An Integrated Subsurface Geological and Engineering Study of Meyal Field, Potwar Plateau, Pakistan*

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Abstract

Meyal Oil Field is one of the major oil and gas producing fields in the Potwar Plateau Upper Indus Basin, and is located in northern Punjab, Pakistan. The field was discovered by Pakistan Oilfields Limited (POL) in 1968 after the seismic data acquisition. The field includes 16 wells and has produced over 36 MMB oil and 250 BCF gas from fractured Paleocene and Eocene shallow marine shelf carbonate deposits of the Lockhart-Ranikot and Chorgali-Sakesar formations. Production has also been obtained from the siliciclastic Jurassic Datta Formation. Oil and gas are produced at depths of 11,984 to 14,084 feet, with the most prolific reservoirs existing in carbonates of the Early Eocene age Chorgali-Sakesar Formation. The underlying reservoirs of Paleocene age carbonates of the Ranikot-Lockhart formations and sandstone of the Jurassic age Datta Formation has produced only about 18 percent of the total field production.

Meyal-Kharpa surface structure is an east-west trending narrow steep faulted anticline with two major thrusts cutting the structure longitudinally. The subsurface structure does not lie directly underneath the surface structure. Previous exploratory attempts were mainly based on the surface geological mapping. Attock Oil Company (AOC) and Burmah Oil Company (BOC) drilled six unsuccessful wells during 1916 to 1948 in Meyal. Seismic data acquisition during 1965-1966 had helped identify the subsurface structure configuration that led to drilling of the Meyal-1 discovery well. At the Eocene level the subsurface structure is defined as east-west trending anticline bounded by thrust faults in the north and south. Most of the wells were drilled in the central part of the Eocene structure.

The primary drive mechanism is solution gas. The early field performance indicated the reservoir did not have significant natural pressure support, and pressure maintenance would be required to maintain high productivity and to improve recovery efficiency.

During 1992-1993 a gas and water injection program for pressure maintenance was initiated in the Eocene section after 24 years of field production. A positive effect of the injection program was observed and declining reservoir pressure was maintained at around 2020 psi. An earlier gas and water break through was observed than anticipated. The injection was ceased in 1999 after producing approximately 3.5 million barrels of additional oil which would not have been possible to produce under the straight depletion mechanism. An additional recovery of 100 BCF gas and 1.2 MMBO could be recovered in this phase which enhanced the ultimate recovery to 39% and 84% for oil and gas respectively. If the field was discovered today, a lot would be changed for reservoir management and the injection program. An earlier EOR program initiation would have been proven more useful.

Introduction

Meyal Field is located in Attock district, near Pindi Gheb, 110 kilometers southwest of Islamabad in an active foreland and thrust belt in the Central Potwar Plateau of the Upper Indus Basin (Figure 1 and Figure 2). Meyal Field is one of the major oil and gas producing fields in the Potwar Plateau. The field was discovered by Pakistan Oilfields Limited in 1968. Discovery resulted after 52 years of continuous exploration efforts in the Meyal-Kharpa area. In 1916, soon after the discovery of Khaur Field, the first well was drilled which was terminated in the Molasse sequence without reaching the Eocene.

The Meyal Field has produced 36 MMBO and 250 BCF gas from three reservoirs (Table 1 and Table 2). The bulk of production has come from the fractured carbonates of the Chorgali-Sakesar formations of Eocene age, whereas marginal production has also been obtained from the carbonates of Paleocene Ranikot-Lockhart formations and Jurassic Datta Formation sandstone. The drilling activity was focused mainly at the central part of the Eocene reservoir. After the discovery, the field was subsequently developed during 1968 to 1997 by drilling 15 more wells. Except well No. 11, all wells reached their objective depths and produced varying volumes of hydrocarbons. The produced gas from Eocene reservoirs contained approximately 2% H_2S which was unfit for the pipeline and for the refinery. A gas sweetening plant and sulfur recovery plant was erected in 1974 for the commercial supply of gas. An LPG (Liquefied Petroleum Gas) plant was also installed to extract the LPG from the producing gas in 1982-83. The producing capacity of this plant is 200 metric tons LPG per day.

After reaching plateau production, at present the field is producing 200 BOPD and 12 MMSCFGD from Eocene, Paleocene and Jurassic reservoirs. LPG plant production is about 80 MTPD which includes LPG from Pariwali and Dhulian.

Discovery of the Meyal Field renewed and further boosted the hydrocarbon exploration activities in the Potwar Plateau area. After the discovery well of Meyal, a number of the world's major oil and gas exploration and production companies applied for the Exploration Licenses in the Potwar Basin, which led to an increase in the pace of exploration and drilling activity in the area.

The continued exploration efforts, the application of the new technology and changing exploration methodology had resulted in the discovery of the Meyal Field. This is a very important message for explorationists.

Exploration and Development History

The Meyal-Kharpa surface feature had remained a key target for petroleum geologists from the onset. At Meyal, the first AOC well was drilled during 1942-44 which was abandoned at 8490 feet due to collapse of 8 5/8 inches casing. AOC well-2 was drilled almost at the same site of well-1, to 10,501 feet during 1945 and was plugged and abandoned due to the belief that the well had crossed a thrust fault and possibly reentered the Miocene age Kamlial Formation (Figure 4). Well-3 was drilled after re-mapping of the structure on the anticlinal nose at the western end of the structure. After drilling to a depth of 8,100 feet, the well had to be abandoned due to mechanical reasons.

Further geological studies were carried out by AOC geologists. Z.H. Jafri and N.R. Martin in 1954 recommended that the previous unsuccessful drilling results could not diminish the prospects of the structure. It was also appreciated that subsurface structural definition could not be interpreted solely on the surface geological data.

Pakistan Oilfields Limited applied for an Exploration License over the Pindi Gheb area, including the Meyal-Kharpa structure, and seismic reflection and refraction survey was conducted in 1960-61 that was found inconclusive. However, it helped to establish that to the south an anticlinal axis appeared to be rising towards the western part of the fold.

After evaluating all the available geological, seismic and well data, another seismic survey was planned over the southern part of the structure. During 1965-1966 a seismic survey was conducted that helped in identifying three subsurface highs (Figure 5). The high was located south of the surface anticlinal feature and was selected for testing.

POL spudded its first well in Meyal on November 2, 1967 and drilled to the Eocene Chorgali-Sakesar formations to 12,514 feet. After testing, the well was put on production in November, 1968. The sustained production of the well was 1,371 BOPD and 5 MMSCFGD on January 1, 1968. Discovered oil was light, having 44.1° API gravity with a Gas Oil Ratio (GOR) of 3423 scf/stb with considerable amount of H_2S. Reservoir pressure was estimated to be approximately 6,900 psi.

Field Development Strategy

Meyal and Uchhri Minning Leases covering 40.05 sq mile and 6.29 square mile area respectively were awarded to POL with effect from December 23, 1967 for thirty years. After the discovery well POL-I, fifteen more wells were drilled to develop the field during 1968 to 1997. One well Meyal No. 11 was abandoned at 2858 feet in Chinji Formation.

Initial seismic data (1965) which aided to locate the discovery well No 1 indicated the crest of the structure at that location. Based on this assumption wells No. 2, 3, 4 and 5, were drilled towards west of well No. 1 to develop the Eocene and to explore new deep reservoirs during 1969 to 1979.

Pakistan Oil Fields Limited (POL) acquired 13 seismic lines of data comprising 149.8 kms using 2400% vibroseis technique during June-September, 1980. The interpretation of the seismic data significantly changed the earlier assumed subsurface structural configuration. The location of well No. 1 was interpreted to be due south of the crest of the structure. As it was initially believed the existence of the two highs were proven as a single high and the fold was more complex from west to east. Toward the west the fold was simpler and more open than in the eastern part.

Based on new structural data, additional wells No. 8, 9 and 6 were drilled on the northern flank of the fold. However, no well was drilled on the crest. In 1978, reservoir pressure reached 4808 psi which was estimated as the field's bubble point. Until that time (1968-1978), the field had produced 9.23 MMBO, 37 BCF gas and 48,700 barrels of water. Further development drilling in the field was planned in a manner that helped to preserve the gas cap and maintain its energy. Those well locations where the high GOR production was expected were systematically avoided. Further drilling was targeted to test the remaining potential of the northern and the western part of the field.

Based on the previous experience of the Dhulian Oil Field, POL planned to test the hydrocarbon potential of Paleocene carbonates and Jurassic clastics reservoir. Therefore, during 1970, well No. 2 was drilled to the Paleocene sequence. The Lockhart Formation was proven to be oil bearing and flowed at a rate of 659 BOPD. Initial reservoir pressure of the Paleocene was estimated to be 7489 psi, the oil was 44-46° API gravity. No H_2S or sulfur was observed during the test.

Jurassic clastics of the Datta Formation flowed sweet oil and gas from well No. 6 for the first time from the depth of 13,338-13,424 feet at a rate of 456 BOPD with a very high GOR of 5297 Scf/Stob. Initial reservoir pressure of the Jurassic was estimated to be over 6300 psi, API° gravity of the oil was between 38° and 42° and found to be sweet and free from sulfur. During the producing life of the field, to-date cumulative oil production was 36.87 MM barrels oil, 129.563 BCF gas, 8.36 MM barrels of water.

Regional Setting and Tectonics

The Himalayan collision system represents an active collision orogen between the Indian and Eurasian subcontinents (Figure 1). The collision was active since about 55 Ma (Jadoon et al., 1999; Powell, 1979) and involves continuous uplifting, erosion and deposition of sediments.

The Potwar Plateau is situated in the lesser Himalayas of Pakistan, a zone of deformed meta-sedimentary and sedimentary rocks originally deposited on the northern Indian continental margin and in the Indo-Gangetic foreland basin (Figure 1 and Figure 2). This zone is south of the high crystalline Himalayas, which contain, from north to south, meta-sedimentary and igneous rocks of the northern Asian continental margins; meta-volcanic, igneous and meta-sedimentary rocks of the Kohistan Island arc terrain; and igneous and high grade metamorphic rocks of the intensely deformed northern margin of the Indian Plate. Thrust faults have been traditionally assigned for the fault contacts between these zones (Sercombe et al., 1998).

Sedimentary strata in the foreland are detached and translated along the Salt Range Thrust over the Indo-Gangetic foreland (Sercombe et al., 1999; Jadoon et al., 1999). The topographically rugged Salt Range and Potwar Plateau is the northernmost feature of Indus Basin, bounded by the Main Boundary Thrust and the Kalla Chitta Range in the north and the Salt Range in the south (Siddiqui et al., 1998). Precambrian Salt and possibly Eocene evaporites and argi Hites are likely the main decollments that produced large scale thrusts and telescoping that had transported the sedimentary units substantial distances from the point of their origin in the Potwar and Kohat basins.

Due to the existence of a number of well-defined mappable surface anticlines in the Kohat-Potwar Basin, hydrocarbon exploration efforts remained active since 1860 when the first well was drilled in Kundal near Mianwali. These efforts were focused in the areas of oil seeps.

The last period of uplift and erosion corresponds to major collision (Figure 3) probably during the Late Eocene (Hasany and Khan, 1998). Oligocene rocks are not present in the Potwar region which also led us to assume that prolific structures were going through the process of folding during that time.

Stratigraphy and Depositional History

Rocks from Precambrian to Quaternary age are present in the Potwar Plateau. These rocks, with a total thickness of more than 26,000 feet, were deposited in a variety of environments ranging from marine to fluvial. Periods of uplift and erosion were quite extensive, as indicated by several major unconformities (Figure 3). The oldest rocks penetrated in the Meyal Field are the Permian clays, encountered at 14,360 feet in Meyal No. 13 well.

The Permian and Triassic strata are separated by an unconformity, reflecting a regression of the sea and emergent conditions persisted during Late Permian to Early Triassic, followed by yet another marine transgression in the Triassic. The rocks of Triassic, Jurassic and Cretaceous age were deposited on a west-northwest facing passive margin after the breakup of Gondwanaland with maximum development of Mesozoic rocks in the western Potwar and Salt Range, overlapped by Paleocene strata towards the east (Yeats and Hussain, 1987; Hasany and Khan, 1999). In the Meyal area, Mesozoic sediments comprise a thin sequence of Triassic and Jurassic sands and shales (Mianwali and Datta formations) overlain unconformably by Paleocene strata. The upper Jurassic strata Samana Suk Formation and entire Cretaceous strata, however, are missing over the field, as the NE-SW directed wedge outs run in just west of the field, and as a consequence, Hangu Formation (Dhak Pass) directly overlies the Datta Formation.

During Paleocene, shallow marine deposition ensued, which was dominated by bioclastic and micrite carbonates of Lockhart Limestone (Khairabad Limestone). The overlying Patala Formation represents alternations of deeper outer and shallower inner shelf facies. This is followed by another period of Paleocene carbonate build-up represented by Upper Ranikot and Oyster Beds and this sedimentation was terminated with the onset of apparently more anoxic deep water deposition of the Nammal Formation.

During the Eocene, shallow marine sedimentation resumed with deposition of a mainly calcareous/argillaceous sequence of the Nammal, Sakesar and Chorgali formations. The overlying Kuldana Formation, which consists of red claystones and shales, was deposited in open marine to partially restricted environments. While the youngest of Eocene rocks in the area, i.e. Kohat Formation, was deposited in more open marine conditions.

The last period of uplift and erosion corresponds to major collision between the Indo-Pakistan and Eurasian plates, probably in Late Eocene. Oligocene rocks are not present in the Potwar region. During the main orogenic phase in Miocene and Pliocene, thick fluvial sediments represented by Rawalpindi Group (Murree and Kamlial formations) and Siwalik Group (Chinji, Nagri, and Dhok Pathan formations) were deposited in the Potwar Foredeep, in response to the continued uplift in the north.

Petroleum Geology

Structure

Meyal-Kharpa surface structure is an east-west trending narrow, steep, faulted anticline with two major thrusts cutting the structure longitudinally. The subsurface structure does not lie directly underneath the surface structure. There is a southwest shift of subsurface structure to the surface structure (Figure 4). This shift is likely due to relatively younger transpressional movement of the blocks. Previous exploratory attempts were mainly based on the surface geological mapping. Seismic data acquisition during 1965-1966 had helped identify the subsurface structure configuration.

At the Eocene level the sub-surface structure is defined as east-west trending pop-up, salt cored, doubly plunging, gentle dipping anticlinal fold bounded by thrust faults in the north and south (Figure 5). The eastern part of the fold is slightly tighter than the west. Most of the wells were drilled in the central part of the Eocene structure. Trapping mechanism in the Meyal Field is structural.

Reservoirs

Eocene

The oil and gas was discovered in the known oil bearing horizons of the Chorgali and Sakesar limestones of Eocene age (Figure 6, Figure 9, Figure 10). The gross thickness of these two formations ranges between 464 to 600 feet. The top 50 to 100 feet of this sequence overlies the Main Oil Horizon, which comprise interbedded limestone and turquoise shale and marl. Water resistivity (Rw) of the Eocene reservoirs is estimated to be 0.314 to 0.464 ohm/m, having Total Dissolved Solids (TDS) of 12,759 to 19,585 ppm (NaCl equivalent).

Paleocene

The lower unit of the Paleocene section is the Lockhart Formation (Khairabad Limestone), which is a massive, argillaceous limestone. This zone has produced hydrocarbons from three wells. (Figure 11, Figure 18 and Figure 19). Production from this reservoir was very limited due to few wells and heterogenous reservoir quality. This reservoir was first tested in well No. 2 which produced 44-46° API oil at a rate of 168 BOPD without any hydrogen sulfide gas. The estimated reservoir pressure of this unit was 7,489 psi.

