SEQUENCE STRATIGRAPHY OF NON-MARINE AND MARINE DEPOSITS OF CAMBRIAN-PERMIAN SYSTEM OF SALT RANGE PAKISTAN

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To my beloved mother and father

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ABSTRACT

Sequence stratigraphy study has been successfully implemented for better understanding of sedimentary basins, its depositional controls, age, distribution of facies and prediction of petroleum play fairways. Any evaluation of sedimentary basin without sequence stratigraphic study will be leading to unreliable correlation of rock strata across basin with respect to age and facies distributions particularly while understanding is required to predict reservoirs. The sequence stratigraphy methodology has been used in present M.S research project as a tool for the study area located in southern Potwar region and Salt Range. This research project is aimed to understand the sequence architecture of Precambrian, Cambrian-Permian rocks using surface and subsurface geological information from out crops, wells and seismic data by correlating and delineating a reliable frame work of depositional system. One of key aim is to evaluate petroleum play of Cambrian and Permian section containing clastics reservoirs. Beside geological information the present work incorporated subsurface seismic data acquired in the area by OGDCL, POL and PPL. This task was supported by field work at three locations where observations were made for sequence boundaries, stratigraphic positions, contacts, facies analysis, thickness, structural features and other rock properties. This work incorporated limited data of wells and seismic survey due to permissions. Litho and sequence stratigraphic correlation in Salt Range is challenging due to change in facies and thickness in Cambrian and Permian levels. Stratal truncations at various levels are associated with the change in environment of deposition. Lateral changes in thickness and facies are not yet clearly understood based on only lithological characteristics. The Cambrian-Permian rock strata exposed in Salt Range and drilled in southern Potwar Basin demonstrated presence of sequence boundaries marked by unconformities and correlative conformities. In the study area three major sequences of the 2nd to 3rd order can be referred after study which are broadly based on lithology, stratal surface geometries, age and presence of three regional unconformable surfaces. Each sequence also indicated number of transgressive and regressive surfaces and where field data and well logs supported evidences and helped to configure internal architecture. The stratal architecture of Cambrian is difficult to understand for proper correlation however based on pronounced unconformaties and spatial change of stratal relationship using surface and well data a sequence framework has been established. The preserved Cambrian system in the study area demonstrated high energy marine to aeolian and to fluvial system of deposition and intercepted by unconformaties. The sequence boundaries and surfaces has been analyzed from base to top in this setting. The truncation of high energy marine cycle at base by aeolian phase has been marked by probable surface of sequence boundary while at top it is marked by regional boundary which is a base Permian unconformity. The understanding of overlying depositional cycles of Permian stratigraphy commencing from glacio fluvial system at base (marking a sequence boundary) and entering to fluvial marine above and subsequently followed by fluvial system and ultimately truncated at top after marine nonclastics (marking upper sequence boundary) sketches another major sequence in the study area.

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CHAPTER 1

INTRODUCTION

Sequence stratigraphic study is playing an embryonic role and became reliable part of geological science that is leading to provide fruitful result to oil and gas during exploration and development stages. The key focus of this methodology is to produce a genetic link of depositional strata and its distribution across the basins formed in specific time period. This subject focus to create a link between rock units based on lateral and vertical distribution of facies, presence and absence of rock units formed and removed or non-deposited during specific time frame in a specified geometry of basin that have been controlled by certain geological processes of tectonism, eustasy or non eustatic environment situation, erosion, deposition, compaction, diagenesis, etc. A reliable geological model based on sequence stratigraphic studies can be obtained by using complete geophysical, geological and biostratigraphic data, SEPM (2017).

Over past few decades' sequence stratigraphy has been increasingly used as a powerful tool in basin analysis. It is used as a means of interpreting stratigraphic relationship that is more reliable than lithostratigraphy. It has been undertaking accurate well and seismic data correlation to predict new play concepts and play fair way analysis and extend the geological predictions of lithological and facies distributions in undrilled areas. Sequence stratigraphy utilizes biostratigraphy and tectonics for a proper correlation and analysis of sedimentary rocks in a specific geologic time period. It helps restorations of paleogeography and establish models which can predict the distribution of sedimentary facies related to hydrocarbon reservoirs, source and seals rocks that deposited during a single sea-level rise to rise or fall to fall cycle (Wheeler, (1958); Middleton, (1973); Vail et al (1977); Galloway, (1989); Catuneanu, et al, (1998); Schwarzacher, (2000); Catuneanu, (2002); Embry, (2002).

According to pioneers of this methodology the stratigraphic studies that uses unconformities as a sequence boundary and their correlative conformities to a sedimentary successions formed in specified time is regarded as a Sequence Stratigraphy. This approach constraining geological time can be implemented to correlation of depositional settings (environments, like glacial, continental and marine). The sequence stratigraphy being a powerful tool in prediction of modern stratigraphic studies incorporates multiple features of stratigraphy like Seismic stratigraphy, Litho-stratigraphy, Cyclo-stratigraphy, Event-stratigraphy, and Biostratigraphy (Vail et al., 1991; Vincent et al., 1998; Emery & Myers, 1996).

In case of marine environment one episode of sea level fall and then subsequent rise controls a deposition of one sequence comprising of system tracts which are smaller units of a sequence and which may have distinct shape, size and type of facies. During this cycle of sea level fall and subsequent rise a complete sequence develops which consist of a lowstand systems tract (LST) formed during regression or fall of sea level to basin floor, followed by a transgressive systems tract (TST) and finally a highstand systems tract (HST). These system tracts are portioned by the boundaries defined as surfaces like transgressive surface, maximum flooding surface and etc. The sequence exposed in out crops, wireline logs from wells, cores, and seismic reflection data are key source of information beside fossil record in helping to build sequence stratigraphic model. The seismic data is mostly useful to study surface geometries defining the system tracts (truncations, onlaps, and downlaps) while lateral change in reflection character leads to define facies change or hydrocarbon accumulation. In seismic sequence interpretation, reflection terminations are marked and sequence boundaries and type of sequence is interpreted on the basis of conceptual models. Wireline logs from wells may be correlated based on log signature to establish a distribution of lithological units across the basin while core are direct indicator of presence of facies types and analysis of sequence boundaries. Wireline logs provides more details of litho units than seismic data. However integration of all the data set ultimately provide a reliable solution to understand sequence stratigraphic model and being successfully implemented in oil and gas sector (Vail, 1987, Emery & Myers, 1996).

Sequence stratigraphy has been used as a tool in evaluation of Cambrian and Permian rock strata in part of southern Potwar region and Salt Range. This research project of M.S aimed to understand the sequence stratigraphy of Precambrian, Cambrian-Permian rock strata present in the study area using surface and subsurface geological information from out crops, wells and seismic data by correlating and delineating a reliable frame work of depositional system in central and eastern Potwar basins (Figure 1.1). This study also evaluated petroleum play of Cambrian and Permian section containing clastics reservoirs. Beside geological information the present work incorporated subsurface seismic data acquired in the area by various companies like OGDCL, POL and PPL. This task was supported by field work at three locations where stratigraphic and structural data was collected. Observations were made for stratigraphic positions, contacts, structural features, rock texture, color and thickness of strata. This work incorporated sparse data of wells and seismic survey due to limited permissions and some of data was mot provided like biostratigraphy and dipmeter logs to support the emerging model of sequence stratigraphy.

The Cambrian-Permian rock strata exposed in Salt Range and drilled in southern Potwar Basin demonstrated presence of sequence boundaries marked by unconformities and correlative conformities. In the study area three major sequences of the 2nd to 3rd order has been referred after study which are broadly based on lithology, stratal surface geometries, age and presence of three regional unconformable surfaces. Each sequence also indicated presence of number of transgressive and regressive surfaces where field data and well logs supported evidences and helped to configure internal architecture. The stratal architecture of Cambrian is critical to understand for proper correlation however using surface and well data a sequence framework has been established which provided as base to understand distribution of rock lithologies across the study area. The preserved Cambrian system in the study area demonstrated high energy marine to Aeolian and to fluvial system of deposition and intercepted by unconformaties. The sequence boundaries and surfaces has been analysed from base to top in this setting. The truncation of high energy marine cycle at base by Aeolian phase has been marked by probable surface of sequence boundary while at top it is marked by regional boundary which is a base Permian unconformity. The understanding of overlying depositional cycles of Permian stratigraphy commencing from glacio-fluvial system at base (marking a sequence boundary) and entering to fluvial marine above and subsequently followed by fluvial system and ultimately truncated at top after marine nonclastics (marking upper sequence boundary) sketches another major sequence in the study area.

1.1 Location of the study area

The study area covers central and eastern part of Salt Range and extends in north to adjacent southern Potwar Basin (Figure 1.1). The major geological features present around the area includes Salt Range Thrust in south, Soan Syncline in north, Kalabagh Right lateral fault in west and Jhelum left lateral fault in east.

Following are bounding coordinates of study area shown in map.

A	33° 00’ 30. 00”
	71° 47’ 57. 00”
B	32 ° 20’ 50. 00”
	72° 03’ 47. 00”
C	33° 20’ 50. 00”
	73° 20’ 15. 00”
D	32° 44’ 20. 00”
	73° 37’ 25. 00”

The study area covers outcrop locations for sequence analysis and position of subsurface geological information obtained through drilling of wells and seismic data. Three surface geological locations covered in this study includes Khewra Gorge, Nilwahan Gorge and Ara Bashrat area as shown in location map. While lithological and well log data used from five wells is also indicated along with seismic line location.

The area of study is topographically referred as Potwar plateau that is uplifted against Jhelum and Mianwali Plains and is broadered in south and west by pronounced mountain ranges of Salt and Tran Indus Ranges. The undulating features of this plateau resides in a ranges 1500 to 1700 feet meters above mean sea level. The ground elevation of Salt and Trans Indus ranges varies from 2000 to 3300 feet meters above mean sea level. The area is well connected with a good network of roads like M-2 motor way and national high ways and is well populated by towns and villages. Numerous lakes and water channels and rivers are present in the study area with active course of water flowing to major rivers. The area is cultivated with crops and vegetation can be also seen from coarse to thin level in the form of trees and herbs. The major towns in the study area are Chakwal, Khewra, Kallar Kahar, Pind- Dadan Khan, Gujar Khan. Talagang.

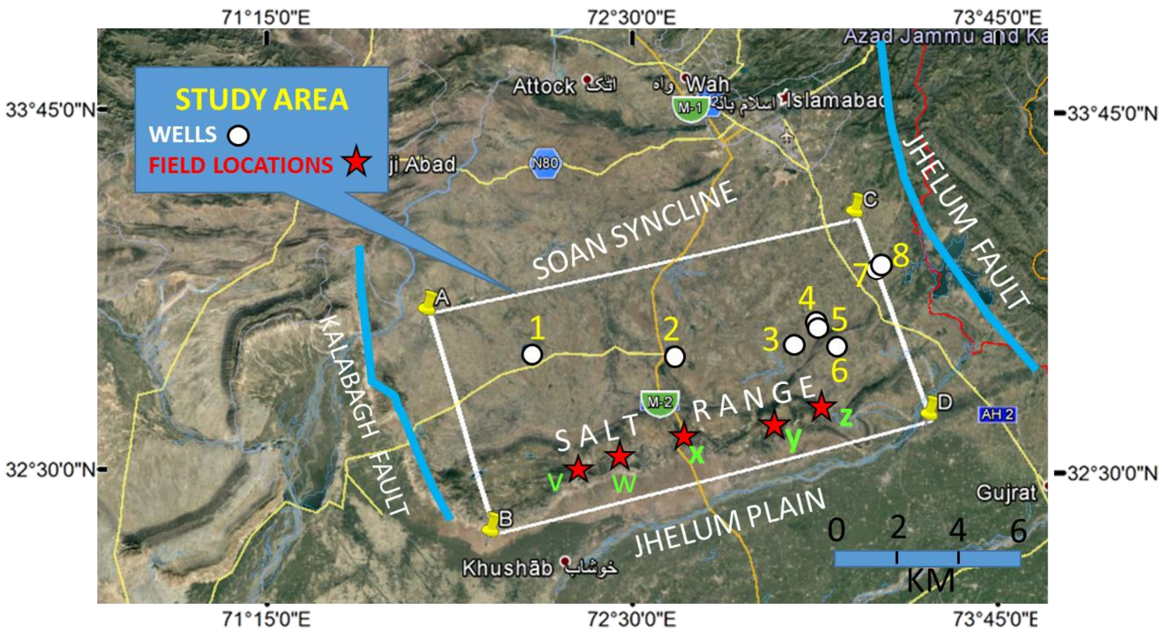

Figure 1.1 Location map of study area. Red stars show surface field locations (V, Khatapail, W Nilawahan, X Motorway, Y Khewra gorge, Z Choa Syedian Shah-Diljaba, Ara Bsharat), White circle show well locations (1 Dhermund, 2 Balkasar POL, 3 Kal, 4 Rajian, 5 Daiwal, 6 Hayal, 7-8 Missa Kaswal 1-3).

1.2 Problem statement

Litho and sequence stratigraphic correlation in Salt Range is challenging due to change in facies and thickness in Cambrian and Permian levels. Stratal truncations at various levels are associated to change in environment of deposition. Lateral changes in thickness and facies are not yet clearly understood based on only lithological characteristics. The stratal relationship of Cambrian is critical and require clear understanding of high energy marine to Aeolian and to fluvial system of deposition and presence of unconformities or sequence boundaries from base to top. The truncation of high energy marine cycle at base by Aeolian phase might be indicating the presence of sequence boundary.

The internal characteristics of the Aeolian sands of Khewra Formation suggests its deposition perhaps strongly controlled by water table dynamics and where the development of multiple horizontal surfaces are truncated and it forms the basal boundary. It appear that relative sea level rise might effected the depth of water table in Aeolian terrain and tabular strata deposition of clastics of Khewra might be related. The Cambrian system at shallow level is fluvial in nature and gradually dominated by marine influence (tidal flat deposits) thus require more likely understanding both from out crops and well data to encounter presence or absence of lithologies.

The understanding of overlying depositional cycles of Permian stratigraphy while probing from glacio fluvial system at base and entering to fluvial marine above and subsequent truncation again by fluvial system remains challenging. This Permian system again influenced by marine deposition at top. Under these circumstances the stratigraphic distribution requires understanding of sequence boundaries to predict lateral correlation in Potwar Basin and to study the facies control. Basal Permian Tobra Formation being regional unconformity mark a prominent sequence boundary and show lateral changes in lithological units. The question for presence of reservoir and seal lithology could not be better understood depending alone on lithostratigraphic correlations. The structural tarps encountering strata units might not be reflecting real thickness of stratal units due to thrust related repetition and of steeply dipping flanks where well might have been landed. The change in thickness associated with erosion or depositional pinchouts is not known and requires understanding, its type and relation to sequence boundary.

1.3 Objectives and Scope

This MS project has been aimed to conclude following objectives:

1. Over all understanding and identification of tectonics and associated structural styles.
2. Evaluation of existing Cambrian-Permian stratigraphic units exposed and drilled in the area of study.
3. Establishing sequence stratigraphic frame work using analysis of outcrops and well logs for defining sequence boundaries, type, and order of cyclicity.
4. Identification and interpretation of stratal surfaces, depositional packages, lithofacies and depositional environments, within chronostratigraphic framework.

5. Recognition of surface types like transgressive, regressive, maximum flooding, unconformities and correlative conformities.
6. Definition of system tracts supported by well log correlation and its signature evaluated through seismic data.
7. Study the outcrop of rocks contributing to a petroleum play in the prospectivity of Potwar basin for hydrocarbon discoveries for Cambrian-Permian level.
8. Identification of erosional truncations and pinchouts in context with stratigraphic play.
9. Identification of structural style and evaluation of repeated thickness due to thrusting and complex folding.

1.4 Methodology

The research work has been achieved through following phases; (Figure 1.2 is a flow chart diagram out lining scheme of work flow).

1.4.1 Phase-I: Data Collection

The required data of topo sheets, reports, and previous maps were collected for conducting field work in Katha Pail, Khewra Gorge and Choa Syedan Shah areas. Beside this 2d seismic and well data from Land Mark Resources was collected after approval from Directorate General Petroleum Concession.

1.4.2 Phase-II: Geological Field Work in Katha Pail, Khewra Gorge and Choa Syedan Shah.

Facies analysis of Cambrian-Permian strata, understanding of depositional system and most likely extent in Potwar Basin has been achieved from visiting outcrops in Khata Pail, Nilawhan and Khewra Gorges and Choa Syedan Shah area. However, this work was not timely archived due to lock down and covid-19 issues and closing of facilities to mobilize in field. The publish information from previous work has been be incorporated during these field visits to validate rock type, geometry of deformation, types of facies, thickness and age. Lithological markers has been analyzed to integrate with probable sequence boundaries. The sequence, parasequence, system tracts, various unconformities has been tentatively established for depositional and sequence stratigraphic modeling.

1.4.3 Phase-III: Data Analysis, interpretation and integration of sequences with 2d seismic and well data of Potwar Basin.

In this stage analysis of data was performed by using Geographix software to integrate results of well data (formation tops, thickness, lithology, log response of SP, GR and Resistivity) and seismic data (correlation of sequence boundaries using time depth chart, reflection character, and impudence contrast). Unfortunately, a reliable time depth data (well velocity or check shot) was not allowed and provided for proper correlation with lithological markers between seismic and well lithologies. Necessary isopach maps were prepared to study abnormal thickness changes associated to structural deformation and repetition. The data analysis and integration stage included following steps.

1. Project setting for proper global position using projection system of software.
2. Review of well data (logs and lithology) to understand nature of lithological and sequence boundaries and its framework in central and eastern Salt Range and Potwar Basin to a level of Cambrian and Permian.
3. Correlation of well base sequences and lithological boundaries among wells and with outcrop stratigraphy.
4. Definition of depositional model type after correlation and order of cyclicity of sequences.
5. Correlation of established sequence frame work with seismic data using time depth relation for correlation and lateral distribution in the study area.
6. Picking of onlapping, truncations, unconformities, channels, and other signatures within seismic data of Cambrian-Permian levels based on quality.
7. Petrophysical evaluation using well logs for porosity and fracture determination for Cambrian- Permian reservoirs.
8. Select and extend reservoir or other horizons through loop and tie positions using reflection character and continuity across structure.
9. Pick discontinuities of seismic reflections for defining fault planes and zones.

10. Delineation of thrust faults and evaluation of repetition of Cambrian- Permian strata in wells.
11. Define most likely a reservoir fairway in southern Potwar Basin based on available data and predict associated risk associated to data limitation and quality.

1.4.4 Phase-IV: Report Writing and Presentation

This stage has been achieved using all the evaluated data and compilation of results as per required format. The results in this document has been supported by data like images prepared in work stations and modified from previous published information. The necessary tables have been added using excel software for charts and tables. The document of the thesis has been submitted in paper (hard copy) and digital format for record purpose as per requirement.

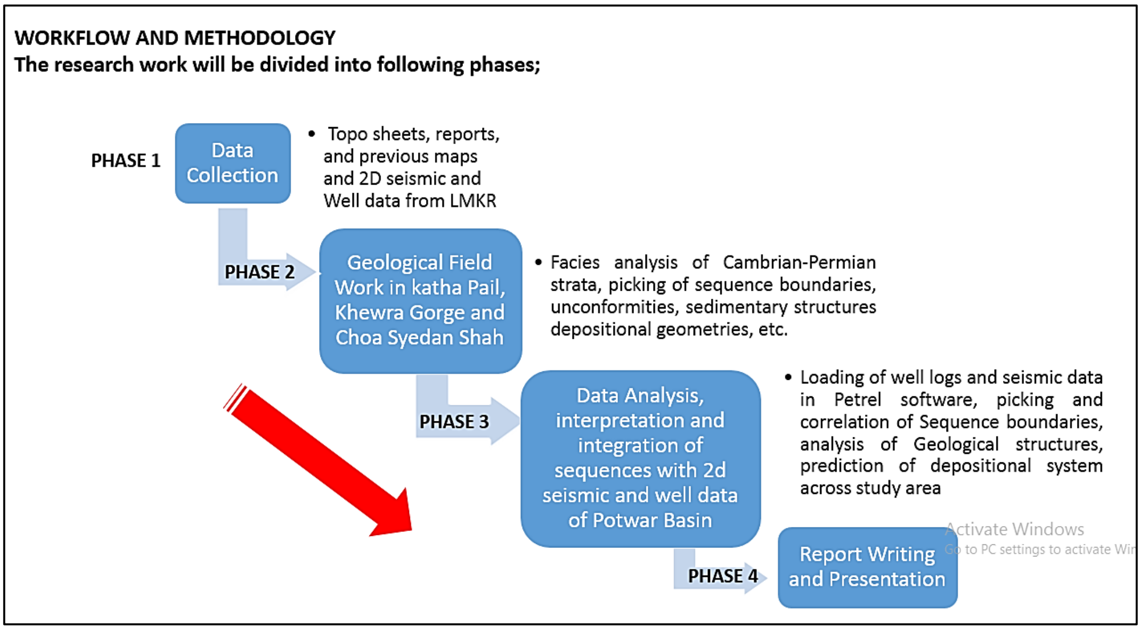

Figure 1.2 Scheme of work flow adopted during project.

1.5 Data Utilized

The data set provided by LMKR and the data available in student domain of archive of Department of Earth and Environmental Sciences Bahria University was used in this work (Table-1).

Table 1.1 Shows data available for study.

DATA AVAILABLE				
SEISMIC LINES		Orientation	WELLS	
1	O/825-SR-55	dip line	1	DHERMUND -1
2	O-815-KK-27	dip line	2	BALKASAR OXY -01
3	O-984-TLG-15	dip line	3	RAJIAN-1
4	O/855-CW-06	strike line	4	MISSA KASWAL-1
5	O-994-GNA-15	dip line	5	DAIWAL-1
6	O/932-GJN-25	dip line	6	KAL-1
7	O/932-GJN-13	strike line	7	MISSA KASWAL-3
8	O/925-GJN-08	dip line	8	HAYAL-1
9	O/-925-GJN-10	dip line	MAPS	
10	O/925-GJN-14	strike line		
11	O/932-GJN-31	Strike line	1	Geology Maps of Salt Range
12	O/932-GJN-37	dip line		Dr. Gee (1998)
13	O/994-GNA-12	strike line	2	Geological Map of Pakistan
14	O/994-GNA-15	dip line		GSP (1993)
15	O/942-GJN-36	dip line	3	Topo sheets Salt Range
16	OX-PBJ-09	strike line		Survey of Pakistan
17	OX-PBJ-04,03	dip line		
18	KSL-07	Strike line		

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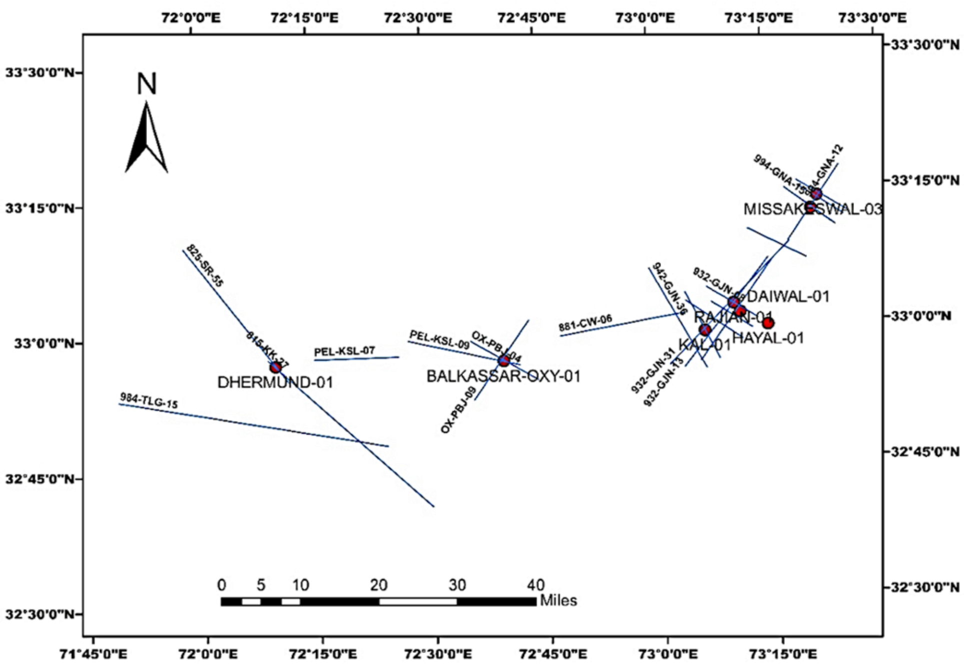


Figure 1. 2 Location map of seismic and well data location.

CHAPTER 2

REGIONAL GEOLOGICAL SETTING OF STUDY AREA

2.1 Summary of tectonic setting and structural style

The study area is a part of Potwar Foreland Fold and Thrust Belt developed in Upper Indus Basin after collision of IndoPakistani Plate with Eurasia in Paleogene time. The northward drift of the Indian Plate and subsequent collision with Eurasian continent resulted in the creation of Himalayan orogenic belt which is characterized by complex geometry and having northeast-southwest general trend in Pakistan which changes to northwest-southeast in Indian side (Figure 2.1). The collision between Indian and Eurasian Plate started about 55 Ma ago at the rate of 5mm/a (Jadoon et.al., 2005; Powel, 1979). The subcontinent was separated from the Gondwanaland about 130 Ma ago (Johnson et.al, 2009). The opening of Indian Ocean in the south and squeezing of the Tethys Ocean in the north started about 130 Ma when Indian Plate progressed its northward drift. From north to south Main Karakorum Thrust (MKT), Main Mantle Thrust (MMT) Main Boundary Thrust (MBT), Salt Range Thrust (SRT) demarcate the major subdivision of the collision zone of the Himalayas (Ahmed et. al., 2013).

During Late Jurassic to Cretaceous the subduction of Neo-Tethys beneath the Asian Kohistan Island Arc (KIA) occurred. (Khan et al., 2011 & 2002, Hamidullah and Onstot, 1992). The MKT is resulted of this collision between Karakorum Plate in the north and KIA in south (Pudesy et.al., 1985). The ocean present between Karakorum Plate and KIA closed in late Cretaceous (Treloar, 1989; Yoshida et al., 1997). Due to continuous subduction between KIA and Indian Plate the ocean present in between was also closed in Eocene along MMT which is also known as Indus suture zone (Gansser, 1981; Tahirkheli, 1982). The convergence is still ongoing since Eocene and resulted to form major fold and thrust belt in south. The MBT and SRT are major members of this fault system which bound the Kohat and Potwar Plateau in north and south respectively

(Ahmad et al., 2004). Deformation in the Indo-Pakistan Plate region can be divided into internal and external zones. The internal zone characterizes large scale metamorphism and ductile deformation along with formation of intrusive and extrusive igneous rocks. The southern boundary of internal zone is marked by Nathiagali Thrust along which Hazara Slates thrusted over the Mesozoic-Cenozoic shelf sequence of Margalla Ranges. The external zone is divided into three tectonic regions which includes hill Ranges, Potwar and Kohat Plateau, Salt Range and Punjab Plain (Coward et al., 1988).

The Potwar Plateau area forms southern part of the Himalayan deformation (Figure 2.1). The Himalayan zone demonstrate bending of fold belt in the form of arcuate lobes and syntaxes. Beside a major Hazara Kashmir Syntaxil bend in north of Pakistan, the bending of fold belt can be seen along southern margin of Kohat-Potwar Basin among Salt and Tran Indus Range and Suleiman Range. The syntaxial bending among Salt and Trans-Indus Ranges also mark zones of strike-slip, oblique-slip, and normal faults and lateral thrust faults. Indo-Pakistani shield in south show monoclinal geometry and interrupted by exposure of Pre-Cambrian Sargodha High (Farrah et al., 1977).

The Potwar basin is complexly deformed fold and thrust belt of north Pakistan where Precambrian (?) to Cenozoic sedimentary strata has been involved in folding and faulting (Figure 2.2). The foreland fold and thrust belt has been detached at the base of Salt Range Formation from the underlying basement. The salt tectonism has played a significant role in deformation where deeper level salt and gypsum rock units moved above the younger rocks from its initial stratigraphic position due to flowage behavior during regional compressional tectonic stresses. The seismic data demonstrate detachment of folds and thrust faults above basement. The deformation style is Potwar foreland basin varies from north to south and east to west due to certain tectonic controls, boundary conditions and detachment levels. The key boundary features are Main Boundary Thrust (MBT) in north, Salt Range Thrust (SRT) in south, Jhelum Fault in east, Kalabagh Fault in west and Soan Syncline in center. The MBT has uplifted the Mesozoic-Paleogene rocks of Margalla and Kala Chitta Ranges over the Miocene molasse sediments of Potwar Foreland Basin while Pre-Cambrian to Paleogene platform rocks have been uplifted against Jhelum Plain along MFT (Figure 2.2). The deformation changes from imbrication to gentle folding between Kala Chitta – Margllah ranges in north to Salt Range in south within a width of about 130 km of Potwar Basin, The overall deformation style along north south cross sections has been illustrated through the central Salt Range and Potwar Plateau from MBT to SRT (Figure 2.3). The area to the north of Soan River is complexly folded and imbricated and regarded as north Potwar Deformed Zone, NPDZ. In this imbricated zone seismic data also demonstrated presence of detachment at shallow Miocene level other than deeper one present regionally at Precambrian Salt Range formation. The dis-concordant relation among the folding from shallower to deeper level is another phenomenon seen as a structural style. In the west the NPDZ merges with Kohat Plateau along strike direction In the south of Soan Syncline the deformation is characterized by folding and thrusting of strata which culminates at emergent Salt Range thrust (SRT) where Precambrian, Paleozoic, Mesozoic, and Paleogene rock strata and appear as a thrust sheet and emplaced on younger and un-deformed Punjab foreland strata (Jaswal et al. 1997; Jadoon et al.1997, 1999).

The deformation in the eastern and northern Potwar Basin is severe as compared to the west. The structures in eastern zone of Potwar Basin are tightly folded and popped up by thrust and transpressional faults. This zone show a change in a structural trend from NE-SW to NNE-SSW in direction and culminated obliquely by Jhelum re-entrant. The change in structural geometry, alignment, trend and tight folding is related to southward movement of thrust sheet of Potwar Basin supported by detachment level in Salt Range formation. This deformed sheet form a western part of Hazara Kashmir syntaxial bend developed against Jhelum strike slip fault. The structural style in western part of Potwar Basin is monoclinal with gentle folding and the sheet is verging south in direction along with transpressioanl zone of deformation preserved along Kalabah strike slip fault. The detachment level in this part of Potwar basin has been reported in Pre-Cambrian Salt Range Formation, The study area resides in southern part of Potwar Basin and extend southward through Diljabba thrust sheet to Salt Range outcrop. It stretches from structural trends of tight folding and popups in east (Missa Kaswal) to subthrust structures of Kal and Rajian, and gently folded and thrusted strata of Balkasr-Joyamir and to west towards monoclinal dipping areas near Kalabagh faults (Figures 1.1 and 2.6). The Potwar region is well known oil prone province where number of commercial discoveries has been made from structural traps at Paleogene-Cambrian level from clastic and carbonate reservoir.

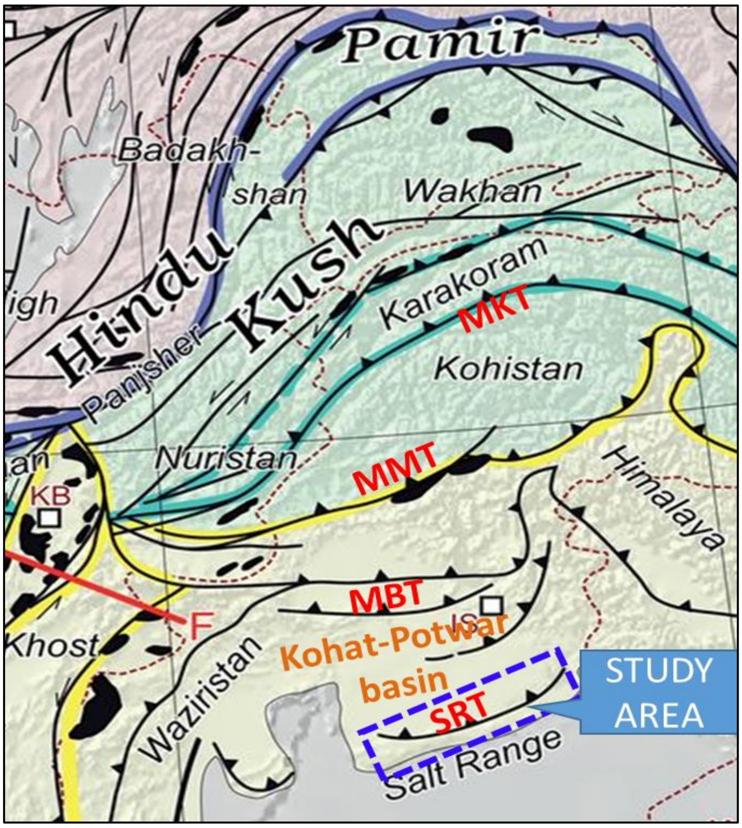


Figure 2.1 Tectonic map showing salient Features of collision of Eurasian and IndoPakistani plates in Pakistan and adjacent areas, modified after Agemar (2015).

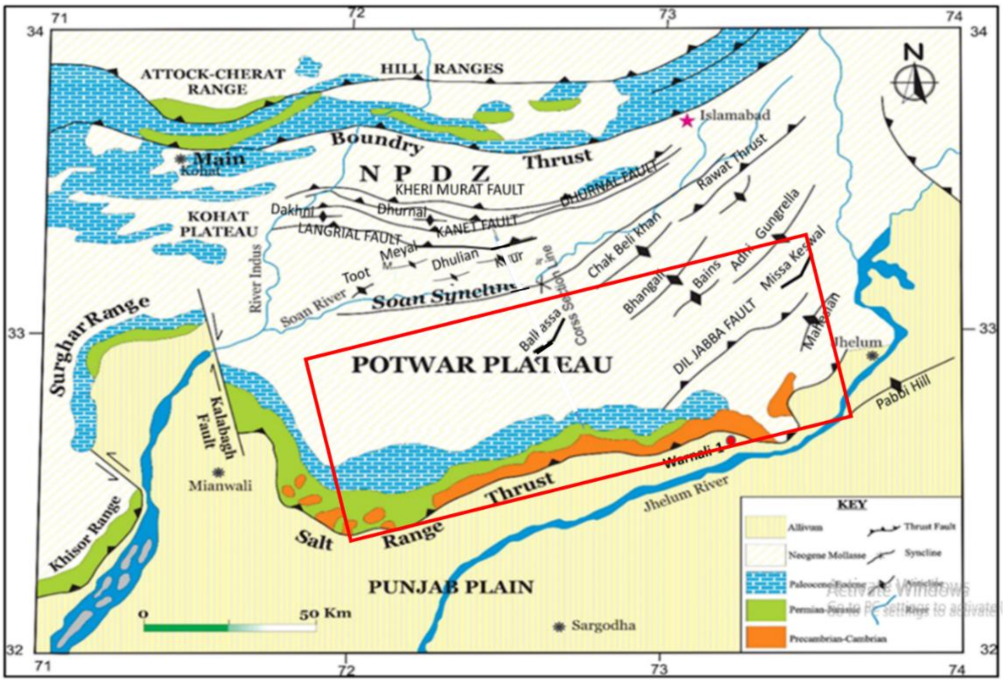


Figure 2.2 Geological Map of the Salt Range/Potwar Plateau showing important geologic and tectonic trends, red box show study area (modified after Jaswal et al., 1997).

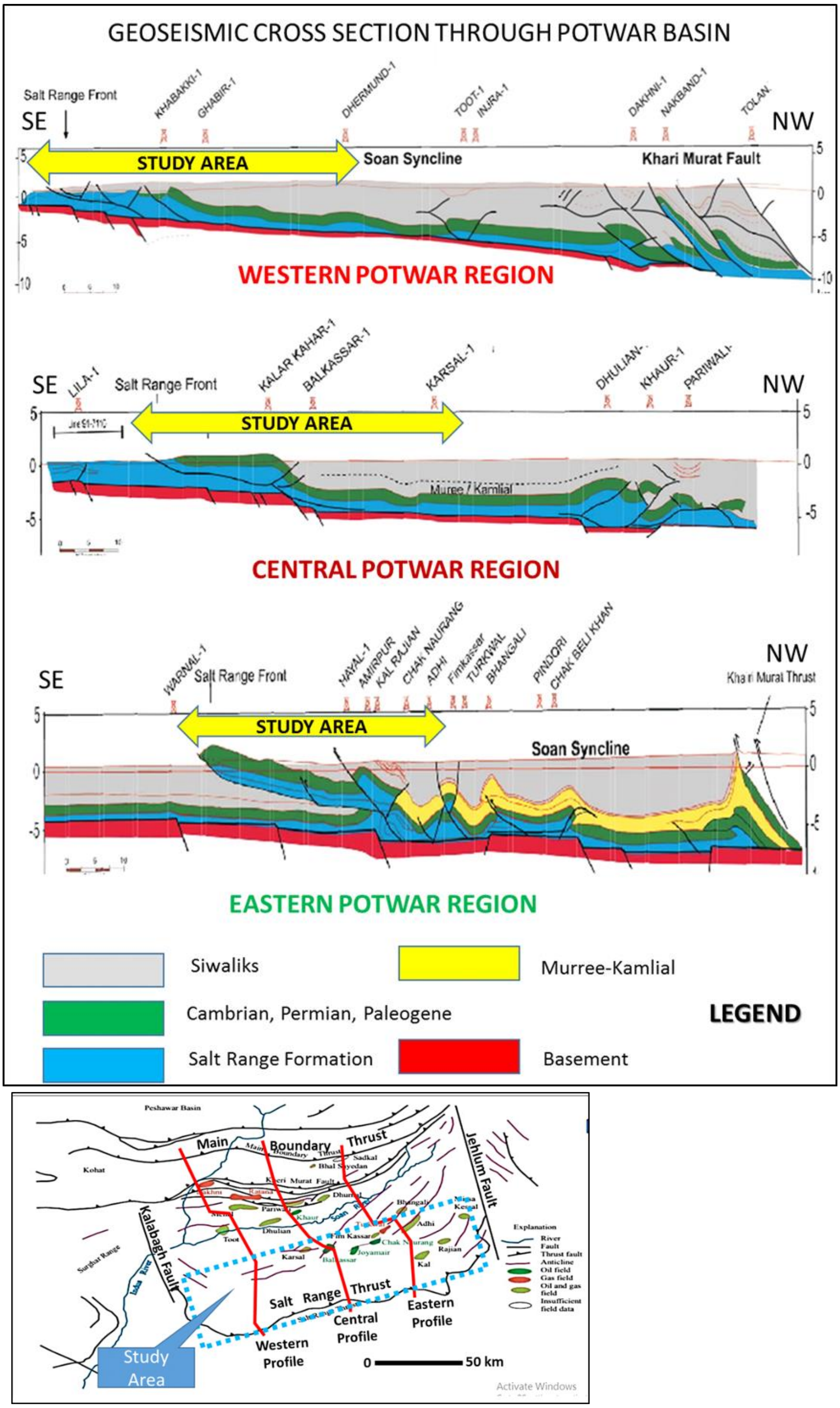


Figure 2.3 Geoseismic profiles through Potwar Basin (modified after Mughal et al., 2007). Study area is shown with yellow arrows.

2.2 Stratigraphic setting of Salt Range and Southern Potwar Basin

The stratigraphic information of Potwar Basin is known from peripheral outcrops (Salt and Trans Indus Ranes, Kalachitta and Margallah Ranges) and wells drilled in and adjacent to Plateau. Stratigraphic setting reveal a diversified distribution of lithologies which started to deposit in the basin that belongs to Gowndwana assemblage prior to pre-rifting stage of IndoPakistani Plate. A thick cover of clastic and nonclastic mainly marine and partially non marine strata (Pre-Cambrian to Permian) of Paleo Tethys domain is associated to this Gowdwana Basin. The information of sedimentary cover is known from out crops in Sargodha Hills, Salt and TransIndus Ranges, Kala Chitta, Margalla Ranges and from the well data (Figure-2.2, 2.4 and 2.6). The post Permian stratigraphic sequence is preserved above Gondwana sedimentary units and that has been accumulated during rifting stage (rifting of Indo-Australian, Madagascar-Indian from African Plate and finally Indo-Pakistani from Madagascar), occurred during Triassic to Cretaceous. The clastic and nonclastic rock units of this time period are reported in Potwar and surrounding region of Kohat and Bannu Basins through drilling of wells and outcrop preserved in Salt and Trans Indus Ranges, Kala Chitta and Margallah Ranges (Kadri 1995).

These lithologies of Mesozoic time resides below Paleocene-Eocene stratigraphic units in Potwar Basin and surrounding region and represent deposition of carbonates and clastics in shelf to slope and abyssal plain settings of Titian basin. The collision of Indo-Pakistani Plate with Eurasia during Tertiary has terminated the deposition cycle of marine strata by closing of Tethys Sea. The uplifting of Himalayas as a result of tectonic collision re-configured the basin setting into foreland and hinterland regions. The foreland region received a piles of fresh water sediments accumulated during Miocene to Quaternary times after erosion from uplifted Himalayan Mountains. These fresh water sediments are exposed and preserved in sub crop above marine strata in Potwar region (Warwick et, al, 2007). The distribution and lateral continuity of entire lithological column ranging from Eo-Cambrain to recent is intercepted by number of unconformities present at multiple levels. The erosional removal and non-deposition has been observed in the lateral distribution and continuity of lithologies across the basin. The prominent unconformities are present at following levels (Figure 2.4).

