

# **Identification of New Potential Source and Reservoir Rock of Early Jurassic Age, supported with Basin Modeling and discussion of Exploration Constraints in the Northern Kirthar Range, Pakistan\***

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Search and Discovery Article #30262 (2012)\*\*

Posted December 31, 2012

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

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## **Abstract**

The Northern Kirthar Range (NKR) is located in the Sindh and Balochistan provinces between latitudes 27°30' N and 30°00' N, covering hilly and mountainous areas up to the ophiolite belt to the west and the Kirthar Foredeep to the east ([Figure 1](#)). This area is represented by a north-south trending fold belt that has been the site for active petroleum searches for more than 150 years. Discovery of commercial gas from Paleogene (Eocene and Paleocene carbonates) to Mesozoic aged reservoirs (Cretaceous sandstone and Jurassic carbonates) proved the adequacy of the petroleum habitat, which offers new exploration opportunities.

In this article we discuss results of the outcrop samples, which suggest for the first time the existence of new potential reservoir and source rock within the Early Jurassic which have never been considered as potential targets in earlier exploration efforts. Reservoir potential has been identified in the massive fine-grained sandstone of the Spingwar Formation of Jurassic age, having porosity and permeability of up to 24% and 329 mD, respectively.

Samples from thick black shales of the Anjira Formation, although collected in highly weathered surface conditions in which large volume of in-situ Total Organic Carbon (TOC) tends to be biodegraded, showed TOC of up to 0.7%. Vitrinite reflectance data, varying from 1.1 to 2.2%, suggests that the source rock falls in the oil to gas window.

The Spingwar Formation can be explored at shallow depths (~1500-2400 m) in uplifted areas in the interior of the Kirthar Range. In the Kirthar Foredeep (eastern Balochistan and western Sindh) the depth of the Spingwar Formation is estimated to be greater than 5000 m. This reservoir is likely to be charged by the Anjira black shales and other source rocks of Mesozoic age. Results of 1D basin modeling acquired

through Basin Mod 1DTM of a pseudo well at the Shutrak Anticline suggests that the Anjira Formation reached the early oil maturation window in Late Cretaceous (Cenomanian 100 Ma), middle oil maturity in Paleocene (Thanetian 52 Ma), and the main gas window in Eocene (Lutetian- Bartonian 42 Ma) time. Basin modeling results of the Jhal-1 well (Kirthar Foredeep) and the Shutrak Anticline (east of Khuzdar) have been included in this article.

The rugged and mountainous Kirthar Range offers immense challenges to successfully complete the geological and geophysical surveys. Despite these difficulties, geological survey and 2D reflection seismic programs can be effectively accomplished if the methodology is optimized to the physiography of the area and the depth of the reservoirs. Operational and interpretational constraints of the G&G and methodology to mitigate interpretation problems are also presented in this paper.

## **Introduction**

A successful petroleum exploration campaign needs careful and balanced planning by considering the physiography of the area, depth of the objective reservoirs and the exploration economics. Rugged and difficult terrain increases the exploration cost and the risk of poor data quality is higher.

The Kirthar Fold and Thrust Belt poses exploration challenges of varying nature. Most of the area consists of 500 to 3000 m high hills and mountains with local elevation varying between 300 to 1500 m above sea level. The mountainous area is scarcely populated with very limited infrastructure, mostly without roads and few dirt tracks which can only be used in dry seasons. Electricity is only available to the villages located in proximity to highways and roads or located in the plain areas.

There are several perennial streams which burst into high flash floods during monsoon and winter rains. The general population of the entire NKR is friendly, polite, hospitable and extends full support during exploration campaigns. However, few areas are security sensitive, especially in the northern and southern part of the NKR where local tribes may offer resistance.

Dense and massive limestone forms, mostly, the crests of the ridges. Due to severe folding and thrust faulting, surface dips are usually high and valleys are deep, narrow and mainly consist of boulders and detritus of limestone and sandstone.

## **Tectonic and Structural Setting**

As stated above, NKR falls between latitudes 27°30' N and 30°00' N, covering mountainous areas up to the ophiolite belt to the west and the Kirthar Foredeep to the east ([Figure 1](#)). The stratigraphic sequence in this area consists of Jurassic to Recent sedimentary rocks ([Figure 2](#)). Rocks have been deposited in varying sea level conditions, marine to continental environments, highlighting the dynamic tectonics having a strong impact on the sedimentation history. NKR is a north-south trending fold belt which is the continuation of the Kirthar sub-basin.

The abrupt and outstanding elevation of the Kirthar Range from the plains of the Kirthar Foredeep is probably related to a major thrust fault which is visible on the seismic data ([Figure 3](#) and [Figure 11c](#)). The estimated throw of the major thrust fault is 3 to 4 km west of Bannh-1 well near Sanni area in Balochistan ([Figure 1](#)). Based on a variety of structural and tectonic styles, NKR may be subdivided into three smaller zones, namely Kalat Anticlinorium, Kalat Plateau and Khuzdar Knot (Kazmi and Jan, 1997).

The Kalat Anticlinorium is composed mainly of thick to massive Jurassic limestone on NNE trending doubly plunging anticlinal hilly ranges. These hills are divided by broad synclines which are covered by alluvium and underlain by Cretaceous and Paleogene sediments. These anticlines are broad, with relatively steep limbs and smoother crests with several small reverse and normal faults offsetting these folds.

Kalat Plateau is located south of Kalat anticlinorium. It is apparently a large graben or depression filled with Eocene limestone. Numerous reverse and strike-slip faults can be observed.

Khuzdar Knot, with an area of about 3000 sq km, is composed mainly of irregular shaped intensely deformed geological features. The intensity of the deformation decreases southeastward. Thick to massive limestone of Jurassic age with varying orientation of tightly folded anticlinal hills are separated by narrow, irregularly shaped small valleys. It is apparently a large horst block developed during a rift phase and reactivated during compressional tectonics. The general structural trend near the Khuzdar Knot area is N-S, NNE or NNW, whereas within Knot no particular trend can be observed. This geometry of a highly disturbed zone probably resulted due to combined effects of salt, postulated to be present over the basement, and the compressional-transpressional tectonic.

The area has been influenced by the tectonic events as a result of separation of the Indian Plate from the African Plate during the Jurassic and northward movement with anticlockwise rotation and collision with the Eurasian Plate in the north during Tertiary. Rifting formed horsts and grabens on the western margin of Indo-Pakistan Plate.

### **Petroleum Traps**

Anticipated traps are preferred hydrocarbon exploration targets in NKR. As discussed earlier, these anticlines trend N-S, NNE-SSW, and NNW-SSE and are often bounded by the reverse or thrust faults to the eastern and western limbs. The cross section in [Figure 3](#) illustrates the general east to west structural trend of the area. Thick Tertiary sediments under the alluvium cover are present in the Kirthar Foredeep area. Foredeep and the Kirthar Range may have been demarcated by a major hinterland verging thrust fault which uplifted the Kirthar Range. The possible explanation for the exposure of the Cretaceous to Jurassic sediments in the central part of the NKR, as shown in [Figure 3](#), is incessant movement along the major and associated minor faults and subsequent erosion of the cores of the anticlines. Basement, at places, is understood to be involved in the faulting, especially in areas where Mesozoic rocks crop out. The effect of erosion is more severe in the anticlines located interior of the Kirthar Range and therefore affecting the petroleum prospectivity of the area.

Discovery of commercial gas fields in and around the eastern part of NKR (Zarghun South, Mehar, Ziarat, Mazarani and Jhal Magsi South), and oil seepages at Gokurt and Sanni proves the presence of active petroleum systems.

### **Anjira Formation (Early-Middle Jurassic) Source Rock**

#### **Outcrop Location**

The rocks of the Anjira Formation are exposed at various locations in the Northern Kirthar Range. The maximum thickness of this unit is 455 m at Firozabad, west of Khuzdar City (Fatimi, et al., 1986; Hunting Survey Corporation, 1961; Pakistan Petroleum Limited, 2005). The rocks of this formation form low relief hills. The formation is divisible into a lower shale unit and an upper interbedded limestone and shale unit. The lower shale unit is exposed around the Shutrak Anticline, 40 km east of Khuzdar and is identifiable by its smooth and dark tone on the wide scarp faces ([Figure 4](#) and [Figure 5](#)).

#### **Lithological Description**

The shale is gray, bluish gray, black and rusty brown, soft and fissile with yellow encrustations and sulfurous odour. The lower shale unit is 77 to 108 m thick. The thin lower shale unit is not identifiable at the Firozabad section in the western part.

The upper interbedded limestone and shale unit is gray, bluish gray to dark gray, black limestone which is comparatively softer, argillaceous and fine-textured and breaks into pencil-like structures. The golden yellow weathering colour makes it prominent. The limestone contains ammonites which are mostly confined to the base of the limestone beds. The shale is gray to dark gray, olive gray, earthy, soft and fissile and at some places grades into marl. The lower contact of the Anjira with the Loralai Formation is sharp to transitional and marked by a change from carbonates to clastics (shale). The Anjira Formation unconformably underlies the Sembar Formation of Cretaceous age.

#### **Source Potential**

During geological field survey of the area, the authors collected Anjira and Goru formation samples from Firozabad (west of Khuzdar), Goru Village and from two other locations at Shutrak Anticline, east of Khuzdar ([Figure 4](#) and [Figure 5](#)). The Anjira Formation samples collected for this study are known from locations where the formation is exposed. Samples were sent to the laboratory for determining Total Organic Carbon Content (TOC). After initial TOC screening samples were sent for Rock- Eval and Vitrinite Reflectance, the Rock-Eval data was found to be inconclusive.

The black shales of Anjira Formation have TOC ranging from 0.09 to 0.75%, whereas Vitrinite Reflectance (VR) values are up to 2.21 (Pakistan Petroleum Limited, 2005).

Vitrinite Reflectance (VR) is used to determine thermal maturity of sediments. VR values vary from 1.0 to 2.21 which demonstrate that maturation varies from the oil to the gas window. However, due to weathering, the original organic matter may have been greatly reduced. Field studies of black shale weathering profiles in the USA carried out by Petsch et al. (2000 and 2001) indicated a 60-100% TOC loss in highly weathered samples relative to initial, un-weathered samples (Luning et al., 2003). If a similar weathering ratio persists in the outcrops of NKR, estimated restored un-weathered TOC would be more than 2.50% (average 70% loss due to weathering). [Figure 6a](#) and [Figure 6b](#) are maps of the Kirthar Range showing isomaturity contours of the Goru and Anjira formations based on VR data. Both maps suggest that maturity increases westward. The closely related maturity trend of Anjira and Goru implies that the basin has a normal thermal history with no evidence of the presence of abnormal hot spots.

