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Subsurface Geometry of Potwar Sub-Basin in Relation to Structuration and Entrapment

M. Anwar Moghal[1], Muhammad Ishaq Saqi[1], Abdul Hameed[1] and M. Nawaz Bugti[1].

ABSTRACT

The Potwar sub-basin is located at the northern margin of the Indian Plate, in Pakistan. It is filled with thick Infra-Cambrian evaporites, thin Cambrian to Eocene calcareous-siliciclastic sediments of Indian Plate and relatively very thick Miocene-Pliocene molasse deposits of the Indus Foredeep.

The Potwar fold region is a prolific area for hydrocarbon occurrence. The first commercial discovery from the Himalayan Foreland was made in Potwar sub-basin at Khaur in 1914.This sub-basin hosts multiple structural leads. Hydrocarbons have been reported from different reservoirs. The Potwar sub-basin has experienced severe deformation during Himalayan orogeny in Pliocene to Middle Pleistocene. Regional unconformities in the stratigraphic profile of the basin reflect the severity of tectonic pulses.

To develop understanding of its structural style, fault types, decollement levels and influence of tectonics, transects in a grid fashion and a regional time structure map at the Base Miocene level have been developed. The mentioned time structure map is also more or less conformable for deeper horizons.

In the Potwar sub-basin occasionally, surface geological features mismatch the subsurface geometry. Interpretation of seismic reflection profiles has confirmed two decollement levels; the lower one in the Infra-Cambrian Salt Range Formation and the upper one at the interface of Eocene and Neogene molasse sediments. The structural architecture of the sub-basin has been strongly influenced by these decollements which led to offset and structural variation above and below these decollements. The lower decollement is a low angle thrust within Salt Range Formation that carries the entire sedimentary section to the south. Foreland verging Salt Range Thrust is the surface manifestation of this decollement. It is believed that the structures have been formed due to southward propagation of faults related to salt movement activated by southward thrusting of sedimentary wedge.

Attempt is made to relate hydrocarbon entrapment in distinctive structural domains. The orientation, styles and geographic distribution of structures and migration of hydrocarbon from the source beds to reservoir via fault planes is discussed. For the carbonate reservoirs it is considered that faults and flexures have enhanced their porosity by developing fractures. In addition, sub thrust plays and hydrocarbon plays on different leads and fairways have been identified. New identified plays include popup, sub thrust and "snake-headed" structures, salt-cored anticlines, and associated imbricate and triangle zones in different parts of this sub-basin which are considered to be the primary drilling targets in future. It will open new horizones for hydrocarbon exploration in the Potwar sub-basin, Pakistan.

[1]Pakistan Petroleum Limited, Exploration Department, Karachi, Pakistan.

INTRODUCTION

The Potwar sub-basin is located in the western foothills of Himalayas in northern Pakistan. It includes the Potwar Plateau, the Salt Range, and the Jhelum Plain. It is bounded in the north by main Boundary Thrust-MBT (recently the term MBT has been challenged by Iqbal and Bannert, 1998 and Iqbal et al., 2007 however without indulging in this controversy the term is used as such in the text due to its common use in the literature) and Salt Range in the south. Jhelum strike-slip fault occurs in the east and Indus River and Kalabagh strike-slip fault in the west. Kohat Plateau is in the western strike extension of the Potwar sub-basin with relatively severely deformed structures.

The Potwar sub-basin is filled with thick Pre-Cambrian evaporites overlain by relatively thin platform deposits of Cambrian to Eocene age followed by thick MiocenePliocene molasse (Figure 1). This whole section has been deformed by intensive Himalayan orogeny in Pliocene to Middle Pleistocene.

The Potwar sub-basin is one of the oldest oil provinces of the world, where the first commercial discovery was made in 1914 at Khaur. So far, about 150 exploratory wells have been drilled of which most could not reach target depths due to operational problems related to extremely high-pressure water in mollasse deposits, thus were prematurely abandoned. This abnormal pressure is related to rapid deposition/burial of molasse deposits, which is further aggravated by structural complexities.

The central, western and the eastern parts of the Salt Range / Potwar Plateau have quite different structural styles. Uneven distribution of salt, occurrence of different detachment levels, faults and flexures in the basement are among the possible reasons for structural complexity. Subsurface picture of the Potwar sub-basin demonstrates that structures are regionally bounded by foreland verging thrusts. These thrusts are generally trending northeast southwest in the eastern part, almost east-west in the central part, and northwest-southeast in the western parts of the Potwar sub-basin. There is less distribution of evaporites in the eastern part where competent rocks (carbonates and sandstones) dominate.

The Jhelum left lateral strike-slip fault in the east and the right lateral strike-slip Kalabagh fault in the west have played pivotal role in shaping the geometry of the Potwar sub-basin. Due to these faults, the structures in the eastern part of the sub-basin are left stepping whereas in the western part right stepping en-echelon aligned. The fault splays of the Jhelum and Kalabagh faults extend respectively from east and west to the central part of the basin where these splays become