- **Base Pre-Cambrian unconformity**

This interface is believing to be an angular unconformity and present between metasediments and Salt Range formation and not well understood for lateral presence, continuity and type due lack of sufficient drilling data. The limited information came from Warnali well-1 in Jhelum Plain south of Salt Range. The nature of unconformity has been assumed based on change from metasedimentry contact with sedimentary unit (preferably Salt Range Formation). No any evidence of this contact is seen in Sargodha outcrop area.

- **Top Lower Cambrian unconformity.**

This unconformity can be marked between Khewra Sands and Kussak Formation and has been observed in the outcrop area of Salt Range in Khewra gorge. Its lateral extent is not well marked and require detail mapping and analysis of well data. This surface has been analyzed during present sequence stratigraphic work.

- **Top Cambrian unconformity.**

This is a significant and very prominently developed unconformity across Potwar Basin and adjacent peripheral ranges. Based on well data and outcrop correlation this surface represents angular erosion and removal of mid Cambrian (Kussak, Jutana and Baghanwala) lithologies in western Salt Range and north of southern Potwar Basin, Figure 2.4 and 2.5. In Potwar Basin and peripheral ranges this unconformity represents deep erosion prior to ice age time span marked by early Permian glacial deposits. It may be also marked as surface of non-deposition as the stratigraphy from Ordovician to Devonian is missing in Potwar region. However, it has been reported in Peshawar basin and Higher Himalayan region. Therefore, it has been inferred that Kohat-Potwar Basin was part of Gondwana residing in southern polar region under ice age. The base Permian glacial and fluvial deposit of Tobra Formation marked deposition of sediments after glacial melting. The Tobra Formation represent facies change from east to west in Potwar Basin and Salt Range masking top of surface of unconformity, Figure 2.4 and 2.5.

- **Top Mesozoic unconformity.**

This surface is representing angular removal of multiple stratigraphic units ranging from Lower Permian to Top Cretaceous levels which are presently trending north south but erosionaly removed from west to east in direction across Upper and Middle Indus basins. The mapping from well and seismic data and support from outcrops in Salt and Trans Indus Ranges show removal of Cretaceous to Permian lithologies after regional tilting, Figure 2.4 and 2.5.

- **Top Eocene unconformity.**

This surface is known as regional unconformity in Kohat-Potwar Region and show angular relation with underlying lithologies beside change from marine cycle of facies to non-marine cycle. The unconformity is well developed in Potwar Basin and can be analyzed in outcrops exposed in Salt and Trans Indus, Kala Chitta and Margalla Ranges, Figure 2.4 and 2.5.

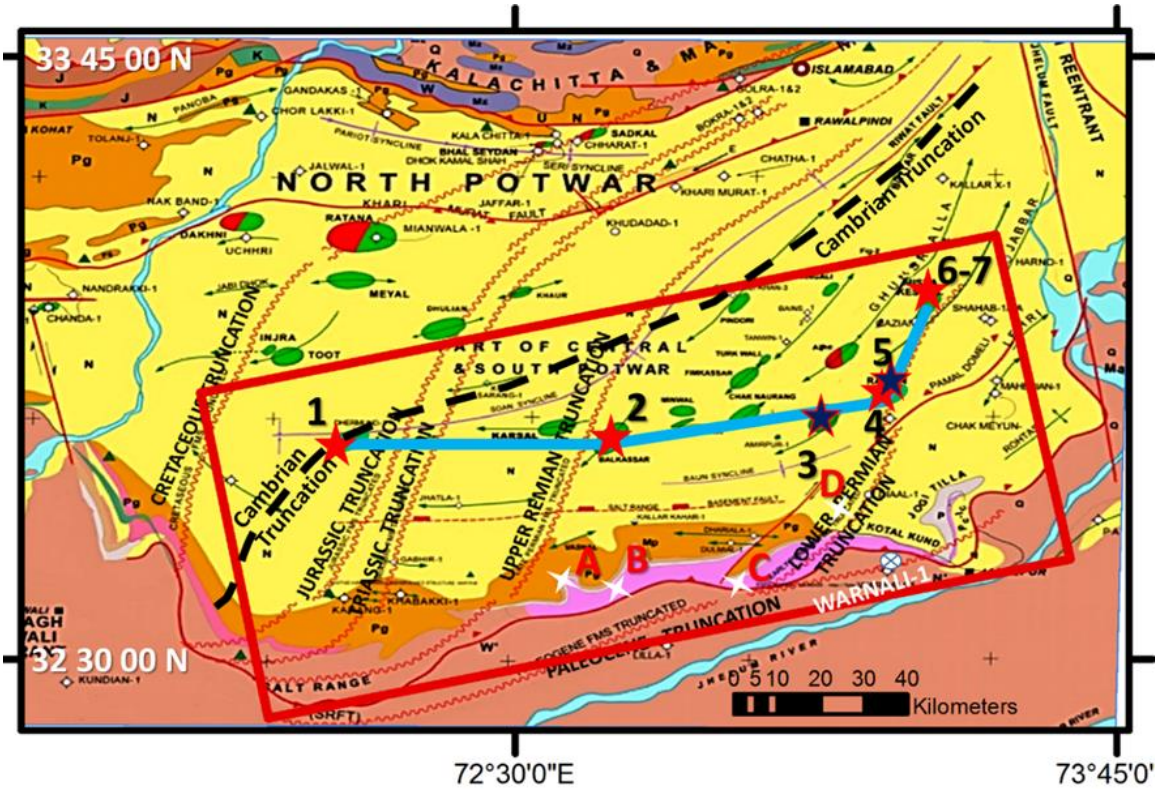


Figure 2.4 Stratigraphic truncations in Potwar Basin and adjacent hill ranges (modified after Mughal et al. 2003).

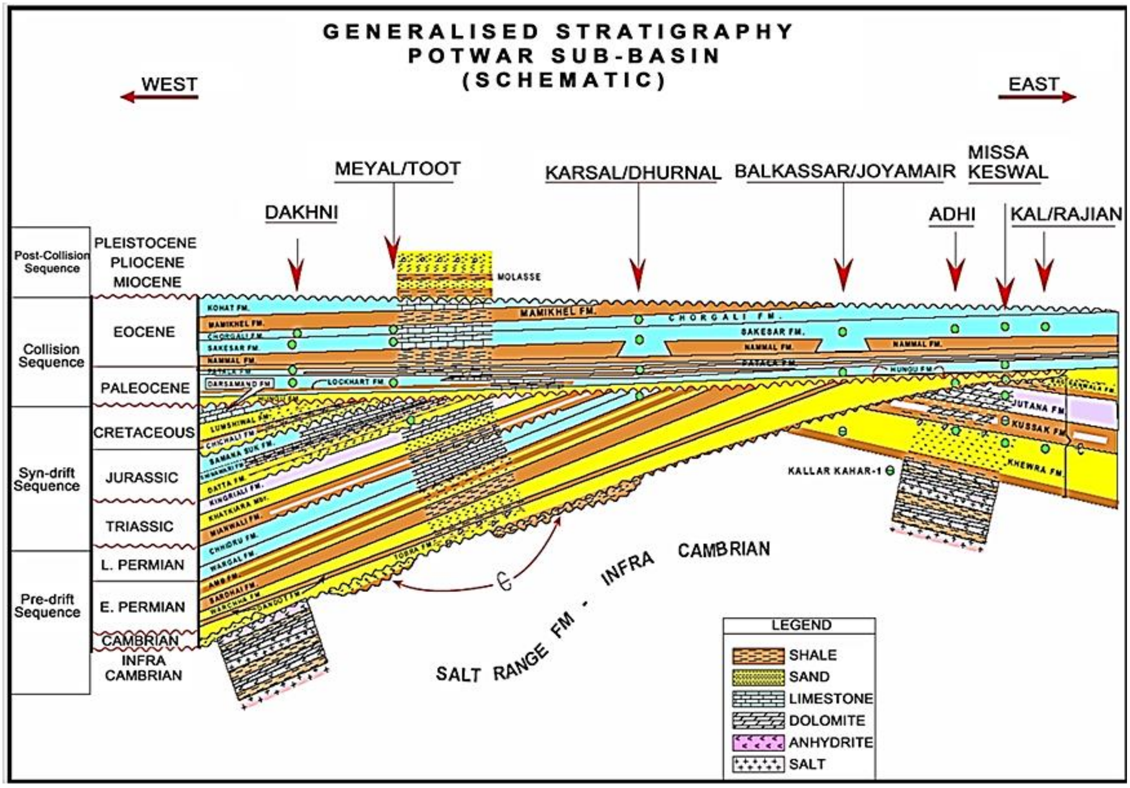


Figure 2.5 East west cross section showing stratigraphic truncations in Potwar Basin (modified after Mughal et al. 2003).

The overall summary of stratigraphy and lithological distribution in southern Potwar Basin and adjacent Salt Range has been discussed in Chapter-3. In general Eo-Cambrian evaporates (Salt Range Formation) and shallow marine to non-marine Lower to Middle Cambrian sequence of sandstones, shales and dolomites (Jhelum Group) are uncomformably overlain by a thick Permian clastic and carbonate succession (Nilawahan and Zaluch Groups) in the study area. The angular unconformity at the base of Permian has widespread distribution and marked by facies of Tobra Formation. The Permian sequence is thickest (700 m) in western Salt Range but it becomes thinner eastward

A paraconformity separates the Mesozoic shelf (Tredian and Datta Formation) and shallow marine deposits (Mianwali, Kingriali, Shinwari and Samana Suk Formations) from the Paleozoic sequence. The exposed Mesozoic sequence is thickest (1,000 m+) in western Salt Range, but it has been greatly attenuated eastward due to erosion and overlap by the Cenozoic sequence. There are a number of minor unconformities indicating disruption is sedimentation and instability in the foreland sedimentary basin during the Mesozoic. The exposed and drilled lithologies along Salt Range from Pre Cambrian to Paleogene platform rocks are show in Figures 2.4 to 2.9.

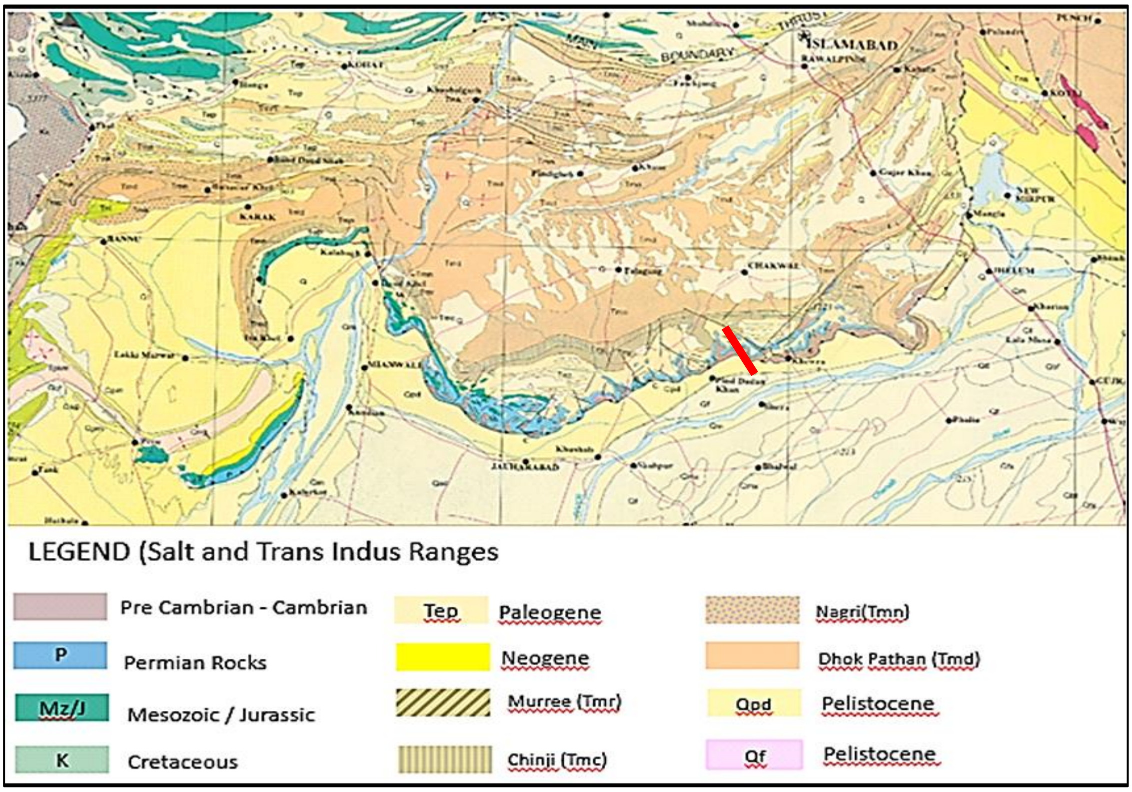


Figure 2.6 Regional geological Map of Kohat-Potwar and Salt Range area (modified after Qureshi et al., 1993). Thick red line showing location of Geoseismic profile.

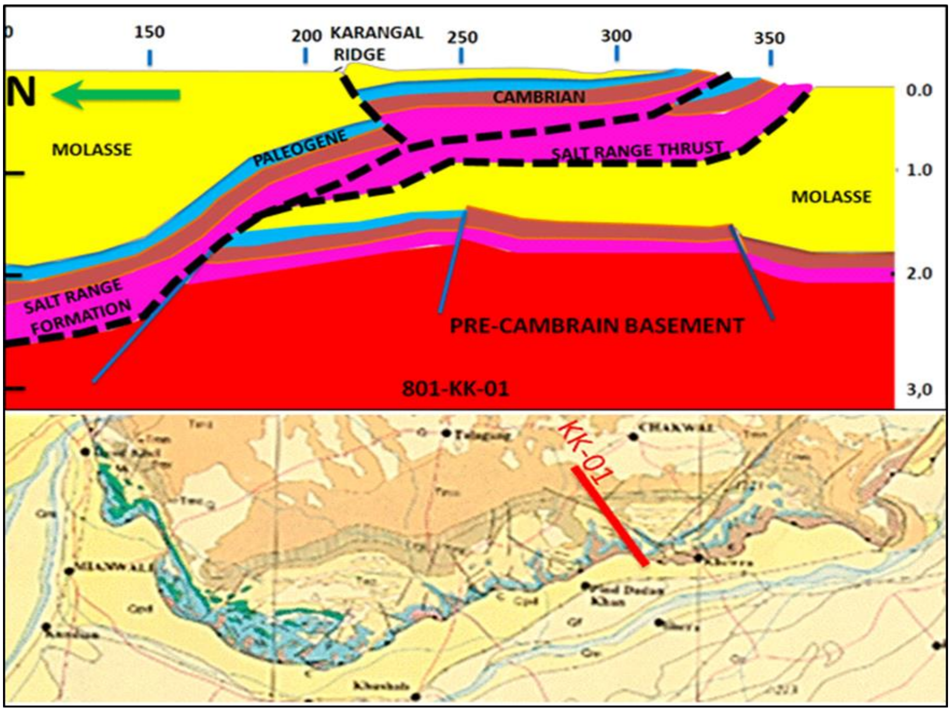


Figure 2.7 Geoseismic cross section elaborating salt range uplift and related deformation (modified after Tahir et al., 2015).

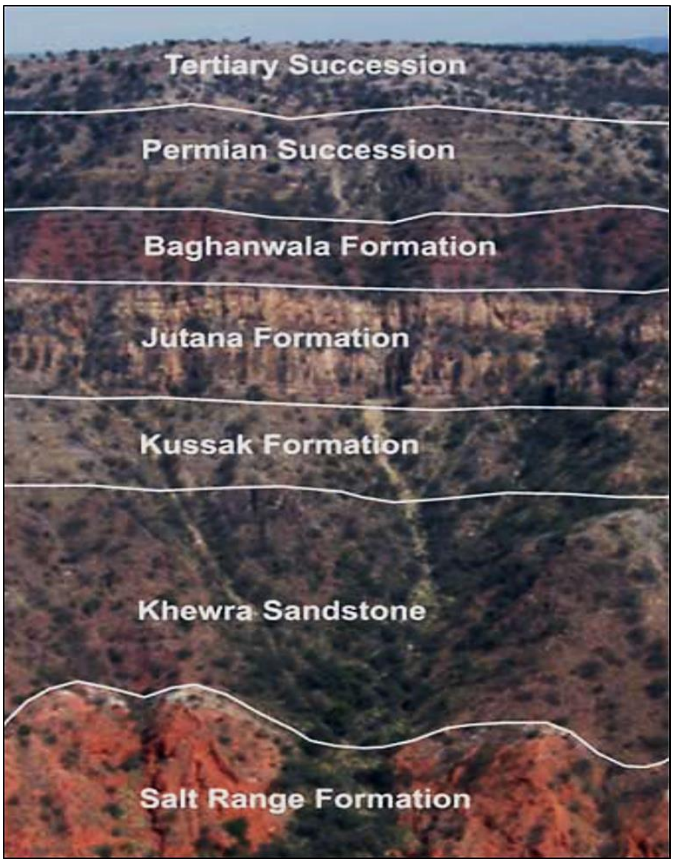


Figure 2.8 Figure showing lithology exposed in Salt Range.

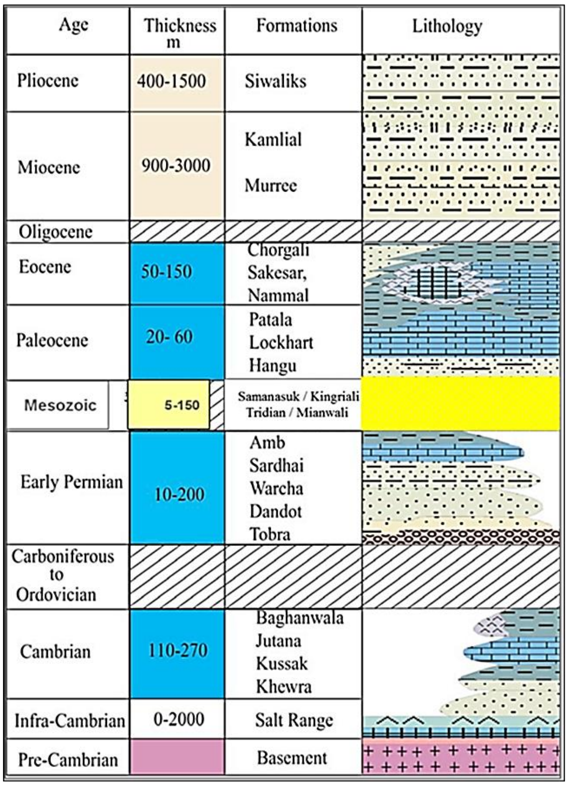


Figure 2.9 Generalized stratigraphy of central and eastern Salt Range and southern Potwar Basin (modified after Aamir and Siddiqui 2006).

CHAPTER 3

LITHOSTATIGRAPHY OF SALT RANGE AND SOUTHREN POTWAR BASIN AND SEQUENCE STATIGRAPHY OF CAMBRIAN-PERMIAN LEVEL

This Chapter deals with stratigraphy of Salt range and southern Potwar basin by taking into consideration of lithology exposed and drilled in the area of interest (Figure-2.4 and 3.1). The compilation of the chapter is based on observation at outcrop locations has been added after field studies to validate the information of lithology and lateral distribution. These field studies were focused to Khewra Gorge, Choa Syedan Shah Road section, Ara Basharat - Krangal valley, Katha Pail road section and Nilawhan Gorge.

This chapter also deals for evaluation of lithology and facies observed by numerous authors and their validation after present field work and with the well data for Cambrian and Permian levels. The field work focused to delineate probable boundaries which can be a candidate surface for fitting in sequence stratigraphic frame work in the area of study. The correlation has been established using GR and SP logs available for the study to establish sequence stratigraphic frame work using stratal pattern and defining system tracts. The outcome of this work stands as a speculative sequence stratigraphic model proposed for the Salt Range and southern Potwar Basin.

There is a major issue is to meet the challenge for accepting the model as per work flow shown in Figure-3.2. The key concerns are related to data limitations, its reliability, quality of logs and seismic, lack of velocity information, conflicts in ages based on biostratigraphy, lack of core data interpretation and ultimately choice of order of cyclicity (Ist, 2^{nd}, 3^{rd}, 4^{th} or higher). One of the key challenge is to work with the logs of compressional structures which may have accounted repetition of strata and where dip meter or higher quality of seismic image might have helped. Unfortunately dip meter data was not available and the available seismic data was of limited support to understand the

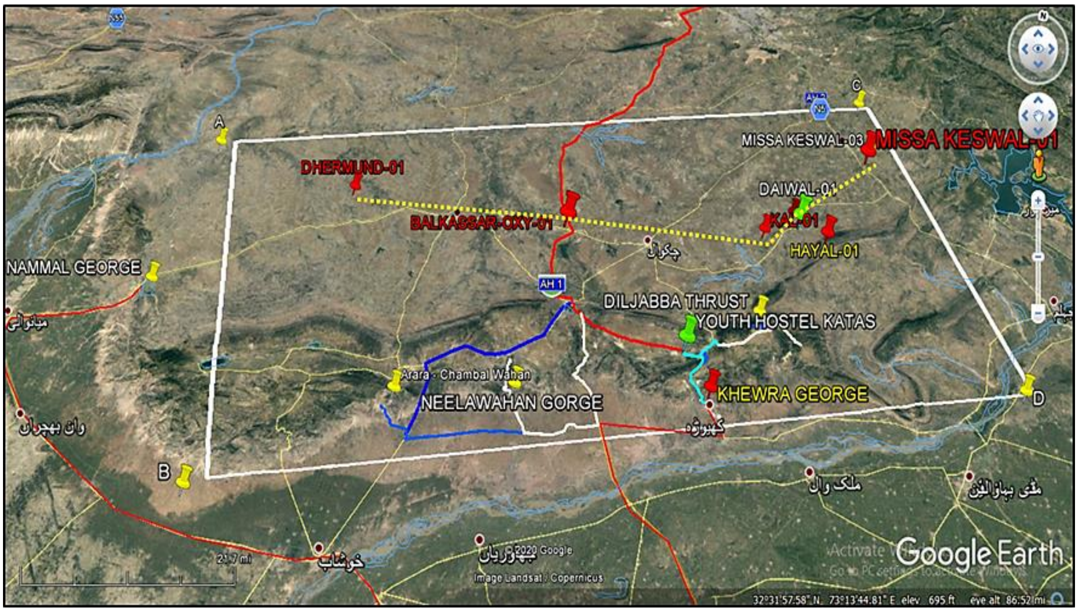


Figure 3.1 Google map showing traverse of correlation between wells and routes selected to reach field location

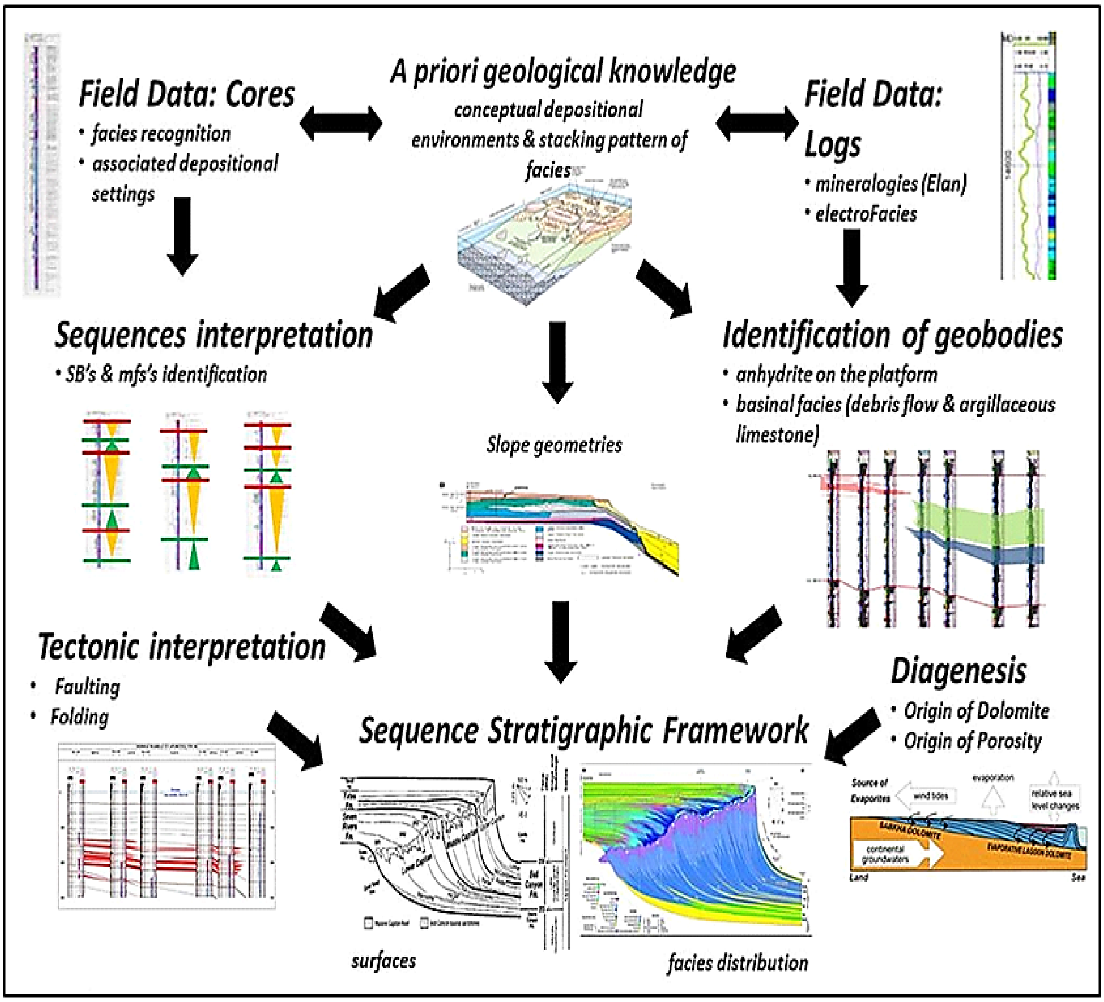


Figure 3.2 Scheme of work flow for detailed geological analysis to populates a sequence stratigraphic framework. (Kendall C.G.S.C. 2016).

structural repetition. Also the frequency contents of 2d seismic to resolve stratigraphy is not appropriate to mark signatures of system tract (onlaps, downlaps, erosional truncation, incision, etc).

Under these circumstances the well logs and lithological tops were considered as a key source of information for evaluation of system tracts. The signatures of log curves and its corresponding changes to stratigraphic facies at well locations and in outcrops in offset areas along Salt Range were factors considered for analysis. The GR log curve behavior and its signatures reflecting corresponding facies for each well (Figure 3.24) were used to set evaluation of system tracts for model building. To a limited extent work was also focused on sedimentary structures and associates facies deposited to highlight parasequence geometries that is bounded by flooding surfaces. The evaluation of available data set was conducted for construction of a framework of systems tracts and bounding surfaces leading to a model independent approach which could fulfill the practical purpose of sequence stratigraphy in the study area. One of the key challenge is to work with model based on numerous approaches which has been discussed in detail in Chapter-5. The model-dependent choices (Figure 5.3 and 5.4) with respect to the selection of the 'sequence boundary' and framework could not be concluded to a full extent for any single approach. For present study the Depositional Sequence IV of Hunt & Tucker, (1992 and 1995) and Genetic Sequence of Galloway (1989) models were considered valuable for developing correlation in the study area (Figure 5.3 and 5.4). Hunt & Tucker, (1992 and 1995) discussed the role of forced-regressions and where the sequence boundary should be placed with respect to sea level position. Hunt believes that the position of the sequence boundary should be placed at the lowest position reached by sea level.

To determine order of cyclicity the duration of deposition for each sequence in Cambrian and Early Permian level were analyzed using Global time scale and Eustatic charts (Figure 3.3). The duration of deposition of Khewra sandstone is about 21 million years and Kussak-Juttana-Bhaganwala is about 32 million years while the early Permian deposited in about 30 million years. Therefore order of cyclicity for sequence frame work of Cambrian - Permian is of the order of second to third as per Wilkinson et al,. 1996 (Figure 3.3).

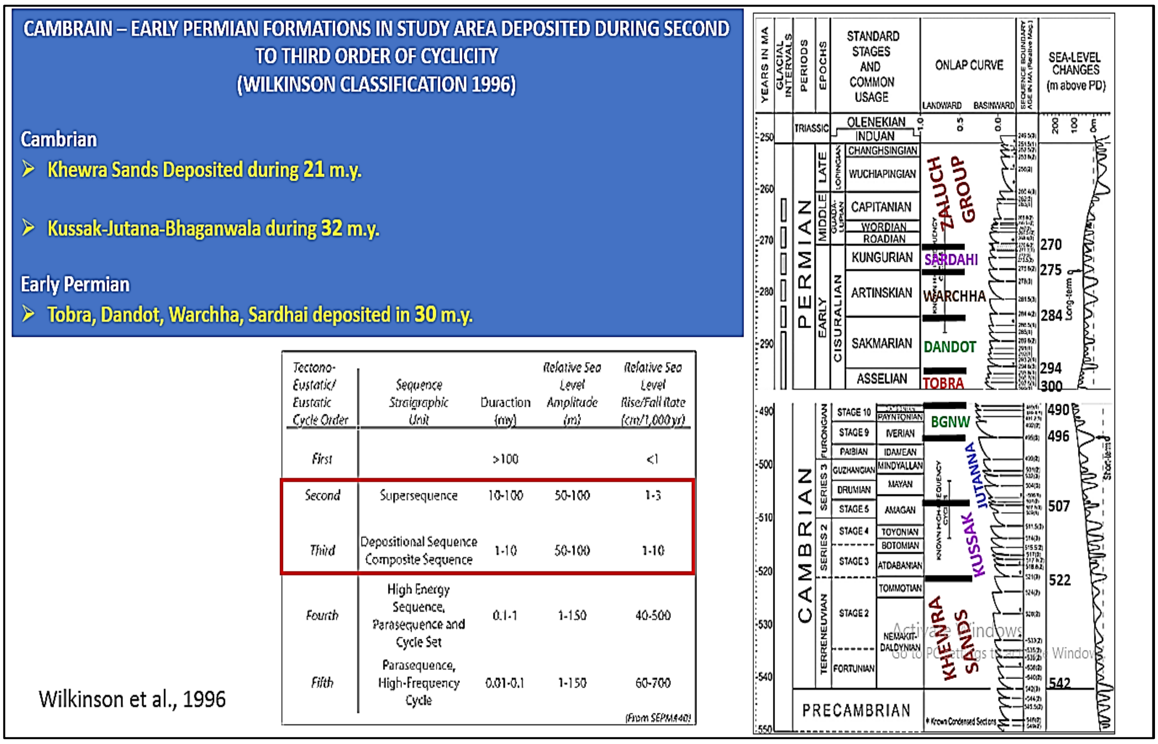


Figure 3.3 Global eustatic chart and order of sequence analysis based on deposition duration (modified after wikinson et, al. 1996)

3.1 Locations visited for outcrop studies

To meet the objective of outcrop study following field traverses were made during 5th to 6th June and 14th June 2010. During ongoing covid-19 situation and taking into considerations of safety the food, hotels and overnight stay were avoided close to field locations and instead each day field visits were started and returned back to Islamabad.

1. Kallar Kahar-Ara Bashrat- Choa Syedan shah road traverse (5th June).
2. Over view along motor way along Kallar Kahar-Lillah section (6th June).
3. Khewra Gorge (6th June).
4. Kallar Kahar, Nilawahan Gorge / Katha Pail Section (14th June).

3.2 Precambrian

3.2.1 Salt Range Formation

The term “Salt Range Formation” has been introduced by Asrarullah (1962) after the Salt Range in the Punjab Province. Earlier this was referred as "Saline Series” by Wynne (1878) and “Punjab Saline Series” by Gee (1945). Khewra Gorge (lat. 32°40’N; long.73°00’30” E) in the Eastern Salt Range, Jhelum district, Punjab Province, has been designated as the type section, Shah (1977).

The Salt Range Formation is divided into following three members starting from older to younger:

1. Billianwala Salt Member
2. Bandarkas Gypsum Member
3. Sahwal Marl Member

The formation in general is composed of marl, shale, salt and gypsum beds (Figure 3.4 to Figure 3.8). The basal part of formation is occupied by Billianwala member which is mainly composed of thick seem of salt along with red-colored gypseous marl. These lithologies underlie below Bandar Khas Gypsum member which is comprised of massive gypsum, dolomite and marl. In the upper part Sahwal Marl Member overlies the Bhandar Kas Member. The lithologies in upper member are comprised of bright red marl with irregular gypsum, dull red marl, dolomite, gypsum beds, greenish clays and low grade oil shales. A highly weathered lithological unit known as Khewra trap or Khewraite which is believed to be originated from igneous source is also present among Sahwal unit. This unit show decomposed radiating needle like structures of light color and is believed to be a pyroxene. The shales in this Shawal unit are dark gray papery in color and are rich in organic matter and have faint kerosene smell when broken. These shales are considered as potential source rock with TOC of 30% in eastern salt range. The formation behaves as a ductile layer for the movements along the MFT.

The outcrops along Salt Range are exposed along frontal thrust (MFT or SRT) in hanging wall and where Salt is being mined from famous Khewra location beside other mines along the range like Nilawahan, Kalabagh and etc. The presence of formation is known in Potwar and middle Indus Basins from drilling of wells. Base of the Formation is not exposed anywhere including the study area. The upper contact with the Khewra Sandstone is transitional. The Salt Range Formation is devoid of fossils. Due to its position below Lower Cambrian sediments and above the metamorphic Precambrian basement, it is considered as Late Neoproterozoic. This is in accordance with the results of Sulphur-isotope measurements carried out on gypsum samples from the top of Salt Range Formation which indicate an age of about 600 m.y.

Depositional Model (LST-EARLY TST System Tract Facies)

Facies of Salt Range formation in the area of study at Khewra, Motorway, Nilawahan, Katha Pail section and in middle Indus Basin suggest deposition in closed environment which were prevailed in the basin after detachment from main marine shore lines and open sea during Neoproterozoic time. It might be a closed sea or shallow water lakes which were drying and evaporation took place under oxidized conditions.

It can be postulated that isolation of salt basin or restricted sea environment might be prevailed on Arabian and Indo-Pakistani region before rifting and extents might be resembling like present day black sea. Moreover, the lack of circulation of open sea water in the area of salt basin may not be happening due to fall of Eustasy in low stand time.

Therefore, it can be inferred that the Billianwala and Bandar kas salt range members were deposited before rise of sea level. The part of GR curve corresponding to shawal member present at upper part show fining upward profile in Hayal-1, Balkasar oxy-1, Daiwal and Kal-1 wells (Figure 3.9 and Figure 3.10). The signature of this curve appear retrogradational and thus indicate probability of TST time in the basin. The facies drilled and exposed in top part of Salt Range do correspond with this transgression cycle.

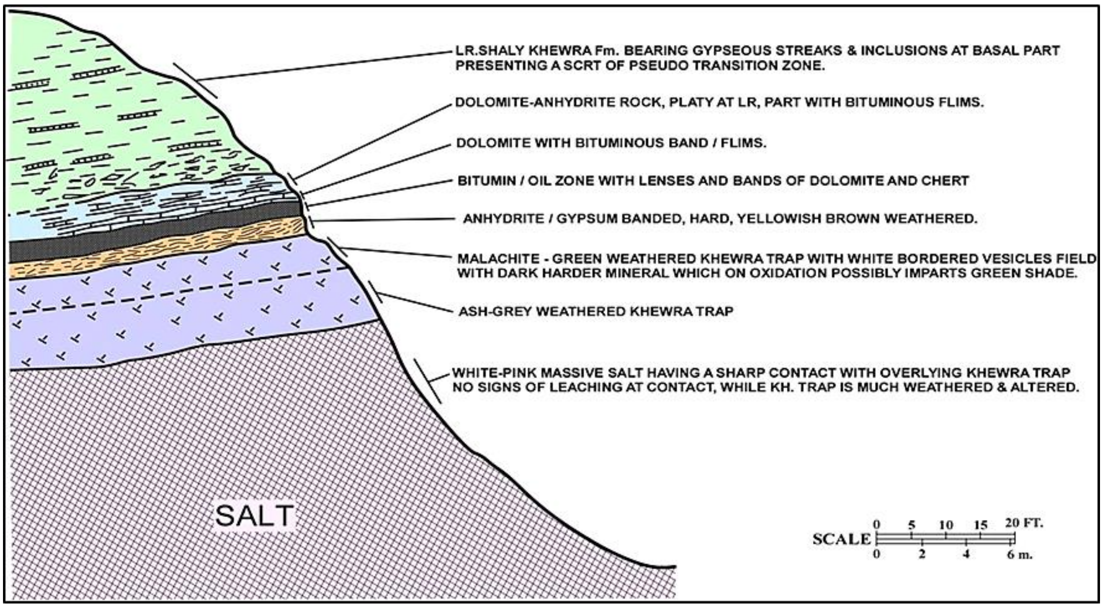


Figure 3.4 Geological section of the Salt Range Formation in Sohal valley in the Central Salt Range, Faruqi (1986.)

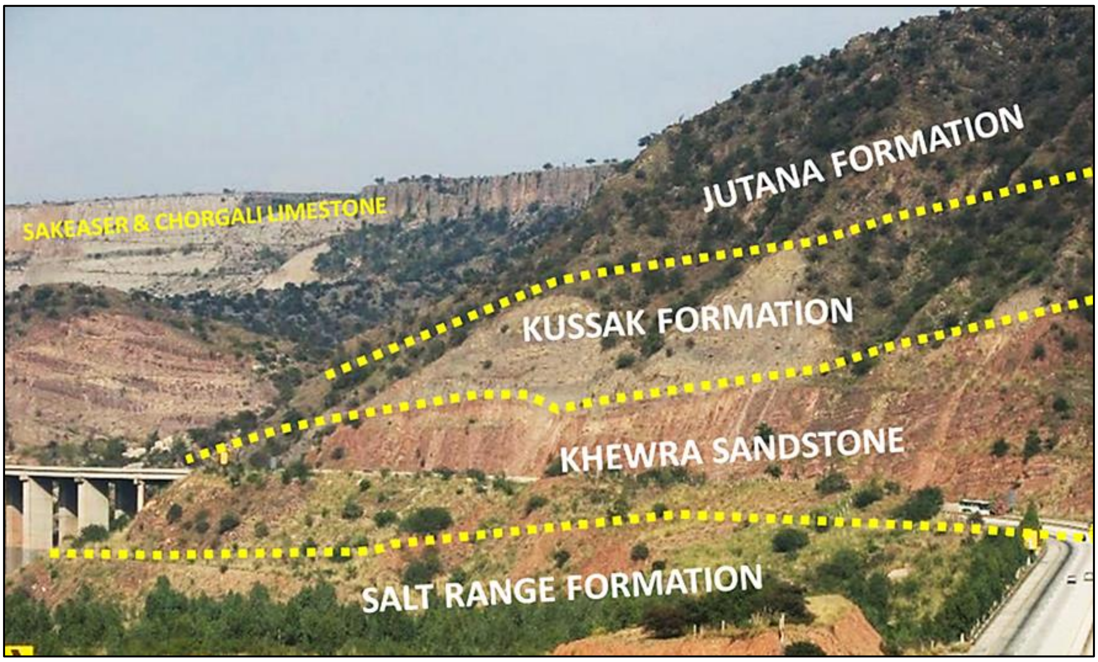


Figure 3.5 Precambrian, Cambrian, Eocene lithological units exposed along motor way M-2 section.

Figure 3.6 A: Exposure of marl and gypsum of Salt Range Formation along Choa-Khewra road. B: Bitumen/Oil shale in Salt Range Formation, Khewra Gorge.

