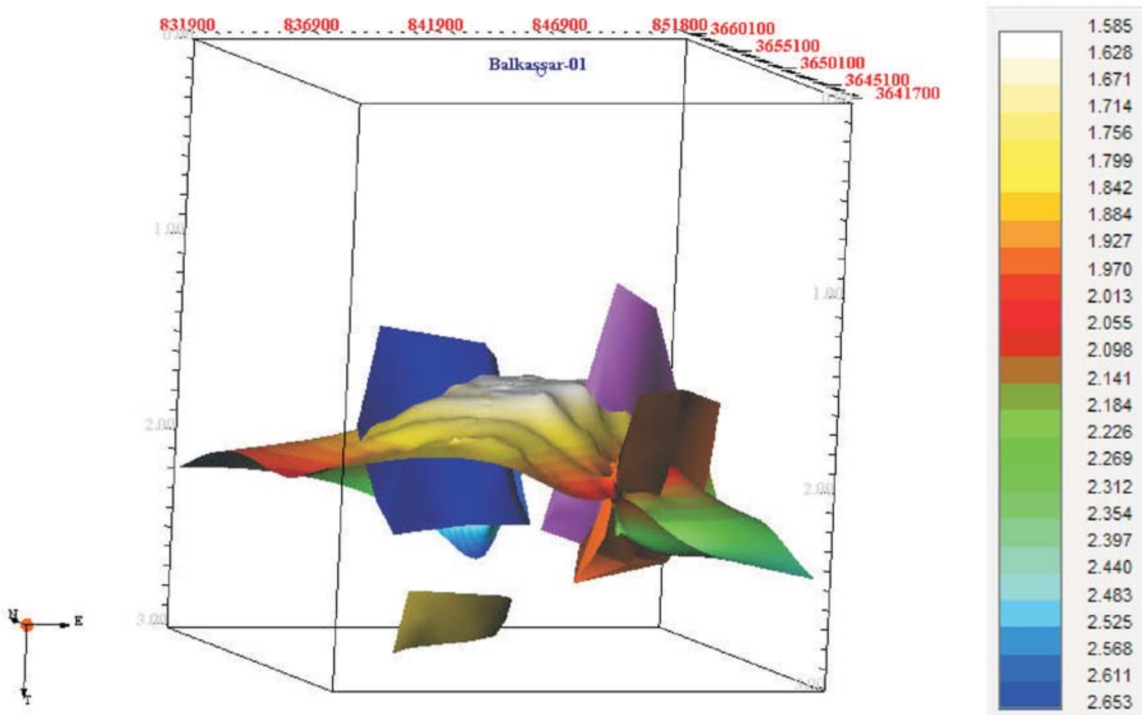

Figure 8 - 3D model of Balkassar anticline at the level of Chorgali Formation.

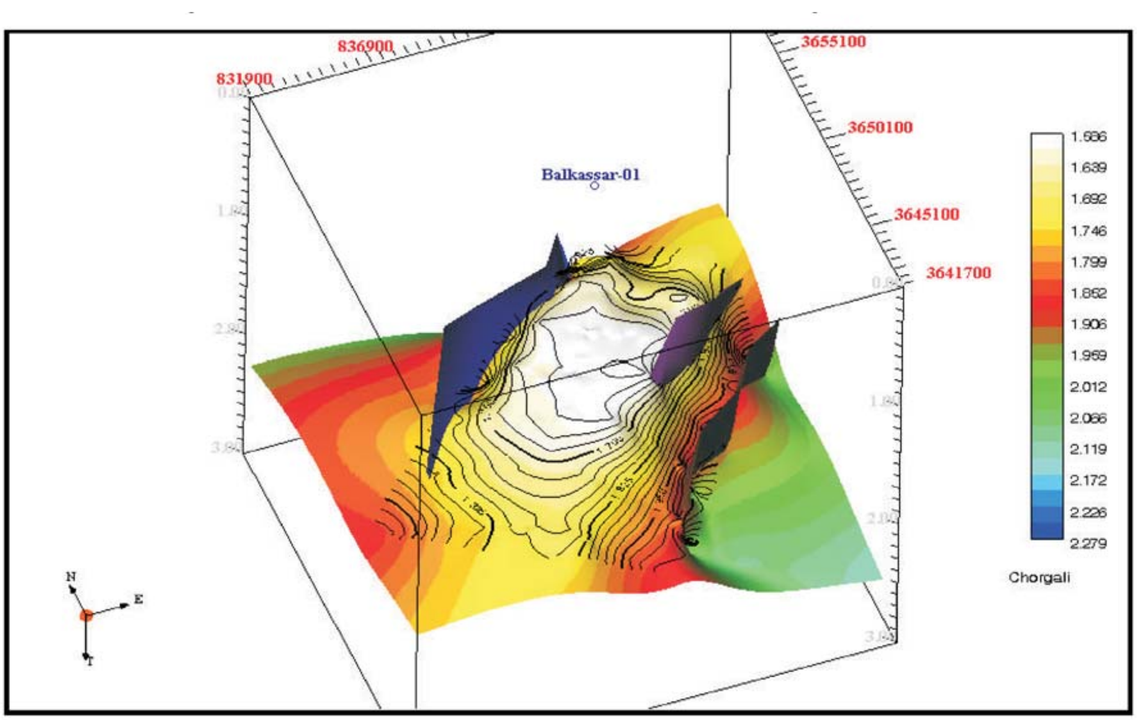

Figure 9 - 3D model of Balkassar anticline with contours at the level of Chorgali Formation.

