Research Article

Muhammad Riaz*, Pimentel Nuno, Tehseen Zafar, and Shahid Ghazi

2D Seismic Interpretation of the Meyal Area, Northern Potwar Deform Zone, Potwar Basin, Pakistan

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Abstract: Meyal Field is considered as one of the chief hydrocarbon producing fields in the Potwar Basin, Pakistan. The present research emphasize on the subsurface structures affecting the Mesozoic-Cenozoic successions exclusively foremost reservoir units comprising the Eocene Chor Gali and Sakesar formations. Data from six seismic lines and three wells (aligned with those lines) have been deliberated comprehensively with remarkable and tremendous calibration. Five prominent and imperative reflectors specifically the Permian, Triassic, Jurassic, Paleocene and Eocene successions were interpreted through seismic tactics. Time structure maps were equipped on the basis of two-way travel time (TWT) of the seismic line. Likewise, four isopach maps portrayed the thickness discrepancy of prospective hydrocarbon strata. Structurally, analytical section reveals that the Meyal anticline is a plunging and faulted anticline. The pop-up structure is constrained by back-thrust from the north and fore-thrust from the south, on the dip lines. These maps depicted potential reservoir, demarcate promising site for future hydrocarbon exploration.

Keywords: Seismic data interpretation; Structural pattern; Time structural map; Isopach map; Hydrocarbon potential; Meyal Oil Field; Potwar Basin, Pakistan

***Corresponding Author: Muhammad Riaz:** School of Earth Sciences and Resources, China University of Geosciences, Beijing 100083, China; Institute of Geology, University of the Punjab, Lahore-54590, Pakistan; Email: riazjass@yahoo.com; ORCID: https://orcid.org/0000-0002-6154-3354
Pimentel Nuno: Instituto Dom Luiz, Universidade de Lisboa, Faculdade de Ciências, 1749-016 Lisboa, Portugal
Tehseen Zafar: Institute of Geochemistry, Chinese Academy of Sciences, Guiyang 550081, China
Shahid Ghazi: Institute of Geology, University of the Punjab, Lahore-54590, Pakistan

1 Introduction

The Meyal Field is located extensively in northern Pakistan, around 60 km south-southwest of Islamabad, Pakistan [1, 2] (Figure 1). The region corresponds to the Potwar Basin, enclosed to the south by Salt Range and bounded to the north through Kala Chitta Range. This area is restricted to the west via Indus River and Jhelum River in the east respectively [1–6]. Regionally, the basin is extremely dissected between the Indo Gangetic plain and foothills of the Himalayas [7–9], with an area of almost 18129.92 km^2. Structural analysis reveals presence of numerous geological structures predominantly comprises of anticlines. The classic sequence of the Cambrian, Permian, Jurassic, carbonate sequence of the Paleocene and Eocene ages are the demonstrated proven reservoirs [10].

Various researchers presented a number of geological in addition to geophysical tools principally seismic reflection schemes for petroleum appraisal [11, 12], which is noteworthy and crucial in tracing surface geological structures in the subsurface and establishing consistent as well as vigorous correlations. An accurate portrayal of the subsurface geological perspectives and structures is critical for hydrocarbon exploration that provides an insight regarding construction and structural set up of a basin [2, 13]. The main detection of oil was productively made in Potwar Basin in 1915 [14]. On the other hand, several wells were unproductive in consequence of intricate subsurface structures. A number of predictions were ineffectively tested in 1950s, and in 1960s were fruitfully reexamined with further seismic data [11, 15]. Based on integrated borehole and seismic records, numerous investigations have been conducted in 1980s and 1990s to demonstrate general structural framework and deformational mechanics [16–20]. Jaswal *et al.* [5] and Jadoon *et al.* [6] presented the multifaceted distortion in the form of imbricate and duplex structures in the Northern Potwar Deformed Zone (NPDZ) using seismic, borehole and paleomagnetic interpretations.

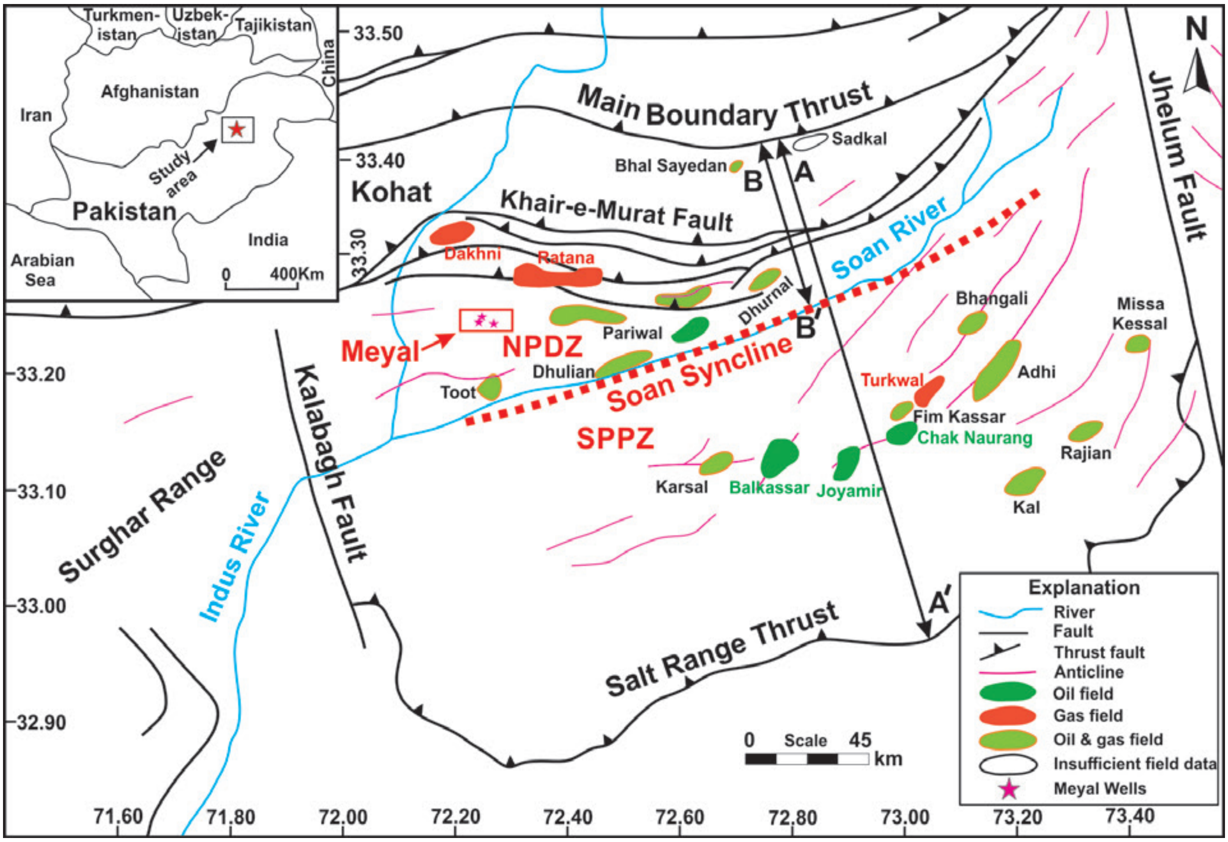

Figure 1: Geological framework, and generalized oil and gas field of Potwar Basin in northern Pakistan (Modified after [2, 30, 37, 41, 43]). Small red rectangle represents the location of Meyal wells, depicted in Figure 20. A- A′ and B- B′ depict cross-sections locations in Figure 3.

Potwar Basin located in Sub-Himalaya division contains significant hydrocarbons restricted in compressional as well as transpressional structures [12]. A number of researchers [2, 21, 22] proposed that at the level of Eocene; geologic structure depicts a general trend in east-west direction. The major structures comprise anticlines constrained by reverse faults, pop-up and salt cored. The folded eastern part is slightly tighter in comparison to the western part and trapping system in the Meyal Field is primarily structural. Meyal Field was discovered by Pakistan Oilfields Limited (POL) in 1968 and until now 16 exploratory wells have been drilled. The aim of this research is to assess the petroleum play of the Meyal Field based on seismic and well data that will be constructive for upcoming exploration in Potwar Basin and adjoining areas.

2 Geological Setting

The Potwar Basin developed in front of rising Himalaya is primarily post-Eocene and syn-orogenic basin which is placed at Indian Plate northern periphery [23–25]. The Potwar subsurface geology is characterized by thick infra-Cambrian evaporite deposits [3] however, deepest well in the Meyal area is penetrated through the Permian sequence. Structurally, Potwar Basin is alienated into central, eastern and western parts [5, 6]. The deformation appears as south verging thrust in central and western parts, while distortion is principally in northeast-southwest direction with tight and sporadically overturned anticlines separated by extensive synclines in the Potwar Basin. This discrepancy may be associated to diverse salt thickness in the Infra-Cambrian eastern areas and very low dip of basement (1°–1.5°) in comparison to central Potwar (2°–3°). In central Potwar, structures are generally bordered by thrusts and back thrusts, whereas at number of places, asymmetric anticlines are enclosed through a single fault. Based on the seismic interpretation, structures in the Potwar area can be alienated into pop-up anticlines, snake-head anticlines, salt cored anticlines and triangle zones [11]. The foremost structure of this basin is the Soan syncline, which runs northeast-southwest direction (Figure 1).