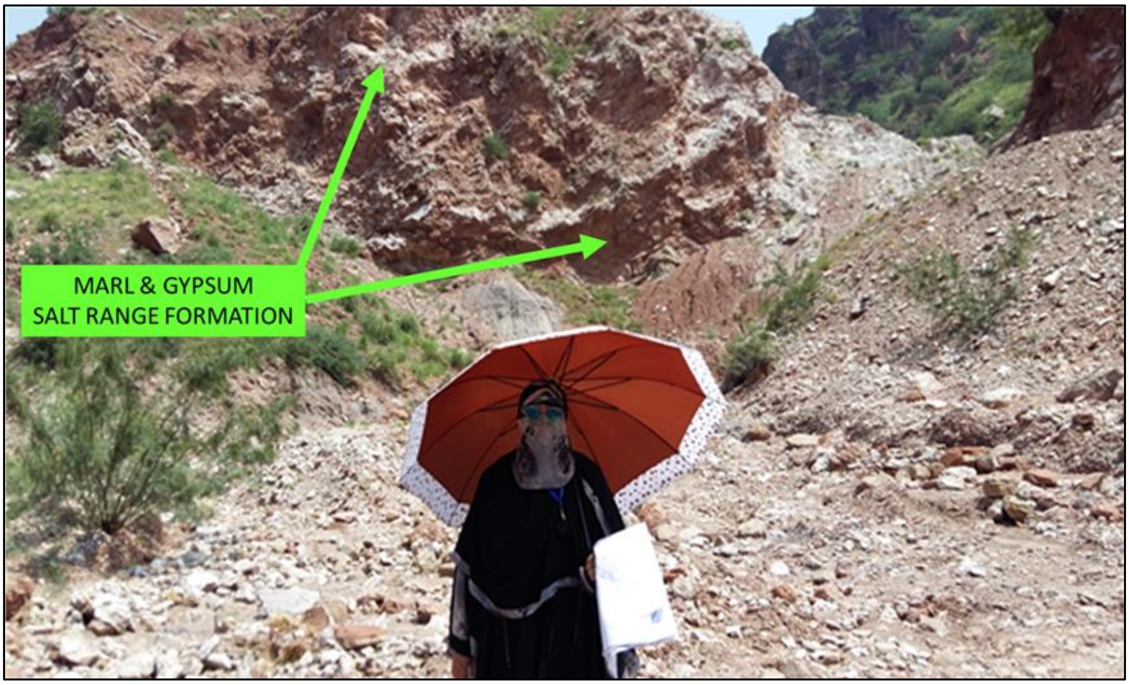


Figure 3.7 Precambrian, Salt Range Formation exposed along Nilawahan Gorge

Figure 3.8 Exposure of Rock Salt, Precambrian, Salt Range Formation Nilawahan Gorge.

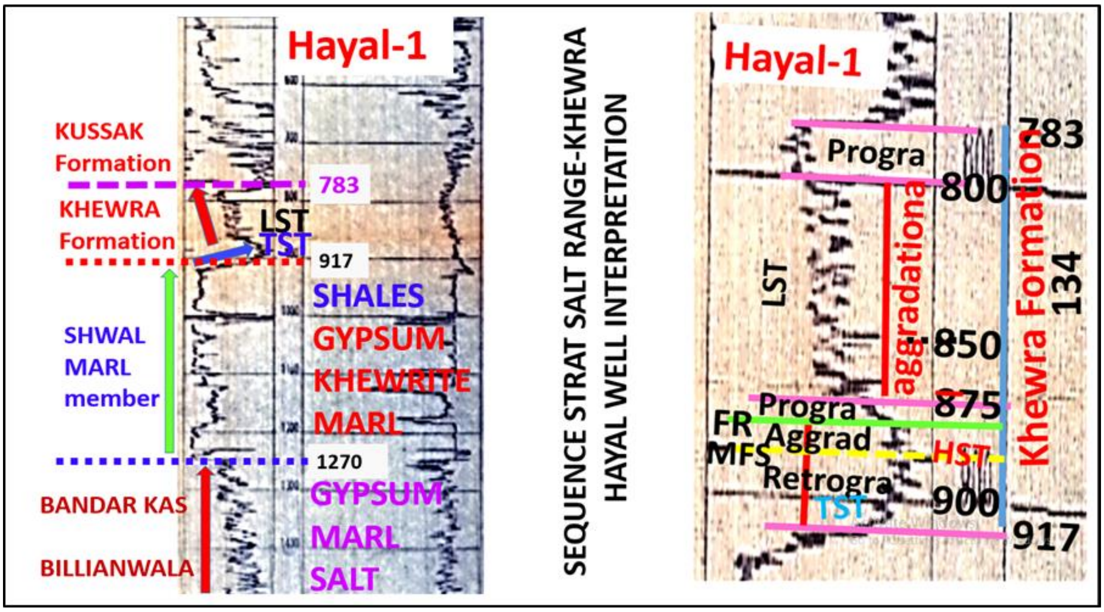


Figure 3.9 GR curve response in Hayal well-1 across Pre-Cambrian and Cambrian stratigraphy. The well drilled at Domali anticline (Figure 3.1),

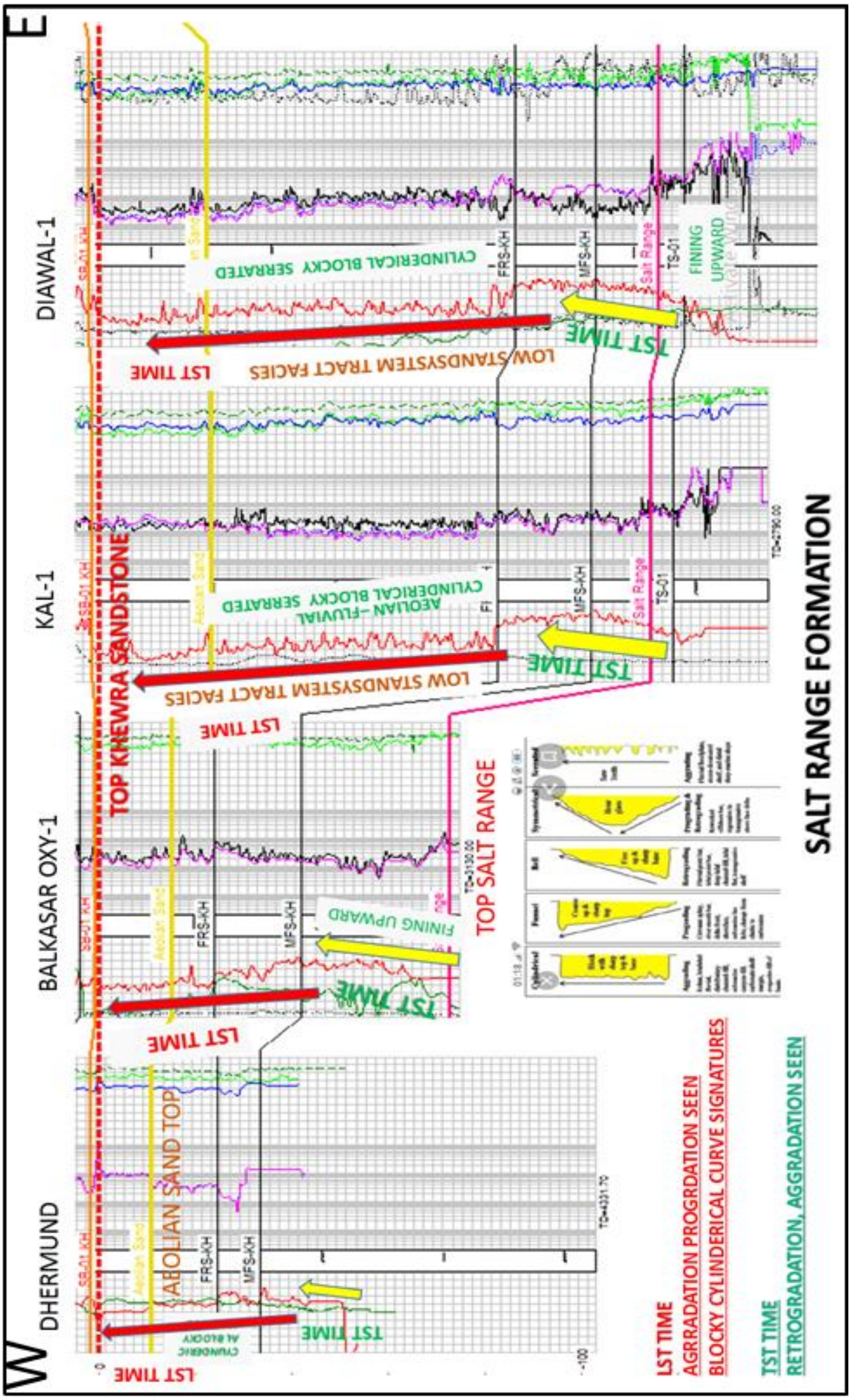


Figure 3.10 Correlation of GR log curve across southern Potwar Basin through Dhermund well in west to Diawal-1 well in east (Figure 3.1), The Top Salt Range - Lower Khewra facies corresponds to finning upward cycle of the curve marking TST and correlate able with Hayal well.

3.3 Cambrian

The Cambrian section is well exposed in Khewra Gorge and also seen along Choa Syedan Shah-Khewra road, Figure 3.11, Kussak Fort, Figure 3.12 and Nilawhan Gorge, Figure 3.13 & 3.14 and Khata Pail Section, Figure 3.15.

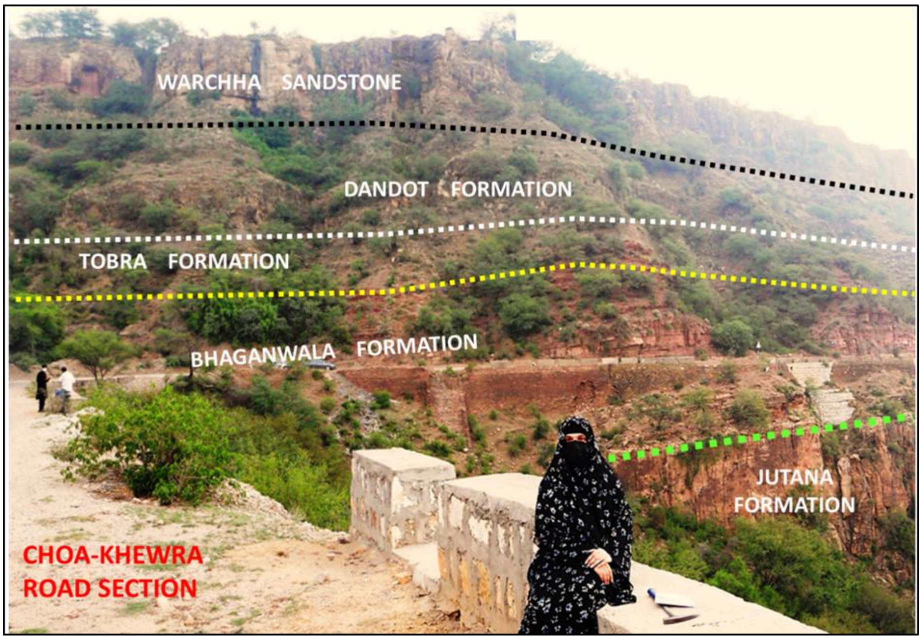


Figure 3.11 Lithological contacts between Baghanwala, Jutana and Tobra formations, Pidh area Choa- Khewra Road.

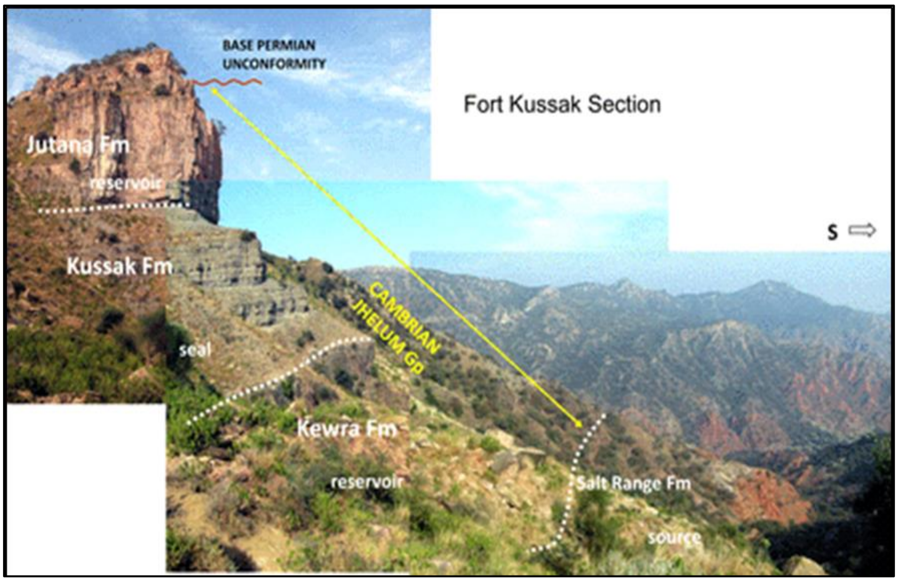


Figure 3.12 Cambrian and Permian Formations of Salt Range near Kussak Fort.

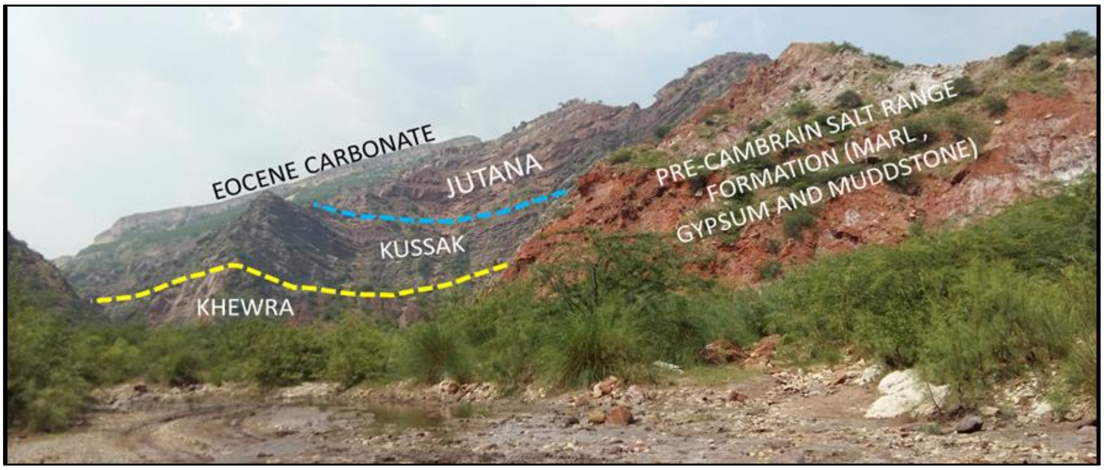


Figure 3.13 Panoramic view of Precambrian and Cambrians lithologies exposed in Nilawahan Gorge

Figure 3.14 Precambrian and Cambrians lithologies exposed in Nilawahan Gorge.

3.3.1 Khewra Sandstone

The “Khewra Group” of Noetling (1894) is formalized as Khewra Sandstone after the Khewra town in the Punjab Province. Other terms were "Purple Sandstone Series” of Wynne (1878), "Khewra Group” of Noetling (1894) and “Purple Sandstone” of most subsequent authors. Khewra Gorge (lat.32°40’N; long. 73°00’E) in the Eastern Salt Range, Jhelum district, Punjab Province, is designated as the type locality.

The Khewra formation is dominated by sandstone lithology with limited shale beds (Figure-3.15 & 3.16). The formation has been measure for about 140 meters in Khewra Gorge. In lower part the formation is represented by thin-bedded fine to medium-grained sandstone of purple to buff color, partly shaly which gradually changes upward into massive and thick-bedded with thin bands of clay intercalations. The sandstone in upper part has reddish brown and yellowish brown colors. The cross bedding, ripple marks and mud cracks are among common features besides convolute bedding at base (Figure 3.23).

Based on facies nature the Khewra Sandstone has been known for four units in field locations and which are correlateable with log data. The lithostratigraphic thickness is not consistent across the basin and decreasing westward as indicated by isopach map compiled based on well data used in the study area (Figure 3.17). Following subdivision has be considered by Saqib et. al (2009) to elaborate lithological division.

1. **Shale and Sandstone Facies (Figures 3.18)**

This unit is also referred as "Maroon Shale Group" and is about 11.5 m thick. It is composed of maroon colored shale intercalated with thin bedded dark red to brown siltstone and fine sandstone. Mud balls and cross lamination are reported in shale and sandstone beds respectively. The muscovite and other rock fragments with minor feldspar were assembled among calcite and silica cements to form these sands. Generally finning upward profile of sedimentation is preserved with the representation of shale and limited sandy beds and such deposition may have been developed in tidal flats formed under near shore or marginal marine environments.

2. **Lower Fine-grained Sandstone Facies (Figures 3.19).**

This unit is formed by fine grained sandstone in association with alternate units of silty mudstone. The mudstone units formed as tidal beds having few centimeters thickness. The total thickness of this unit is about 24 m. The tick beds of sandstone show planar-parallel lamination, tabular and tangential cross-laminations. Sedimentary structures like ripple marks, honey-comb weathering and lenticular bedding are noticeable features of this unit (Figures 3.23). The vertical variation in sedimentary structures suggest near shore depositional setting.

3. **Upper Fine-grained Dune Sandstone Facies (Figures 3.20).**

This unit represents fine grained sandstone which is thick to massive bedded and about 98.7 m thick. In upper part these sands are micaceous and calcareous. The sandy beds are brick red to purple in color. These sands are intercalated with thin layers of maroon and green color silty and micaceous mudstones ranging from 5-10 cm. This part of Khewra sand stone is deposited in Aeolian environment which has been interpreted from sedimentary feature like bed forms and dune cross stratification, large-scale planar and trough cross-bedding, lenticular bedding, and low amplitude wind ripple marks. (Figures 3.23). The texture and mineral composition support Aeolian dune depositional environment. The interbedded mudstone layers are representing deposition in toe of lee side of inter-dune area.

4. Uppermost Medium-grained Sandstone Facies (Figures-3.21).

This unit is known to have reservoir properties and is hydrocarbon bearing in south eastern part of Potwar basin. It is medium grained, friable, well-sorted arenaceous sandy facie that yield yellowish white color and it has a thickness of 6.7m in Khewra gorge. This unit is overlain by a conglomerates layer of about 90 cm that is marks the top of Khewra formation (Figures 3.22, 3.23). The sands are characterized by planar and tabular cross-laminations.

This sandstone facie is porous, generally uncemented, containing abundant iron-oxide concretions either in the lenses preserved parallel to bedding and also have random distribution. The occasional overgrowth of silica cement, few rock fragments and feldspar grains are also reported among the lithological composition. This facies was deposited as a sheet sand bodies in a sandflat environment based on its lateral distribution in the existing oil field like Adhi (PPL internal report1991). The deposition in association by wind-blown processes can be considered. The climatic conditions were probably semi-arid.

The presence of Khrewra Formation in subsurface of Potwar basin has been proven up to Dhulain structure or Soan syncline. Further north this formation is missing and truncated (Figure 2.4 and 2.5). The nature of this truncation in the north as erosional or non-depositional is not known, however towards south near Sargodha high the truncation is erosional as shown by seismic data. This formation has been also drilled in Punjab Platform. The west ward truncation in Punjab Platform is seen by seismic data forming wedge geometry. Its thickness in Khewra gorge is about 140 meters. The contact of Khewra Sandstone with the underlying Salt Range Formation is conformable and gradational. Its upper contact with Kussak Formation is sharp and marked by surface of erosion (Figures 3.21 and 3.22). The Khewra Sandstone does not contain well-preserved fossils but retains evidence of organic remains and trace fossils which have been interpreted as “diggings of trilobites” (Schindewolf and Seilacher, 1955). Because of its position between the Late Proterozoic Salt Range Formation and the fossiliferous Early

Cambrian Kussak Formation, in the Eastern Salt Range the Khewra Sandstone is thought to represent the basal part of the Lower Cambrian.

Depositional Model

It appears from the lithological composition that basal part of the formation accumulated after the onset of relative a sea-level rise. The well data in southern Potwar basin encountered basal part of Khewra Formation where the clastic facies show fining upward cycle and show retrogrdatioanl pattern on GR logs (Figure 3.24) thus suggesting presence of Transgressive System Tract (TST). The middle part of sandy facies of the formation show aggradational pattern and mostly coincides with part of Aeolian sandy units deposited during low stand time. The presence of Aeolian nature of sand is an indicator of force regression cycle which triggered and prevailed the continental conditions and where sand was reworked by blowing wind. The top part of Khewra formation again represent coarsening upward profile on well logs and that relates to medium grained sandy facies at top and encountered as oil and gas reservoir. The top part also represents progradational nature of GR curve thus leading to indicate association of deposition low stand system tract.

The signature of GR log curves shown by wells drilled from west to east, (Dhermund-1, Balkassar Oxy-1, Daiwal-1, Rajian-1 and Missa Kaswal-1 and 3) Figures 3.25 and 3.26 indicate a uniformity in lateral distribution of facies and support deposition of facies. The curve data at base level of Khewra formation show fining upward profile marking retrogradational event and which than changes to blocky and show aggradational pattern in the middle part. The top part the log data related to Khewra Sands is showing coarsening upward profile of progradational pattern (Figure 3.25 - 3.27). This clearly lead to identify system tracts from TST at base to LST above during the deposition of Khewra facies across the area and that has been confirmed from outcrops in south of drilled locations along Salt Range (Ara Bashrat, Choa – Khewra section, Khewra gorge, Motorway section, Nilawahan and Katha Pail section).

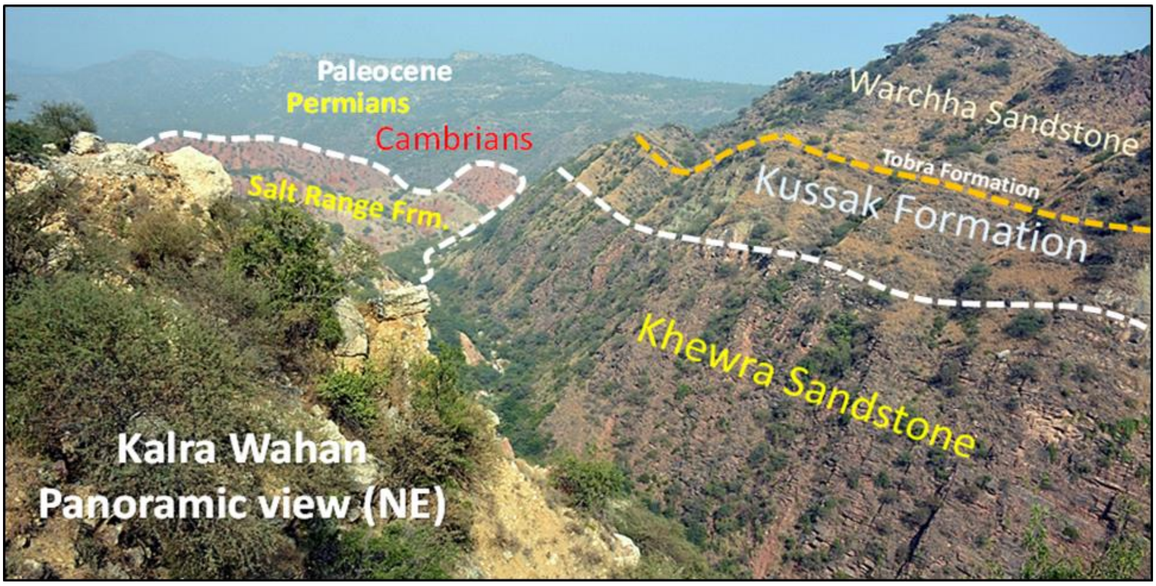


Figure 3.15 Precambrian and Cambrians lithologies exposed in Khata-Pail section.

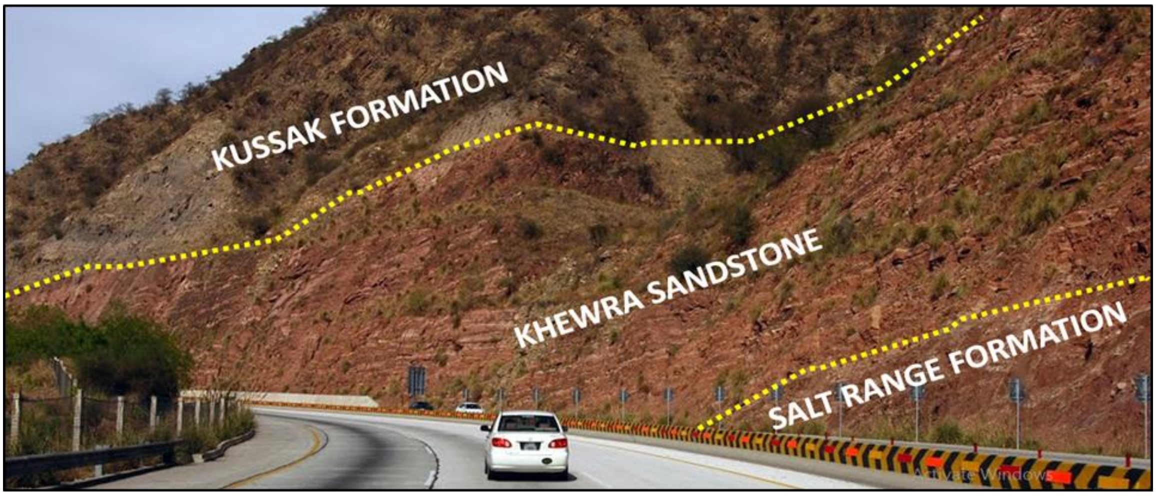


Figure 3.16 Exposure of Khewra Sands along motorway M-2.

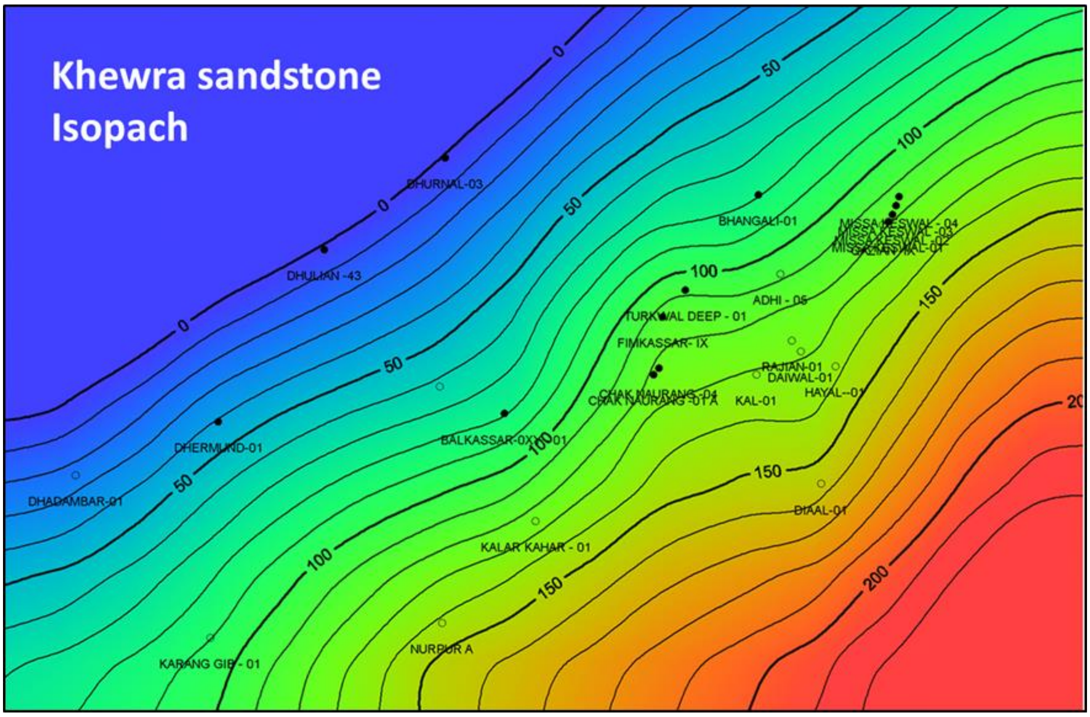


Figure 3.17 Isopach of Khewra Sandstone based on well data in central and eastren Potwar Basin.

Figure 3.18 Lower shale and sandstone facies Khewra Formation, M-2 Motorway section.

Figure 3.19 Lower fine grained sandstone facies Khewra Formation, M-2 Motorway section.

Figure 3.20 Upper Fine-grained Dune Sandstone Facies Khewra Formation, M-2 Motorway section.

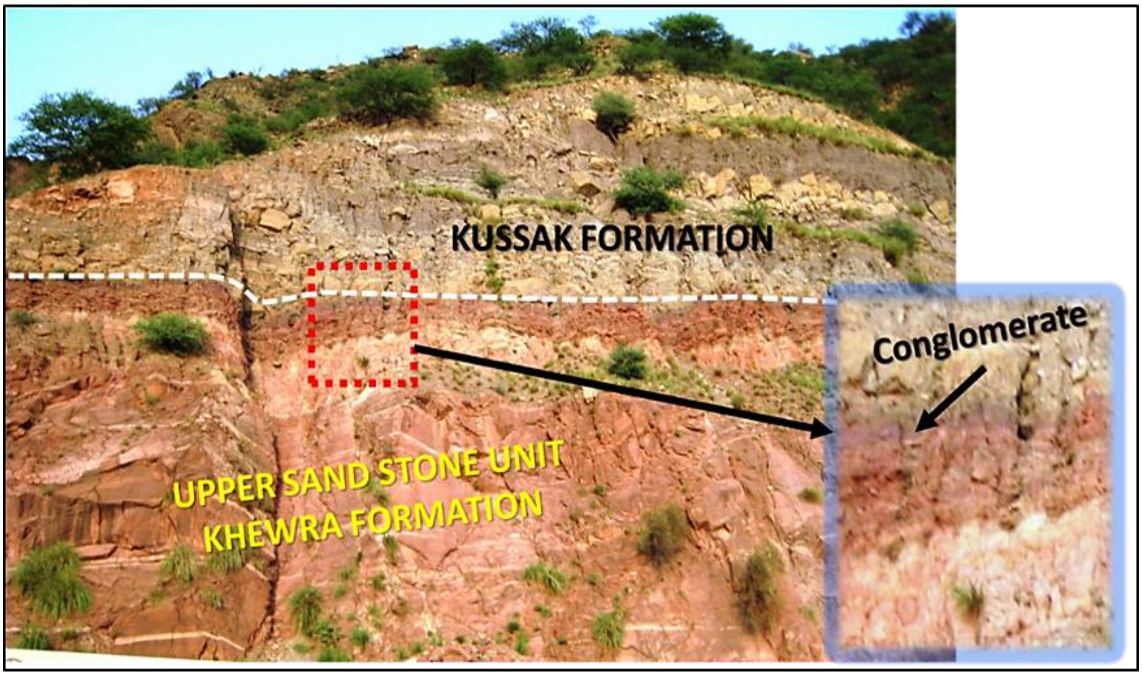


Figure 3.21 Maroon color Khewra Sandstone facies in contact with greenish gray Kussak Formation exposed along M-2 Motorway section.. White line marks Top of sequence boundary.

Figure 3.22 Top Khewra Unconformity with conglomeratic beds also marking sequence boundary, Khewra Gorge.

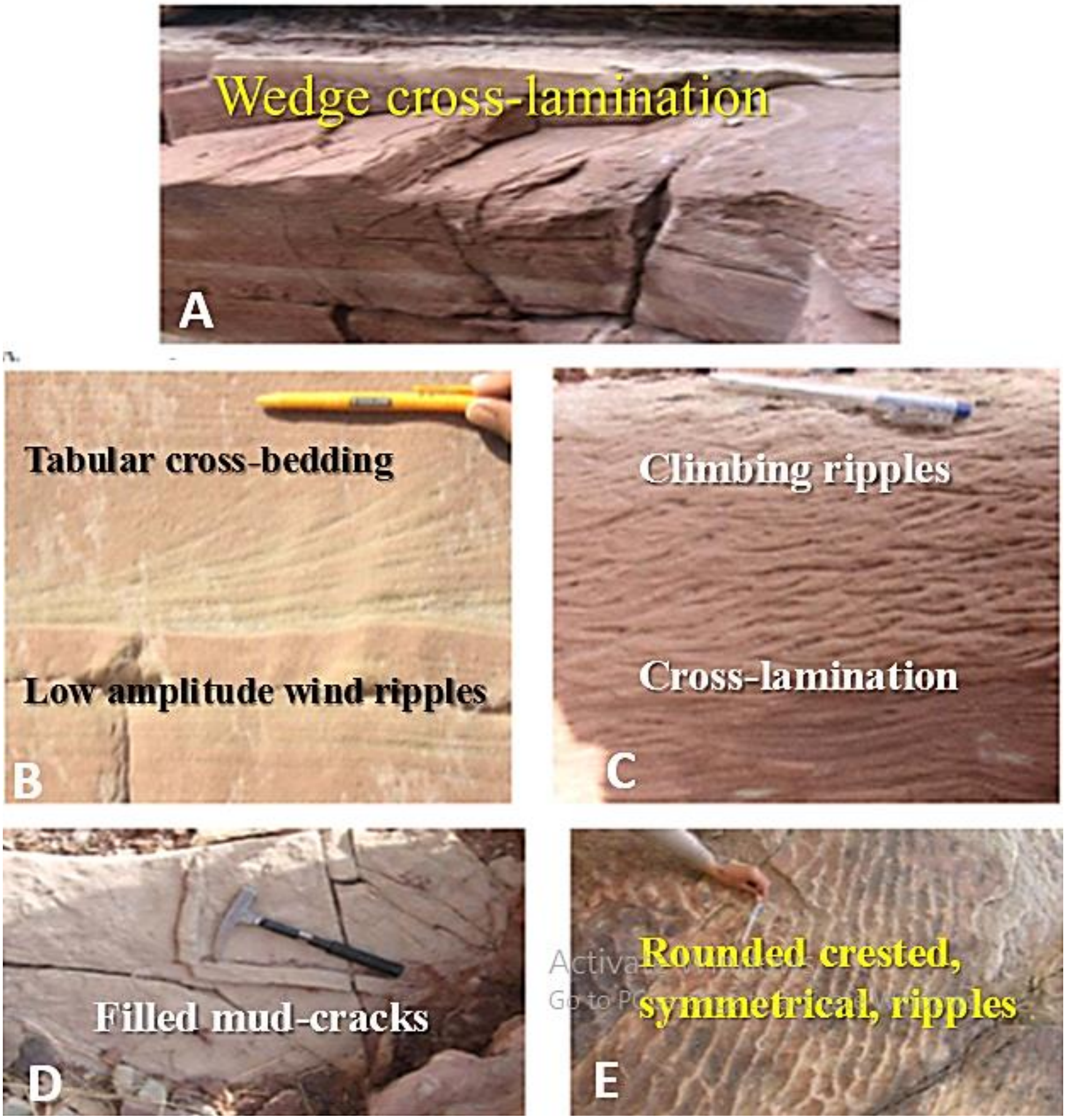


Figure 3.23 Sedimentary features of Khewra Sands (modified after Saqib et. al 2009). A. Wedge cross-lamination in middle part of Khewra Sandstone. Planar parallel lamination in upper part, deposited in upper-phase, in fine sandstone. Parting lineation is typical on bed surfaces. B. Cross-laminated sandstone showing tabular cross-bedding curved bases and sharp erosive tops. Low amplitude wind ripples present at the bedding interface. C. Climbing ripples cross-lamination (lower part) and trough cross-lamination (upper part). D. Filled mud-cracks in lower central part of Khewra Sandstone, formed through more complete drying up of the surface layer of sediments on sub-aerial exposure. E. Rounded crested, straight, symmetrical, ripples.

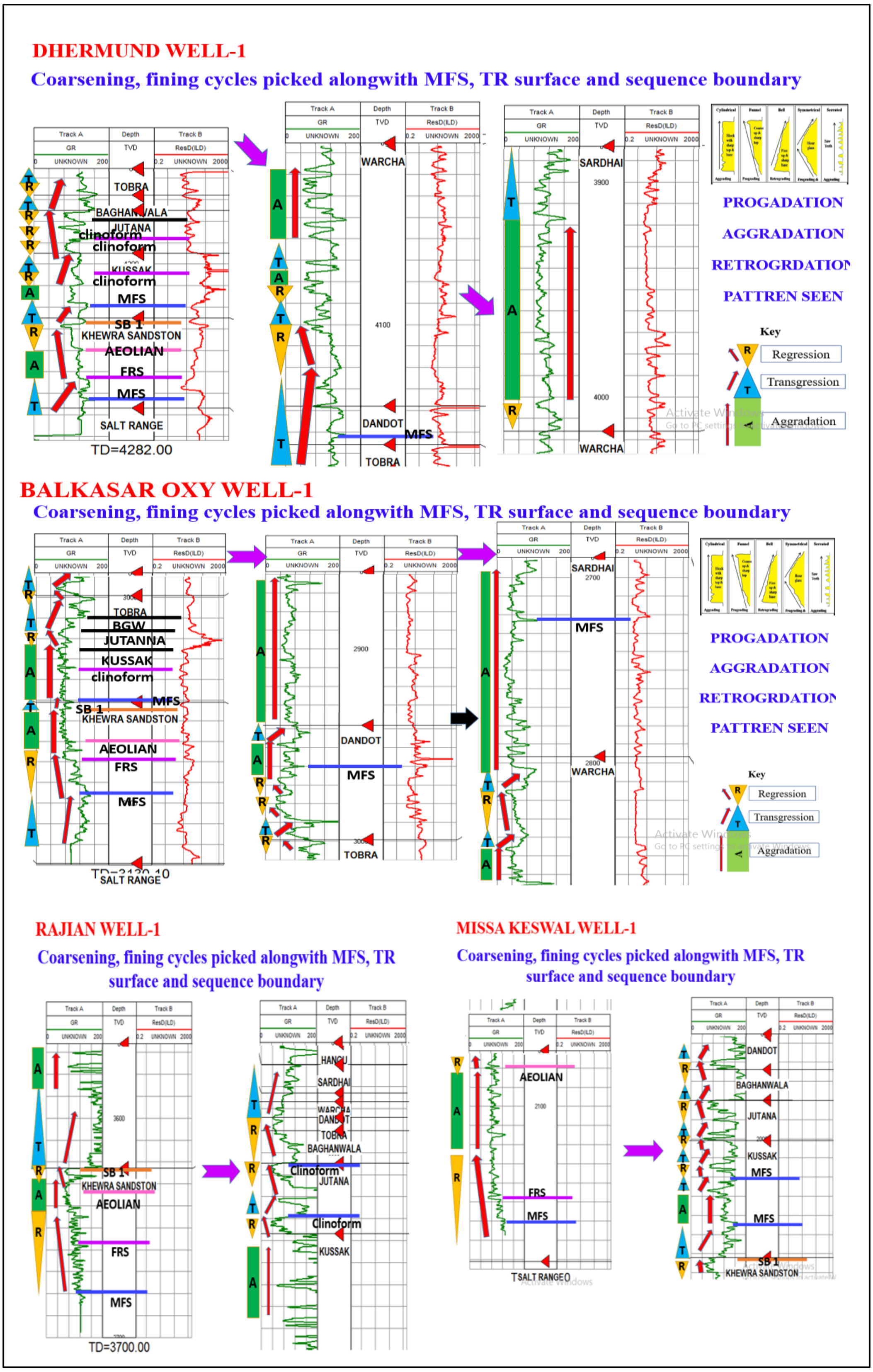


Figure 3.24 Panel Diagram showing piking of coarsening and finning upward cycles of Cambrian-Early Permian strata for the wells in study area.