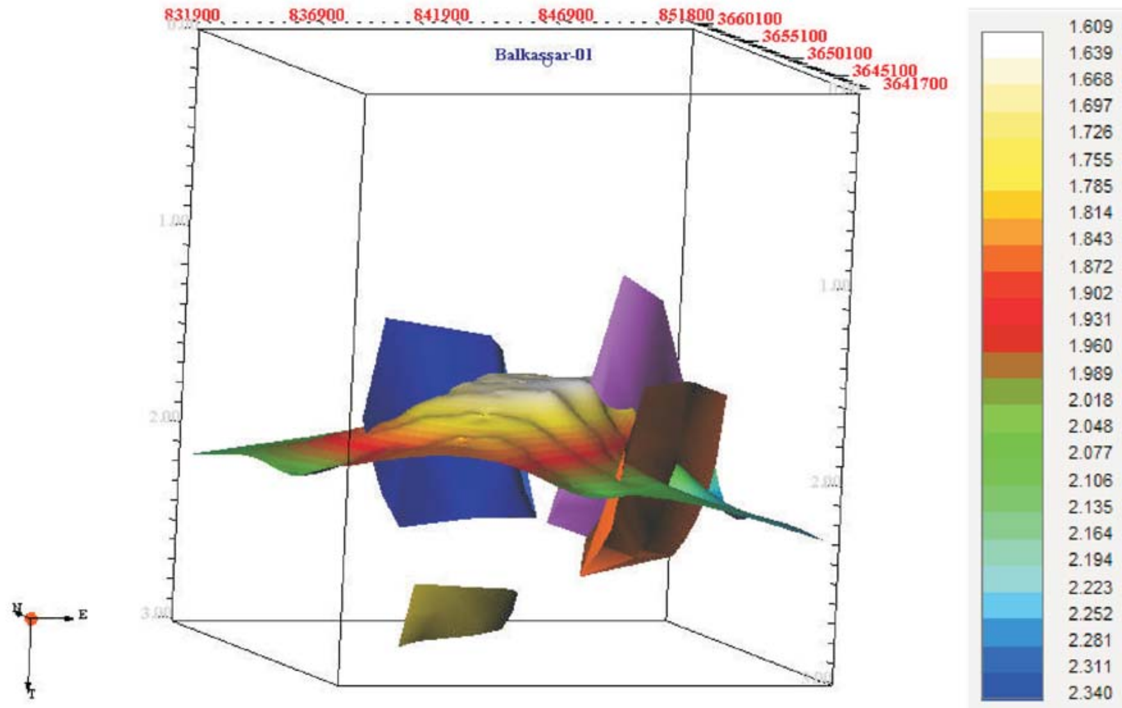

Figure 10 - 3D model of Balkassar anticline at the level of Sakesar Limestone.

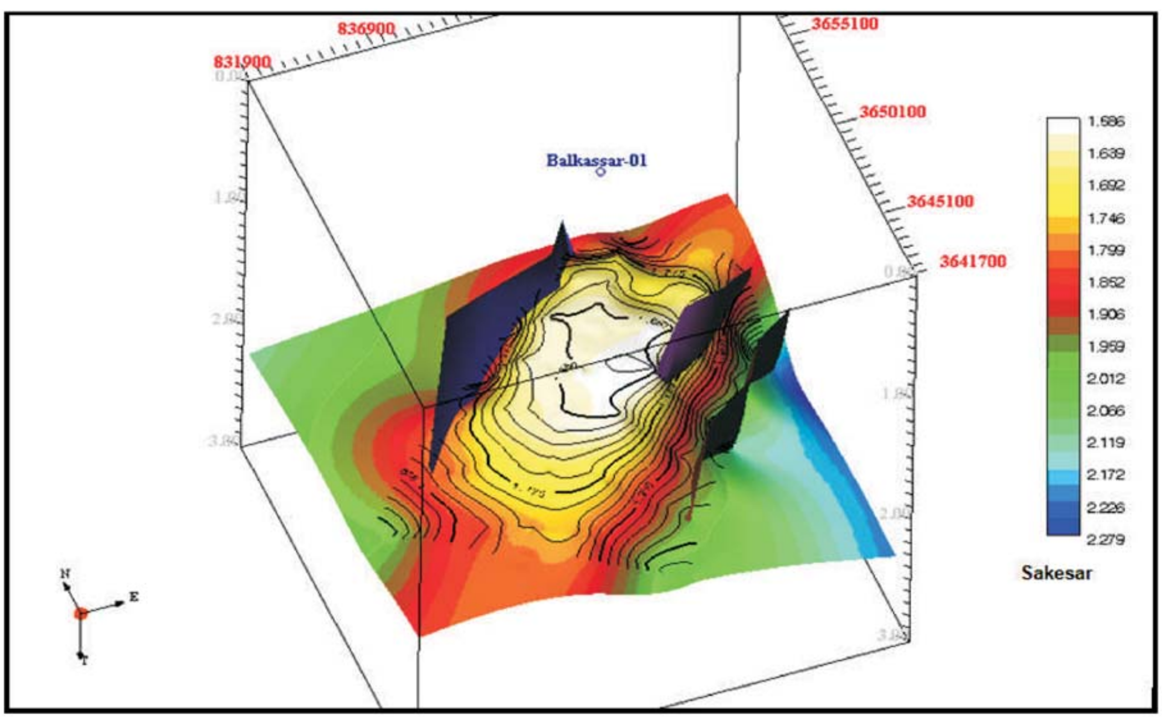

Figure 11 - 3D model of Balkassar anticline and contours at the level of Sakesar Limestone.

same as Chorgali Formation. However, below Cambrian rocks effect of salt tectonics is present whereas the Basement reflector is relatively smooth (Figure 16 and 17). Overall, the perusal of all the 3D models (Figure 8 to 18) constructed for Balkassar anticline indicate that the subsurface structure, due to its double plunge, is proposing a four way closure for the hydrocarbons accumulation. As the overall dip of the Indian plate is in the northwest direction therefore the four way closure also has the same dips. This results in increase in the thickness of strata in the northwest thereby facilitating up-dip migration of the hydrocarbon to accumulate in the center of an anticlinal structure. As the size of the structure narrows in the eastern part and widens in western part thereby suggesting that well may be planned in central part of the structure.