The faults of entire Meyal Field area normally indicate east northeast-south southwest trend and corresponds to

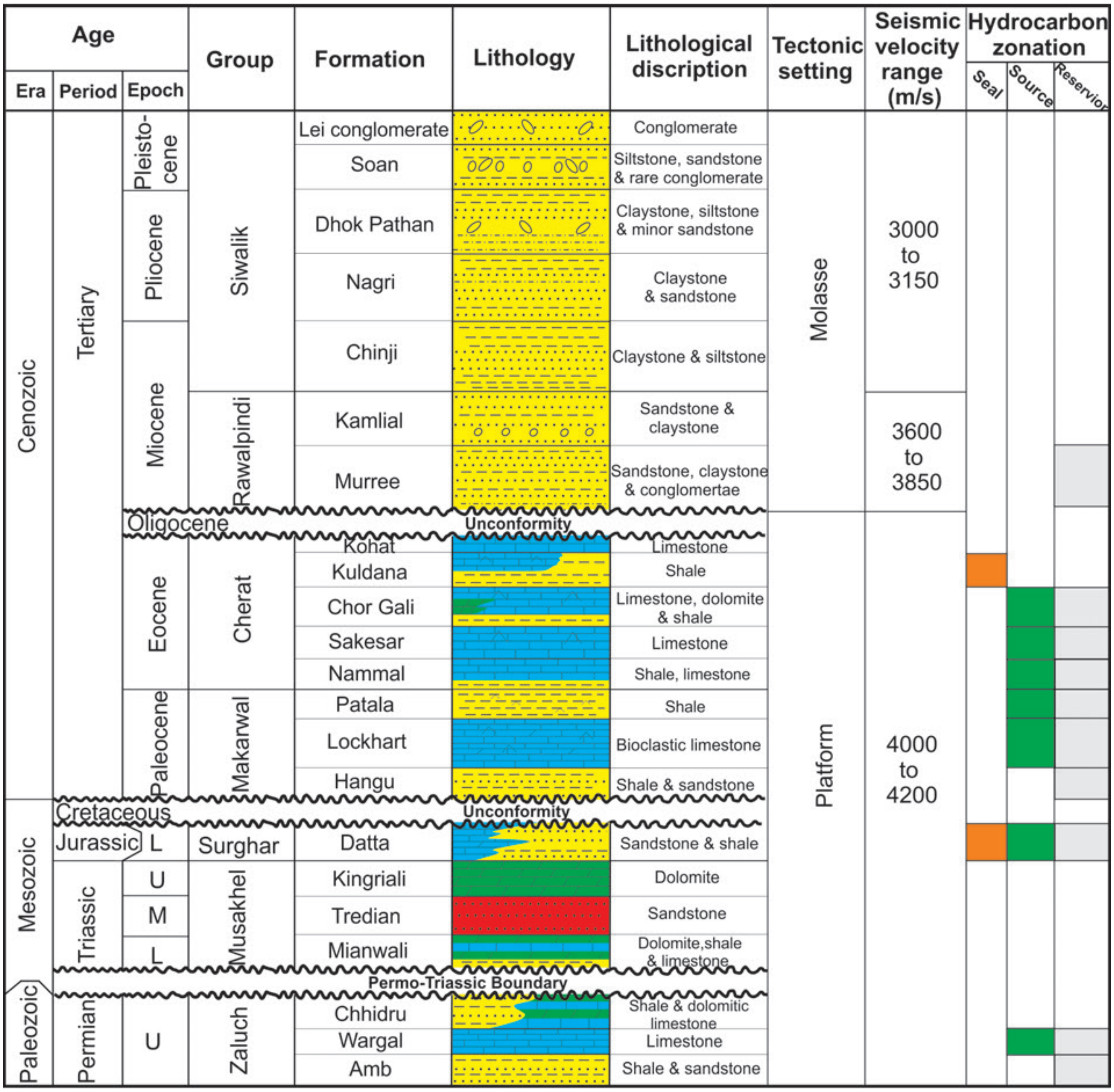

Figure 2: Lithostratigraphic column of NPDZ, Potwar Basin (Northern Pakistan) (Modified after [2, 35, 44]).

Neogene deformation belt. The east-west Soan syncline isolates this region into less deformed Southern Potwar Platform Zone (SPPZ) and more deformed Northern Potwar Deformed Zone (NPDZ), [2, 5, 12, 26–28] (Figure 1). The extremely dissected NPDZ deformation framework immediately changes from east to west and reveals presence of extensive syncline, compressed fold as well as closely spaced imbricate thrust [5, 29]. The eastern NPDZ portrays buried thrust front along with foreland syncline, triangle zone and hinterland dipping imbricate stack farther northwards [29–31]. Whereas, the western NPDZ represents prominent faulted anticlines alienated through synclines along with developing thrust [30]. Jaswal *et al.* [5] determined ~55 km of horizontal shortening between the Soan syncline and Main Boundary Thrust and projected minimum rate of shortening 18 mm/yr.

The maximum depth of well drilled in the Meyal Field is up to Permian strata (Figure 2). An unconformity separated the Permian sequence from overlying the Triassic sequence [32]. The Triassic and the Jurassic deposits are characterized by sandstone and shale of the Mianwali and Datta formations respectively [2, 32] (Figure 2). The Mesozoic strata are overlain by the Paleocene sediments. The contact relationship between the Mesozoic and the Paleocene successions is unconformable [33]. The data from three wells illustrate that Cretaceous is miss-

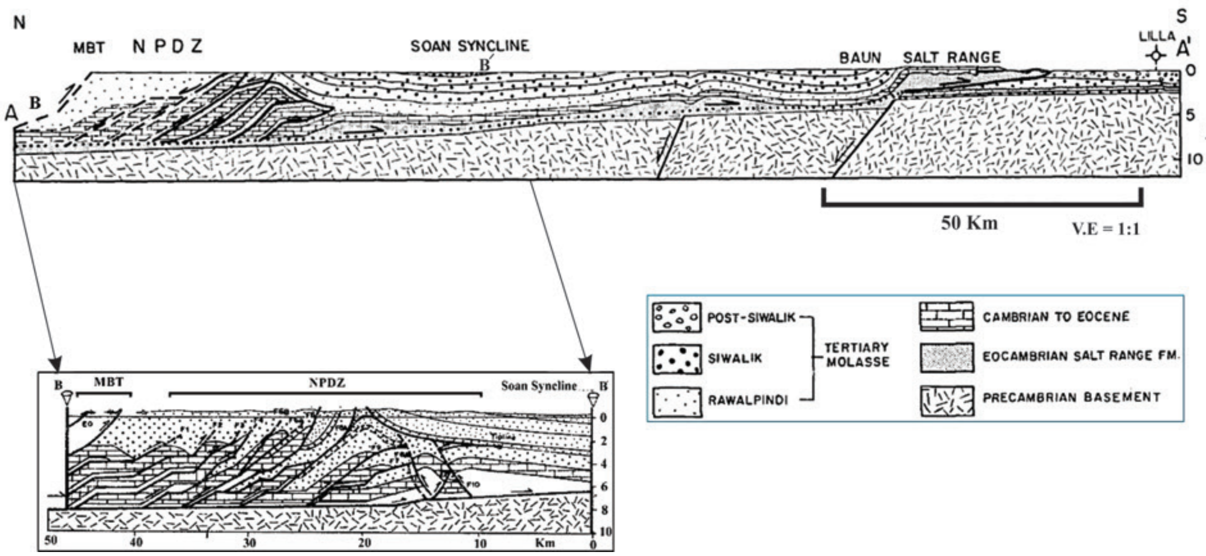

Figure 3: Schematic cross section for the Potwar Basin in Northern Pakistan, detailing the NPDZ (Inset section B-B′) (Modified after [1, 5, 45]).

ing in this area as the Paleocene Hangu Formation directly overlies the Datta Formation [2, 12, 22, 34] (Figure 2). Moreover, calcareous claystone of the Nammal Formation making the beginning of the Lower Eocene, followed by massive bedded limestone of Sakesar Formation which is overlain by dolomitic limestone and calcareous claystone/shale of the Chor Gali Formation [35–39]. Continental collision in the Middle Eocene resulted in the end of marine deposition [2, 12, 13, 21] and led to the deposition of the Rawalpindi and the Siwalik Groups, dominantly composed of stream channel sandstones, flood plain mudstones and shale [2, 40–42]. Furthermore, Pliocene to Middle Pleistocene sediments are extremely deformed by Himalayan Orogeny [2, 3, 41].

3 Petroleum Geology

The Meyal-Kharpa surface structure is significant and vital geological structure in the Potwar Basin that remained a key target for the petroleum geologists [21]. It is a narrow, steep and faulted anticline extending east-west with two major thrusts cutting the structure longitudinally (Figure 3). In 1980, Sunmark Exploration Company suggested the possibility of two source rocks in the Potwar Basin. The shale of the Nammal Formation have been analyzed as a major producer of oils to the reservoirs of Dhulian (Chor Gali-Sakesar), Joya Mair (Sakesar), Khaur (Murree Sandstone) and Balkassar fields (Sakesar) [21] (Figure 2). Jurassic variegated sediments are deliberated as second possible potential source rock actively contributing at the generation of oil in this area [22] (Figure 2). This unit provided oil to the Meyal (Jurassic, Paleocene and Eocene) and Dhulian fields (Variegated beds and Lockhart). The oil producing reservoir in the Meyal Field is Eocene sequence [2], while the Datta Formation (Sandstone) is reflected as both oil and gas producer (Figure 2). The upper parts of the Nammal and Datta formations considered as a seal for the reservoirs of the Meyal Field. Ghazi [22] demonstrated and marked upper part of the Jurassic sequence (shale beds) as seal rock.

4 Methodology

The subsurface data used for interpretation of the Meyal area have been collected from Landmark Resources (LMKR) with the prior approval from the Directorate General of Petroleum Concession (DGPC) and assistance from the Institute of Geology, University of the Punjab. A total of six seismic lines were investigated, two strike lines (97-MYL-12 and 13) and four dip lines (97-MYL-06, 07, 08 and 09). Three wells (MYL-10, 12 and 13) have also been scrutinized comprehensively, allowing for a remarkable calibration, taking into account that they are located along the studied seismic lines (Figure 4). MYL-10 and 12 are positioned at strike line 97-MYL-12 and attained a total depth of 3960 m and 3765 m respectively, whereas MYL-13 at dip line 97-MYL-09 reached 4533 m. These wells drilled through the formations ranging from Eocene to Jurassic.