### **Spingwar Formation (Early Jurassic) Reservoir Rock**

#### **Location of the Outcrop**

Spingwar Formation is only exposed in Firozabad section in the NKR ([Figure 4](#) and [Figure 7](#)).

#### **Lithological Description**

Measured thickness in the Firozabad section is more than 209 m. Net sandstone is about 71 m in 7 beds varying in thickness from 3.5 to 13.2 m. In Jhat Pat-1 exploratory well, the Spingwar Formation is reported to be 419 m thick with hydrocarbon shows observed during drilling. This well, located 170 km northeast of Khuzdar, was drilled to a total depth of 4664 m in the Triassic by AMOCO in 1974.

The Spingwar Formation, the lowermost and oldest formation of the Firozabad Group of Jurassic age, is composed mainly of mixed carbonate and clastic lithology deposited in an inner shelf to shore-face environment. The oldest beds consist of flaggy, gray, brown micritic limestone, unfossiliferous, followed by sandy limestone, calcareous sandstone, quartzose sandstone with poorly preserved Mollusc shells, with subordinate shales and marls. The sandstone is coarse- to fine-grained, silty, highly calcareous, light gray to white in color. The coarse sandstone is cross bedded while the fine-grained sandstones are cross laminated.

The Spingwar Formation is overlain transitionally by the Loralai Formation consisting dominantly of thick to massive dark gray hard and dense limestone, while the lower contact is not exposed in the area (Fatimi et al., 1986; Pakistan Petroleum Limited, 2005). In the NKR, Spingwar Formation age equivalent sandstone is exposed having different names: Shrinablower part (Lukh Rud), Alozai Group (Near Fort Sandeman) and Winder Group (Bela Area) (Fatimi et al., 1986; Hunting Survey Corporation Ltd, 1961). The samples of Spingwar Formation were collected from the Firozabad section and after visual description sent to the laboratory for porosity and permeability determination.

## Reservoir Potential

The properties of the Spingwar Sandstone demonstrate a favorable reservoir potential. The porosity in Spingwar Formation varies from 10 to 24%, with 32 to 329 mD vertical and up to 49 mD horizontal permeability. [Figure 8](#) shows microphotographs of Spingwar Sandstone thin sections. The interconnected pores between the sand grains (blue epoxy) is quite obvious. The most appropriate location in the NKR for Jurassic Petroleum System is in the core of the structures where Tertiary to Cretaceous rocks crop out. In such structures the Spingwar Sandstone is expected to be at shallow depth (~1500-2500 m) especially in uplifted areas inside the Kirthar Range. However, the estimated depth of Spingwar in the Kirthar Foredeep is estimated to be more than 5 km.

The top of Spingwar was encountered at 3371 m in the Jhatpat-1 well. There are only three wells in the Middle and Lower Indus Basin, namely, Nabisar-1 (TD 3054 m in Triassic), Jhat Pat-1 (4664 m in Triassic) and Shadani- 1 (TD 3601 m in Lower Jurassic) that have been drilled down to Triassic through Jurassic rocks. Information about the reservoir potential in these wells is not available to the authors. All these wells are more than 500 km away from the Spingwar Formation outcrop section discussed in this article, making correlation inappropriate.

## Thermal and Burial History Reconstruction through Basin Modeling

The Jhal-1 well data and measured section of Shutrak Anticline (pseudo well) were used for the reconstruction of thermal and burial history. Jhal-1 is located in the eastern part of Kirthar foredeep in the NKR, whereas Shutrak Anticline is 40 km east of Khuzdar inside the fold belt ([Figure 1](#))

The basin modeling plots are given in [Figure 9](#) and [Figure 10](#). The assumptions for the basin modeling are as follows (Gretener, 1981; Lucazeau and Le Douaran, 1984; Von Herzen and Helwig, 1984):

- Heat flow from Triassic to Present 45 mW/m<sup>2</sup>.
- Surface temperature 25° C.
- Present elevation 1600 m from mean sea level.
- Estimated geothermal gradient 35 to 50°/km.
- Sedimentation from Triassic to Quaternary, with two episodes of uplifting: (1) Late Jurassic to Early Cretaceous as evidenced in Shutrak anticline, and (2) Middle Eocene to Oligocene as evidenced in Jhal-1.

- Final uplifting and present structuration; from 2 to 0.5 Ma in Quaternary.
- VR data calibration; VR 1.01 to 2.24; average 1.3.

### **Results and Interpretation**

The burial and thermal history of the Anjira Formation at the pseudo well at Shutrak Anticline suggests that the potential source rock reached the early oil maturation window at 100 Ma (Cenomanian), mid oil maturation window at 52 Ma (Thanetian). Presently it is in the late oil maturation window, since 42 Ma (Lutetian - Bartonian). The Anjira Formation was buried to a maximum depth of 3800 m below mean sea level at which it is expected to have experienced a maximum temperature of around 150° C prior to the recent uplift.

These results are in close conformity with our outcrop regional VR data ([Figure 6b](#)). The VR data vary between 1.0 to 1.3. However, higher VR measurements were observed at the Sumbaji (eastern flank of the Shutrak Anticline) which is possibly related to the section being in closer proximity of a deep fault, ensuing elevated temperature.

The Jhal-1 well, located at the foredeep, east of the NKR, was drilled to the Goru Formation ([Figure 1](#)). However, the Goru Formation presently falls in the late oil maturation window suggesting that Anjira in the foredeep, despite excessive depth, would possibly be within the late gas maturation window as well in the Kirthar foredeep area, considering that normally maturity increases with depth due to increasing temperature.

### **Exploration Constraints in Northern Kirthar Range**

#### **Geological and Geophysical Operational Constraint**

The movement of geophysical equipment such as receiver accessories and energy source (vibrators and drilling rigs) to the top of the mountains and hills is very difficult, if not impossible, due to rough terrain. Therefore, pop shots are used as an energy source (Pakistan Petroleum Ltd, 2004). The pop shot is a shallow hole about 1 to 2 m deep where dynamite is placed and blasted for creating sound waves. Although this is the preferred source type in difficult mountainous areas, the energy penetration level is limited and the resultant data quality is usually difficult to interpret; ideally, 10 to 20 m deep shot holes would provide better results. In order to drill deeper holes at the desired location, access roads need to be constructed using heavy bulldozers, an expensive and difficult option in such rugged terrain.

The vibrators could also be used in the plains of the survey areas. However, plate coupling of vibrators, especially in the undulating surfaces, is another reason for poor energy penetration. The use of mixed sources, dynamite on mountains and vibrators in plains area, is the preferred option in such difficult conditions, and may produce better results than a single source.

## **Planning for Acquisition and Processing Parameters Selection**

### ***Acquisition***

Acquisition parameters' comparison chart used in the geophysical surveys carried out in the NKR in the vicinity of Mazarani Gas Field, Bannh-1 well (drilled by PPL in 1957 to a TD of 3962 m) and Dadhar Block is shown in [Table 1](#). The increasing number of folds and receiver points has enhanced the data quality, allowing better interpretation of complex sub-surface geology (Pakistan Petroleum Ltd, 1989; Pakistan Petroleum Ltd, 2004).

More emphasis should be given during the selection of the following parameters:

- 1) The maximum spread offset should be sufficient to control migration and diffraction produced by dipping horizon and folded sub-surface bedding (reflectors).
- 2) Increase number of folds to enhance signal-to-noise ratio.
- 3) Placement of dynamite source under weathered layer (if possible) by deep drilling on mountain areas and vibrators in plain areas (where possible) to enhance energy penetration.

In thrust and fold belts where more than one phase of tectonic events have taken place, subsurface and surface structural geometry may not necessarily be conformable and usually significant shifts have been experienced. Therefore, it is advisable to acquire gravity and magnetic data before planning a seismic survey. It will then be utilized for proper placement of seismic lines taking account of actual subsurface dip and strike direction.

### ***Processing***

The precision of picking the First Break and building of Static Model is most critical to overcome the effects of undulating surface and lateral velocity variation due to severe thrusting. Careful processing of the mixed source data and proper phase match can produce quality results.

After reviewing acquisition and processing parameters of 2001 and 2004 data of NKR, we conclude that any data less than 200-fold with routine processing techniques may not be able to image the subsurface geology properly at greater depth.



## ***Interpretation***

The most challenging aspect of seismic data interpretation in the NKR is identification of the key horizons. We have three control points: first the surface geology which includes thicknesses of important geological horizons and the fault's behavior, second, well data of Bannh-1 and Mazarani Field which helped to identify the subsurface horizons, and third, the typical seismic character of the limestone.

Identification below the Paleocene was not possible on seismic due to poor energy penetration, except in Mazarani where the Pab Formation was identified on the basis of well data ([Figure 11a](#)). However, we have confidently identified and interpreted dense and massive Laki (Eocene) and Dunghan (Paleocene) formations carbonates, underlying 1 km thick shales of Ghazij Formation respectively as the strong reflector with high amplitude ([Figure 11b](#) and [Figure 11c](#)).

Interpreted the Jurassic horizon has been identified by phantom thicknesses of the surface sections and isopach maps ([Figure 11b](#)), as data below Dunghan cannot be interpreted.

## **Conclusions**

In this article we have attempted to prove the presence of potential Early Jurassic source and reservoir rocks in the Anjira and Spingwar formations, respectively, which were not considered earlier in the NKR and adjacent areas. Anjira Formation is suggested to be in the mature oil to dry gas window in NKR and might still be in the active gas generating phase at places. Sandstone of the Spingwar Formation has good permeability. The reservoir depth may vary from 1800 m in the cores of the anticlines where Cretaceous rocks are exposed, and probably deeper than 5 km in the Kirthar Foredeep area.

The NKR is a difficult and rugged place for exploration, but through effective planning, exploration can successfully be undertaken. Interpretable seismic data may be acquired down to the Dunghan Formation, whereas data below Dunghan could not be properly imaged due to weak energy penetration particularly in areas where thick and massive limestone is exposed. However, to circumvent interpretational problems associated with horizons deeper than the Dungan level, we adopted an integrated approach by using outcrop sections and surface structural geology with seismic data.

## **Acknowledgements**

The authors gratefully acknowledge the management of Pakistan Petroleum Limited for the permission to present this article. We are also indebted to all our colleagues who prepared charts, figures and maps. We are also thankful to Dr. Syed Asif Ahsan for his time in reviewing the manuscript and providing useful suggestions to improve the contents.