TIME CONTOUR MAPS

Time Contour map of Chorgali Formation

Time contour map of NE-SW oriented Balkassar anticline at the level of the reflector marked to delineate Chorgali Formation (Figure 19) shows a flat and shallow area (TWT= Two way travel time 1.590 to 1.690 sec) that forms NE-SW oriented crustal part of the anticline. The structure in the SE and NW side of Balkassar anticline is ambiguous, forms peaks and saddles and its depth increases on the sides (Figure 19). Peaks and saddles might have been originated due to compressional forces and movement along the faults. The two waytravel time (TWT) for these peaks at Chorgali level ranges from 2.170 to 2.470 seconds on north western side whereas the time is from 2.010 to 2.370 seconds on south eastern side. Moreover, time contour map generated for Chorgali Formation depicts that both limbs of the Balkassar anticline are dipping steeply and reverse and back thrusts terminate the flanks. In all, Balkassar anticline is a four way closure structure and favorable for the hydrocarbons accumulation.

Time Contour maps of Sakesar/Lockhart/Khewra formations

Time contour maps generated for Sakesar /Lockhart/Khewra formations in Balkassar anticline depict a flat crustal part at these levels (Figures 20, 21, 22). The contours are broader in the NW side of Balkassar anticline indicating that the limbs of the anticline have become gentler in this direction, whereas in the SE direction the limbs between the Thrust 1 and 2 have steeper dip which is probably due to the regional compressional tectonic regime. However, dips become gentler away from the Thrust 1 in SE direction due to fading compressional forces. At the level of Paleocene Lockhart Limestone contour closure (about TWT 1.800 to 1.940 seconds) along the back thrust is present which may act as a possible lead for hydrocarbon (Figure 21). Similarly at the level of Eocene Sakesar Limestone two fault bounded

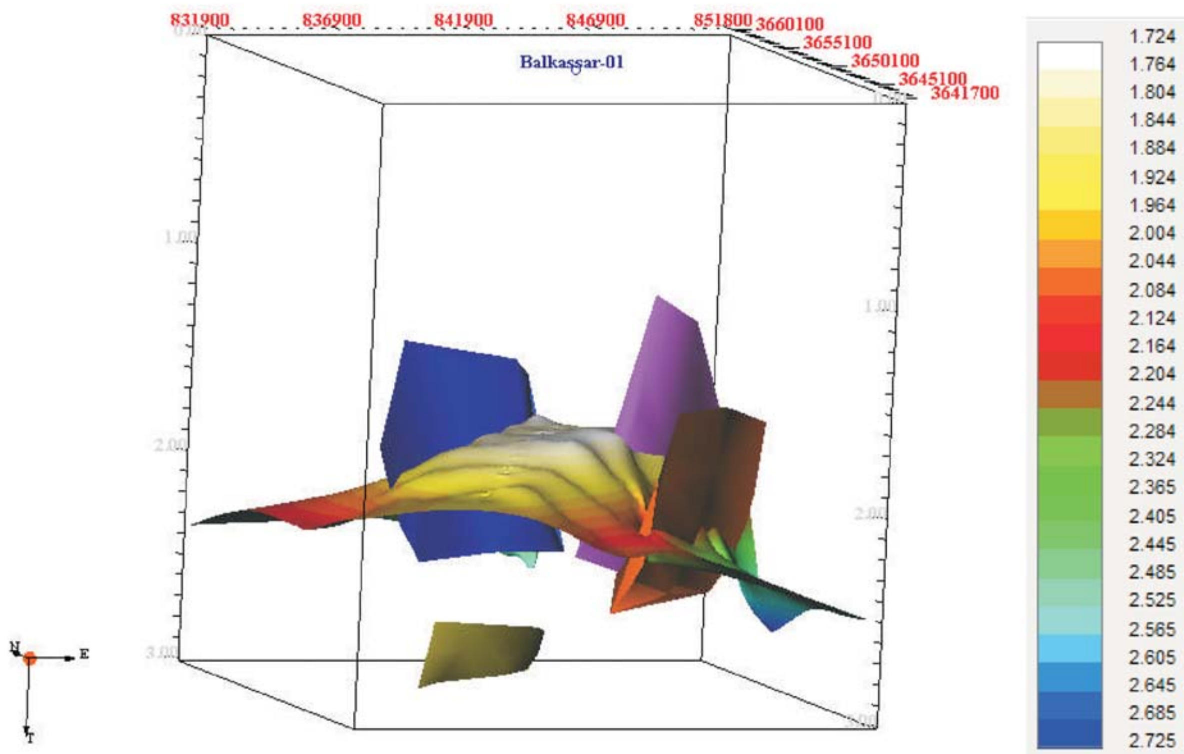

Figure 12 - 3D model of Balkassar anticline at the level of Lockhart Formation.