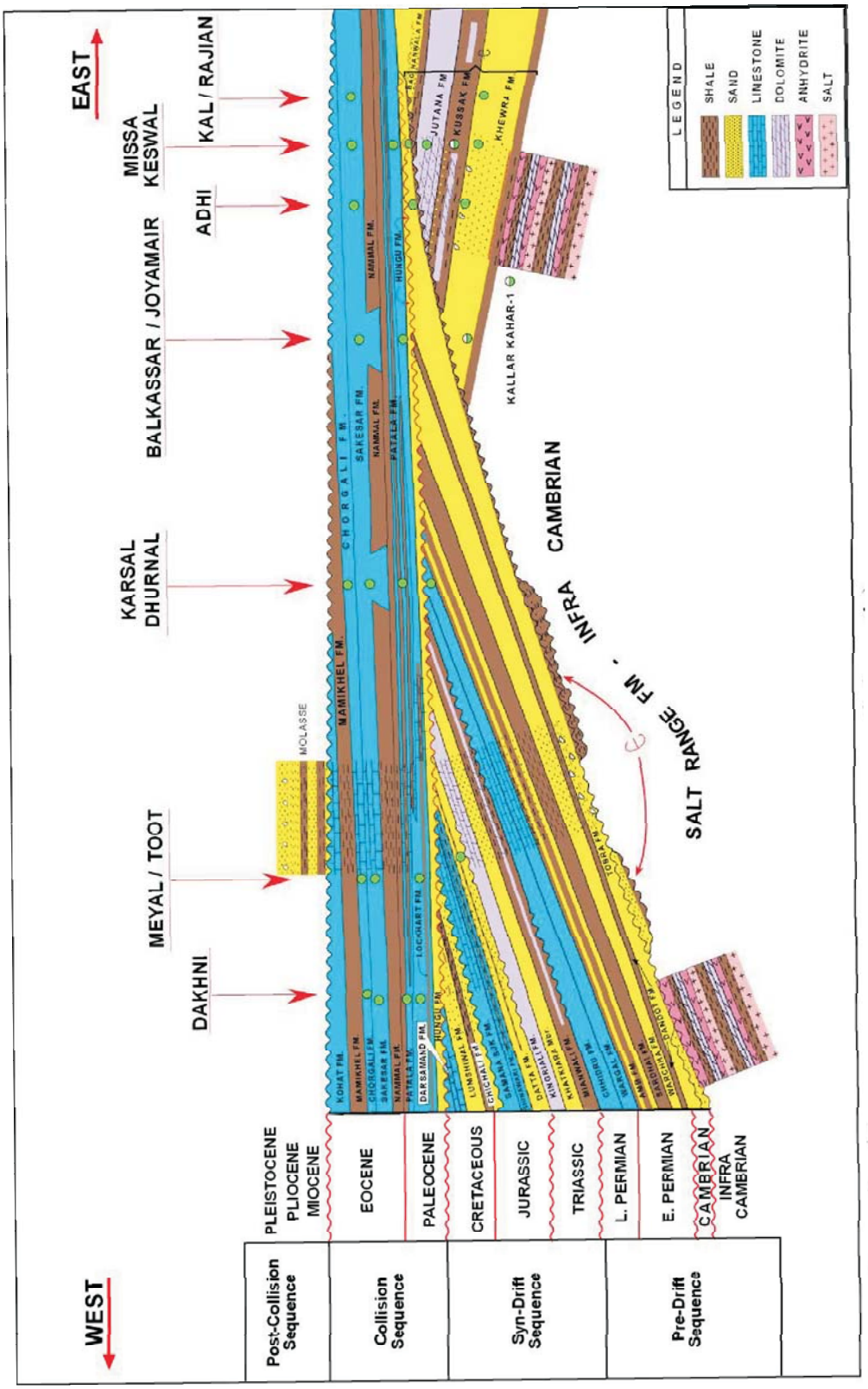

Figure 1- Genealized Stratigraphy of Potwar Sub-Basin (Schematic).

relatively diminished and fold axes are, therefore, east west oriented. Additionally, the combined effect of these faults has resulted in southward migration of the entire Potwar sub-basin. The southward shift of the Potwar sub-basin is manifested by recent deformation in the southern part of Potwar sub-basin along Salt Range Frontal Thrust (Figure 2) where Precambrian Salt Range Formation has thrusted over Quaternary sediments.

The sub-surface picture of Potwar sub-basin provides the best insight into the framework and structural styles of the basin. The architecture of the Potwar sub-basin is a function of complex interplay of compressional forces, basement slope, and variable thickness of Pre-Cambrian salt over the basement, and deposition of very thick molasse and tectonic events. In Potwar sub-basin some surface features mismatch subsurface structures due to decollements at different levels. In such circumstances, it is necessary to integrate seismic data with surface geological information for precise delineation of sub-surface configuration of various structures. In this paper an attempt has been made to define subsurface geometry of Potwar sub-basin based on integrated geological and geophysical studies. Subsurface geometry proposed for the Potwar sub-basin along seismic transects and their tectonic transposition exhibit distinct domains from south to north and in the eastern and western parts of the basin which in turn may be associated with the density and occurrence of effective fracture systems in various reservoirs, particularly Eocene carbonates.

REGIONAL DEPOSITIONAL HISTORY

The generalized stratigraphic succession of the Potwar sub-basin is shown in Figure 1. Generally these formations are exposed in the east west trending Salt Range. The depositional sequence in the Potwar sub-basin may be summarized as follows:

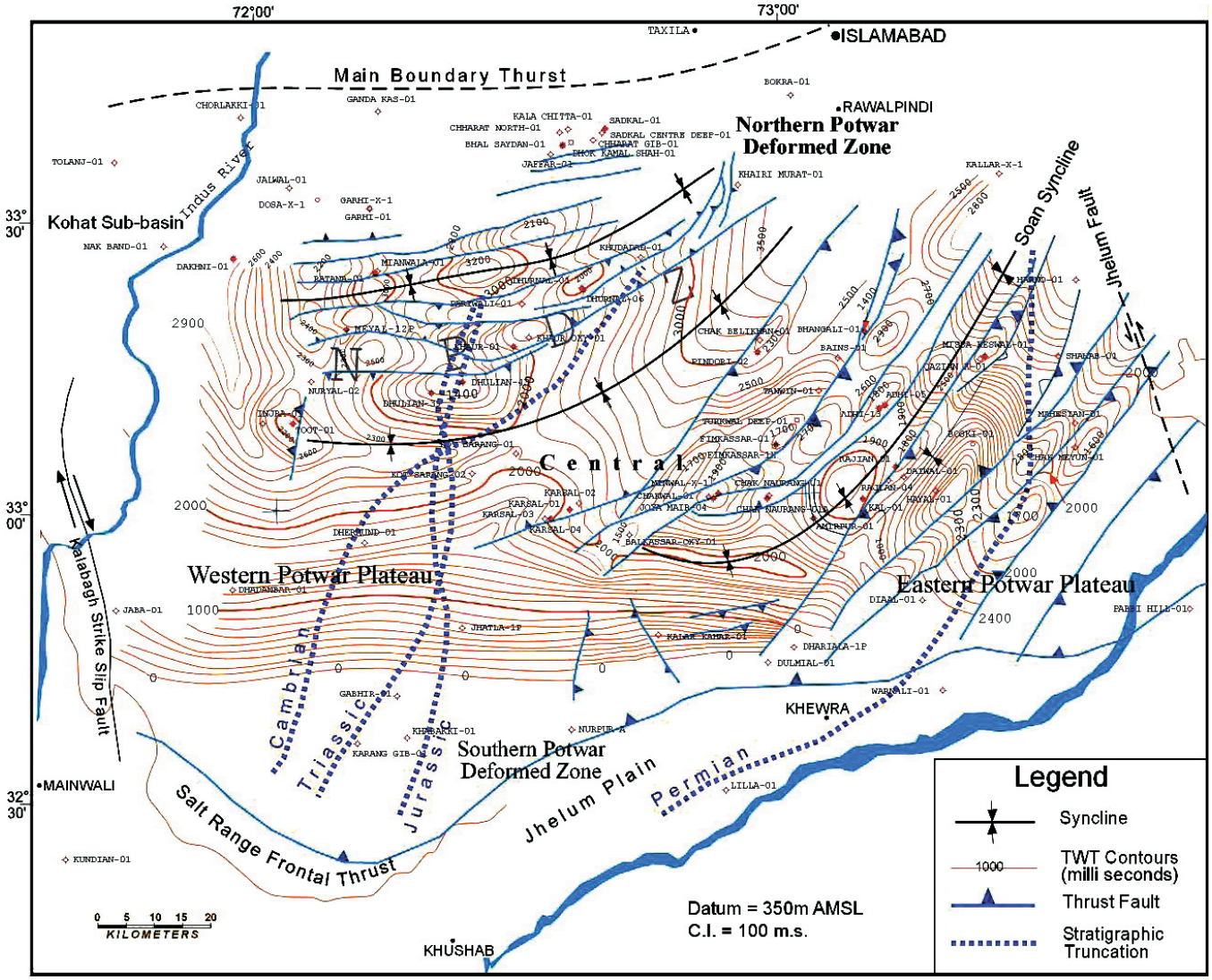

Figure 2- Two Way Time Map at Base Miocene in the Potwar Sub-basin, Pakistan.

The Infra-Cambrian evaporites were deposited in intra-cratonic setting in a basin that extended from Pakistan to Turkey through Iran and Oman. This deposition occurred over the basement of the Indian Plate. The evaporite sequence is overlain by Cambrian rocks of Jhelum Group which comprises Khewra Sandstone, Kussak, Jutana, and Bhaganwala formations. Deposition of the Jhelum Group was followed by a period of limited deposition and/or erosion from Middle Cambrian to Early Permian. Therefore, the strata belonging to these periods are missing in Potwar sub-basin. The Nilawahan Group of early Permian is restricted to the eastern part of Potwar / Salt Range and is predominantly of continental origin. This group includes Tobra Formation, deposited in predominantly glacial environments, Dandot Formation of olive green sandstones and claystones, Warcha Formation predominantly red sandstone, and Sardhai Formation's claystone. The Zaluch Group is restricted to the western and northern/central part of Potwar / Salt Range. It includes marine limestones and claystones of the Amb, the Wargal and the Chhidru formations, deposited during the Late Permian. The Triassic formations are Mianwali and Tredian deposited in deep to shallow marine environment and the Kingriali formation comprising shallow water dolomite. The Jurassic formations include Datta Sandstone, Shinawari (limestone and shale sequence) and the Samana Suk (Limestone) formations.

The Cretaceous sequence is represented by the clastics of Chichali and Lumshiwal and the carbonates / clays of Kawagarh formations; the later being restricted to the northern Kohat Basin, while former is more pervasively present in the western Potwar, Salt Range, and Kohat basin. Mesozoic sediments are present only in the western part of the Potwar/Salt Range, as the Base Tertiary unconformity progressively oversteps Jurassic, Triassic and Permian formations to the east. In the eastern-most Salt Range this sequence directly overlies Cambrian rocks.

Shallow marine foraminiferal limestones and dark grey shale with large foraminifera were deposited during the Paleocene and Eocene times which are marked by a laterite bed at the base of this succession. The Paleocene formations include Hangu Formation that consists of shales, siltstones and sandstone, Lokhart Limestone and Patala Formation comprising predominantly limestone and shale, respectively. Deposition of calcareous claystone of the Nammal Formation marking the beginning of Lower Eocene was followed by massive shelfal limestones of the Sakesar Formation, which is overlain by dolomitic limestones and calcareous claystones of the Chorgali Formation.

Continental collision in the Middle Eocene resulted in the uplift of the Sargodha High, which ended marine deposition in the area . Oligocene age sediments are missing in the Potwar sub-basin, as during this time the Higher Himalayas were building for the subsequent molasse sedimentation. The foreland sedimentation in the Potwar sub-basin commenced in Early Miocene, which is represented by fluvial and fluvio-deltaic lithology of Rawalpindi and Siwalik Groups including Murree, Kamlial, Chinji, Nagri, Dhok Pathan, and Soan formations. The thickness of the molasse sequence generally increases towards north.

DATA BASE

Following integrated geological and geophysical (seismic) data have been used for interpretation and mapping to decipher the sub-surface structures:

(1) Regional seismic transects/cross sections consisting of seismic profiles that were brought to a uniform datum and vertical scale.
(2) Well seismic data including VSP / Check Shot surveys.
(3) Available geologic data of the wells.
(4) Review of previous studies and compilations.

Though there are several vintages of seismic data, dating from 1970s, generally the data quality is good. The well and seismic data, located on or nearby the regional grids have been used as an aid for horizon identification with due consideration to geological characters.

INTERPRETATION METHODS

Time structure contour map at Base Miocene level was generated at 1:500,000 scale which is considered applicable to deeper horizon in the perspective of regional structural styles. After interpretation of each transect, it was transposed into regional time structure map (Figure 2). Through synthesis of seismic transects, well synthetics and geological information, significant regional unconformity surfaces were recognized. Interpretation and mapping led to delineation of various regional structural domains with different orientation and styles.

POTENTIAL DECOLLEMENT LEVEL(S) AND FAULTING

The Salt Range and the Potwar Plateau of Pakistan are parts of the Himalayan foreland fold-and-thrust belt. The deformation / structuration in these structural elements have occurred as a result of the ongoing collision between the Indian and Eurasian plates. In the Potwar sub-basin at least two main decollement levels have been recognized, i.e. one at the base of the Eocene molasse sequence and the main decollement level at the interface of platform deposits and evaporite sequence relating to Infra-Cambrian salt particularly in the Salt Range and southern Potwar (Figures 3 a and 3 c).