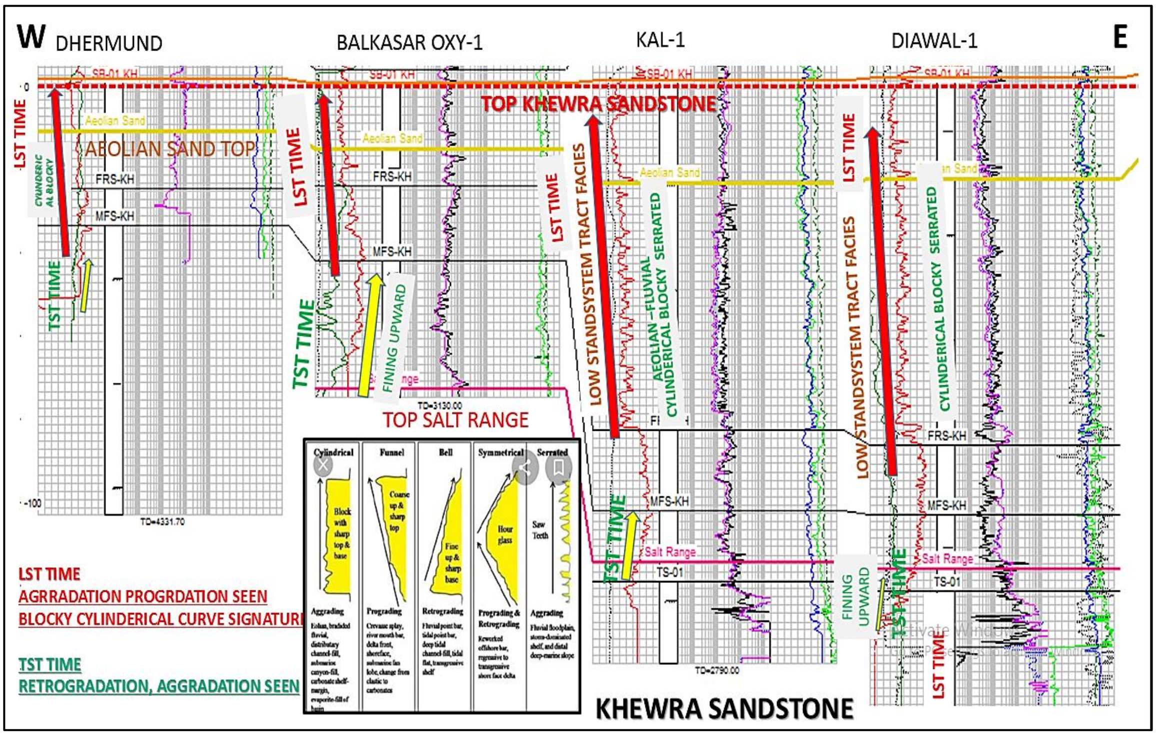


Figure 3.25 Correlation of well logs from west to east (Dhermund-1 to Diawal-1 for Khewra Formation showing MFS, TST, HST, LST surfaces. Location of cross section shown in (Figure-3.1),

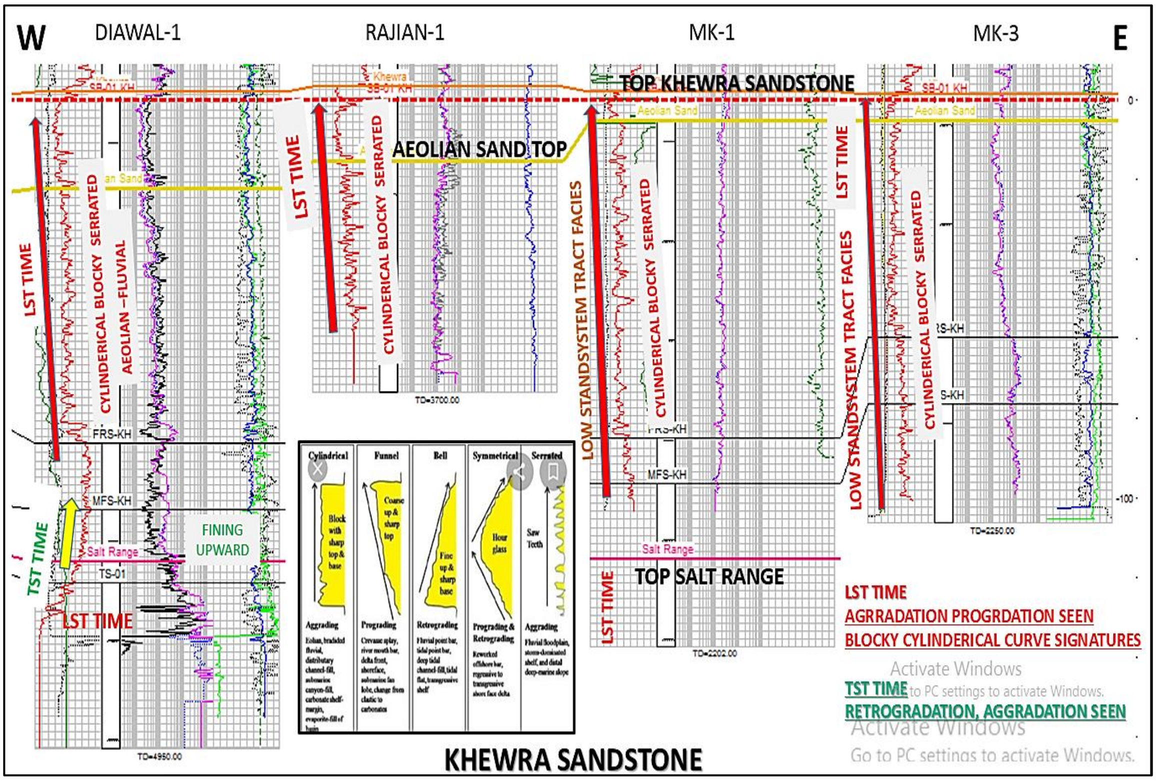


Figure 3.26 Correlation of well logs from west to east (Diawal-1 to Missa Kaswal-3) for Khewra Formation showing MFS, TST, HST, LST surfaces. Location of cross section shown in (Figure-3.1),

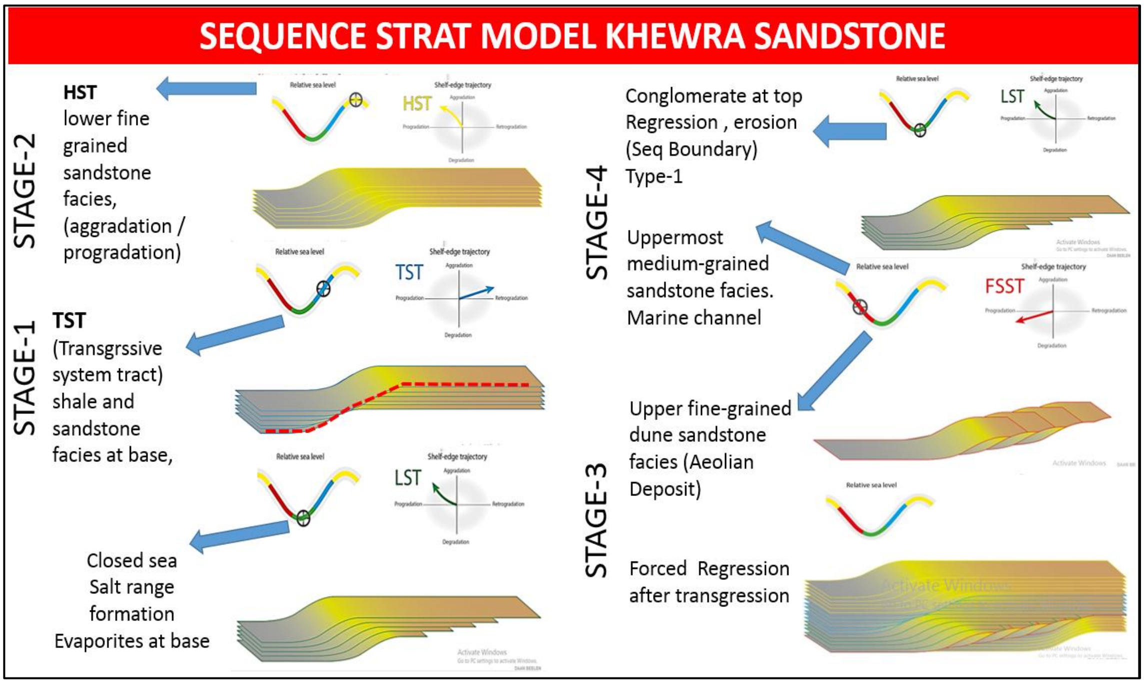


Figure 3.27 Evaluation of system tracts for Cambrian rock facies of Salt Range and South Potwar Basin using hypothetical eustatic curve.

3.3.2 Kussak Formation

The "Kussak Group" of Noetling (1894) is formalized as Kussak Formation after Kussak Fort in Eastern Salt Range. This Formation includes Obolus or Siphonotreta Beds of Wynne (1878), Neobolus Beds of Waagan (1884) and Kussak Stage of Pascoe (1959).

Lithology of Kussak formation in Salt Range and adjacent Potwar Basin is known for cyclic deposition of clastic strata comprises of shale and sand intercalations. This formation is well distributed in area of study and exposed in Salt Range. The Kussak Formation is sealing Khewra reservoir sands in eastern Potwar basin. The facies were observed at different locations (Figure 3.1) like M-2 Motorway (Figure 3.16), Choa-Khewra and Khewra George (Figure 3.28-3.29), Ara Bashrat (Figure 3.30) and Katha pail (Figure 3.31) and Nilawhan sections (Figure 3.32-33).

This formation exhibits a dominant dark gray shaly section at base. The shales of Kussak Formation contain thin bands of glauconitic sandstone. Shale is grey, greenish grey and purplish in colour. Sandstone is micaceous and also dolomitic having creamy appearance. The sandstones are coarse to fine grained, laminated. massive to thin bedded occasionally flaser. The claystone also show lamination. The study based on Kussak lithologies of Nammal section suggested that formation show fining upward sequence with few medium grained sandstones in upper part (Wajeeha et, al, 2014). The silt and claystone intercalations are present through-out the succession. From the sedimentary features observed in Kussak formation in Khewra and Nilawahan gorges, it has been inferred that the Kussak Formation is of meandering river to deltaic in origin (Figure 3.34). The presence of hummocky cross stratification are indicative of large storms in tidal flat area of deposition while preservation ripple cross lamination and oscillatory ripple marks and its occasional complex pattern show shallow water conditions. The mud cracks suggest supratidal conditions (Wajeeha et al 2014). The mudstones, capstones and silt stones are bioturbated. The common sedimentary structure are shown in Figure 3.34.

At type locality (Kussak Fort) it is thick about 70 meters. In southeast of Salt Range it may have thickness more than 200 meters. The formation is also drilled in the wells of Punjab Plain, Qadri (1999). It has sharp disconformable lower contact with Khewra Sandstone (Figure 3.22) while upper contact with Jutana Formation is transitional (Figure 3.30).

In north of southern Potwar Basin this formation is absent may be due to erosional removal. The isopach map (Figure 3.35) compiled using well data of study area show thickness ranging from 5 to about 100 meters. The Formation is fossiliferous, especially in the upper part. Schindewolf, Seilacher (1955) and Pascoe reported Neobolus Warthi, Lingulella wanniecka, Hyolithes Wynni and Redlichia Noetlingi species preserved. Age of the Formation is Early Cambrian, Schindewolf and Seilacher (1955).

Depositional Model

The lower part of Kussak Formation show preserved facies which were accumulated after transgression and a relative sea-level rise. The well data in southern Potwar basin encountered basal part of Kussak Formation where the clastic facies show fining upward cycle (Figure 3.24) and show retrogrdatioanl pattern on GR logs thus suggesting presence of Transgressive System Tract (TST). In the upper part the GR curve responded to presence of intercalated sandy units which may be associated to tidal flat deposits.

The signature of GR log curves shown by wells drilled from west to east (Dhermund-1, Balkassar Oxy-1, Daiwal-1, Rajian-1 and Missa Kaswal-1 and 3) indicate a uniformity in lateral distribution of facies and support deposition of facies (Figure 3.36 and 3.37). The correlation of log curve signature from Daiwal-1 to Missa Kaswal wells in east is good and marks consistency for lateral distribution of facies. However, the correlation of GR log curve signature with Balkassar oxy-1 and Dhermund-1is trickier and reasonable due to a change in thickness, marking absence of facies in upper part of Kussauk lithological units. The event suggested by high GR response in upper part of Diawal-1, Rajian-1 and Missa Kaswal well is regarded as flooding surface (FS-2 KSK) and the section above this surface is believe to be absent in Balkasar Oxy-1 and Dhermund-1 wells. The maximum flooding surface MFS has been marked at higher gamma ray event and which has been correlated across the wells (Figures 3.36 -3.38). In lower part an event of higher gamma ray suggest presence of flooding surface (FS-1 KSK) across the wells marking presence of shaly facies.

The basal part of GR curve commenced upward as a fining upwards (Figure 3.24) profile after a sharp change from coarsening upward profile (Low Stand Tract) of Khewra sands marking sharp contact and where disconformaity is reported both in outcrop locations and well data (Figure 3.22, Figure 3.37-3.38). A fair to good correlation of GR curves of well data from coarsening upward in Khewra sands to finning upward in Kussak has been also demonstrated clearly by the presence of relevant dominant sand facies below shaly facies in the outcrop locations in south Salt Range (Ara Bashrat, Choa – Khewra section, Khewra gorge, Motorway section, Nilawahan and Katha Pail sections) Figures 3.31-3.34. The suggested eustacy curve and trajectories can be related to understand the model as shown in Figures 3.38 and 3.39.

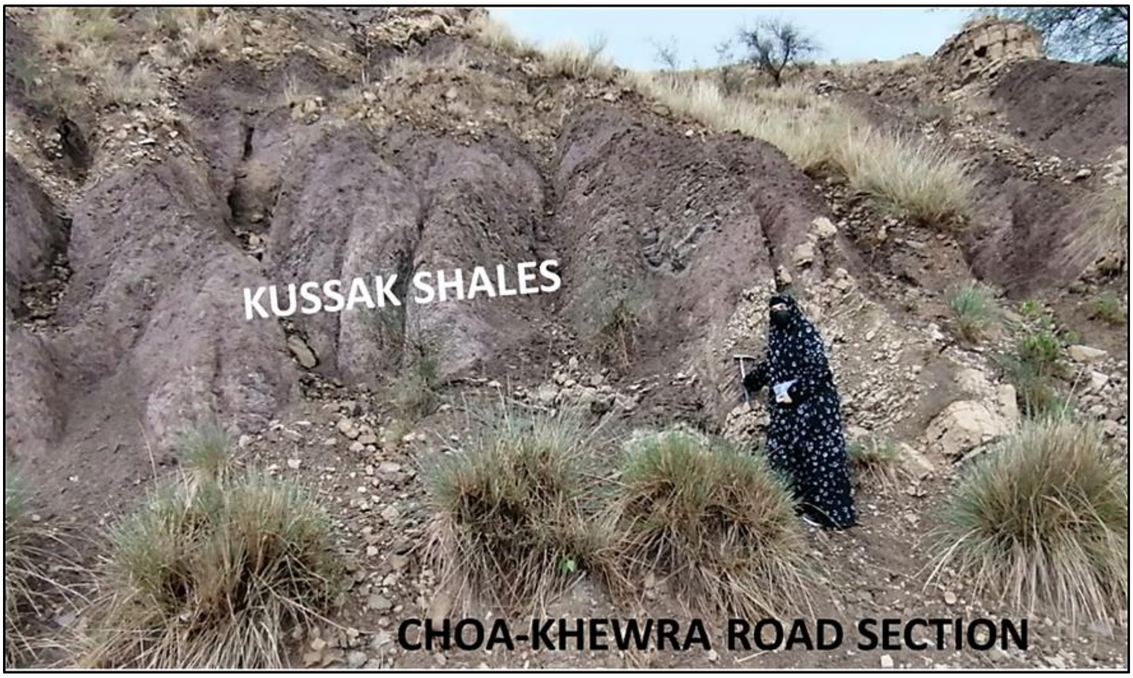


Figure 3.28 Kussak Formation showing shaly and sand beds, Choa-Khewra Road.

Figure 3.29 Kussak Formation showing shale and micaceous silt stone beds, Khewra Gorge

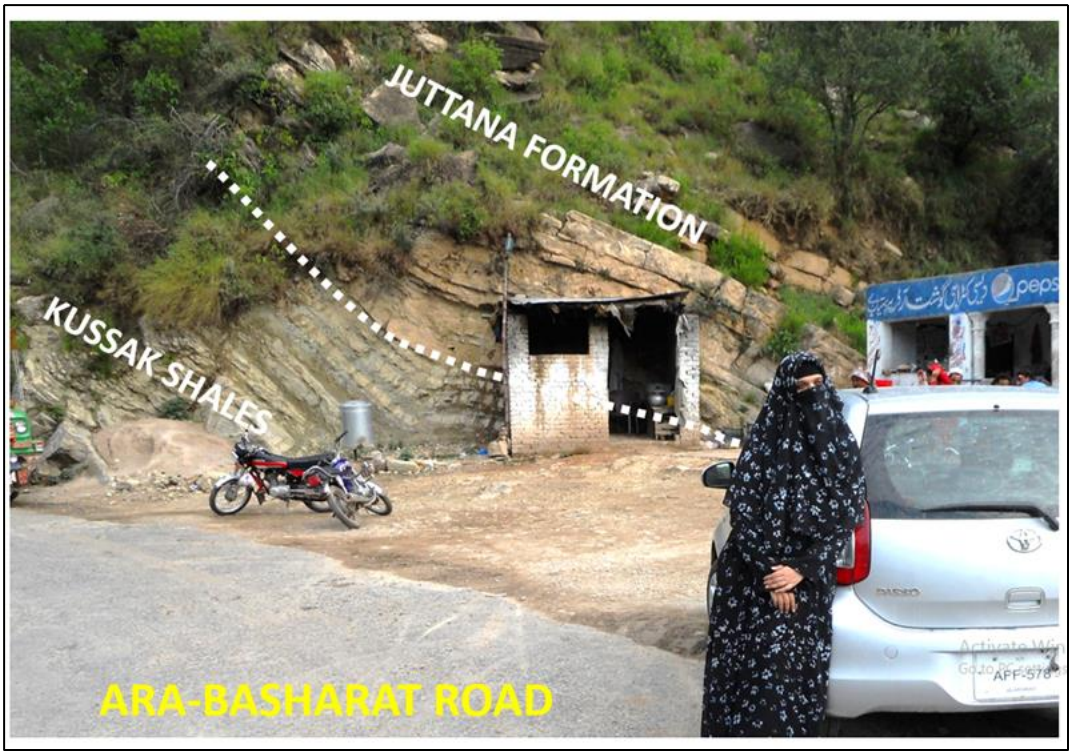


Figure 3.30 Kussak Shales in contact with Juttana dolomitic sands, Ara Bashrat Road,

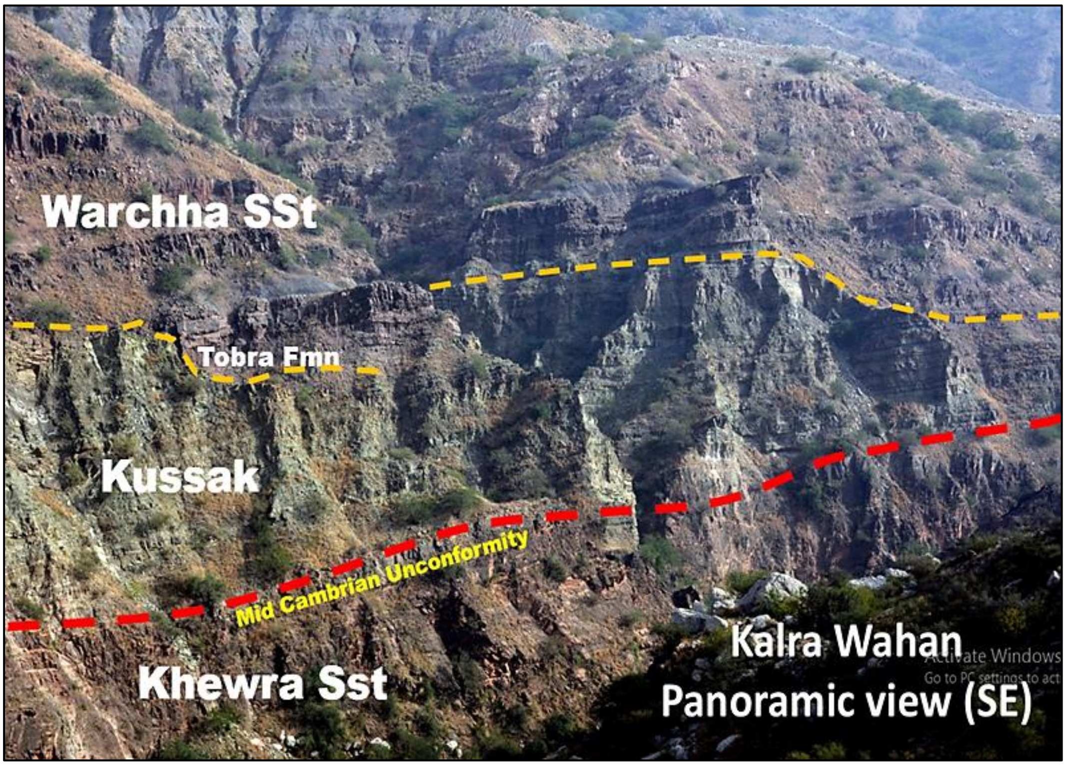


Figure 3.31 Khewra-Kussak contact, Katha Pail section**.**

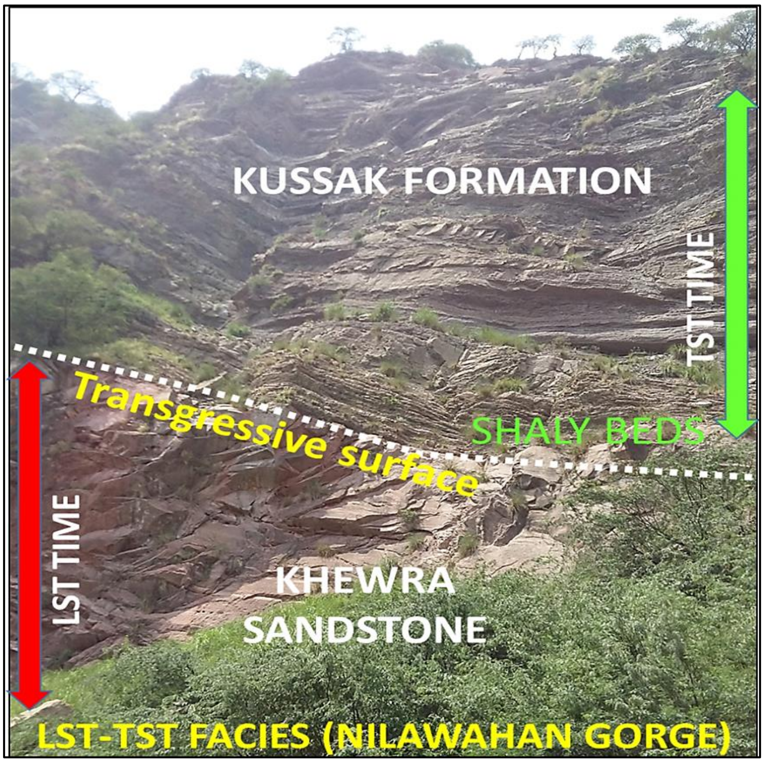


Figure 3.32 Kussak formation residing above Khewra Sandstone in Nammal Gorge showing shaly units intercalated with sands.

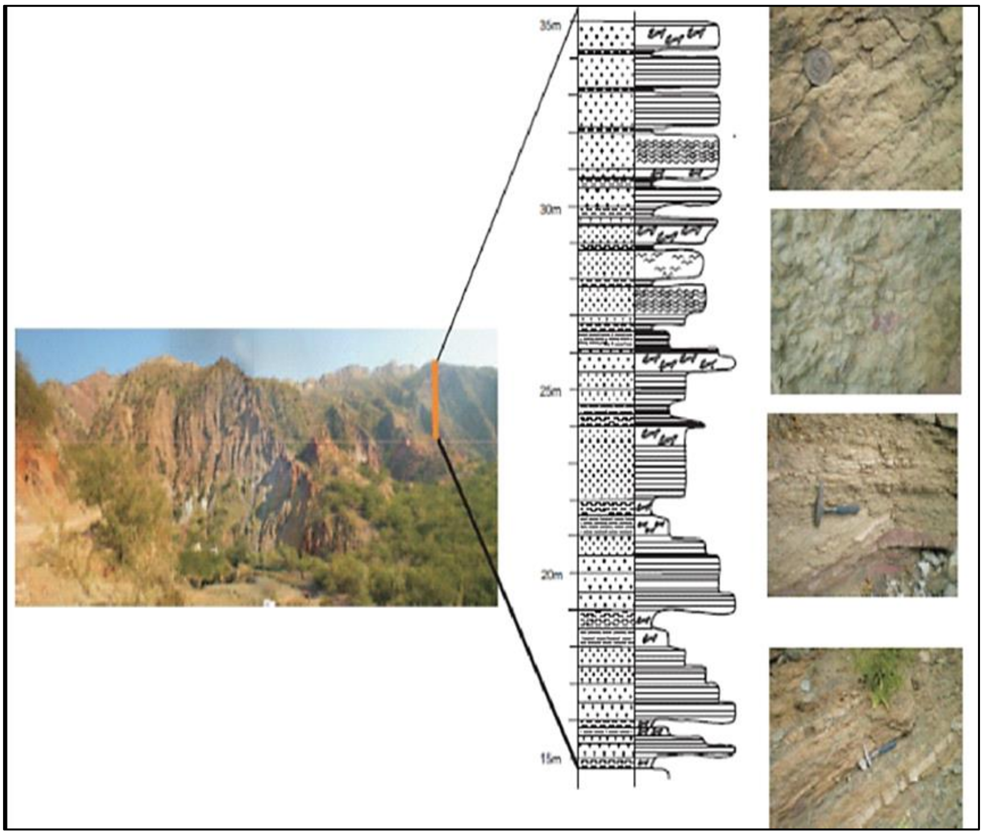


Figure 3.33 Panel diagram showing the lithological log of the Kussak sandstone from the Nilawahan gorge (Wajeeha et al. 2014).

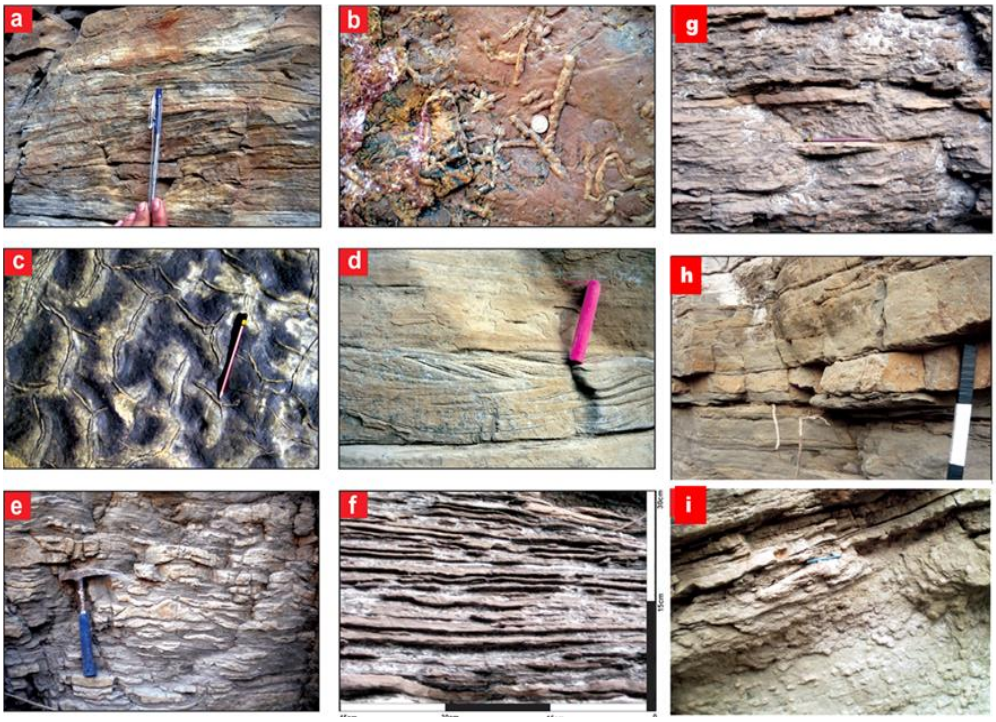


Figure 3.34 Sedimentary structures in Nilawhan and Khewra area seen in Kussak Formation, a) Cross Lamination, b) Bioturbation, c) syanaresis cracks, d) Hummocky cross bedding, e) Flaser Bedding, f) Wavy bedding, g) Bioturbated Mudstone, h) dolomitic sandstone, i) Glauconitic Sandstone (Wajeeha et, al. 2014).

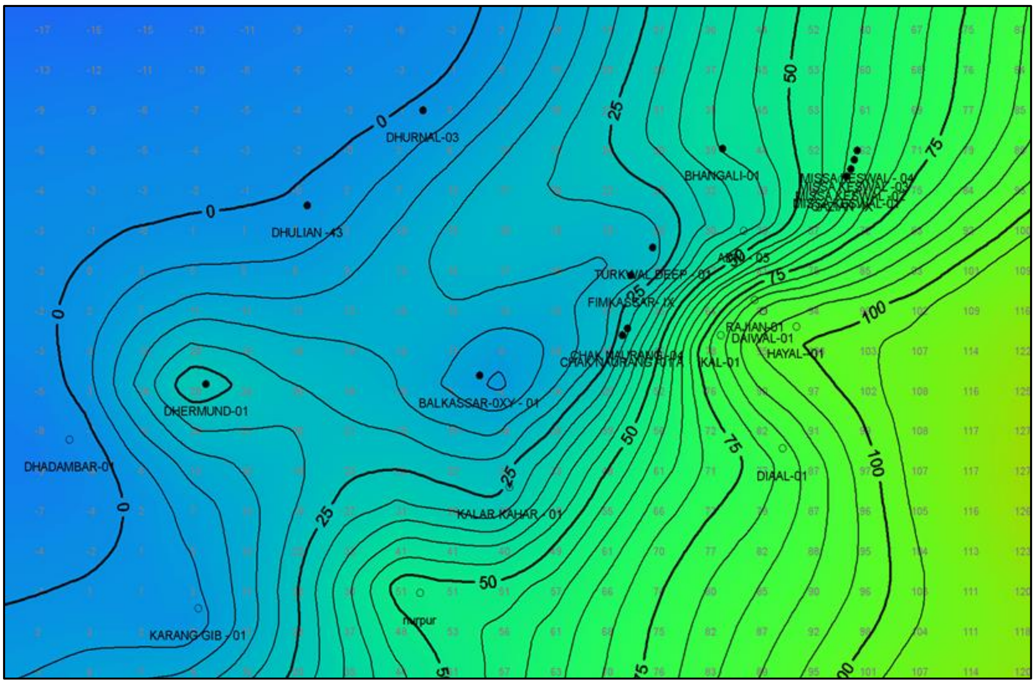


Figure 3.35 Isopach map of Kussak Formation, central and eastern Powtar Basin based on well data correlation outcrop thickness information has not been accounted during map compilation.

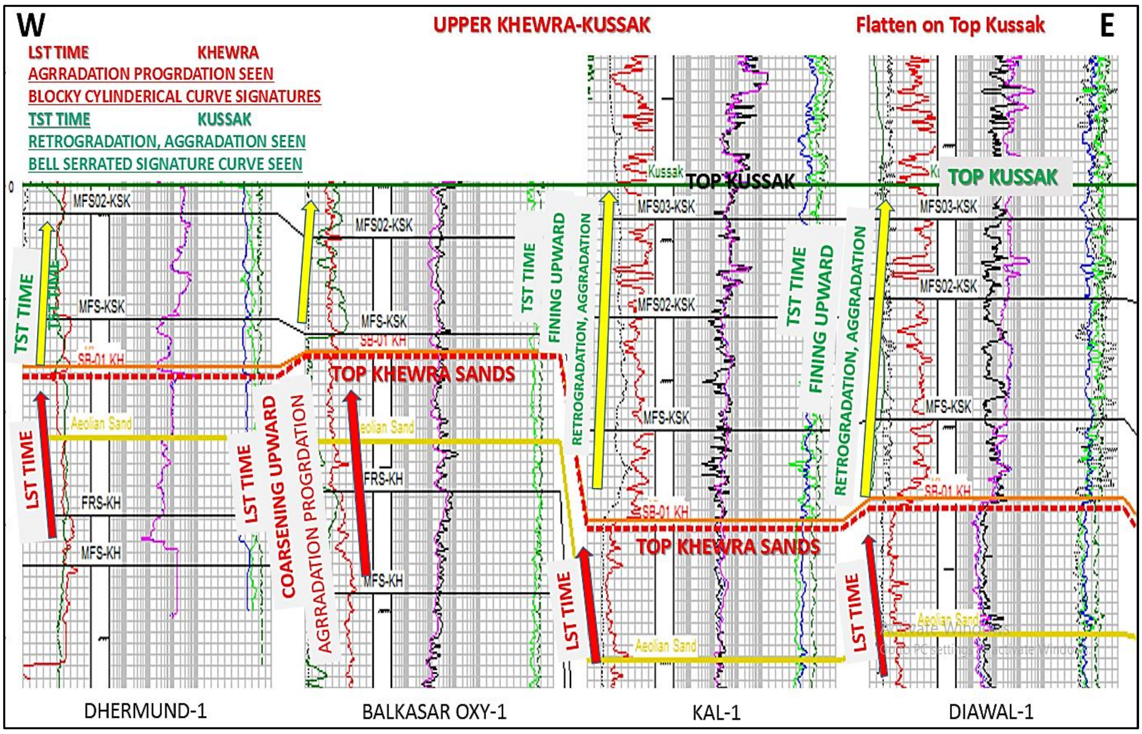


Figure 3.36 Correlation of GR log curve between Dhermud-1 to Diawal-1 (flatten at top Kussak) showing FS-1, FS-2 and MFS surfaces.

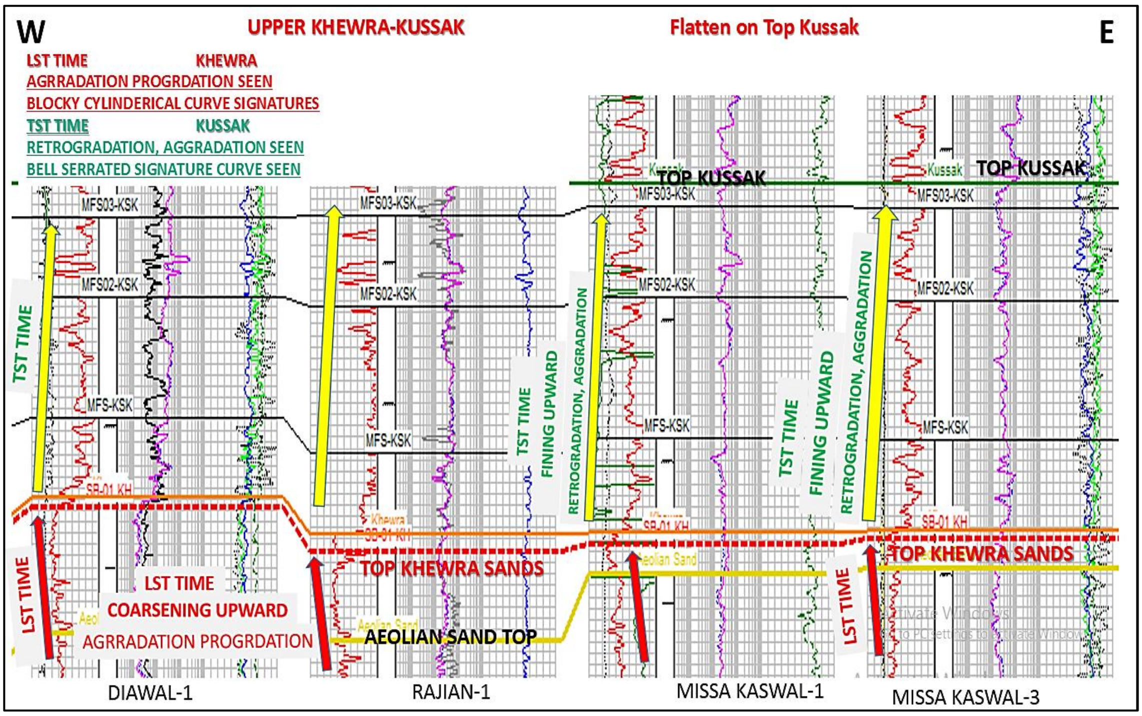


Figure 3.37 Correlation of GR log curve between Diawal-1 to Missa Kaswal wells (flatten at top Kussak) showing FS-1, FS-2 and MFS surfaces.

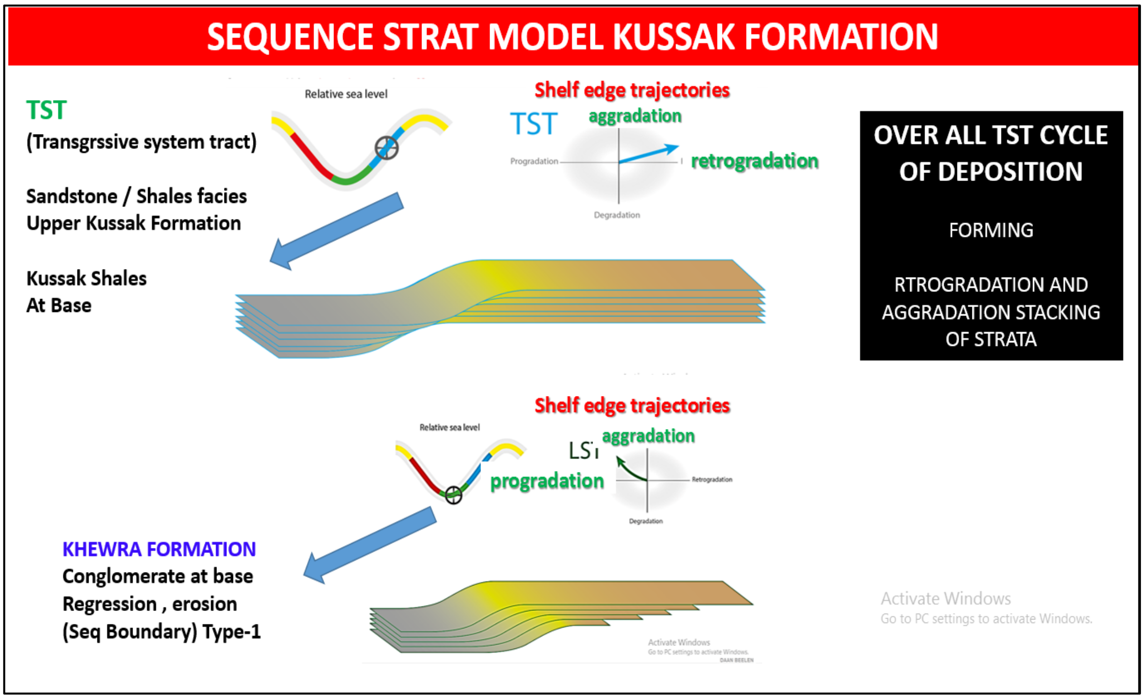


Figure 3.38 Probable correlation of Kussak-Facies, its correlation with eustasy and evaluation of relevant system tract (TST).

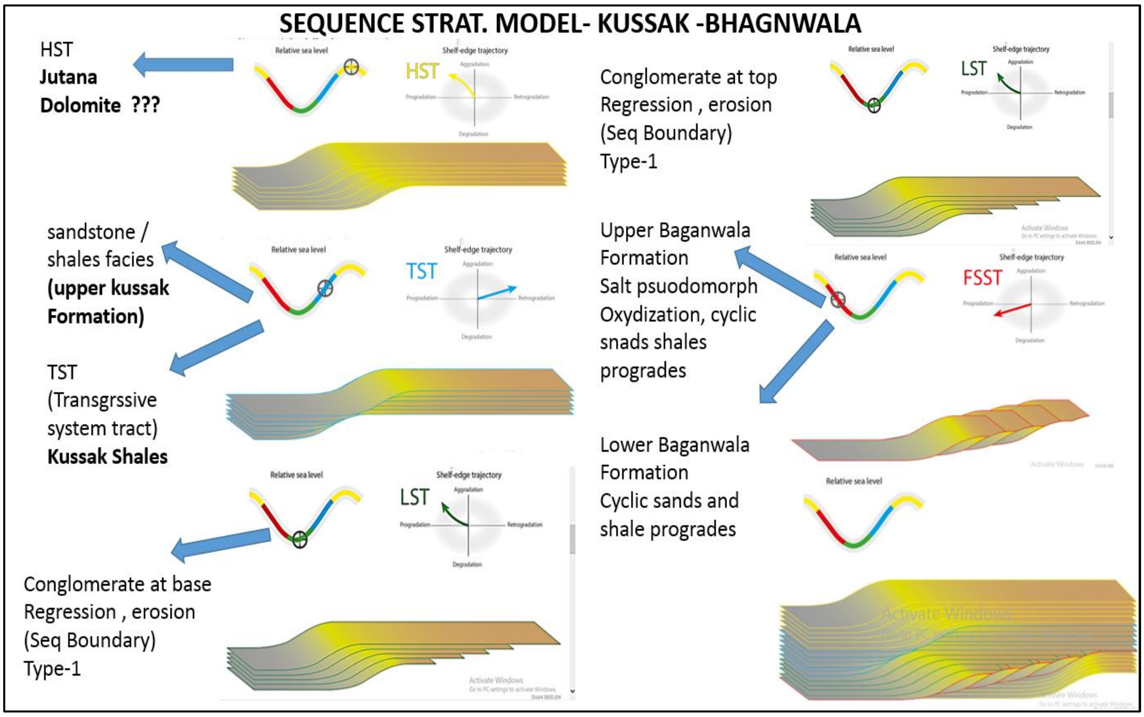


Figure 3.39 Evaluation of system tracts for Cambrian rock facies of Salt Range and South Potwar Basin using hypothetical eustatic curve.

3.3.3 Jutana Formation

The Jutana Group of Noetling (1894) is formalized as Jutana Formation after Jutana Village in eastern Salt Range. It has been also reffred as a Magnesium Sandstone of Fleming (1852) "Jutana Group" of Noetling (1894)”.

The Jutana Formation is composed of dolomites which was deposited under calm, warm, shallow, and well-oxygenated marine environments. These conditions were prevailed during high stand time of eustasy. These dolomites show porous nature and are valid hydrocarbon reservoirs in the area (Ahmad et al., 2013; Kadri, 1995; Quadri and Quadri, 1996). The dolomite has undergone recrystallization which resulted in the partial elimination and occasionally complete destruction of original textural and structural features. The lithological analysis and contact relationship with Kussak and Jutana was observe along Choa-Khewra (Figures 3.40), Motorway (Figures 3.41) and Choa-Ara Bashrat (Figures 3.30), Choa-Khewra Road (Figure 3.11), Kussak Fort section (Figure 3.12), and Nilawahan Gorge (Figure 3.13). The Jutana formation is divided into Interbedded dolostone-sandstone in lower part, Shale unit in middle and Massive dolostone in upper part (Shah, 2009).

Shah et, al. (2019) studied lithological units of Jutana Formation in outcrop areas of Khewra Gorge and along M2 motorway (Figures 3.43A to 3.43F). The lower part in these sections show interbedded sandstone and dolostone lithologies that were formed after cyclic deposition of clastic and non-clastic sediments. The sandstone is characterized by ripple marks, trough and herring-bone crossbedding. These features developed during transition from sub-tidal to intertidal depositional settings before diagenetic modifications. (Ahmad et al., 2013; Ghauri, 1979; Khan, 1977).