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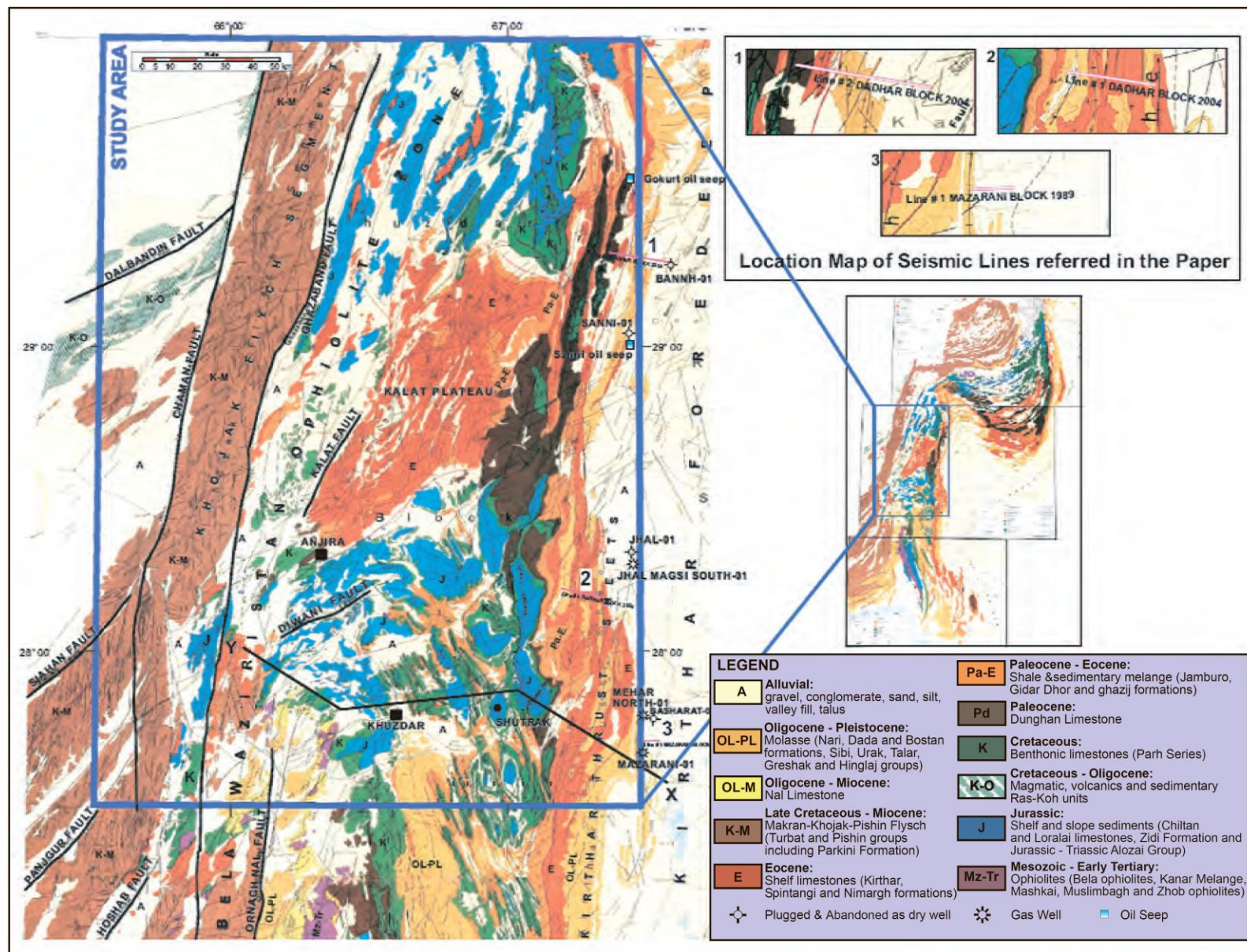


Figure 1. Generalized geologic map of Northern Kirthar Range showing rocks from Jurassic to Recent. Locations of X-Y structural cross section, seismic lines, Jhal-1 and Pseudo wells, and Shutrak Anticline are shown, which are discussed in this article (modified after Bannert et al., 1995).



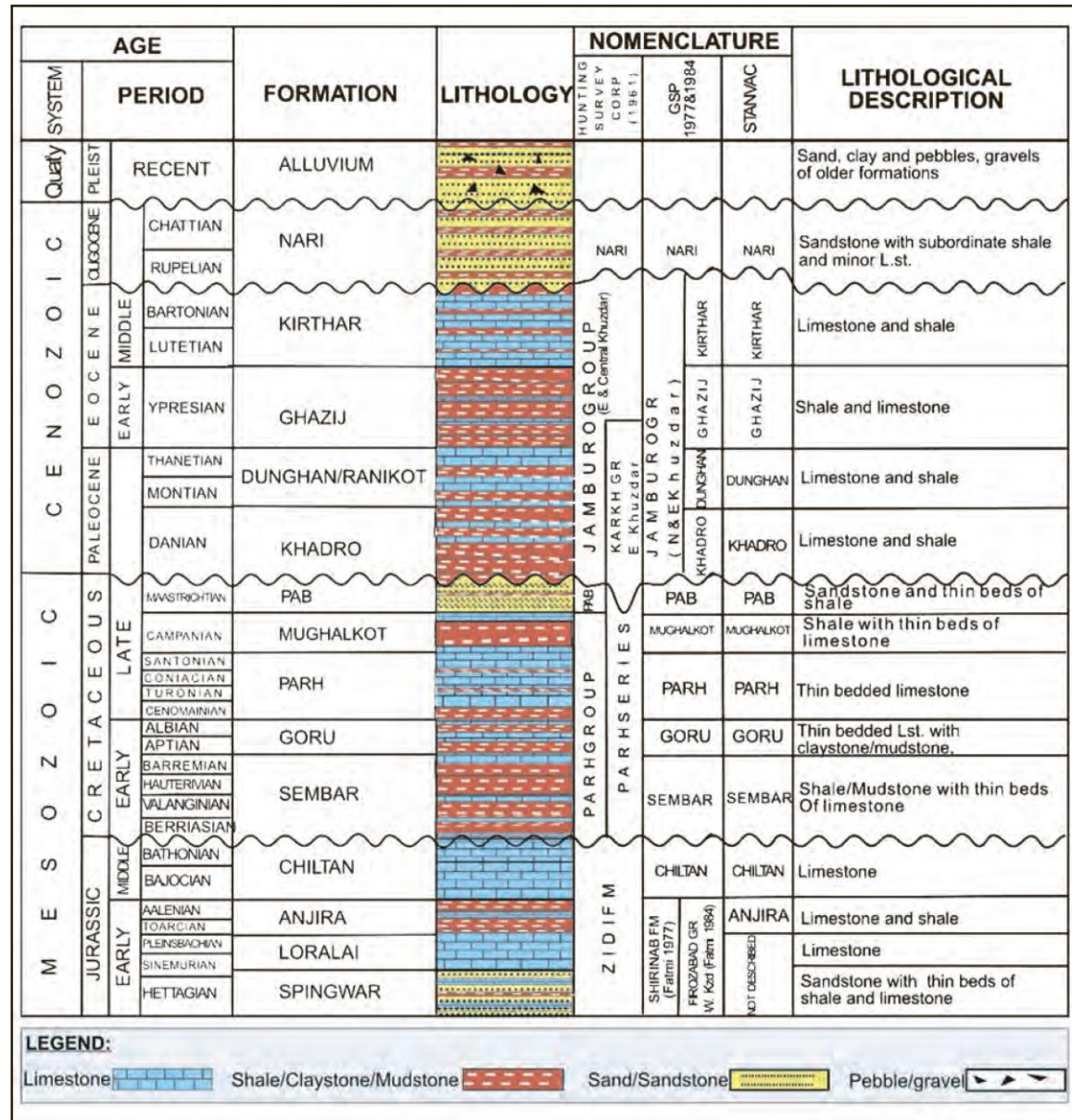


Figure 2. Generalized stratigraphic column of the Northern Kirthar Range (NKR). Stratigraphic nomenclatures as discussed in this article. Modified after Hunting Survey Corporation Ltd (1961), Shah (1977), and Fatimi et al. (1986).

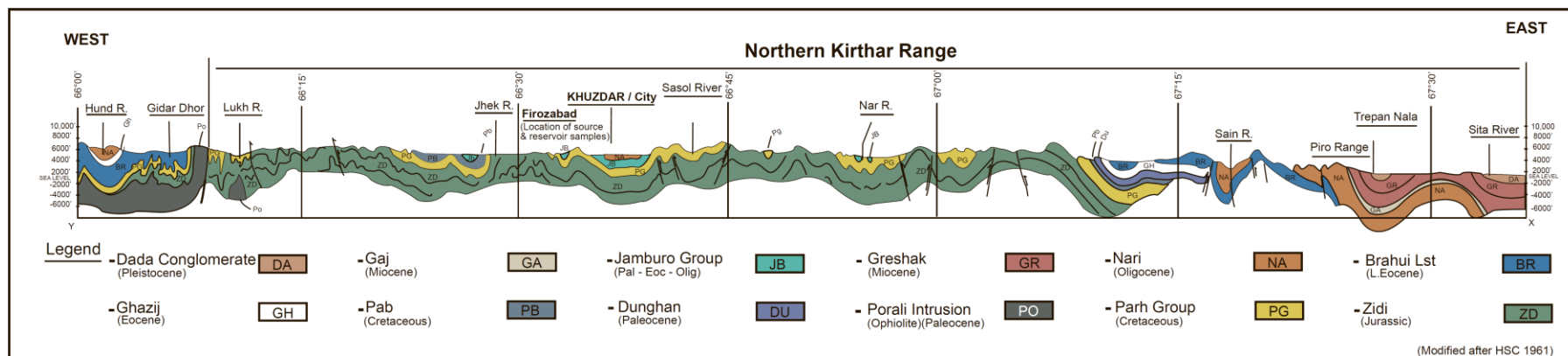


Figure 3. Generalized East-West cross section. To the east of the section, thick Tertiary sediments are present in foreland basin. Due to progressive uplifting and faulting over the basement highs, the Mesozoic is exposed in the eastern part of the NKR. Inside of NKR, Mesozoic rocks are present in the core of the anticlines, whereas the Tertiary crops out in the synclines (for location refer to [Figure 1](#)).