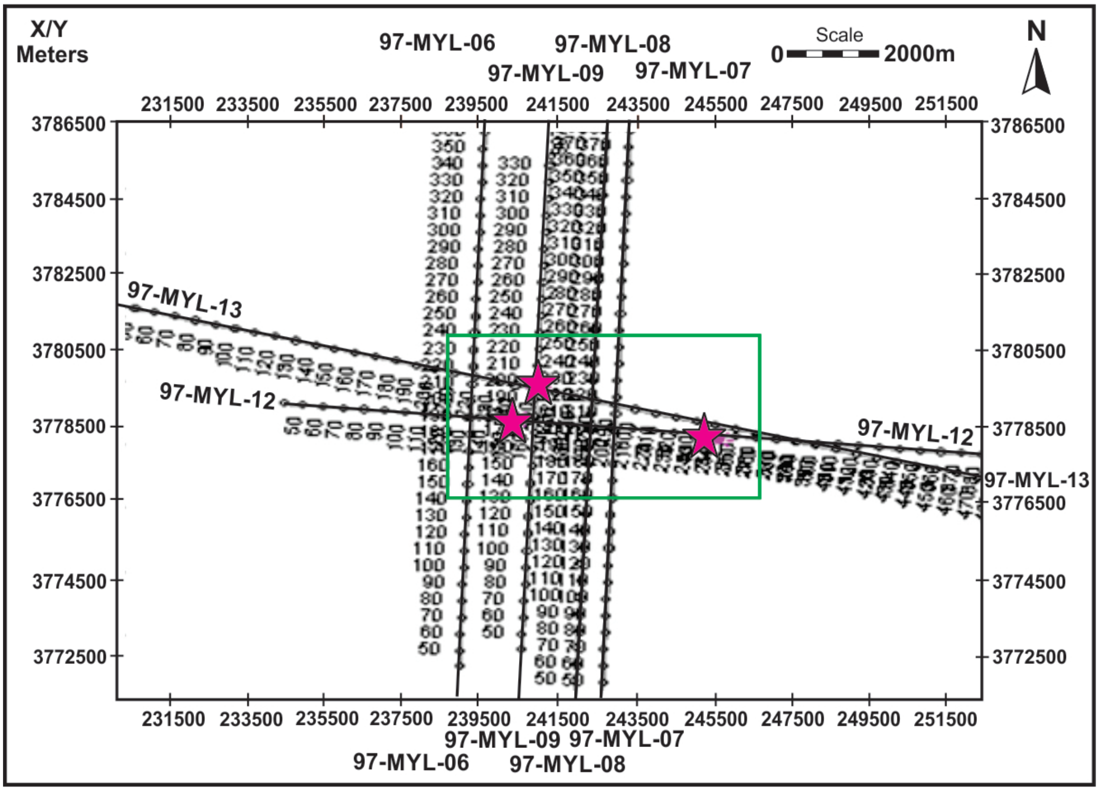

Figure 4: Base map showing orientation of the 2D seismic lines and wells location (green rectangle) in the Meyal area.

Kingdom Suite software 8.2 (SMT) was utilized for the interpretation of seismic and detailed well data. Besides using the software, manual analysis of both seismic and well data has also been conducted cautiously. For structural as well as stratigraphic assessment, five prominent reflectors were marked on the seismic lines. The depth of each noticeable seismic reflector calculated by the TWT, which was correlated with well tops to confirm the position of distinct reflectors and were allotted a specific age. The strike lines reveal the continuous reflectors, while the dip lines depict the major along with minor faults on the basis of breaks in the continuity of the reflectors. Time contour maps were constructed from top of the Permian to the top of the Eocene. These five horizons have its time contour map, which elaborates its TWT on entire study area in the form of grids. Each reflector of these maps indicates the subsurface structure of that reflector.

These maps portrays the presence of geologic structures particularly folds and faults along with numerous others structures. Basinal architecture of the Meyal area is interpreted by the isopach maps. The four isopach maps were equipped from the five-marked reflectors with the help of Kingdom software. These maps represent the travel-times for specific horizon in diverse places and also provide thickness discrepancy in terms of time in the study area. The domains of these maps were TWT of the base reflectors and time of top reflector of the particular horizon. In this portion, time of the isopach maps has been correlated with the well tops data and thicknesses of rocks in terms of meter (m) have been calculated.

5 Results and Discussion

5.1 Interpretation of Seismic Lines

Six reflectors were marked on each seismic line, five reflectors having different ages from Permian to Eocene and a sixth one corresponding to the base of the Noegene molasses.

5.1.1 Line 97-MYL-13

The reflectors on line 97-MYL-13 (Figure 5) are almost flat and run in east-west direction. This line cut all the dips lines as well as the strike line 97-MYL-12 as presented in the base map (Figure 4). The TWT of these reflectors on the eastern and western side is greater than the central part.

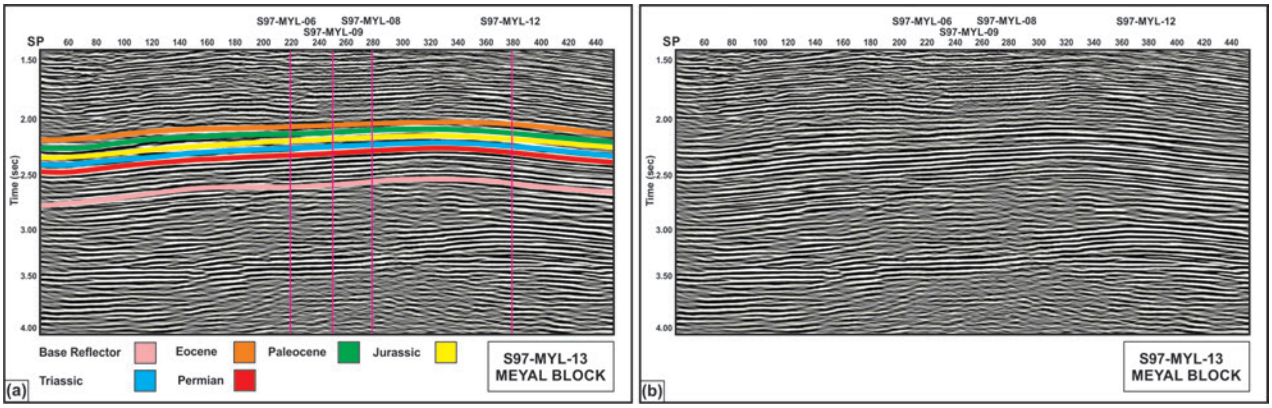

Figure 5: (a) Interpreted seismic cross section of strike line 97-MYL-13 indicating prominent parallel reflectors and tie-lines **(b)** Non-interpreted section of (a).

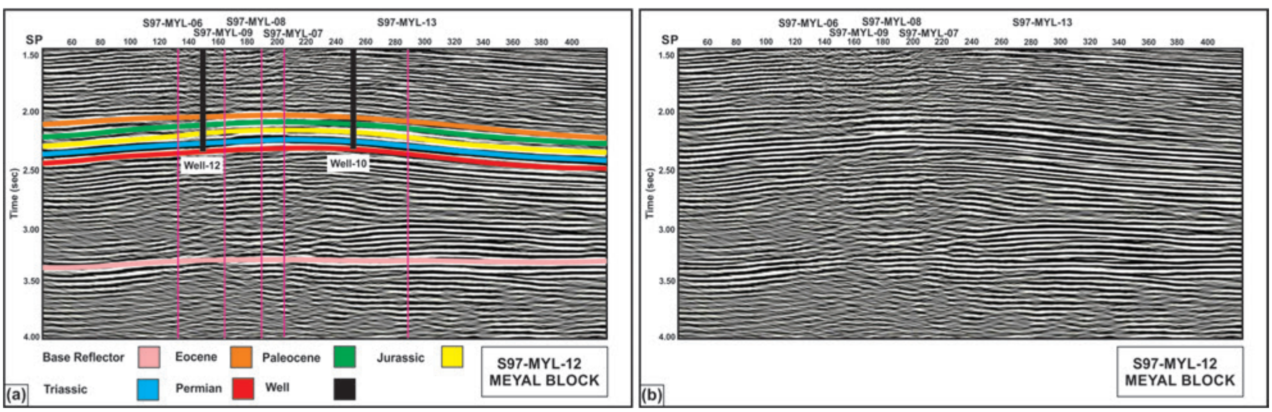

Figure 6: (a) Interpreted seismic cross section of strike line 97-MYL-12 showing plunging anticline, tie-lines and wells **(b)** Non-interpreted section of (a).

This line is essentially along the strike of the rock, hence, change in depth along the strike line means that axis of the anticline is horizontal. It, therefore, characterized as plunging anticline revealed in Figure 5.

5.1.2 Line 97-MYL-12

Line 97-MYL-12 (Figure 6) is also a strike line and used as a reference line for interpretation attributable to two reasons. Firstly, it contains two wells (Meyal-10 and Meyal-12), which are valuable to determine age of the reflector. Secondly, the reflectors are almost flat, thus picking the prominent reflectors is relatively easy. The TWT of all the five reflectors are greater in the east as compared to west, consequently, it exhibits the presence of plunging anticline.

5.1.3 Line 97-MYL-09

Line 97-MYL-09 is a dip line and contains well 13 (Figure 7). Three minor faults exist on the central and western part of the major fault. The throw of back-thrust is relatively greater than the throw of the back-thrust of the eastern dip lines, while throw of the fore-thrust decreases toward the west. Furthermore, throw of the fore-thrust in the form of TWT is about 0.3 s, whereas the back-thrust is about 0.95 s.