The regular production from the Paleocene started in March, 1976 and continued until 1998 (Figure 22). Water resistivity (Rw) of the Paleocene reservoirs is estimated to be 0.05 to 0.060 ohm/m having TDS 133,475 to 137,451 ppm (NaCl equivalent)

Jurassic

The Jurassic Datta Sandstone in the Potwar Basin was first established as an oil and gas producer in the Dhulian Field. The Jurassic reservoir in Meyal Oil Field has produced oil but due to lack of substantial reservoir potential the total oi1 production does not exceed 2 million barrels as yet. Water resistivity (Rw) of the Jurassic reservoirs is estimated to be 0.060 to 01.570 ohm/m, having TDS of 3,788 to 240,712 ppm (NaCl equivalent).

Source Rock

The source rock-oil correlation study was not carried out in any of the Meyal wells that could have enabled us to characterize the source rock of the field with confidence. However, a detailed study had been carried out by Sunmark Exploration Company under the title of Geochemistry of Nine oils from the Potwar Plateau region, Pakistan, during 1980. The report suggests the possibility of the occurrence of two source rocks in the Potwar Basin, Nammal shales interpreted to be the major contributor of the oils to the reservoirs of Dhulian (Chorgali-Sakesrar), Joya Mair (Sakesar), Khaur (Murree sandstone) and Balkassar fields (Sakesar). Another potential source rock considered actively participating generation of oil is the Jurassic Variegated series. This unit provided oil to the Meyal (Lockhart and Jurassic and Sakesar) and Dhulian fields (Variegated beds and Lockhart). The chemistry of the oils found in the Meyal Field in Sakesar, Jurassic and Paleocene reservoirs suggests that the hiatus separating the Tertiary and the Mesozoic is also the boundary between source units that are in a state of moderate maturity (Tertiary) and units that are in the advanced maturity (Jurassic).

However, the Eocene Chorgali-Sakesar carbonates and shales of Paleocene Patala black marine shales are also considered as the potential source rocks. Derived data from nearby fields, where source rock studies were carried out, support this view. However, due to variations in the chemistries of the oil found in Sakesar and Lockhart-Jurassic suggest the infilling history of the trap of these two groups of oils varies in geological time and space.

Seal Rocks

Kuldana Formation

The Kuldana Formation is mainly composed of multi-colored shale (red, reddish brown and purple), usually silty and brittle but occasionally clayey and soft. The thickness of this formation is 120 to 192 feet in the Meyal Field. Due to its impermeable and argillaceous character the Kuldana Formation forms an effective seal over the Eocene reservoirs of the Meyal Field.

Nammal Formation

The Nammal Formation is predominantly shale with marl and soft argillaceous chalky limestone. Shales of the Nammal are developed all over the Meyal Field. A 45 to 108 feet thick unit provides a top seal to trap oil in the Paleocene reservoirs.

Datta Formation

The top part of the Datta Formation consists of varicolored shales, siltstone, mudstone and claystone with thin sands bed (Variegated Beds). These beds overlie the "Main Oil Sand" of the Datta Formation and are considered to be the top seal for the Jurassic reservoirs. It is 217 to 277 feet thick in the Meyal Field.

Reservoir Compartmentalization

After acquiring new seismic data during 1993, reinterpretation of Dhak Pass/Jurassic Variegated and Jurassic Main Oil Sand helped identify two possible highs, "A" and "B" at the crest of Meyal Jurassic structure and five reverse faults, F1 through F5, parallel to the strike of Meyal anticline have been recognized at this level (Figure 5 and Figure 6). Wells Meya No. 6 and Meyal No. 9 were drilled between the fault F2 and F3 in the footwall block relative to the southern hanging wall. Fault F3 separates these two wells from the crest of the Meyal Eocene, Paleocene and Jurassic structure. Meyal No. 9 is an Eocene producer, was drilled to the Eocene Nammal Shale and completed in the Chorgali and Sakesar formations as a producer. Meyal No. 6 was tested in the Jurassic but testing incidentally may not be truly representative of Jurassic. Faults at the Jurassic level are likely to be sealing and if true, the Jurassic compartmentalized oil in the footwall block may not yet have been completely or partial1y drained. The crestal Jurassic oil and gas potential also exists and needs to be verified by drilling.

Reservoir Properties and Zonation

A detailed reservoir zonation of the Eocene Chorgali-Sakesar and their properties are described in detail. This zone is the primary reservoir in the Meyal Field where they can be divided into eight different possible flow units (Figure 12). The top part of the Chorgali Formation, which comprises of turquoise marl and bluish green to gray shale with minor light gray limestone, is excluded. The zonation is based on the log response of Litho-density, Neutron, Resistivity, SP, and Sonic logs.

C1 – Topmost fractured limestone

C2 – Shaly and marly interval, poor N/G

C3 – Dolomite

C4 – Dolomitic limestone

S1 – Fractured limestone, excellent SP def.

S2 – Fractured limestone, no SP def.

S3 – Apparent increase in volume of clay

S4 – Further increase in volume of clay

Unit C 1 comprises the fractured dolomitic limestones. In most of the wells this layer was prone to drilling losses. Inclusions of anhydrite and streaks of dark gray shales are also present which develop with depth. The SP is generally poorly developed across this layer. Core descriptions frequently report calcite filled fractures, 2 to 8 mm in width and steeply dipping. The net-to-gross ratio in this unit ranges between 0.8 and 0.9 across the field. In flank wells this unit becomes more dolomitic in comparison to apex wells. 1 to 9% primary porosity was observed in this zone.

Unit C2 is characterized by three thick marly argillaceous sections evident from log response, separated by gray limestone (sample description) whose log response appears dolomitic. The layer is frequently washed out due to the soft nature of the marly sections. The SP is generally poorly developed across this layer. Core descriptions report light to dark gray semi-porcellaneous limestone, with marls and bituminous shales. Calcite infilled fractures and some open fractures are common. The net-to-gross ratio in this unit does not exceed 0.4 in the field and generally remains around 0.35. The primary porosity was estimated to be 0 to 8% by log response.

Unit C3 is described as dolomite, containing chert, pyrite, carbonaceous shale and inclusions of anhydrite. In the majority of wells, SP deflection begins at the top of this unit and increases toward its base, reaching a maximum SP deflection at the base of C4/top of S1. The top deflection can also be uttered due to lithology. Primary porosity id interpreted to be 0-9%, however, most of the log curve response reflects a low porosity (Neutron and PhiD and PhiS) and relatively clean calcareous dolomite, with minor borehole rugosity that may reflect the presence of secondary porosity. The presence of primary porosity is not evident from core descriptions. The net-to-gross ratio in this unit ranges widely, between 0.7 and 1. (100% net in Meyal No. 9, while 70% in Meyal No. l).

Unit C4 consists of dark gray dolomitic limestone. At its base alveolina, a miliolid foraminifera, is present marking the top of the Sakesar Formation. In some of the wells the unit includes part of top Sakesar Formation. This section contains inclusions of anhydrite and shale (sample and core descriptions), though logs indicate the layer is a relatively cleaner limestone, displaying the best overall porosity development within the reservoir. The net-to-gross ratio in this unit ranges widely, between 0.8 and 1. (100% net in Meyal no. 9, while 80% in Meyal No. 10). As in Unit C3, Vclay commutation in Meyal No. 9 is questionable.

Unit Sl is crystalline gray hard limestone, containing Alveolina microfossils. Both open and calcite-filled fractures are reported. In almost all wells, except Meyal No. 15, good fracturing was inferred from openhole logs. The upper portion of the unit displays good SP deflection in most wells (the best in Meyal No. 7), which deteriorates with depth. Logs indicate the section to be a relatively clean, low porosity, slightly dolomitic limestone. In most of the wells this layer was prone to losses even with water. Frequent borehole rugosity, as evidenced from the caliper, microlog, density and density correction curves, may indicate the presence of secondary porosity. In Meyal No. 1 a porous layer at t-h@ base of Sl (as interpreted by GLOBAL). Possibly Vclay commutation is questionable in this part. If Vclay of these CPIs is accepted, then net-to-gross ratio becomes 1000/0, otherwise it ranges 85-900/0.

Unit S2, is distinguishable from Unit S1 by an increase in Sw inferred from the electrical logs. A different resistivity envelope (in comparison to S1) is evident on almost all the wells. In most of the wells the SP is not developed across this layer. The possibility of secondary porosity, however, is evident from log response and borehole rugosity. In Meyal No. 1 (Side track) which was drilled ten years after discovery, LLS was reading over LLD (not very common in Potwar). The net-to-gross ratio is 100% for this unit).

Unit S3 is distinguishable from Unit S2 by an apparent increase in argillaceous content as inferred from the density-neutron, gamma ray and resistivity curves. In most wells the SP is not developed across this layer. The possibility of secondary porosity, however, is evident from log response to borehole rugosity. The net-to-gross ratio ranges between 80 to 90% in this unit.

Unit S4 is the lowest layer within the Sakesar Formation and is characterized by a further apparent increase in argillaceous content. In all wells, except POL-2, the SP curve shows no development. Borehole rugosity and corresponding tool response indicate possibly the presence of secondary porosity. In western most well (Meyal No. 15) the base of this unit becomes more argillaceous. The net-to-gross ratio is 70-80% in this unit.

Reservoir Pressure and Temperature

The discovery well produced oil from 213 feet thick Chorgali-Sakesar formations in Meyal Field. Reservoir pressure as recorded on October 1, 1968 was 6,898 psi at the -11,372 foot (subsea) and the Bottom Hole Temperature was 250° F.

Field Production

Production from the Meyal Field began soon after the discovery during 1968, initially from the Eocene reservoirs. During 1969, the annual average oil production was 1200 BOPD and 4 MMSCFD gas. Oil and gas production remained steady from 1970 to 1975 with average production of 2000 BOPD and 8 MMSCFGD gas. The production doubled in 1976 reaching 5148 BOPD and 20 MMSCFGD gas; peak production of the field was during 1982 when it produced 6320 BOPD and 42 MMSCFGD gas from 5 wells.

Reservoir Studied and Reserve Estimates

Eocene Reservoirs

The first detailed reservoir study to assess the reserves and to quantify the type of hydrocarbon and in-place behavior of the three known reservoirs was carried out by DeGolyar and MacNaughtan (D&M) in 1979. According to their results, within the three reservoirs, Eocene, Paleocene and Jurassic, estimated recoverable oil reserves were 27.9 MMBO, 8.88 MMBO and 83 MMBO respectively. However, due to the poor recovery from the Jurassic, it appeared that reserve estimation was rather optimistic.

Study results showed that the Chorgali-Sakesar reservoirs have partial pressure support from either a limited aquifer or from a larger reservoir segment. This has not been confirmed either by drilling or by the interpretation of available seismic data. The Lowest Known Oil (LKO) is estimated to be -11,333 ft. However, after drilling the well No. 16, LKO was found at -11,690 ft. The Eocene reservoir in well No. 15, which was drilled at the western extreme of the Meyal structure as a water injector, was at -12,464 ft, having low porosity and permeability.

Another D&M study (1982) was carried out which was focused on assessment of reserves and to provide an insight for the further development of the field. Based on the D&M study, Eocene reservoirs original oil in place (OOIP) reserves were estimated at 83.4 MMBO, recoverable reserves 24.53 MMBO, and the remaining reserves 8.32 MMBO, whereas OGIP reserves were 317 BCF, recoverable reserves 208.92 BCF gas and remaining reserves were 136.94 BCF gas. Another 5 wells were drilled after 1982, out of which 4 wells had produced 16 MMBO and 133 BCF gas from the Eocene. Well No. II was abandoned at 2858 ft without reaching the objective depth.

Reservoir Simulation Study (CIDA, SSI, and POL, 2000) for the Eocene reservoirs estimated that 1.37 MMBO and 37.96 BCF gas may further be yielded from the existing wells. A PVT analysis on Chorgali-Sakesar crude classified the producing crude as volatile oil which was close to its critical pressure and temperature. Core Laboratories Inc., Dallas, USA, had also performed a reservoir fluid study on recombined wellhead separator samples of oil and gas from well No. 1 during 1978 and reported it to be a retrograde condensate reservoir.

Paleocene Reservoirs

Reserves of Paleocene reservoirs (Lockhart and Ranikot) were estimated to be OOIP 11.37 MMBO, recoverable reserves 3.28 MMBO and remaining reserves 0.16 MMBO, whereas gas OGIP 81.36 BCF, recoverable 40.68 BCF and remaining reserves were 7.3 BCF gas. The Ranikot-Lockhart reservoir, as a result of these studies, was considered a retrograde condensate or a dew point reservoir, i.e. a type of hydrocarbon system which is in gaseous form at the reservoir temperature and pressure. The increase of GOR was considered to be evidence of a fall in reservoir pressure far below the dew Point pressure. The LKO for Lockhart is at -12,342 feet, from well No.7.

Jurassic Reservoir

Based on the D&M study (1982) the Jurassic sandstone reservoir OOIP was 77.06 MMBO, recoverable reserves 20.04 MMBO and remaining reserves were 19.81 MMBO. The gas reserves were OGIP 279 BCF, recoverable reserves 181.47 BCF and remaining reserves were 179.45 BCF. The total production from the Jurassic reservoir (March 2001) was 1.9 MMBO and 22.477 BCF gas. Due to poor reservoir performance of the Jurassic sandstone, less attention was given for the development of this reservoir.

Well No. 9 was selected for deepening and drilling of horizontal due to its structural position in 1995 (Figure 6). This well was first drilled in 1981 to 12,849 feet in the Ranikot Formation. During November, 1995 to June, 1996 the well was deepened and drilled to the Jurassic to 14,047 feet (well depth) and the total vertical depth (TVD) was 13,664 feet. The hole azimuth was 206 degrees and the maximum inclination of the hole was 90 degrees at the bottom. The well was successfully drilled to the target depth, but due to mechanical reasons the well could not be tested. Drilling results suggest that a highly porous and permeable sandstone reservoir exists toward the updip side of the structure, contrary to the other parts of the Meyal structure where sandstone has been found having less than 3 to 8% porosity and extremely difficult to drill.

The remaining reserves of the Jurassic indicate that future drilling in Meyal can be carried out to exploit the Jurassic reserves. The Jurassic reservoir fluid is found to be volatile oil above the bubble point. The LKO was taken at -12,780 ft from well No. 7.

Enhance Oil Recovery (EOR)

IPR conducted a study in 1990 to evaluate the Eocene reservoir for enhanced oil recovery. The study recommended carrying out simultaneous gas and water injection in order to maintain and possibly increase the reservoir pressure.

Eocene reservoir gas and water injection programs were initiated during 1992-1993. This program, although initiated after 24 years of field production, resulted in recovering additional volumes of oil and gas.

The primary objective of the EOR program has been to conserve the reservoir energy for Ultimate Recovery by shutting down high GOR crestal production and augmenting low GOR flank production through gas lifting that provided pressure maintenance to the falling reservoir pressure of the field. The field pressure before the EOR was 2018.6 psi, which was elevated to 2112 psi as recorded on December 25, 1993 (Figure 21). This indicates an increase of 94 psi. It was estimated that if EOR was not initiated at this stage, reservoir pressure would have dropped to 1830.76 psi. The injection was discontinued in 1999 after producing approximately 3 million barrels of additional oil which would have been unlikely obtained under straight the depletion mechanism.

For gas injection, two compressors with a capacity of 5 MMSCFD each were installed. The gas gathering system was expanded to accommodate the compressors and injection well (Gardezi and Naveed, 1994).

For the water injection, a stream bed 9 kms away, where 5 shallow wells were drilled, was selected for the main water source. A 12" water line was laid from the water source and a water treatment facility was assembled for deoxygenation, filtration and chemical treatment. A separate produced water treatment plant was set up to occlude H_2S and emulsion removal facilities along with scale inhibition treatment. Well No. 10 was worked over and prepared for the water injection. Well No. 15 was drilled exclusively for the water injection.

Gas injection was commenced during September, 1992 from existing well No. 13 as a temporary arrangement as this well was located fairly close to the producing well No. 4. Another well, No. 12 ,was selected during January, 1995 as the alternate well for gas injection to replace well No. 13. Well No. 12 was at the structurally highest location toward the northern flank of the well significantly distant from the producing wells. Approximately 65-70% of the produced gas was injected back into the reservoir.