Presence of different decollement levels has resulted in offset of the subsurface structures from their surface manifestations. For example, Dhurnal anticlinal structure is a surface monocline and similarly, Missa Keswal and Fim Kassar (Figure 2) discoveries were made on previously drilled surface structures by correctly delineating the position of the crest at depth by reinterpretation of the seismic data.

The main decollement level at the interface of platform sequence and evaporite sequence relates to Pre-Cambrian salt particularly in the Salt Range and southern Potwar. In the eastern part, most of the deformation appears to have been shifted toward shallower intra-molasse decollement horizons due to progressive thinning of the salt layers. There may be some other local decollement levels within under compacted Neogene molasse sediments near the top of Kamlial Formation.

INTERPRETATION OF SUBSURFACE STRUCTURAL MAPPING

The Salt Range, itself an ENE trending structure, separates the Potwar sub-basin from the Indus foreland. The lowest E-W

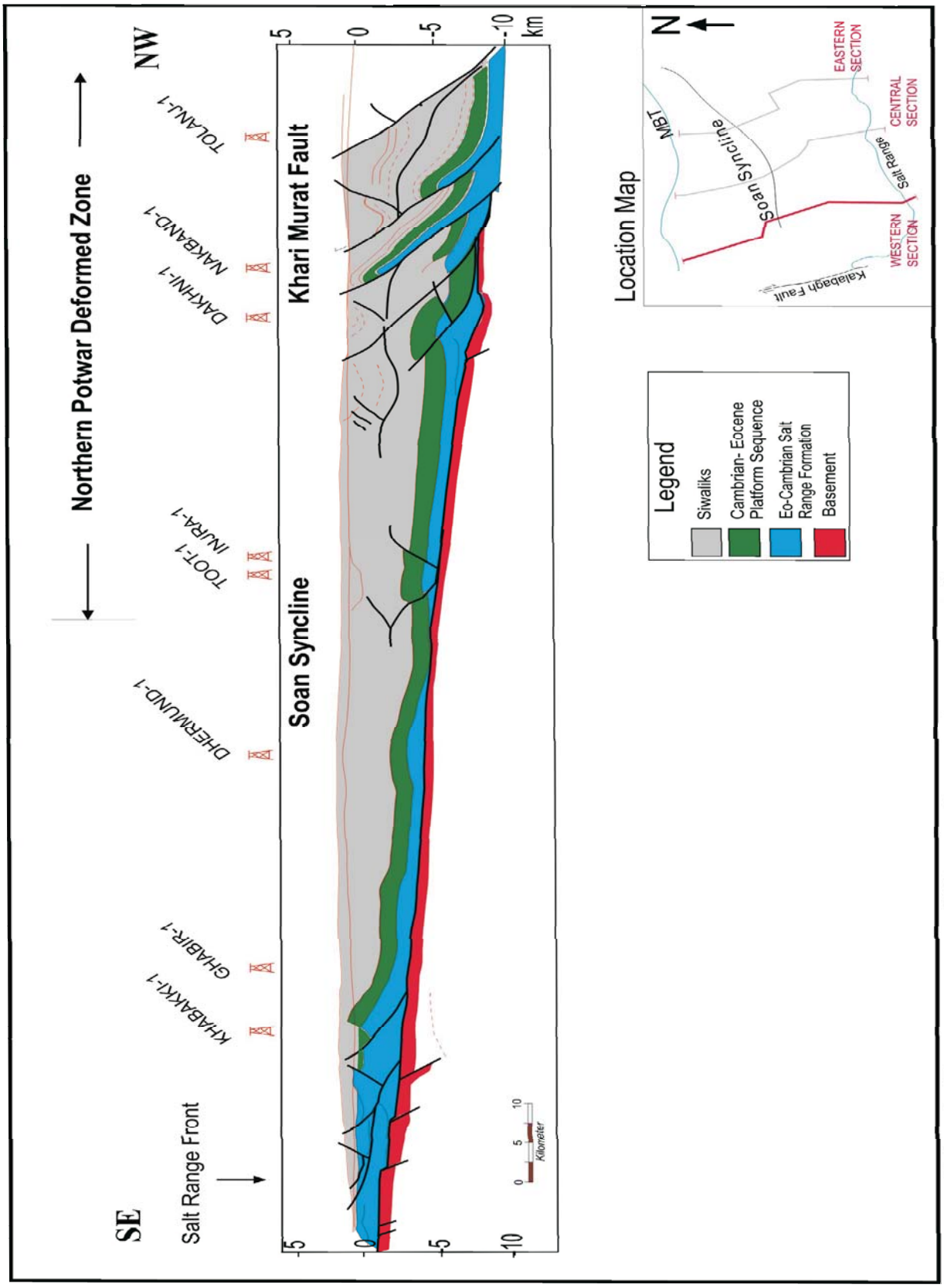

Figure 3a- Seismic Transect across Western Part of Potwar Sub-basin.

