Refound Exploration Opportunities in Infracambrian and Cambrian Sediments of Punjab Platform, Pakistan*

Syed Tariq Hasany[1], Muhammad Aftab[1], and Raza A. Siddiqui[1]

Search and Discovery Article #50576 (2012)
Posted March 19, 2012

*Adapted from oral presentation at PAPG Annual Technical Conference 2007, Islamabad, Pakistan, March 27-28, 2007

[1]Pakistan Petroleum Limited, Karachi (tariqhasany@hotmail.com, m_aftab@ppl.com.pk, a_raza@ppl.com.pk)

Abstract

Punjab Platform represents the eastern segment of the tectonically stable Middle Indus Basin covering an area of more than 100,000 km^2 and located roughly between 27.5°N - 32°N latitude and 70.3°E -74.00°E longitude. Hydrocarbon search started in mid 1950s when Shell drilled first exploratory well, Karampur-1 in 1958, which provided an evidence for occurrence of heavy oil in Infracambrian; Infracambrian play is thought to be analogous to Oman. Out of 23 wells in Punjab Platform, only 12 were drilled for Infracambrian and Paleozoic targets and rest of the wells for Mesozoic Play in a vast sedimentary basin. So far, three gas discoveries have been made in Cretaceous aged Lumshiwal Formation and Jurassic aged Samanasuk Formation, demonstrating to an extent, optimistic hydrocarbon prospects.

Thermal maturity data for Mesozoic indicated lack of mature source, and that the petroleum charge is from the long distance migration to the west. However, nonbiodegraded- sulfur rich heavy oil (API 17.6) data supported with age diagnostic biomarker from Baghewala-1 in adjoining Bikaner- Nagaur basin (India) highlights the occurrence of Infracambrian source, which falls in early oil window. Karampur-1, heavy oil from Salt Range Formation interpreted to be geochemically similar to Baghewala oil. Maturity tends to increase with depth and deeper source rocks expected to be present in Punjab Platform. However, wells failure analysis suggests that lack of favorable mature source rocks are the major reason of failures.

This paper highlights the selected areas of better-defined hydrocarbon prospectivity zones and will attempt to prove the significance of localized smaller scale subbasins. These sub-basins are expected to be present on basement. These grabens are identified on the seismic data and interpreted to be formed due to sculpting of the basement during Early Cambrian unconformity. Subsequent faulting and tilting may have reshaped the grabens. The source and reservoir rocks deposition and geometry therefore have largely been affected by graben geometry.

Source rock analysis of cores and cutting samples from wells that were drilled in the horst portray a negative picture regarding source maturity in the areas as the repeated subaerial exposures or non-conducive depositional environment may have severely affected the potential in the horsts areas. The grabens areas however, are expected to have better source quality and favorable maturation due to deeper burial and within the improved thermal regime than its chronostratigraphically equivalent sediments on structural highs.

Similarly, better reservoir intervals may also be preserved. Suitable structural, stratigraphic and combination traps formed as a result of tilting and uplifting of the basin through Phanerozoic are expected to be found. We also envisage that the role of the Infracambrian evaporites and carbonate/clastics sequences halite (salt), evaporites in the formation of a plausible complete petroleum system (source-reservoir seal and trap) in the basin is of critical importance.

Our interpretation is based on analysis of more than 2,500 line kilometers 2D seismic data and time structure maps on Basement and Infracambrian and Paleo depth structure maps on Basement, present day Time structure map on Infracambrian, Isochron map on top Basement to top Infracambrian, interpreted restored seismic lines from Infracambrian, early Permian, Jurassic, Eocene, and present day seismic data and evaluation of exploratory well logs and other data.

Introduction

The limits of the Punjab Platform and Bikaner Nagaur Basin are defined by the northeast-southwest trending, Aravallis to the east and Sulaiman Fold and Thrust Belt to the west (Figure 1). This large sedimentary basin covers approximately 290,000 km^2. Aravali Range is considered one of the oldest mountain chains of the world (Ganseer, A, 1964). Surface geology to the west of the Aravali and east of Sulaiman Fold and Thrust Belt is completely obscured by thick alluvium cover except sporadic exposures of igneous crystalline basement rocks of Kirana Hills in the Pakistani Punjab and in Tosham area, and Hissar, Haryana, India.

In this paper, we focus the Pakistani part of the basin, which covers approximately 117,000 km^2.

Exploration History

Exploration in the Punjab Platform started back in 1950's by Shell when they acquired single fold seismic data and drilled Karampur-1 to 3034m to the basement. Additional exploratory wells were drilled in this area between 1973 and 2006. Drilling and seismic data proved the occurrence of Recent through Infracambrian sediments over the westward dipping basement. So far, only three gas fields have been discovered from Mesozoic reservoirs whereas 12 Infracambrian and Cambrian wells were plugged and abandoned as dry hole. Heavy oil discovery in Baghewala-1 (1991) in Bikaner - Nagur Basin, Rajasthan India, from Infracambrian sandstone and carbonates has renewed exploration activity for Infracambrian Play, which was almost abandoned in Pakistan (Peters K. E, et. al, 1995). Summarized information of the wells drilled in Punjab Platform is presented in Table 1.

Geology and Tectonics

During the present-day Indo-Pakistan Plate was fused with the northeastern flank of the African and Arabian Plate by a complex process of terrain accretion and plate collision (Bois C, P. Bouche and R. Pelet, 1982; Paliwal B. S., 1992; Scotese et. al., 1979), (Figure 2). Depositional history of these plates specially those located along the margins is believed to have close stratigraphic resemblance and can be correlated at far distances. The Indo-Pakistan Plate has experienced various tectonic events during Proterozoic including several of episodes of volcanism associated with rifting. General trend of the horst and grabens appears to be north-south whereas shelf-slope-basin stretched from east to west (Paliwal B. S., 1992; Pareek. H.S., 1981; Pareek. H.S., 1983; Peters et. al., 1995). Drilling results suggest that over the basement rocks of

Paleozoic to Cenozoic is present (Figure 3 and Figure 4). Basement received sedimentation during Infracambrian by marine transgression, which resulted in deposit of shallow marine siliciclastics in the shallow shelf through fluvial influx (Paliwal B. S., 1992; Pareek. H.S., 1981; Pareek. H.S., 1983). The deposition of carbonates took place at the shallow and broad shelf. During cyclic sea level change, evaporites were deposited including massive rock salt. (Figure 5)

Subsidence, possibly due to reactivation of the basement faults provided additional accommodation space in the grabens, which is considered being preferential site for siliciclastics deposition (Paliwal, 1992). This added accommodation space is interpreted to be the reasons for considerable sediments thickness at Punjab Platform. Cambrian clastics and carbonates have been deposited at shallow marine-continental depositional environment. Absence of Late Cambrian to Carboniferous rock strata in the entire Indus Basin is possibly due to the uplifting phase of the Indian Plate.

The scarcity of distinct folding and rifting suggests that the area remained tectonically stable during most of the Mesozoic-Cenozoic. Punjab Platform owing to its distant location to the site of major tectonic event remained mostly undisturbed. However, minor tectonic events appear to have re-modified the preexisting structures. Salt and evaporites may have also participated in the structuring.

Summarily it may be suggested that tectonic history of the Indian Plate is mainly related to two major events: Mesozoic rifting of Gondwanaland and Cretaceous-Tertiary Indian Plate collision with Eurasian Plate. These two events have been the main building blocks of the Petroleum Play in Pakistan and the evaluation of the influence of these events is critical in establishing Petroleum System of the country.

Source Rock Distribution and Thermal Maturity

Infracambrian

A large number of oil and gas fields, including the giant ones, have been discovered in the Infracambrian of the Siberian Platform and Oman (Bois et. al., 1982 and Hunt, 1979). This emphasizes the suitability of more extensive hydrocarbon exploration in the Infracambrian of the Punjab Platform.

The Infracambrian time was of low biodiversity restricted only to unicellular organisms like Blue-Green algal mats or stromatolites that lived in reducing conditions such as sulfate reducing bacteria that are found today in anaerobic, stagnant waters (Hunt, 1979).

Required conditions conducive to organic matter preservation are expected to be prevalent during Infracambrian and Cambrian. However, subsequent tectonic events may have contributed to erosion and decay of organic source matter. Erosion, as evidenced by several unconformities, may have cracked the reservoir hydrocarbon.

In eastern Salt Range Infracambrian is extensively rich in Total Organic carbon (TOC) up to 30% with yield capacity of more than 20% rock weight. Infracambrian oil from Oman has strong resemblance and considered comparable source type as found in the heavy oil of Karampur-1 and oil seepage of Salgi Nala, Salt Range, Punjab (Ahmed and Alam, 1999 and Peters et. al., 1995).

Two types of source facies in Salt Range Formation have been identified. The upper part contains lenticular bodies of high-grade oil shales whereas low-grade oil shales are present in the middle part, which is laterally more consistent, but their thickness varies from few centimeters to few meters (Ahmed and Alam, 1999). Most of the maturity data indicate marginal mature source (GEOCHEM, 1989; I.E.D.S., 1995, OMV, 2000, and Pakistan Petroleum Limited, 2005).

In Bikaner Nagaur Basin, the Bilara Formation contains abundant algal mats and samples from outcrops of dark carbonates generated oil and combustible gas on distillation.

Baghewala-1, heavy oil was discovered in Bikaner-Nagaur basin in Rajasthan, India from Infracambrian Jodhpur sandstone (Peters et. al., 1995). Analyses of the oil suggest that charge of the oil primarily sourced from Infracambrian source. The heavy oil is non-biodegraded sulfur rich oil (API 17.6) and age diagnostic biomarker supports the presence of source potential in Infracambrian and provides a basis for consideration that chances for finding mature source will be higher in Punjab Platform area due to increasing depth. Karampur-1 heavy oil from Salt Range Formation interpreted to be geochemically similar with Indian oil (Peters et. al., 1995). It also suggests the occurrence of potential Infracambrian source, which falls in early oil window.

Baghewala heavy oil discovery is perplexing due to shallow presence of source rock at very shallow depth implying that these depths are too shallow for early oil generation window. Shallow source depths at Baghewala offers two possible explanations; firstly, Igneous intrusion into the vicinity of the source rock and secondly, the basinal deepening in the geological past and subsequent shoaling. First option can be disregarded as to the authors knowledge, no igneous intrusion have been reported in literature.

Heavy oil and bitumen shows in Infracambrian and Cambrian reservoirs from few wells drilled in Punjab Platform have been reported and their presence may be attributed to the two possible explanations; firstly that organic matter has been converted to oil but does not convert into lighter oil due to the absence of appropriate thermal regime, secondly that oil generation takes place in close contact with reservoir. We have collected the Vitrinite Reflectance (VR) data of Kamiab-1, Sarai Sidhu-1 and Tola-1 and plotted the VR data against the geological timescale in order to infer the expected deeper thermal maturity at Infracambrian level (Figure 6) (GEOCHEM, 1989). This plot shows that Infracambrian has been in early oil generation window.

Reservoir Quality and Distribution

Infracambrian

Six stratigraphic units in the Infracambrian are recognized (Paliwal, 1992, Pareek, 1981, Pareek, 1983, Peters et. al., 1995), (Figure 3 and Figure 4). Oil production has been reported from Bilara Carbonate and Jodhpur Sandstone in Baghewala-1 (Peters et. al., 1995).

We have adopted the stratigraphic distribution of the Infracambrian as proposed by B.S. Paliwal (1992). Four out of six Infracambrian units have been identified in Infracambrian in Punjab Platform (Figure 3 and Figure 4). These are Sonia Shale, Jodhpur Sandstone, Bilara Carbonates and Hanseran Evaporites.

The wireline logs, drilling data and stratigraphic descriptions helped us to identify these units (OMV, 2000; Shell, 1980, Shell 1981). These Baghewala-1 Infracambrian equivalent intervals have been extended to Punjab Platform area. These units were identified in Suji-1, Marot-1 and Bahawalpur East-1. (Figure 7) Sediments overlying Basement to the base of Khewra Formation is termed as Salt Range Formation (SRF) in Pakistan. Upper part of the SRF is mainly composed of carbonates (limestone and dolomite) with intervening evaporites (halite, gypsum and anhydrite) and varying grained size clastics units (siltstone, sandstone and conglomerate.

The reservoir properties of Infracambrian and Cambrian units as identified in above mentioned wells have been summarized in Table 2.

The composite gross thickness map of SRF (Top Basement to Top Infracambrian) is presented in Figure 8. Thickness of this unit increases eastward. Significant evaporite cyclic influence has also been identified in Marot-1, which suggests the possibility of a tongue of the shallow sea with restricted seawater circulation and higher surface temperature favorable for the deposition of evaporites.

Gross Jodhpur Sandstone thickness varies from 31 to 170 m with a southward thinning trend at Punjab Platform whereas Net to Gross (NTG) varies between 60 to 100%.

Average porosity in Jodhpur sandstone in Punjab Platform varies from 16 to 20%. High reservoir porosities in this reservoir can be attributed to its continental to shallow marine origin, minimum cementation with preservation of initial pore spaces. Thermal history method of the basin suggests that Jodhpur Sandstone burial did not exceed the quartz overgrowth depth. Quartz overgrowth occurs at temperature from 110° to 125° C (Worden et. al., 2000).

Cambrian

Four stratigraphic units in Cambrian have been identified. Although Cambrian oil has been discovered in Potwar Basin (e.g. Khewra sandstone in Adhi) but good reservoir potential of the Khewra-Nagaur Formation (Early Cambrian) has also been observed in Bahawalpur East-1 (Shell, 1980).

Composite gross thickness map of top Infracambrian to top Khewra shows eastward thickening trend over the Punjab Platform suggests proximity of clastic source in that direction (Figure 9). Perhaps the clastic source may have been near the Aravali Range or other crystalline basement highs.

Average porosity in Khewra (Nagaur equivalent from Bikaner-Nagaur Basin) ranges from 5 to 18%. Thickness of this unit varies, from 10 to 100 m, a net to gross ratio NTG) of 0 to 25% (Table 2).

Type of Possible Traps

The types of traps expected to be present in Punjab Platform are discussed below:

Structures: Rollover Anticlines or Faulted Traps

Shape and geometry of structural traps are mainly controlled by the tectonic activity and its extent. Punjab Platform and adjoining areas experienced Proterozoic rifting. Consequent to this rifting, blocks were possibly reactivated particularly during Late Paleozoic and Jurassic – Cretaceous time. The reactivation times should be considered important episodes for terrain modification having a direct impact on the thickness and geometry of post event sediments. Similarly, Himalayan orogeny has mild effect in trap building. Himalayan Orogeny initiated in Early Tertiary and persisted at varying pace until Late Tertiary is considered a suitable time for the formation of rollovers. Reactivation of deep and old faults and newly formed fault bend rollovers may also be expected at Paleozoic reservoirs. Present seismic data indicates the presence of low relief rollovers in the area (Figure 10).