Water injection was initiated at about 6700 BWP on February 7, 1993 through well No. 10 and 15. This peripheral water injection was to support the edge water influx.

The initial average water injection to well No. 15 was 2424 BWPD whereas 3625 BWPD was injected in well No. 10. Due to low intake of well No. 15, acidization into the reservoir was carried out to enhance the rate of injection, which then increased the injection rate to 4000 BWPD. Total water injection into both wells from February, 1993 to February, 1999 was 32.100 MMB at an average rate of 6000 BWPD.

The initial average gas injection to well No. 13 was 2.024 MMSCFD (August, 1992) which was increased to 10.551 MMSCFD. Gas injection in this well was halted from January, 1995 to October, 1995. Total gas injection into well No. 13 to October, 1999 was 1,002,876 MMSCF.

Present Status of the Field

At present the Meyal Field is at the Blow Down stage and producing from the secondary gas cap from Eocene and Jurassic reservoirs. Total production from the field is 207 BPD oil, 11 MMSCFD gas, 130 BPD water. Approximately 30 Metric tons of LPG and 100 barrels of gasoline were also extracted.

At present the most promising prospect to enhance the field production lies in the Jurassic reservoirs where approximately 19 MMB oil remains to be drained. Horizontal drilling in the tight Jurassic reservoir is an appropriate and assuring method to develop the field successfully.

Important Lessons Learned

The Meyal Field was developed during 1968 to 1997 during the time when technological innovations moved at a brisk pace. After very careful technical evaluations, these new techniques were profusely adopted for the improvement of production. One such example is the hydraulic fracturing in well No. 10 for improving of the Jurassic reservoir production. Perforations through conveyed tubing (TCP) were also introduced for the first time in Pakistan. There are numerous inborn problems related to the tectonics of the Potwar region, such as abnormal and subnormal pressures in Siwaliks and in the Rawalpindi Group. New plans have been made to overcome the problems.

Foam-Air drilling for drilling through depleted Eocene reservoirs was also attempted but it was not mechanically successful, however, it should not be out of place to include some critical points that may help the future improvement and planning, particularly for those who are involved in developing fields in geologically similar areas as the Meyal Field.

We believe it would be useful to review the lessons we have learned. The most important aspect which was needed during the initial stage of the field was to acquire seismic data during various stages of the field life. In the case of Meyal, there was a gap of 14 years between the first and the second phase of seismic. Early seismic data control would have been useful for better field development.

To improve the maximum recovery, early EOR or water injection for pressure maintenance should have been planned in the very early life of the field. In Meyal, EOR was commenced at the time the secondary gas cap was developed.

The production from the crestal wells, once the field reached below its bubble point, should have been avoided. The wells No. 8 and 12 were producing very high GOR. These wells are located at the higher side of the structure. In Meyal, all modern suites of logs, using technology offered in Pakistan, were run to acquire necessary information related to reservoirs, structure and production.

Through experience it was learned that complex dual completions, as in the wells No. 2, 6 and 7, were found to be problematic in later life of the field. These wells were worked over and recompleted as single unitized producers. Such workover operations led to loss of production and extra expenditure. Simple well completions were proven to be successful in complex areas like Meyal.

Conclusions

1) Meyal Field was discovered in 1968 after the continued and tireless exploratory efforts of 52 years (1916 to 1968). Initial exploratory efforts were primarily focused on geological interpretation.

2) Meyal Field is an east-west fault bounded anticlinal structure. However, subsurface structure is shifted toward the southwest.

3) Discovery only became possible by the continuous evolution of geological models, which were driven by new lessons learned through the failures of drilling experiences. Seismic data acquisition (1965) helped to locate the optimum subsurface structural position.

4) Based on the regional geological understanding of the source rock distribution in Potwar Basin, it can be estimated that source potential lies in the rocks of the Nammal Formation and Jurassic Variegated units. Other potential source rocks are Patala shales, Sakesar and Chorgali formations.

5) The Meyal Field has produced 36.8 MMB oil and 250 BCF gas from 10 wells during 1968 to 2001 from three reservoirs. Chorgali-Sakesar is the primary reservoir, which produced approximately 80% of the total field production from the naturally occurring fractures network. Ranikot-Lockhart and Datta sandstone are other reservoirs that produced the remaining oil from the field due to relatively poor reservoir properties. The remaining estimated reserves of the Eocene are 1.37MMB oil and 136.94 BCF gas. Paleocene remaining reserves are too low to be of economic value. The remaining Jurassic reserves are estimated to be 19.81 MMB oil and 179 BCF gas.

6) Initial reservoir pressure of the Eocene was 6815 psi in 1968. The EOR project, which was initiated in 1992, not only helped to maintain the pressure of the field but it also enabled the yield of an additional over 3 million barrels of oil which would have unlikely been produced with a straight depletion mechanism. Initiation of the EOR at initial stages of the field life would have been more meaningful and useful.

7) The field discovery attracted a number of major oil E&P companies to explore in the Potwar Plateau.

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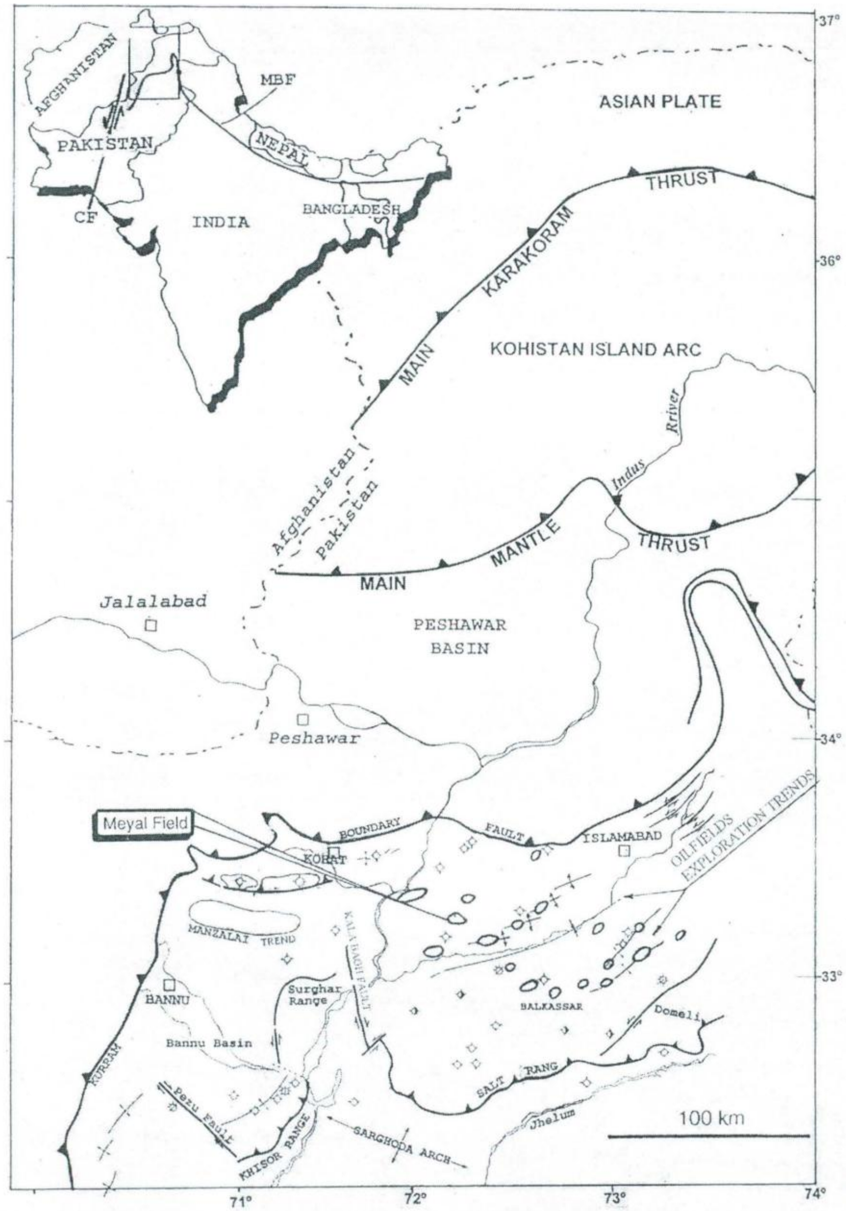

Figure 1. Regional map showing location of the Meyal Field and tectonic features associated with Northern Pakistan.

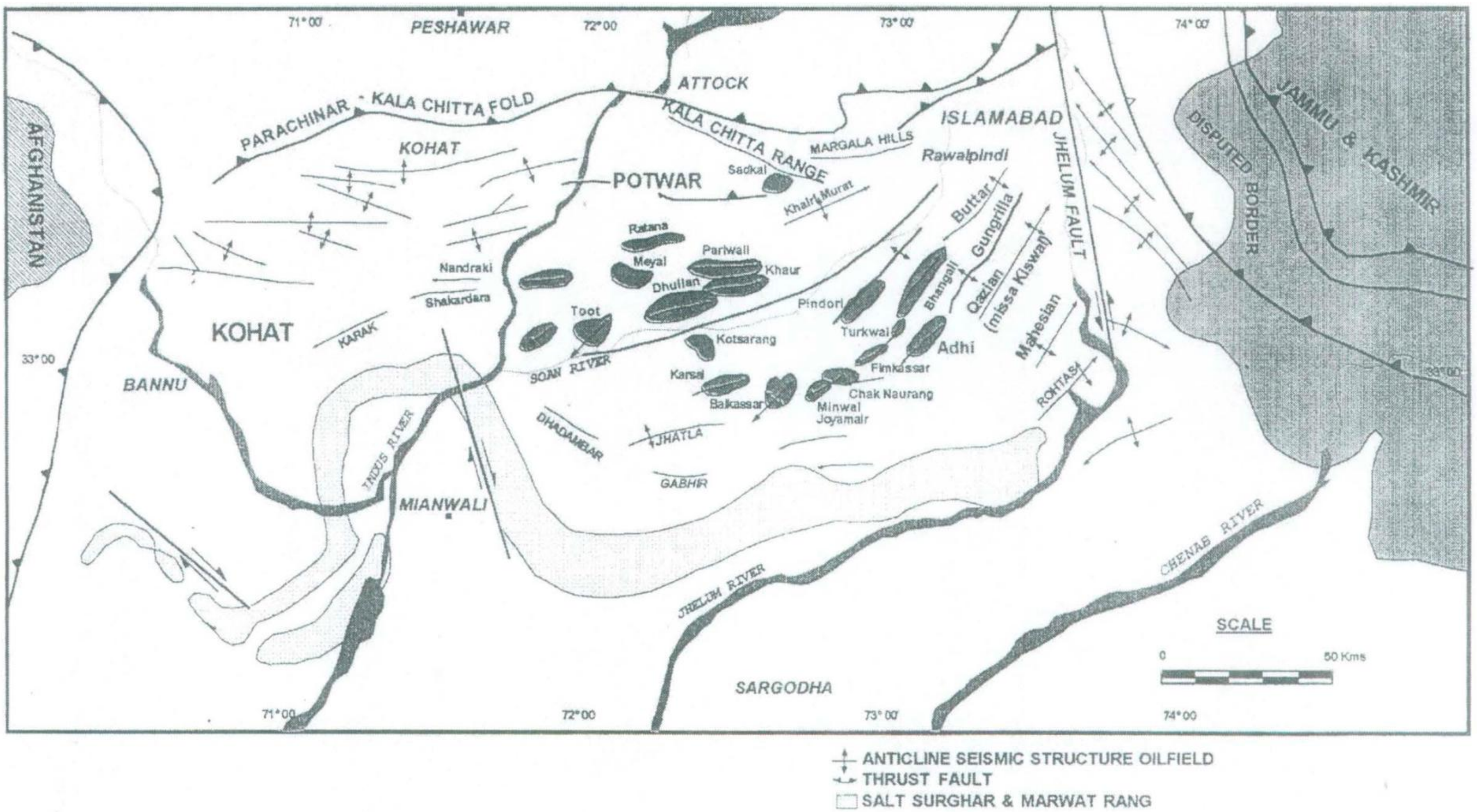

Figure 2. Generalized map of Potwar Plateau and Salt Range, showing geologic features and tectonic trends.

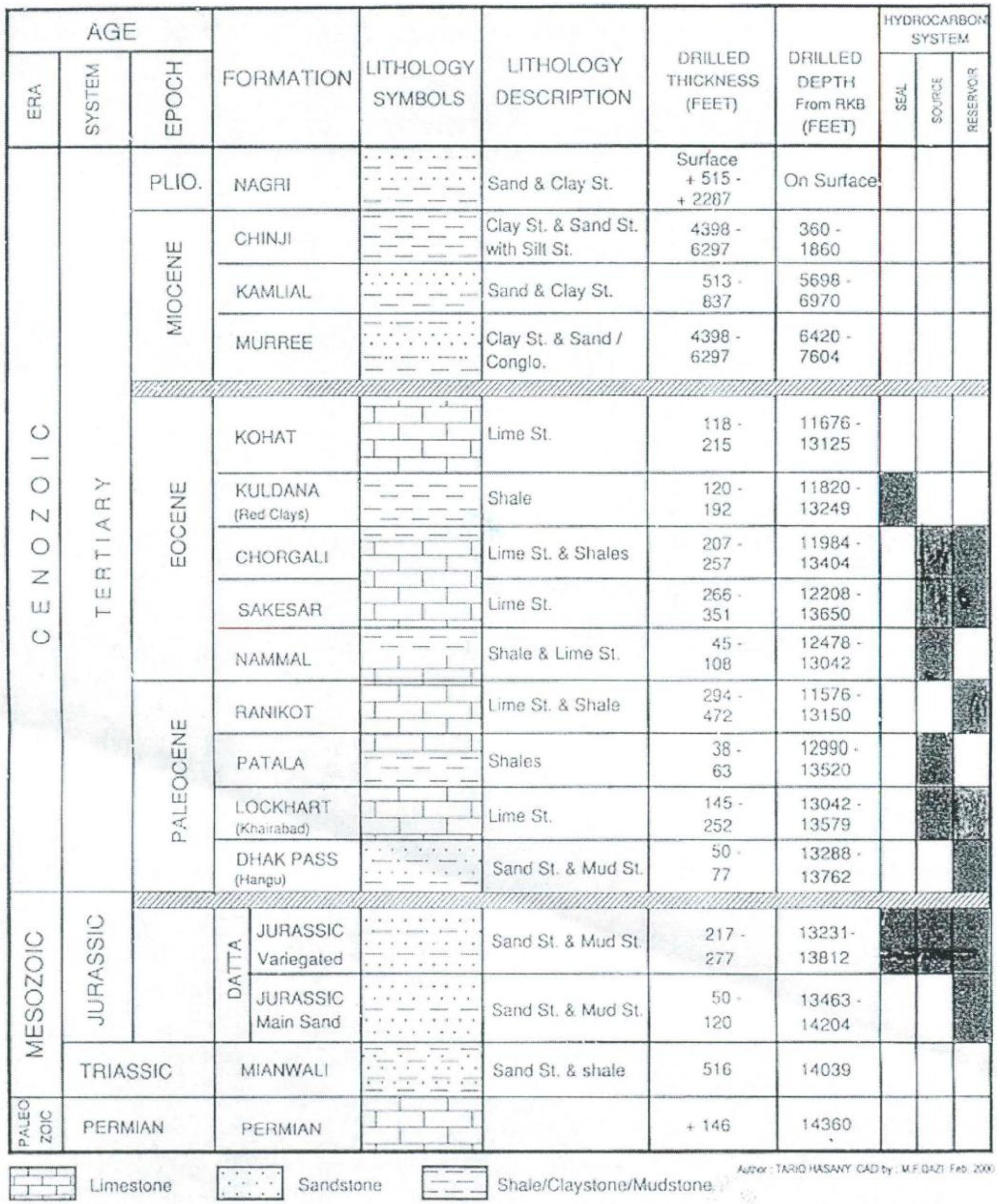

Figure 3. Generalized stratigraphic column of Meyal Field.