5.1.4 Line 97-MYL-08

Line 97-MYL-08 (Figure 8) lies in the west of line 97-MYL-07. The shot points increase south to north and pop-up structure is deciphered between the shot points 120 to 240. The study area is actually subjected to compressive forces from the post-Eocene, therefore, the pop-up structure also extends on this line. In addition, minor fault is also inter-

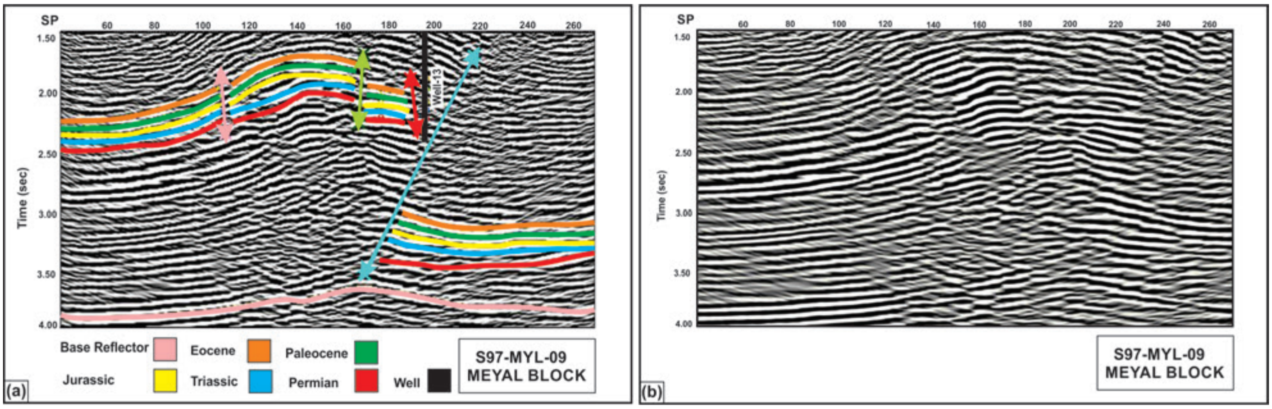

Figure 7: (a) Interpreted seismic cross section of dip line 97-MYL-09 depicting minor faults (pink, green and red arrows) and major fault (blue arrow) **(b)** Non-interpreted section of (a).

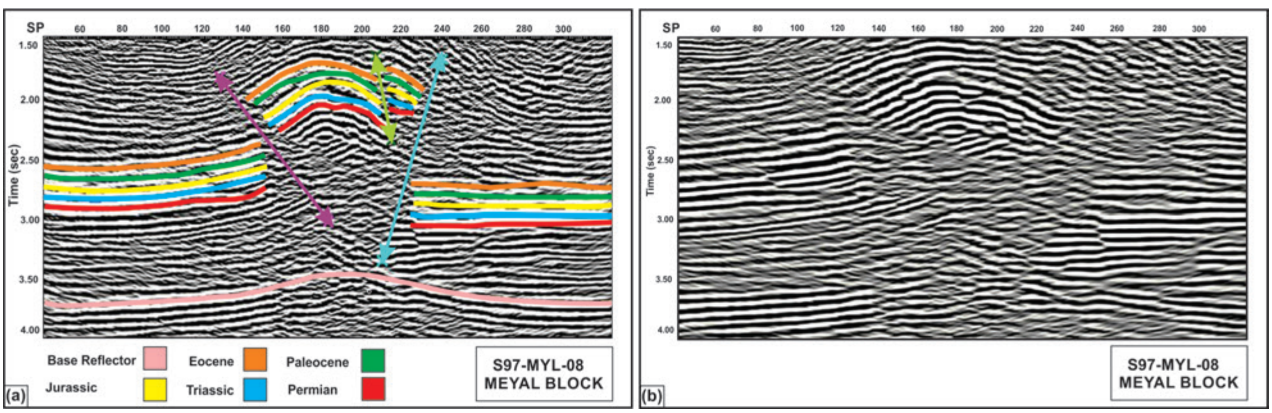

Figure 8: (a) Interpreted seismic cross section of dip line 97-MYL-08, purple and blue arrows displaying pop-up structure, and green arrow showing minor fault **(b)** Non-interpreted section of (a).

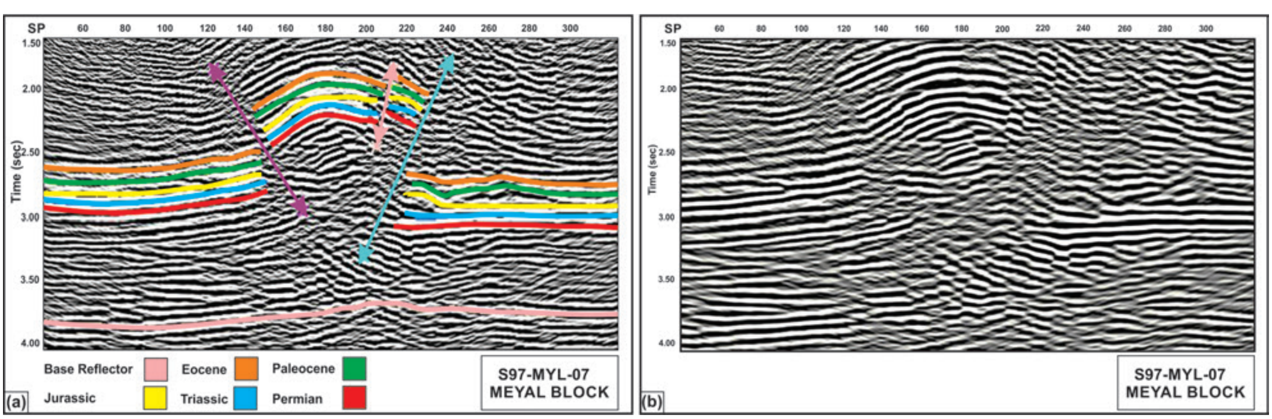

Figure 9: (a) Interpreted seismic cross section of dip line 97-MYL-07 representing major pop-up structure (purple and blue arrows) and minor thrust fault (pink arrow) **(b)** Non-interpreted section of (a).

preted in the up thrown block of the pop-up structure (Figure 8). Both back-thrust and fore-thrust exist on this line that indicates the throw of back-thrust in the form of TWT is 0.85 s, however, throw of fore-thrust is noticed about 0.50 s.

5.1.5 Line 97-MYL-07

The reflectors on line 97-MYL-07 (Figure 9) portrays two major thrusts, southern thrust is a fore-thrust dipping toward the hinterland, while northern thrust is a back-thrust

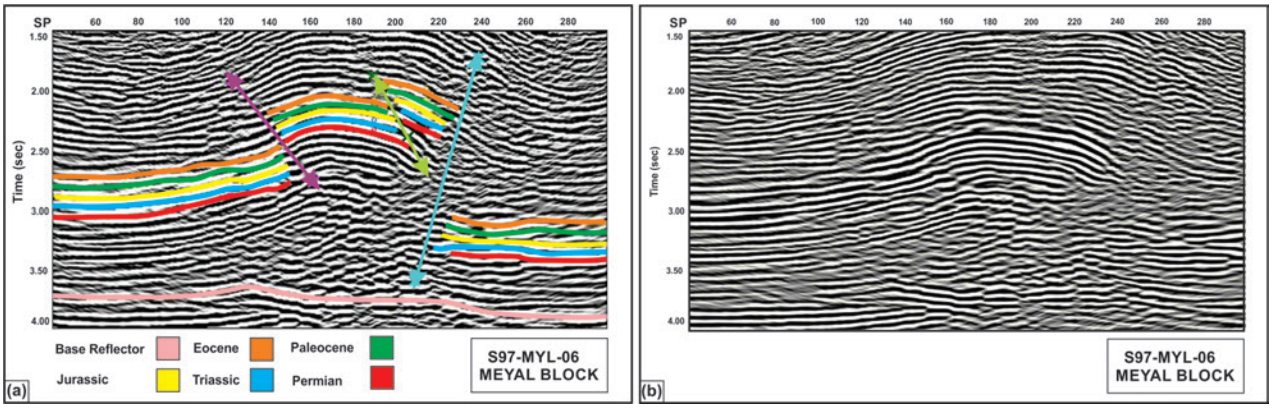

Figure 10: (a) Interpreted seismic cross section of dip line 97-MYL-06 indicating pop-up structure (purple and blue arrows) and a minor fault (green arrow) **(b)** Non-interpreted section of (a).

since it is dipping toward south in the direction of foreland. The pop-up structure produced by these thrusts is almost in the center of the line (Figure 9). The throw of the back-thrust is greater than fore-thrust, signifying that the forces from the hinterland are greater than the foreland. In the north of the pop-up structure, a minor reverse fault is also prominent (Figure 9).

5.1.6 Line 97-MYL-06

Back-thrust is perceived in the northern part of the line 97-MYL-06 (Figure 10). In the southern portion, two minor thrusts are witnessed, one of them is back-thrust and other is fore-thrust, as a result it makes a pop-up structure on the minor scale (Figure 10). The evaluated TWT of back thrust is approximately 1 s.

5.2 Time Structure Maps

5.2.1 Time Structure Map of Eocene

The time structure map of the Eocene reflector represents a plunging anticline, which is bounded by the thrust from north and south. In the study area, the Eocene sequence acts as reservoir attributable to secondary porosity induced by the presence of compressional zones. Figure 11 also presents the TWT, which varies from 3.17 s to 1.67 s. Furthermore, the Eocene succession also specifies the pop-up structure, in which the central block moved upward up to 2.141 s to 1.795 s. In the eastern part, the range of TWT is 2.388 s to 2.141 s, while in the western side 2.042 s to 1.943 s.