The dolostone is thick bedded and yields light cream to grey color and bear alternating layers of medium to thinly laminated impure micaceous sandstone. The lower unit (the sandstone/dolostone unit) is 31m and 28 m in the Khewra gorge and motorway sections, respectively. The isolated clasts of host limestone are also preserved in dark grey colored dolomite. Small scale ripple marks are also observed (Figure-3.43 A). Low angle cross bedding is also reported (Figure 3.43 B). The ooids and pisolites of centimeter scale are present among dolomites (Figure 3.43 D) along with foraminiferal assemblages.

These bedding parallel stylolites are also reported (Figure 3.43 E). The middle shale unit 3 to 4 meters is dark-grey greenish to maroon shale, interbedded with glauconitic sandstone.

The Jutana formation in the Khewra gorge and the Motorway sections is 52m and 43.7m, respectively. However, in type locality it is about 72 meters. Isopach map in the study area based on well data show thickness from 5 to 55 meters (Figure 3.44). The Jutana Dolomite is conformably overlying on Khussak Formation. The contact is sharp and can be observed below hard, massive dolomitic bed. The upper contact is also conformable with Baghanwala Formation and regarded as gradational with a sharp color contrast. The Formation contains tracks and burrows of Trilobite. Early Middle Cambrian age is assigned to the Formation on the basis of faunal record, (Techert 1964).

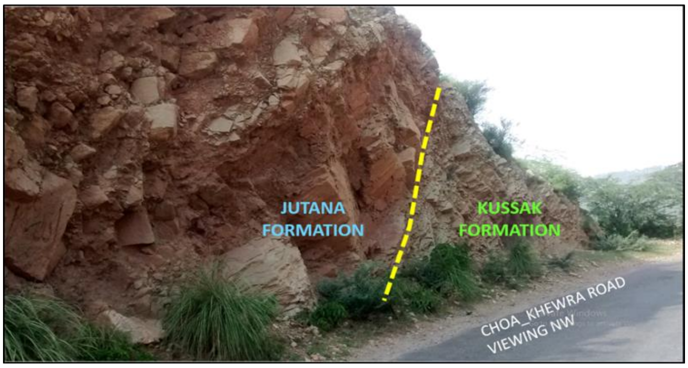


Figure 3.40 Kussak-Jutana contact along Choa-Khewra Road Salt Range.

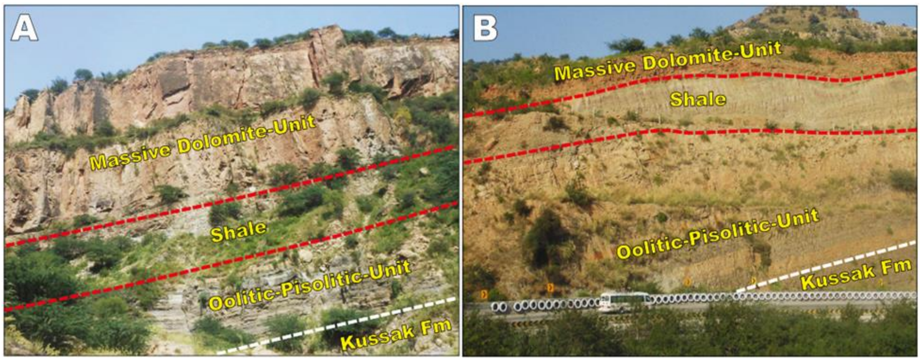


Figure 3.41 Jutana faices and contact with Baghanwala Formation along M-2 Motorway Kallar Kahar and eastern Salt Range: A) stratigraphic units of Jutana Fm. in the Khewra gorge and B) Units of Jutana Fm. in the Motorway section. The contact of Jutana Fm. with the underlying Kussak Fm. is shown in both locations (Khan, S., Shah, M.M., 2019).

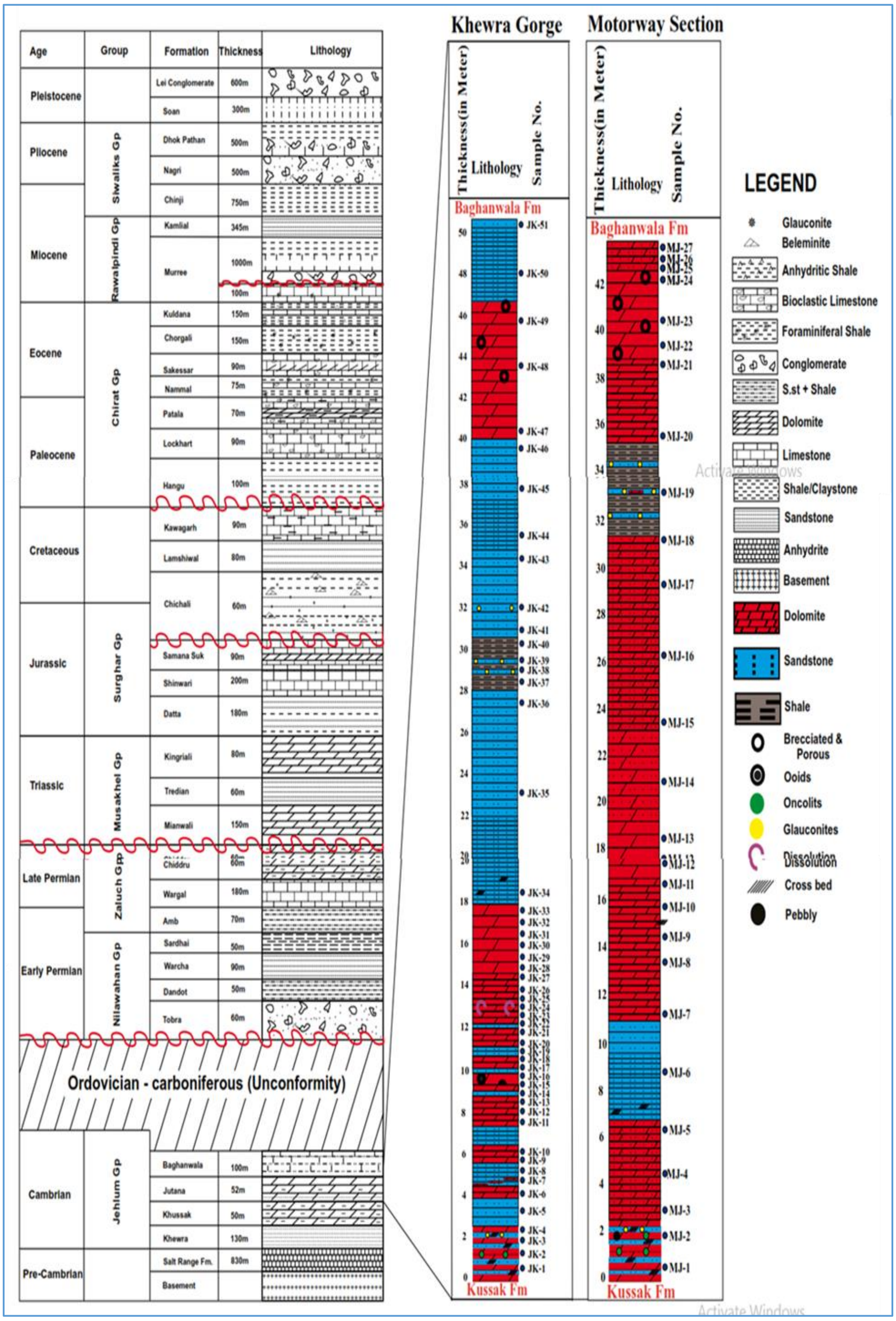


Figure 3.42 Lithostratigraphic chart Showing Jutana Facies along motorway M2 section. Unconformities are marked by red undulating lines (modified after shah, 2009). Insert columns represents stratigraphic logs of two sampled section (Khewra and Motor way) of the Jutana Formation (Khan, S., Shah, M.M., 2019).

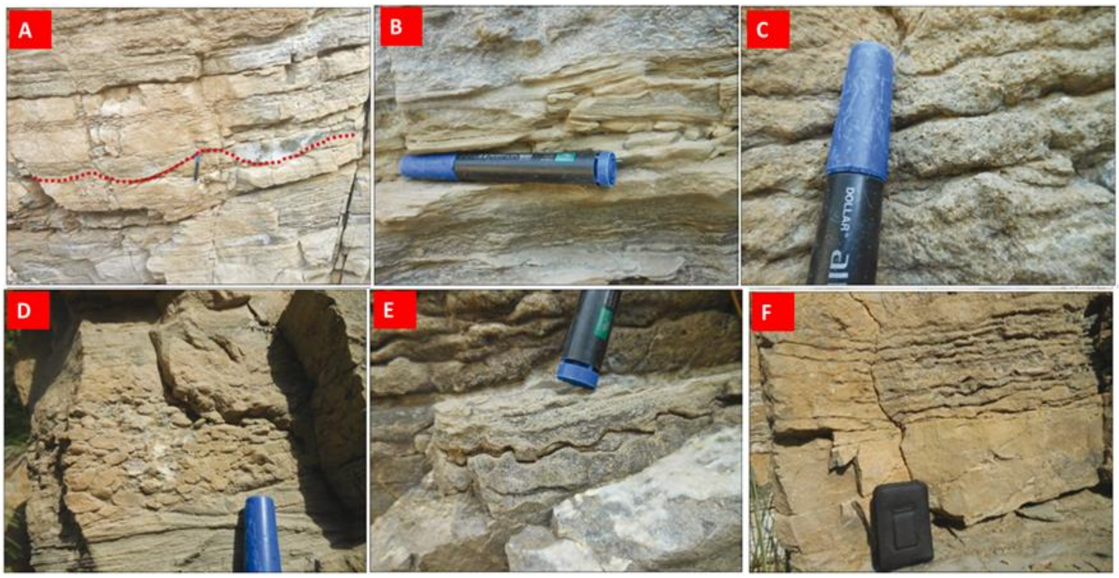


Figure 3.43 Sedimentary structures of the Jutana Formation, M2 motorway section: A) Centimeter-scale ripple marks in the sandstone beds; B) Low-angle, cross bedded sandstones; C) Dolomitized limestone with preserved foraminiferal assemblages,; D) Oolitic pisolitic unit in the dolomitized part; E) Bedding parallel stylolites; F) Fractures development in the studied dolostone. (Modified after Khan, S., Shah, M.M., 2019).

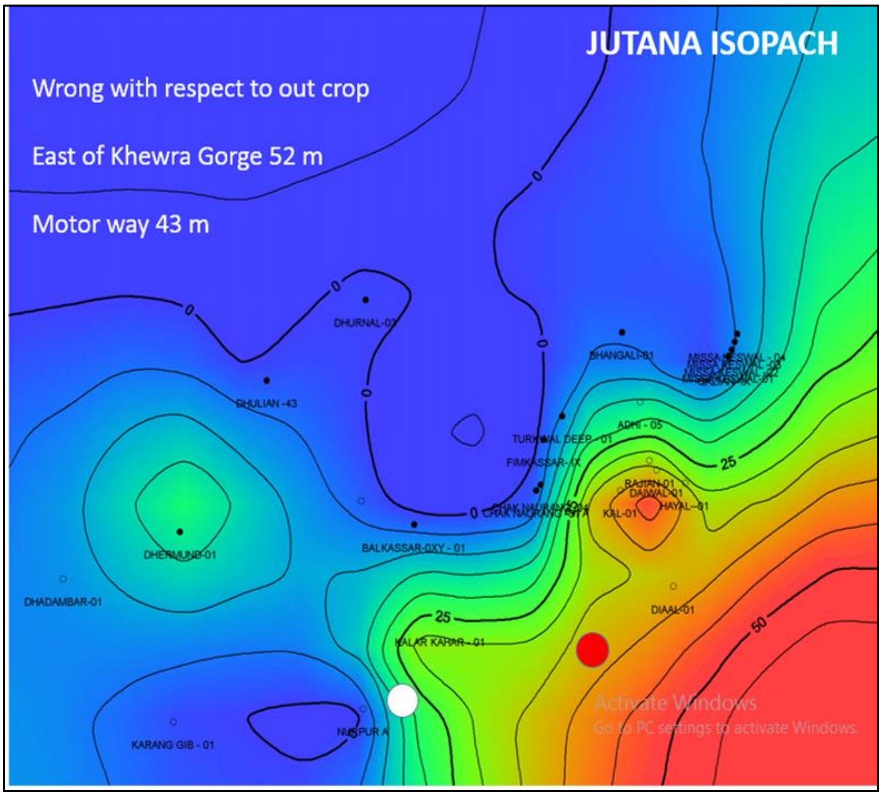


Figure 3.44 Isopach Map of Jutana Formation based on well data, central and eastern Potwar Basin.

Depositional Model

The log response of GR curves from wells in the study area and nature of facies in outcrop support deposition in high stand time of eustacy. The stacking patterns of GR curve exhibit prograding and aggrading clinoforms based on coarsening/finning upward cycles (Figure 3.24) and these clinoforms commonly thin northwest (from Kal-1 to Balkasar Oxy-1 and Dehmund-1) Figures 3.47-3.48. The presence of MFS-02 near top Kussak formation and below Juttna dolomites is also indicating high stand system tract. Multiple clinoforms with prograding curve signature are marked between Kal well and Missa Kaswal wells. However in the northwest these clinoforms are not obvious and show thinning.

There may be a probability for presence of FSST facies at the top of HST level (Top Jutana level) which subsequently is capped by LST time. The top Jutana dolomitic sand clinoform may be related to such changes associated to HST to LST events. At this junction the GR curve interpreted as top part of HST show coarsening of event and may relate to regression cycle created by forced regression at top and thus may belongs to FSST. However, such assumption may require more data analysis for evaluation of attached or detached parasequence stacking patterns using better quality high resolution seismic data.

The Jutana outcrop along Choa-Khewra road at one location show multiple clinoforms (Figures-3.45) portioned by thin bedded sandstone and mudstone unit. These are dolomitic sand bodies which are creamy and massive in appearance. Both the units resides below Bhaganwala Formation. These both massive dolomitic sand units might have been developed during FSST phase. The GR curves of the wells do show coarsening of event Figure 3.47 and 3.48 which may relate to regression cycle created by forced regression at top and thus may belongs to FSST.

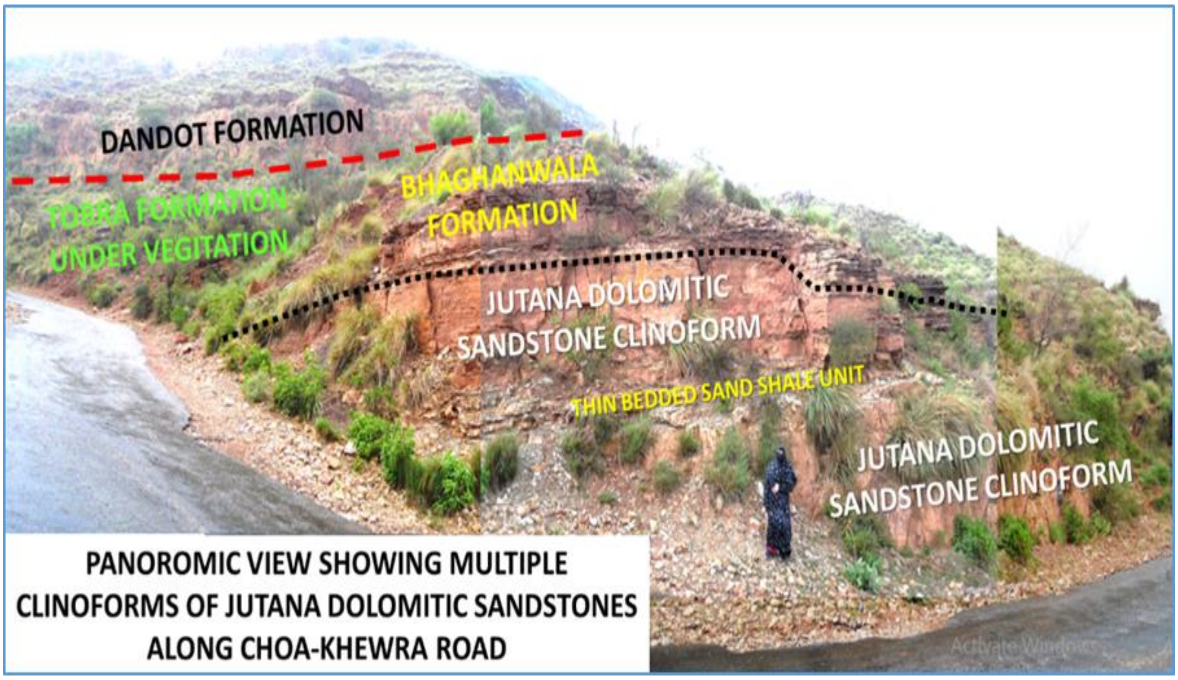


Figure 3.45 Probability for presence of FSST facies at the top of Jutana level (HST) which subsequently is capped by LST facie of Bhaganwala Formations, along Choa-Khewara Road. The top Jutana outcrop at this location show multiple dolomitic sand clinoforms probably related to changes associated with HST to LST events.

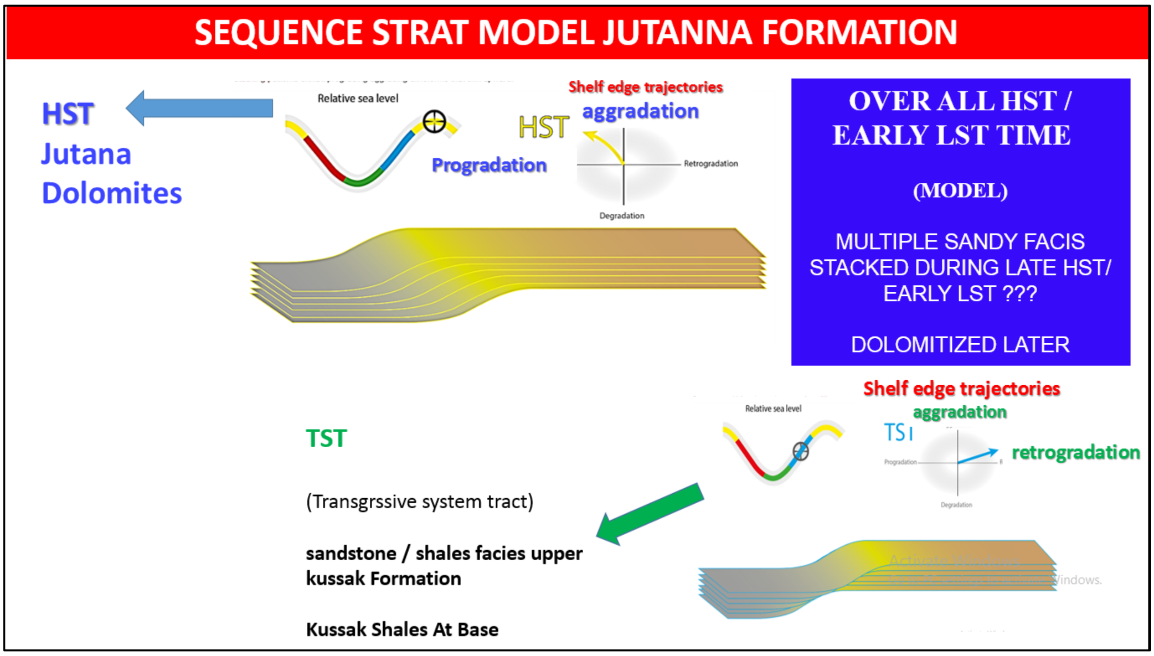


Figure 3.46 Probable correlation of Jutana Facies, its correlation with Eustasy and evaluation of relevant system tract (TST).

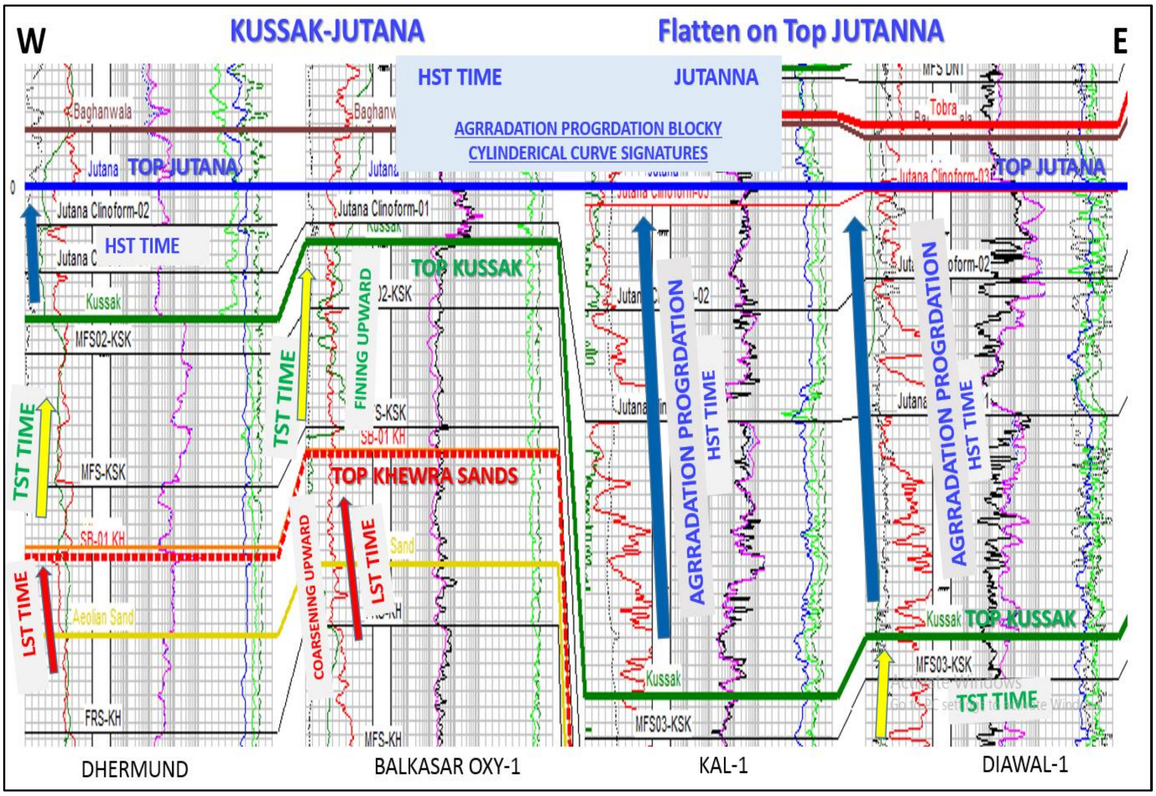


Figure 3.47 Correlation of GR log curve for Jutana Formation between Dhermud-1 to Diawal-1 showing FS-1, FS-2 and MFS surfaces..

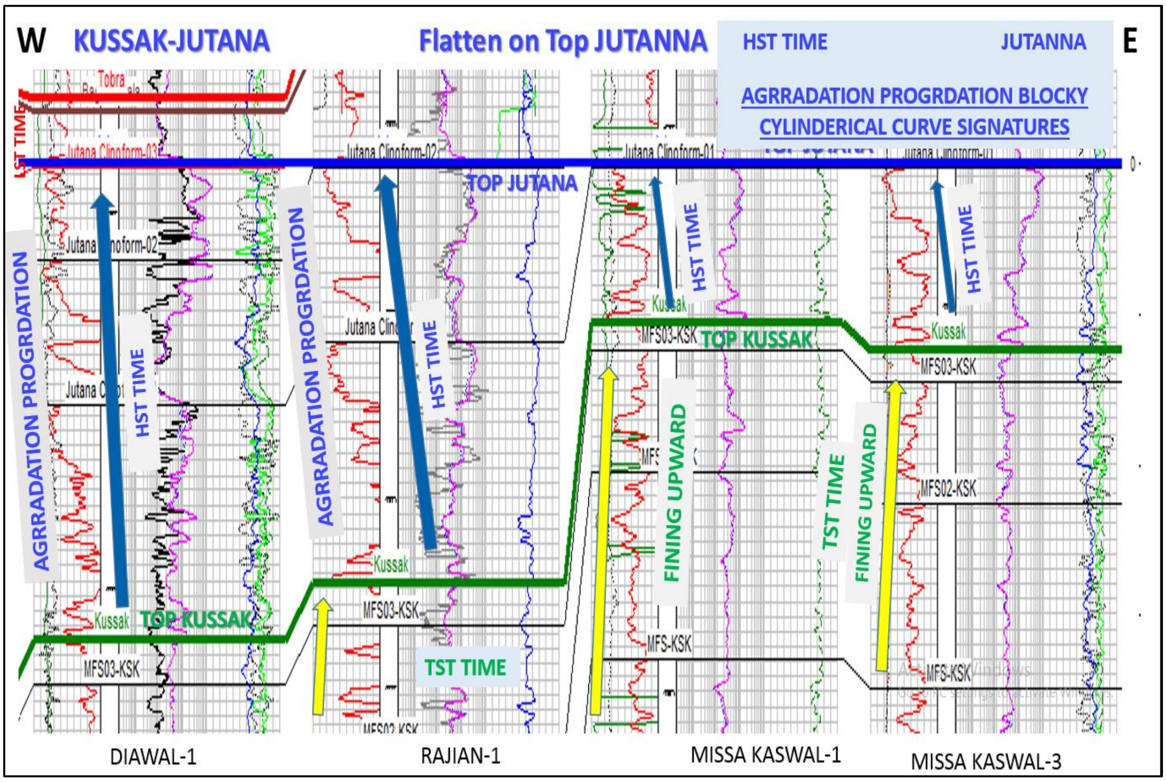


Figure 3.48 Correlation of GR log curve for Jutana Formation between Diawal-1 to Missa Kaswal wells showing FS-1, FS-2 and MFS surfaces.

3.3.4 Baganwala Formation

Baghanwala Group of Noetling (1894) is formalized as Baghanwala Formation after the village Baghanwala, Jhelum distric Punjab Province. Wynne (1878) named this lihostratigrphic unit as Pseudomorphic Salt Crystal Zone. Holland (1926) called it Salt Pseudomorphic Beds. Pascoe (1959) as a "Baghanwala Stage" exposed near Baghanwala village Eastern Salt Range, Jhelum District.

The outcrops of the Baghanwala Formation are prominently exposed in the eastern Salt Range at Pidh, Dandot, Chambel, Makrach, and Jogi Tilla ridges. Exposures of this formation are also present in the eastern side of the Nilawahan. The lithological evaluation for the contact analysis and facies has been made along salt range in the area of Choa-Khewra Road, Figure 3.11 and 3.49 and Ara Basharat Road, Figure 3.50, This formation is composed of cyclic facies associated as intercalation of variegated claystone, mud stone, siltstone and thin bedded sandstone. The sandstone appear purple, grey or blue green. The mud stone and silt stone in upper part are in maroon and reddish brown colour. The sandstones at few stratigraphic levels are calcareous and argillaceous in composition. The cubic pseudornorphs salt crystals are the most important feature and are well developed in upper part of the formation. These are preserved along the bedding planes of muddy sandstones deposited at the end of each cycle. Each cycle ended with evaporation in oxidization stage under arid condition or drying of water. Such process show over all fall in sea level curve under fluctuating conditions. The presence of calcite/dolomite is common in the lower part of the formation indicating warm, well oxygenated, calm, and shallow marine environments. These carbonate were accumulated after overflow of marine water (containing dissolved carbonates) during deposition cycle. The preservation of primary sedimentary structures (wave ripple marks and mud cracks) and presence of salt pseudo morphs (Figure 3.51). indicate the deposition of the formation under shallow water environments in strongly oxidizing, evaporitic and higher saline arid and drying conditions.

Total thickness of the Baghanwala Formation, measured on the eastern side of the Khewra Gorge is about 33 meters. At type locality the Formation is 100 to 105m thick. The upper contact with Tobra Formation is unconformable whereas lower contact is conformable with Jutana Formation. Isopach map compiled based on available well data in the area of study show thickness ranging from 5 to 15 meter in the southern Potwar basin (Figure 3.52). The formation is Middle Cambrian in age.

Depositional Model

The deposition of cyclic units of Bahganwala suggest over all fall in sea level under fluctuating conditions. The log response of GR curves from wells in the study area and nature of facies in outcrop support deposition in low stand time of eustacy. The stacking patterns of GR curve exhibit prograding and aggrading clinoforms. In general behavior of GR log curve represents coarsening upward profile of clinoform present in Baghanwala formation between Dhermund-1 well in west to Rajian-1 well in east (Figure 3,24), however this curve in the area of Missa Kaswal appear aggradational and blocky indicating vertical piling up of deposition cycles that could be considered for association to HST (Figures 3.53 and 3.54). The deposition of cyclic units of Bahganwala suggest over all fall in sea level under fluctuating conditions and belongs to FFST (Figure 3.55). The log response of GR curves from wells and facies in outcrop support deposition in low stand time of eustacy.

Figure 3.49 Baghanwala Formation along Choa- Khewra Road showing abrupt change in lithologies from Sands to shale and change in bedding thickness.

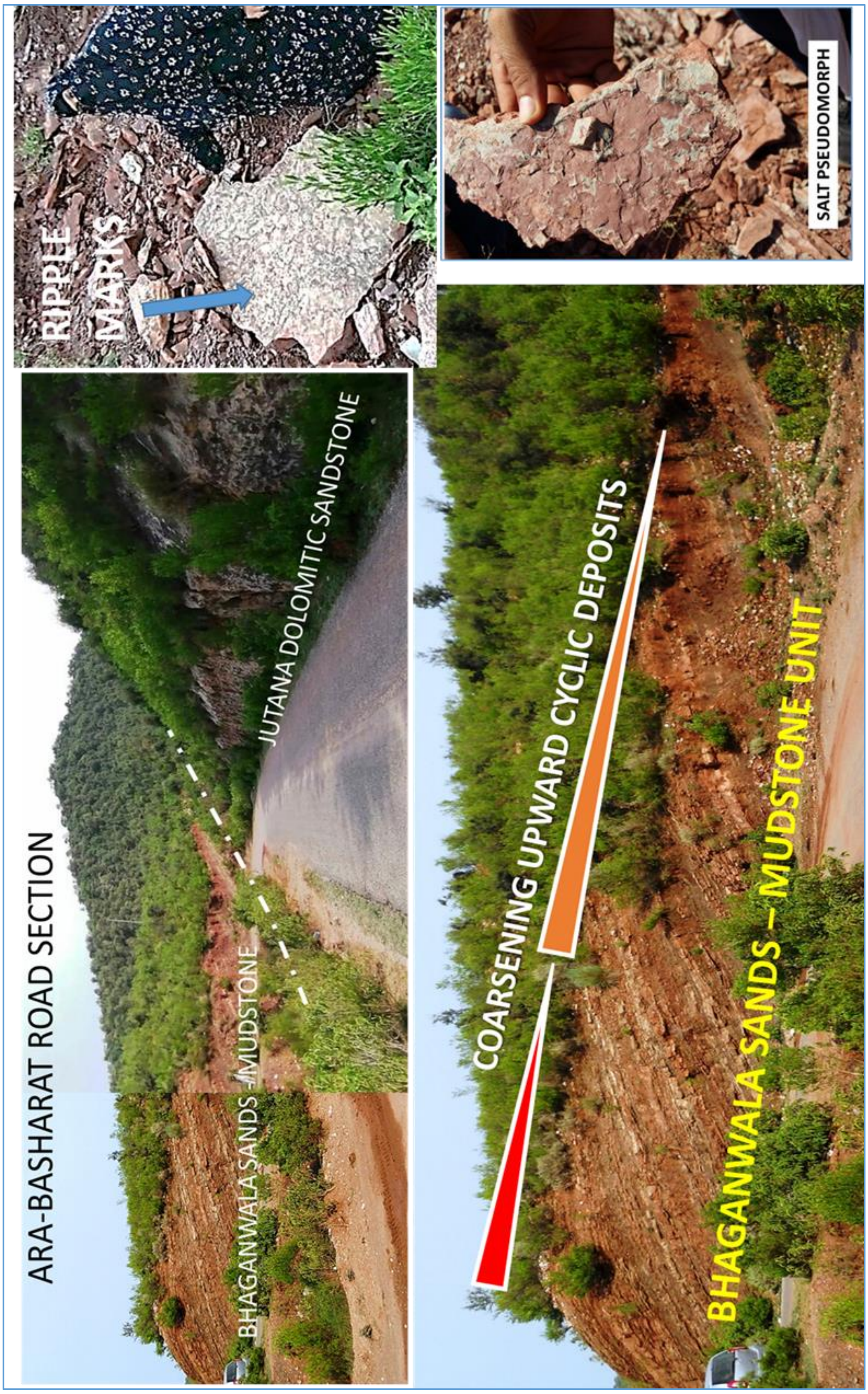


Figure 3.50 Change in lithologies from sands to mudstone, claystone to shales (maroon colors) in Baghanwala Formation, Ara Bashrat Road.

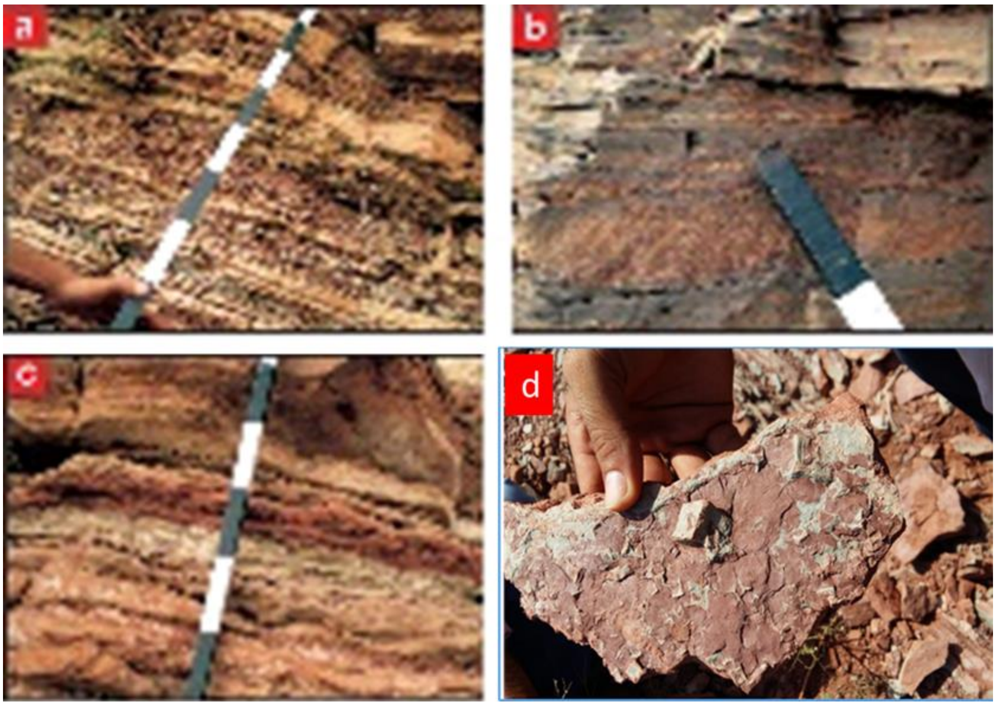


Figure 3.51 Sedimentary structures present in Baghanwala Formation in Salt Range. (a) stratification (b) Lenticular bedding (c) Flaser Bedding (d) Salt pseudomorph

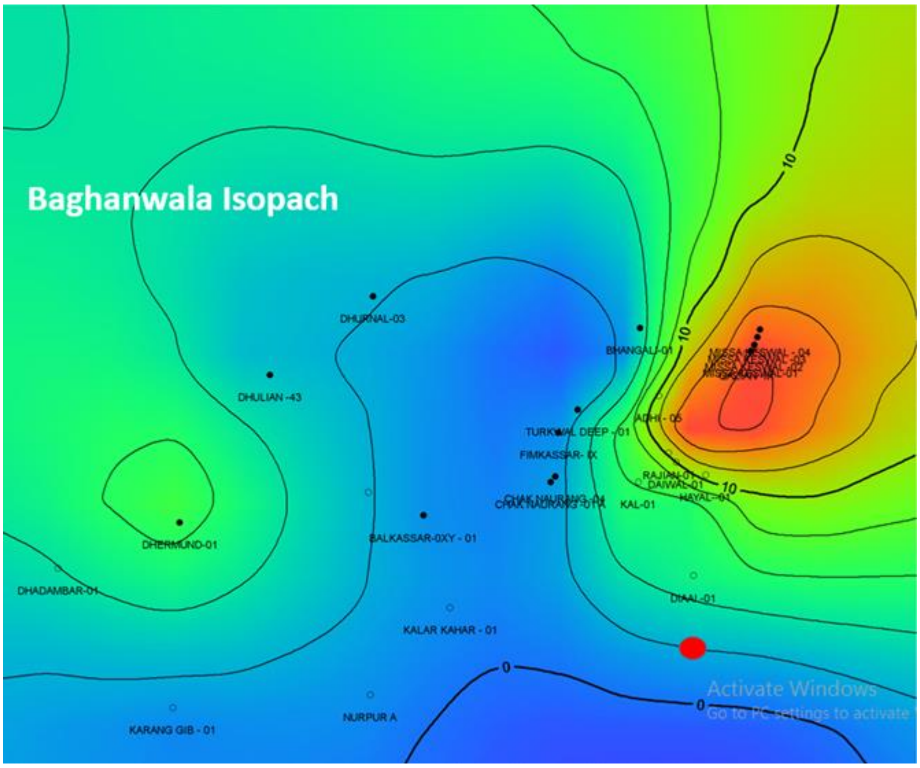


Figure 3.52 Isopach Map of Baghanwala Formation compiled based on well data, central and eastern Potwar Basin.

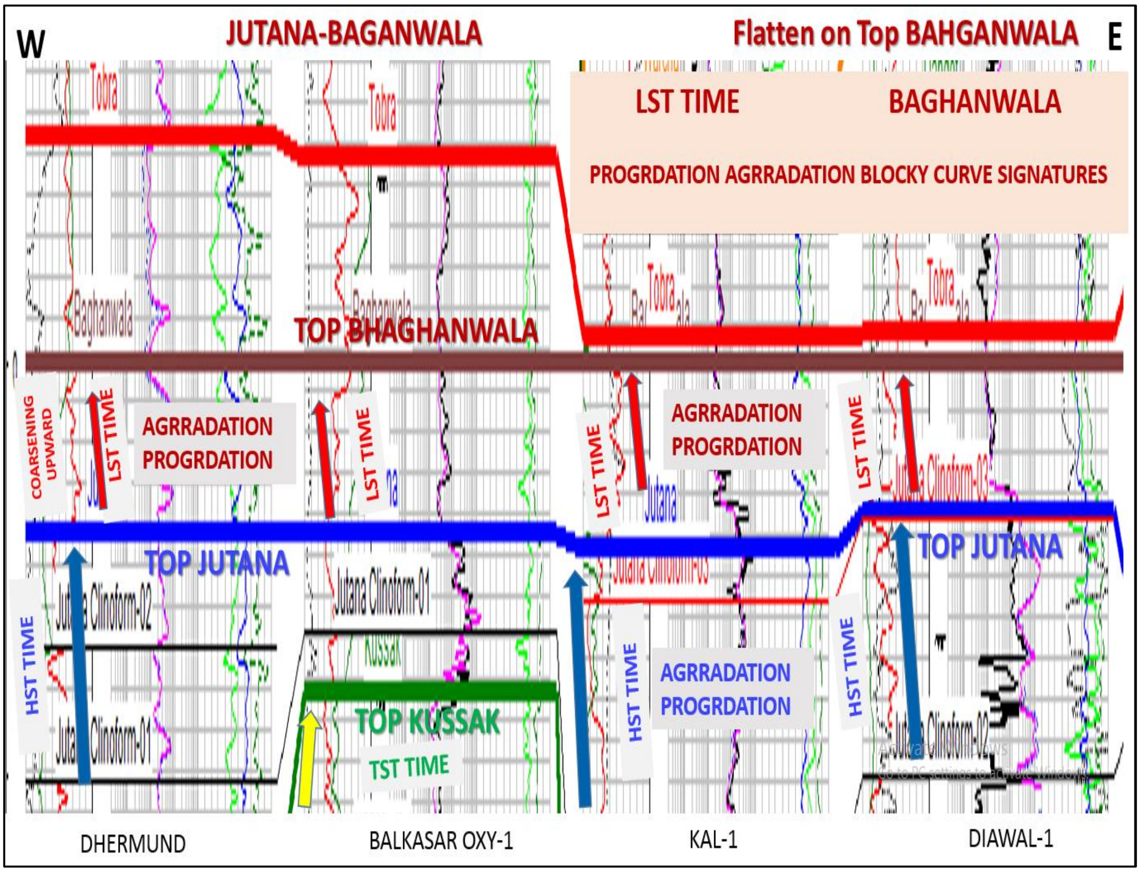


Figure 3.53 Correlation of GR log curve between Dhermud-1 to Diawal-1 showing FS-1, FS-2 and MFS surfaces.