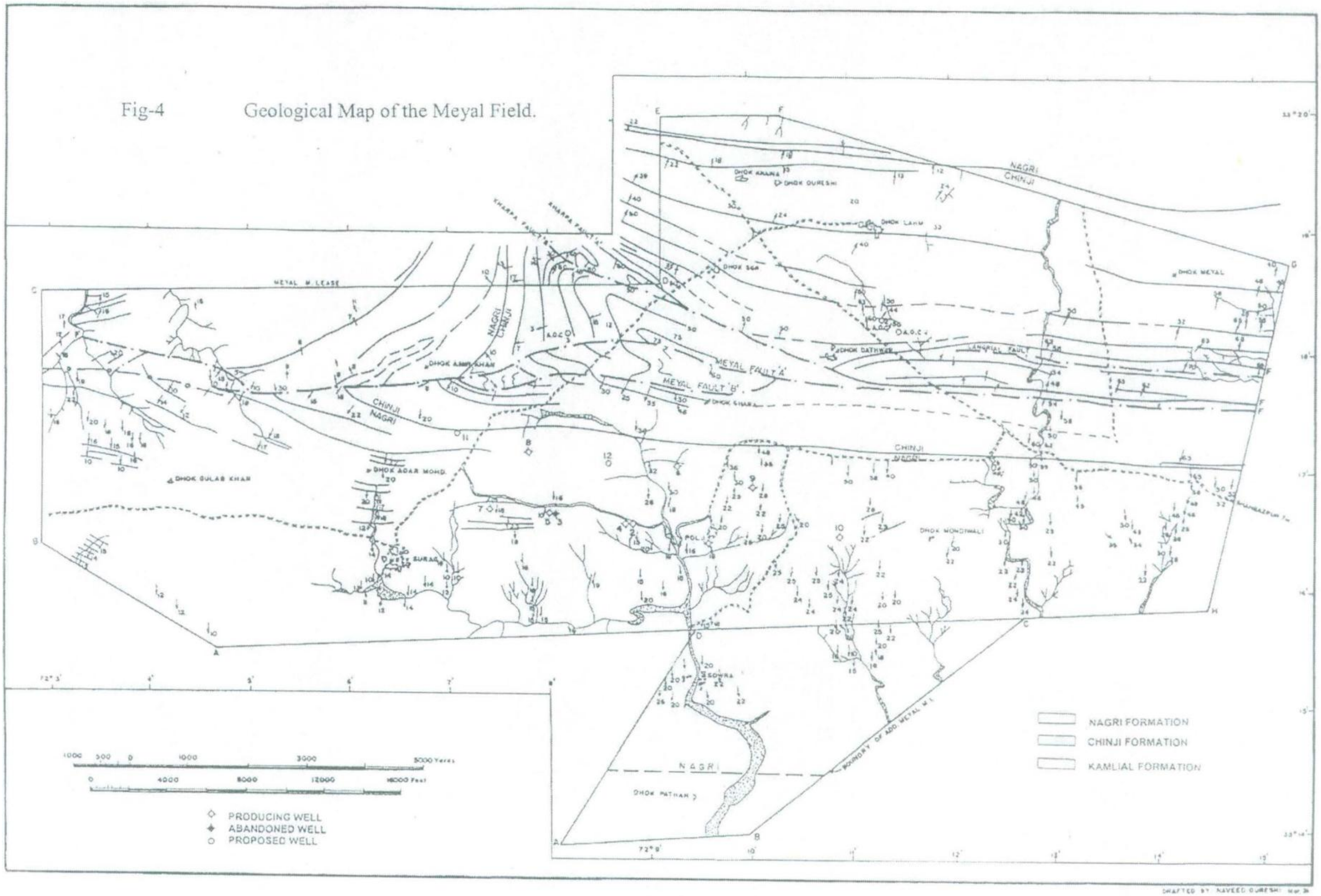

Figure 4. Geologic map of the Meya1 Field.

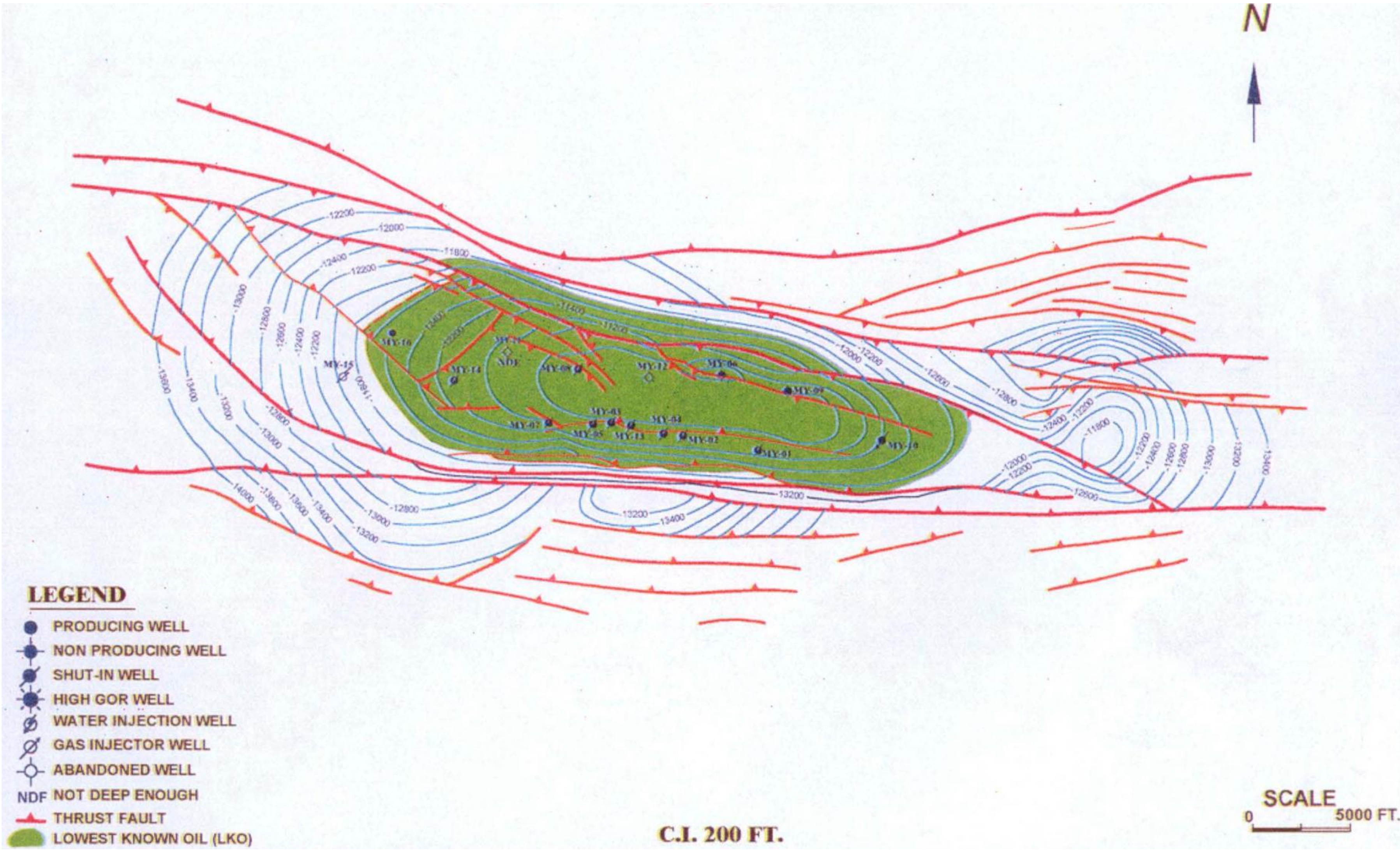

Figure 5. Structure contour map on top of Chorgali Formation.

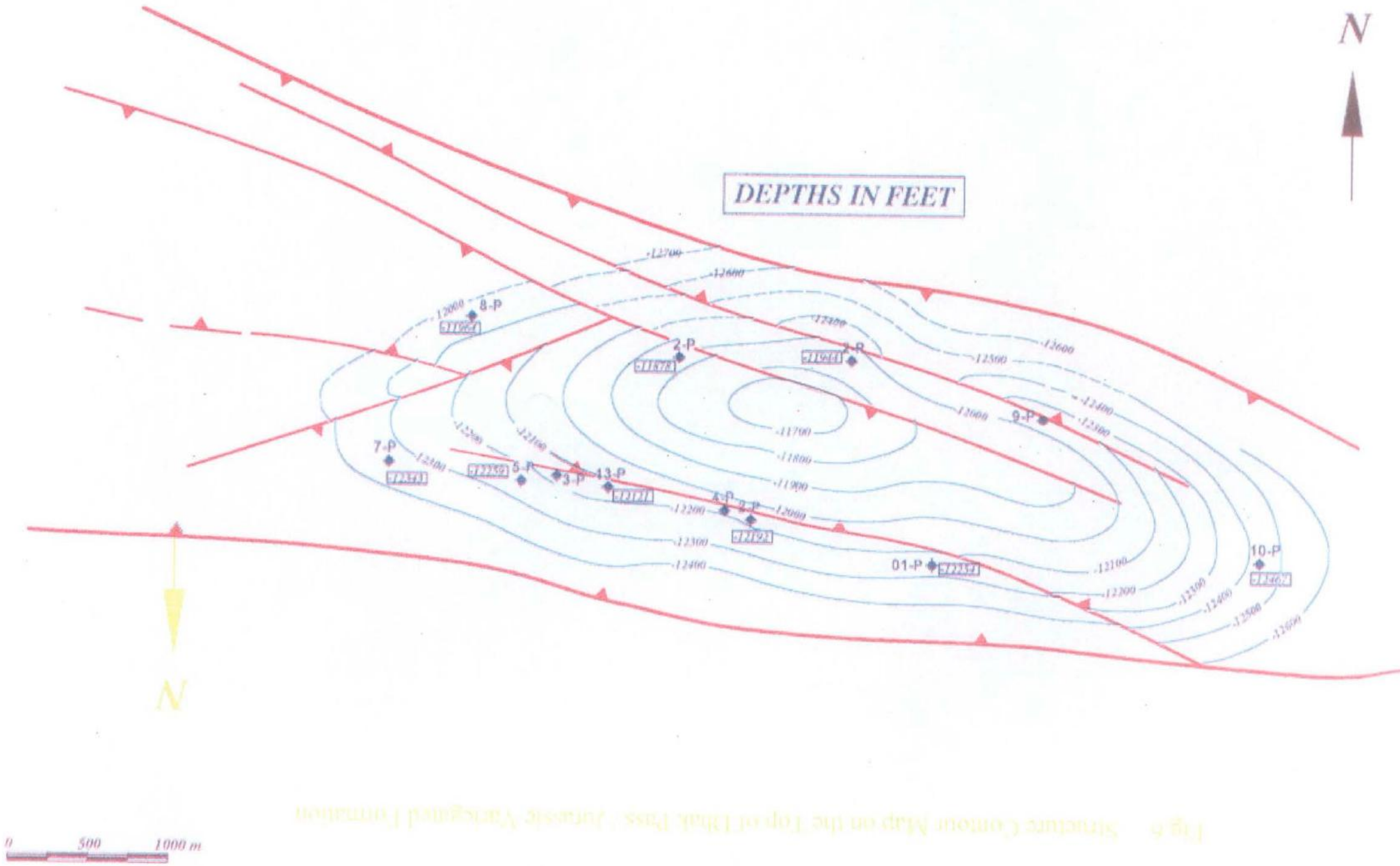

Figure 6. Stucture map on the top of Dhak Pass/Jurassic Variegated Formation.

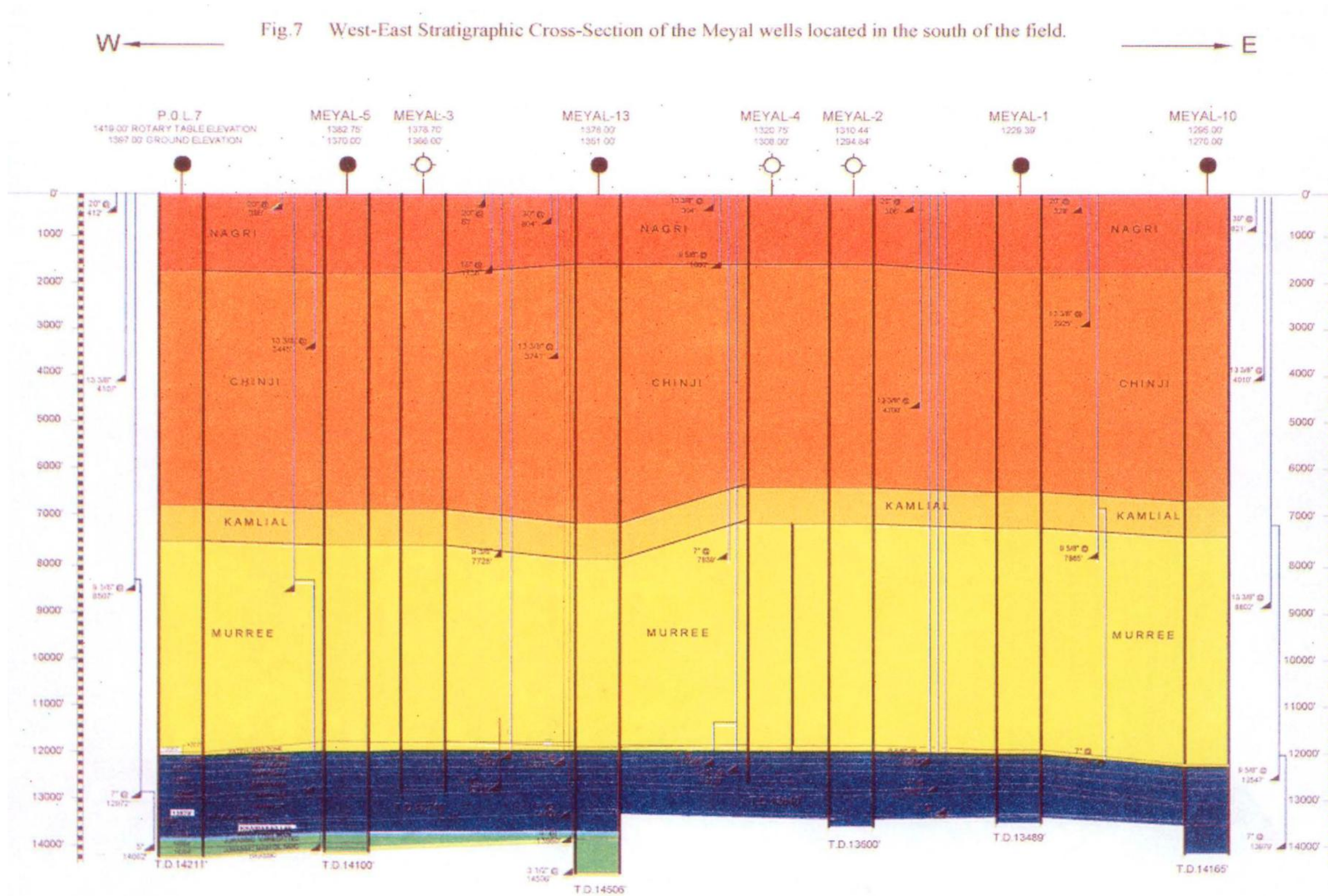

Figure 7. West-East stratigraphic cross section of the Meyal wells located in the south of the field.