5.2.2 Time Structure Map of Paleocene

Paleocene reflector indicates the influence of two major thrusts in the northwest-southeast direction, dipping opposite to each other and forming a pop-up structure in the center (Figure 12). Actually, all the reflectors from the Permian to Eocene moved up, thrown between the two major thrusts, therefore the shape of the time structure maps are almost comparable. According to this map, the Meyal anticline axis is oriented east-west and plunging to the south, as well as thrusted. The throw of these thrusts decreases towards northwest as presented in Figure 12.

5.2.3 Time Structure Map of Jurassic

The time structure map of the Jurassic reflector demonstrates that the study area is present in the compressional zone where the thrust faults and pop-up structure developed in the differential compression settings (Figure 13). The reason for the back-thrust production is the differential compression from the hinterland and foreland. The contours are also closed at the up thrown block of the Jurassic reflector. Two major thrusts are also present in this map demonstrating that the eastern part of this map is deeper than the western portion, which represents Meyal area as a plunging anticline. The central most part of this map is shallower area and two wells locations are present on it (Figure 13).

5.2.4 Time Structure Map of Triassic

Triassic map also exemplifies the pop-up structure with two major thrusts (Figure 14). The southern part of the map

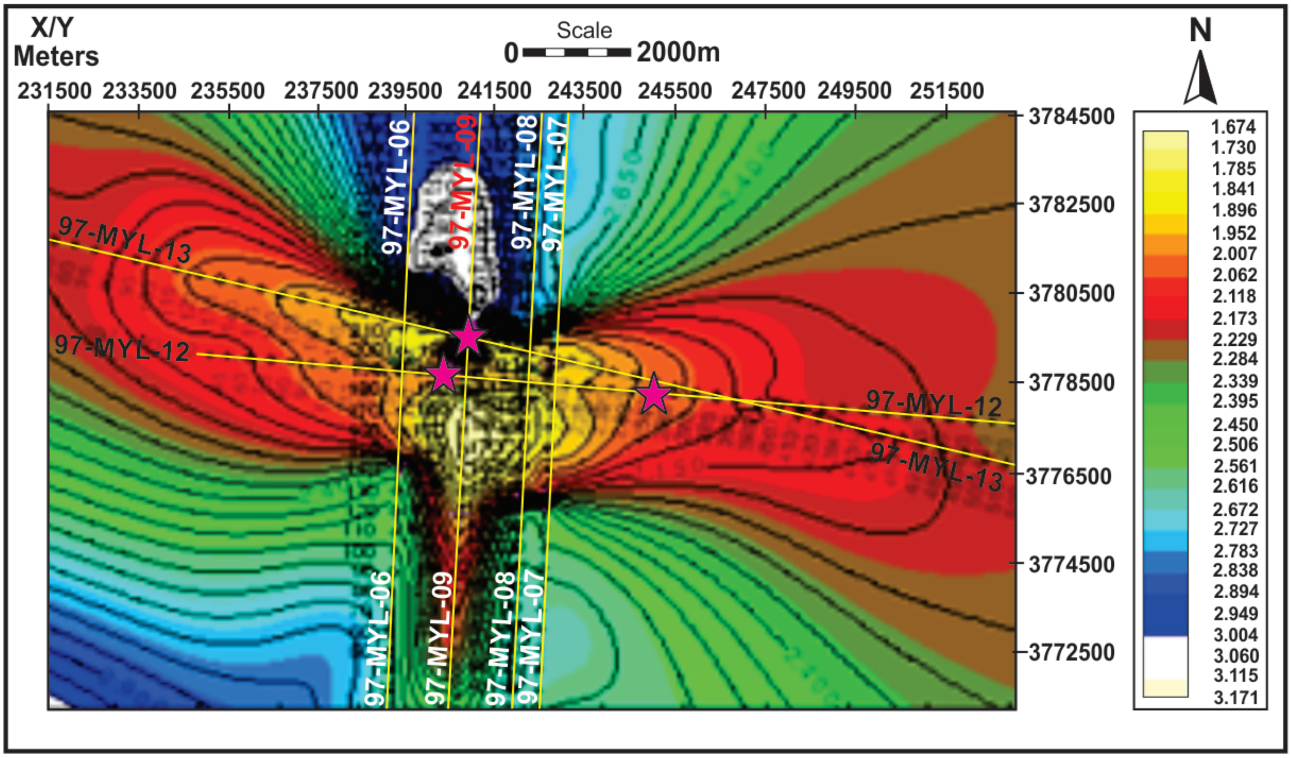

Figure 11: Time structure map of top of the Eocene and color bar from figures 11-15 exhibiting TWT in second (s).

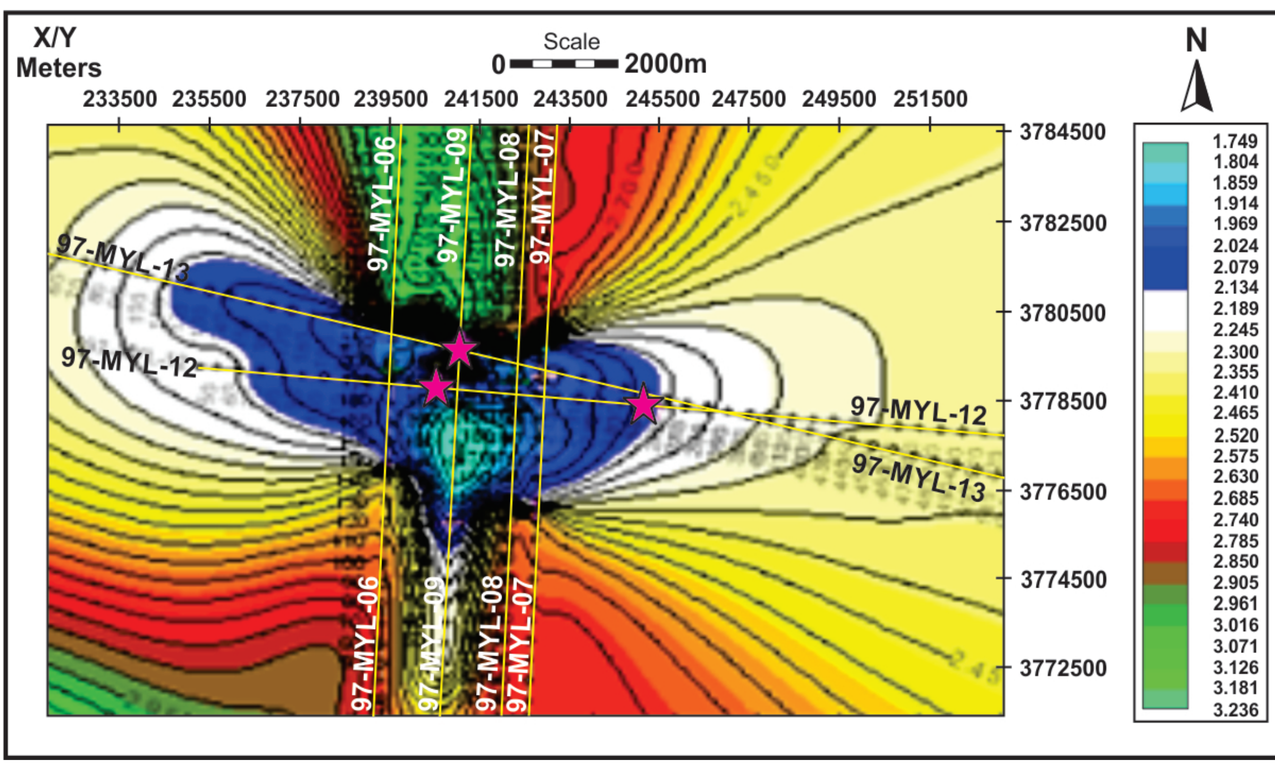

Figure 12: Time structure map of top of the Paleocene showing pop-up structure in the center.

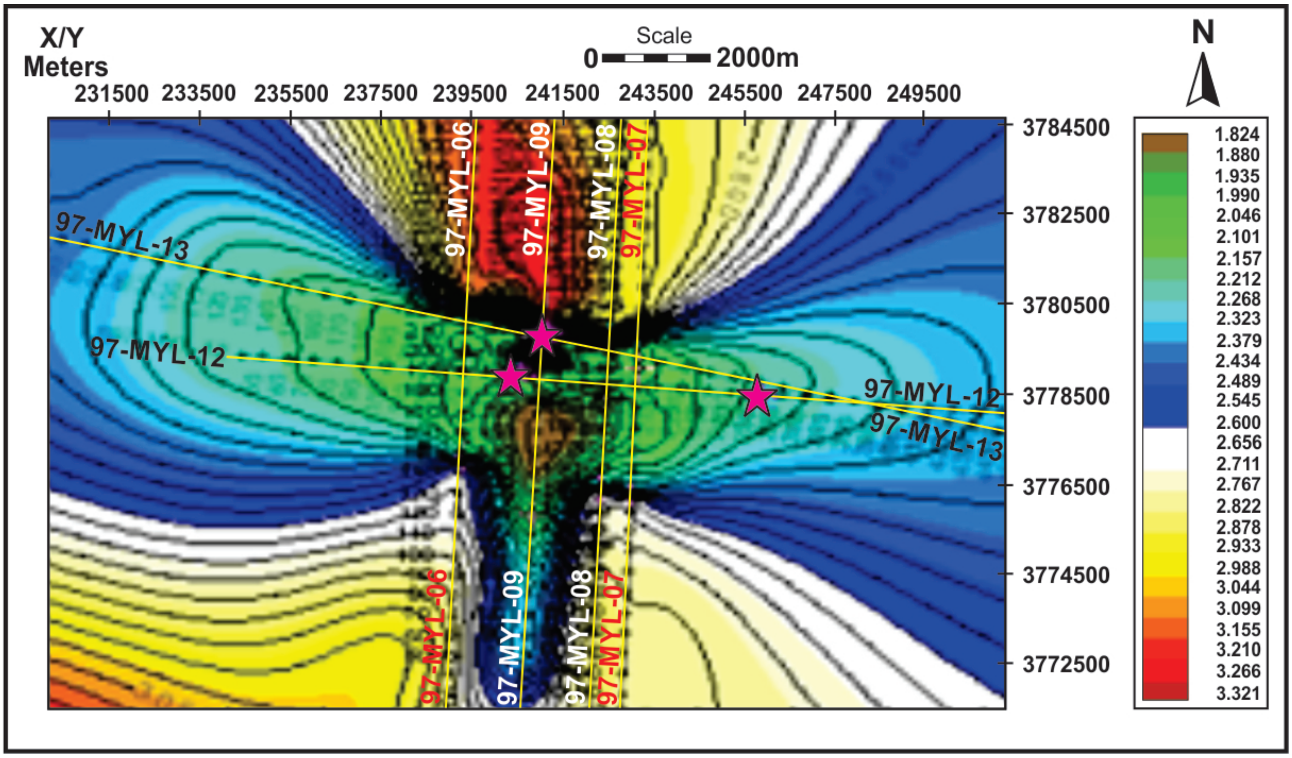

Figure 13: Time structure map of top of the Jurassic depicting compressional faulting.