Stratigraphic (Pinch out due to Tilting and Unconformities)

Figure 11 illustrates the westward thickening of the Mesozoic sediments over the westward dipping Paleozoic strata and Basement. There is a greater likelihood of finding stratigraphic traps in the sedimentary package from Jurassic to Eocene especially in the Cretaceous sandstone units.

Stratigraphic traps, as in Mesozoic may also be explored in Cambrian, which includes Kussak and Khewra - Nagaur sandstone. These formations were exposed during long depositional hiatus followed by erosion, which lasted about 200 Ma. Structures that would have been modified by erosion are thought to be effective traps, which would have been buried by Mesozoic and Tertiary sedimentation. Our interpretation based on regional 2D seismic data suggests presence of such traps. However, finding such unconformity related traps appear quite challenging and need high-resolution 3D seismic data.

Paleo Highs (Paleozoic)

East-west seismic lines across the Fort Abbas-1 and Bahawalpur East-1 wells illustrate that on the top of Permian Tobra Formation a prominent rollover exists whereas the overlying strata of Jurassic through Tertiary appear unaffected (Figure 12 and Figure 13). It appears that Fort Abbas and Bahawalpur East structure have formed during Late Permian unconformity due to differential erosion. Such traps if found in Punjab Platform offer preferred location for exploratory drilling. The maturity level of Infracambrian source and the level of oil expulsion were attained during Tertiary when such traps were already present.

Salt Related Structures

Salt structures have been recognized as important petroleum bearing traps worldwide in onshore and offshore basins. Immense salt and evaporites of Infracambrian age are exposed in eastern part of the Potwar basin. Up to 400 m thick rock salt also penetrated in Marot-1 in Punjab Platform (Shell, 1981). However, little attention was given to interpret the role of salt in the development of structures in Punjab Platform.

The role of the salt movement in the development of new structures and modification of existing structures needs to be critically evaluated for successful exploration in the area. Seismic line across Marot-1 well suggests that structural development took place during the pre-Jurassic unconformity and the salt movement is likely to be the major cause of this structure (Figure 11 and Figure 14). For example, Marot-1 salt movement has not affected Tertiary and Cretaceous sediments suggesting the age of the structure Late Permian to Middle Cretaceous. This confirms that salt played a critical role in the trap building but cautious evaluation is needed while interpreting the cause and age of the structuring on other structures. Not all Infracambrian structures in Punjab Platform are salt related (Figure 12 and Figure 13). Early salt induced traps and late stage source rock maturation and migration are expected to be present.

Thermal and Burial History Reconstruction through Basin Modeling

Reconstruction of thermal and burial histories of Marot-1, Bahawalpur East-1 and Suji-1 wells are presented in Figure 15 1a-b, Figure 15 2a-b and Figure 15 3a-b). This figure was generated from numerical solution of a one dimensional transient heat flow equation using the BasinMod-1D software.

The present heat flow is 45mW/m^2, with estimated geothermal gradient of 12.5 to 25°C/km. The heat flow during Infracambrian to Jurassic is 80mW/m^2 from Jurassic to Late Eocene is 100 mW/m^2, typical of active rift passive margin and from Eocene to present 80 mW/m^2, which is typical of active collision. Present Basal temperature is 1500°C (Gretener, 1981; Lucazeau and Le Douaran, 1984; Von Herzen and Helwig, 1984).

Bahawalpur East-1 was drilled to the Basement at 3,024 m, which will be explained here (Shell, 1980). Sedimentation started in Infracambrian time and continued through Cambrian. No rock record from Ordovician through Carboniferous rocks spanning about 200 Ma in India-Pakistan in Indus and Rajasthan basins have been found. However, we have assumed that up to 1200m thick sediments (500-288 Ma) deposited and eroded during an uplift, which initiated in middle Carboniferous sediments deposited and removed during this large geological time gap (Raza, 2000). Deposition continued through Permian and break during Triassic (255-203 Ma). Rapid sedimentation and subsidence during Jurassic-Cretaceous rift phase, followed by uplift during early Paleocene (56-50 Ma).

Primary source for Infracambrian is Bilara Formation which has been exposed to more than 90° C from 16 Ma to present; an appropriate temperature for the generation of hydrocarbon (Allen and Allen, 1990; Hunt, 1979). Presently basal part of Bilara carbonates, an important source reached early oil maturation level. All other younger horizons are immature.

Identification of the Mature Areas

As discussed in the previous section basin modeling results suggests favorable maturity for the Infracambrian. Infracambrian Isochron map (Figure 14) substantiated by Paleo- depth structure map at Basement (Figure 16) indicates that Infracambrian attained greater thickness in the areas around Fort Abbas-1, Marot-1 and towards the south of these wells. Near these areas it is expected that the Infracambrian source and reservoir would be thicker and of better quality.

Exploration Strategy

Discussion

In this paper, we have discussed exploration play concepts in Punjab Platform area. Infracambrian and Cambrian reservoirs have been unsuccessfully explored although only 12 wells have been drilled for Infracambrian and Cambrian reservoirs. Despite these failures, three gas fields have been discovered in Cretaceous and Jurassic reservoirs. Baghewala-1 in Bikaner-Nagaur Basin (Rajasthan, India) is the only known heavy oil discovery from Jodhpur Sandstone and Bilara carbonates, giving continued impetus for exploration efforts in these reservoirs in Punjab Platform. The petroleum system element is expected to be favorably located in parts of the Punjab Platform.

The area is reasonably covered by 2D seismic data but the drilling is sparse. Only five wells penetrated Infracambrian and only five penetrated the upper part of the Basement. Summarized wells information drilled in Punjab Platform area have been given in Table 1 which clearly indicate that this play has not yet been adequately explored. Despite various unsuccessful drilling campaigns, which initiated fifty years ago, we believe that renewed efforts need to be initiated making full use of the state of the art seismic techniques.

We have to review and analyze the data with fresh look; there are few common findings among the wells drilled in Punjab Platform; these are a) heavy and asphaltic oil; b) fairly porous Infracambrian Jodhpur Sandstone (average porosity 18 %) and c) Bilara carbonates (average porosity 12%) reservoirs suggesting plausible Infracambrian in the area. The play concept may further be enhanced by presence of good quality source intervals and maturation in early oil window.

We suggest that paleo structural and stratigraphic history of the basin should be restored by flattening specific horizon; for instance, we prepared flattened seismic sections to decipher the depositional and structural history from Infracambrian to Eocene time (Figure 17, Figure

18, Figure 19, Figure 20). This methodology helped us determine distribution of major grabens (paleo-lows) and horsts (Paleo-highs) during Infracambrian. Paleo-reconstructed maps will help to recreate the basin history and locate the areas where good reservoir sands could possibly been deposited.

It is envisaged that Paleo-lows became less pronounced during uplifting and inversion and are not as significant as trap at present time. Such lows would be possible where better source facies depositional sites and are likely to be preserved with favourable maturity. Reservoir potential in Jodhpur sandstone and Khewra- Nagaur has been recognized. We consider the areas around Fort Abbas-1 and Marot-1 may have better Infracambrian reservoir in Palo lows.

Geothermal gradient of the area is low (15°C/km to 25°C/km) which increases westward demonstrating that basin remained relatively cool and tectonically stable. Despite the low geothermal regime, favorable oil maturity for the Infracambrian is envisaged.

We also believe that Infracambrian and Cambrian reservoir units may be independently mapped. Each Infracambrian unit such as Sonia shale, Jodhpur Sandstone, Bilara carbonates and Hanseran Evaporites and Cambrian Khewra-Nagaur sandstone need to be interpreted and based on their structural appropriateness drilling decisions may be taken. Relationship of the faults and their stratigraphic extent and the overlying sediments loading affect on salt movement leading to the growth of the structures should be critically evaluated.

Seismic Database and Interpretation

We have studied 2500 line kilometers vintage 2D seismic data. This data of varying quality was acquired from 1970 to 1998 by AMOCO, Shell, POL, OGDCL and OMV. The data acquired up to 1980's were 12 fold have poor quality. The data quality improved during succeeding years owing largely to increase in the number of fold.

Following table gives the historical data of seismic and their quality.

Year of acquisition	Fold	Percentage to total acquired
1973, 1981	12	50 %
1991, 1992	20	15 %
1991	24	2.5 %
1993, 1994	30	19 %
1998	120	13.5 %

The best quality of seismic data was acquired in 1998. We have identified the various geological horizons on seismic sections, which were than correlated with Suji-01, Bahawalpur East-1, Fort Abbas-1 and Marot-1 wells (Figure 10, Figure 11, Figure 12, Figure 13). This data was loaded to the PC based software 'Geographix' and interpreted. Interpretation was also carried out by flattening horizons of interest to study the paleo-topography of the specific horizons (Figure 17, Figure 18, Figure 19, Figure 20).

Conclusions

This paper has been written to provide an insight into the petroleum prospectivity of Punjab Platform, which has not been keenly explored due to dry wells. We have proved that Bilara carbonates source rock with just about right thermal maturity is present in the Punjab Platform. Jodhpur Sandstone with high porosities and substantial thicknesses has been documented as excellent potential reservoir in Punjab Platform. Past exploration has been mainly focused on drilling structural traps, whereas we emphasize stratigraphic traps especially those modified by erosion during unconformities should be preferred exploration objectives. Graben area as located southwest of Fort Abbas and Marot-1 area is the possible site where thick Infracambrian sediments are expected to be present. In order to find low relief but sizeable stratigraphic and structural traps the combined use of high-resolution 3D seismic and AVO analysis are recommended.

Acknowledgement

Authors gratefully acknowledge the management of Pakistan Petroleum Limited for the permission to present this paper. We are also indebted to Omair Fayaz, M. Tarique, Saleem Hashmi and Najam Warsi who prepared the graphics for this paper with dedication. We are also thankful to Dr. Syed Asif Ahsan for his time for reviewing the manuscript of this paper and providing useful suggestions to improve the contents.

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S. NO	WELLS	OPERATOR	YEAR	KBE(M)	TD (M)	TD FORMATION	STATUS
1	KARAMPUR-01	SHELL	1958	142.33	3034.1	Basement	ABD
2	BAHAWALPUR EAST-01	SHELL	1980	135	3024	Basement	ABD
3	MAROT-01	SHELL	1981	143	2596	Basement	ABD
4	BIJNOT-01	OGDCL	1996	129.4	1914	Basement	ABD
5	SUJI-01	OMV	2000	110	2626	Basement	ABD
6	SARAI SIDHU-01	AMOCO	1973	145.26	3279.5	Salt Range	ABD
7	DARBULA-1	OGDCL	1989	184	1550	Salt Range	ABD
8	FORT ABBAS-01	OGDCL	1994	144	1651	Salt Range	ABD
9	BAHU-1	OGDCL	2006	145.6	2936	Salt Range	GAS
10	KAMIAB-01	AMOCO	1974	163.18	2298.4	Samanasuk	ABD
11	PIRANWAL-01	OGDCL	1986	143.7	2581	Baghanwala	ABD
12	TOLA-1	AMOCO	1974	146	1828.7	Warcha	ABD
13	PANJPIR-01	OGDCL	1985	142.3	2120	Tredian	GAS
14	NANDPUR-01	OGDCL	1984	141.5	2110	Kingriali	GAS
15	AMIR WALI-1	OGDCL	2005	144.7	2049	Kingriali	ABD
16	ALI SAHIB-1	OGDCL	2005	142	2052	Kingriali	ABD
17	JANDER-1	OGDCL	2005	143	2055	Kingriali	ABD
18	CHAK-12-1	OGDCL	2006	135	2130	Kingriali	ABD
19	BAGH X-1	OGDCL	2006	148.57	1398	Kingriali	ABD
20	AHMEDPUR-01	POL	1992	114.6	2634	Datta/Shinawari	ABD
21	JIWANWALA-01	OGDCL	1999	131.4	2100	Shinawari	ABD
22	BUDHUANA-01	AMOCO	1974	153.7	1279.5	Samanasuk	ABD
23	SARO-1	OGDCL	1992	166.7	1040	Samanasuk	ABD
24	BAGHEWALA-1	OIL	1991			Basemant	OIL
25	PUGAL-1	OIL	1960			Salt Range	ABD

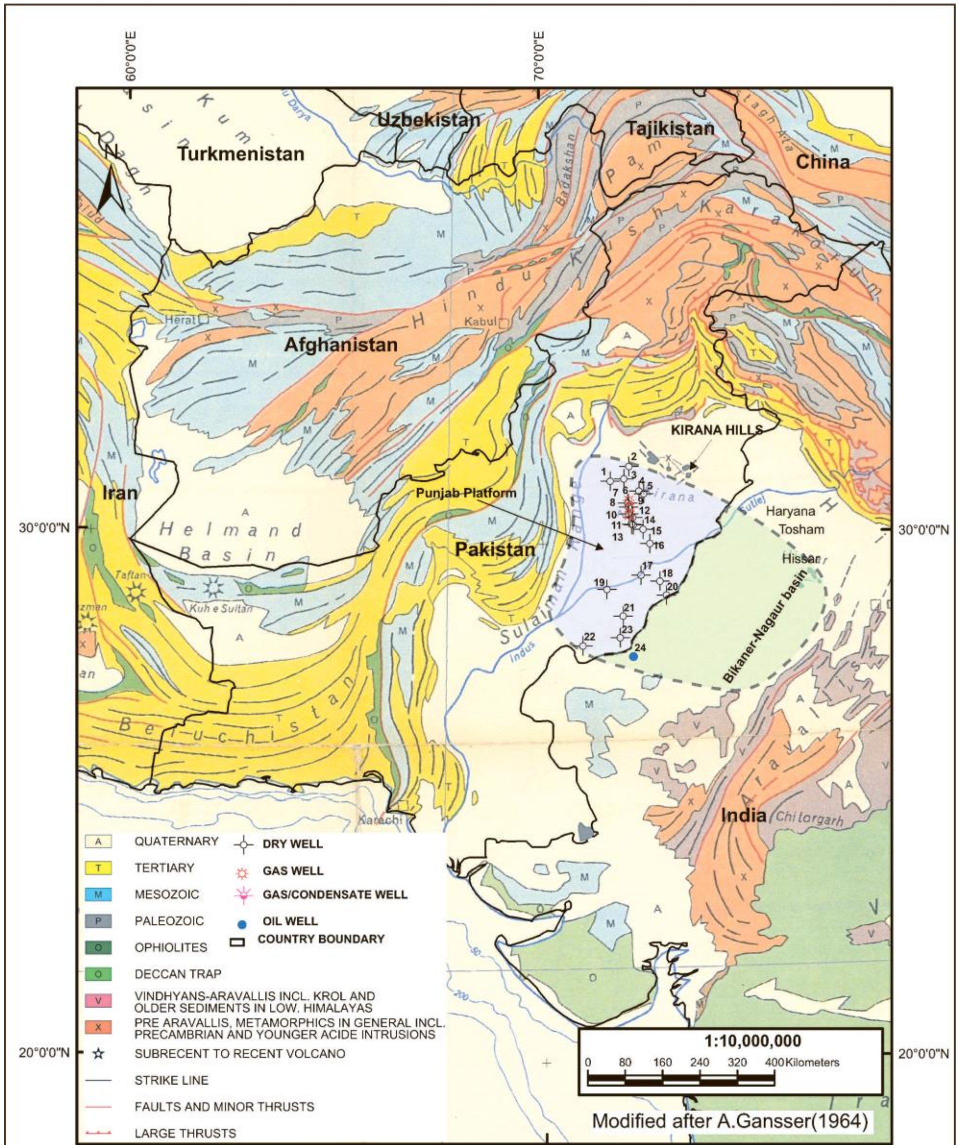
Table 1. Summary of wells drilled in Punjab Platform.