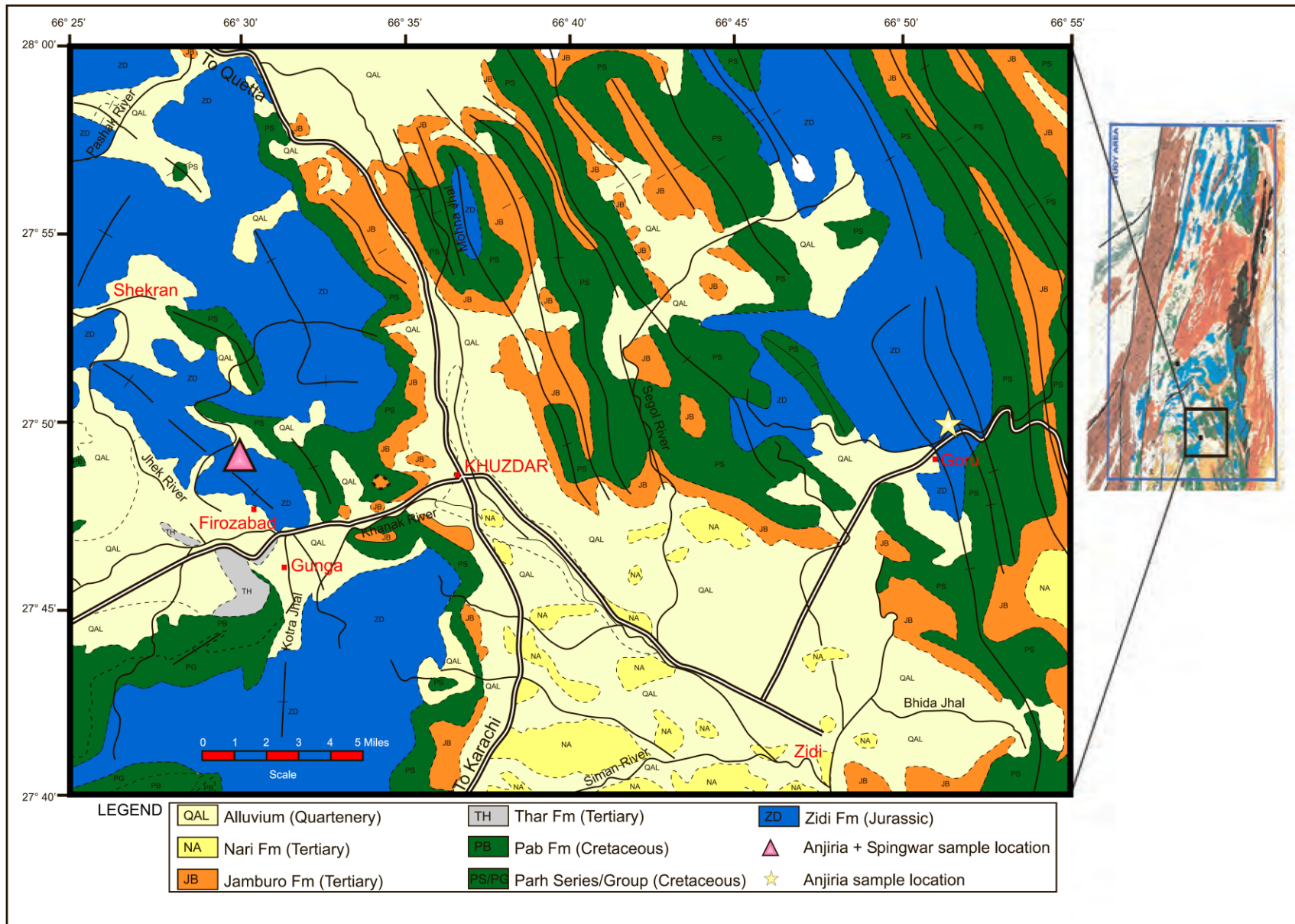


Figure 4. Generalized geological map of the Khuzdar area showing Jurassic to Recent rocks. Location of Firozabad Section is also given where Jurassic Spingwar samples were collected for petrographic and reservoir studies. Modified after Hunting Survey Corporation Ltd (1961), Khuzdar sheet No. 15 (35/I), and Fatimi et al. (1986).





Figure 5. Thin bedded limestone and black shales of Anjira Formation at eastern flank of Shutrak Anticline, 40 km east of Khuzdar City.



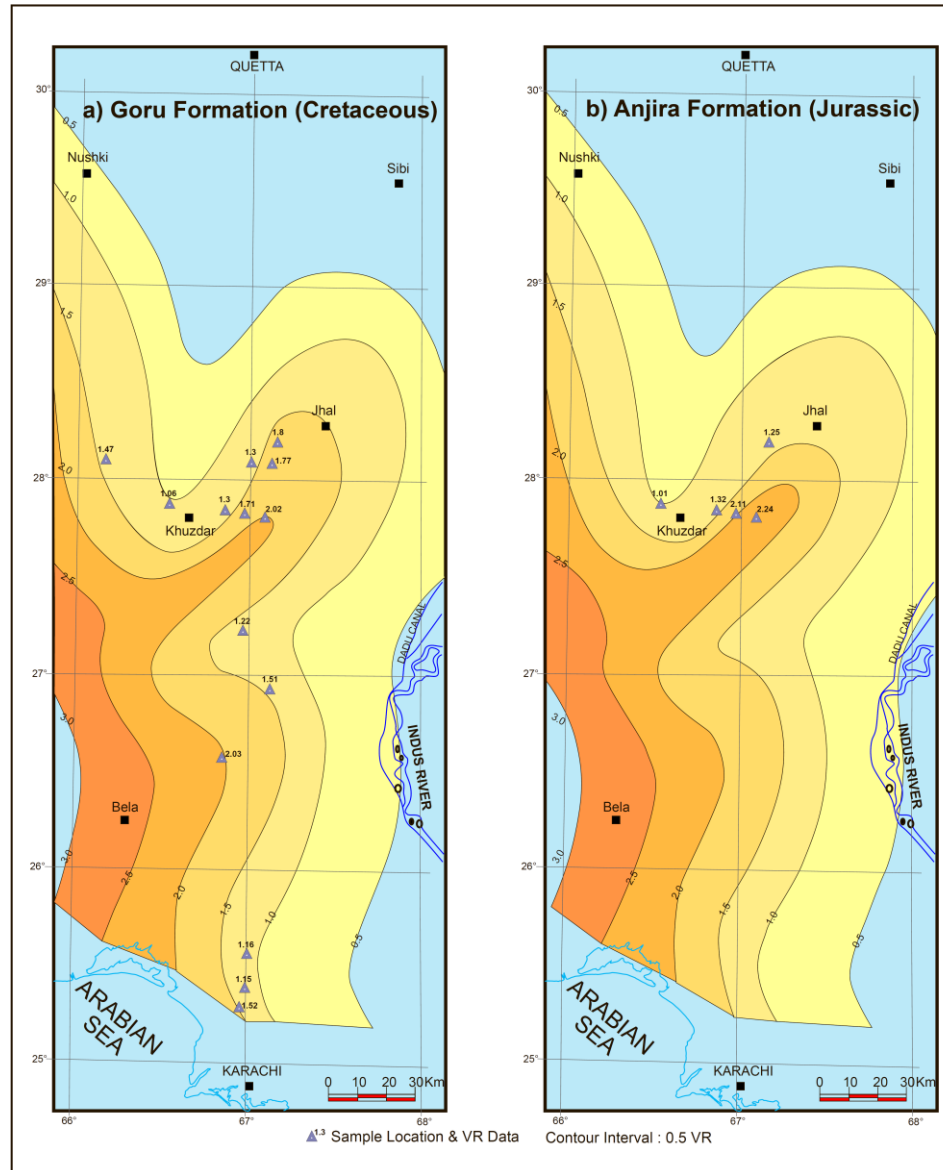


Figure 6. Maps showing thermal maturity data on Vitrinite Reflectance in (a) Goru (Cretaceous), and (b) Anjira (Jurassic) formations. Maturity is increasing from east to west in the Northern Kirthar Range (NKR). The slightly higher maturity trend near Khuzdar is probably due to the presence of a deep fault where maturity increases due to elevated temperature conditions. Similar trends may be inferred in other parts of NKR.

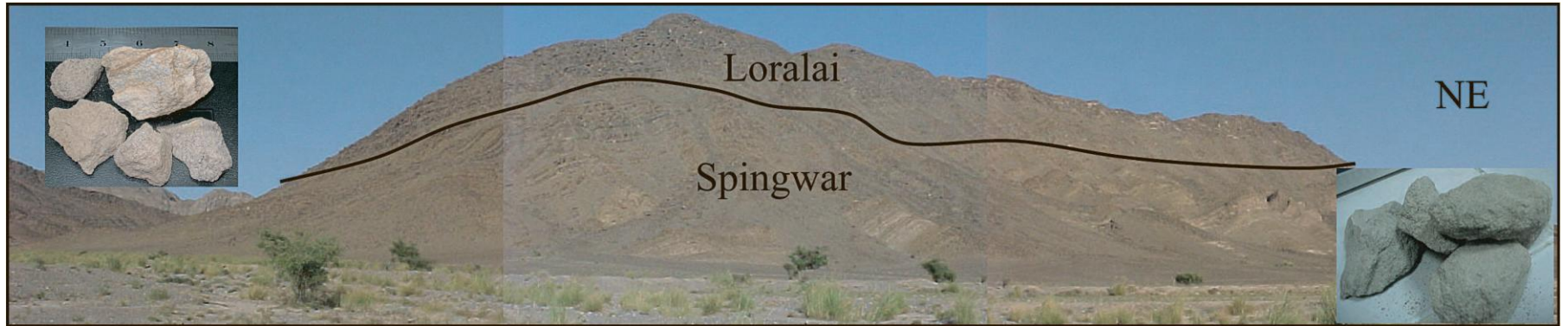


Figure 7. Outcrop photos showing contact between the Spingwar and Loralai formations at Firozabad Section. Insets are hand samples of Spingwar Sandstone from outcrop.