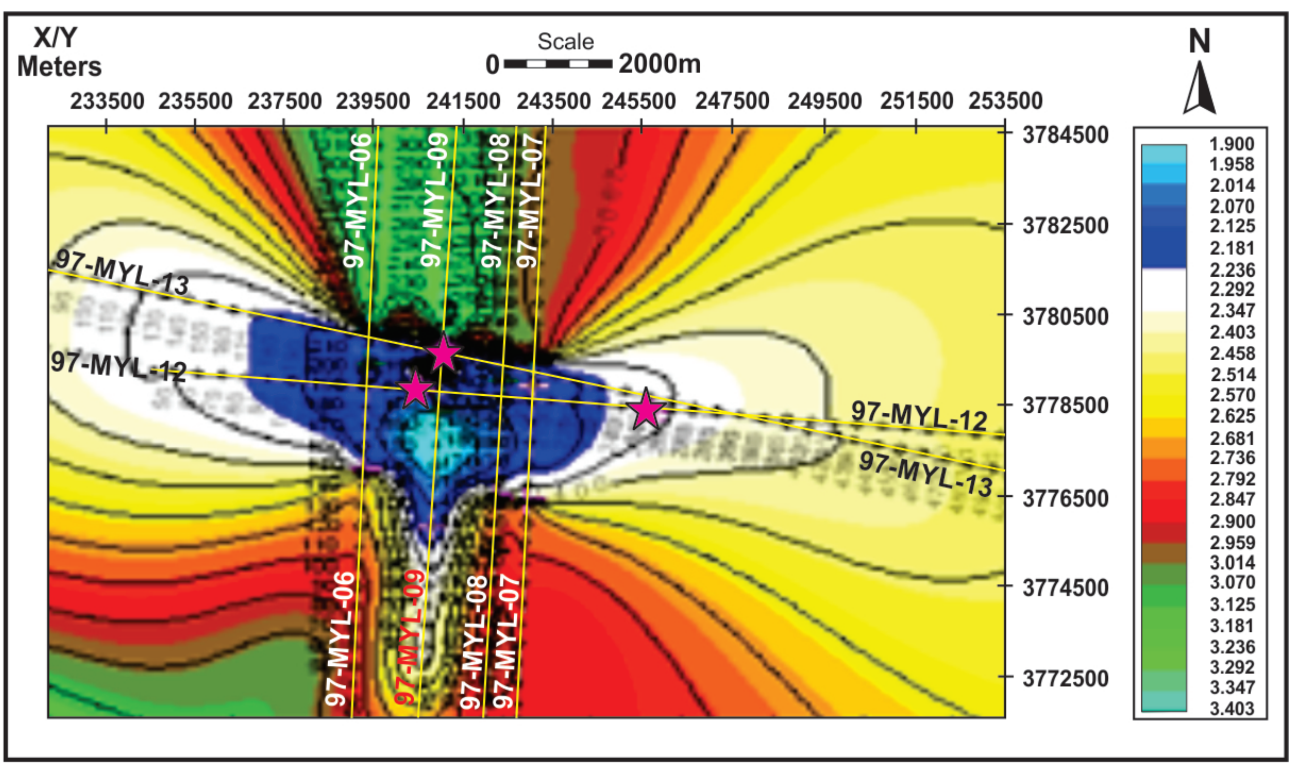

Figure 14: Time structure map of top of the Triassic showing plunging anticline.

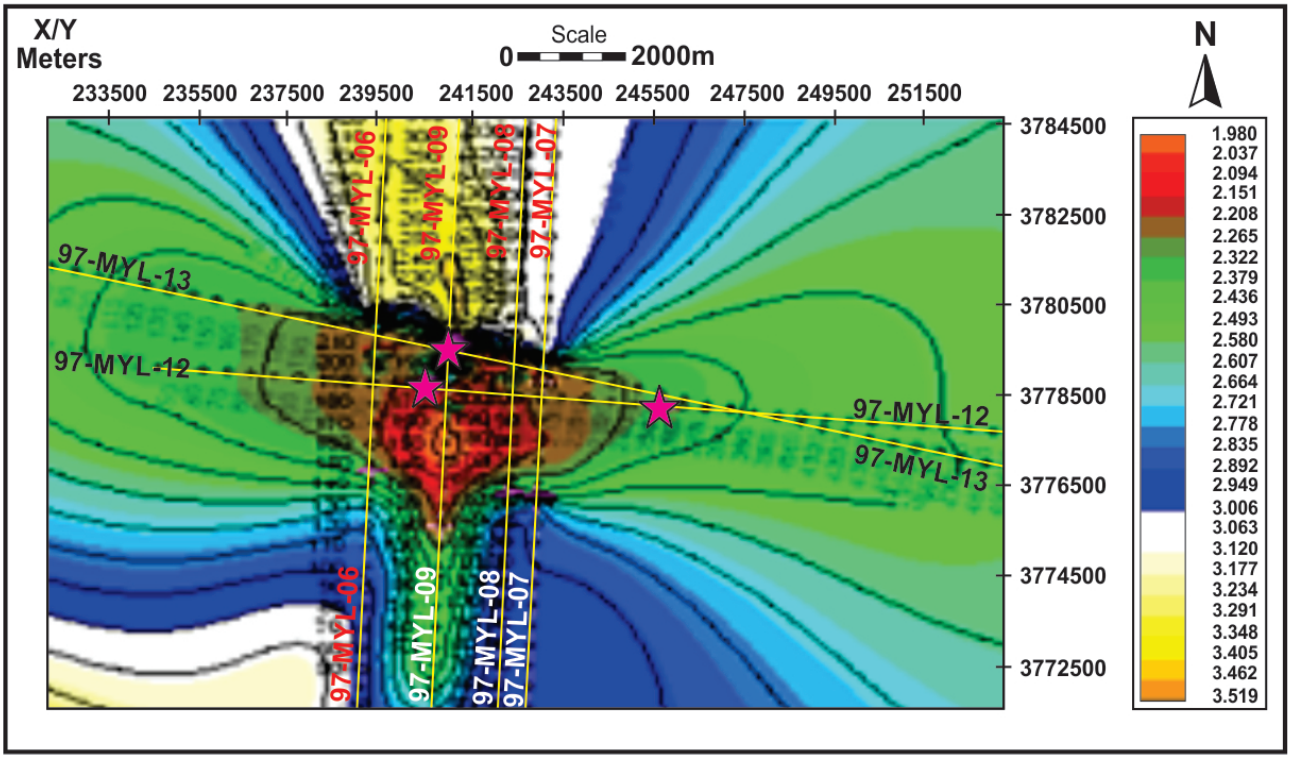

Figure 15: Time structure map of top of the Permian depicting shallow depth in the center.

has comparative less TWT than the northern part, which represents the relatively greater throw of the northern part than the southern segment. The eastern part of this map is at greater depth than the western part implying Meyal anticline as plunging anticline.

5.2.5 Time Structure Map of Permian

Time structure map of the Permian reflector explains two major thrust which run northwest-southeast direction and middle block has less TWT, which specify the shallow depth. The southern thrust of the map does not extend on the dip line 97-MYL-06 and throw is relatively less than northern thrust, while the northern thrust has extended on all the dip lines (97-MYL-06, 97-MYL-07, 97-MYL-08 and 97 MYL-09) and comparatively greater throw, as shown in Figure 15. All the three wells lie on up thrown block. The contours of the TWT are closed on the up thrown block, which propose that the study area is a thrusted anticline. The seismic line 97-MYL-12 almost runs along the axis of this anticline.

5.3 Isopach Maps

5.3.1 Isopach Map of Triassic

Isopach map of the Triassic units is measured by travel time of the seismic waves which vary from −0.83 s to 0.89 s and it also exhibit thickness variation of the Triassic age. The thickness of the Triassic in the well MYL-13 is 161 m, which is calculated from well tops data of the MYL-13. In this map, the value of the travel time of the seismic wave along the position of the MYL-13 is 0.048 s. According to this map, the thickness of the Triassic units in term of time generally decreases toward the limbs and increases in the core of anticline. The western side of the anticline axis is relatively thicker than the eastern part of the axis. Three small depressions are also present, first is in the form of circle towards the north-west of the well MYL-12, second, in the south of the well MYL-12 having thickest sedimentary cover of Triassic and third depression is present in the west of the well MYL-12. The isopach map of the Triassic age is indicated in Figure 16.