AGE	FORMATIONS	BAHAWALPUR EAST-01				
		TOP	THICKNESS	NTG	AV.POROSITY (Range)	Description
		(m)	(m)	(%)	(%)	
CAMBRIAN	BAGHANWALA	1740	129	80	20 (8-25)	80% Sandstone; 20% Claystone
	JUTANA	1869	7	100	8 (5-12)	100% Dolomite
	KUSSAK	1876	184	85	25 (20-30)	85% Sandstone; 15% Siltstone
	NAGAUR	2060	94	20	18 (12-25)	80% Siltstone; 20% Sandstone
INFRACAMBRIAN	HANSERAN	2154	96	20	12 (5-25)	80% Siltstone, anhydrite; 20% Dolomite
	BILARA	2250	350	62	10 (0-30)	62% Dolomite, limestoen; 38% Siltstone, shale & anhydrite
	JODHPUR	2600	140	60	16 (2-25)	60% Sandstone; 40% Siltstone
	SONIA	2740	231	11	12 (0-20)	74% Siltstone, shale, marl, anhydrite; 15% Salt; 11% Dolomite
	BASEMENT	2971				

AGE	FORMATIONS	MAROT-01				
		TOP	THICKNESS	NTG	AV.POROSITY (Range)	Description
		(m)	(m)			
CAMBRIAN	BAGHANWALA	NP	NP			
	JUTANA	1089	11	100	20 (10-28)	100% Dolomite
	KUSSAK	1100	200	100	25 (21-30)	100% Sandstone
	NAGAUR	1300	100	0	18 (12-25)	100% Siltstone, clay
INFRACAMBRIAN	HANSERAN	1400	410	3	10 (2-18)	83% Salt; 9% Claystone, anhydrite; 8% Dolomite, limestone
	BILARA	1810	420	38	12 (0-30)	48% Siltstone; 48% Dolomite, limestone; 4% Salt
	JODHPUR	2230	170	*90	*18 (3-22)	90% Sandstone; 10% Siltstone, anhydrite
	SONIA	2400	143	17	15 (0-20)	75% Siltstone, traces of marl; 25% Limestone, traces of anhydrite
	BASEMENT	2543				
	*The interpretation of Jodhpur Formation suggest radioactive sands due to its high GR value ranging 30-150 API					

AGE	FORMATIONS	SUJI-01				
		TOP	THICKNESS	NTG	AV.POROSITY (Range)	Description
		(m)	(m)			
CAMBRIAN	BAGHANWALA	NP	NP			
	JUTANA	NP	NP			
	KUSSAK	NP	NP			
	NAGAUR	1825	10	25	5 (3-8)	75% Siltstone; 25% Sandstone
INFRACAMBRIAN	HANSERAN	NP	NP			
	BILARA	1835	337	32	15 (0-28)	72% Dolomite, limestone; 18% Sandstone; 10% shale, siltstone, anhydrite
	JODHPUR	2172	31	*100	*20 (10-25)	100% Sandstone
	SONIA	2203	97	12	10 (8-12)	70% Shale; 12% Sanstone; 10% Siltstone; 8% Dolomite, traces of anhydrite
	BASEMENT	2300				
	*The interpretation of Jodhpur Formation suggest radioactive sands due to its high GR value ranging 80-180 API					

Table 2. Summary of the Reservoir Properties of Bahawalpur East-01, Marot-01 and Suji-01 wells from Infracambrian and Cambrian units.



1) Kamiab-1 2) Darbula-1 3) Saro-1 4) Budhuana-1 5) Bagh-X-1 6) Bahu-1 7) Amir Wali-1 8) Jander-1 9)Panjpir-1 10) Sarai Sidhu-1 11) Nandpur-1 12) Ali Sahib-1 13) Chak12-1 14) Piranwal-1 15) Tola-1 16) Karampur-1 17) Bahawalpur East-1 18) Marot-1 19) Ahmedpur-1 20) Fort Abbas-1 21) Suji-1 22) Jiwanwala-1 23) Bijnot-1 24) Baghewala-1

Figure 1. Generalized geological map of India and Pakistan and wells drilled in Punjab Platform. Baghewala-1, Heavy oil discovery well, is located in Bikaner-Nagaur Basin, south of Punjab Platform.

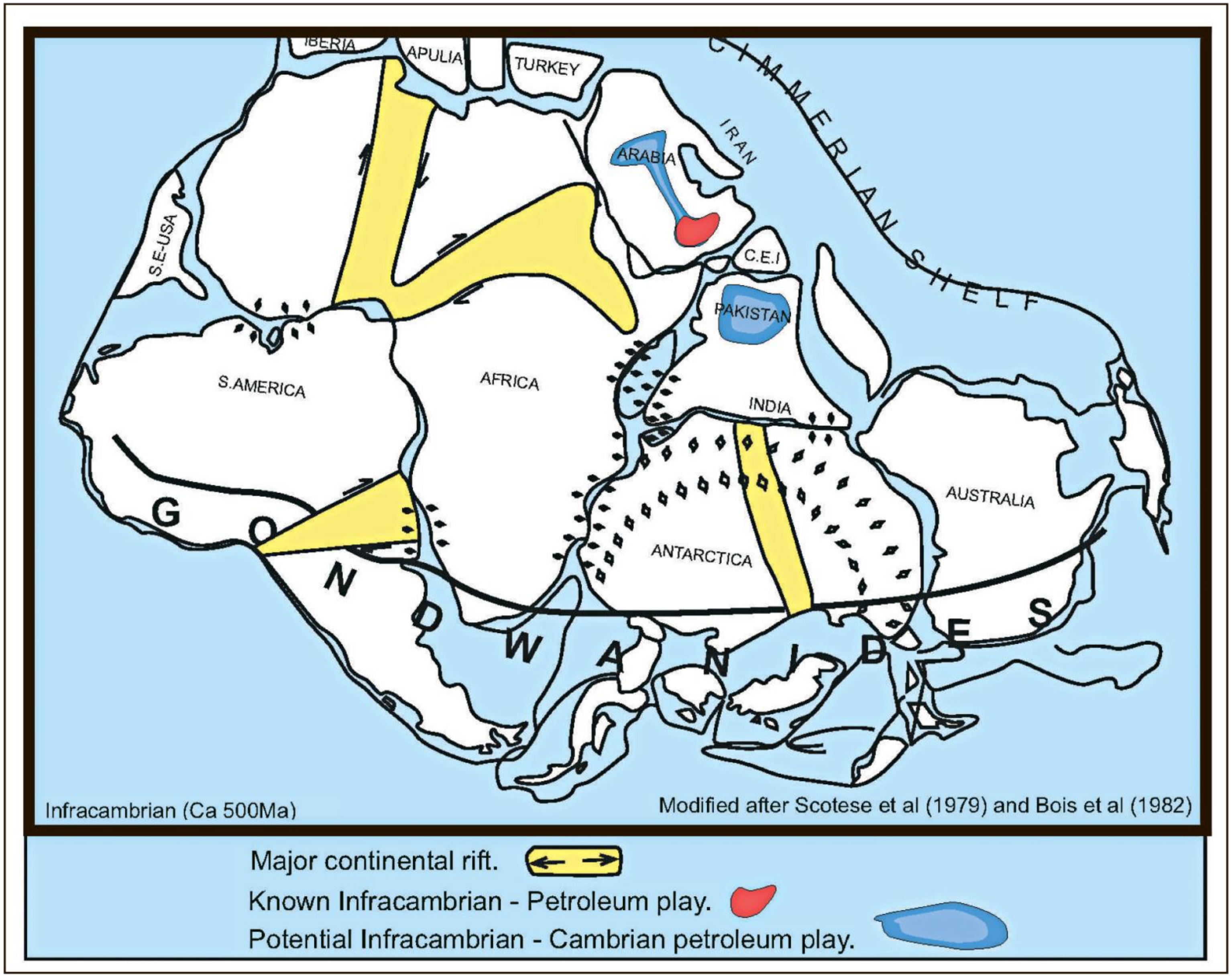


Figure 2. Paleogeographic tectonic map of Gondwanaland during Infracambrian. Indian, Arabian and African plates were fused together. Indian and Arabian plate margins are believed to be common depositional site at the Cimmerian shelf during Infracambrian and Cambrian.

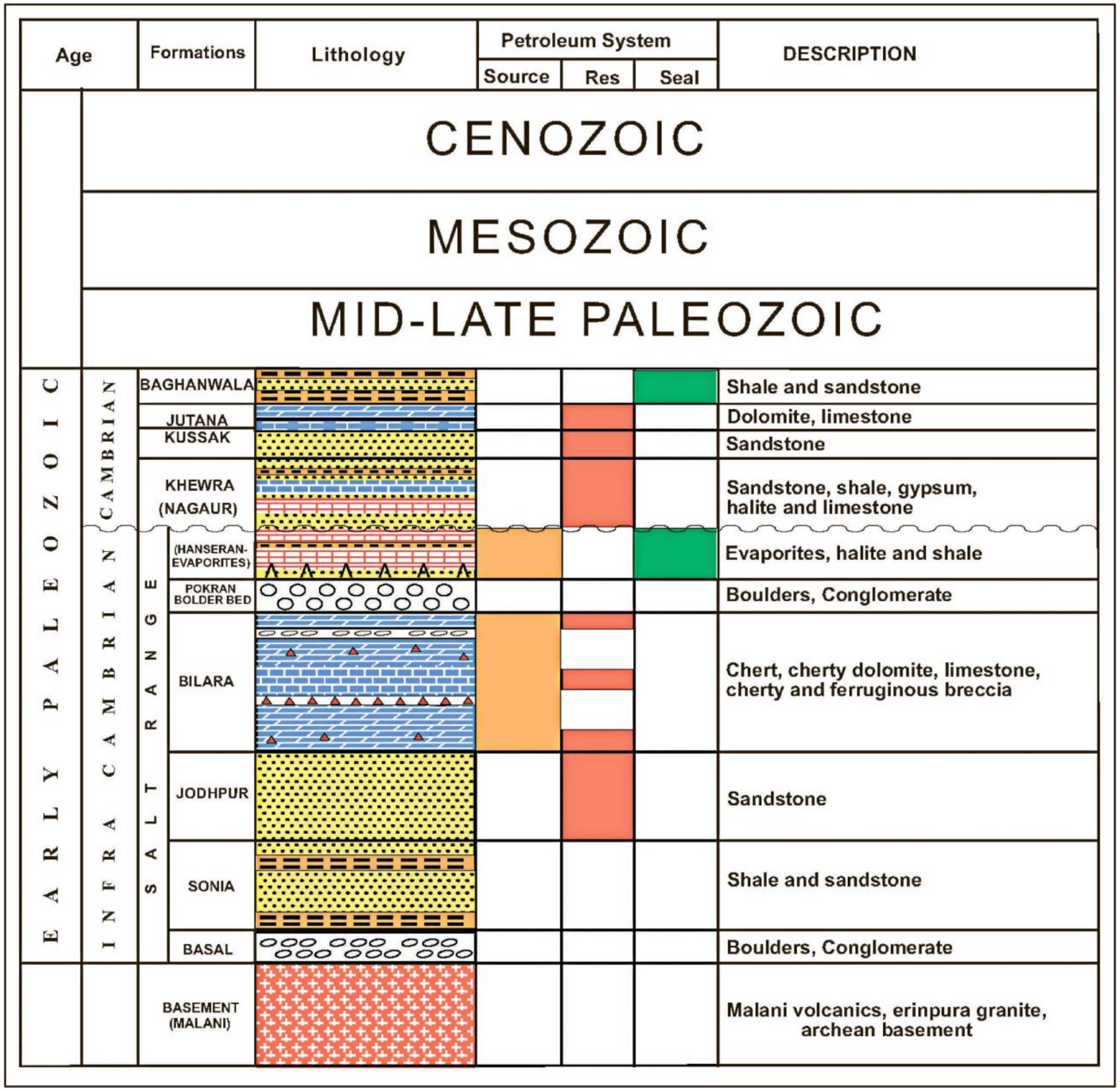


Figure 3. Generalized stratigraphic column and summary of Petroleum System of Infracambrian-Cambrian of Punjab Platform and Bikaner-1 well Hanseran evaporites forms perfect top seal for underlying reservoirs. (Modified after Pareek H.S. (1981 and 83), Peters et al (1995), B. S. Paliwal (1992) and Raza S. Mahmood (2000).