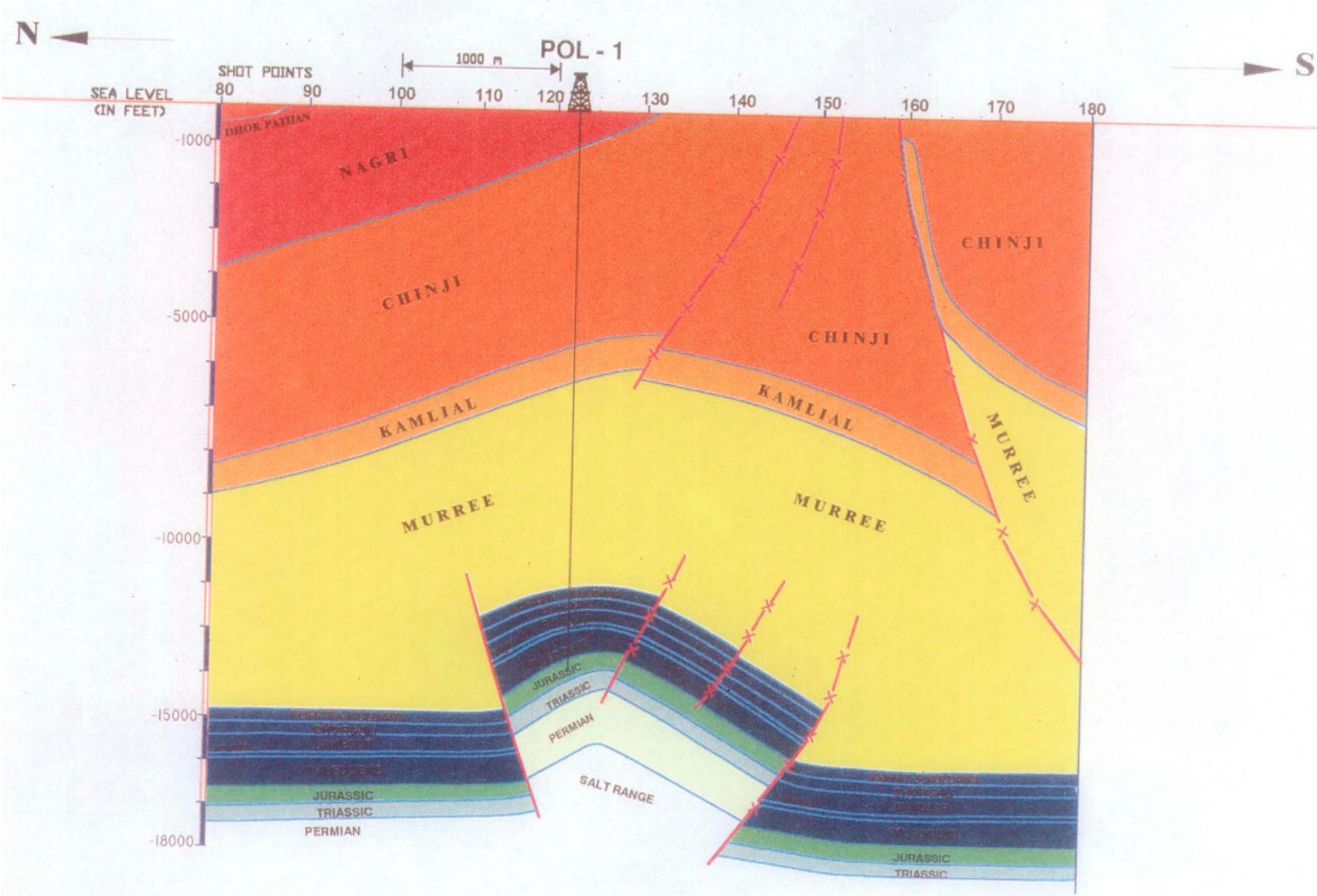

Figure 8. North-South structural cross section across Meyal Field.

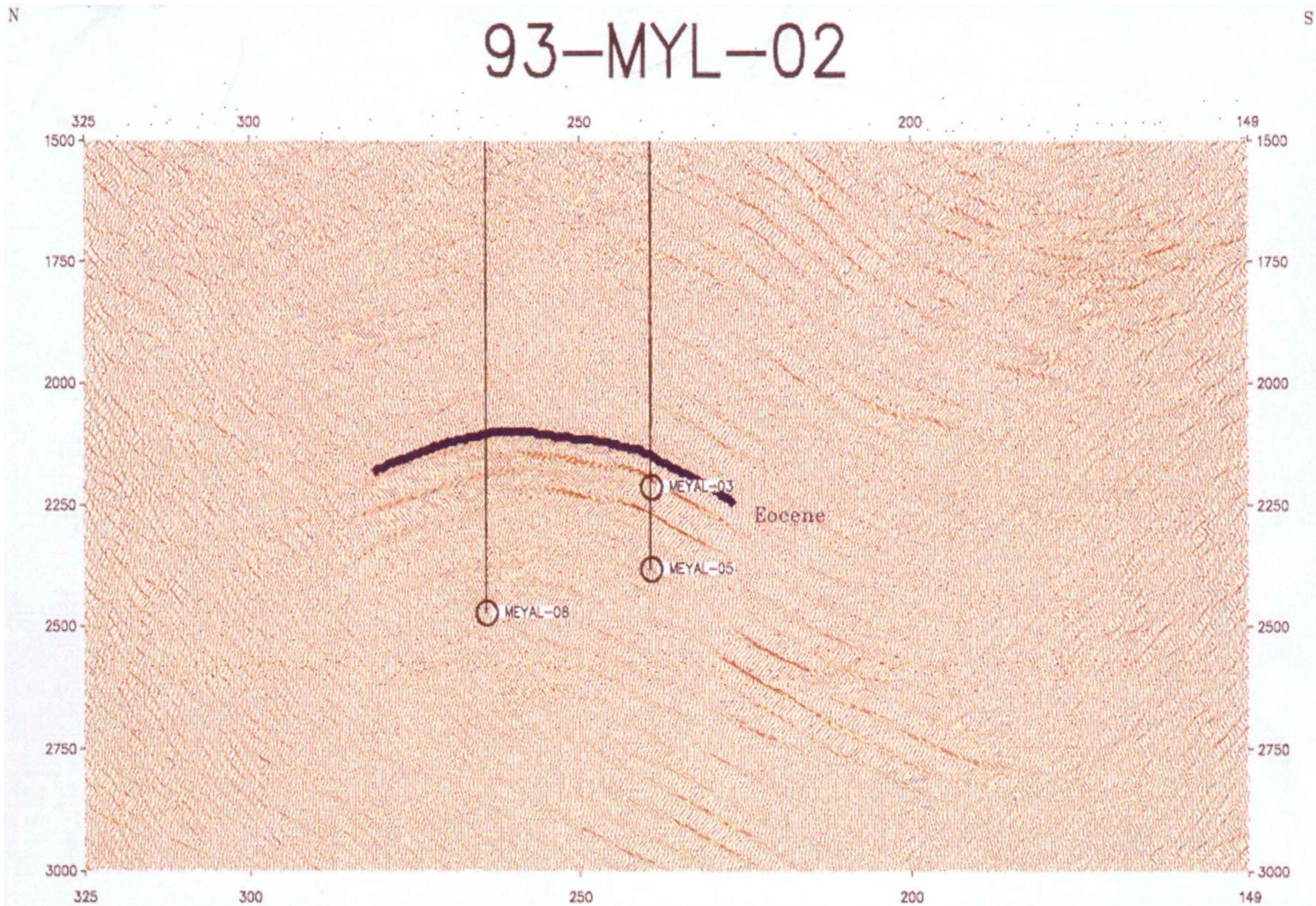

Figure 9. North-South seismic line 93-MYL-02 passing through the crest of the Meyal structure across dip.

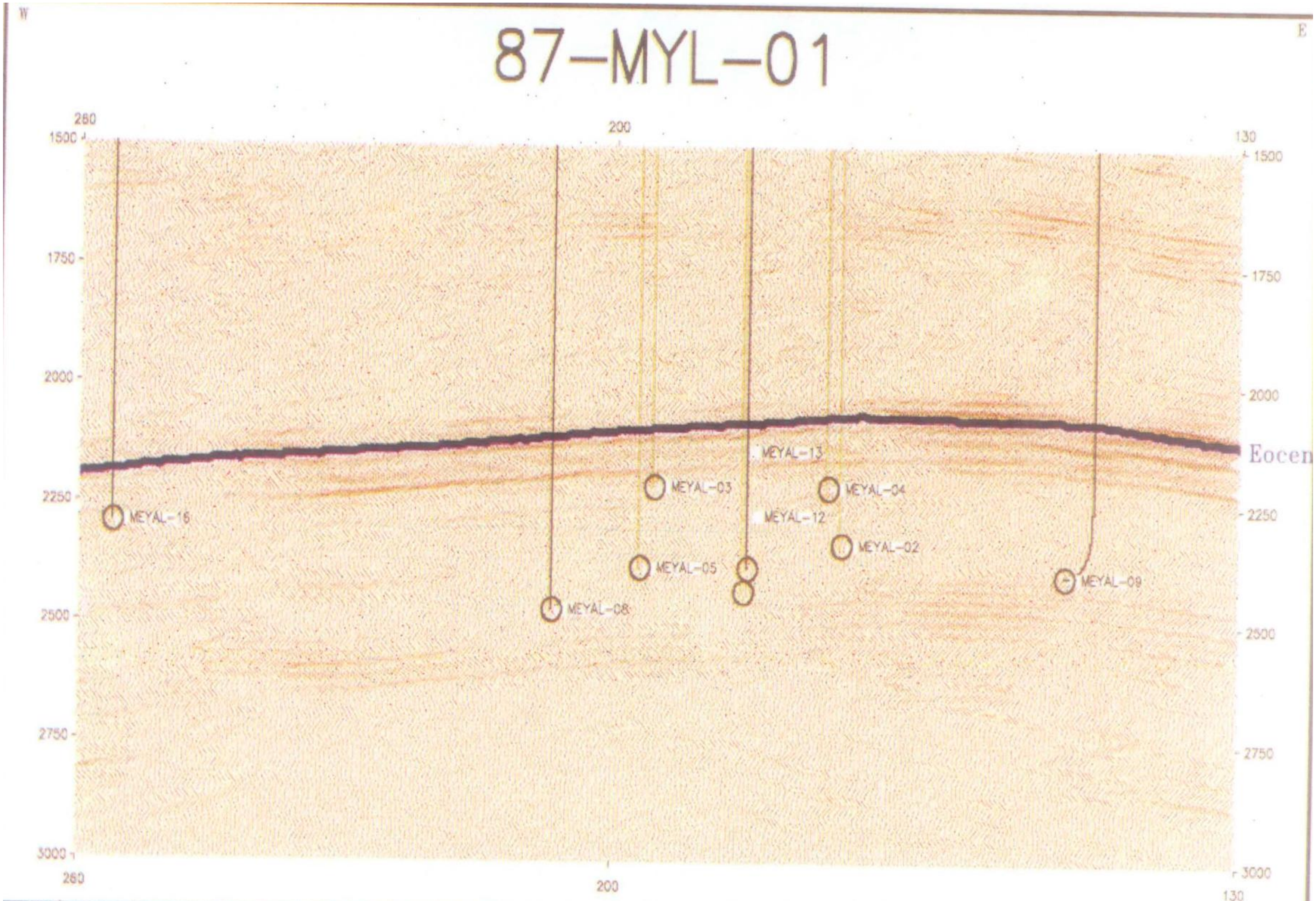

Figure 10. East-West seismic line 87-MYL-01 passing through the crest of the Meyal structure along strike.

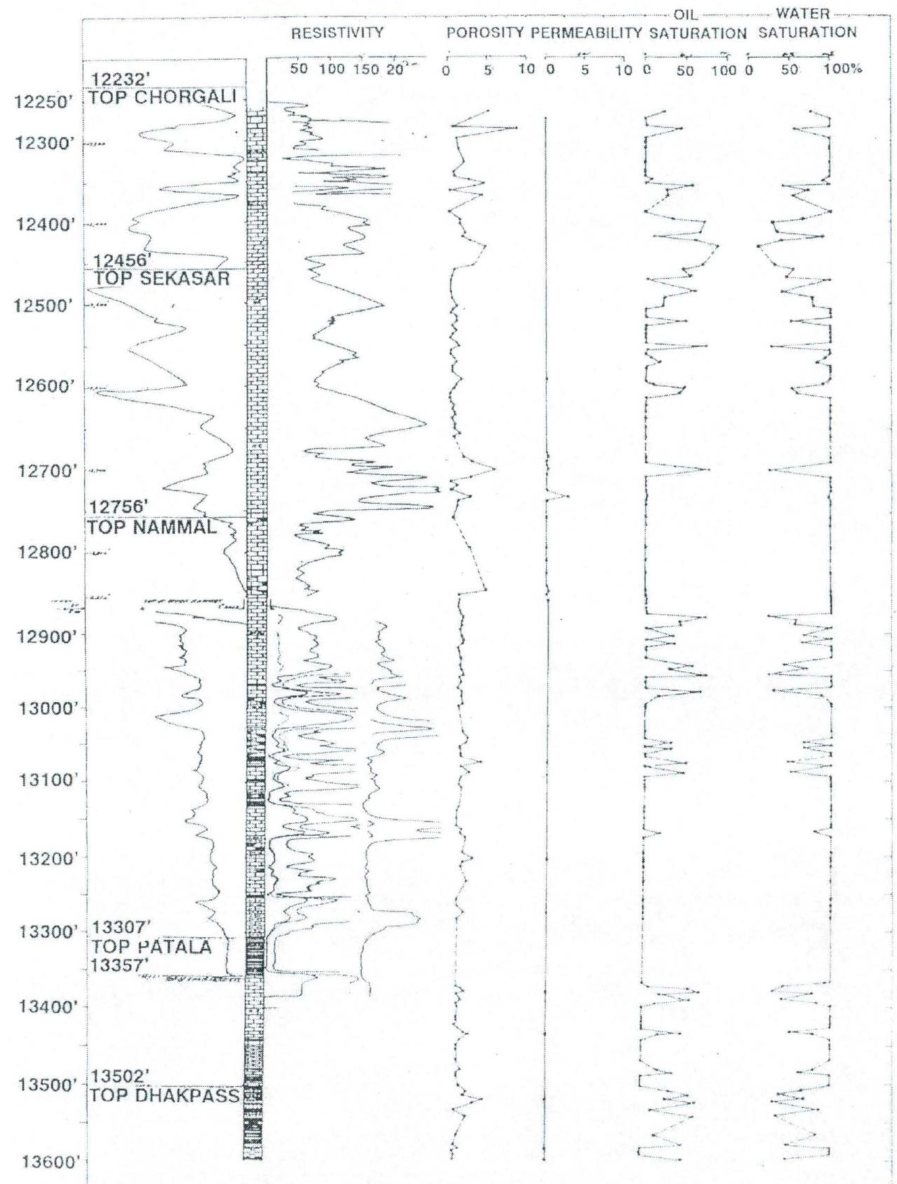

Figure 11. Core data analysis plotted against depth showing very low porosity (< 10%) and zero permeability. Fractures are the primary producing mechanism in Meyal Field.