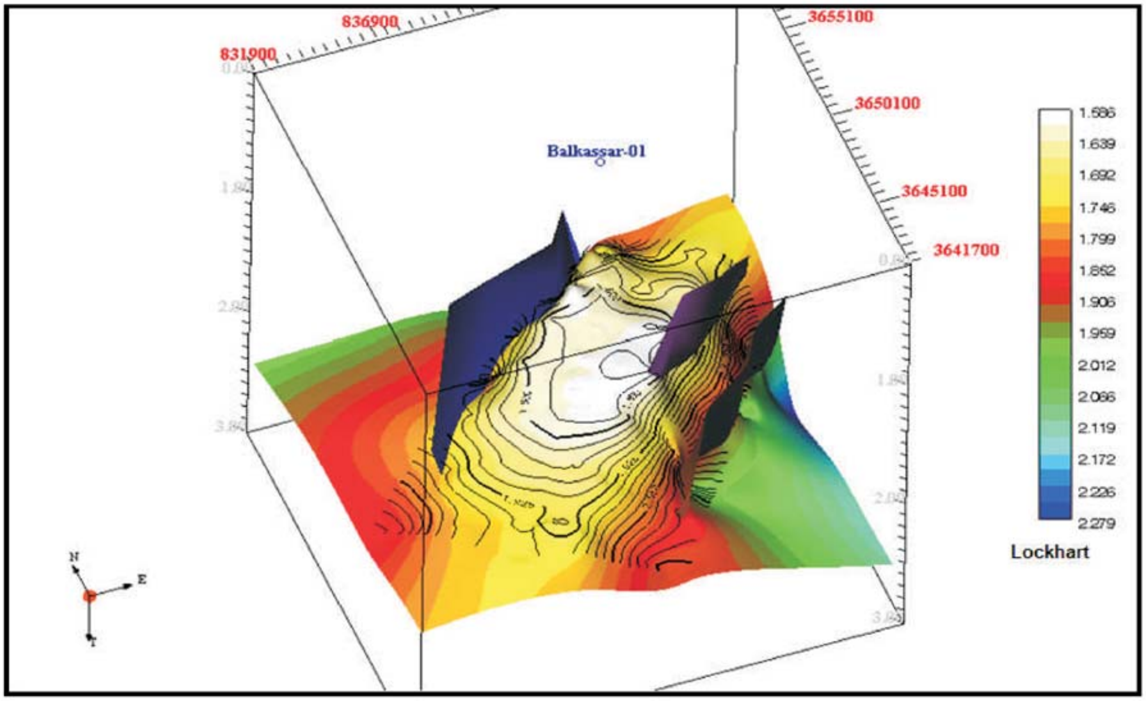

Figure 13 - 3D model of Balkassar anticline at the level of Lockhart Formation indicating contours.

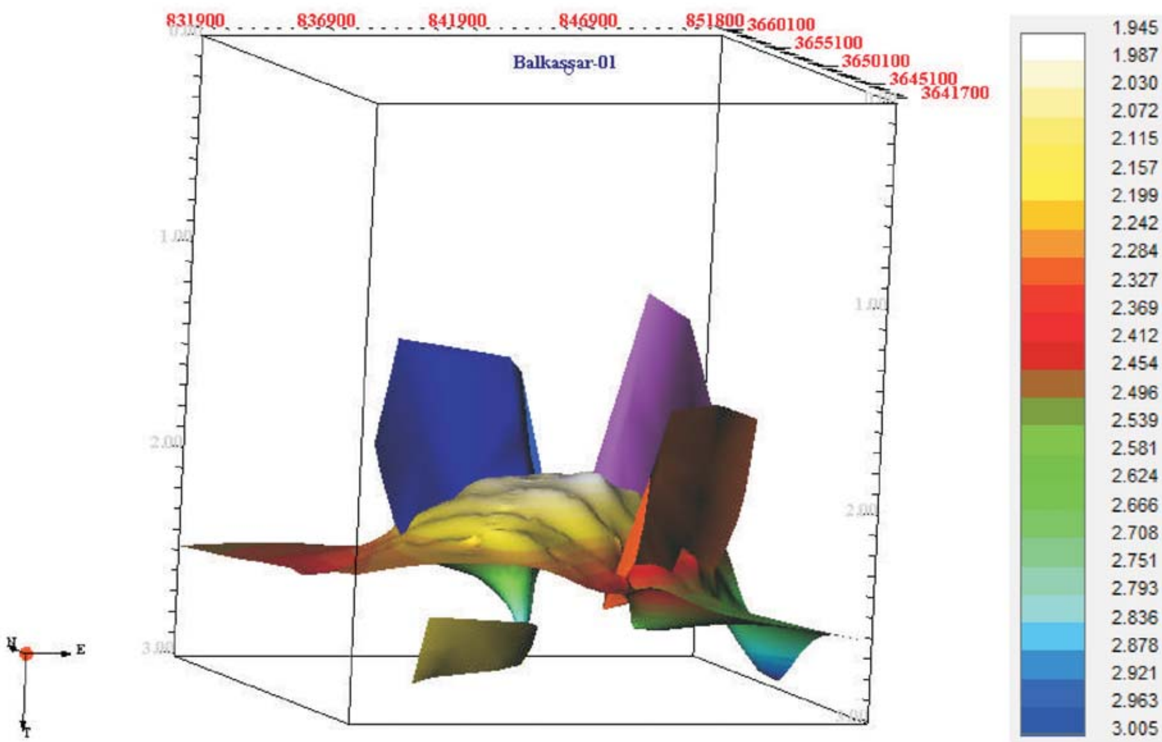

Figure 14 - 3D model of Balkassar anticline at the level of Khewra Sandstone.

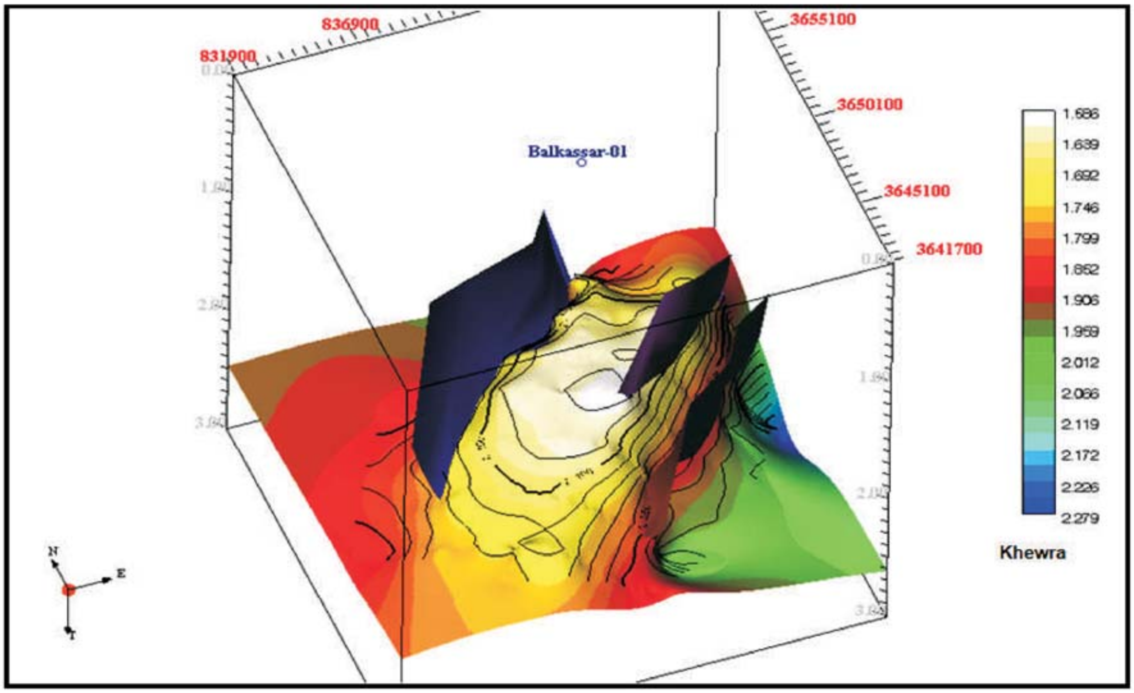

Figure 15 - 3D model of Balkassar anticline and contours at the level of Khewra Sandstone.