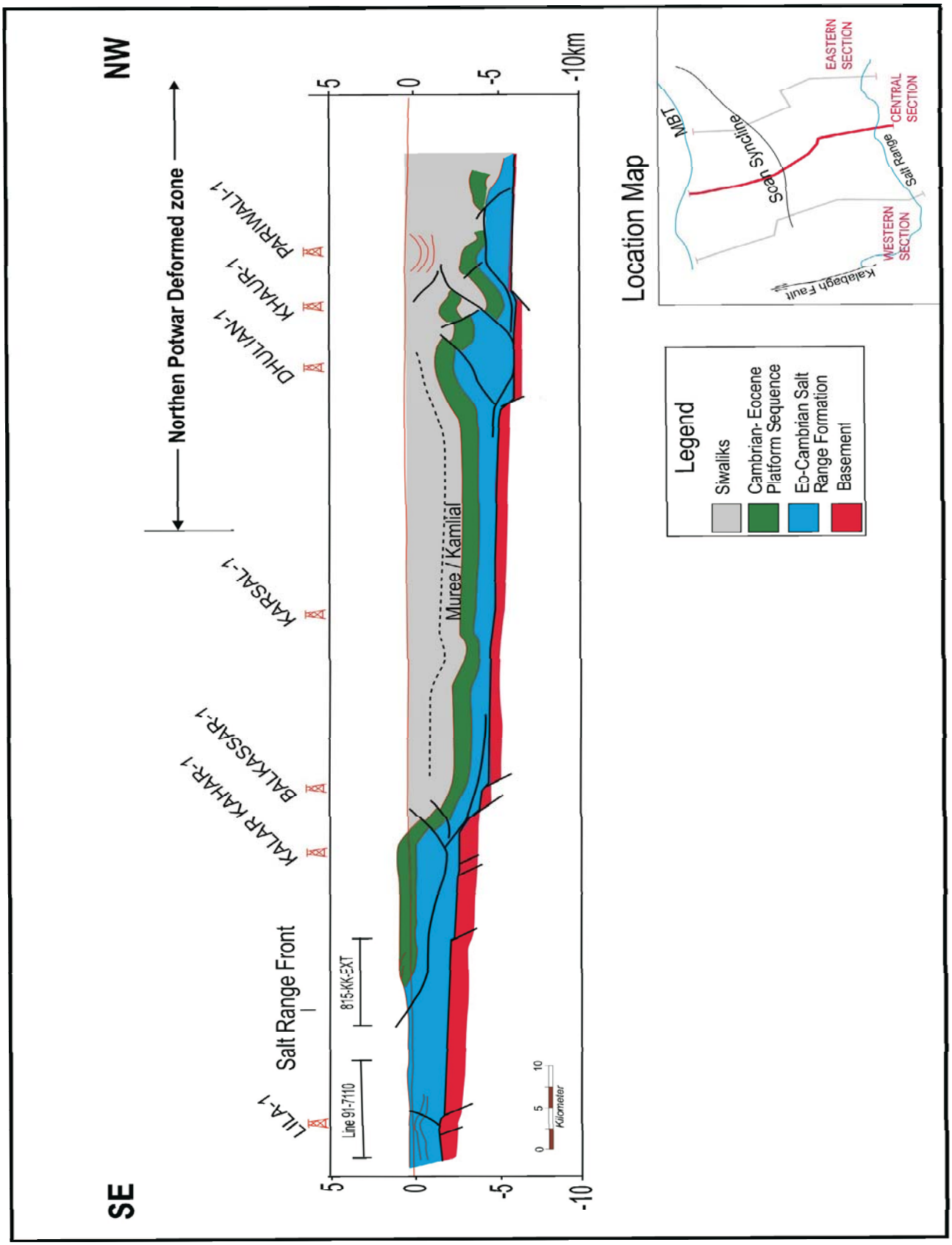

Figure 3b- Seismic Transect across Central Part of Potwar Sub-basin.

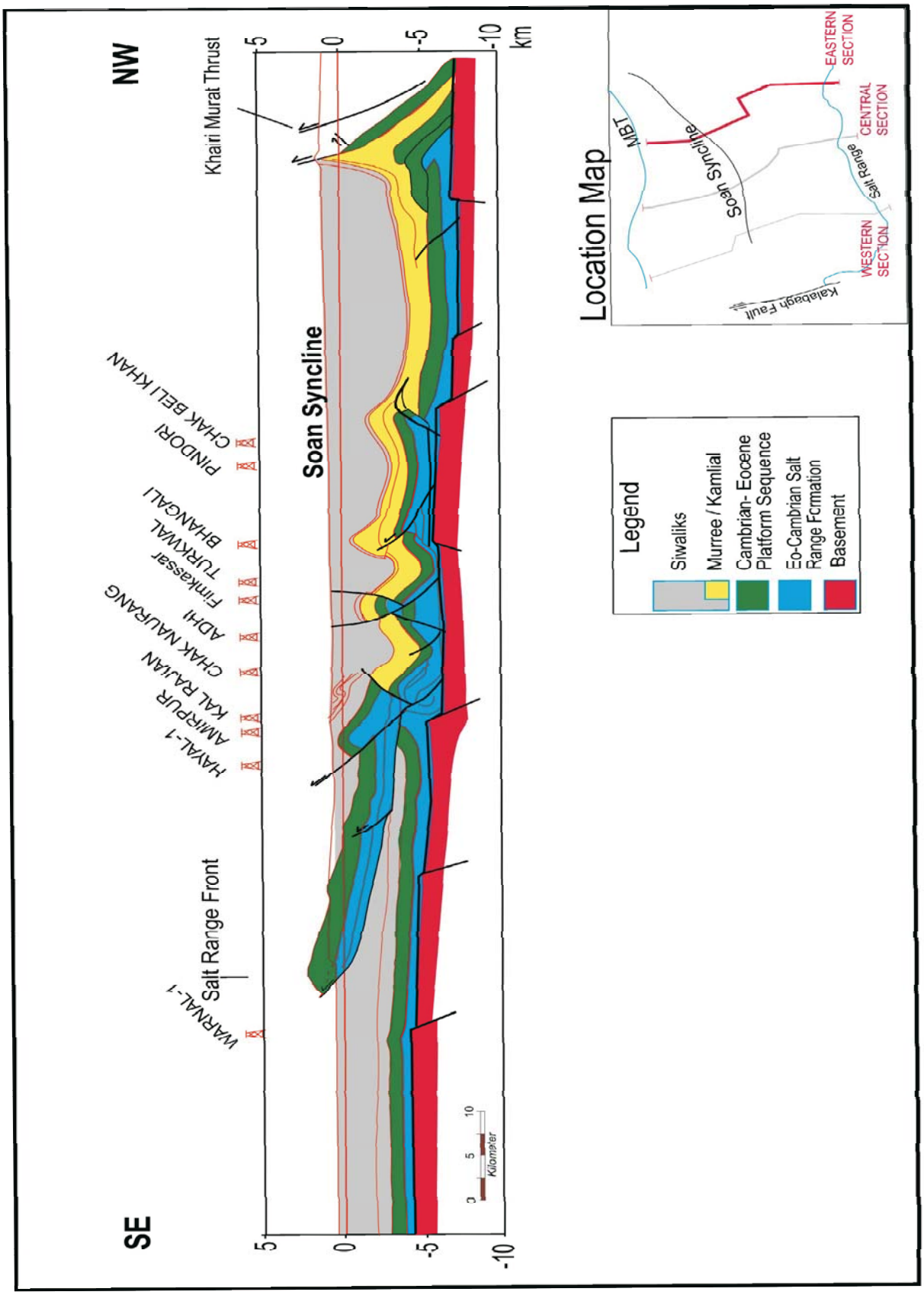

Figure 3c- Seismic Transect across Eastern Part of Potwar Sub-basin.