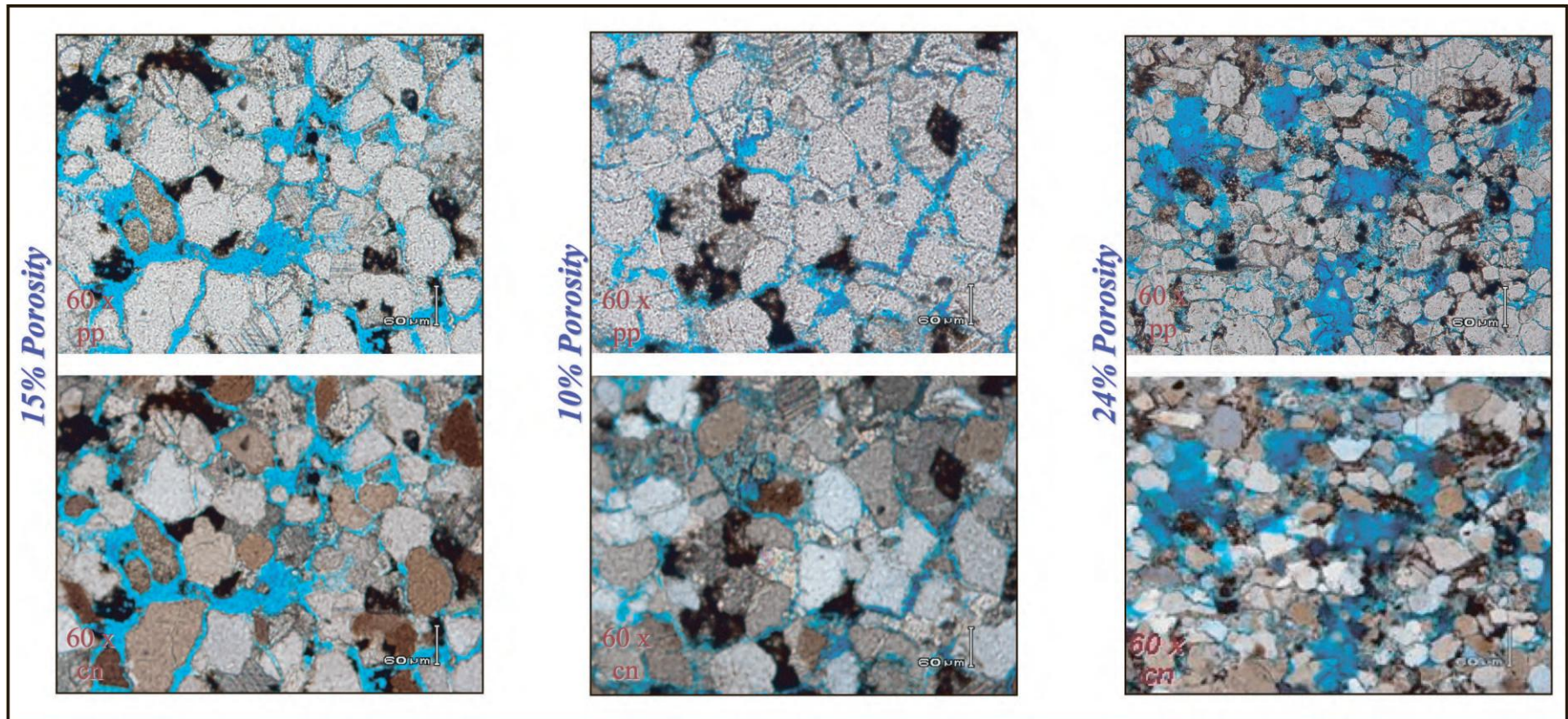


Figure 8. Thin section petrographic slides of Spingwar Formation samples collected from Firozabad Section (for location see [Figure 4](#)). This sand is fine-grained, generally moderately to well sorted, quartzose with calcite cement; blue epoxy resin in open pores shows porosity.



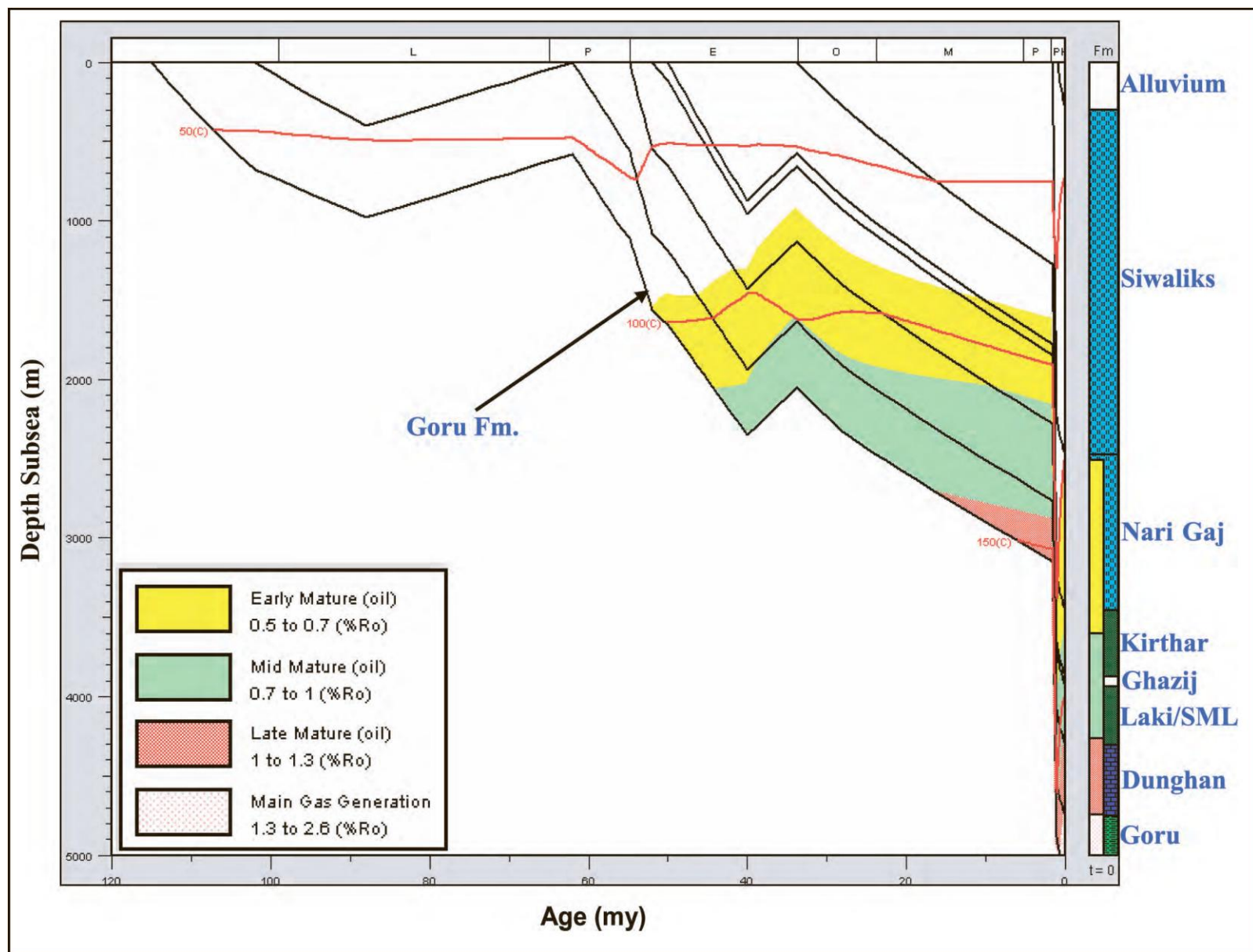


Figure 9a. Burial and thermal history of Jhal-1 well, located in the Kirthar Foredeep drilled into the Goru Formation to 5000 m. Early oil generation of Early Cretaceous age sediments attains maturation window in Ypression (50 Ma). Present day maturation level falls in the gas generation window.

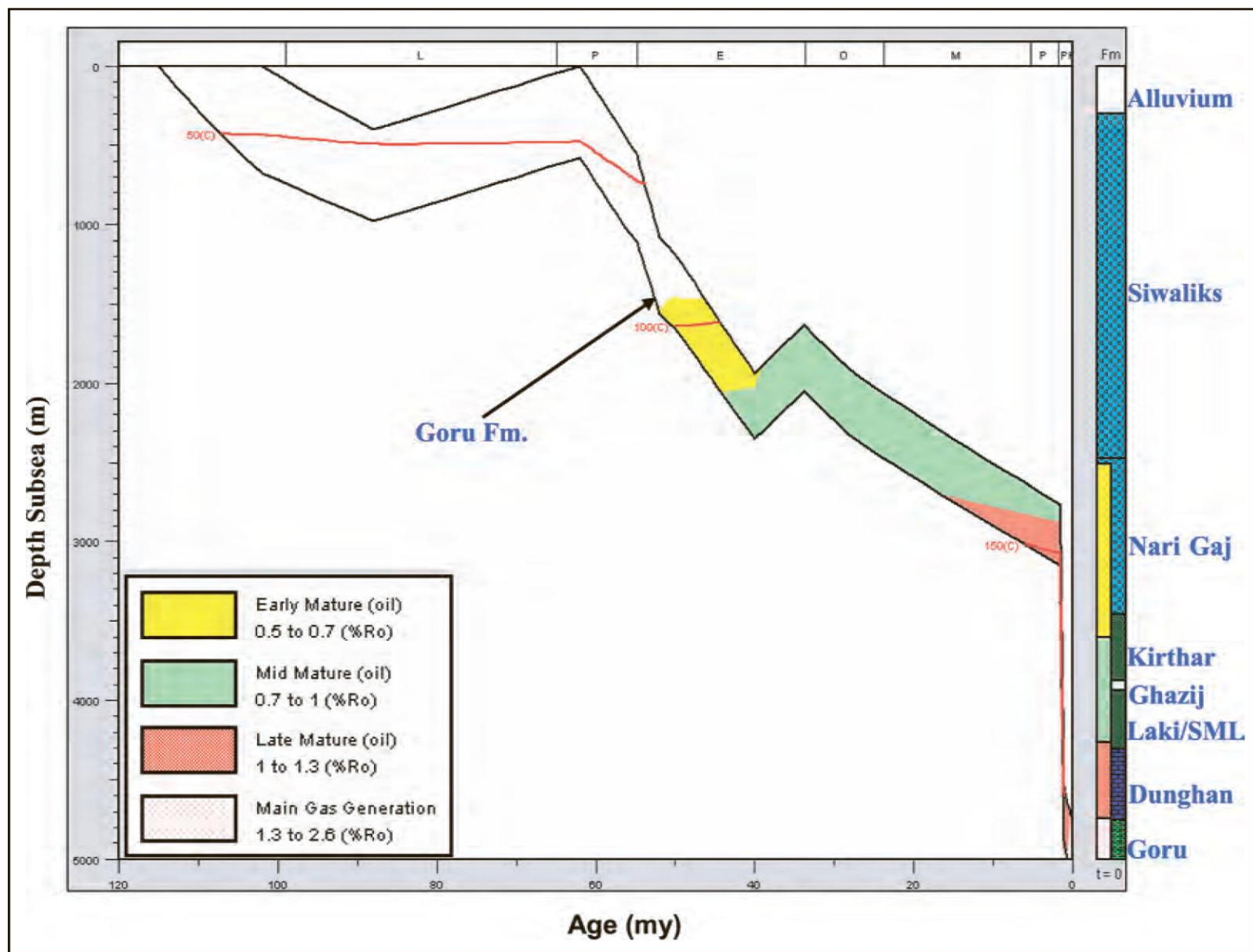


Figure 9b. Thermal and burial history of Goru Formation in Jhal-1 well. Present day maturity falls in the gas generation window.