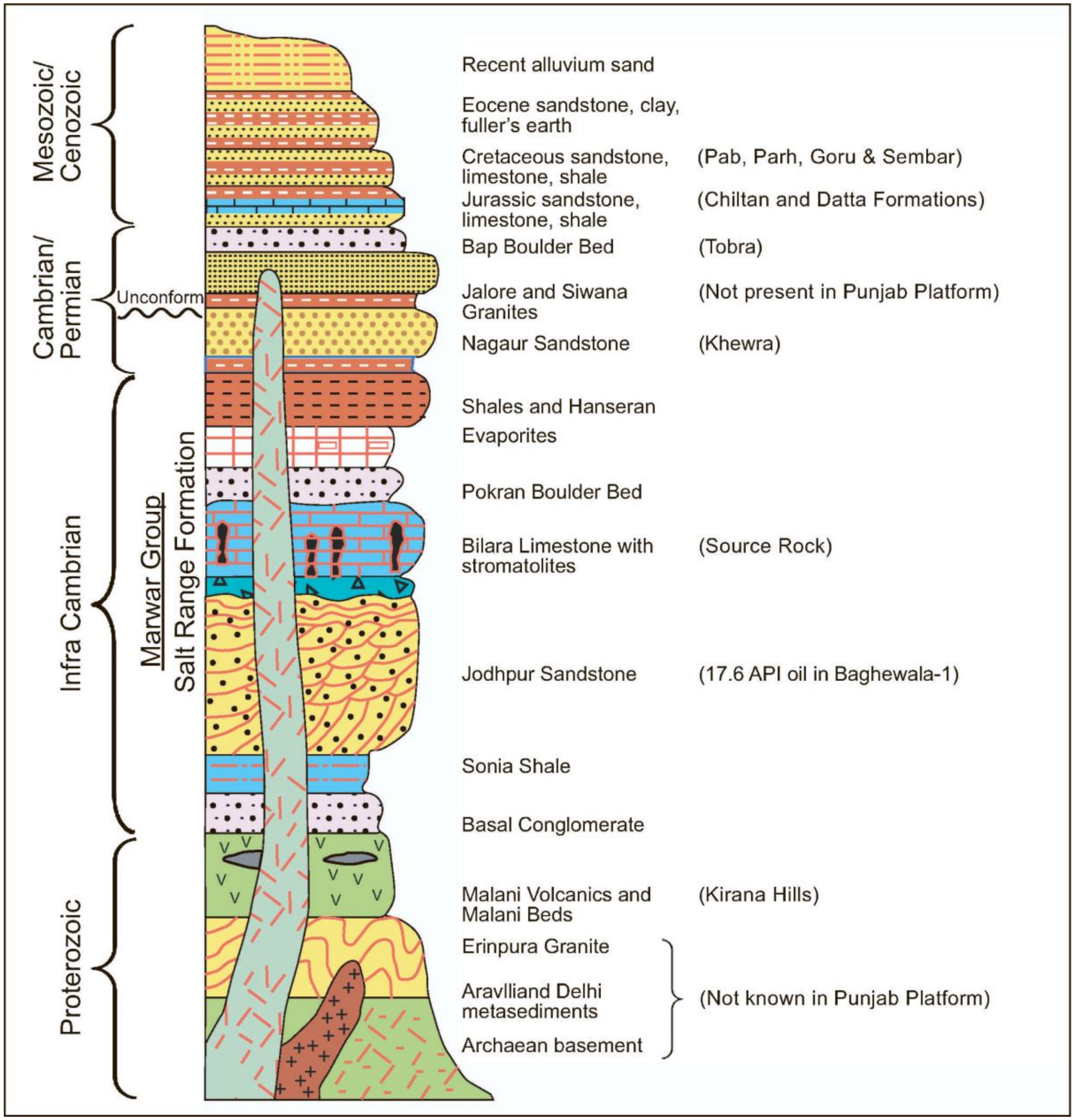


Figure 4. Lithostratigraphic column of the Aravalli Range (Rajasthan, India), where entire section from Proterozoic to Quaternary are exposed at various localities. These sections helped to identify the diverse lithostratigraphic distribution of Infracambrian in Punjab Platform. Modified after Pareek H.S. (1981 and 83) and B.S. Paliwal (1992) and Peters et al (1995).

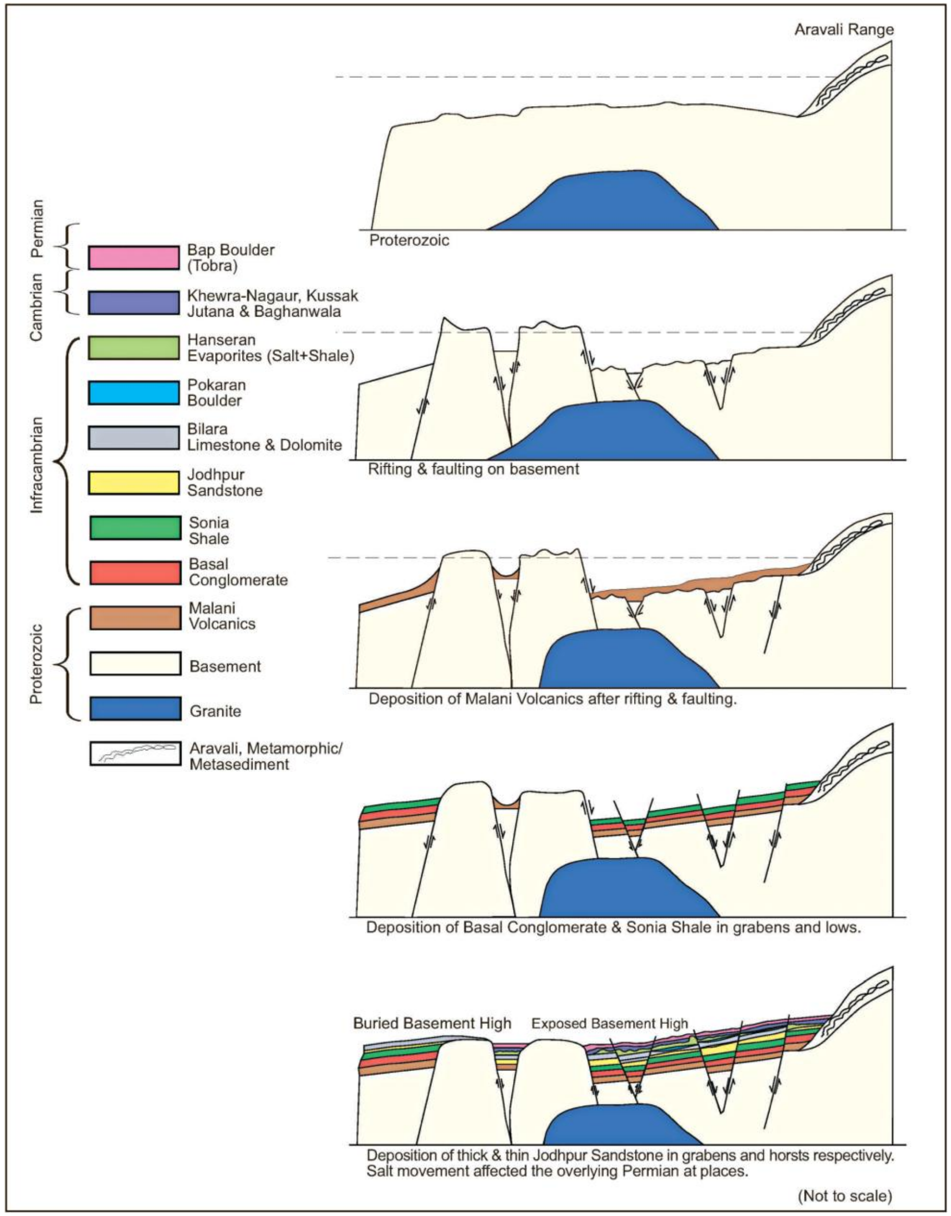


Figure 5. Schematic diagram showing the tectonic and stratigraphic evolution from Proterozoic to Permian, west of Aravali Range Bikaner-Nagaur Basin to Punjab Platform. (Modified after B.S. Paliwal 1992).

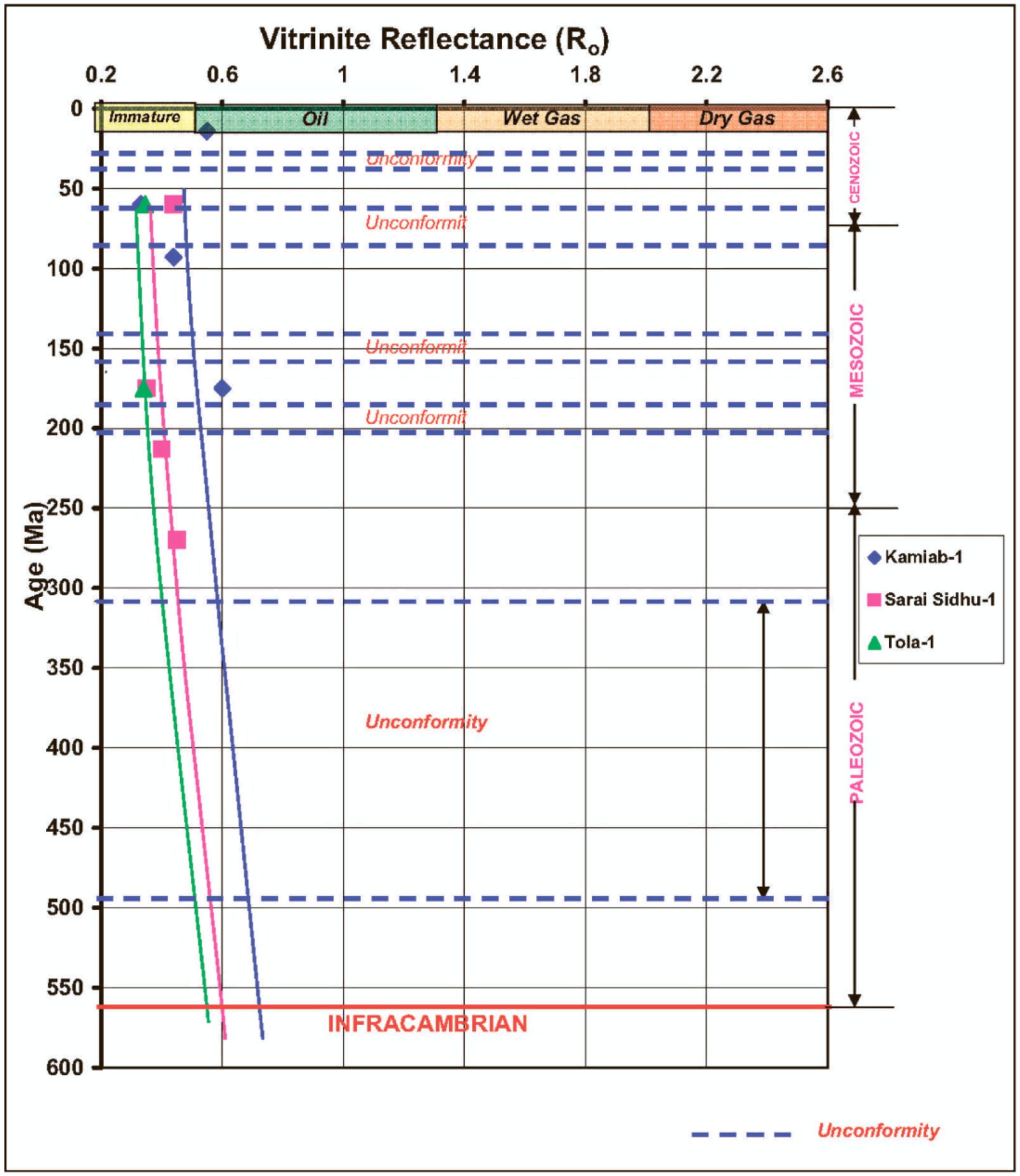


Figure 6. Plot showing Vitrinite Reflectance (VR) vs. Geological Time Scale. Three wells data of Kamiab-1, Saral Sidhu-1 and Tola-1, have been used for determining the possible thermal maturity in Infracambrian. The trend shows that Infracambrian falls within early oil generation window. (For well locations, refer Figure 1).

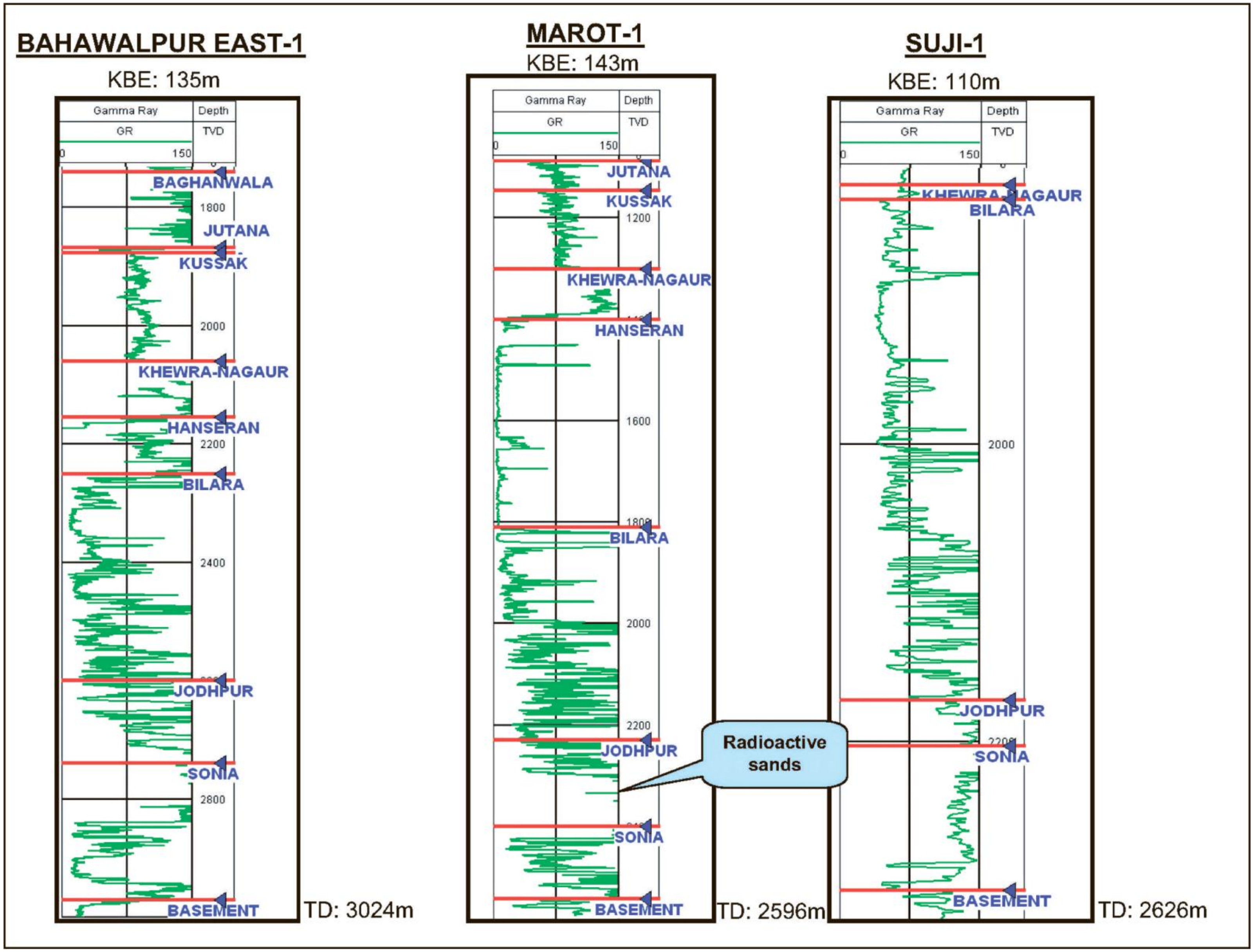


Figure 7. Stratigraphic distribution of Infracambrian to Cambrian units on GR logs. Jodhpur Sandstone is thickest in Marot-1 (170m) with porosity varies from 3-22%. High GR values in Jodhpur Sandstone of Marot-1 well suggest radioactive sandstone. Average 12% porosity in Bilara Formation at Bahawalpur East-1 (For location of wells, please refer to Figure 1).