imbricate Salt Range Frontal Thrust has brought the entire sequence over the Quaternary and it deepens towards north in this area (Figure 2). The structural elements in the area are primarily compressional, however, the pre-existing normal faults in the crystalline basement have also played a role in the formation of structures in the sub-basin (Pennock et al., 1988). A comprehensive picture, depicted through transects and maps, broadly explain the structuration style in the basin. Anticlinal structures in the Potwar sub-basin have generally sub-latitudinal orientation and the structural complexity increases in the north due to proximity of collision zone as manifested by the existence of highly complex Northern Potwar Deformed Zone (NPDZ) with its southern boundary marked by Soan syncline (Figure 2). Generally, structures are progressively more tightly folded and more complexly faulted while going from south to north. The folds in this part of the area are isoclinal and imbricated / overturned with Tertiary sediments exposed in the crests of these structures. Cross sectional balancing studies by various authors show that thrust stacks of ramp anticlines have accommodated most of the shortening in the NPDZ. A triangle zone has also been formed by shallow decollement (within Neogene) in the foothill of Khairi Murat Ridge (Figure 3a) (Jadoon et al., 1997).

The structural style of the central, western and eastern parts of Potwar sub-basin suggests a marked difference. In the central and western parts of Potwar, the deformation appears to have occurred by south-verging thrusting (Figures 3a and 3b), whereas in the eastern part the deformation is mainly in northeast-southwest with tight and occasionally overturned anticlines separated by broad synclines(Figure 3c). This difference may be related to lesser thickness of salt in the Infra-Cambrian in the eastern area and very low dip of the basement (1°-1.5°) as compared to central Potwar (2° to 3°). Major anticlinal and synclinal features are bounded by major thrusts and back thrusts trending almost E-W in the northern part, while in eastern part fault trend is almost NE-SW. The paleomagnetic studies have shown that originally the structural trends developed perpendicular to the transport direction and subsequently acquired the present alignment because of tectonic rotation as manifested by strike-slip nature of the left lateral Jhelum strike-slip fault (or Jhelum Basement Fault of Bannert and Raza 1992). In central Potwar, structures are mainly fault bounded mostly by thrusts and back thrusts (Figures 4 and 5), while at some places; asymmetric anticlines are bound by a single fault. Based on the seismic interpretation, the structures in Potwar area may be divided into:

Pop-up anticlines (Figures 4 and 6)
Triangle zones (Figure 5).
Snake-head anticlines(Figure 5),
Salt cored anticlines (Figure 6)

Excluding the above conventional structures the network of transects also depicts and confirms existence of sub-thrust closures situated in Kal/Rajian (Figure 3c), structure beneath Toi Banda and in adjacent Nashpa and under Nandrakki fault in the Kohat area.

HYDROCARBON ENTRAPMENT

As mentioned earlier, oil and gas exploration in the Potwar sub-basin has a long history and seems to have attained maturity, but it can still offer some pleasant surprises. The discovery at Rajian in the eastern Potwar sub-basin in a sub-thrust play is very encouraging lead for explorationists. In Adhi, Pop-up structure sub-thrust play has also been identified and is being focused for exploration (Figure 6). Hence, it opens new plays within the area. It warrants that besides conventional and firm structural plays, concentration has to be focused on identifying new hydrocarbon plays and fairways through integrated G and G studies. Structures on which the wells were prematurely abandoned due to operational reasons or then considered less economical merit revisit with new exploration concepts and modern technology.

The play types in the Potwar sub-basin are generally faulted anticlinal structures, which are mostly salt cored, occasionally highly asymmetrical to overturned. The occurrence of hydrocarbon in various parts of Potwar sub-basin may be related to varying structural styles.

The severe structuration in the eastern part has resulted in abundant fracturing as compared to the western part. The fracturing in the western part may be attributed to its proximity to the Main Boundary Thrust. Another important reason of deformation in the eastern Potwar sub-basin may be attributed to the fact that in that part the ductile salt strata change to competent sequences of carbonate and sandstone lithologies, which are relatively more brittle to tectonic stresses that are transmitted from the adjacent Himalayas.

The oil and gas discoveries in the eastern part of the Potwar Plateau (generally south of the Soan Syncline) are mostly in the elongated anticlines, trending NE SW with steeply dipping flank due to salt pop-up.

The hydrocarbons discovered near NPDZ are mostly from asymmetric E-W oriented anticlines (e.g. Ratana) whereas, those in the north/northwest of Soan Syncline are mainly from the symmetric northeastward to eastward trending thrust decollement Cenozoic anticlines (e.g. Dhurnal, Toot and Dakhni fields).

Sub-thrust plays may have significant potential in the Potwar area and merit pursuance. Oil discovery in Rajian was first of its kind in the area. However, difference between single down-thrown block and sub-thrust block concept may be taken into consideration for closure identification.

The shales of Patala Formation are considered to be established source rocks in Potwar sub-basin. The Salt Range Formation also contains oil shale with upto 23 % TOC and some solid bitumen. The occurrence of hydrocarbons in the older formations (Cambrian, Permian, Jurassic) is explainable by vertical migration from the footwall across the thrust faults and back thrusts. The faults are likely to act as major conduits for the fluids when still located with platform series.

Besides conventional plays, there exist various non conventional hydrocarbon plays including:

(i) Sub-thrust (autochthonous) plays in the central and western Potwar and NPDZ.
(ii) Eocene carbonate digenetic (matrix porosity) play fairway between Balkassar and Fim Kassar oilfields.
(iii) Datta Sandstone structural / truncation plain in the western part, and
(iv) Salt diapers associated plays in the vicinity of the Kalabagh strike-slip fault.