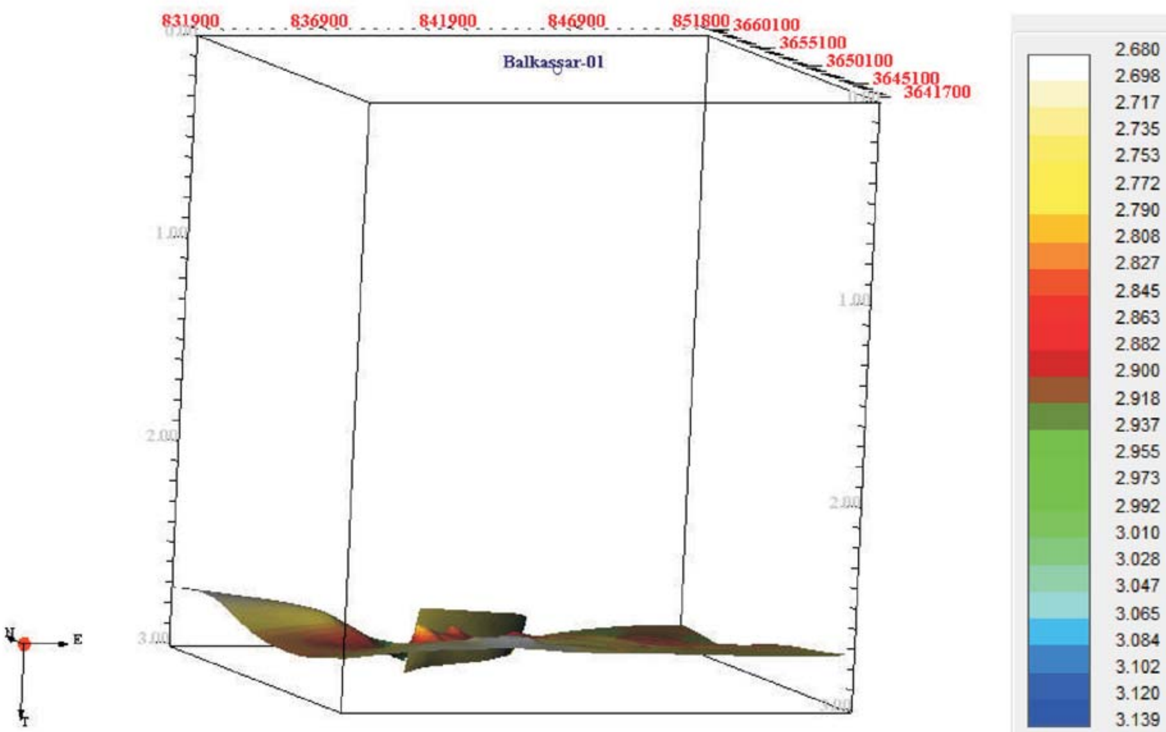

Figure 16 - 3D model of Balkassar anticline at the level of Basement.

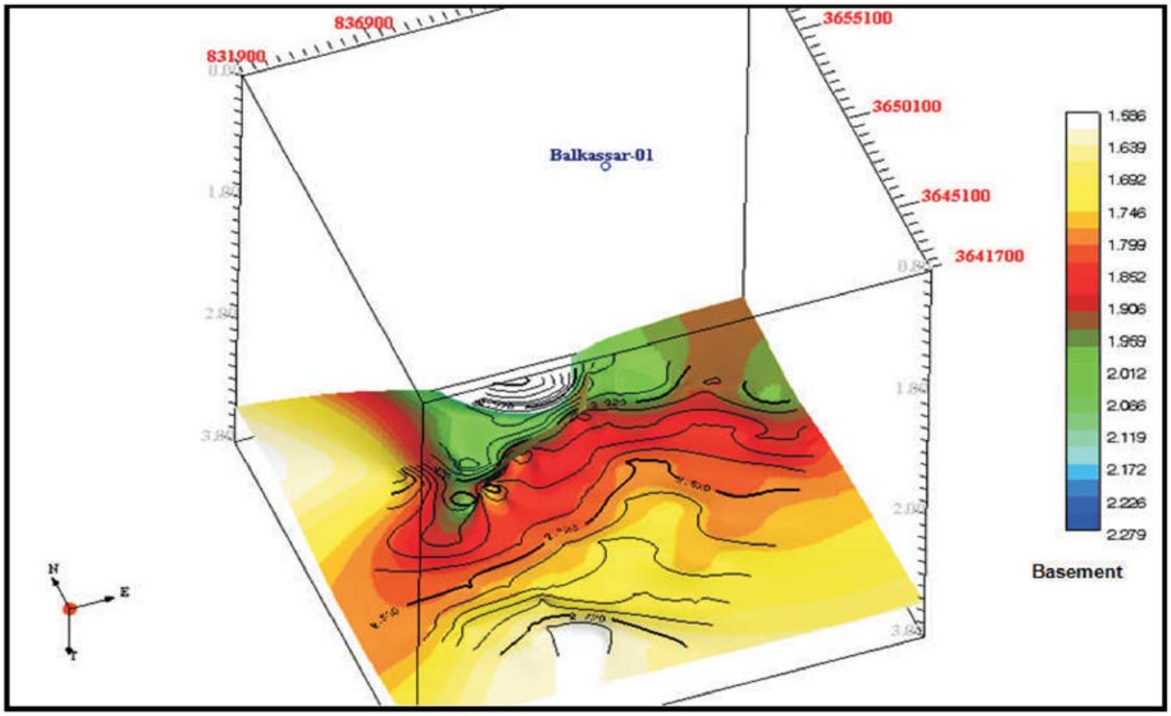

Figure 17 - 3D model of Balkassar anticline at the level of Basement with contours.