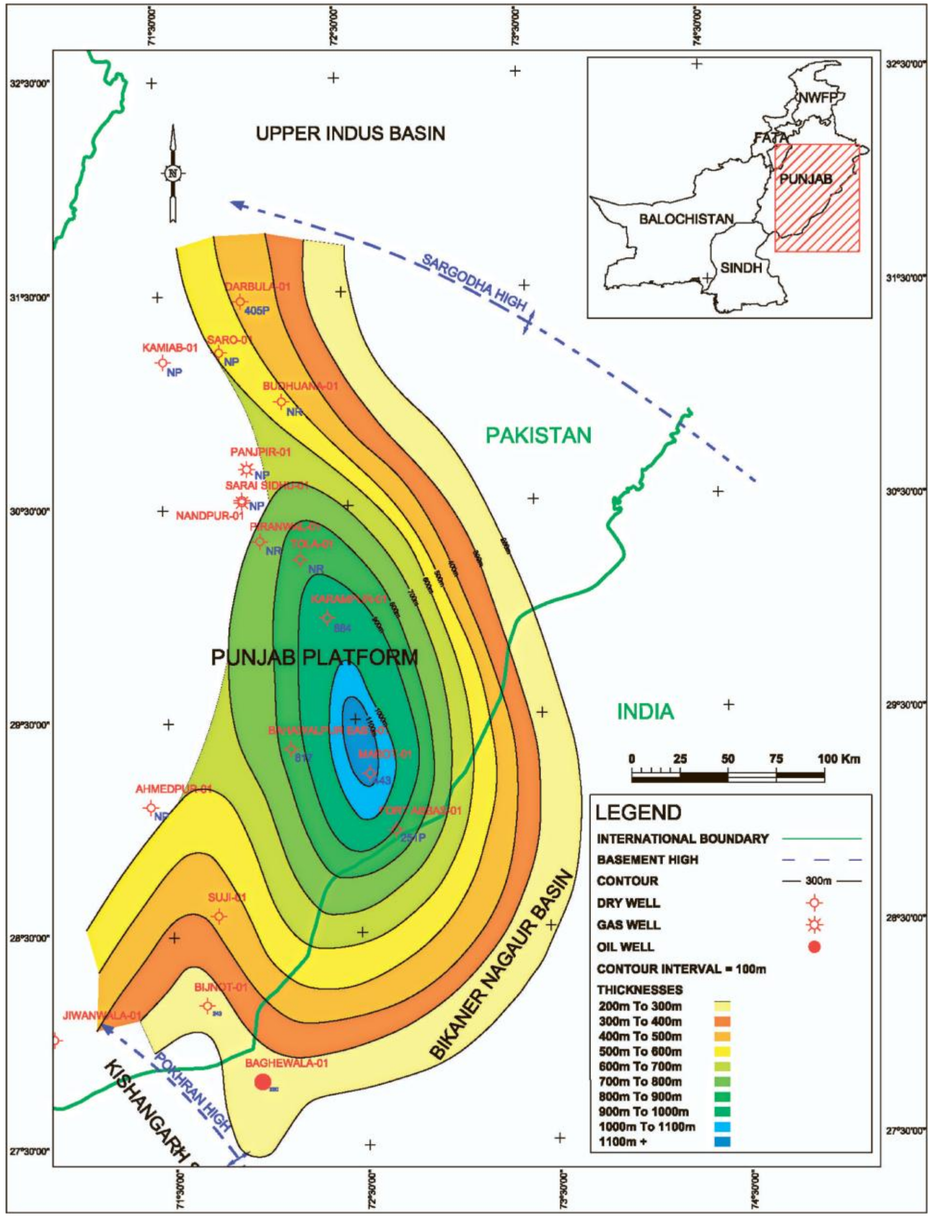


Figure 8. Gross thickness map of Infracambrian. This unit is termed as Salt Range Formation in Pakistan. Maximum thickness near Marot-1, Bahawalpur East-1 and Fort Abbas-1.

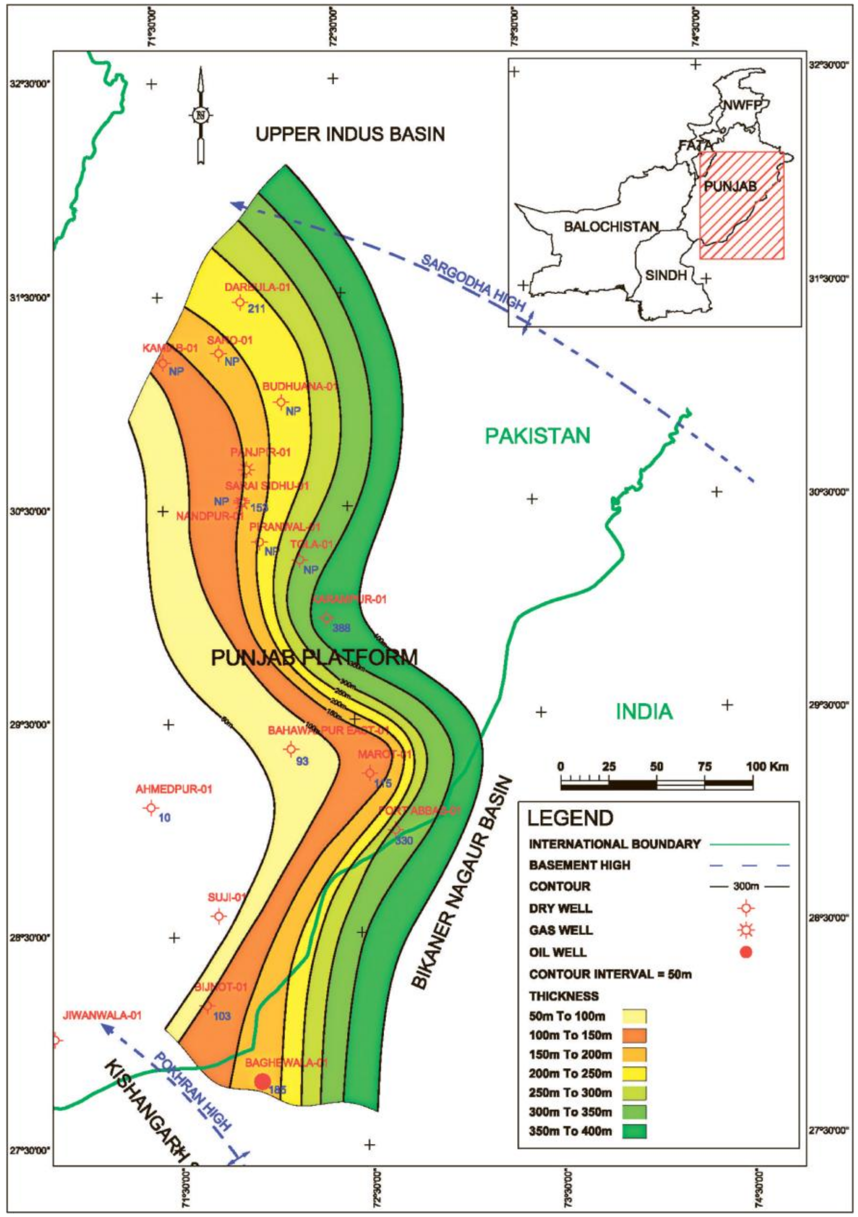


Figure 9. Gross thickness map of Khewra-Nagaur Formation of Cambrian age. Thickness increasing towards east near the major clastic supply area around Aravali Range and associated highs.

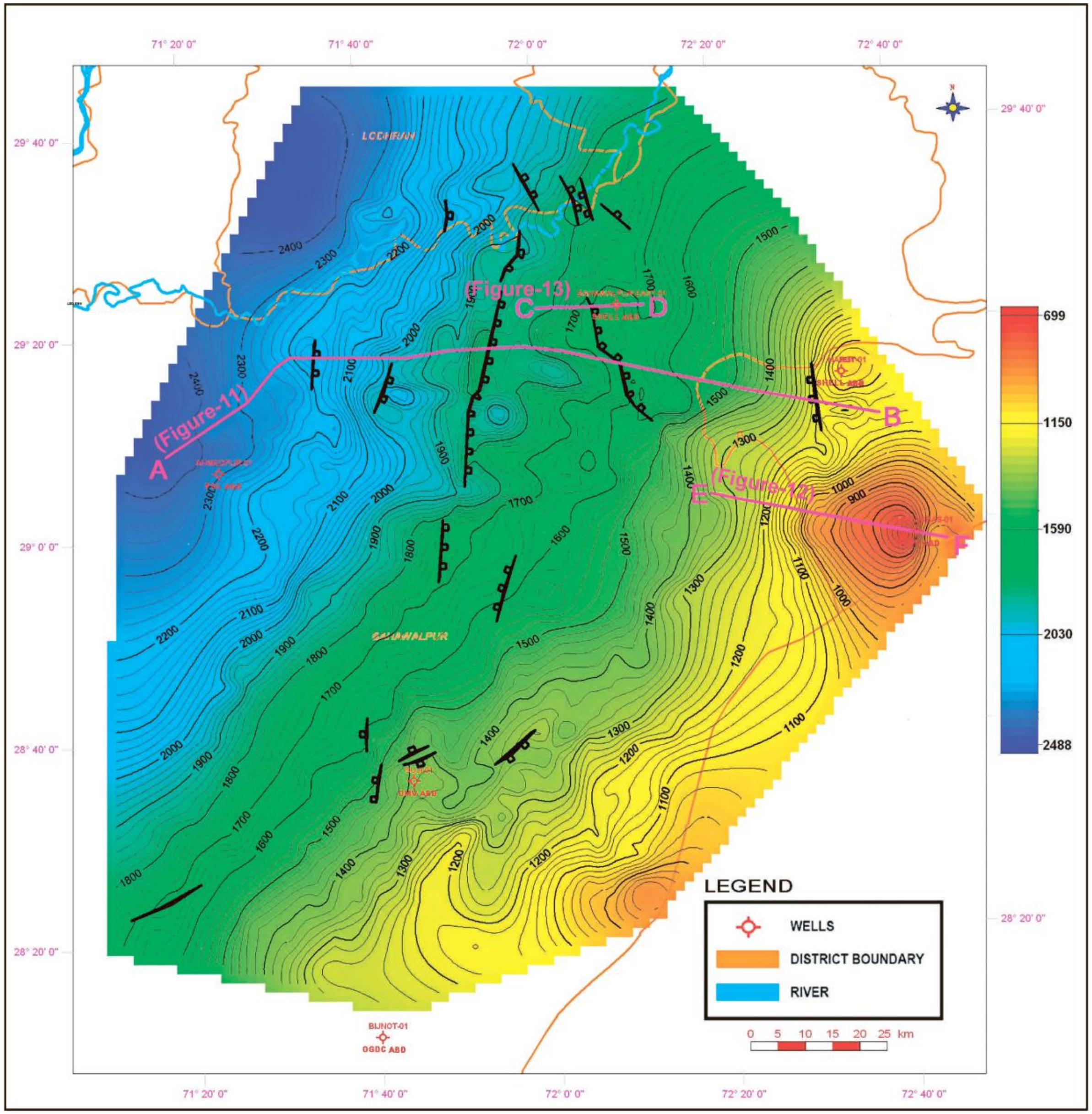


Figure 10. Time structure map at top Infracambrian level with seismic reference datum (SRD) at mean sea level, showing the presence of structural leads. Regional westward dip shows significant uplifting of eastern side after basin inversion.

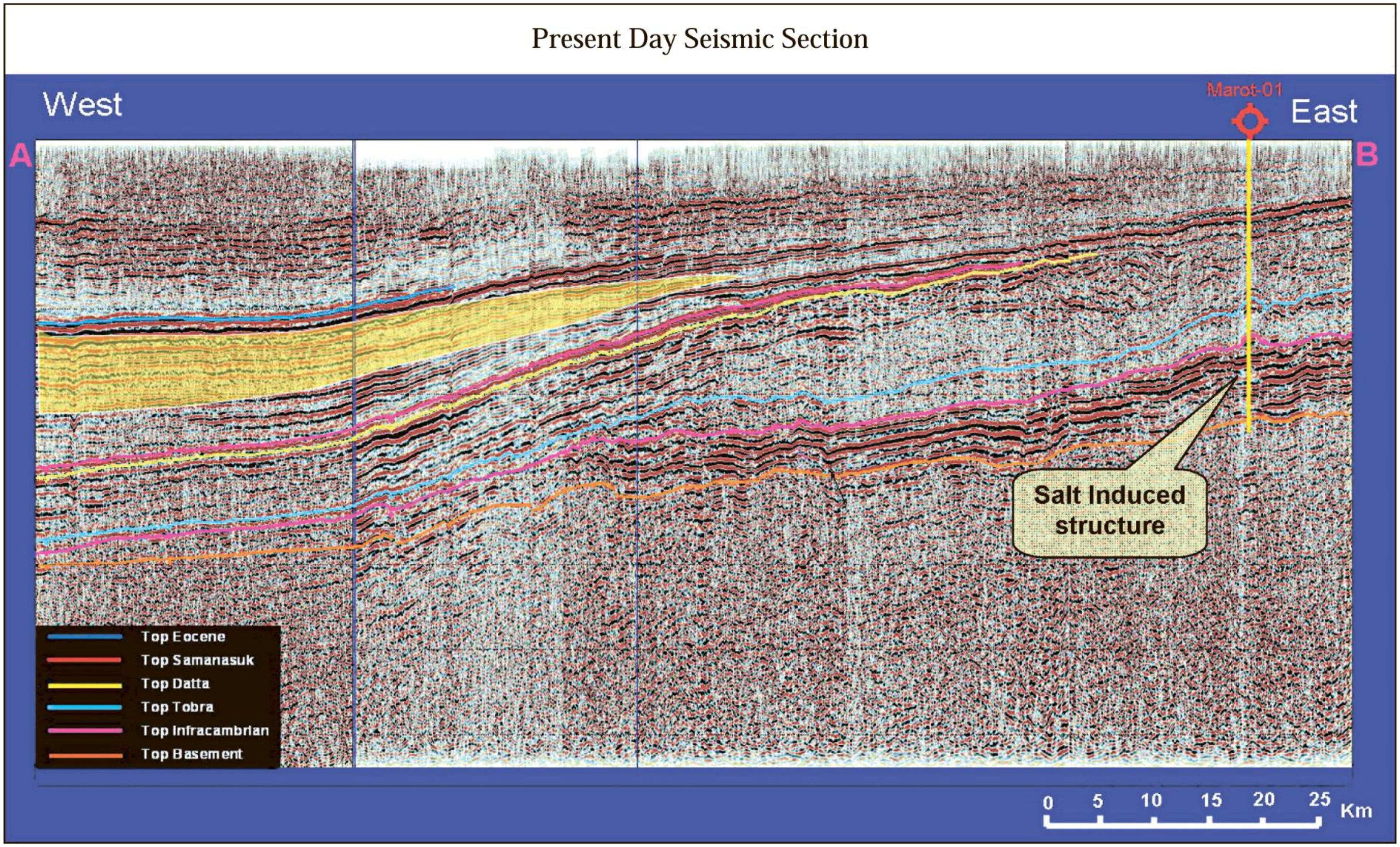


Figure 11. Depositional direction remains from east to west from Jurassic to Recent time. Significant unconformities can be identified above Eocene, Permian and Jurassic sediments. The stratigraphic pitchouts between Jurassic and Eocene time are prominent, and need to be explored after better quality seismic acquisitions (for location of the seismic line see Figure 10).