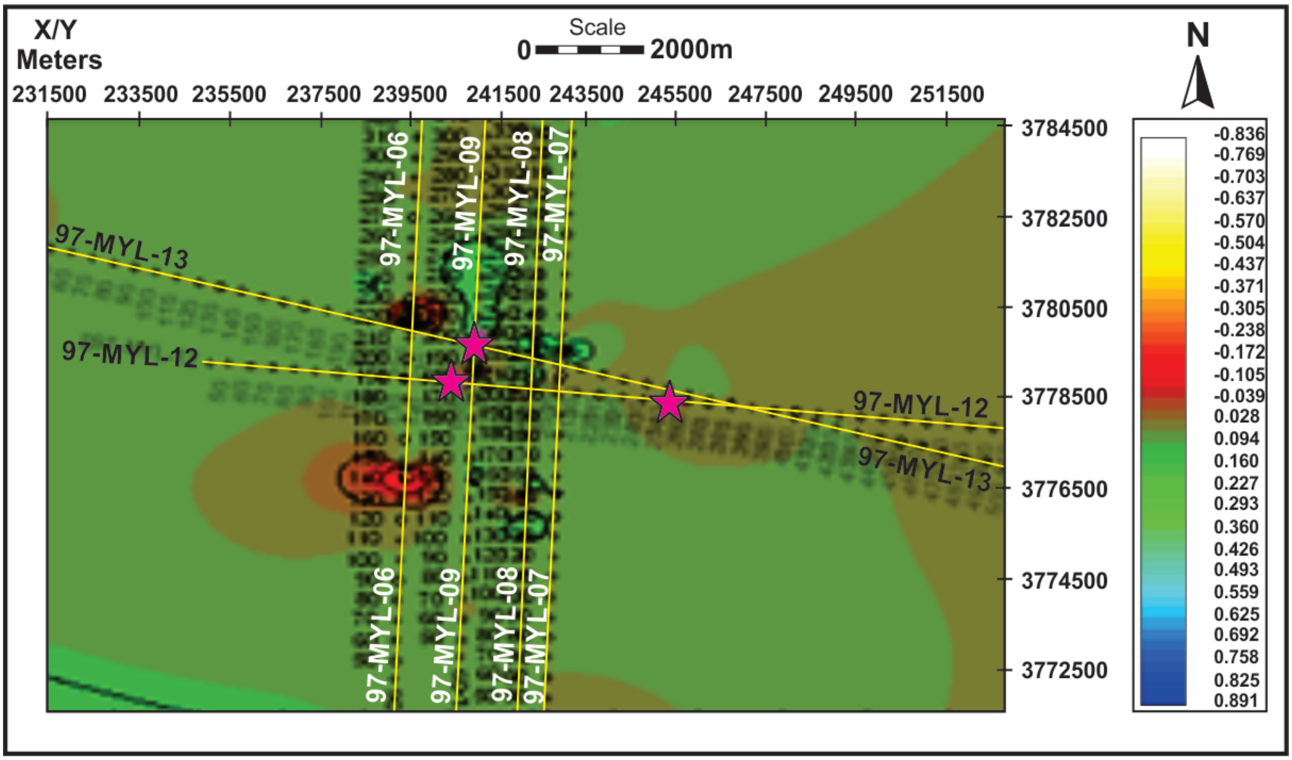

Figure 16: Time based isopach map of the Triassic showing three small depressions of Triassic sediments and color variation from figures 16-19 showing depth in meter (m).

5.3.2 Isopach Map of Jurassic

Jurassic map displays the thickness variation of the Jurassic sediments in term of TWT of the seismic waves, the time range is −0.27 s to 0.96 s. There are two depressions which are present in the west and southwest of the well MYL-12 and comprise thickest Jurassic sediments. The northern limb of the anticline is relatively thicker comparative to southern limb. Generally, the thickness of the Jurassic sequence decreases from the southern limb to central and, northern limb is also thinning toward the axis of the anticline (Figure 17).

5.3.3 Isopach Map of Paleocene

The isopach map of the Paleocene sequence is exhibited in the Figure 18, which signifies thickness variations of sediments. The range of TWT is −0.25 s to 0.62 s. The well MYL-12 has greater thickness than the other two wells, which show TWT is about 0.60 s. This map expresses that smaller depressions are present in the Paleocene sequence.

5.3.4 Isopach Map of Eocene

The isopach map of the Eocene sequence on the basis of time is provided in Figure 19. The thickness range of the Eocene units in term of TWT in map is −0.22 s to 1.08 s. The center of the map reveals the thickest area of the Eocene rocks on which well MYL-12 is present. Northern side of the map has less sedimentary cover and form a circular shape whereas southeast and southwest depict thick sedimentary cover. The interpretations delivered the clue of Eocene rocks as reservoir in this area.

5.4 Eocene Reservoirs Structures

Subsurface structure shifted south-west to the surface (Meyal-Kharpa) structure that extend east-west (Figure 20) which is conceivably owing to younger transpressional blocks movement [21]. Seismic reflection data depicted that subsurface structure does not lie directly under the surface structure. This structure trends east-west indicating pop-up, salt cored, plunging, gentle dipping anticline restricted by thrusts in the north and south at the Eocene level (Figures 7 to 10). The folded eastern portion is tighter

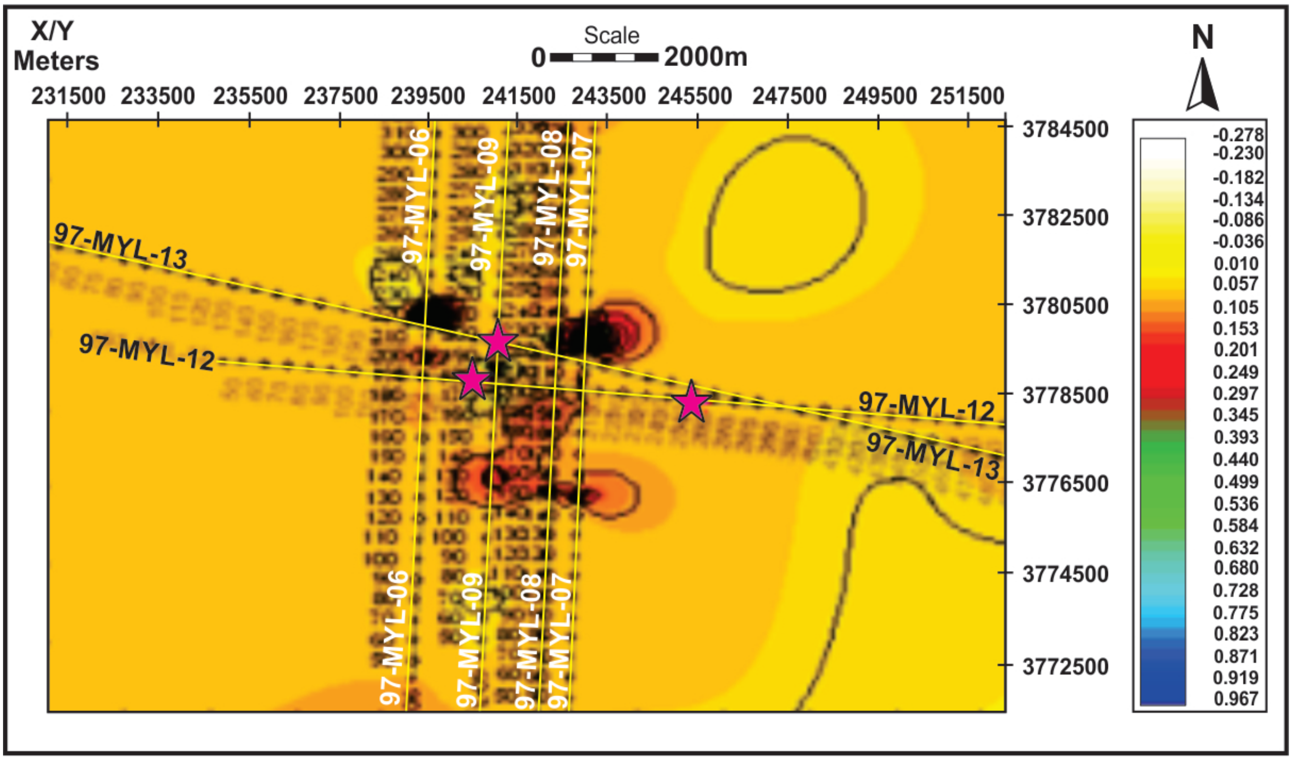

Figure 17: Time based isopach map of the Jurassic showing thick Jurassic strata in two small depressions.