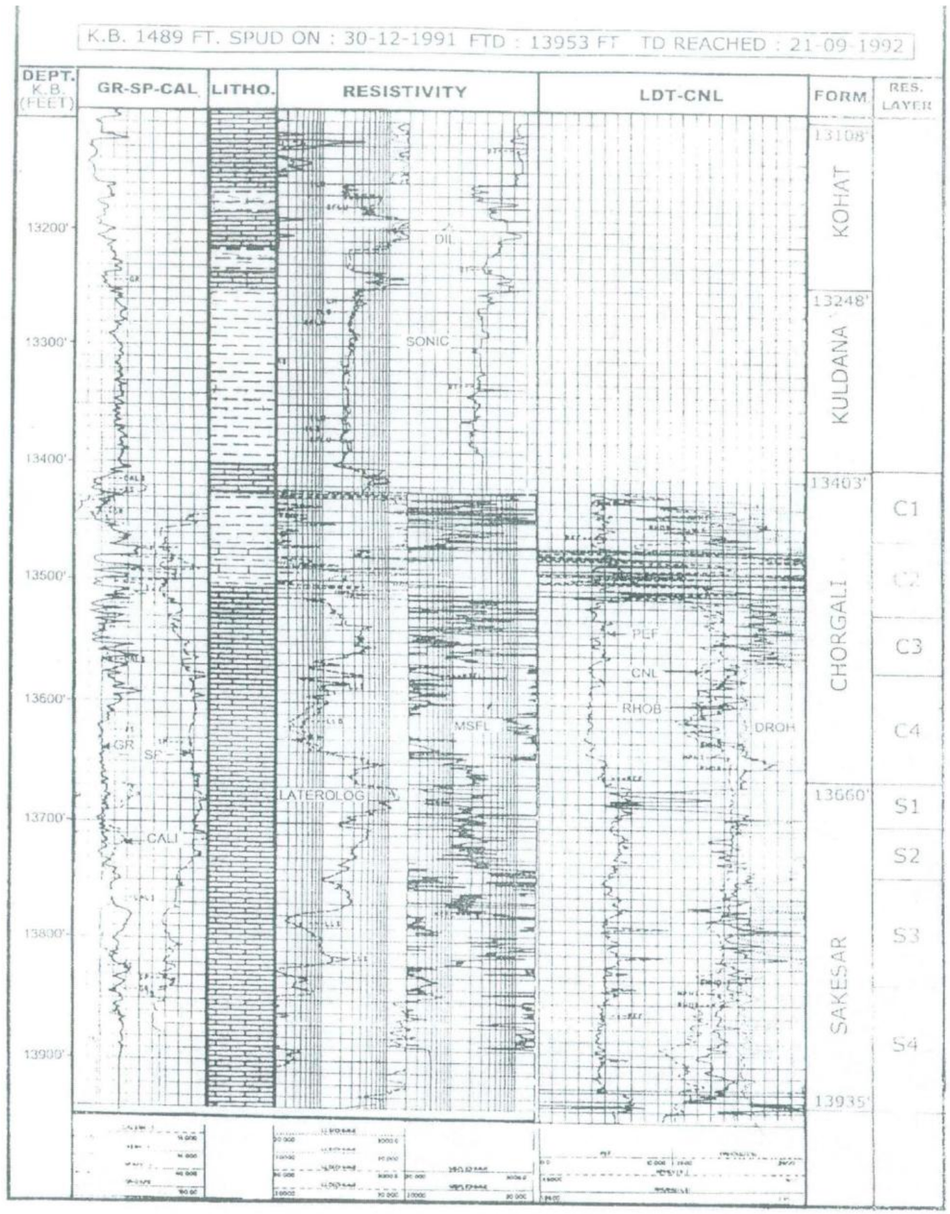

Figure 12. Eocene reservoir stratigraphic divisions and reservoir zonation within the Chorgali Sakesar Formation.

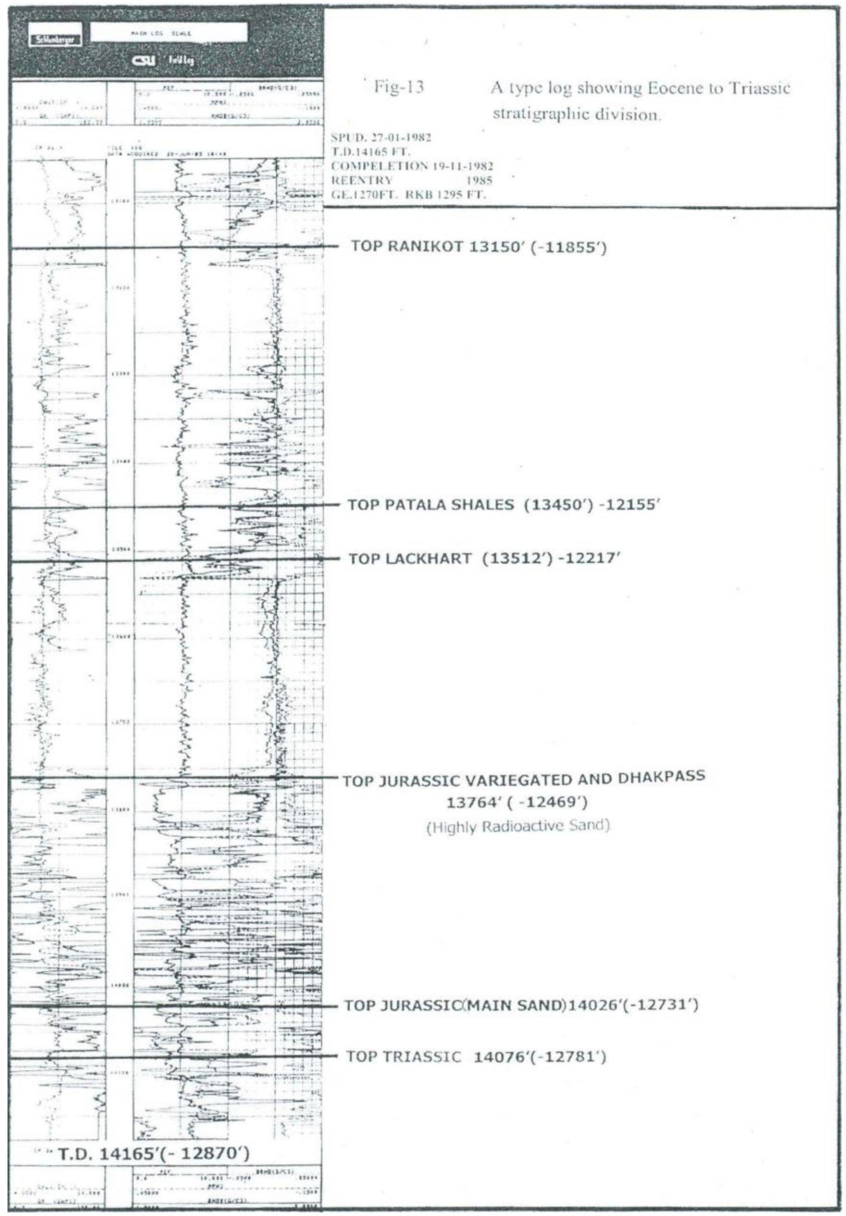

Figure 13. A type log showing Eocene to Triassic stratigraphic divisions.

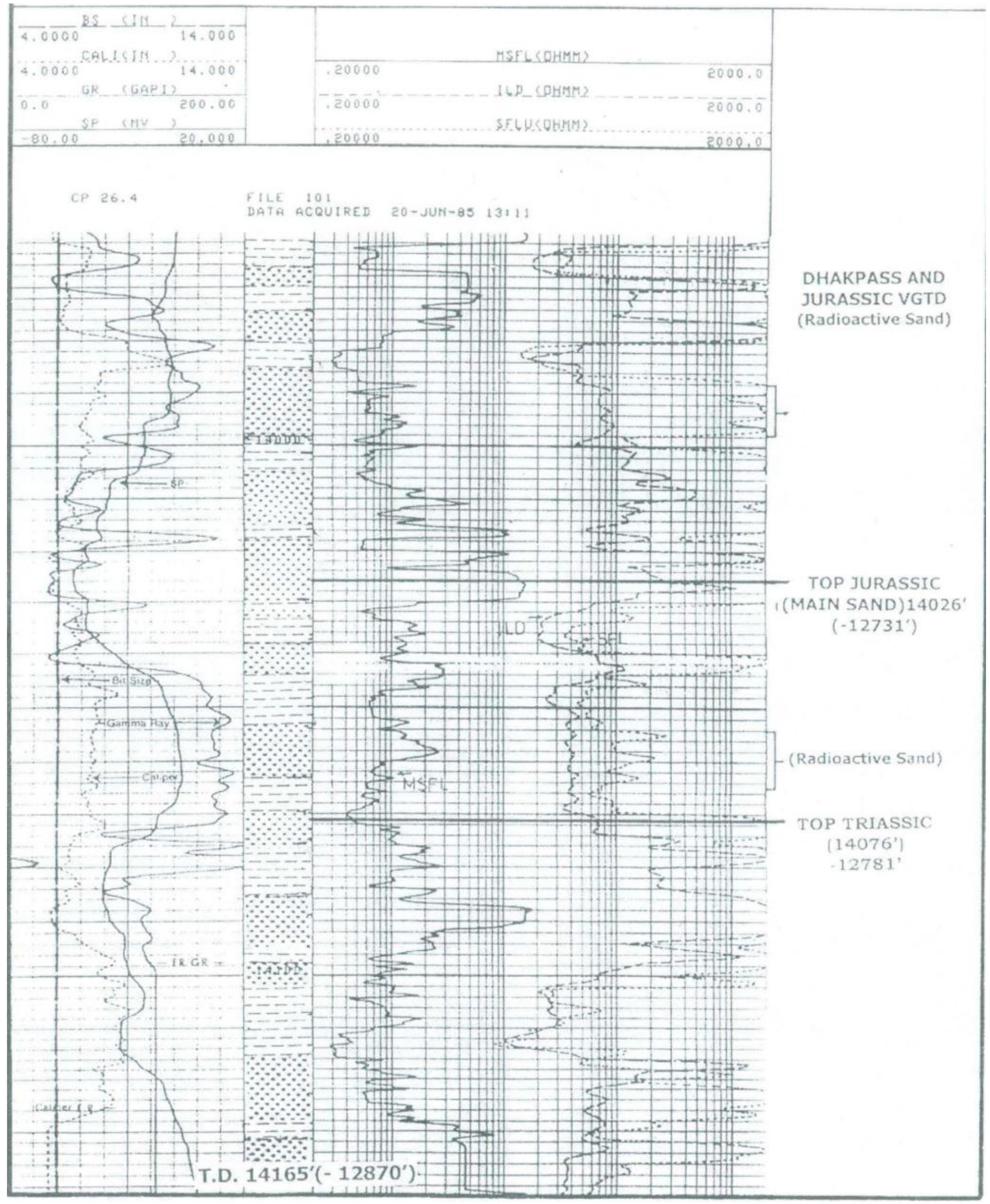

Figure 14. A type log showing stratigraphic division of Early Paleocene and Jurassic Main Oil Sand Datta Formation.

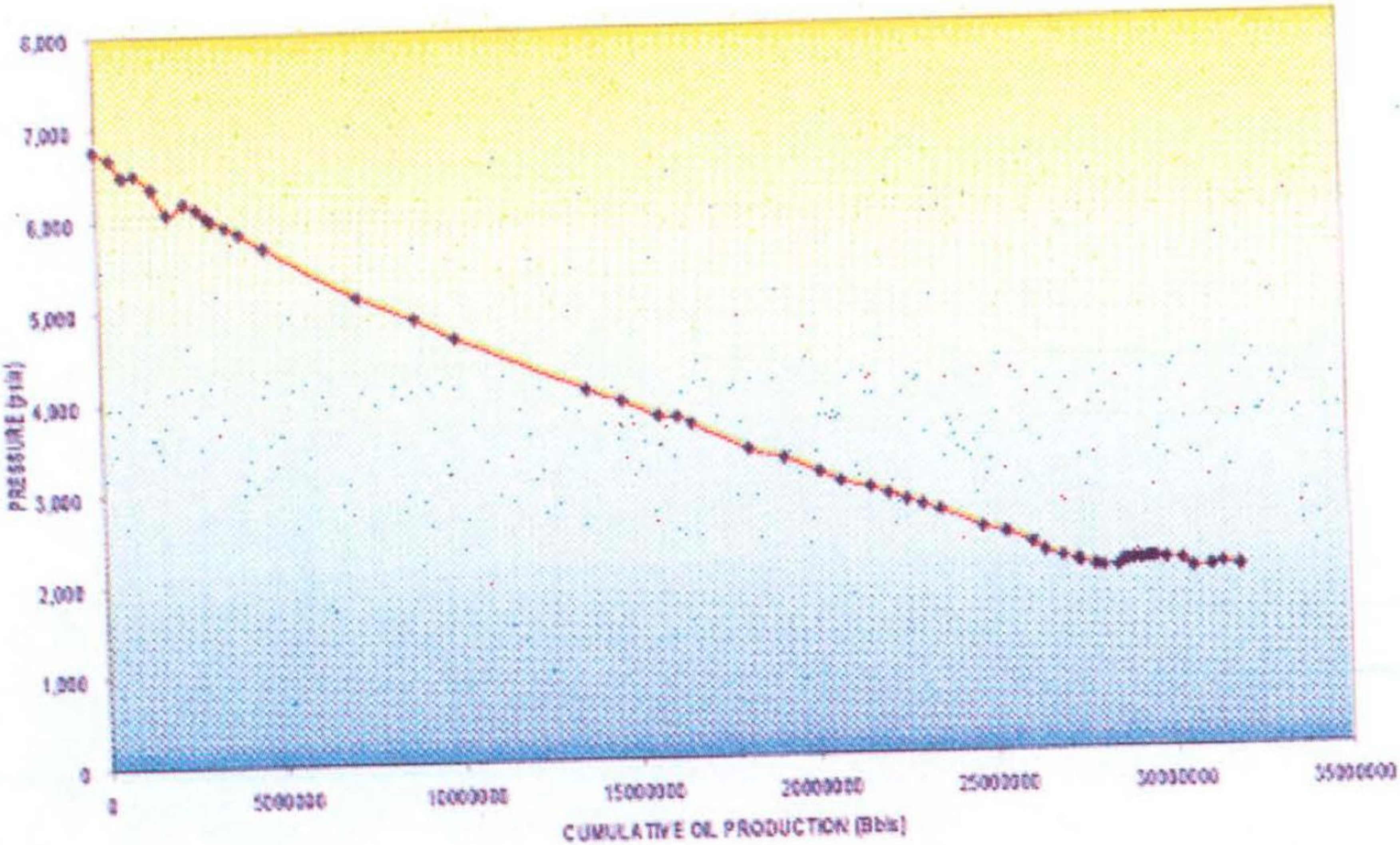

Figure 15. Eocene reservoir pressure decline vs. cumulative oil production.

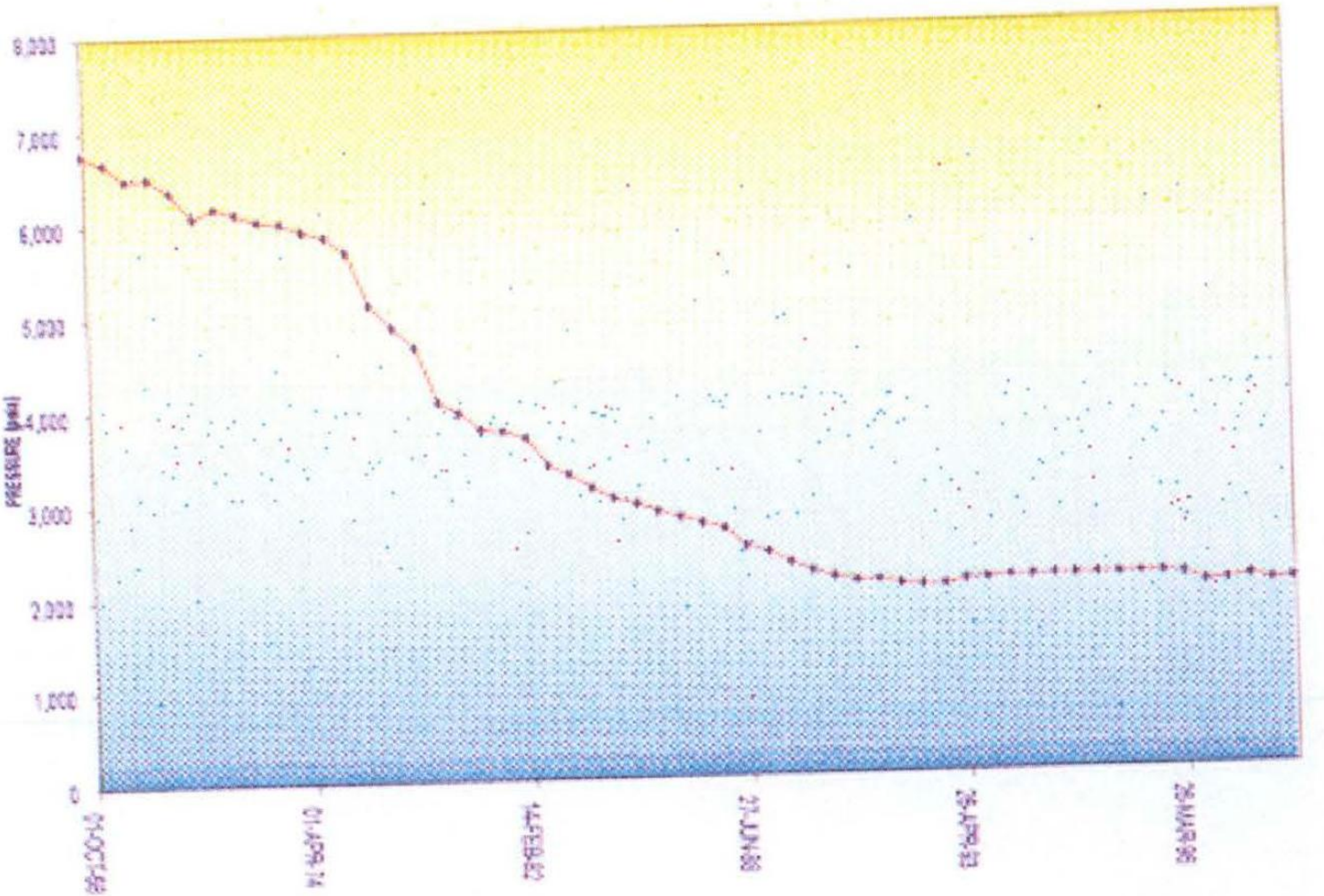

Figure 16. Eocene reservoir pressure decline vs. time.