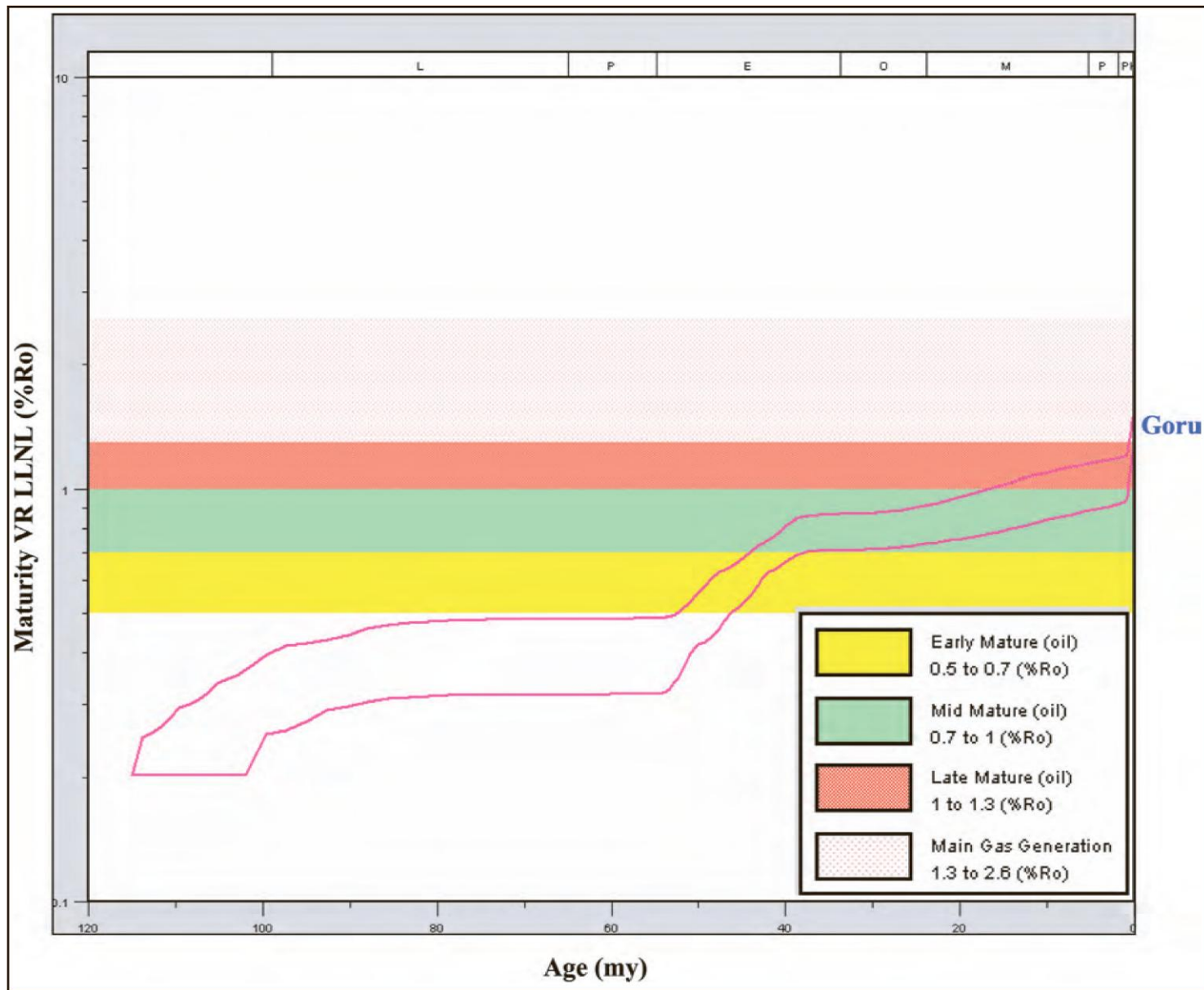


Figure 9c. Time vs. VR maturity profile of the Goru Formation. The basal part of Goru Formation achieved maturation in Ypression, whereas it presently falls in the main gas generation window.

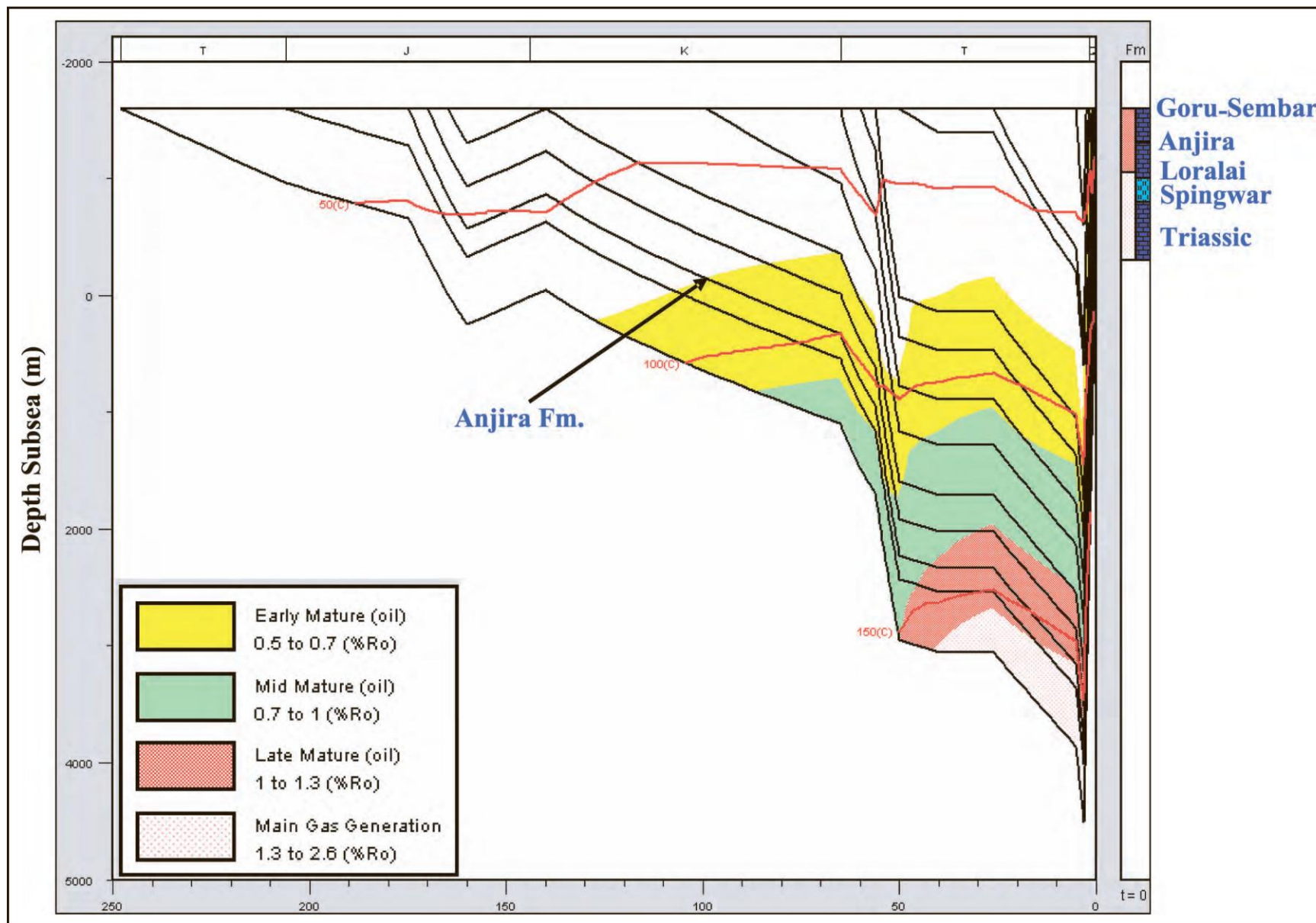


Figure 10a. Thermal and burial history of Pseudo well at Shutrak Anticline located interior of the NKR fold belt, east of Khuzdar City. Anjira Formation attains the early oil generation window.