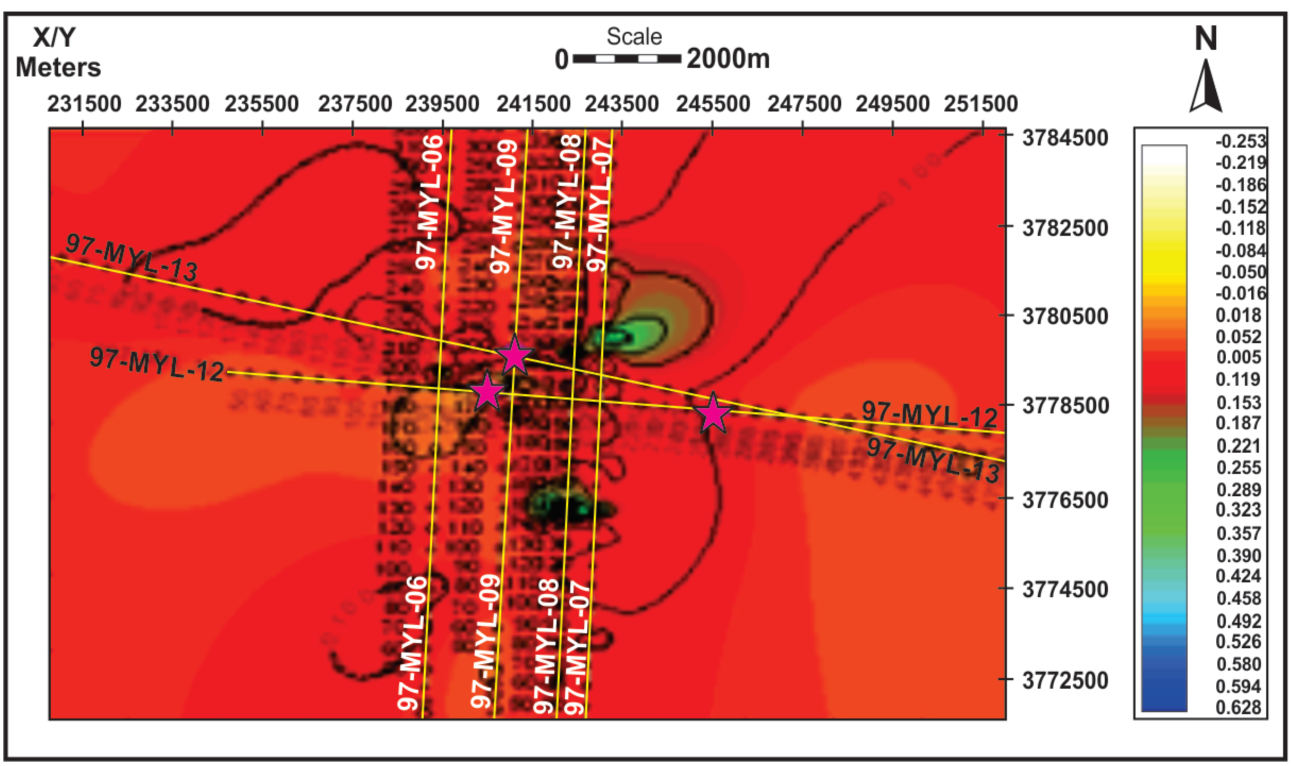

Figure 18: Time based isopach map of the Paleocene depicting high Paleocene sediments in well-12.

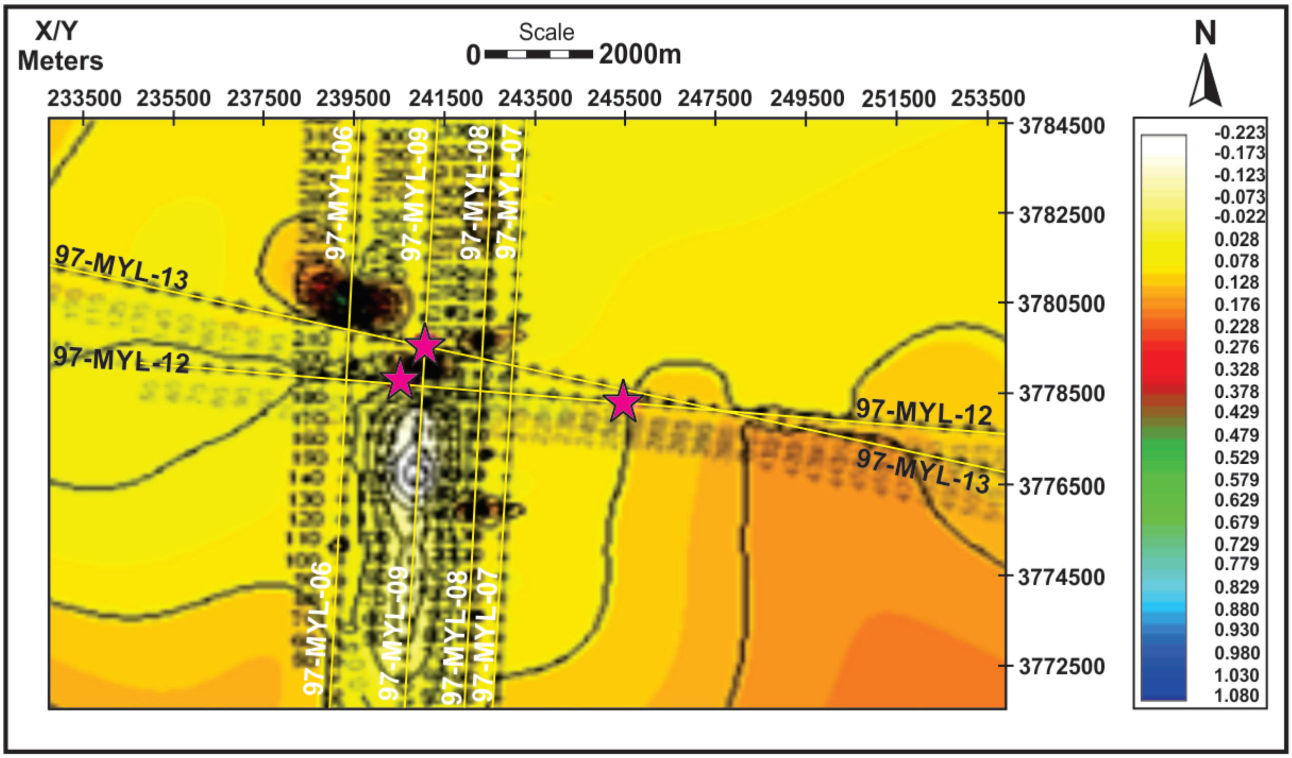

Figure 19: Time based isopach map of the Eocene indicating high sedimentary strata in east-west as compared to north.

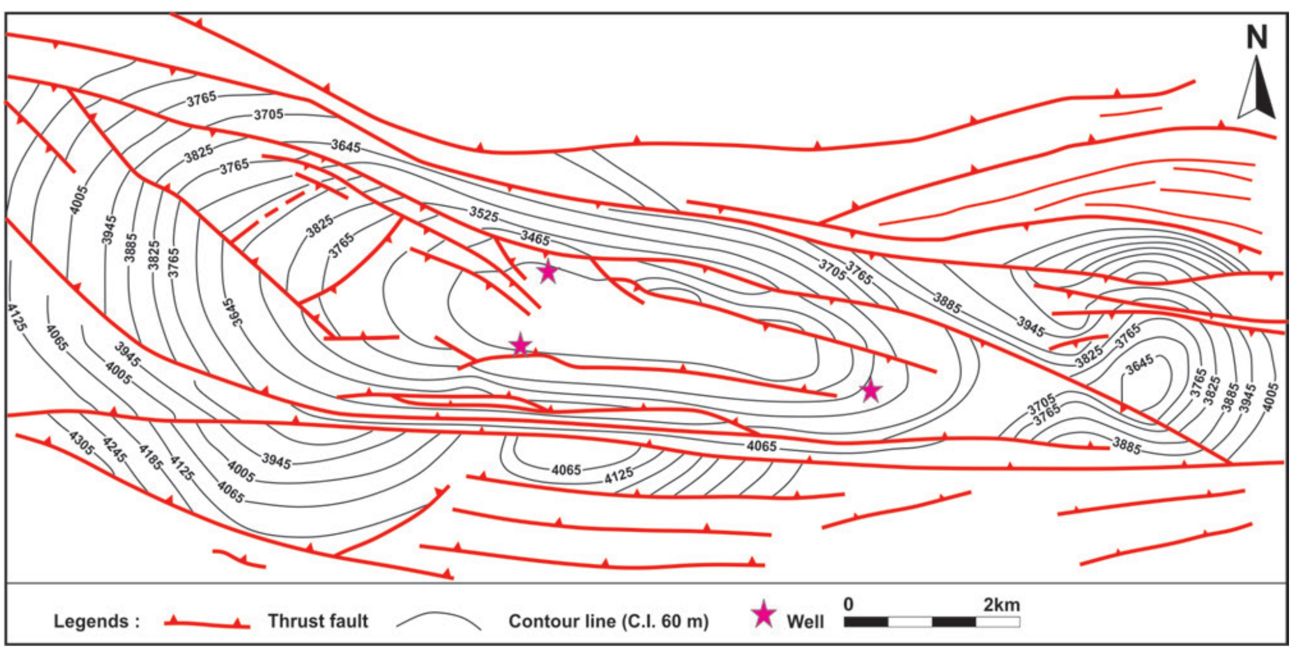

Figure 20: Structure contour map on top of Chor Gali Formation (Modified after [2, 21]). The E-W distance between the Western two wells and the Eastern well is about 4 km.

than the west. Wells were drilled in thick Eocene strata which provide suitable trapping system in Meyal Field.

The oil and gas are revealed in the famous oil-bearing zone in the Eocene rocks (Sakesar and Chor Gali formations) (Figures 5 to 10). These two Formations show thickness ranging from 145 to 187 m. The top 16 to 32 m of this succession overlies the Main Oil Horizon, which comprise of interbedded shale, marl and limestone. Eocene reservoirs have water resistivity predictable to be 0.314 to 0.464 ohm/m, having Total Dissolved Solids of 12,759 to 19,585 ppm (NaCl equivalent) [21, 22].

6 Conclusions

2D seismic interpretation confirm the presence of thrusting on all dip lines (97-MYL-06, 97-MYL-07, 97-MYL-08 and 97-MYL-09), which might be the result of compression. The Meyal anticline is an elongated and trending east to west with two major reverse faults, dipping towards each other on the dip lines. The northern thrust has more throw as compare to the southern thrust. The central block of the Meyal anticline has moved upward along the fault surfaces thus forming a pop-up structure. In addition, the time structure maps also confirmed the upward movement of central block of the Meyal anticline and demonstrate that Meyal anticline is thrusted anticline and its trend is northwest-southeast. Furthermore, the basin architecture of the anticline is confirmed by isopach maps that suggest high post-deposition in the center as compared to limb. Our current research implies that the pop-up structure and post-Eocene deposits provide appropriate structural trap for the accumulation of hydrocarbons. The reverse fault acted as a seal and shale of the Eocene strata as a cap rock. Moreover, the source for the hydrocarbon is the Patala shale and the prospective reservoir rocks are Eocence Chor Gali and Sakesar formations.

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