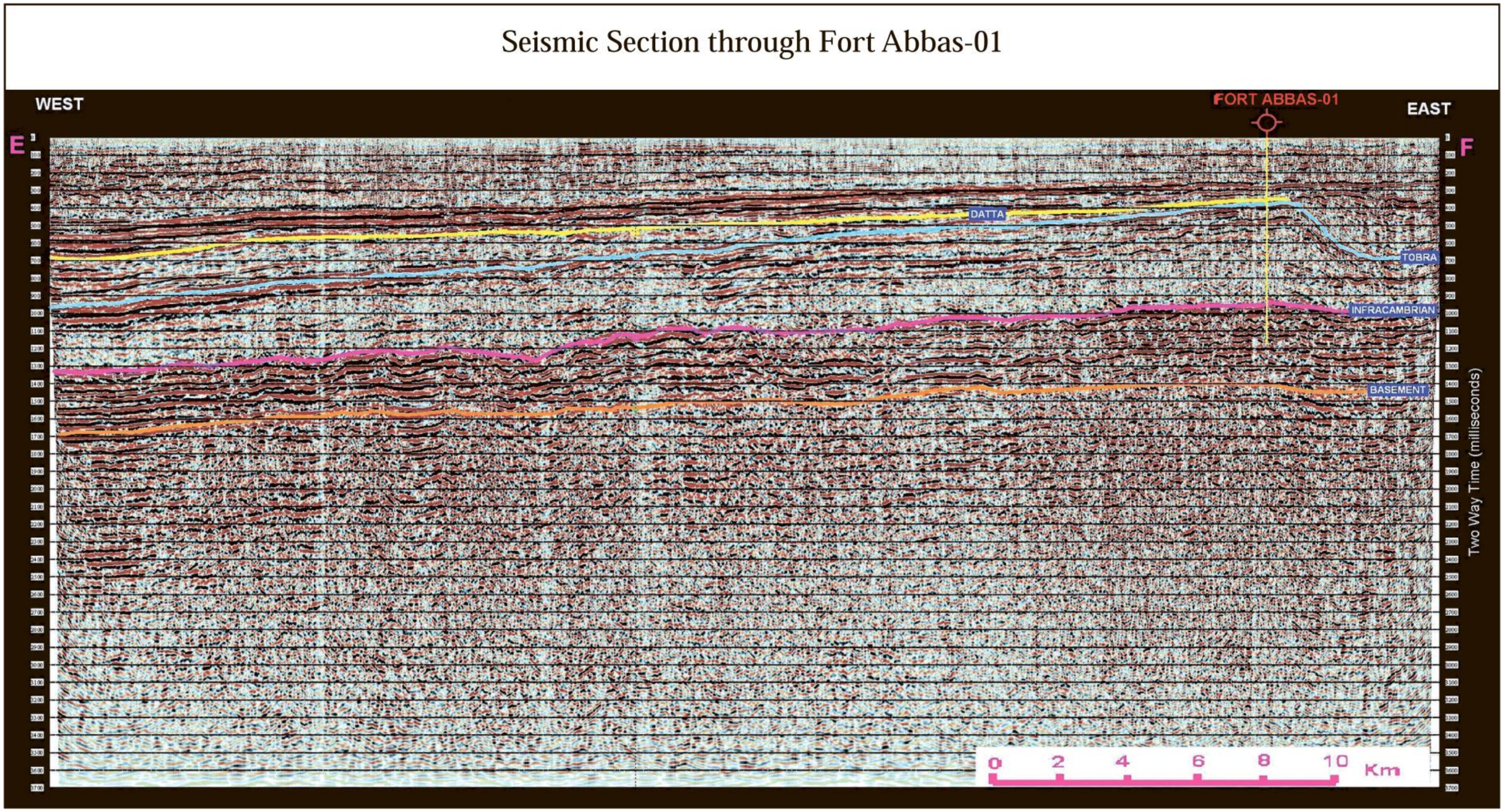


Figure 12. Asymmetrical anticlinal structure at Permian level perhaps formed due to deposition of Permian sediments over an erosional high (for location of the seismic line see Figure 10).

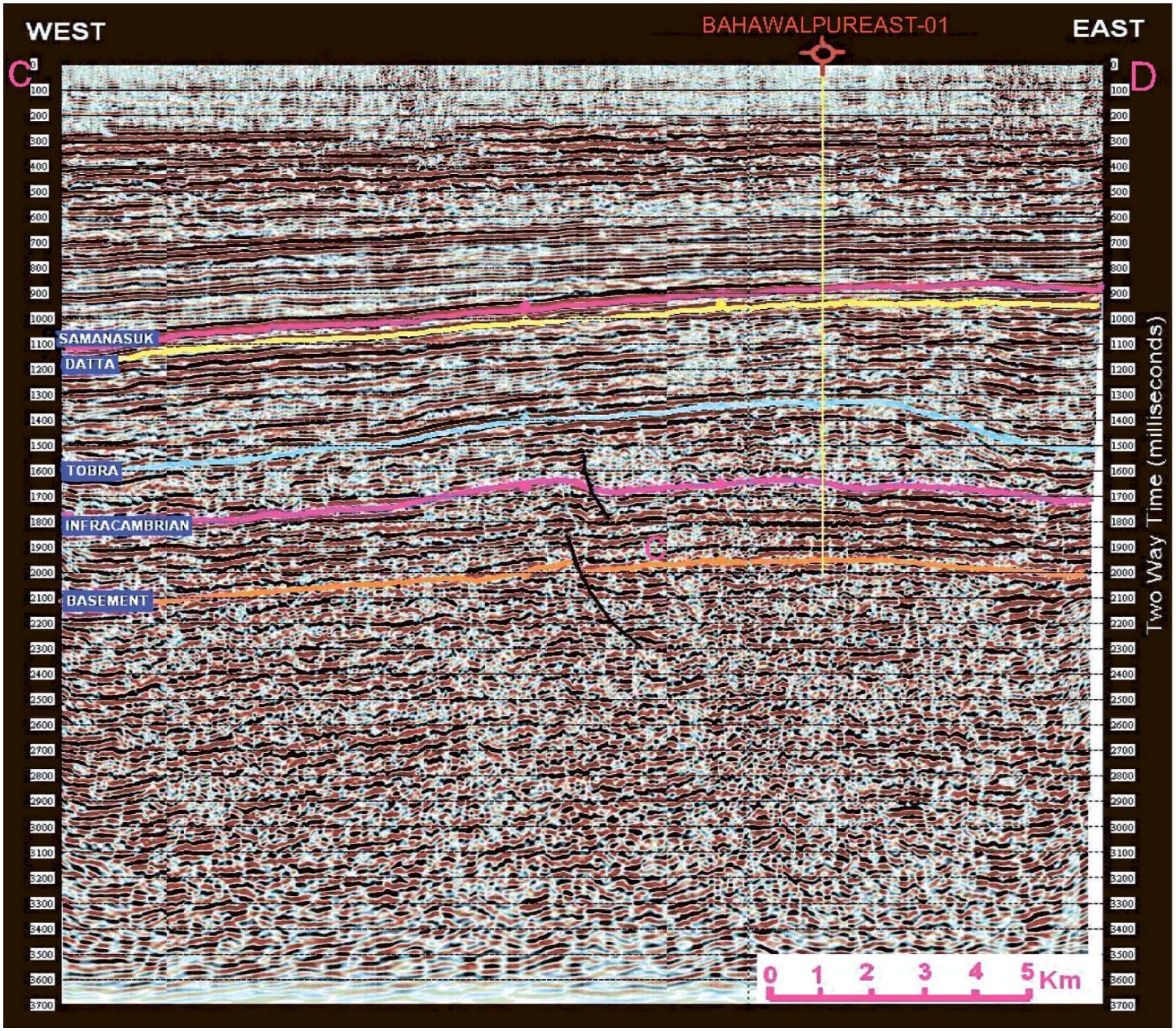


Figure 13. East West seismic section across Bahawalpur East-01 well, showing a structural high at Tobra (Permian) level and minor rollover at Infracambrian level whereas overlying sediments appear unaffected by Tobra structural growth which indicates that structure is older than Jurassic time (for location of the seismic line see Figure 10)

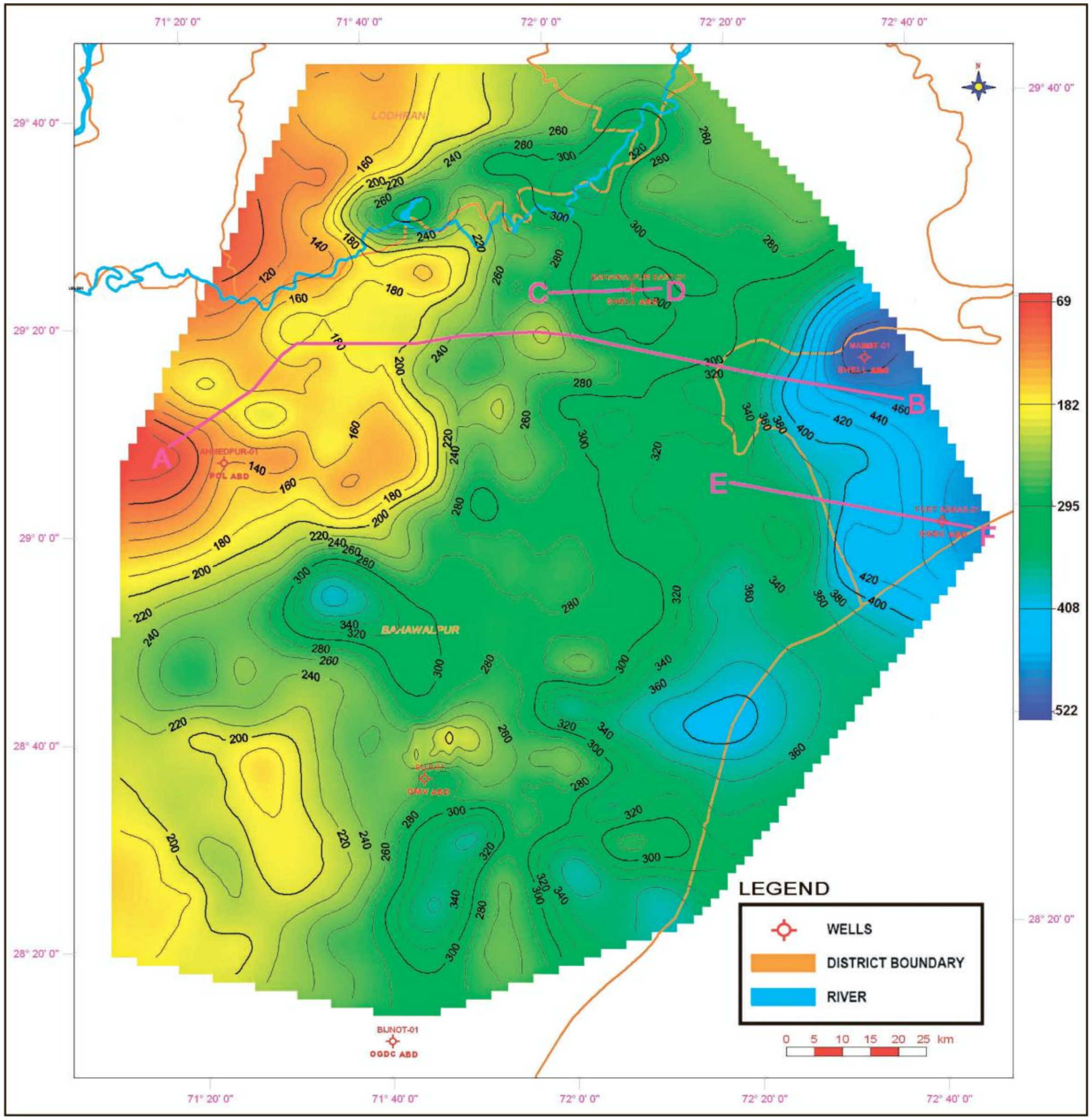


Figure 14. Ishochron Map from top Infracambrian to top Basement, showing the variation in thickness of Infracambrian sediments.

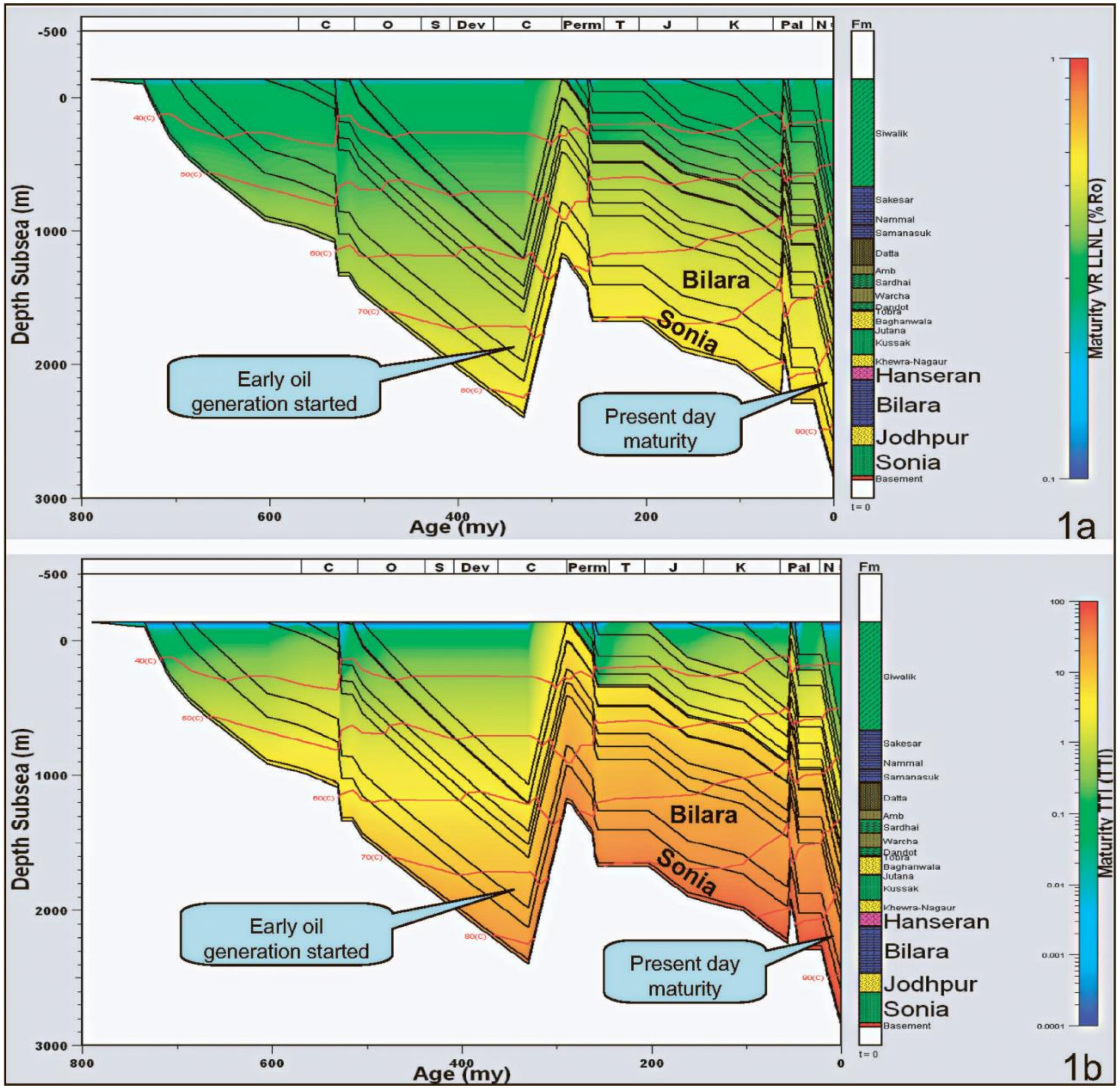


Figure 15 (1a-b). Burial and thermal history of Bahawalpur East-1 well VR values suggest that Bilara Formation reached early oil generation window at 341 Ma (Carboniferous). Present day calculated maturity is 0.55 Ro% TTI values suggest that Bilara Formation reached into early oil generation window at 337 Ma (Carboniferous). Present day calculated TTI is 35.