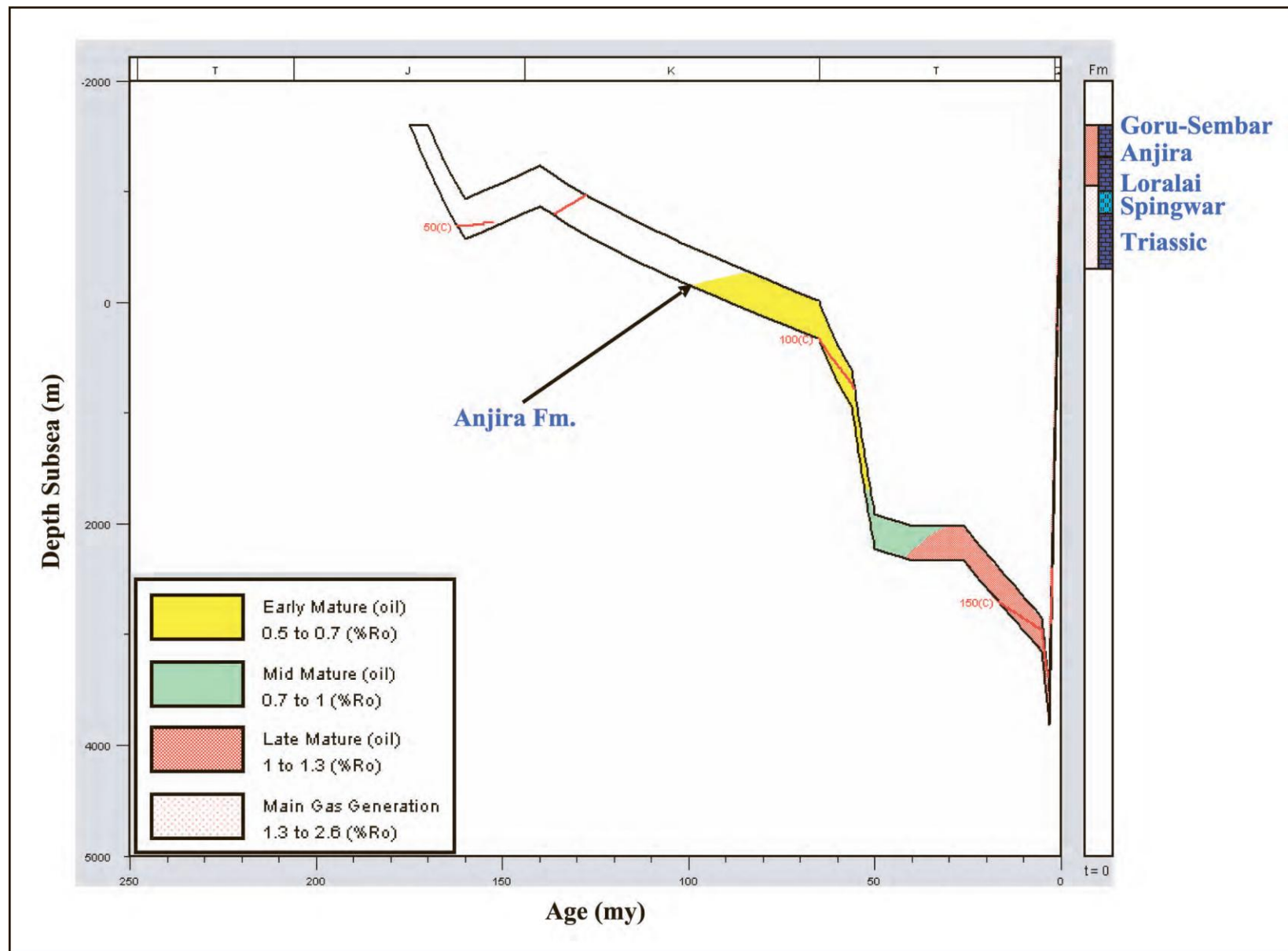


Figure 10b. Thermal and burial history of Anjira Formation at Shutrak Anticline. Present day maturity falls in the gas window.



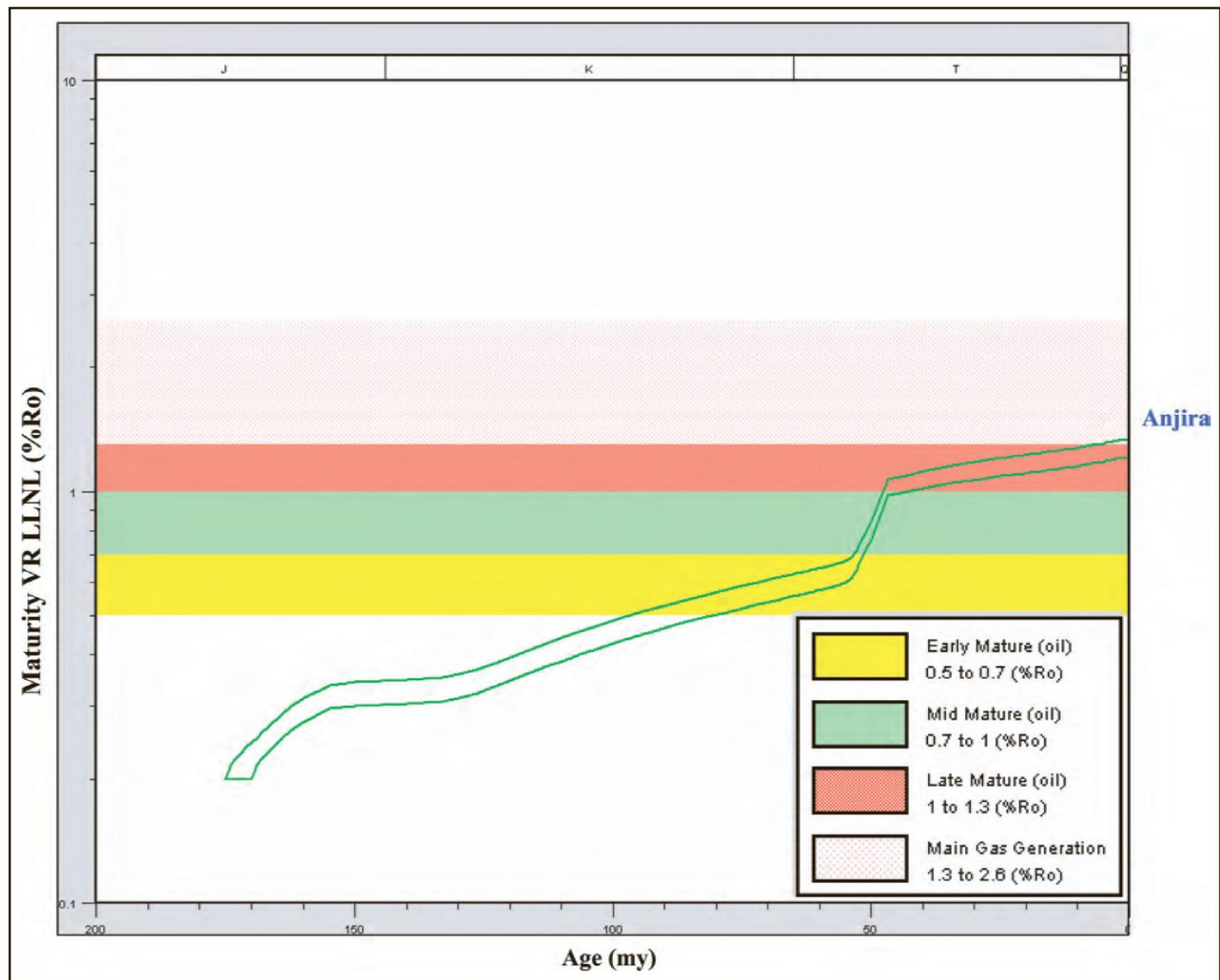


Figure 10c. Time vs. VR maturity profile of Anjira Formation at Shutrak Anticline which attains maturity in Cenomanian time, and presently falls in the main gas generation window.

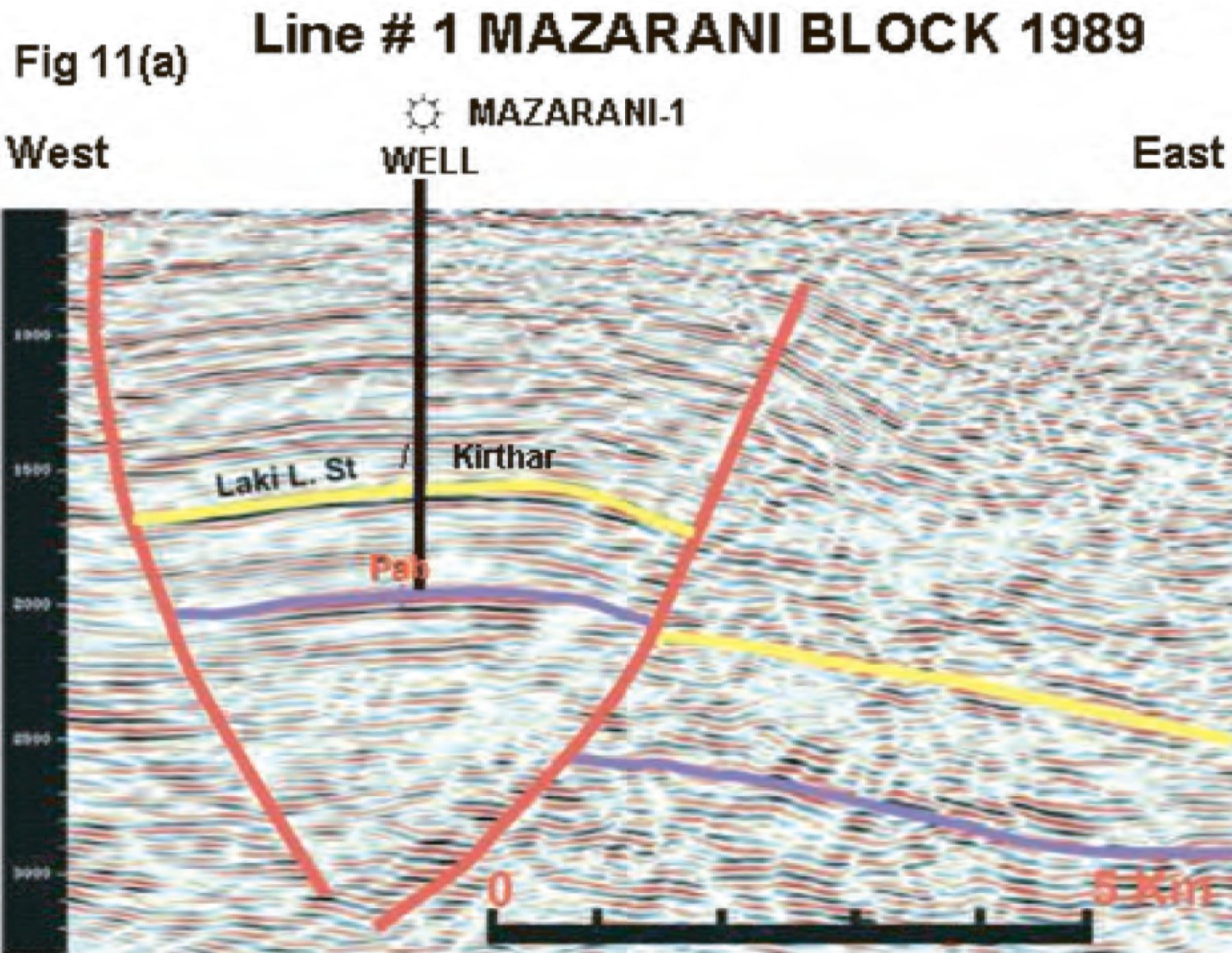


Figure 11a. East-West seismic section illustrates the thrust geometry of the popup Mazarani Anticline. Eastern part of the seismic line lies in the relatively flat area covered with alluvium, whereas the western part is in the low relief fold belt covered with Miocene.