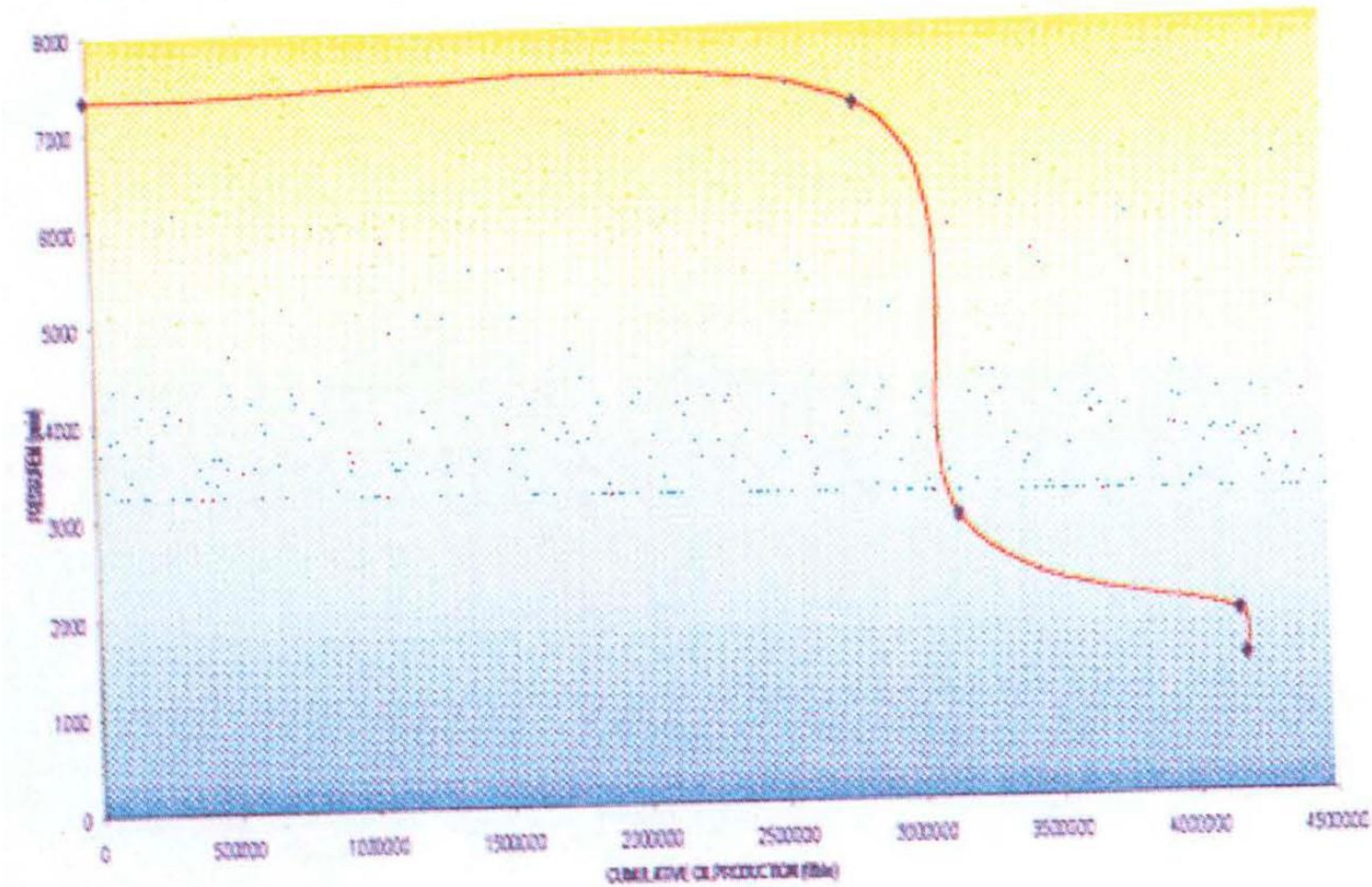

Figure 17. Paleocene reservoir pressure decline vs. cumulative oil production.

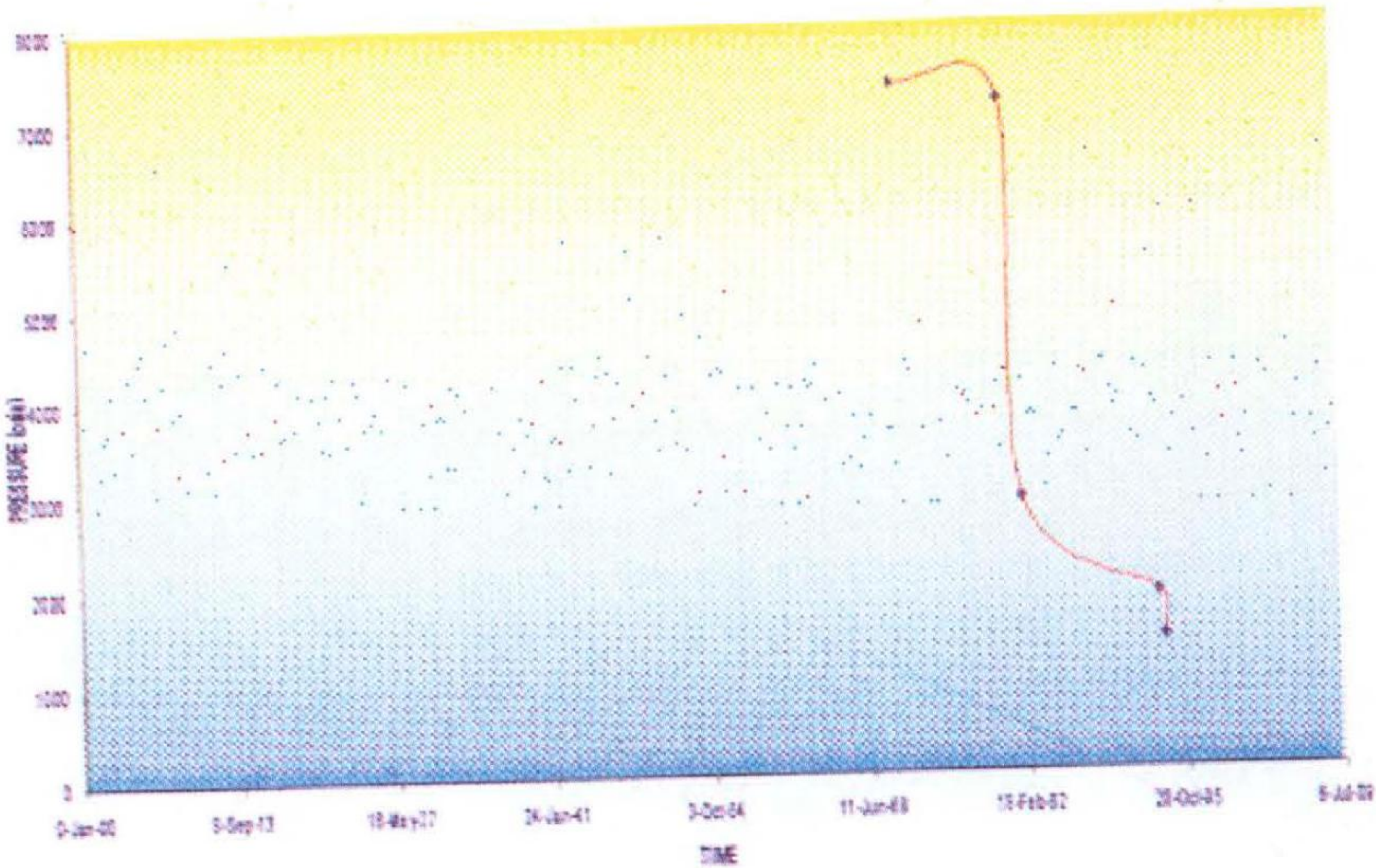

Figure 18. Paleocene reservoir pressure decline vs. time.

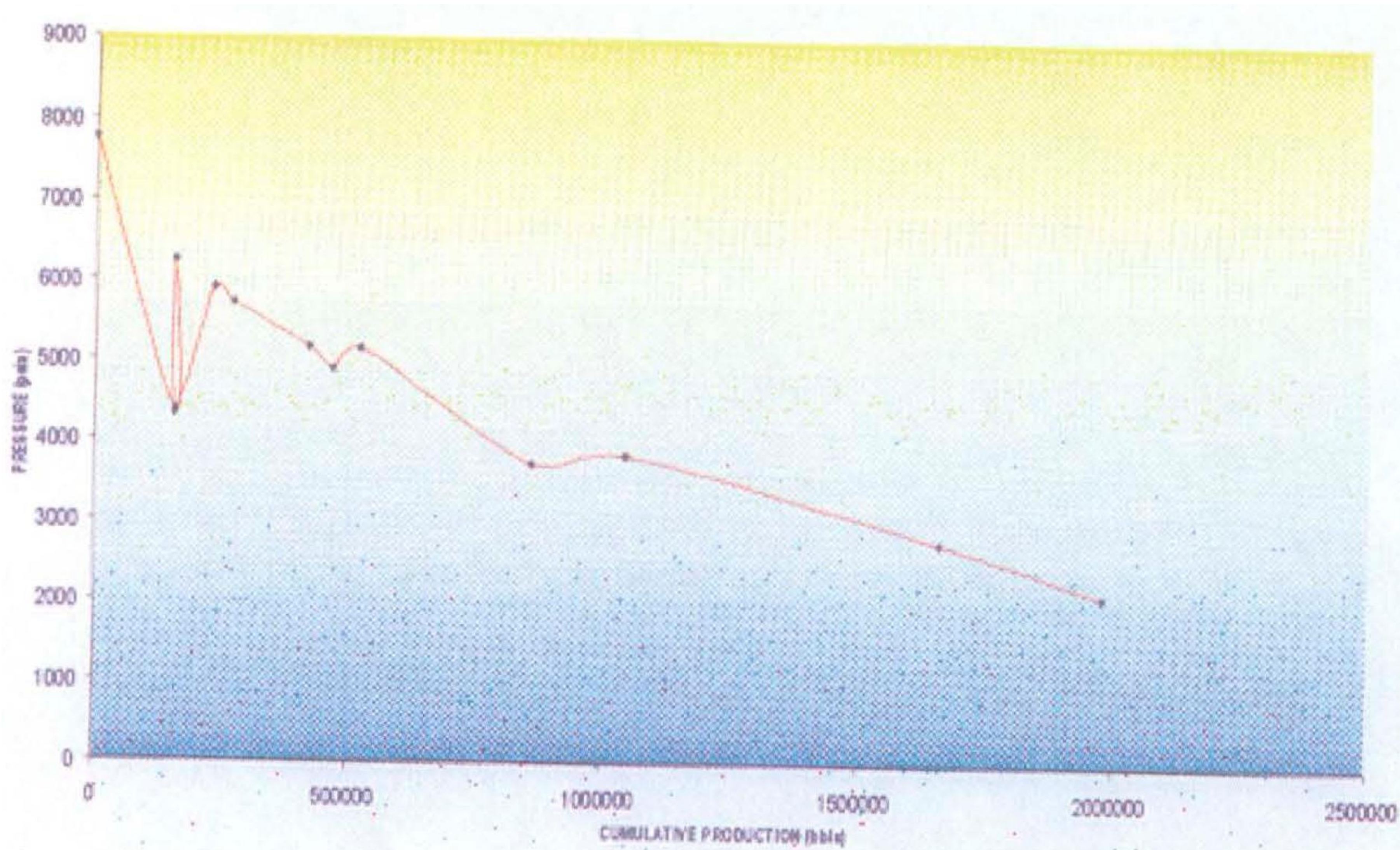

Figure 19. Jurassic reservoir pressure decline vs. cumulative production.

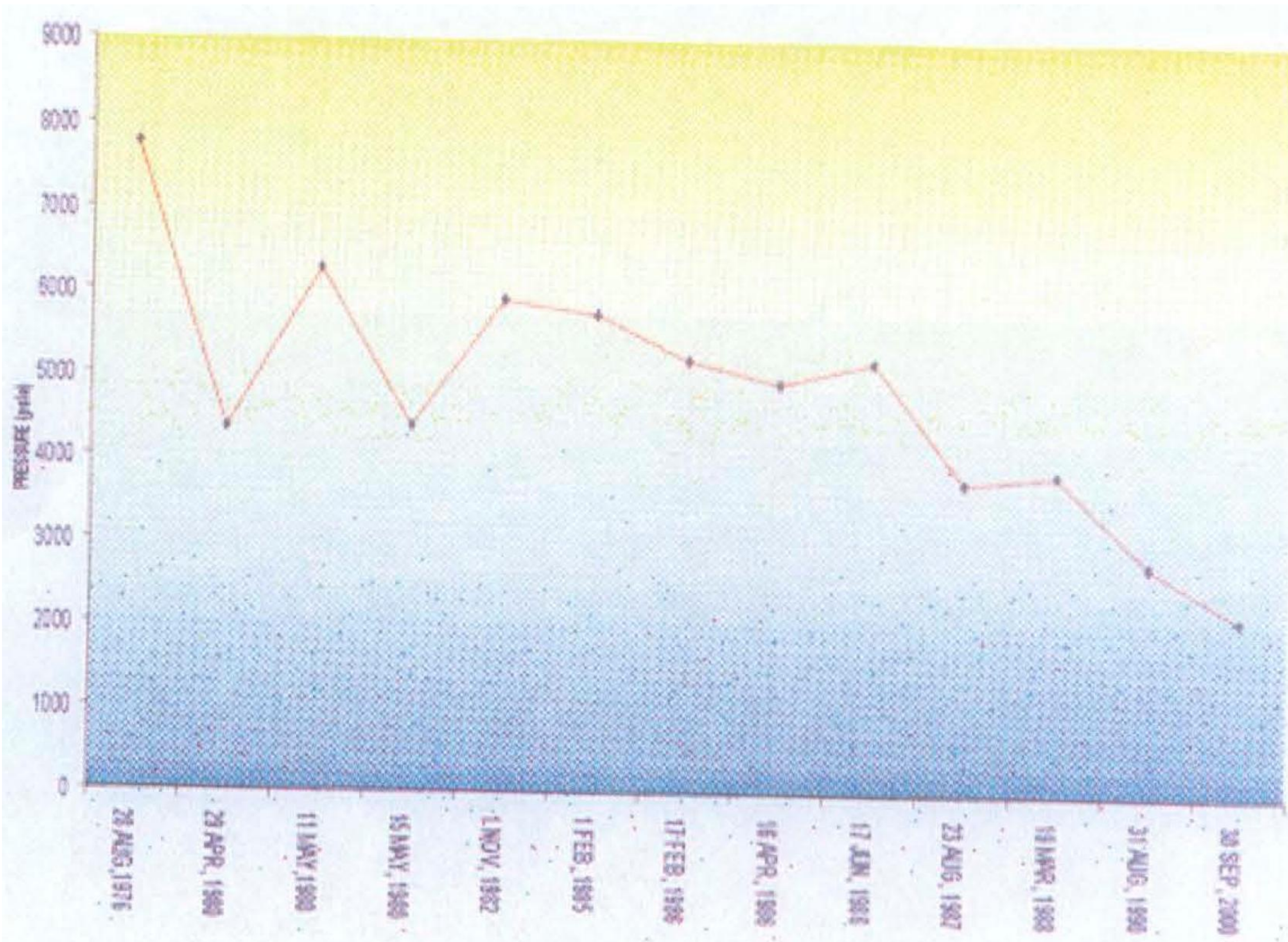

Figure 20. Jurassic reservoir pressure decline vs. time.