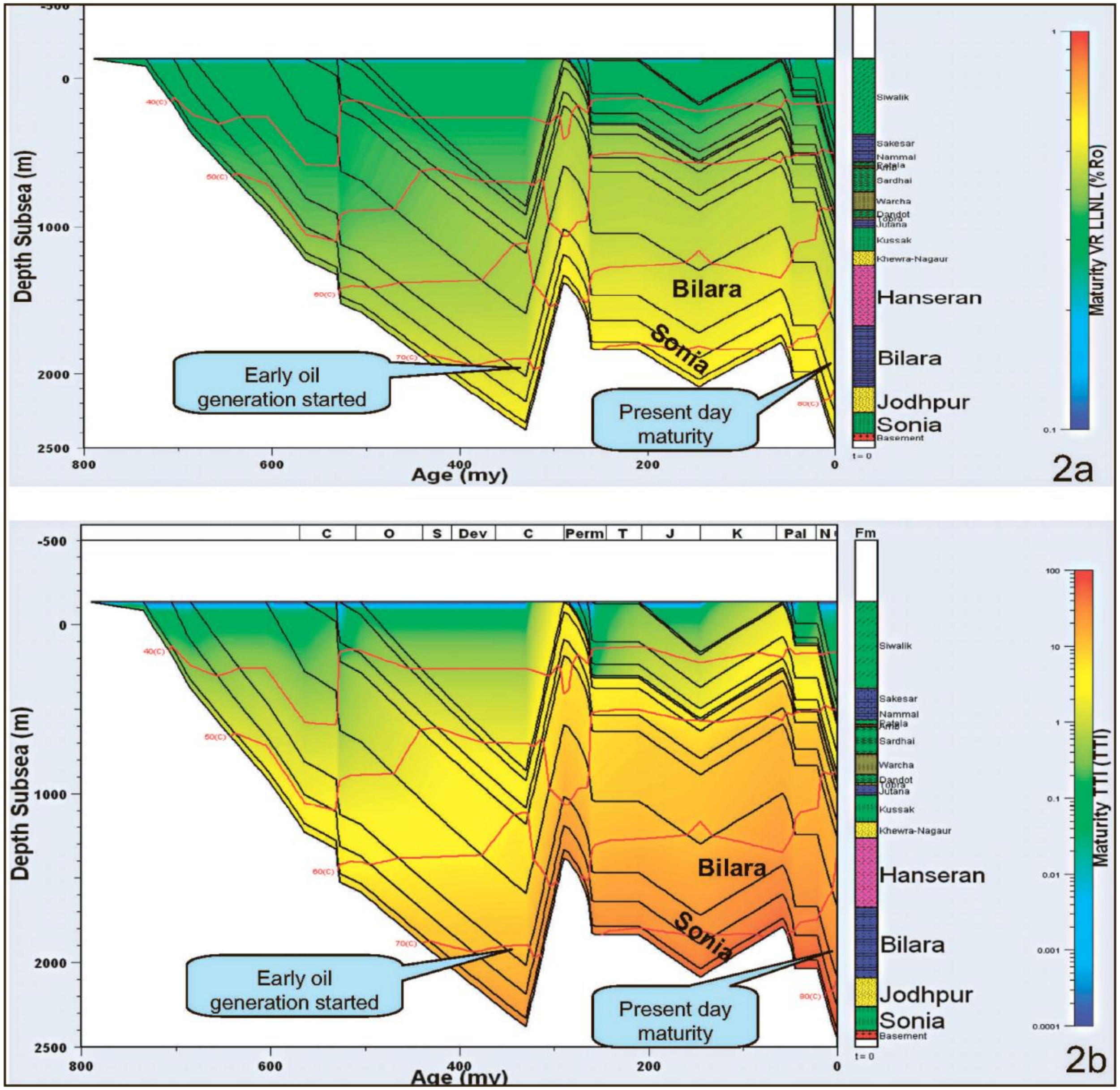


Figure 15 (2a-b). Burial and thermal history of Marot-1 well VR values suggests that Bilara Formation reached early oil generation window at 330 Ma (Carboniferous). Present day calculated maturity is 0.56 Ro% TTI values suggest that Bilara Formation reached into early oil generation window at 335 Ma (Carboniferous). Present day calculated TTI is 32.

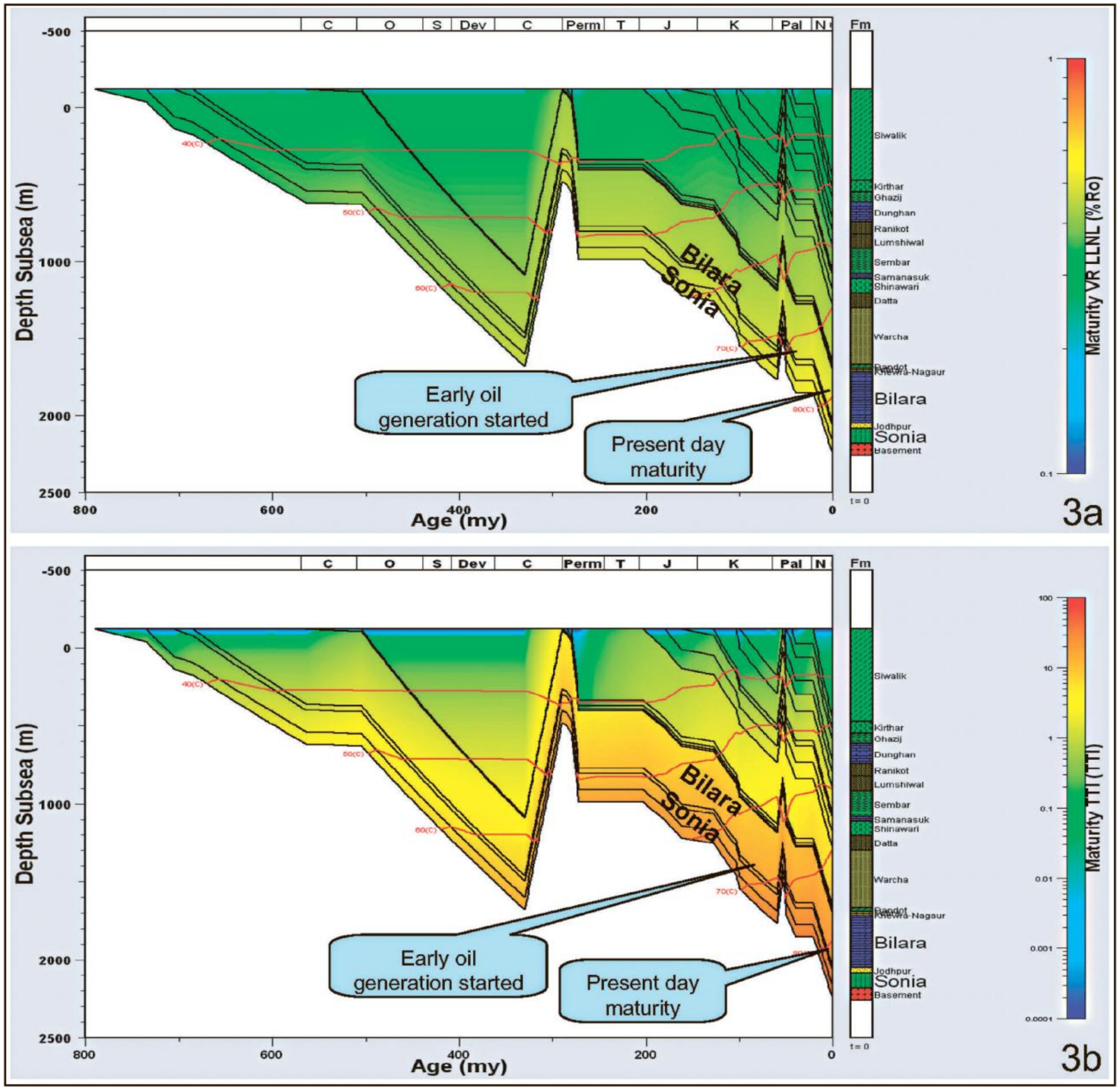


Figure 15 (3a-b). Burial and thermal history of Suji-1 well VR values suggests that Bilara Formation reached early oil generation window at 30 Ma (Oilgocine). Present day calculated maturity is 0.6 Ro% TTI values suggest that Bilara Formation reached into early oil generation window at 82 Ma (Late Cretaceous). Present day calculated TTI is 20.

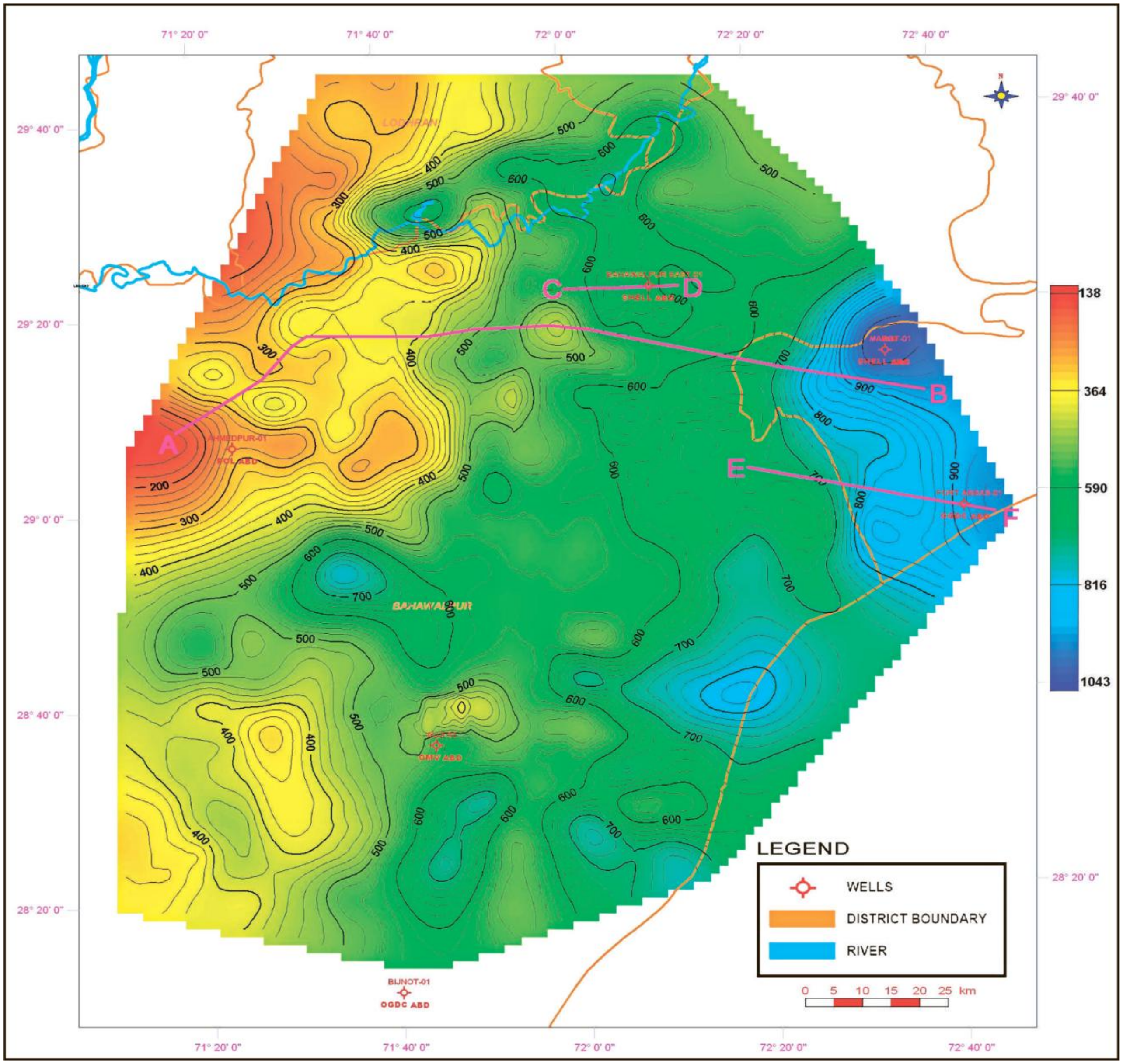


Figure 16. Paleo-depth Structure Map at Top Basement level (Infracambrian time) with reference datum at paleo mean sea level, showing the topography of basement at the time of deposition of Infracambrian. The paleo-lows represent the areas where Infracambrian sediments might have attained higher temperature condition before basin inversion.