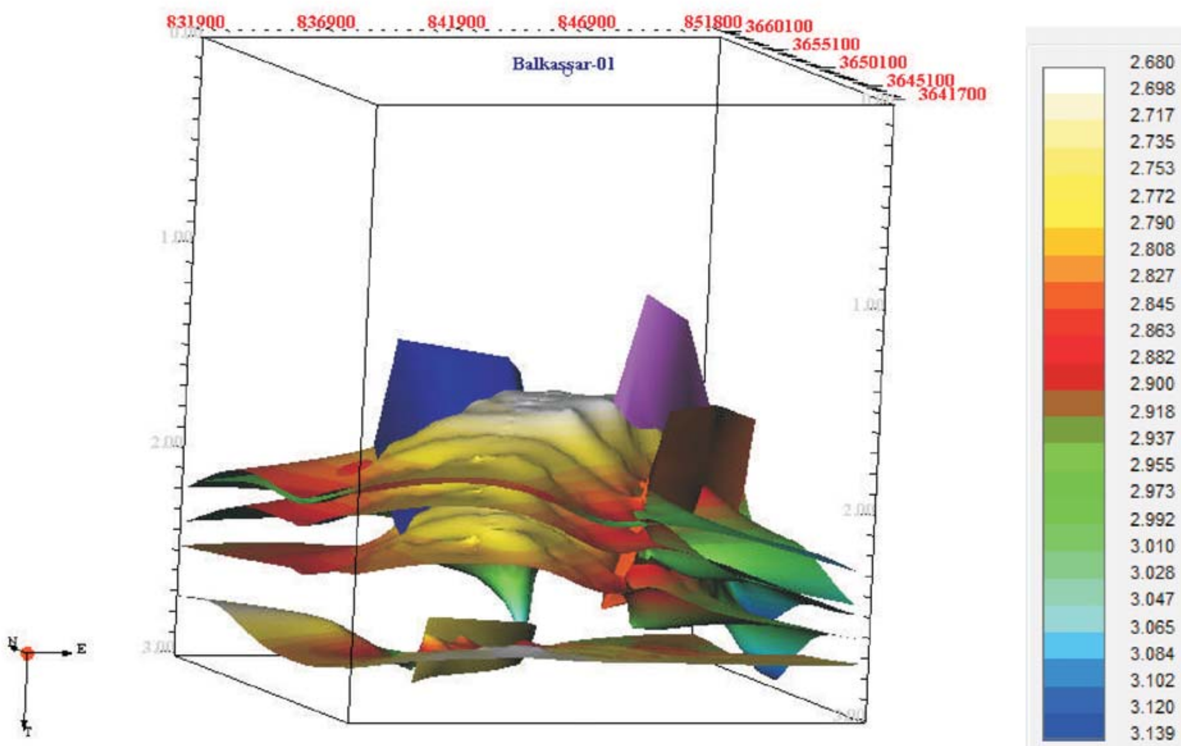

Figure 18 - 3D Model of Balkassar anticline at all horizons.

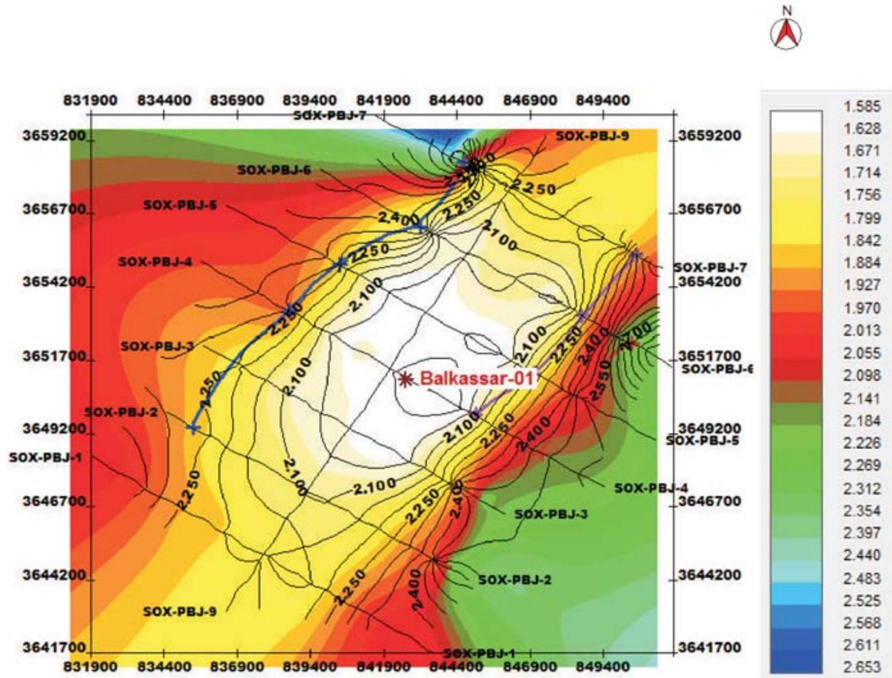

Figure 19 - Time contour map of NE-SW oriented Balkassar anticline at the level of Chorgali Formation.