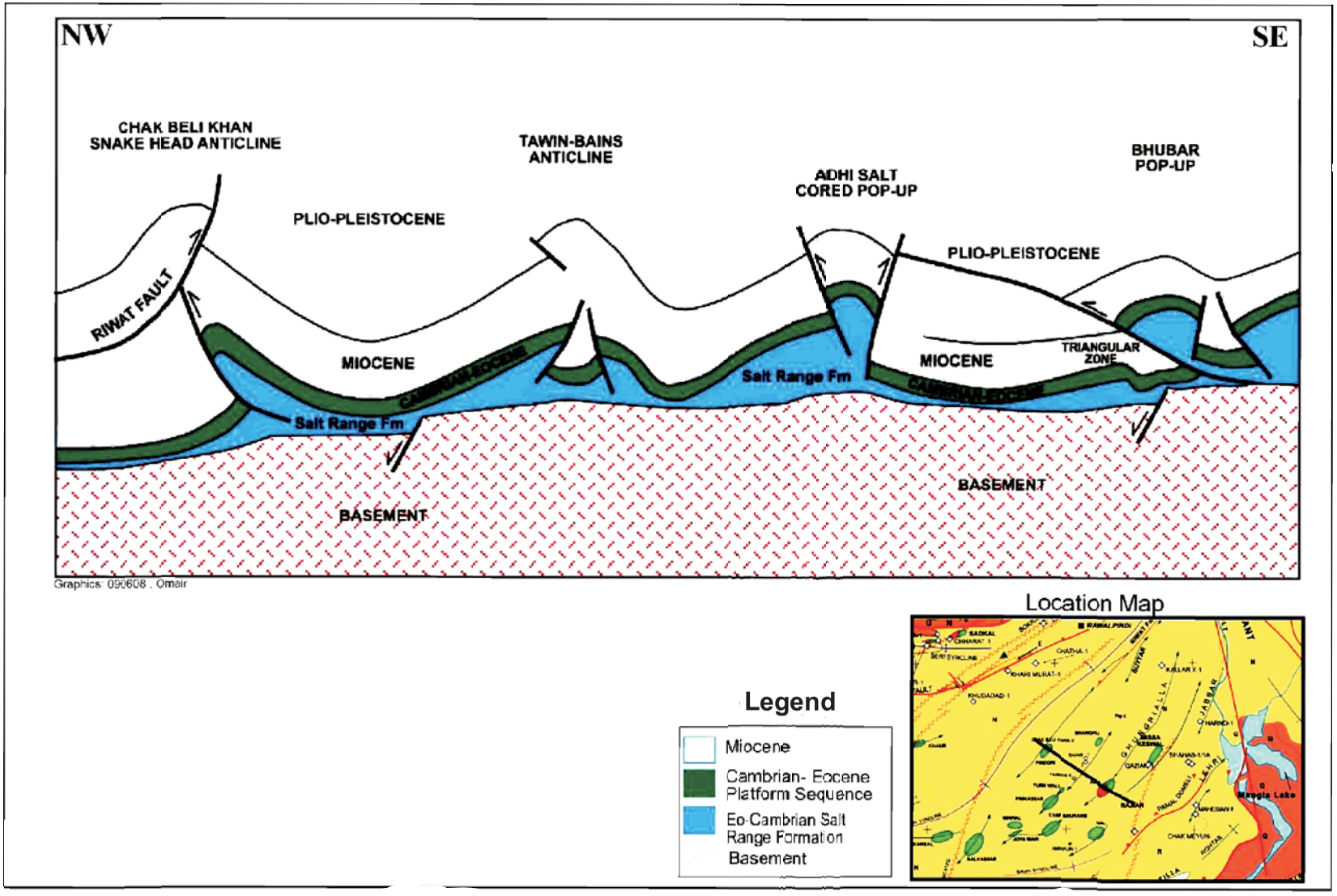

Figure 4- Geoseismic Cross-Section Through Central/Eastern Potwar along Chak Belikhan, Tanwin Bains, Bhubar Structures.