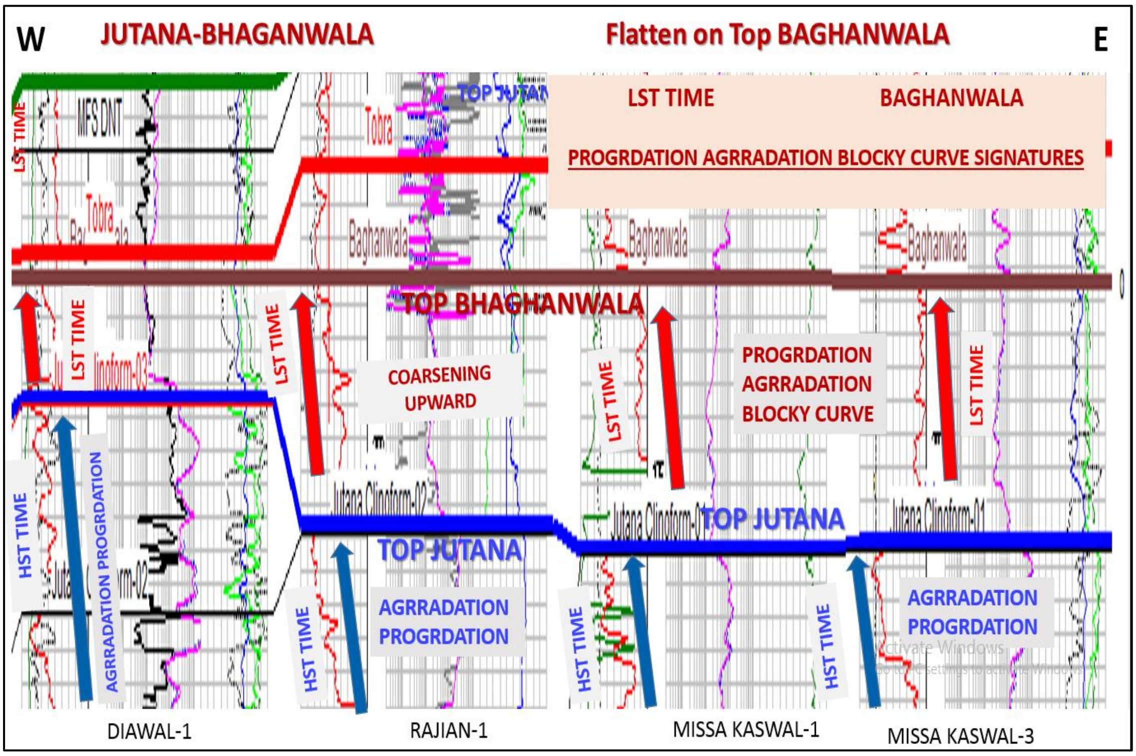


Figure 3.54 Correlation of GR log curve between Diawal-1 to Missa Kaswal wells showing FS-1, FS-2 and MFS surfaces.

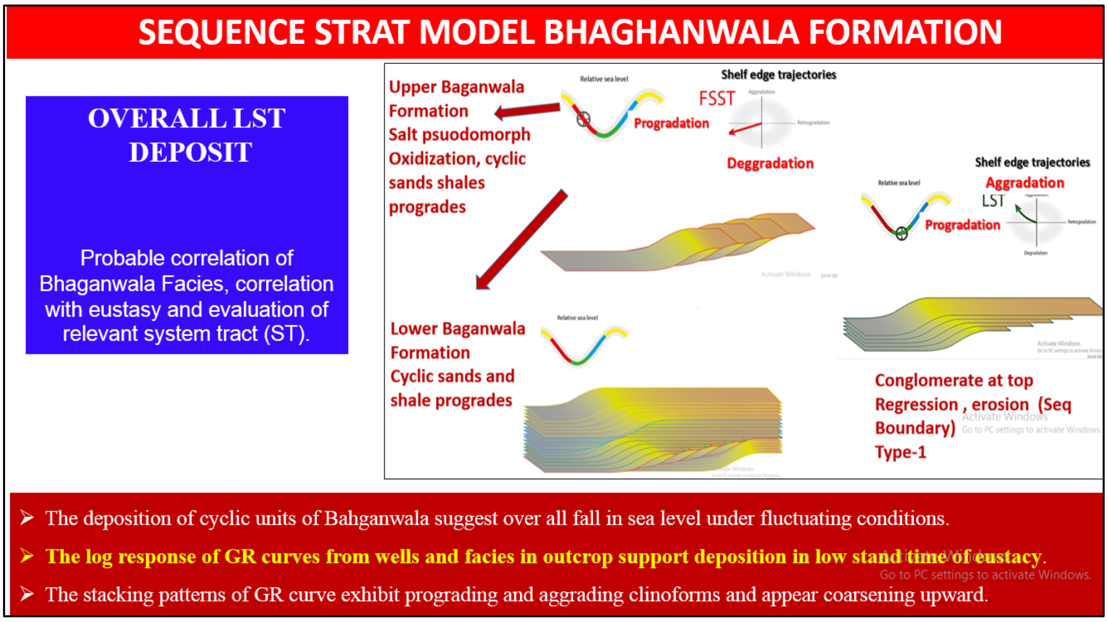


Figure 3.55 Probable correlation of Bhaganwala facies, its correlation with eustatic curve and evaluation of relevant system tract (LST / FSST).

3.4 Permian

The Permian stratigraphy exposed in Salt-Trans Indus ranges and preserved in subsurface of Potwar-Kohat-Banuu basins, Mianwali and Indus Plains is dividable into

1. Clastic facies of Early Permian Nilawahan Group
2. Carbonate facies of Late Permian Zaluch Group

The Early Permian Gondwanaland clastic sediments resides above Late Permian Tethyan carbonate deposits which are highly fossiliferous. The Permian stratigraphy has been divided into seven lithostratigraphic units (four in Nilawhan Group and three in Zaluch Group) in the upper Indus Basin. These stratigraphic units are gradually truncated by Base Tertiary unconformity from west to east in Potwar and upper Indus Basin (Figure 2.4 and 2.5). The present trend of truncation is aligned NNE to SSW in direction. The relationship of lower most Permian unit (Tobra Formation) with underlying Cambrian stratigraphy (Khewra, Kussak, Jutana and Bahganwal) varies due to angular relationship as a result of erosion and removal or non-deposition. The deepest level of this unconformity is marked between southern and northern Potwar where entire Cambrian is missing north of Soan syncline (Figure 2.5). The Early Permian sequence was deposited in a continental and marginal-to shallow marine setting (Gee1989; Shahid et.al 2009) while the Late Permian is entirely of marine in origin (Kummel and Teichert 1970; Wardlaw and Pogue, 1995).

The four lithological units which belongs to early Permian stage show accumulation in a late glacial and post-glacial episode. During these episodes a range of glacio-fluvial, marine and fluvial environments were prevailed due to change in eustacy along with change in climatic conditions. These climatic conditions were associated with the northward drift of the Indian plate along with eastern Gondwanaland from polar to equatorial region. Shahid et.al (2009) suggested deposition of four lithostratigraphic units of early Permian age from cold to hot climates in Gondwanaland basin and where Indus basin was also a part of this setting (Figure 3.57).

The behavior of Eustatic curve during entire lower and upper Permian sedimentation indicate multiple fluctuations of rise to fall and rise that started after de-glaciation and are generally associated to climatic conditions prevailed at different latitudes during northward movement of eastern Gondwanaland. During these fluctuating levels of Eustasy the conditions of maximum flooding were prevailed and has been recognized within Dandot and Sardhi lithologies and where coal has been reported in association with this flooding surfaces. In present study the lower Permian section has been studies for its facies in outcrop areas of Salt range and its relation with GR and SP log data of wells drilled in southern Potwar basin.

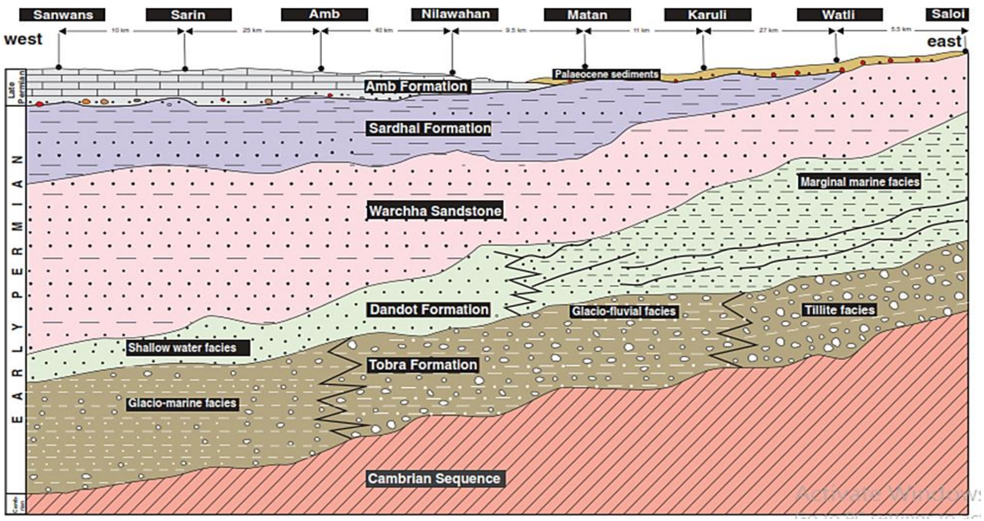


Figure 3.56 Regional stratigraphic framework of the Early Permian Nilawahan Group in the Salt Range region, (Shahid et.al 2009).

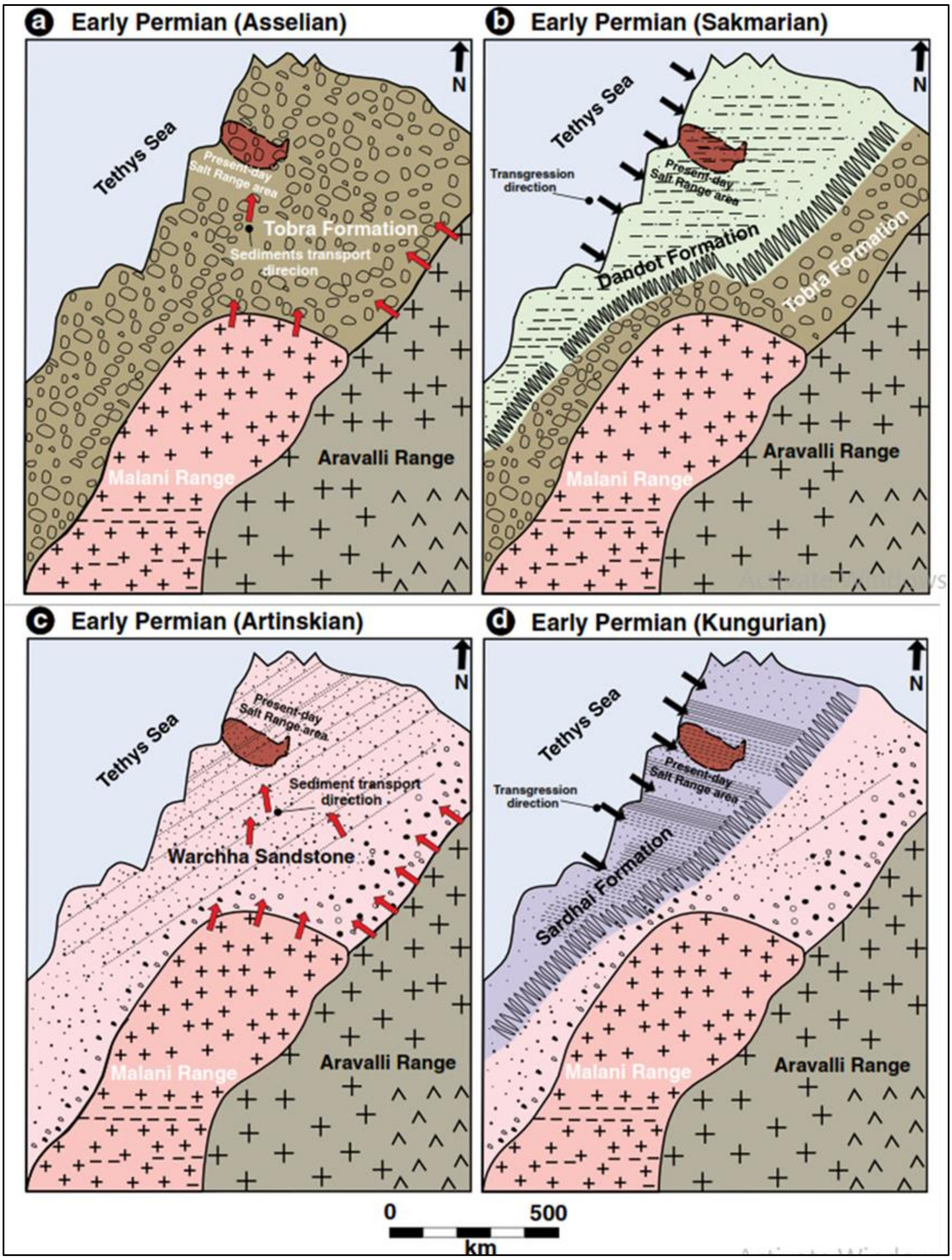


Figure 3.57 Tectono-stratigraphic evolution of the present-day Salt Range area through the Early Permian (a-d) Asselian to Kungurian times. These maps illustrate the change of sedimentation style from fluvio-glacial (Tobra Formation), to shallow to marginal marine (Dandot Formation), to meandering fluvial (Warchha Sandstone) and shallow marine (Sardhai Formation) modified after (Shahid et.al 2009).

3.4.1 Tobra Formation

The term Tobra Formation has been introduced by Gee for the lowest unit of the Nilawahan Group. This formation was also referred as "Talchir Series" of Blanford (1856),"Talchir Conglomerate", "Talchir Stage" of Gee (in Pascoe, 1959), "Talchir Boulder Beds" of Pascoe (1959), "Salt Range Boulder Bed" of Teichert (1967) in previous literature. The Tobra village (lat.32°40’N; long. 72°50’E) Eastern Salt Range, Jhelum district, Punjab Province is the type locality for the outcrop area.

Three lithofacies were identified by Teichert (1967) in the Tobra Formation (Figure 3.56).

1. A tillite facies is restricted to the eastern Salt Range.
2. A fresh water facies of alternating siltstone and shale and containing a spore flora and a few scattered boulders in its basal parts (glacio-fluvial facies) is located predominantly in the central Salt Range.
3. A mixed facies of diamictite, sandstone and boulder beds of marine and estuarine origin (glacio-marine facies) is located predominantly in the western Salt Range.

The Formation is composed of tillite, diamictite and fresh water facies and includes, 1) boulders which are mainly pink granites and greyish quartzite, 2) Red pebble bedded sandstone, 3) Greyish cross bedded siltstone, 4) White massive sandstone and 5) Black shale with grit lenses (Shahid et, al. 2009). The lithological characteristics were observed in the field along Salt Range (Choa-Khewra road, Motorway M-2, Nilawahan and Khata Pail sections. Pink granite, gneiss and quartzite in a poorly sorted sandy and olive-green-coloured silty and mudy matrix appear as a pebble to boulder-sized clasts in these locations (Figure 3.58, 3. 59 and 3.60 a & b). The greenish-grey to dark-grey, brown and black-coloured conglomerate and sandstone also appear in Tobra Formation.

The Tobra is distributes in the Salt and Trans-Indus range with a thickness varies from 10 m (Khewra area of the eastern Salt Range) to 150 m (Sarin and Zaluch areas of the western Salt Range). The Isopach map compiled based on well data in the study area show relevant thickness (Figure 3.61). The lower contact of the Tobra Formation is a widespread unconformity with Baghanwala Formation while the upper contact with the

Dandot Formation is (gradational) conformable. The lower contact can be recognized with change in lithology from boulder bed to black and dark brown shales of Dandot Formation along Choa- Khewra, and Katha Pail section (Figure 3.58, 3. 59). The Tobra Formation contains ostracizes, and fresh water bivalves, pollen, spores, microplanktons as well as flora remains including Glossopteris and Gangamopteris (Shahid et al. after Reed1936). On the basis of fauna the age is considered as Early Permian (Shah, 1977). Based on the occurrence of age-diagnostic plant fossils including Gangamopteris, Glossopteris and Striatopodocarpites sp., an Early Permian (Asselian) age has been assigned to the Tobra Formation (Shahid et al. after Balme and Teichert 1967; Shah and Sastry 1973; Gee 1989).

Depositional Model

The deposition of the facies of Tobra Formation have been restricted to glacio-fluvial cycle which at later stage might have been impacted by fluvial and marine interaction phase. In order to set a correlation between facies reported in outcrop of Salt Range with subcrop of southern Potwar Basin the log data of the wells provided for the study were evaluated. Both GR and SP logs show response of regressive and transgressive nature to understand facies relationship. The signatures of GR curve log from western part of southern Potwar basin to eastern part is not consistent and do show variation Figure-3.62 & 3.63. The correlation may be the trickier but suggest presence of multiple stacked lithologies. In Missa Kaswal, Rajian and Balkasar area the GR curve indicate a coarsening upward profile. This profile near upper level of Tobra also show finning upward behavior which is more obvious in Balkasar Oxy-1 location. Such signatures do represents relationship with facies of glacial deposits formed in association of fluvial and shallow marine environments. In general most of the facies like tillite, diamicite and sands, siltstone represents stacking and inter-fingering along lateral and vertical distribution which commenced from lowstand and continued till early transgression times, hence represented by both coarsening and limited fining upward cycles seen in log data.

The coarsening upward, blocky and finning upward behavior of the GR curves in the study area (Figure 3.24) can be associated with the regression and transgression of Tethys Sea across the shelf slope area of Potwar Basin which was prevailed during Cambrian-Permian time. The behavior of Eustatic curve during entire lower and upper Permian sedimentation indicate rise in sea level after glaciation time which later entre to falling stage and then subsequent rise to a maximum flooding level. Under these conditions the entire or part of Permian stratigraphy represents a sequence having a lower boundary at the base of Tobra Formation while the upper boundary may be placed after a complete cycle near top Warchha Sands. The top surface is again marked by unconformable contact with Sardhai shales. Within this sequence maximum flooding surface may present near Top Dandot level.

Figure 3.58 Lower contact of Tobra with Bhaghanwala Formation along Choa-Khewra Road. The Tobra formation show clasts of granite boulders, quartzite pebbles, sandstones embedded in matrix. Yellow line below Tobra Formation is a sequence boundary.

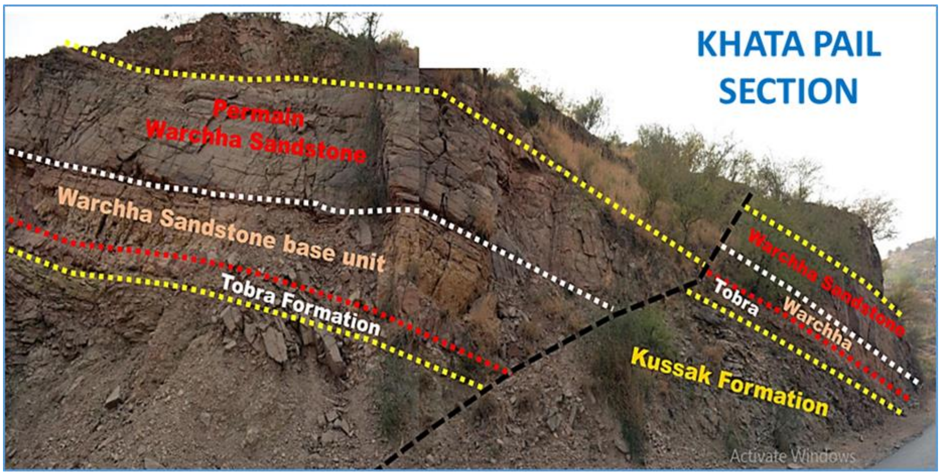


Figure 3.59 Lower contat of Tobra with Kussak Formation along Khata-Pail Road. The Tobra formation show clasts of granite boulders, quartzite pebbles, sandstones embedded in matrix.

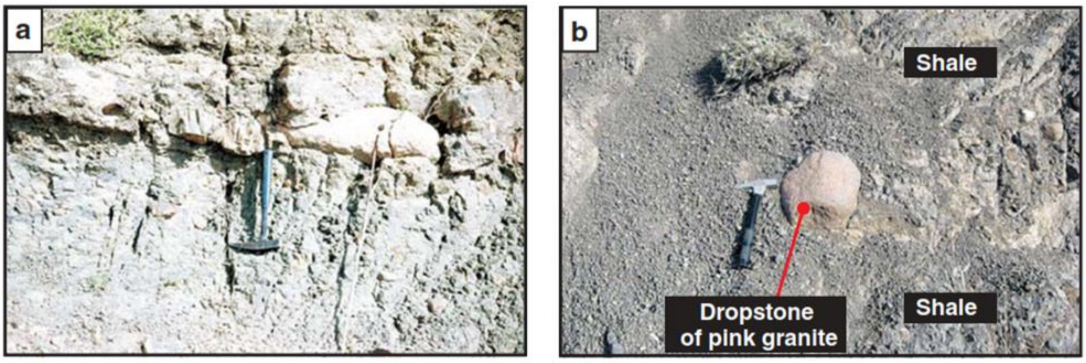


Figure 3.60 (a) Example of matrix-rich conglomeratic tillite deposits in the upper part of the Tobra Formation in the Watli area, eastern Salt Range. Note the varied composition and size of the clasts. (b) Example of stratified glacio-marine diamictite (shale with large drop stone of pink granite) in the upper part of the Tobra Formation in the Sarin area, western Salt Range (Shahid et.al 2009).

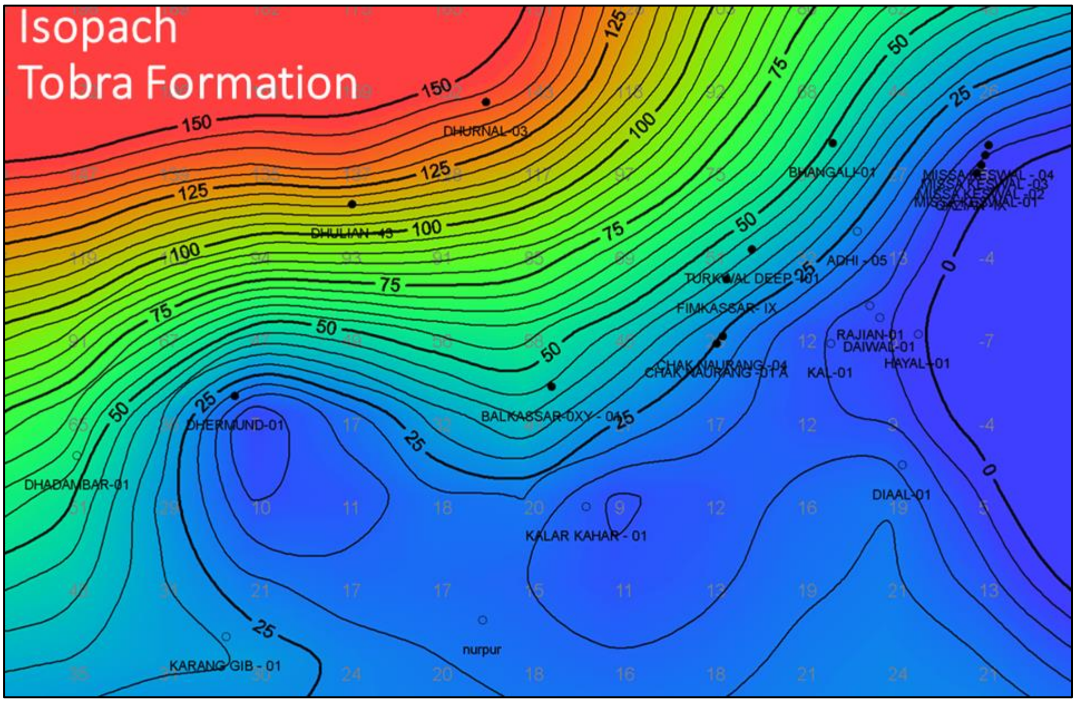


Figure 3.61 Isopach map of Tobra Formation compiled based on well data, Central and Southern Powtar Basin. The thickness is being increased in northwest direction from 10 m to 150 meters.

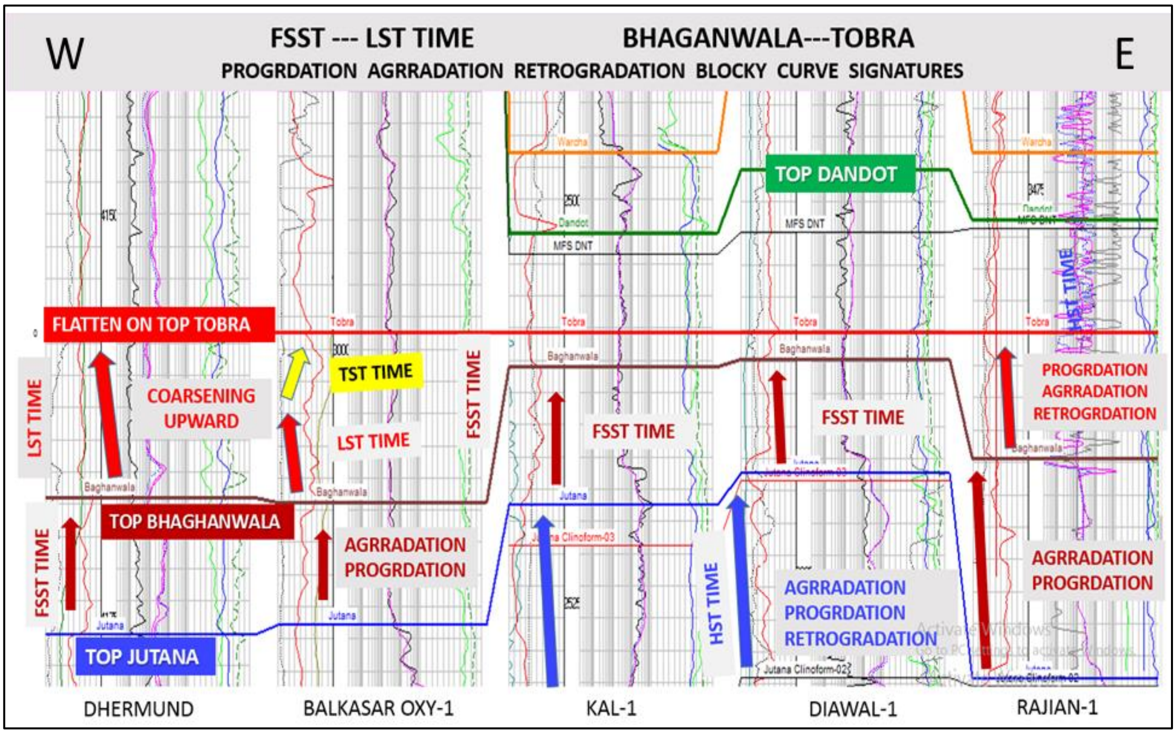


Figure 3.62 Correlation of GR log curve between Dhermud-1 to Diawal-1 showing coarsening and fining upward response indicating mix lithologies of fluvial and deltaic shallow marine environment.

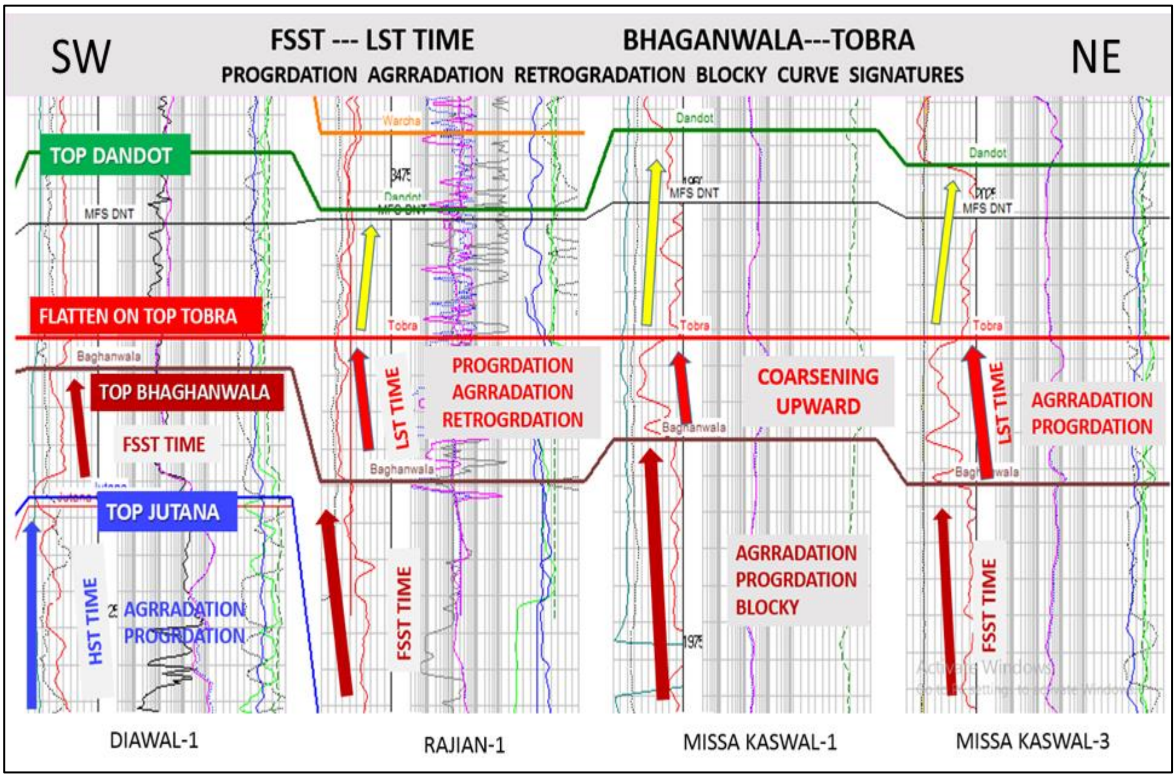


Figure 3.63 Correlation of GR log curve between Diawal-1 to Missa Kaswal-1 showing coarsening and fining upward response indicating mix lithologies of fluvial and deltaic shallow marine environment.

3.4.2 Dandot Formation

The "Dandot Group" of Noetling (1901 a, b) is formalized as Dandot Formation after the village Dandot in eastern Salt Range which is a type locality. The Olive Series, Conularia Beds, Erydesma Beds of Wynne (1878) and Dandot Group of Noetling (1901) were different names used for the formation exposed in the east of Dandot (lat. 32°39'N; long. 72°58'E) Jhelum district, Punjab Province. The Khewra-Choa Saiden Shah road section is designated as the principal reference section.

The lithological contents of this formation were studied along Choa-Khewra road section where it is represented by light-grey to olive green fine grained sandstone with occasional pebbly beds and subordinate shale of dark-green to dark-grey colour (Figure 3.65 and 3.66). In addition, the interbedded sandstone, siltstone and shale units are rich in glauconite in places. In this area these units show cyclicity of sedimentation as indicated by the presence of pebbly beds at various intervals. This section marks preservation of fluvial strata (erosional channels) along with marginal shallow marine sands and shales. Thin beds of black shale (1–2 m thick) are recorded at a few places.

Sandstone unit is comprises of flaser, lenticular and wavy-bedding, and ripple cross-lamination. In upper part of the fine grained siltstone and claystone and shale beds show extensive burrowing. The bituminous staining in the lower and middle parts of the formation is also reported. Thin coal seams are reported in top-most part of the Dandot Formation in Sarin area of the western Salt Range. In the Saloi area, large pieces of petrified wood (5–10 m long and 0.6 to 0.12 m thick) have been observed at the top of the formation (Figure-3.67).

The lithofacies of the formation gradually changes and show lateral variation which represents preservation strata of marginal marine origin in east to the strata of shallow marine in western Salt Range (Noetling, 1901). In central Salt Range the lower part of the formation in the area of Karuli, Matan and Nilawahan show sandstone beds of about 20–30 mm thick which are intercalated with shale units. The lower parts of the formation in the western Salt Range comprises of thick, dark-coloured massive mudstone and fine to medium-grained sandstone units. The lithofacies and its lateral and vertical changes in composition represents deposition during transgression of Tethys Sea after the deglaciation time.

The Formation is about 50 m thick at its type locality in the Dandot area of the eastern Salt Range (Fatmi, 1973; Shah, 1977). The maximum thickness of this formation is about 70 m in the Sarin and Sanwans areas in the western Salt Range. The isopach compiled based on well data for the area of study in southern Potwar basin show thickness ranging from 5 m to 50m in subcrop area (Figure-3.68). The upper contact of the Dandot Formation with the overlying Warchha Sandstone is unconformable (Figure-3.65 and Figure-3.66) and is characterized by an abrupt change in lithology and sedimentary style. The Dandot Formation has a gradational contact with the underlying Tobra Formation. The Formation contains rich fauna of brachiopods, bivalves, gastropods, pteropods, bryozoans and ostracodes, as well as spores (Kadri, 1995). An abundant and varied of faunal assemblage has been reported from the Dandot Formation, including Eurydesma, Conularia, Discina, Martiniopsis, Chonetes, Neochonetes as reported by Shahid et al 2009 after Waagen 1883; Reed 1944; Waterhouse 1970 and Fatmi 1973. On the basis of the stratigraphic position of the formation above the Tobra Formation, and the presence of fauna in the formation, Early Permian age has been assigned. (Telchert, 1967)

Deposition Model

The gradational, transitional nature of the change from the underlying Tobra to the overlying Dandot Formation implies a gradual but significant regional rise in relative sea-level and a regional wide transgression of the Tethys Sea, probably in response to deglaciation across many parts of the Gondwanaland at this time (as reported by Shahid et al 2009 after Ahmad 1970; Shah and Sastry 1973; Dickins 1977, 1985; Dasgupta 2006). This evaluation of the rise in Eustasy has been reflected by the preserved facies of Dandot Formation seen in outcrop along Salt Range while the same has been indicated by the well data of the study area. The GR log response show consistency in curve signature when correlated across the wells from east to west (Missa-Kaswal-1 & 2 to Dhermund-1). A fining upward profile in general can be interpreted for all the wells used in study for Dandot level (Figure 3.24, 3.69 & 3.70). This suggest transgressive of sea and can be inferred for buildup of retrogradational and aggradational stacking of sedimentary units across the shelf slop region in this part of Potwar Basin which can be associated with transgressive system tract (TST). The strike of Paleo shelf slope geometry can be assumed to align along present NNE-SSW direction and deposition is being sourced from fluvial feeders originating and transporting sediments from Aravalli Ranges present in SSE and offloading in the study area. The facies observed in the west of the study area for Dandot Formation also indicate increase in water depth relevant to geometry of shelf slope setting beside rise in sea level. The eastern Salt Range during this time faced fluctuating sea level even during overall rising stage thus allow preservation of channels among sandy and shaly units.

The GR curve in upper level below Dandot-Warcha contact responded to higher values in all the wells thus suggesting presence of maximum flooding surface and have a consistency in correlation across the study area (Figure 3.69 & 3.70). In the western Salt range the coal and preservation of petrified wood corresponds to MFS event. The presence of MFS event and association of coal lead to indicate relationship with high stand system tract (HST) facies in the upper part of Dandot Formation.

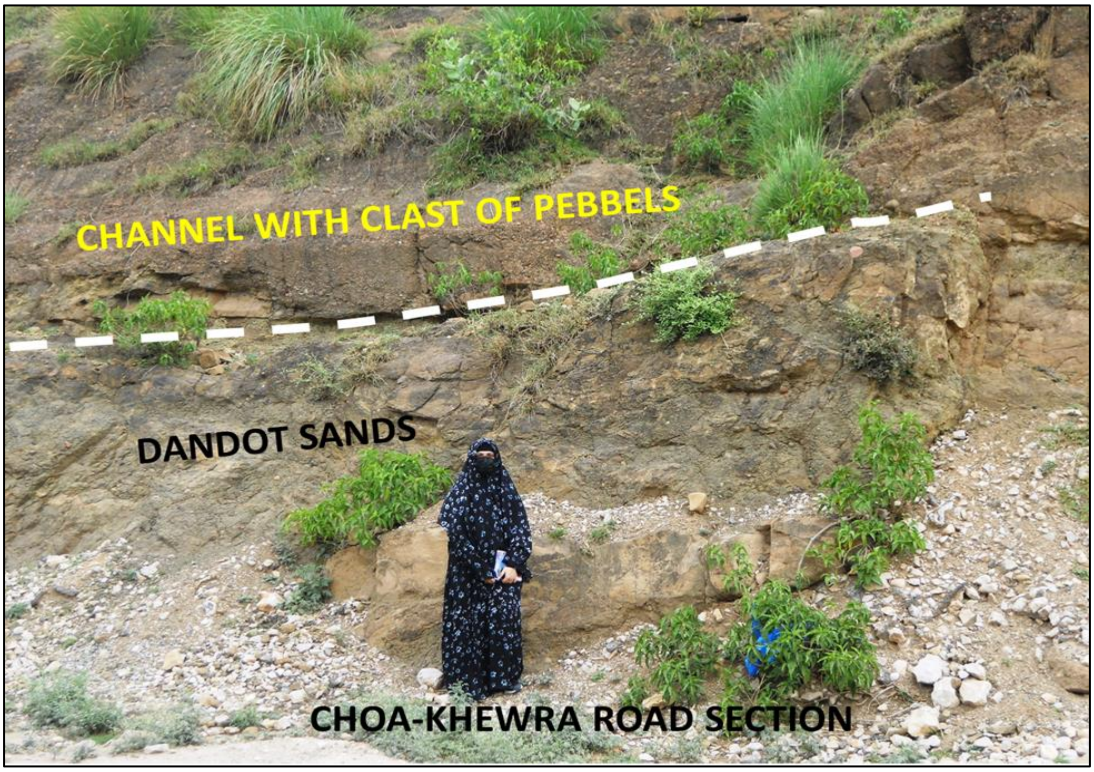


Figure 3.64 Light-grey to olive green fine grained sandstone with occasional pebbly beds and subordinate shale of dark-green to dark-grey colour of Dandot lithologies exposed near Pidh, Choa-Khewra Road.

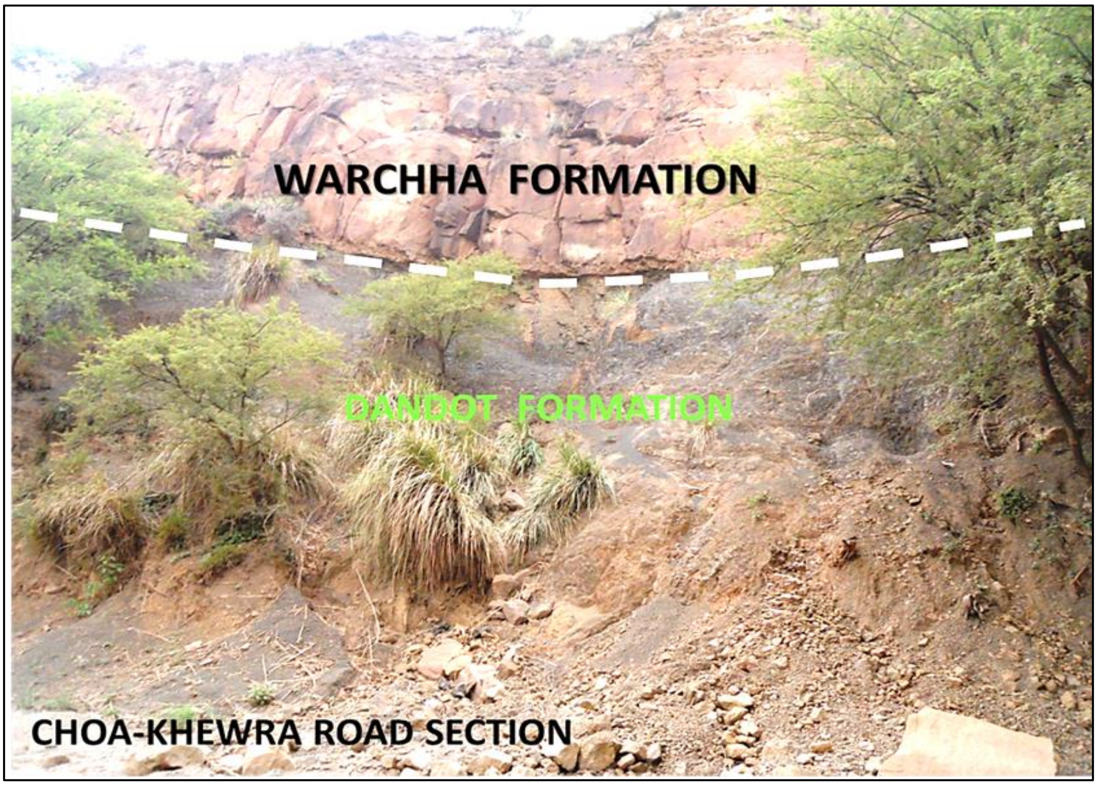


Figure 3.65 Dondot Formation in contact with Warchha Sandstone, Pidh, Choa-Khewra Road section.

Figure 3.66 Lithological contact between Dandot, Tobra and Warchha Formations in the Sanwans area, western Salt Range (modified after Ghazi at, al. 2012).

Figure 3.67 Pieces of petrified wood (5-10 m long and 0.6 - 0.12 m thick) preserved in top part of Dandot Formation, Saloi area eastern Salt Range. (modified after Ghazi at, al. 2012).