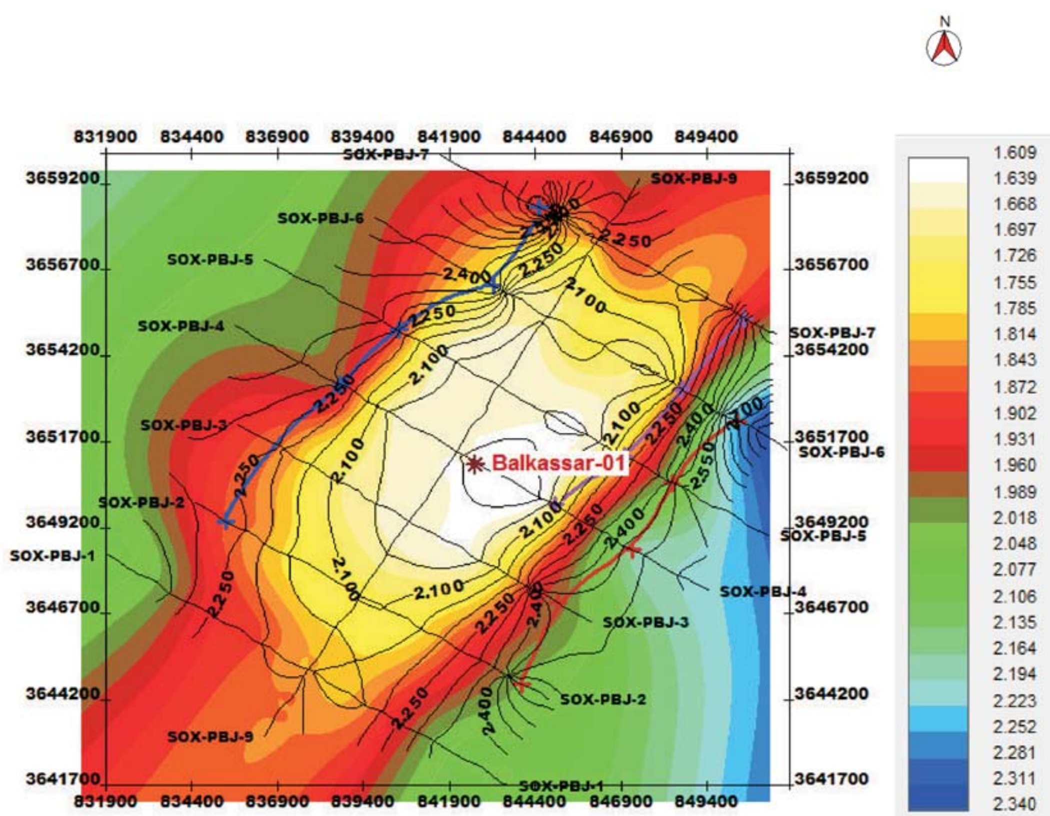

Figure 20 - Time contour map of NE-SW oriented Balkassar anticline at the level of Sakesar Limestone.

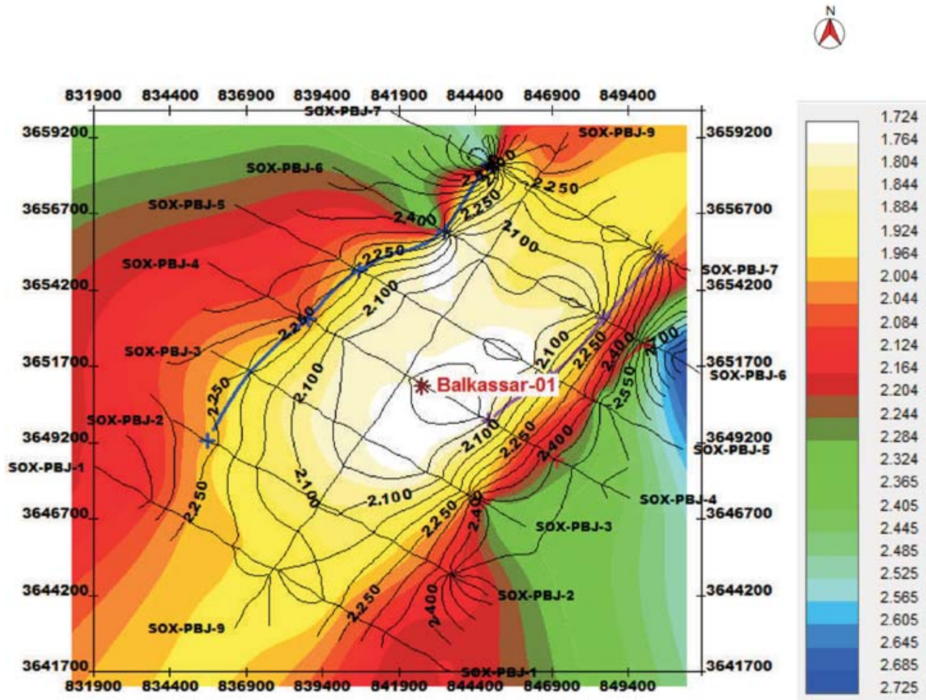

Figure 21 - Time contour map of NE-SW oriented Balkassar anticline at the level of Lockhart Limestone.

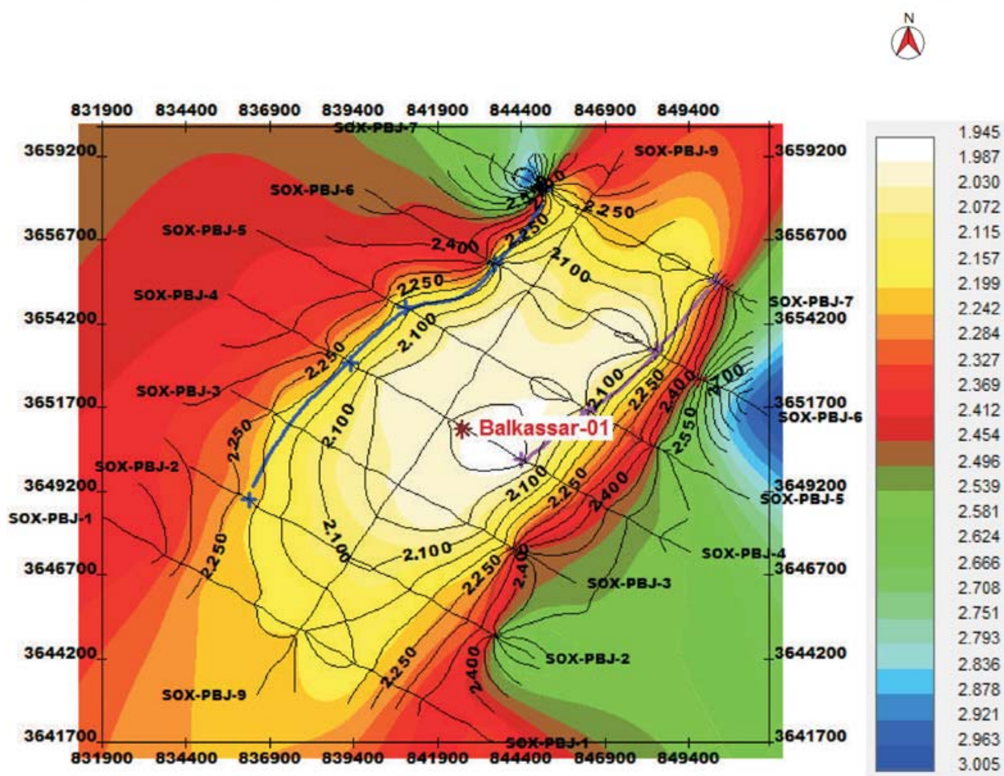

Figure 22 - Time contour map of Balkassar anticline at the level of Khewra Horizon.