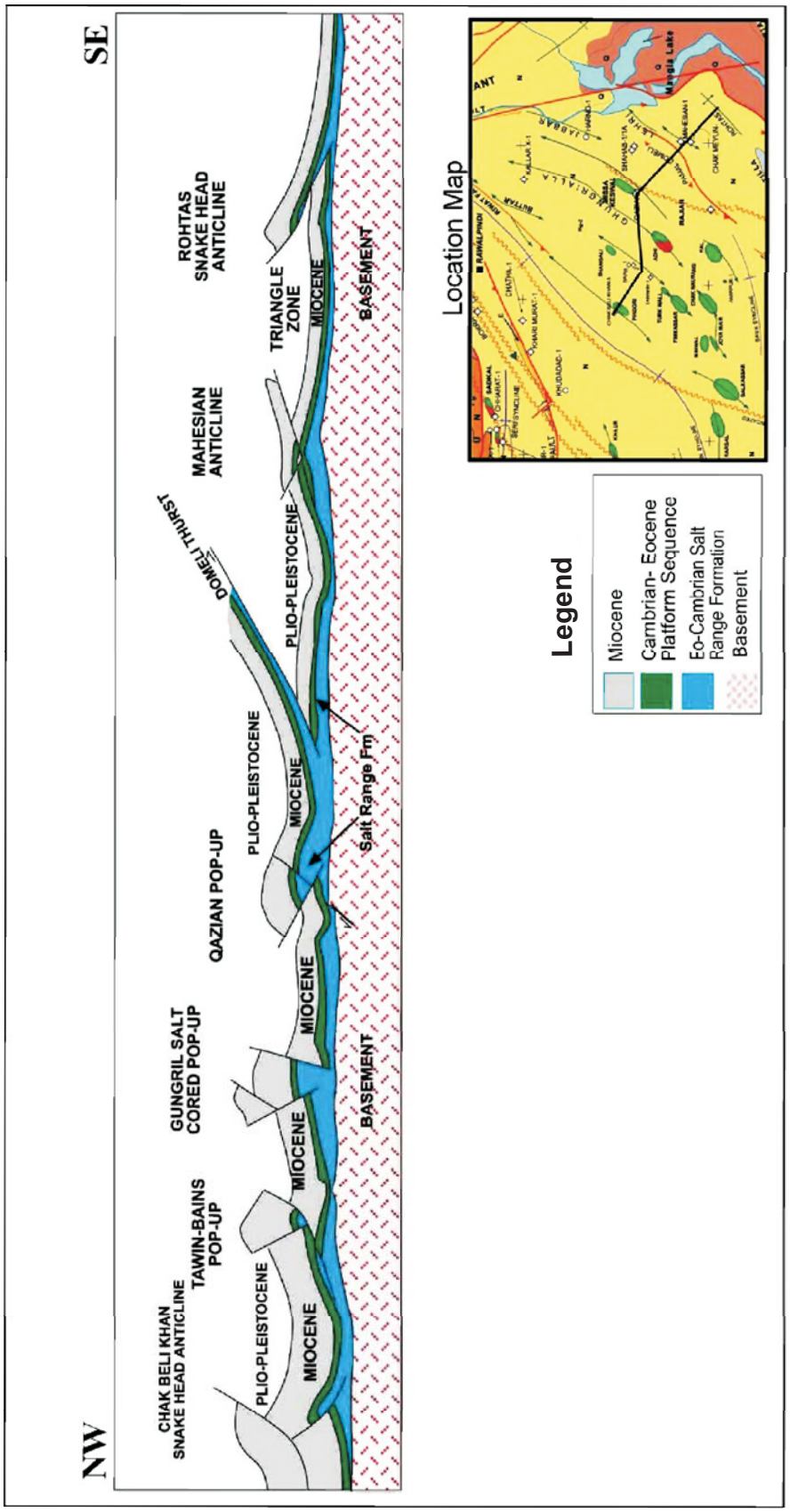

Figure 5- Geoseismic Cross-Section Through Central/Eastern Potwar along Chack Belikhan, Tanwin Bains, Gungril, Qazian, Mahesian and Rotha Structures.

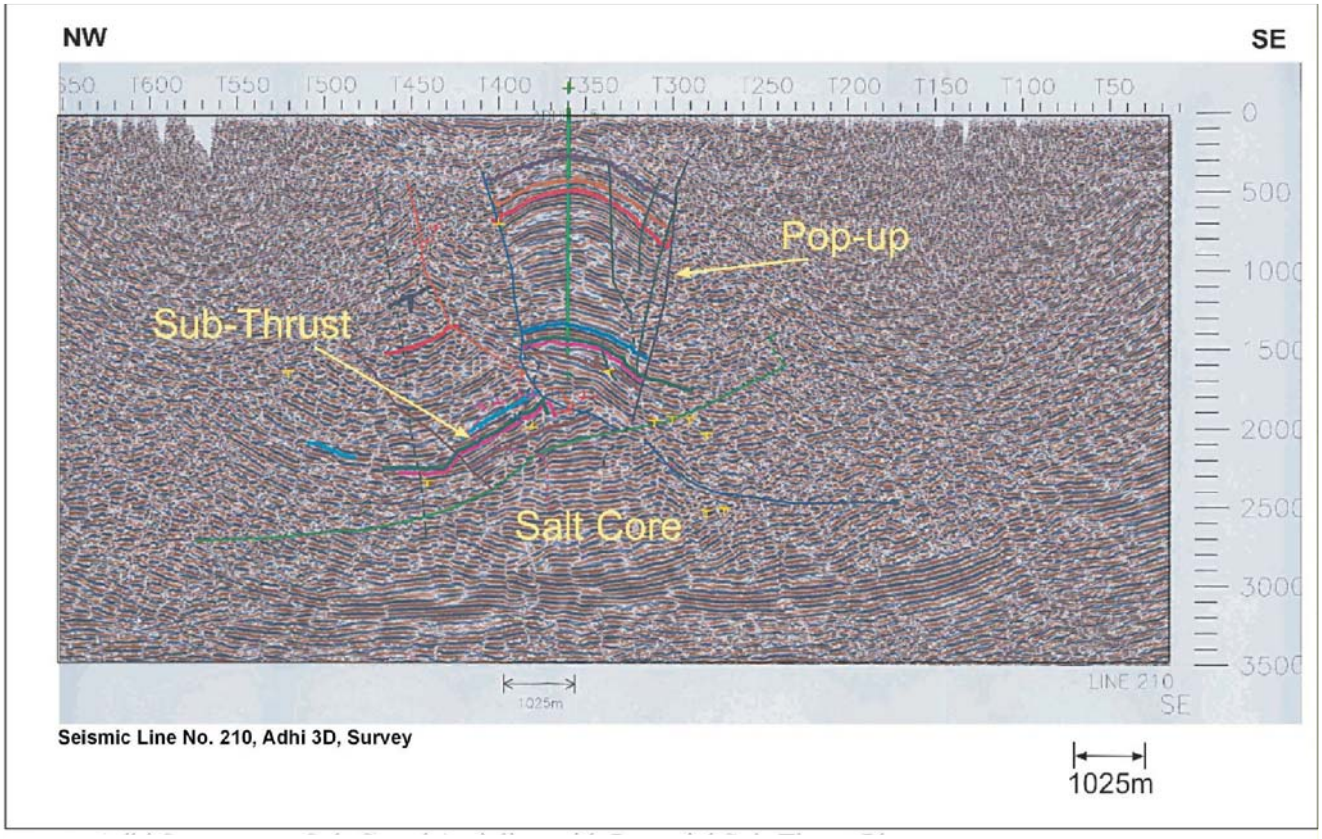

Figure 6- Adhi Structure: a Salt Cored Anticline with Potential Sub-Thrust Play.

In central Potwar, Karsal field has produced about 135,000 barrels of oil. Interpretation of recent seismic conducted by Pakistan Petroleum Ltd. PPL in 2002 over the area does not indicate any structural closure and it appears that the producing wells were located apparently on a monocline / flexure nose and the field produced from local permeability network associated with updip permeability pinchouts in the vicinity of faults.

CONCLUSIONS

Network of seismic transects and transposed geological sections provide a framework of structural architecture in the Potwar sub-basin. This framework, supported by other data, forms a basis for delineation of structural domains.

Faults and decollement levels have played most important role in structural development of Potwar sub-basin.

There are local decollement levels identifiable besides two main ones at the interfaces of Eocene and molasse sequence and platform and evaporite sequence (Salt Range Formation).

Potwar sub-basin is divisible into various zones on the basis of structural styles. Interpretation of the mapping indicates that the structures in various regional structural domains have different orientation and styles.

Besides conventional plays, there is significant potential of finding various non-conventional plays including stacked thrust imbricates, which may offer deep exploration targets in numerous culminations, particularly in the NPDZ.

Sub-thrust plays have most significant potential for the future exploration in Potwar area and merit concerted efforts and pursuance. Oil discovery from one of these prospects in Rajian was first of its kind in the area, which has established suitability of sub-thrust plays for petroleum accumulation.

Seismic acquisition and processing including pre-stack time and depth migration should be directed towards the enhanced imaging of the geometries of deep-seated structures in order to develop better understanding of the petroleum system such as migration pathways, thickness of sediments and other factors, e.g. permeability barrier etc.

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