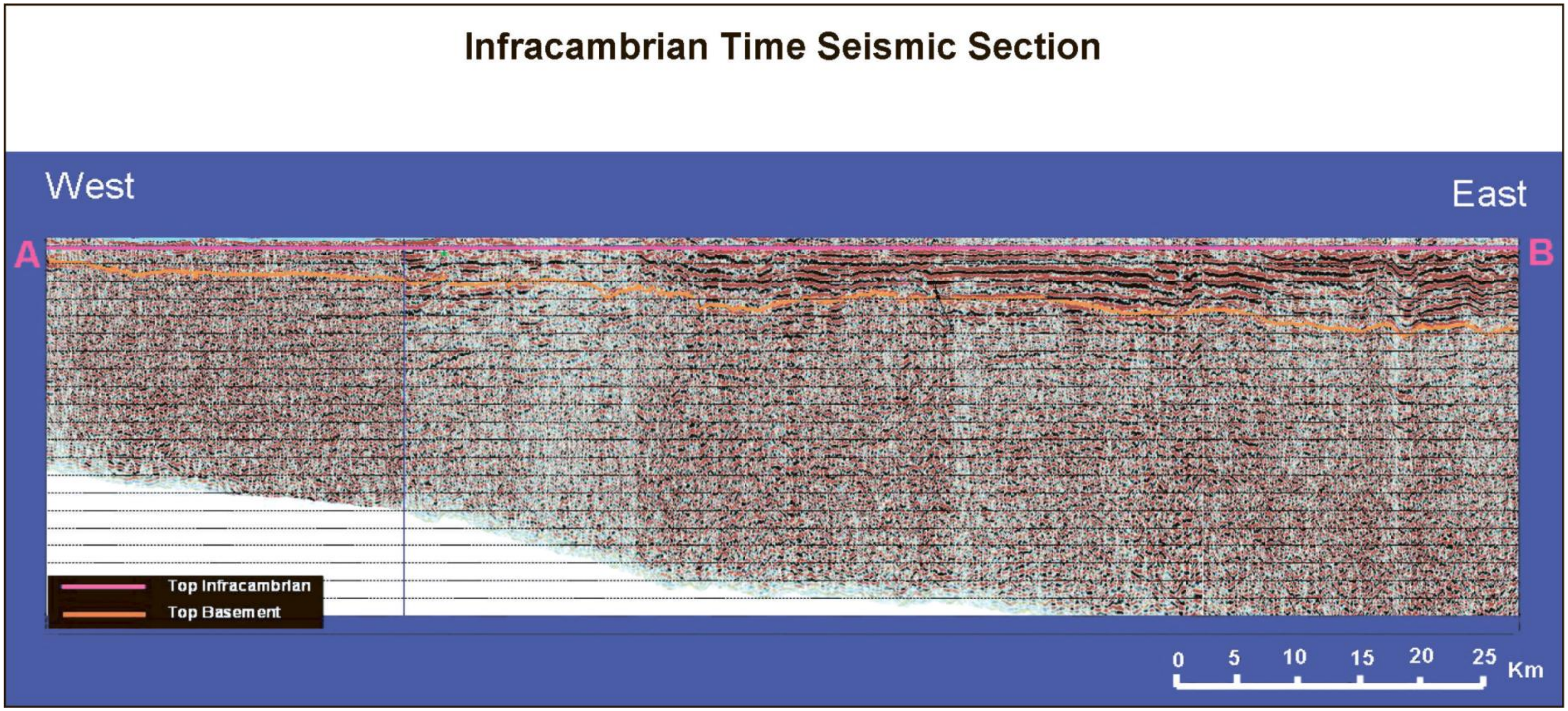


Figure 17. Infracambrian paleo time seismic section showing eastward dipping basement. The Infracambrian deposition likely to be taken place from west to east (for location of the seismic line see Figure 10).

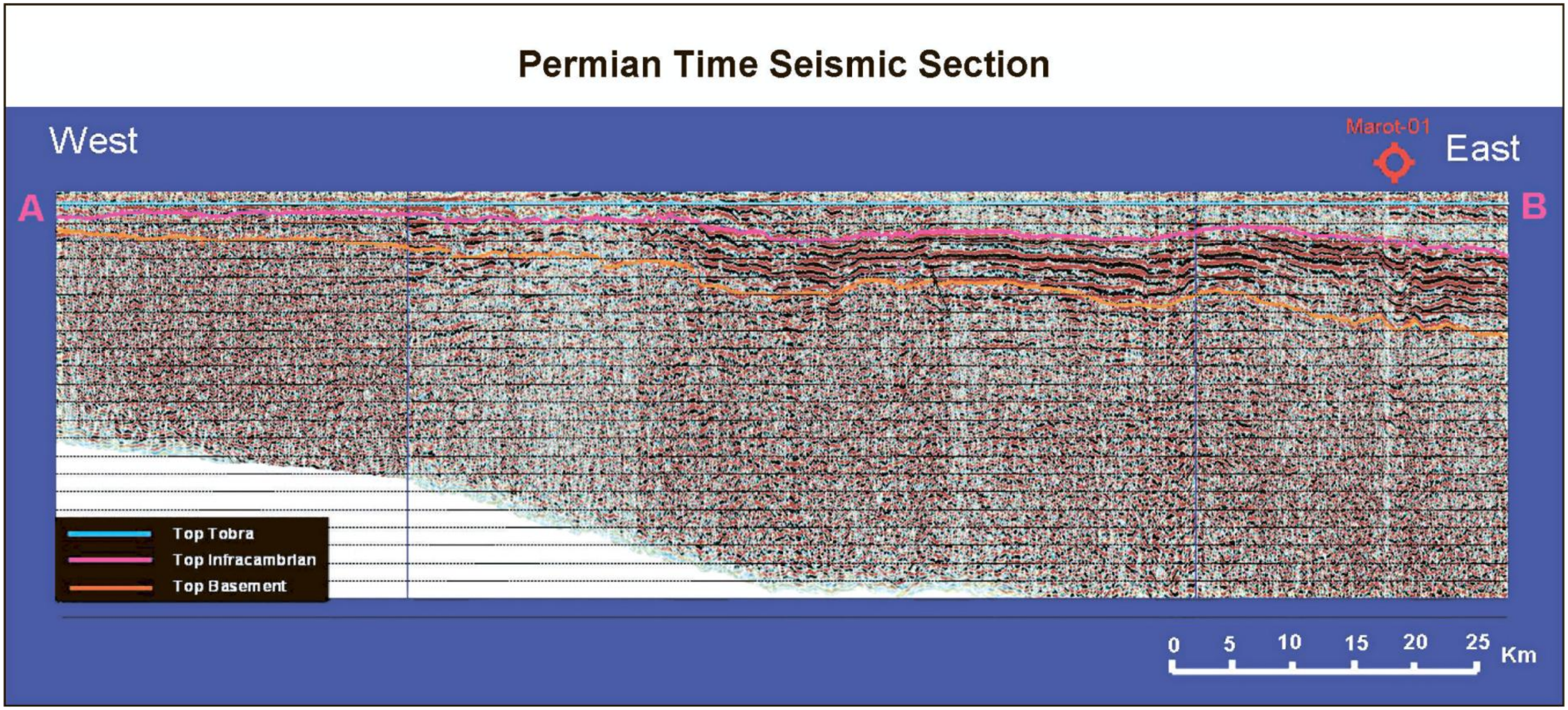


Figure 18. The depositional direction from west to east continues until Permian. The deeper burial of eastern part of Infracambrian is obvious. There was no structure at Marot-01 location until deposition of Permian sequence (for location of the seismic line see Figure 10).

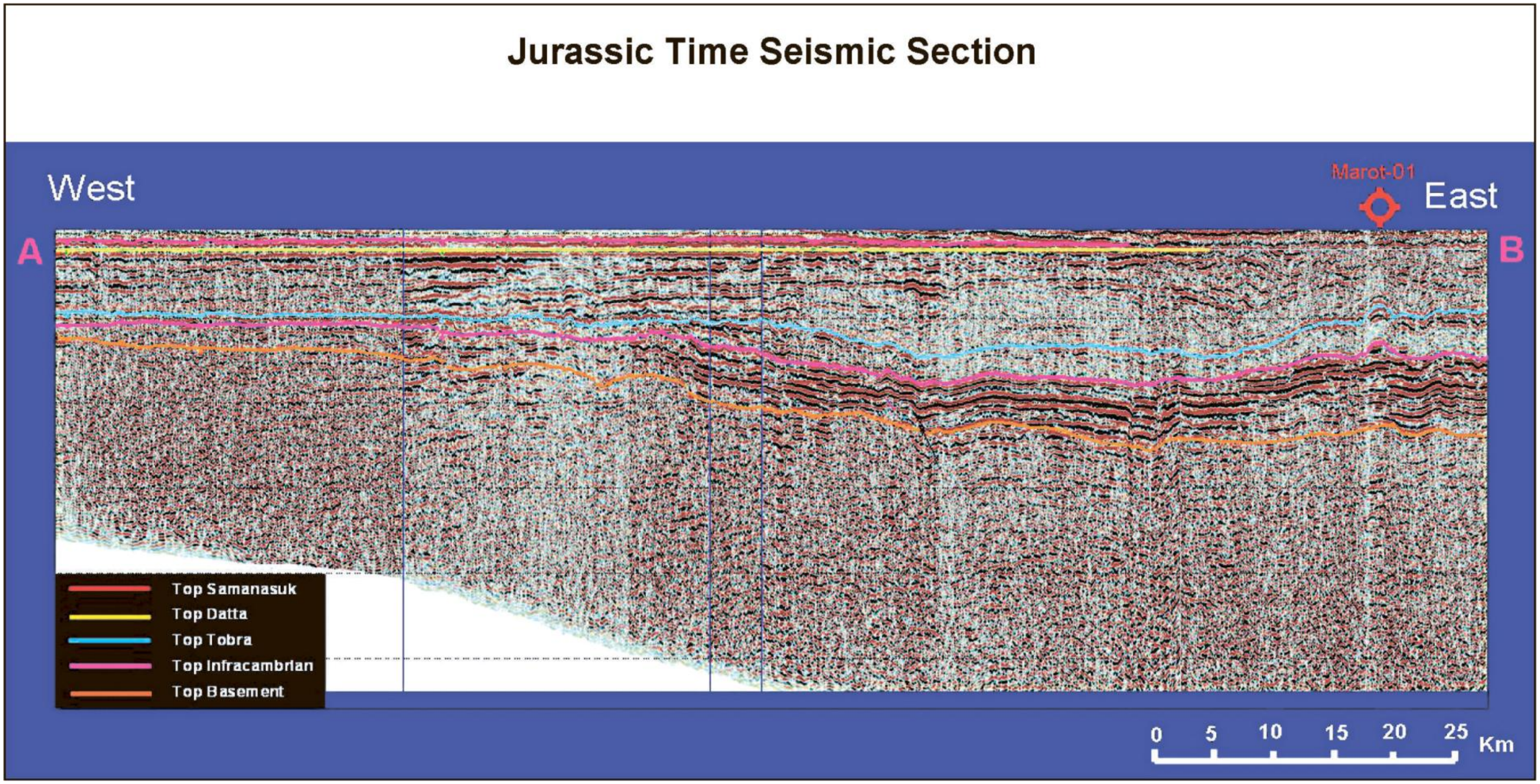


Figure 19. Depositional direction from west to east continues until Jurassic. The significant burial of eastern side of Infracambrian. The Marot-01 structure developed in Jurassic time due to a salt plug (for location of the seismic line see Figure 10).

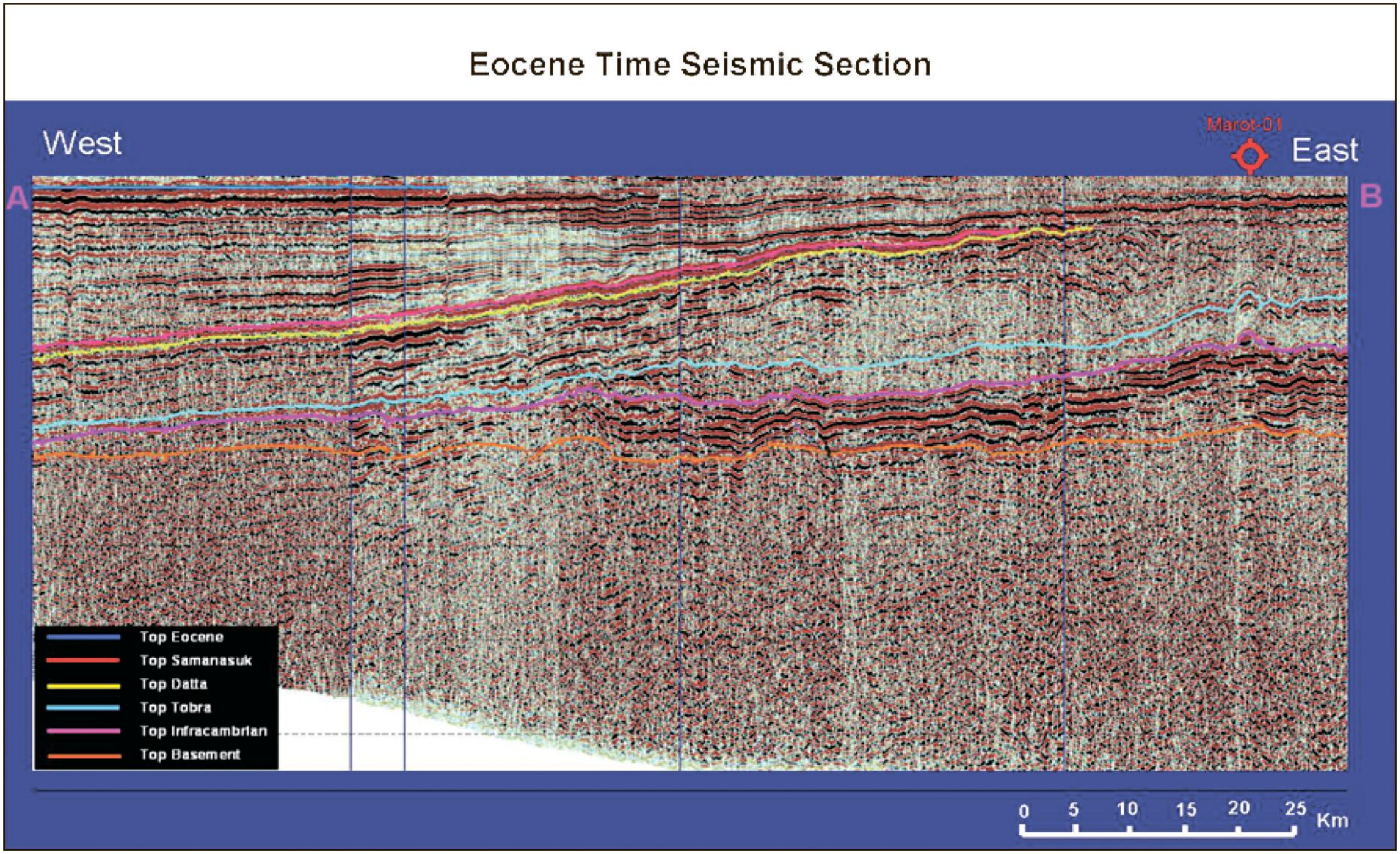


Figure 20. Reversal in depositional direction after deposition of Jurassic sediments due to uplifting of eastern side of platform. Samanasuk and Datta formations truncate before Marot-01 well (for location of the seismic line see Figure 10).