closures at about TWT 1.750 to 1.950 in NW side can be observed which may also be a potential prospect for hydrocarbon exploration (Figure 20).

Time Contour map of Basement

Time contour map of Balkassar anticline at the level of Basement horizon (Figure 23) indicates uplifting of the basement horizon in the southern and northwestern side. Moreover, a depression in the northern side is present whereas in the east and west directions intermediate depth is evident. A normal fault trending in the NEE and SWW direction is also present.

CONCLUSIONS

- Borehole data indicates about 4km thick succession of Precambrian to Pliocene sedimentary rocks interrupted by four unconformities present at Precambrian-Eocambrian, Cambrian-Permian, Permian-Paleocene and Eocene-Miocene time.
- Himalayan orogeny related compressional forces in Balkassar area generated a pop-up structure with inflow of Infra-Cambrian evaporates.
- A décollement in the Salt Range Formation produced shortening in the overlying sedimentary sequence.
- Shortening/folding initiated movement along NW dipping Thrust 1 followed by creation of Thrust 2 in the same dip direction. At a later stage, back thrust dipping to SE direction at the northwestern side of the Balkassar anticline was created.
- 3D models indicate steep limbs of Balkassar anticline at the northwestern side and they are terminated by southeast dipping back thrust. The flanks of anticline are gentle on the southeastern, also terminated by faults.
- The Balkassar structure is an elongated, northeast southwest trending four way closure anticline and may be a structural trap for the accumulation of hydrocarbons.
- Contour closure at the level of Paleocene Lockhart Formation, along the back thrust, may act as a probable lead for hydrocarbons.

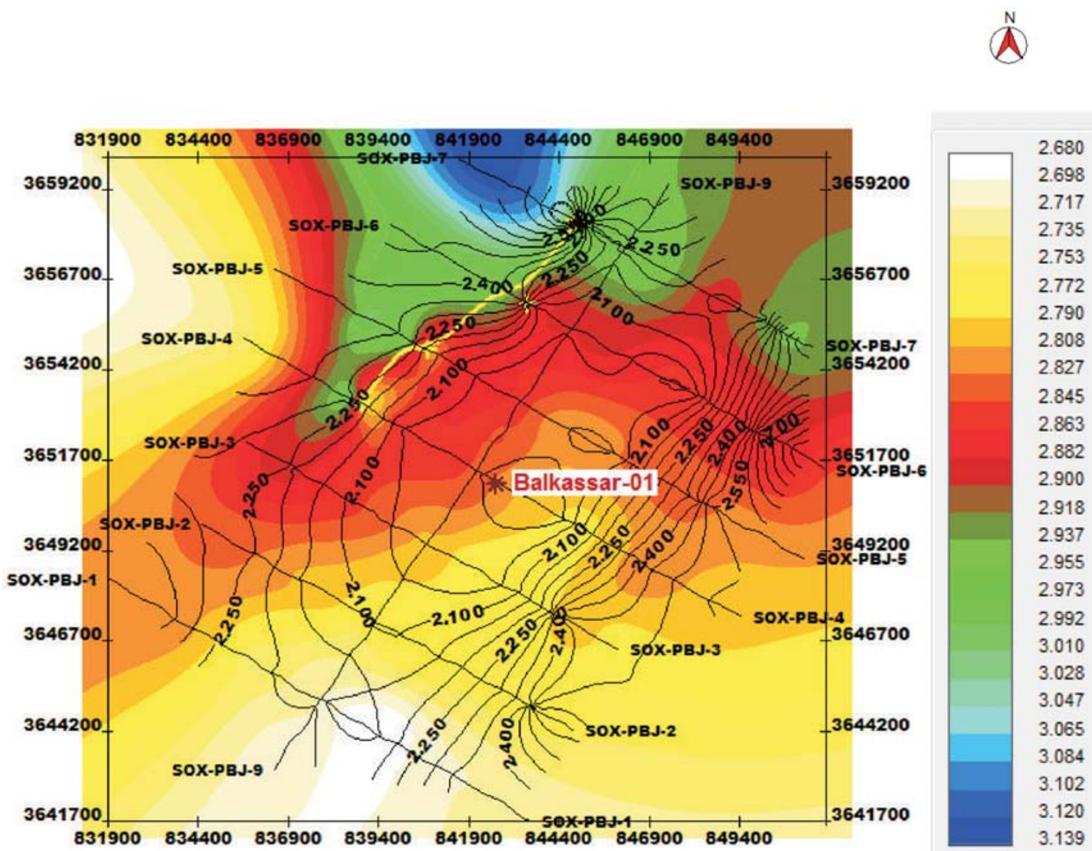

Figure 23 - Time contour map of Balkassar anticline at the level of Basement Horizon.

Similarly, at the level of Eocene Sakesar Limestone two fault-bounded closures in NW side along the back-thrust may also be a potential prospect for hydrocarbon exploration.

RECOMMENDATIONS

3D high resolution seismic data of the area should be acquired so that neglected subsurface structures may also be worked out and re-evaluated.

The anticline at the level of Paleocene and Eocene along the back thrust may be evaluated for hydrocarbon prospects.

Fault seal analysis should be carried out to know the exact length of the prospect/lead.

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Received June 12, 2013, revised Aug. 30, 2013 and accepted Dec. 31, 2013.