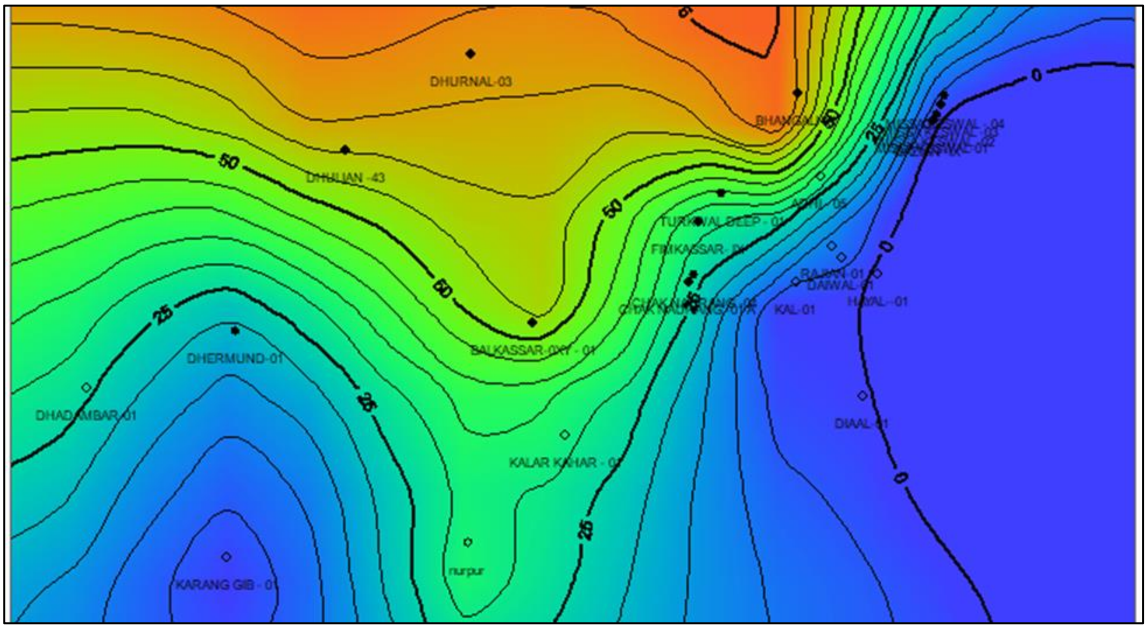


Figure 3.68 Isopach map of Dandot Formation based on well data in central and eastern Potwar Basin.

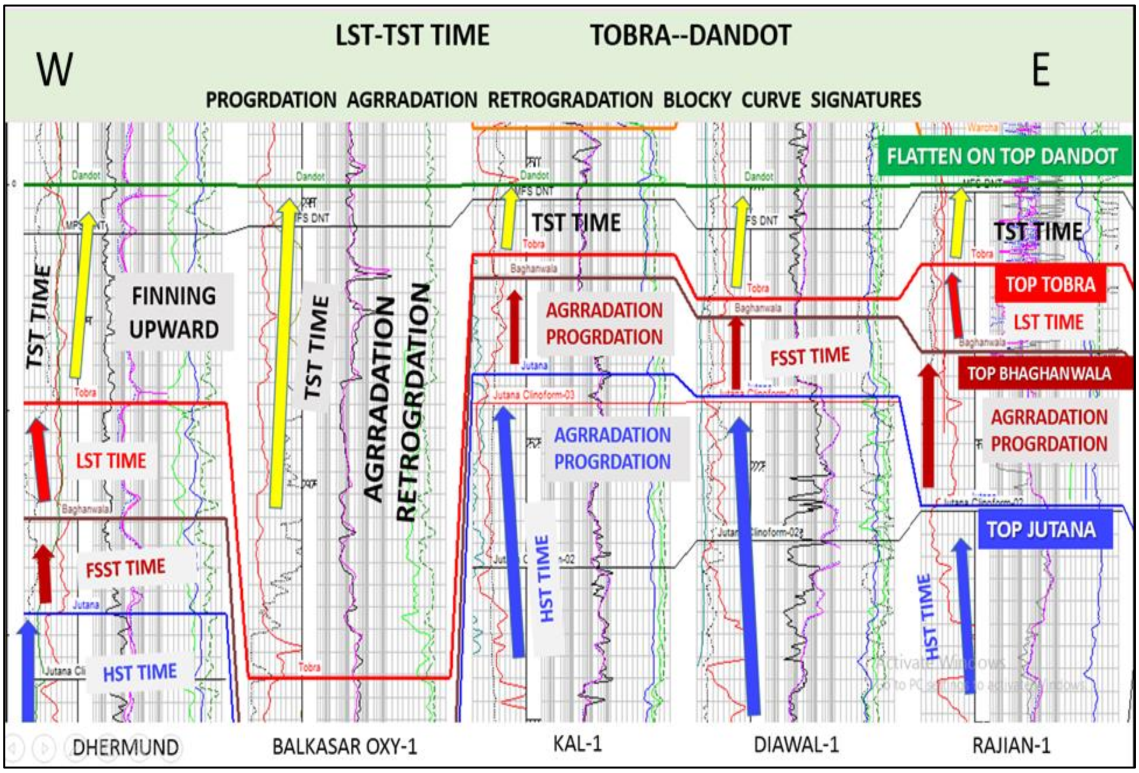


Figure 3.69 Correlation of GR log curve between Dhermud-1 to Diawal-1 showing finning upward response. The presence Maximum flooding surface (MFS) has been marked below Top Dandot Formation marking high gamma ray response.

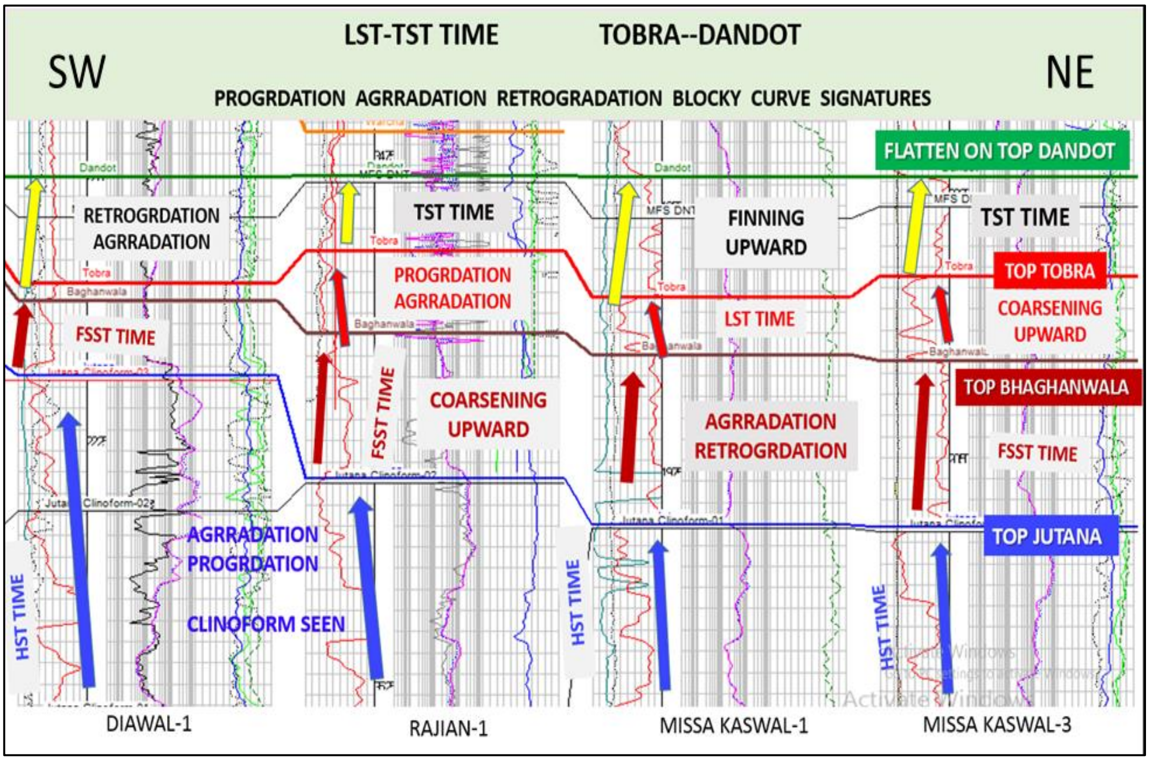


Figure 3.70 Correlation of GR log curve between Diawal-1 to Missal Kaswal wells showing finning upward response. The presence Maximum flooding surface (MFS) has been marked below Top Dandot Formation marking high gamma ray response.

3.4.3 Warchha Sandstone

The name Warchha Sandstone was created by Hussain (1967) and in past this lithological unit was referred as Warchha Group by Noetling (1901) having exposures in Warchha Gorge as a type locality which is present in Salt Range in Mianwali district, Punjab Province. This lithological unit was also referred as Middle Speckled Sandstone of Waagen (1889-91) and Speckled Sandstone of Gee (1945) in the published literature.

The Warchha Sandstone is fine to coarse grained lithological unit and is conglomeratic, arkosic and friable at places with interbeds of siltstone and claystone. The conglomeratic pebbles are formed of pink granite, quartzite and feldspar. The lithological unit show light-pink, red, reddish-brown and white colors and is locally speckled and jointed. The formation indicated cyclic deposition of course to fine grained lithologies. The basal part of each cycle is composed of conglomerate and cross-bedded sandstone while upper part has preserved bioturbated siltstone and claystone / mudstone in their upper part (Shahid et. al, 2005, 2009; Ghazi and Mountney 2009). Complete examples of such cycles are characterized by seven lithofacies that occur in ascending order as:

1. stratified gravely sandstone,
2. coarse grained trough cross bedded sandstone,
3. medium to coarse grained planar cross bedded sandstone,
4. ripple cross laminated sandstone,
5. very fine to medium grained sandstone with flat bedding,
6. parallel laminated siltstone and claystone,
7. Massive claystone/mudstone.

The nature of sedimentary structures and cyclic appearance of the Warchha Sandstone suggest deposition in a fluvial environment (Shahid et al 2009). The lithological relationship of Warchha Sandstone with the formation above and below has been reported along Choa-Khewra road (Figure 3.11 and Figure 3.64 - 3.65), Motorway M-2 (Figure 3.71) and Katha Pail section (Figure 3.79-3.80).

This formation unconformably resides over Dandot Formation of Early Permian age (Figure 3.64 Choa-Khewra area). In eastern Salt Range, the Warchha Sandstone is unconformably resides below Paleocene strata (Figure 3.72). The Warchha is unconformably overlain by the Sardhai Formation and reported in western Salt Range (Figure 3.73). The exposures of Warchha Sandstone are preserved in Salt Range with a range of thickness from 30m in east to 155 m in west. The Isopach map compiled based on well data of the study area show thickness from 0 to 160 m (Figure 3.74). No diagnostic fossils are known from this Formation except from worm- casts and petrified wood (Fatmi, 1973). On the basis of stratigraphic position, Early Permian age has been assigned to this Formation (Hussain 1967). Balme (1970) and Wardlaw and Pogue (1995).

Depositional Model

The presence of sandy units of Warchha above Dandot facies suggest a regression of Tethyes Sea from Shelf-Slope region of Potwar basin and Adjacent Salt range region. The regional sea-level fall resulted to a change in depositional environment from shallow marine to mainly a fluvial system during Artinskian time. In this setting the Warchha Sandstone was deposited by high sinuosity meandering, avulsion prone river with well-developed flood plains, Figure 3.75**,** (Ghazi and Mountney 2009). This episode of fluvial sedimentation was terminated by a widespread marine transgression, as represented by the abrupt upward transition to the overlying shallow marine Sardhai Formation (Kungurian). The well log data of southern Potwar Basin from Dhermund in west to Missa Kaswal 1 & 2 in east demonstrate erosional removal of Warchha Sandstone by base Tertiary unconformity. This sandstone is missing in east and not encountered in Missa Kaswal area. However, the formation in west is residing below Sardhai shale unit.

The GR log data responded to sandstone unit of Warchha as a coarsening upward profile signature marking progradational and aggradation style in stacking pattren (Figure 3.24, 3.76-3.77). The log signature is matching from east to west and in particular show a good correlation between Balkasar Oxy-1 and Dehmund-1 due to sufficient lithological thickness. While towards east this correlation is not leading to a reliable conclusion due to very thin lithology. The eastern area might be a zone of bypass shelf and a depositional zone of meandering, avulsion prone river with well-developed flood plains as indicated by Ghazi and Mountney 2009. In either case these facies suggest deposition in low stand time of Eustacy thus marking presence of facies related to lowstand system tract (LST). In the area of eastern Salt range the top of Warchha sands is a sequence boundary which have a correlative surface in west at the base Sardhi Formation to complete the cycle of sequence extending to base Tobra Formation.

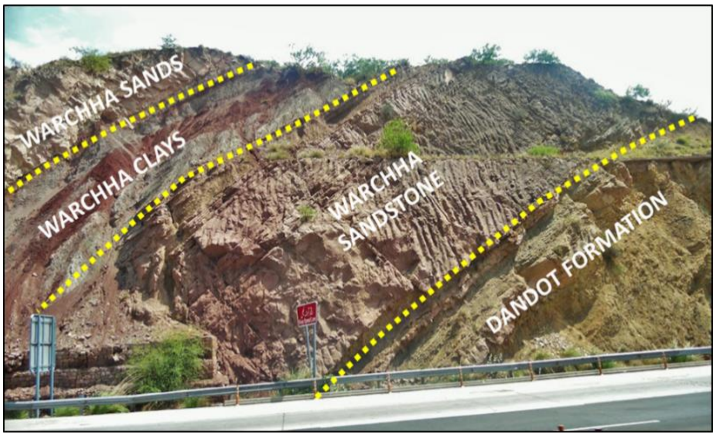


Figure 3.71 Photograph showing facies of Warchha Sandstone and contact with Dandot Formation along M-2 Motorway, Salt Range area.

Figure 3.72 Photograph showing upper erosional contact of Warchha Sandstone with Paleocene sequence in the Saloi area, eastern Salt Range (Ghazi and Mountney 2009).

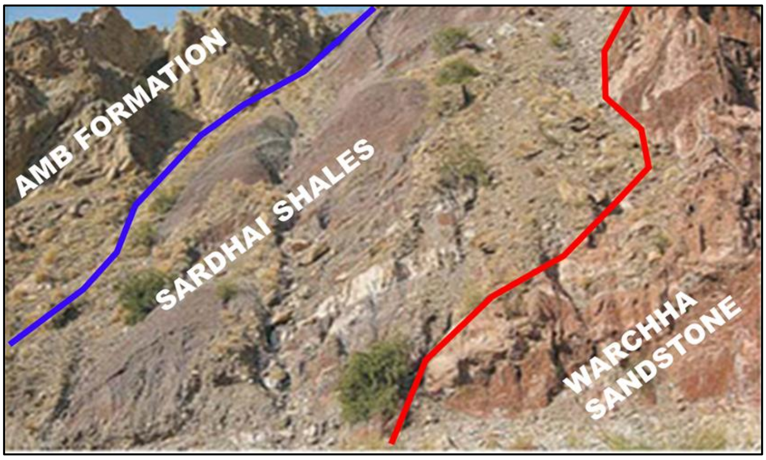


Figure 3.73 Photograph showing the Sardhai Formation overlying the Warchha Sandstone with an unconformable relationship and itself overlain by the Amb Formation of the Zaluch Group in the Sarin area, western Salt Range (Ghazi and Mountney 2009).

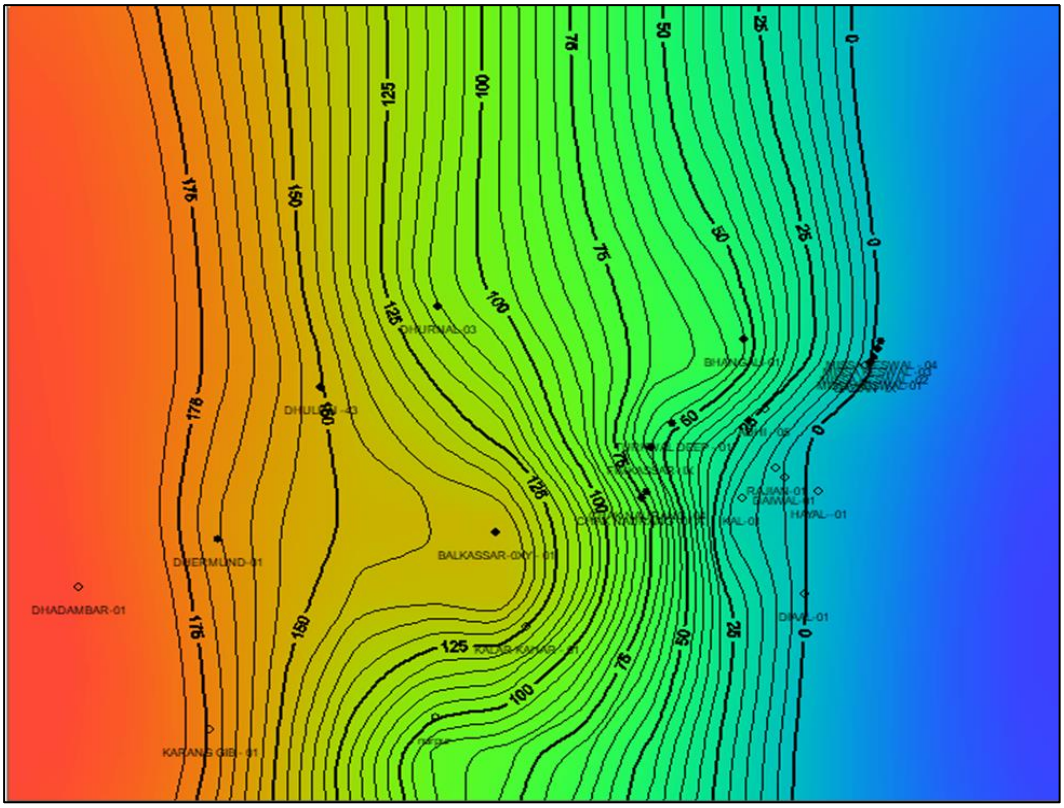


Figure 3.74 Isopach Map of Warchha Sandstone compiled based on well data central and eastern Potwar Basin.

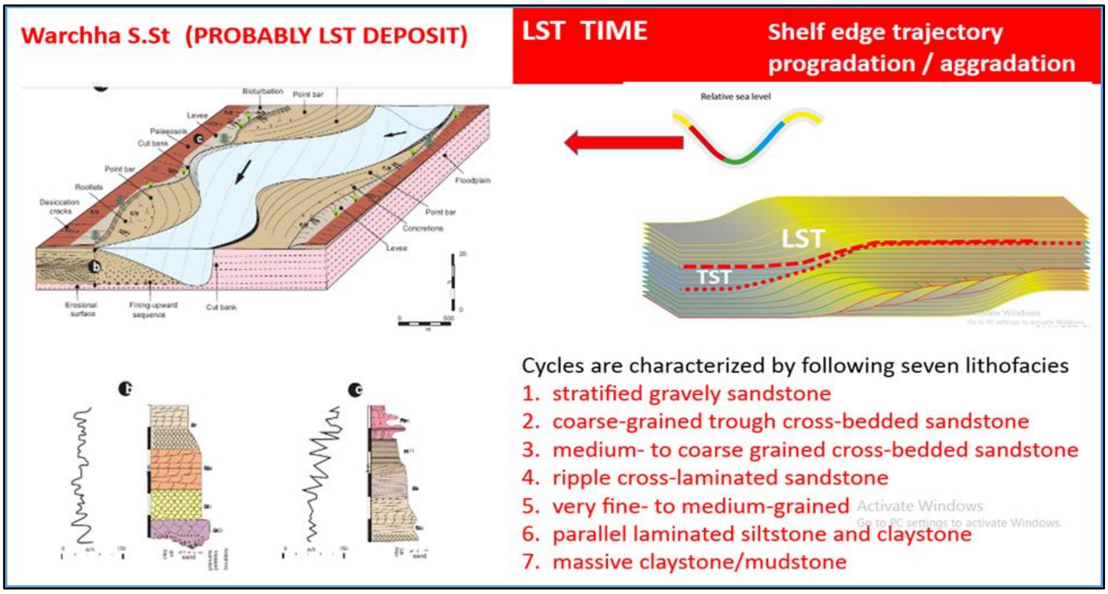


Figure 3.75 Model for facies of deposition of Warchha by high sinuosity meandering, avulsion prone river with well-developed flood plains (Ghazi and Mountney 2009). The fluvial condition prevailed during low stand during falling of sea level after HST period.

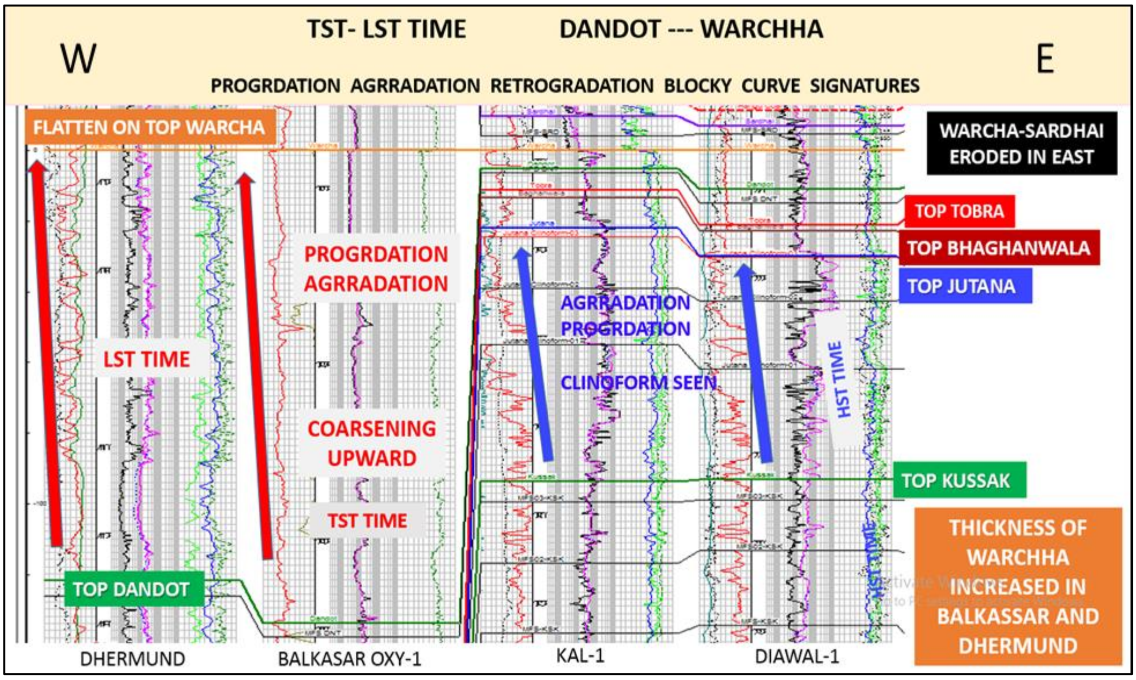


Figure 3.76 Correlation of GR log curve between Dhermund-1 to Diawal-1 showing coarsening upward response. The thickness of Warchha Sands reduced eastward and absent in Missa-Kaswal area. This coarsening profile also indicate progradational and aggradation pattern of clinoforms.

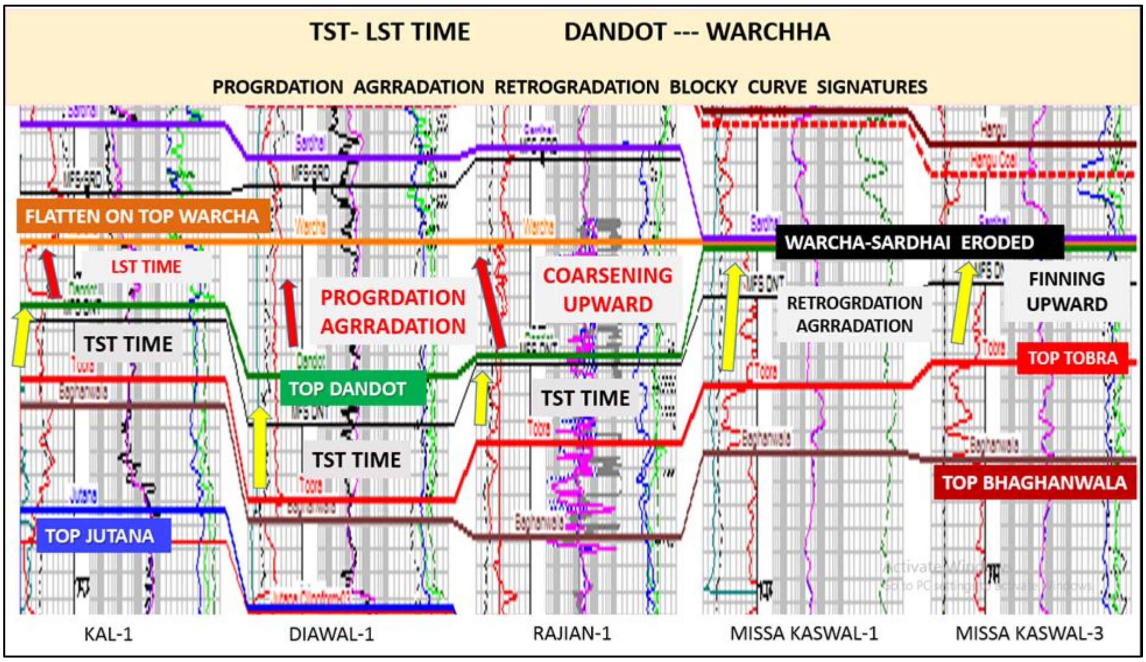


Figure 3.77 Correlation of GR log curve between Diawal-1 to Missal Kaswal showing coarsening upward response. The thickness of Warchha Sands reduced eastward and absent in Missa-Kaswal area. This coarsening profile also indicate progradational and aggradation pattern of clinoforms.

3.4.4 Sardhai Formation

The unit was previously referred as 'lavender clay' by Waagen (1878) and the upper part of 'Warchha Group' by Noetling (1901). The name Sardhai Formation was taken from the Sardhai Gorge of the central Salt Range and was proposed by Hussain (1967) for the type locality present at 32 ° 78' 33" N; 78 ° 64' 72" S. This locality has been accepted by the Stratigraphic Committee of Pakistan as the type section (Fatmi 1973).

The Sardhai Formation in the Salt Range can be divided into three parts on the basis of lithology (Ghazi and Mountney 2009). In basal part of the formation comprises of reddish-brown, lavender and dark-grey shales. These shales are interbedded with greenish-grey to grey-coloured, fine-grained sandstone occasionally with siltstone. The middle part has lavender and greenish-grey claystone which are interbedded with very fine-grained light-grey sandstone. The upper level is predominantly represented by shales of lavender, blueish to greenish-grey interbeded with thin layers of greenish-grey siltstone. The gypsum and calcareous beds are also present in the upper part. The Sardhai Formation is preserved in the central and western Salt ranges and Potwar Basin while absent in the eastern side (Figure 2.4-2.5). The absence or only limited development of the Sardhai Formation in the eastern Salt Range and adjacent southern Potwar Basin is related to its erosional removal after regional uplifting resulted from Pre-Paleocene tectonic events (Gee 1989). The formation is exposed along M-2 Motorway across Salt Range / Nilawahan gorge (Figure 3.78) and along Katha Pail sections of the study area (Figures 3.79 and 3.80).

In type section this formation is about 42 m thick however its thickness ranges from 25 to 65 m in east to west direction. The thickness of the formation ranges from 02 to 80 meters in southern Potwar basin as indicated by the Isopach map compiled based on well data of study area (Figure 3.81). The lower contact of Sardhai formation with the Warchha Sandstone is erosional. The upper contact with the Paleocene strata in the central Salt Range (Figure 3.78) and with the Amb Formation of Zaluch Group in Katha Pail section (Figures 3.79 and 3.80) and western Salt Range is unconformable. The Early Permian Gondwana sequence represented by the Nilawahan Group is capped by predominantly shallow shelf carbonate deposits of the Tethyan realm in eastern part of

Potwar Basin and adjacent Salt Range and also proven by wells drilled in study area. Brachiopods are commonly found in this formation. Hussain (1967) reported a variety of fauna including Anastomopora, Fenestella, Athyrsis and Spirifer from the Sardhai Formation. Based on fossils and stratal relationship with Warchha Sandstone an Early Permian age is assigned to this formation.

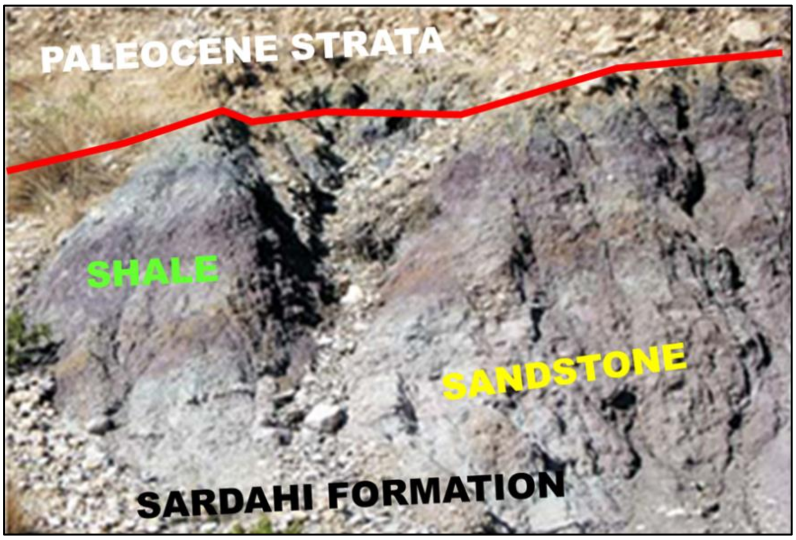


Figure 3.78 Photograph showing the Sardhai Formation unconformably overlain by Palaeocene Strata in the Matan area, central Salt Range (Ghazi and Mountney 2009).

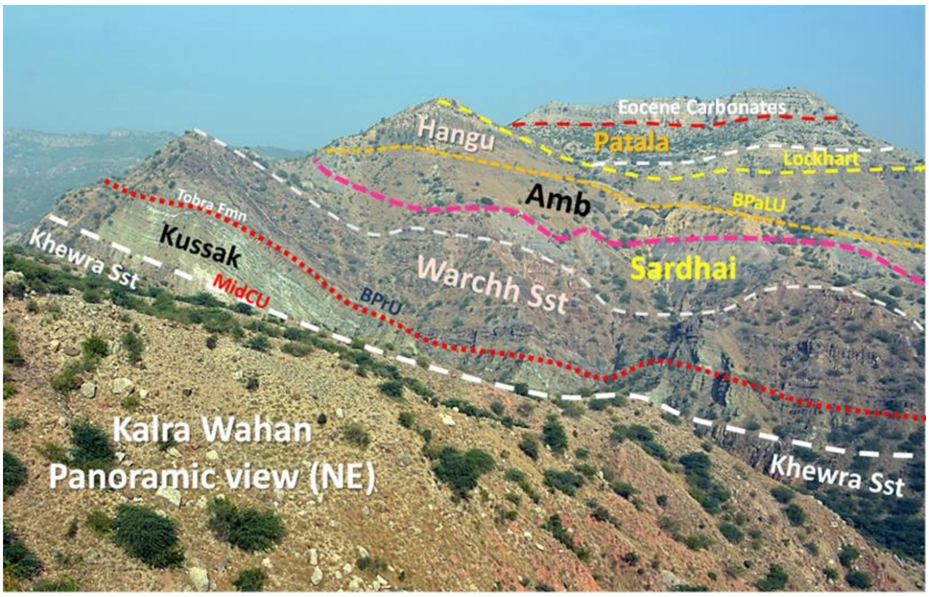


Figure 3.79 Sardhi Formation residing above Warccha Sandstone and below Amb Formation, Section exposed along Katha Pail Road, Central Salt Range.

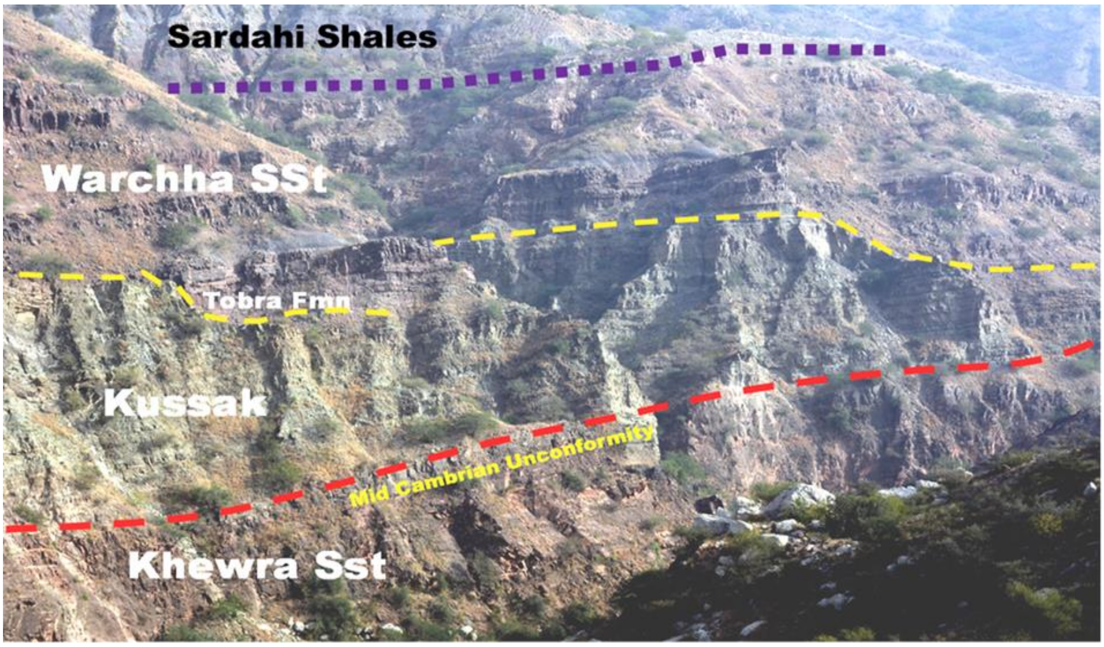


Figure 3.80 Sardhi Formation residing above Warccha Sandstone, Section exposed along Katha Pail Road, Central Salt Range.

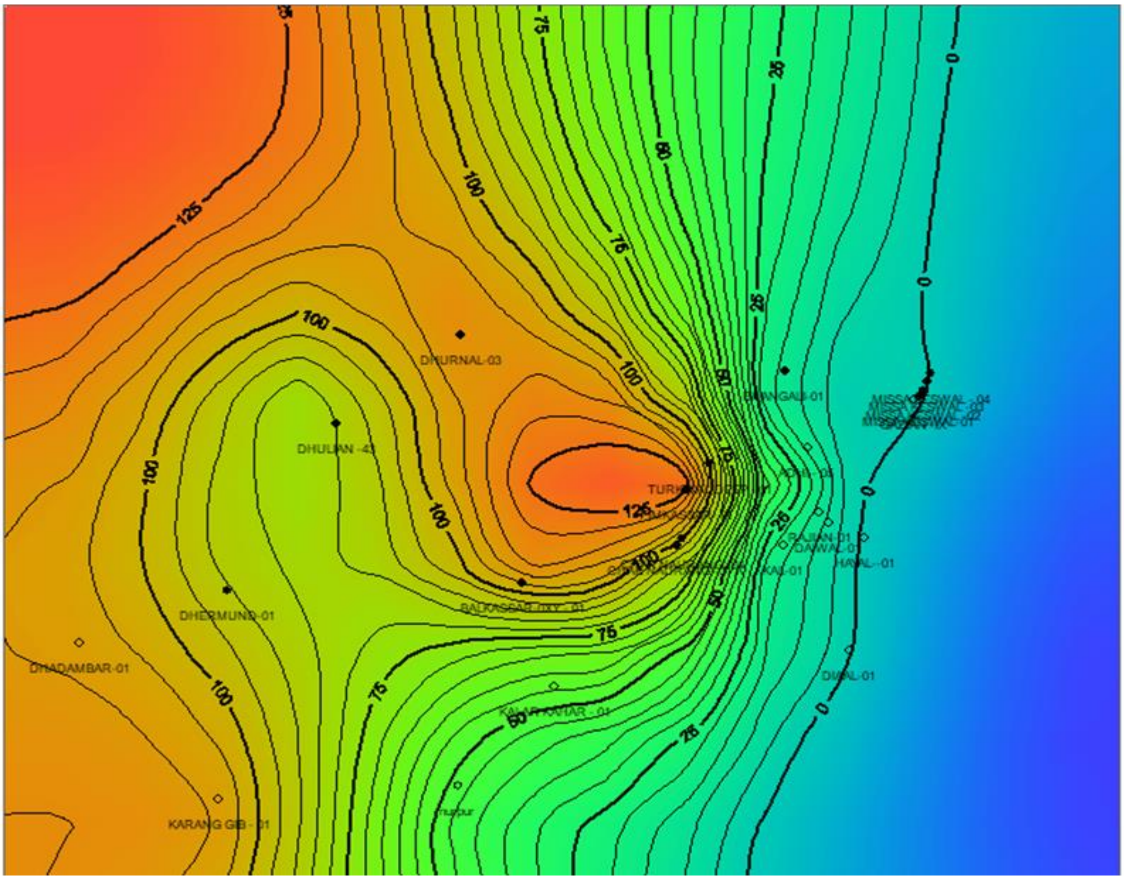


Figure 3.81 Isopach map of Sardhi Formation compiled from well data base of study area.

Deposition Model

The lithologically dominated by light to medium-grey, greenish-grey and lavender-coloured shale with thin interbeds of siltstone and fine-grained glauconitic sandstone deposits of the Sardhai Formation were deposited in warm–hot climatic conditions (Singh 1987; Veevers and Tewari 1995). The presence of chert along with gypsum, chalcopyrite and mineral glauconite are all evidence for the prevalence of marine environmental conditions during deposition of the Sardhai Formation (Wardlaw and Pogue 1995).

The well log data from the study area from Dhermud-1in the west to Rajian-1 in east show a change in GR curve behavior in Sardhi formation (Figure-3.82 & 3.83). In general the curve responded to shaly lithologies and show finning upward image. There is a reliable match of the signature of curve for finning/coarsening cycles (Figure 3.24) between Dhermund-1 and Balkasar Oxy-1 representing retrogradational and aggradational features corresponding to preserved stratal geometries of Sardahi lithological units. While in the east this match is not reliable due to very thin strata present in Diawal, Kal and Rajian wells. It might be the basal part of formation preserved in these wells while upper and middle part has been eroded. In general these thin lithologies also yield finning upward behaviors of the curve.

It can be inferred from the well data that Sardhai facies were deposited during transgression of Tethys Sea as a retrogradational and aggradational units in Potwar Basin and Salt Range areas. This transgression stage suggest onset of transgressive system tract TST in the basin which continue to maximum flooding event marking maximum flooding surface near top of Sardhai unit. This cycle of Eustatic curve at the stage of maximum flooding (MFS) along with warm climatic conditions favored the deposition of carbonate facies that belongs to lithological units of Zaluch group which resides above Sardhai shales.

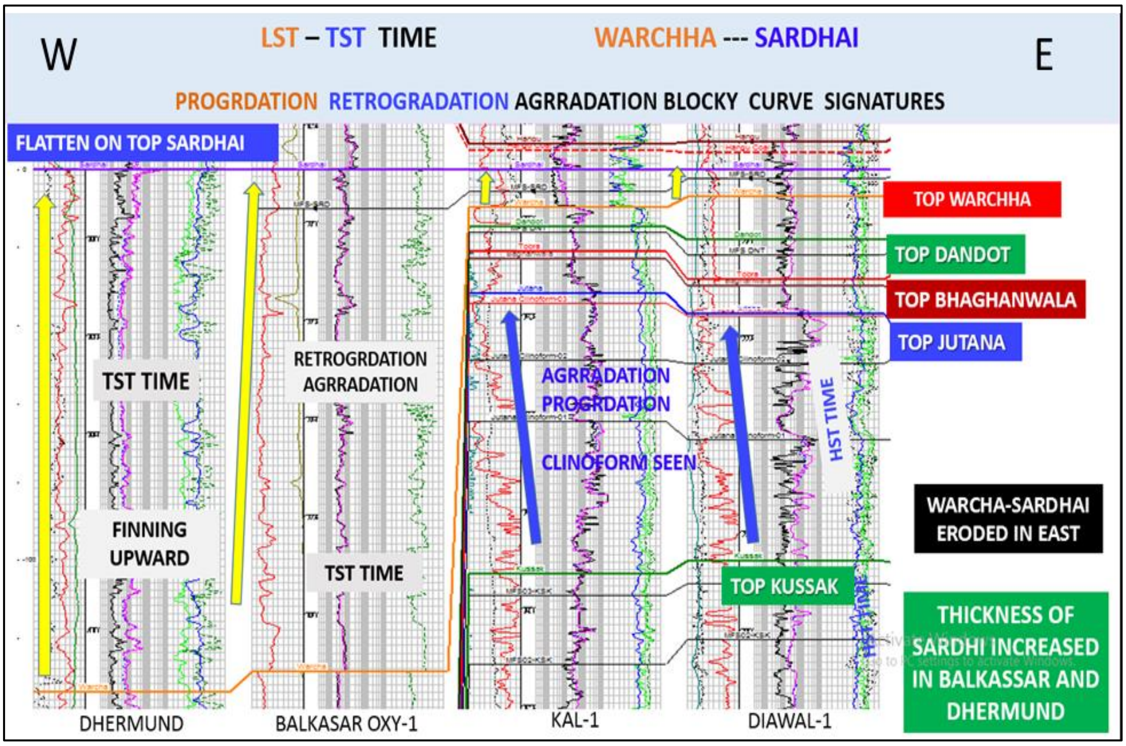


Figure 3.82 Correlation of GR log curve between Dhermund-1to Diawal-1 wells showing finning upward response. The presence Maximum flooding surface (MFS) has been marked below Top Sardhi Formation marking high gamma ray response.