## Line # 1 DADHAR BLOCK 2004

Fig 11(b)

West

East

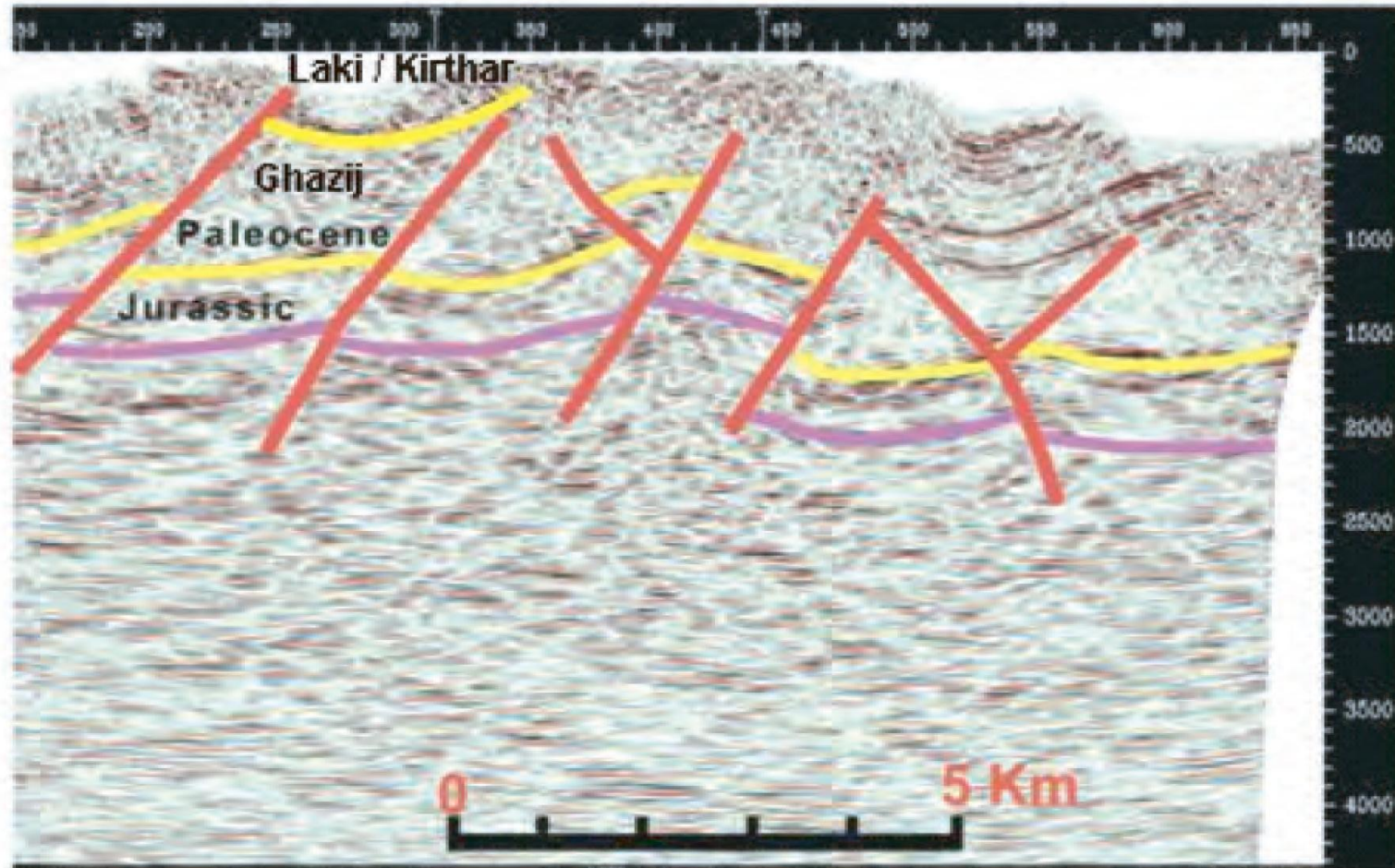


Figure 11b. This seismic line was acquired on the central part of NKR where elevations of hills varies from 300 to 1000 m. Kirthar Limestone is present in this area forming tight folds which affect the energy source penetration during seismic surveys. The complexity of subsurface structure makes the interpretation difficult. Imaging below the Paleocene was not possible.



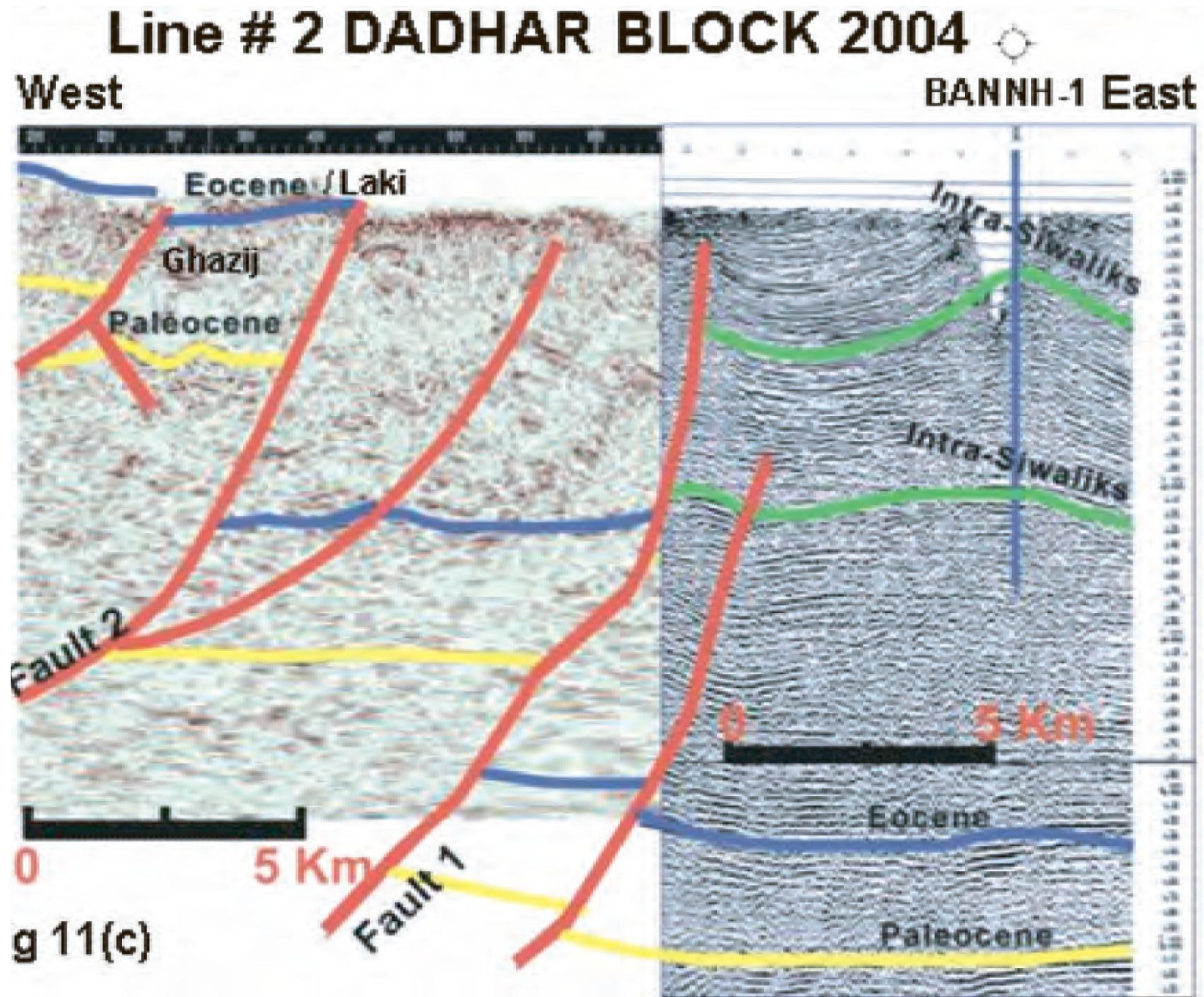


Figure 11c. Subsurface geological model conceived by correlation of Bannh-1 well results which was drilled on a surface structure in the foredeep area and abandoned in Siwaliks. Hanging wall movement along the fault plane 1 and 2 from 3000 to 4000 m can be observed (for location refer to [Figure 1](#)).

### Acquisition Parameter Comparison (a)

Parameters	PPL Mazarani	Premier Exploration	PPL Dhadar
<b>Source Parameters</b>			
Source Type	Dynamite	Dynamite	Vibroseis
Number of Hole	1	9	12
Hole Depth	20 m	1.5 m	12 sec
Charge Size	2 Kg	450 grams	0.5 kg
Source Interval	100 m	50 m	50 m
<b>Receiver Parameters</b>			
Receiver Interval	50 m	25 m	25 m
Number of Channels	120	240	400
Geophone per Group		36 (3 Strings)	36 ( 3 Strings )
Spread Type	Symmetric Split	Symmetric Split	Symmetric Split
Near Offset	150 m	87.5 m	12.5 m
Far Offset	2550 m	3062.5 m	4987.5 m
Fold	30	60	100

### Processing Parameter Comparison (b)

Parameters	PPL Mazarani	Premier Exploration	PPL Dhadar
Transcription	✓	✓	Resample
Geometry	✓	✓	Trace Kill and Edit
Editing	✓	✓	Band Filter
Deconvolution	✓	✓	Tomo Refraction Statics
TAR	✓		TAR
Resampling	✓	✓	Ensemble Decon
Prestack Filtering	✓	✓	NMO
Prestack Noise Attenuation	✓		F-K Filter
Phase matching	✓		Residual Statics
Satatics	✓	✓	NMO
Velocity Analysis 1st Pass	✓		CMP Binning
Residual Statics 1st Pass	✓		Mute
Velocity Analysis 2nd Pass	✓		F-X Decon
Residual Statics 2nd Pass	✓		Inverse NMO
NMO	✓	✓	Curved Ray Kirchoff PSTM
Mute	✓	✓	Inverse NMO
Offset binning	✓		NMO
DMO	✓		AGC
NMO	✓		CDP/Ensemble Stack
Velocity Analysis 3rd Pass	✓		F-X Decon
NMO	✓		AGC
Stack	✓		Band Pass Filter
Datum Statics	✓	✓	
Poststack Decon.	✓		
Poststack Noise Attenuation	✓		
Migration	✓	✓	
Poststack Filtering	✓	✓	
Scaling	✓	✓	

Table 1. (a) 2D Seismic data acquisition, and (b) Processing parameters used by their operators (Mazarani, 1989; Dadhar, 2001 and 2004).