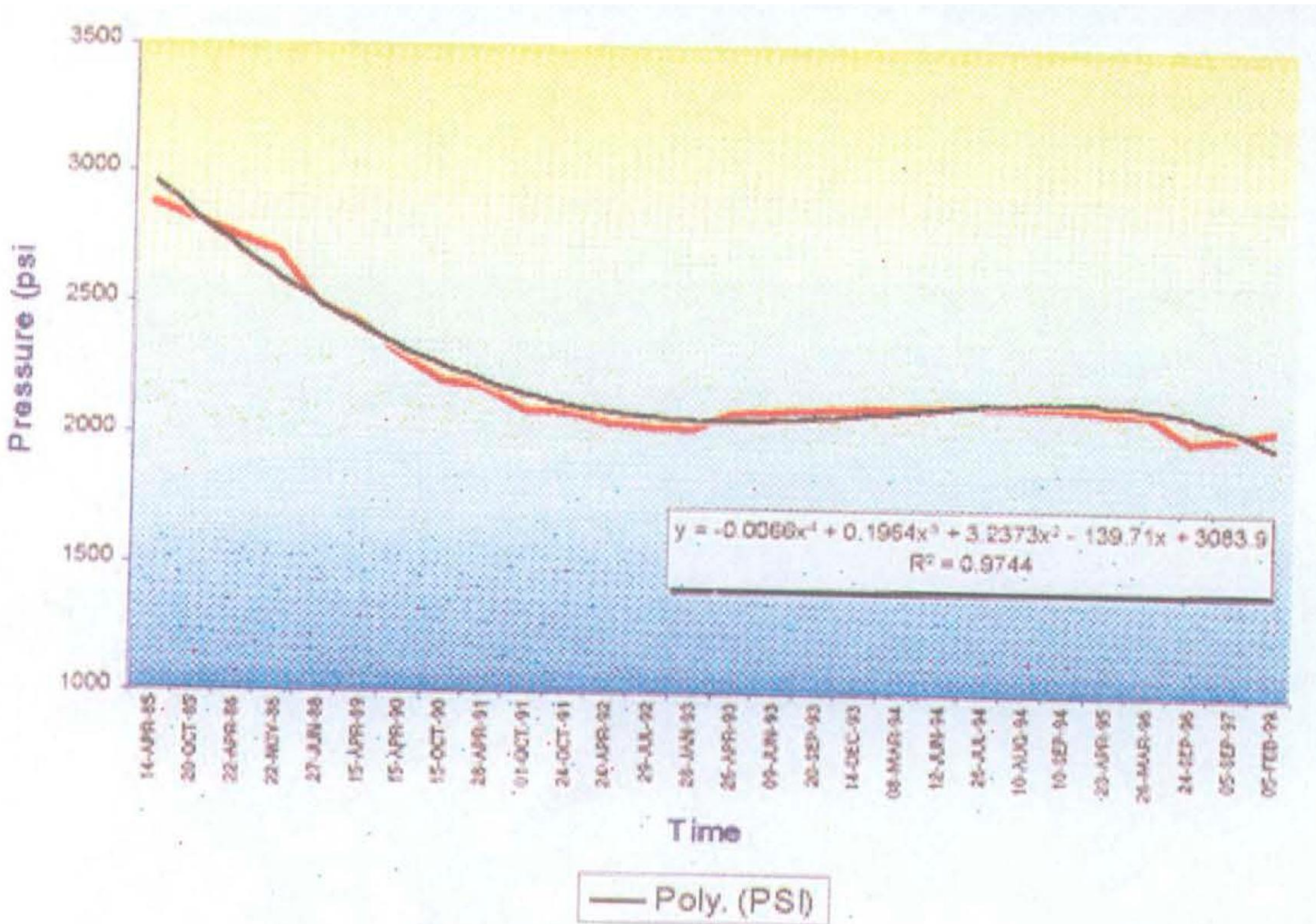

Figure 21. Reservoir pressure maintenance .

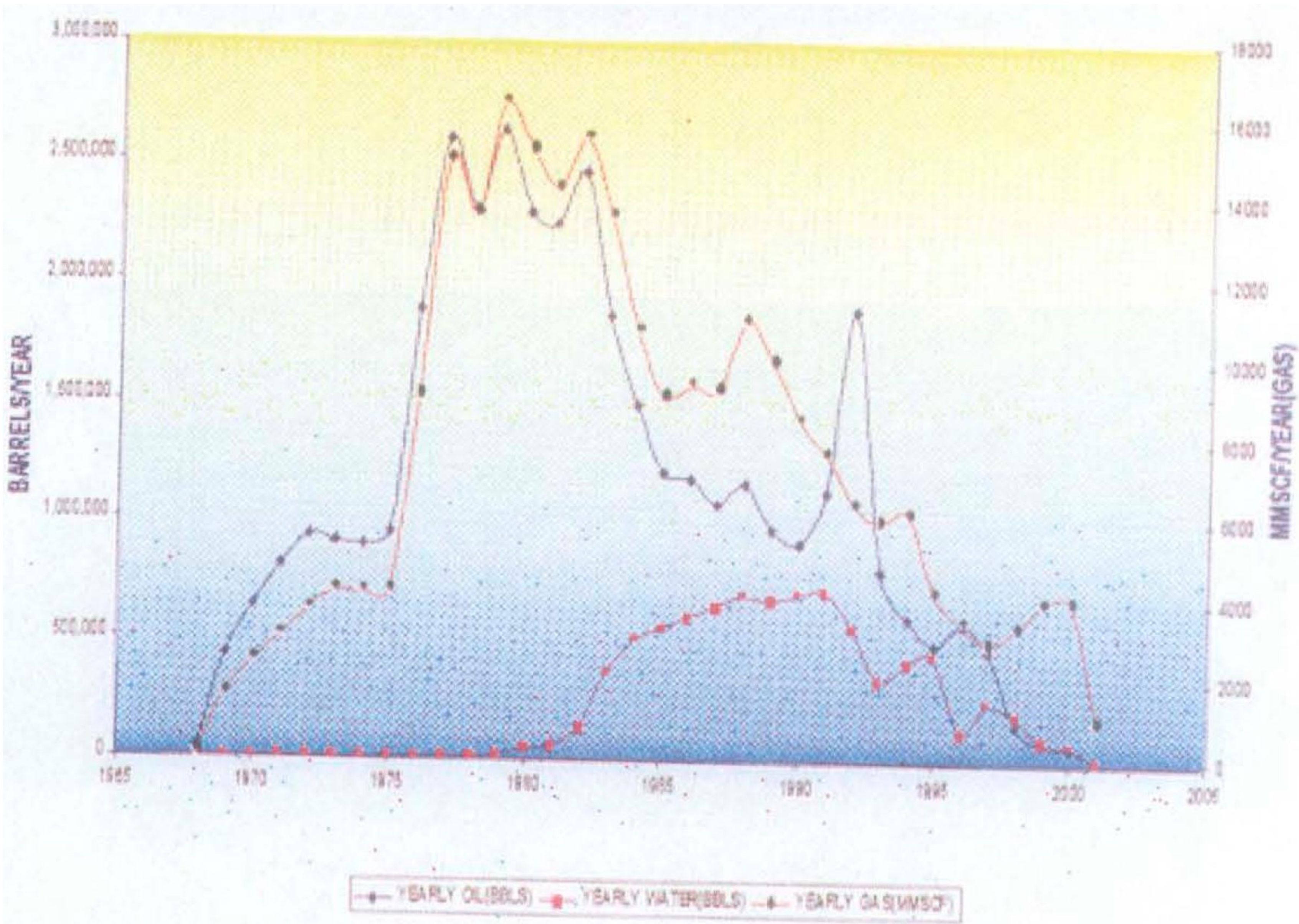

Figure 22. Meyal Production 1968-2001.

Meyal Field Wells Summary. Formation Tops and Casing Details																
Well No	1	2	3	4	5	6	7	8	9/9H	10	11	12	13	14	15	16
Spudded on	2.11.67	1.10.69	15.6.72	14.11.74	6.1.79	3.12.75	6.10.76	16.5.80	7.2.81	27.1.82	4.6.82	13.2.82	31.1.84	2.12.89	30.12.91	8.7.96
Completed on	13.11.68	4.6.71	21.7.73	15.11.75	6.3.80	16.9.76	11.6.77	18.6.81	3.12.81	27.11.82	5.3.83	5.1.83	23.12.84	7.1.91	21.9.92	19.3.97
Reentry/Workover	14.3.83				28.7.86		21.8.86		17.6.94	1985					4.1.93	
Completed on	31.3.85				12.11.86		29.12.86		12.6.95	1985					17.1.93	
KB Elevation	1,229	1,310	1,379	1,321	1,382	1,344	1,419	1,420	1,341	1,295	1,454	1,353	1,377	1,468	1,459	1,505
Ground Elevation	1,217	1,295	1,351	1,308	1,370	1,322	1,397	1,408	1,324	1,270	1,442	1,328	1,351	1,443	1,464	1,480
Formations																
NAGRI	Surface	Surface	Surface	Surface	Surface	Surface	Surface	Surface	Surface	Surface	Surface	Surface	Surface	Surface	Surface	Surface
CHINJI	1,860	1,674	1,706	1,680	1,722	1,007	1,710	640	1,336	2,312	360	970	1,764	890	1,352	515
KAMLIAL	6,463	6,299	6,870	6,283	6,844	5,698	6,888	5,875	5,964	6,710		5,822	6,830	6,290	6,970	6,812
MURREE	7,300	7,030	7,553	7,040	7,543	6,420	7,505	6,568	6,740	7,468		6,506	7,535	6,870	7,604	7,325
KOHAT	11,975	11,865	11,996	11,870	12,017	11,760	12,075	11,810	11,898	12,269		11,676	11,943	12,302	13,108	12,619
KULDANA	12,099	12,080	12,152	12,085	12,159	11,920	12,239	11,928	12,082	12,422		11,820	12,080	12,440	13,248	12,790
CHORGALI	12,248	12,232	12,327	12,245	12,341	12,078	12,431	12,078	12,232	12,542		11,984	12,224	12,588	13,403	12,960
SAKESAR	12,461	12,456	12,565	12,479	12,577	12,290	12,667	12,327	12,439	12,762		12,208	12,470	12,818	13,642	13,183
NAMMAL	12,766	12,756			12,864	12,560	12,986	12,678	12,696	13,042		12,478	12,736		13,935	
RANIKOT	12,862	12,850			12,966	12,658	13,087	12,723	12,798	13,150		12,576	12,833			
PATAL SHALES	13,302	13,307			13,420	12,990	13,520	13,180	13,092	13,450		13,048	13,294			
LOCKHART	13,343	13,357			13,475	13,040	13,579	13,234	13,155	13,512		13,086	13,344			
DHAK PASS	13,483	13,502			13,641	13,288	13,762		13,394	13,764		13,231	13,498			
JURASSIC VARIEGATED					13,718	13,338	13,812	13,384	13,664							
JURASSIC MAIN SAND					13,935		14,084	13,626		14,026		13,463	13,714			
TRIASSIC					14,039		14,204	13,763		14,076		13,582	13,844			
PERMIAN													14,360			
FIRST TOTAL DEPTH	12,514	13,600	12,719	12,640	14,100	13,424	14,211	14,181	12,849	14,121(Vert)	2,858	13,622	14,506	13,028	13,953	13,195
SECOND TOTAL DEPTH	13,489								13884(TVD)	14, 165(Dev)						
Casing Shoe Depth																
30"																
20"	329	306	66**		398	369	412	419	815	821	720	869	804	660	582	723
13 3/8"	2,925	4,780	1735***	304***	3,445	4,040	4,107	3,627	4,000	4,010	2,840	3,960	3,741	2,546	2,984	3,995
9 5/8"	7,865	12,247	7,726	1686y	8,157	12,090	8,507	6,770	8,484	8,802		7,816	12,292	5,185	5,139	7,940
7"	12268*	12,865	12,342	7,839	12345*	12604*	12972*	12,095	12,770	12585*		12103*	13493*	8,524	8,297	12,962
5"		13,362	12717*	12,266	14097*	13369*	14062*	13,784		14145*		13597*	13960*	12593*	13,060	13,043
3 1/2"				12640*									14506*	12833*	13,424	
Producing Reservoir	Eocene	Eocene		Eocene	Pal/Jur	Eoc/Pal/Jur	Eocen	Eoc/Pal/Jur	Eocene	Eoc/Jurassic	–	Eoce/Pal/Jur	Eocene	Eocene		Eocene
Present Status	Abandoned	S.I	S.I	S.I	S.I	Prod	S.I	Prod	S.I	Wat/ injec	–	Prod	S.I	S.I	wat/injec	S.I

* liner
**25" casing
***16" casing

11 3/4" casing
Well No 9 was the horizontal well drilled to 14047 ft

Table 1. Meyal Field wells formation tops and casing details.

Meyal Field Reservoir Summary				
	Units	Chorgali-Sakesar	Ranikot-Lockhart	Datta
Reservoir Type		Gas/Oil	Gas/Oil	Gas/Oil
Drainage Area	Acres	6959	1951	2108
Reservoir Volume	Acre/ft	1,022,558	275,088	286, 646
Thickness	Ft	147	141	136
Initial reservoir Pressure	Psi	6815	7489	5750
Initial production rate	Oil/Gas	1371	659 BOPD	456 BOPD
API Gravity	degree	44.1	44-46	44-46
Initial GOR	SCF/STB	3423	5500	5297
Primary Porosity	%	1.9-5.7	3.1	3-8
Effective Water Saturation	%	23.2	16.5	19.3
Primary Permeability	Md	n.a	n.a	n.a
Reservoir Temperature	F	267	279	280
Present Reservoir Pressure	Psi	2011	1439	2131
Original Gas in Place.	BCF	263.97	77,97	206
Original Oil/Condensate in Place.	MMBBls	69.42	10.88	25.76
Gas Gross Ultimate Recovery.	BCF	154.52	48.89	124.63
Oil/Condensate Gross Ultimate Recovery.	MMBBls	28.4	4.25	10.66
Total Production as on December 31, 2000	Oil: 36,793, 653 Barrels, Gas 25, 0667 MMSCF			
Oil	Barrels	30593202	4222369	1978082
Gas	MMSCF	179798.051	48858.965	22010.37
Gas Reserves	BCF			
Oil/Condensate Reserves	MMBBls			

Table 2. Meyal Field reservoirs summary.

Statistical Summary of Meyal Field	
First Exploration Attempt	1916
Discovery	1968
Operator	POL
Total wells drilled Before discovery	6
Total wells drilled After discovery	16
Total Wells Drilled	22
Producing Wells	14
Abandoned Wells	7
Period during which wells drilled	1916-1997
Youngest formation drilled	Pliocene (Nagri)
Oldest formation drilled	Permian
Number of Reservoirs	3
Depth of Reservoirs Top	11984-13463

Table 3. Statistical summary of Meyal Field.