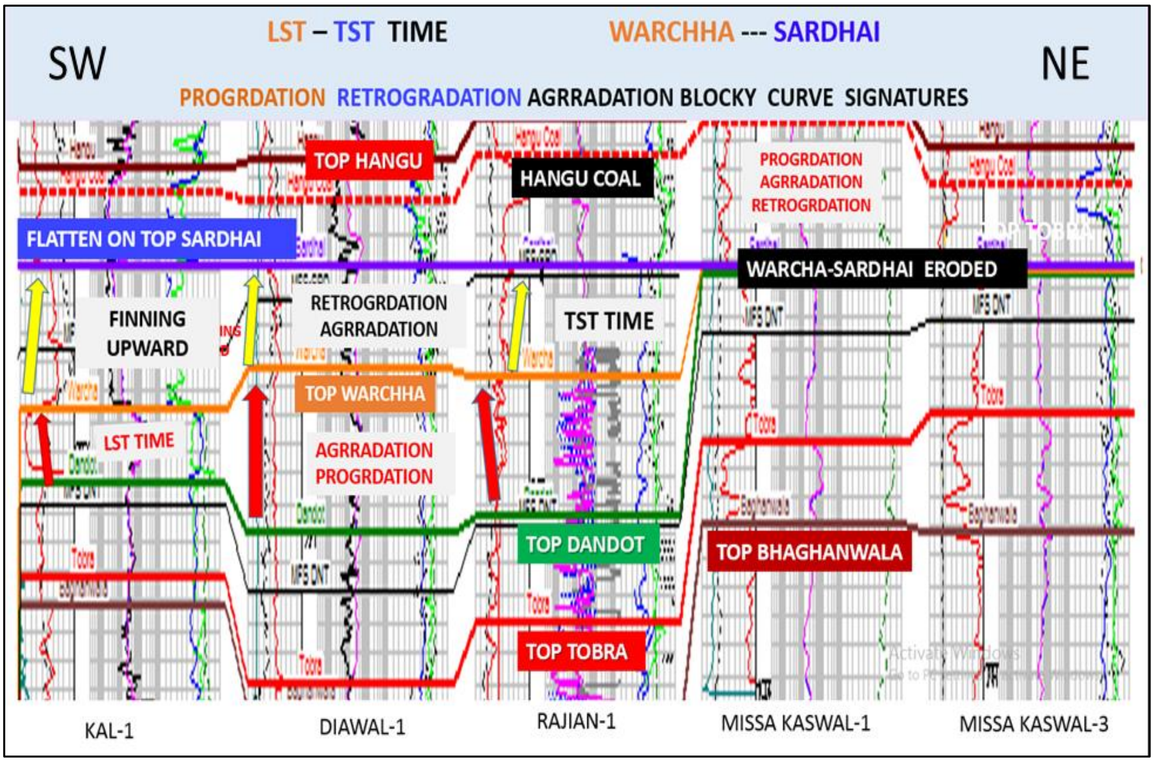


Figure 3.83 Correlation of GR log curve between Diawal-1 to Missal Kaswal wells showing finning upward response. The presence Maximum flooding surface (MFS) has been marked below Top Sardhai Formation marking high gamma ray response.

3.5 UPPER PERMIAN (SUMMARY)

The Zaluch Group in the Salt Range is a well-exposed and is a succession of shallow marine to intertidal deposits. This group includes Amb, Wargal and Chhidru formations (Kummel and Teichert 1970; Fatmi 1973; Shah 1977; Gee1980, 1989; Mertmann 2003). The upper Permian is composed of limestone lithology and commonly regarded as Productus Limestone units based on limestone fossils.

The Zaluch section resides below Mianwali Formation of Triassic age. The lower contact of the Amb Formation of Zaluch Group is unconformable with the Sardhai Formation and the upper contact of the Chhidru Formation is unconformable with the overlying Mianwali Formation of Triassic age (Kummel and Teichert 1970; Gee1980; Mertmann 2003).

The scope of present study is not covering any analysis for upper Permian stratigraphy for sequence analysis. However the entire section is trusted to deposit in high sand level as it is characterized by carbonate succession. The lithological units are well exposed in western Salt Rang and Trans-Indus Ranges.

CHAPTER 4

INTEGRATION OF SEISMIC REFLECTION DATA FOR LITHOSTATIGRAPHY AND SEQUENCE STATIGRAPHY OF CAMBRIAN-PERMIAN LEVELS

This chapter is focused to integrate seismic reflection data of the study area to validate sequence stratigraphic setting in the study area which has been evaluated based on well log data and field observations. This objective was most challenging due to quality, resolution and limited number of seismic line allowed to conclude and firm the relation of sequence boundaries and features of system tracts. The most puzzling part was to work with this limited data set in complex fold and thrust belt without dip meter and velocity logs and using software not capable to deal with 3d view for interpretation and precise correlation. However, this challenging phase was managed with following work flow.

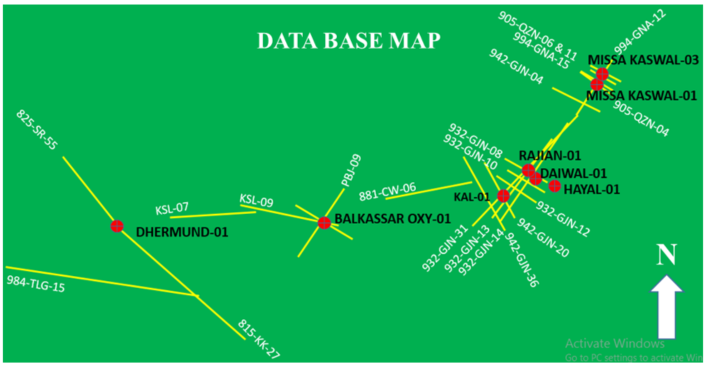
- Loading of available seismic data set.
- Analysis of quality and resolution of seismic data set.
- Correlation of well data with seismic lines.
- Analysis of repetition of stratal surfaces and thickness.
- Analysis of Dhermud Structure.
- Analysis of Balkassar Structure
- Analysis of Kal, Rajin, Daiwal and Hayal Structural zone
- Analysis of Rajian and Daiwal Structures
- Analysis of Kal Structure
- Analysis of Missa Kaswal Structure
- Identification of signatures of depositional and erosional features
- Picking of truncations, onlaps, downlap, off lap events

The issues to meet the objective are also highlighted during discussion in the relevant topic.

4.1 Data Set Available

Post stack migrated seismic lines of Southern Potwar Basin in Seg Y format along with navigation data, formation top and logs (LAS format) of selected wells has been obtained after permission of DGPC for the dissertation. The velocity data (VSP and check shot was not provided), however tie to seismic marker with wells were managed using stacking velocity availed along with seismic data. In addition, the selected data already grated to university students in past has been used to help the evaluation in study area. The location of available seismic data is shown in Figure 4.1.

DATA AVAILABLE				
SEISMIC LINES		Orientation	WELLS	
1	O/825-SR-55	dip line	1	DHERMUND -1
2	O-815-KK-27	dip line	2	BALKASAR OXY -01
3	O-984-TLG-15	dip line	3	RAJIAN-1
4	O/855-CW-06	strike line	4	MISSA KASWAL-1
5	O-994-GNA-15	dip line	5	DAIWAL-1
6	O/932-GJN-25	dip line	6	KAL-1
7	O/932-GJN-13	strike line	7	MISSA KASWAL-3
8	O/925-GJN-08	dip line	8	HAYAL-1
9	O/-925-GJN-10	dip line	MAPS	
10	O/925-GJN-14	strike line		
11	O/932-GJN-31	Strike line	1	Geology Maps of Salt Range
12	O/932-GJN-37	dip line		Dr. Gee (1998)
13	O/994-GNA-12	strike line	2	Geological Map of Pakistan
14	O/994-GNA-15	dip line		GSP (1993)
15	O/942-GJN-36	dip line	3	Topo sheets Salt Range
16	OX-PBJ-09	strike line		Survey of Pakistan
17	OX-PBJ-04,03	dip line		
18	KSL-07	Strike line		



SEISMIC DATA APPROVED
SEISMIC DATA HIRA & IRFAN 2021
SEISMIC DATA BPUBLISHED
WELL DATA APPROVED
WELL DATA HIRA & IRFAN 2021
WELL DATA BPUBLISHED

Figure-4.1 Seismic lines and well location map of study area

4.2 Quality and Resolution of seismic data set

The data quality is a major concern in the area of study to resolve geological objectives associated to geometries of folds, faults, wedges related to thickness changes, erosional, depositional events (truncations, on-lapping, down-lapping) and picking of relevant lithological and sequence boundaries. The impedance contrast related to lithological changes for thin layers was another challenge to fix the correlation with well data and outcrop geology. The quality of available seismic is not good enough to resolve and address and resolve the definition of lithostratigraphic and sequence stratigraphic features. One of the key objective is to address thickness changes and lateral distribution of stratigraphic features which was most difficult part as the frequencies after processing were on lower side which cannot adequately resolve this concern.

The seismic data is capable to address axial parts of structures while flanks of folds defining real size and shape of structure closure depends on migration and velocities finally used during processing to acquire the proper image. The issues of migration and elimination of diffractions and noise is still a key concern while interpreting real reflectors corresponding to concerned geological boundaries. The mingling of wavelet hampered the clear picking of truncating events to address features related to system tracts. The fault picks are not obvious and limit of hanging wall with foot wall cut by a fault is not clear because of limited velocity analysis, proper migration and elimination of noise.

To eliminate the doubt of repeated strata by thrust faults having small throw was also an important issue to understand and resolve thickness changes not related to structural deformation. This was required to address real depositional thickness of lithological units in the area of study and that has been encountered in the area of structural crusts of anticlines drilled by the wells. The quality of present data set in terms of resolution is generally capable to address relevant thickness drilled in the wells but the factor of true thickness evaluation is not precisely managable as this data is not adequate to pick very minor faults having a displacement of less than 5-10 milliseconds.

The change in thickness of lithology observed after well data correlation for the objective levels (Cambrian and Permian) cannot be illustrated by existing seismic data. The quality of 2d vintage seismic data (825-SR-55 and 815-KK-27) at the location of Dehrmund structure in the west is fair to poor (Figure-4.2). The stacking of reflections in this data indicated low frequencies to image structure along with faults. The quality of seismic data in the area of Balkasar is fair to good as shown by lines PBJ version (Figure-4.5). In the area of Rajian, Kal and Daiwal the quality of seismic data is fair. The reflection geometries in the drilled localities (sub thrust part) is deteriorated by noise and diffraction and difficult for picking thickness changes (Figures 4.10 and 4.15).

In the area of Qazian and Missa Keswal (QZN vintages) the quality of data is very poor while the quality is fair on (994 GNA vintage) where stratigraphic changes, thinning and erosion related to Permian is playing a major role in understanding of correlation for both lithostratigraphic and sequence stratigraphic models. In this area correlation of thin stratigraphic intervals for multiple levels is forced to pick in a single wavelet (trough or crest) Figure 4.15, 4.19 and 4.20.

4.3 Well Ties, Structural Geometry, Analysis of repetition of stratal surfaces and thickness.

One of the key objective of this study was to consider the lithological thicknesses for sequence stratigraphic analysis free of any repetition by faults and over turning of beds due to folding. The area of study involved into structural deformation and resulted into folding thrusting that could easily add repetition in thickness of lithological units. Such repetition may mislead and will result into incorrect evaluation of deposition cycles laid down on undisturbed surfaces. A repetition of any prograde may lead to conclude aggradation of strata which is incorrect evaluation of any depositional cyclic. The evaluation of structural geometry, lithostratigraphy and sequence stratigraphic correlation was based on interpretation of 2d seismic line using data both in strike and dip directions through the drilling location of the structure. The correlation of sequence stratigraphic interpretation for the stratal surfaces, boundaries, unconformities and correlative conformities was made by using computed velocities from time depth relation. Following analysis has been done for each well location allowed in present study to understand frame work of stratigraphy and sequence stratigraphy at Cambrian and Permian levels.

Dhermund Structure

The mapping of 2d seismic data across this structure show rollover geometry having low relief (Figure 4.2). The quality of seismic data is poor and unable to address clear issues of stratigraphic repetition. This structure has been intercepted by complex thrust fault geometries having a throw between 10-20 milliseconds which are obvious on Eocene and Paleocene levels. The structure encountered Salt Range formation at TD level residing below Cambrian, Permian and Paleogene stratigraphic sequences. The lithological and sequence boundary picks have been inferred using time depth chart

(Figure 4.3) complied after correlation of sequence stratigraphic framework based on log data interpretation. Due to absence of any minor or major faults in this structural crossing well bore, the thickness changes due to structural repetition are ruled out (Figure 4.2). Therefore the stratigraphic thickness are considered valid for Cambrian, Permian, Paleocene and Eocene levels. The Dhermund structure (Figure 4.4) is present on a dipping flank and developed by back thrusting which intercepts to a deeper level and terminate against major frontal thrust soling above the basement within Salt Range Formation and verging SE in direction. The reflection truncation geometries are difficult to address on objective level (Cambrian-Permian stratal changes) but can be considered to some extent with higher degree of doubt due to certain processing and noise elimination issues.

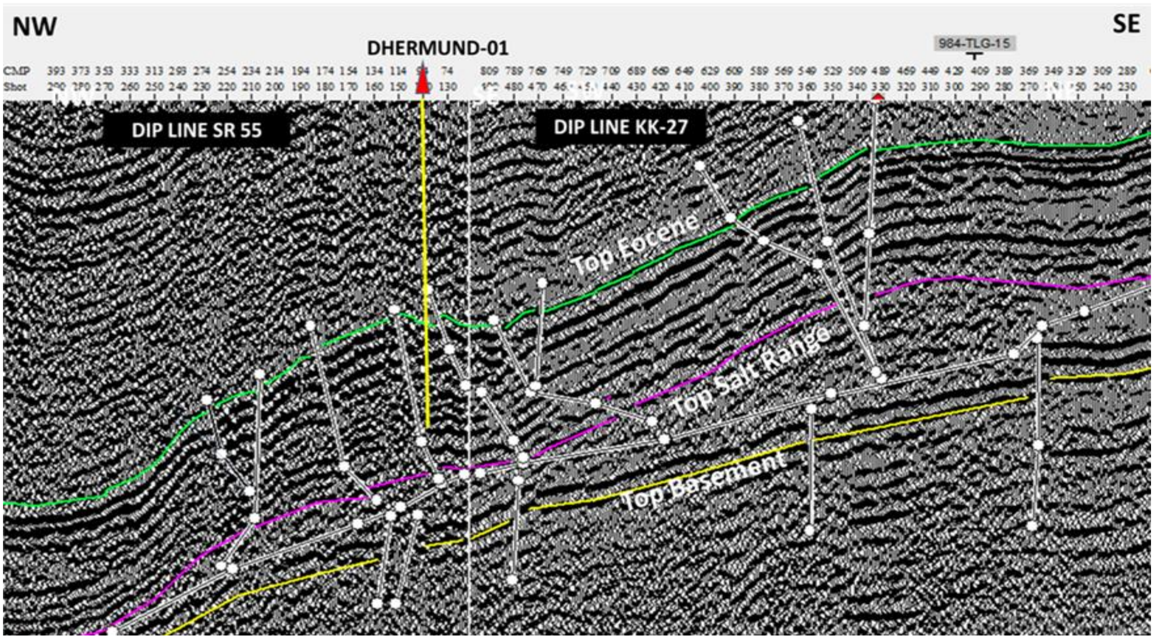


Figure-4.2 Composite seismic line 825-SR-55 and 815-KK-27 showing structural dip in northwest direction. Number of back thrust can be seen dipping SE and culminate on sole thrust (main thrust in Salt Range Formation dipping NW in direction. The Dhermund structure is a feature formed by back thrust fault system with no stratal repetition at Cambrian-Permian levels.

DHERMUND-01						
FORMATION	Formation tops (KB) 423.5 M	KB	SRD	Formation tops (SRD) 350 M	TVT (ms)	Velocity m/s
DHOK PATHAN	0	423.5	350	-73.5		
NAGRI	545	423.5	350	471.5		
CHINJI	1529	423.5	350	1455.5		
KAMLIAL	2459	423.5	350	2385.5		
MURREE	2527	423.5	350	2453.5		
KOHAT	3059	423.5	350	2985.5		
RED CLAYS	3093	423.5	350	3019.5		
BHADRAR	3109	423.5	350	3035.5		
CHORGALI	3109	423.5	350	3035.5	1840	3299
SAKESSAR	3131	423.5	350	3057.5	1851	3304
NAMMAL	3232	423.5	350	3158.5	1904	3318
PATALA	3327	423.5	350	3253.5	1953	3332
LOCKHART						
DHAKPASS						
KHAIRABAD						
HANGU / Dhakpass	3447	423.5	350	3373.5	2016	3347
DATTA	3460	423.5	350	3386.5	2022	3350
KINGRIALI	3528	423.5	350	3454.5	2057	3359
CHIDDRU	3600	423.5	350	3526.5	2094	3368
WARGAL	3664	423.5	350	3590.5	2127	3376
AMB	3776	423.5	350	3702.5	2185	3389
SARDHAI	3883	423.5	350	3809.5	2241	3400
WARCHA	4016	423.5	350	3942.5	2310	3413
DANDOT	4138	423.5	350	4064.5	2374	3424
TOBRA	4156	423.5	350	4082.5	2383	3426
BAGHANWALA	4168	423.5	350	4094.5	2389	3428
JUTANA	4175	423.5	350	4101.5	2392	3429
KUSSAK	4195	423.5	350	4121.5	2405	3427
KHEWRA	4225	423.5	350	4151.5	2420	3431
SALT RANGE	4267	423.5	350	4193.5	2450	3423

Figure 4.3 Time depth and velocity table for Dhermund-1.

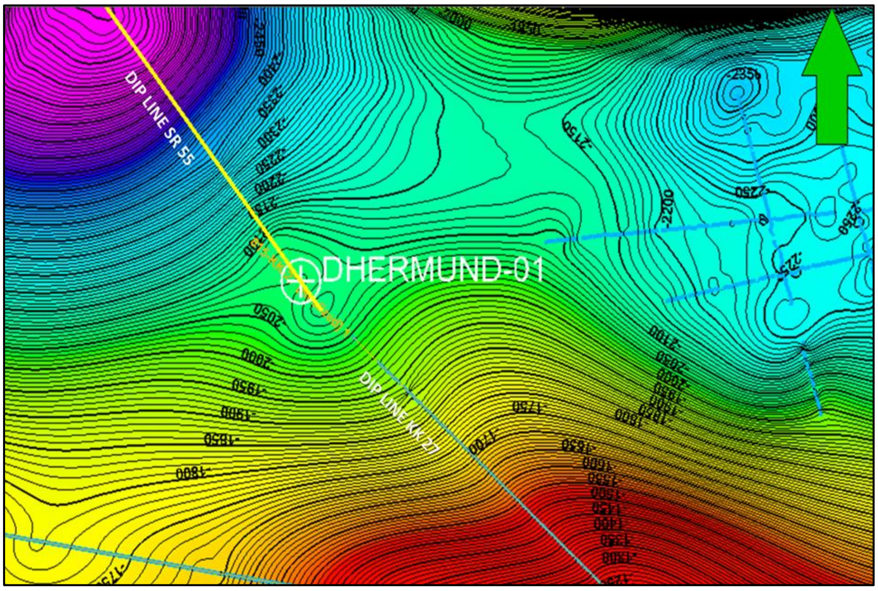


Figure 4.4 Two way time contour map Top Eocene level showing dipping strata in the area of Dhermund well-01 with very small structural closure,

Balkassar Structure

The structure has drilled down to Salt Range formation by Balkasar Oxy-1 well and encountered lithofacies from to Cambrian to Permian levels below Paleogene strata

(Figure 4.5). This structure is proven for containing hydrocarbons which flowed from Paleocene and Eocene levels through number of wells. The 2d seismic data across this structure show anticlinal feature with a clear rollover geometry. The quality of seismic data at this location is good enough to address issue of stratal repetition by faults. The lithological and sequence boundaries picks has been plotted using time depth chart (Figure 4.6) complied after correlation of sequence framework based on log data interpretation.

Structural repetition by minor or major faults are not seen in this structural rollover at well bore location (Figure 4.5). Therefore the stratigraphic thickness are considered valid for depositional cycles during Cambrian, Permian, Paleocene and Eocene times. Structurally this is salt cored anticline as proven by the drilling and seismic image (Salt Range Formation at TD). The detachment can be placed between basement reflector and within Salt Range Formation. This structure show a rollover bounded by a pair of frontal and back thrust faults which lifted the structure up to form asymmetrical feature where SE flank is steeply dipping to certain length while the NE flank is intercepted by back thrust fault. However none of these major faults intercepted the stratigraphy within the well bore. The structure show a four way dip closure bounded by faults in NW and SE at multiple mapping levels from Top Salt Range to Top Eocene reflectors (Figure 4.7). The erosion truncation, down lapping of seismic event are seen in Balkasar seismic data between Cambrian, Permian and shallow levels. The details of these geometries in context of system tract signatures are discussed in section 4.4.

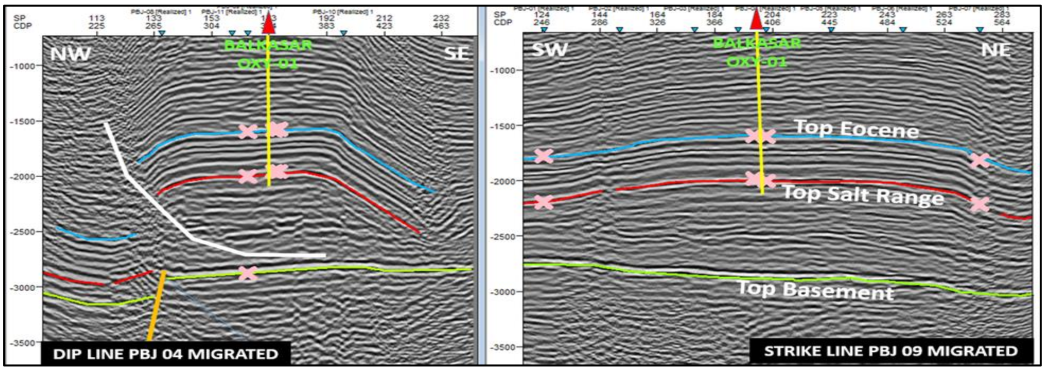


Figure 4.5 Seismic lines through dip (PBJ-04) and strike (PBJ-09) of Balkassar structure. The dip line shows asymmetrical rollover with flat crust of structure at Balkassar oxy well location. Structure is bounded by NW verging back thrust fault. The strike line shows doubly plunging anticline.

BALKASSAR OXY-01						
FORMATION	Formation tops (KB) 535.5 M	KB	SRD	Formation tops (SRD) 350 M	TVT (ms)	Velocity m/s
CHINJI	478.8	535.5	350	293.3		
KAMLIAL	1408.1	535.5	350	1222.6		
MURREE	1514.8	535.5	350	1329.3		
CHORGALI	2421.5	535.5	350	2236	1596	2802.01
SAKESSAR	2467.2	535.5	350	2281.7	1621	2815.18
NAMMAL						
PATALA	2602.9	535.5	350	2417.4	1697	2849.03
LOCKHART	2624.2	535.5	350	2438.7	1708	2855.62
HANGU	2659.3	535.5	350	2473.8	1727	2864.85
SARDHAI	2659.3	535.5	350	2473.8	1727	2864.85
WARCHA	2796.4	535.5	350	2610.9	1750	2983.89
DANDOT	2938.1	535.5	350	2752.6	1845	2983.85
TOBRA	2999.1	535.5	350	2813.6	1880	2993.19
BAGHANWALA						
JUTANA						
KUSSAK						
KHEWRA	3050.9	535.5	350	2865.4	1950	2938.87
SALT RANGE	3129.2	535.5	350	2943.7	1993	2954.04

Figure 4.6 Time depth and velocity table for Balkasar Oxy-1 well.

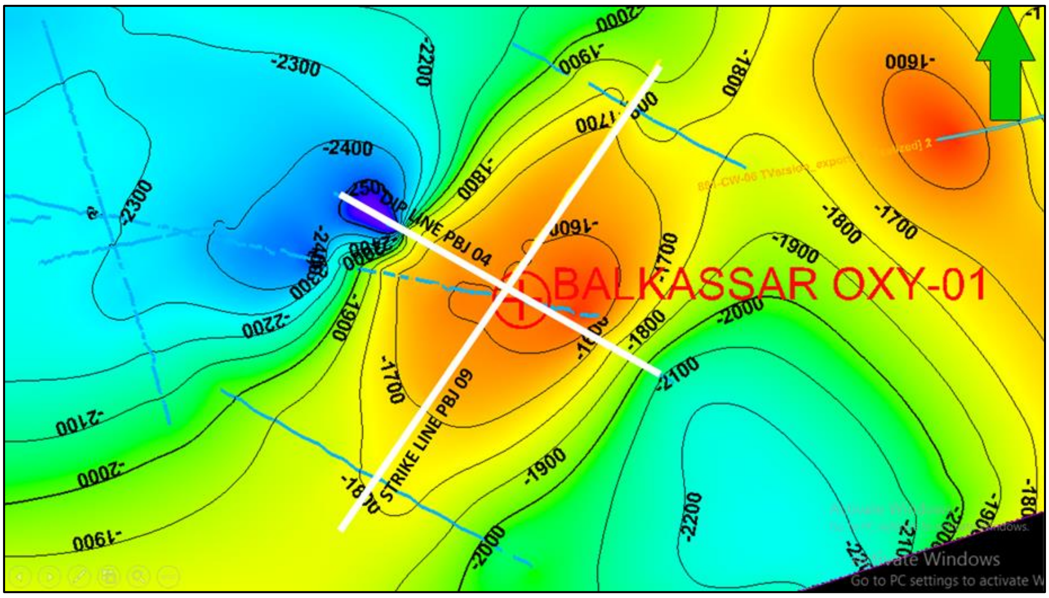


Figure 4.7 Two way time contour map Top Eocene level Balkasar structure.

Kal, Rajin, Daiwal and Hayal Structural zone.

This structural zone is present in northwest of Pamil-Domali fold line and aligned parallel to this trend. In this complex structural zone analysis of Cambrian-Permian strata for sequence stratigraphy analysis requires understanding of features related to depositional geometries. In order to delineate these features four drilling location has been analyzed for stratal correlation and to understand nature of structure. The geometries related to stratal changes are addressed in section 4.4.

The study conducted by Aamir et, al. 2006 suggested presence of triangle zone of deformation in this area of Missal Kaswal, Rajian, Daiwal and Kal (Figure 4.8). This Kal, Rajian, Daiwal and Hayal Structural zone has been deformed into a complex folding in the northwestern dipping flank of Domali anticline. The Pamil Domali trend is a zone of salt core anticlinal features bounded by frontal and back thrust system and preserved at shallow depths. While in the NW of this trend the Daiwal, Rajian, Kal and Missa Kaswal structures developed in the sub thrusted sheet as a folded features, each forming independent structural closures. The Pamil- Domali anticline has been drilled by Hayal well-01 down to Pre-Cambrian Salt Range Formation. The 2d and 3d data interpreted in this zone of deformation show sub thrusted folded structures and where Pamil-Domali back thrust system appear as a roof thrust which is verging SE in direction.

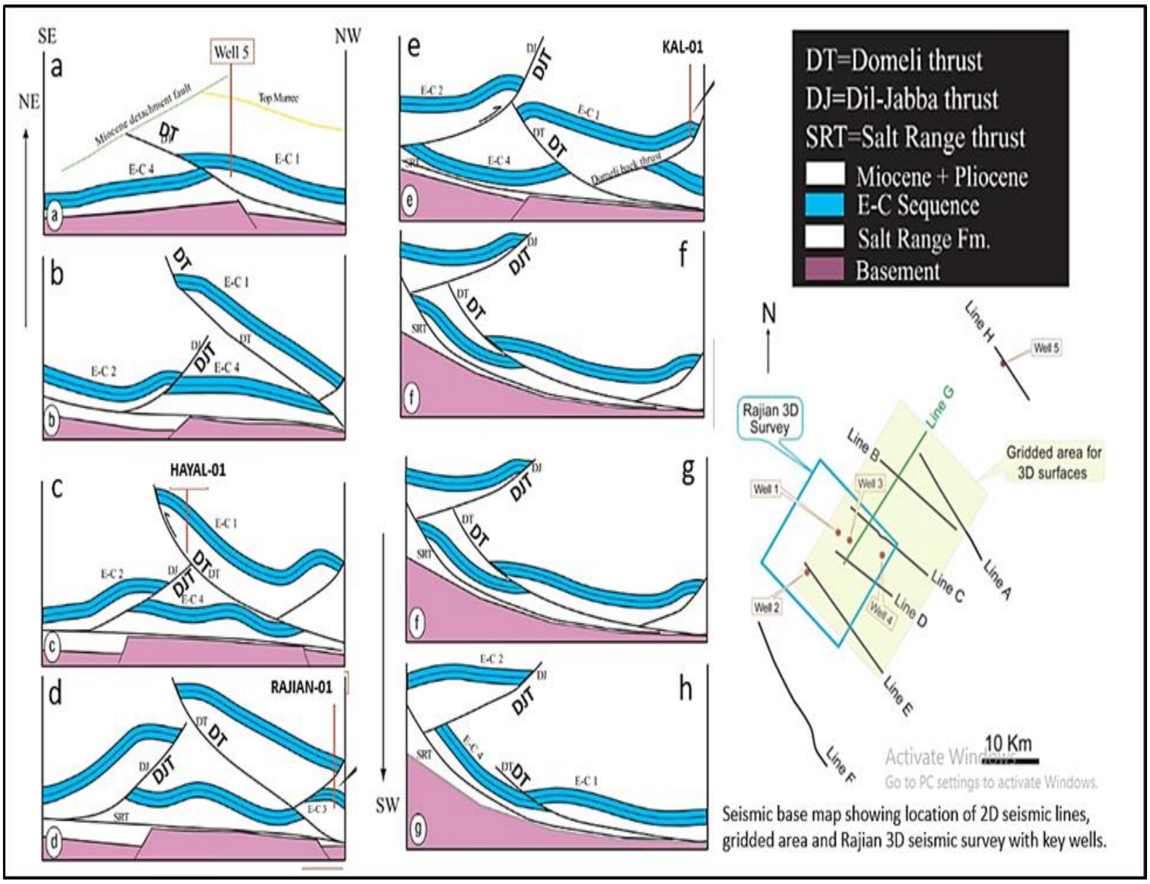


Figure 4.8 Structural cross-sections in the deformed zone of Pamil Domali and Dijabba and adjacent Potwar basin from NE to SW in direction. Structural changes in fault and

fold geometries can be seen from NE to SW (Figure 4.8a to 4.8h). See the legend for details of stratigraphic units, (Modified after Aamir et, al. 2006).

Rajian and Daiwal Structures.

These structures are part of sub thrust sheet which are present below Pamil-Domali thrusted and folded strata. The Pamil-Domali thrust sheet has uplifted Domali anticline and exposed the platform strata in the core. The Hayal-1 was drilled to test the uplifted strata of Domali structure and this well encountered Pre-Cambrian salt Range Formation at T.D. In the northwest of this well the two structural rollovers (Daiwal and Rajian) are preserved below hanging wall strata bounded by back thrust (Figure 4.9 and 4.10). The Daiwal and Rajian structures are appeared portioned by a fault dipping NW in direction. The Rajian structure is a rollover feature and is residing below Domali back thrust and splay faults. The well at this location encountered the subthrust sheet below Neogene Mollasse section. However, the Daiwal structure due to its structural position encountered both the thrust sheets (Hayal and Daiwal thrust sheets). Both Rajian and Daiwal structures has been drilled down to Top Salt Range Formation and are known for producing oil fields from Khewra, Tobra and Eocene levels. Structurally these are salt cored anticlinal rollovers as proven by the drilling data and seismic image (Salt Range Formation at TD).

The quality of seismic data along these structures is fair to good to address issue of structural mapping. Structural repetition by minor or major faults are not seen in these structural rollovers at well bore location. Therefore the drilled stratigraphic thickness from independent structural sheets are considered valid for depositional cycles during Cambrian, Permian, Paleocene and Eocene times. The reflection signatures corresponding to internal geometries and its link to system tract analysis is discussed in section 4.4. The lithological and sequence boundaries pick has been plotted using time depth chart complied after correlation of sequence framework based on log data interpretation (Figure 4.11 and 4.12).

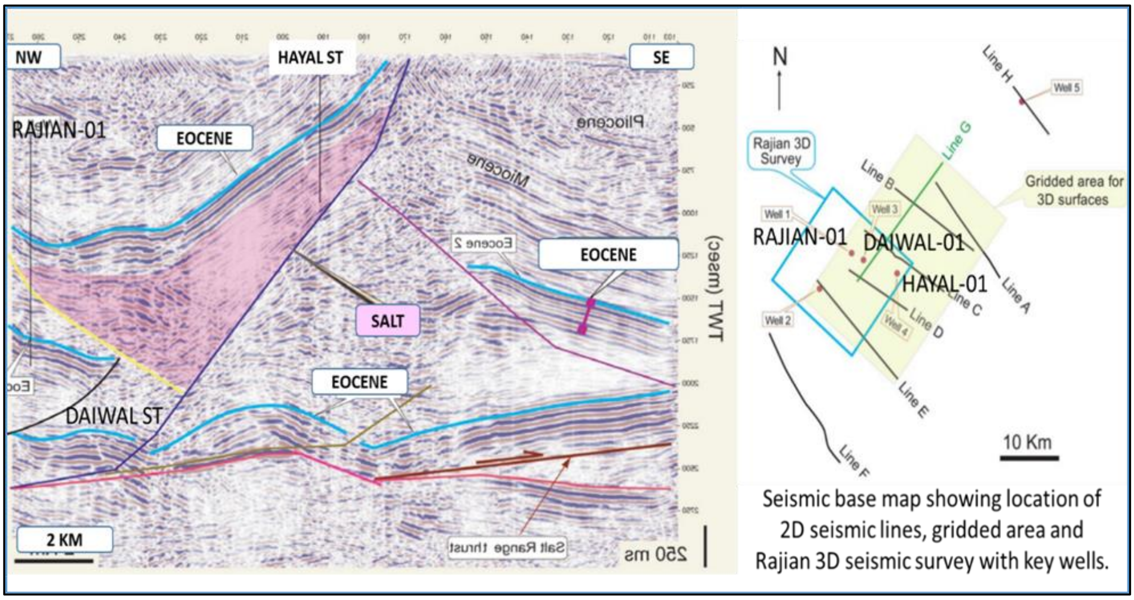


Figure 4.9 Dip oriented line C showing northeastern flank of Rajian structure (Modified after Aamir et, al. 2006).

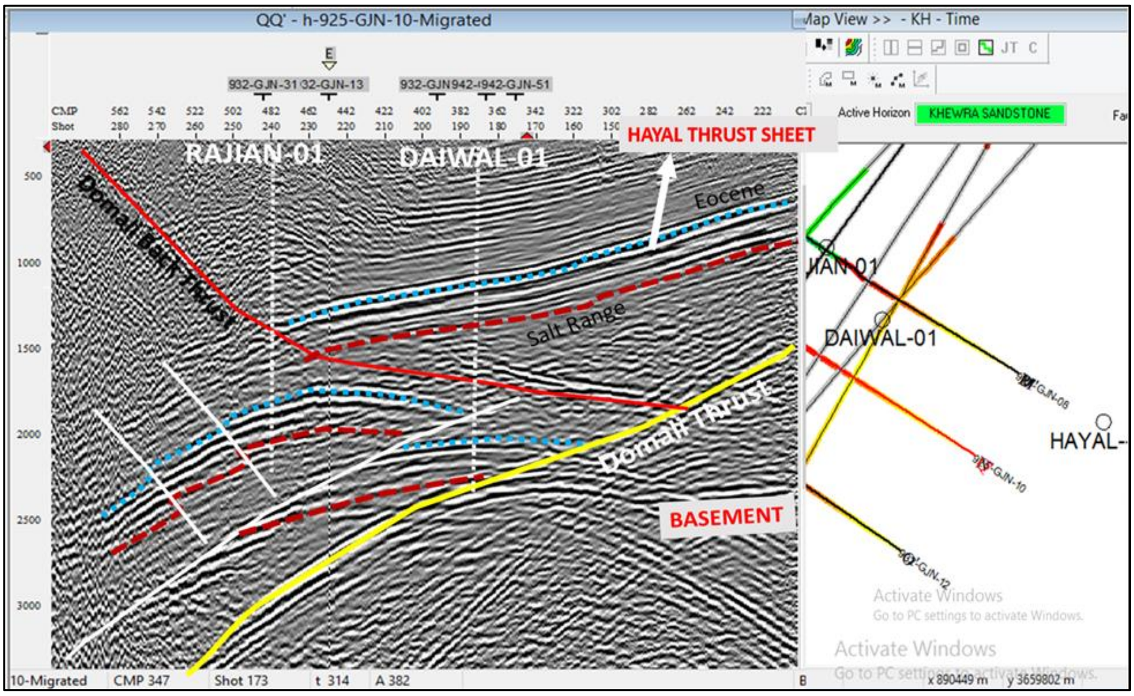


Figure 4.10 Dip oriented line 925-GJN-10 showing Rajian and Daiwal structures below Domali Back Thrust.

RAJIAN-01								
Formations	Formation tops (KB) 546 M	KB	SRD	Formation tops (SRD) 350 M	Thickness (m)	Interval time (ms)	TVT (ms)	Velocity m/s
CHINJI	0	546	350	-196	570		1226	-320
KAMLIAL	570	546	350	374	198	124.03	1252	597
MURREE	768	546	350	572	2538	1589.80	1302	879
CHORGALI	3306	546	350	3110	29	18.17	1762	3530
SAKESSAR	3335	546	350	3139	79	49.49	1787	3513
NAMMAL	3414	546	350	3218	11	6.89	1829	3519
PATALA	3425	546	350	3229	14	8.77	1849	3493
LOCKHART	3439	546	350	3243	11	6.89	1863	3481
HANGU	3450	546	350	3254	10	6.26	1874	3473
SARDHAI	3460	546	350	3264	13	8.14	1886	3461
WARCHA	3473	546	350	3277	4	2.51	1894	3460
DANDOT	3477	546	350	3281	7	4.38	1901	3452
TOBRA	3484	546	350	3288	6	3.76	1908	3447
BAGHANWALA	3490	546	350	3294	15	9.40	1917	3437
JUTANA	3505	546	350	3309	32	20.04	1937	3417
KUSSAK	3537	546	350	3341	86	53.87	1504	4443
KHEWRA	3623	546	350	3427	117	73.29	1960	3497
SALT RANGE	3740	546	350	3544	-3544	-2219.96	2041	3473

Figure 4.11 Time depth and velocity chart and lithological correlation of Rajian well-01.

DAIWAL-01								
Formations	Formation tops (KB) 577 M	KB (577)	SRD (350)	Formation tops (SRD) 350M	Thickness (m)	Interval time (ms)	TVT (ms)	Velocity m/s
NAGRI	0	577	350	-227	395	244.39	1015	-447
CHINJI	395	577	350	168	640	395.97	1034	325
KAMLIAL	1035	577	350	808	162	100.23	1074	1505
MURREE	1197	577	350	970	841	520.33	1080	1796
CHORGALI	2038	577	350	1811	36	22.27	1037	3493
SAKESAR	2074	577	350	1847	79	48.88	1052	3511
NAMMAL	2153	577	350	1926	6	3.71	1095	3518
PATALA	2159	577	350	1932	8	4.95	1102	3506
LOCKHART	2167	577	350	1940	8	4.95	1110	3495
HANGU	2175	577	350	1948	7	4.33	1116	3491
SARDHAI	2182	577	350	1955	7	4.33	1121	3488
WARCHA	2189	577	350	1962	11	6.81	1125	3488
DANDOT	2200	577	350	1973	10	6.19	1130	3492
TOBRA	2210	577	350	1983	8	4.95	1136	3491
JUTANA	2218	577	350	1991	37	22.89	1242	3206
KUSSAK	2255	577	350	2028	83	51.35	1242	3266
KHEWRA	2338	577	350	2111	117	72.39	1210	3489
SALT RANGE	2455	577	350	2228	-2228	-1378.47	1297	3436

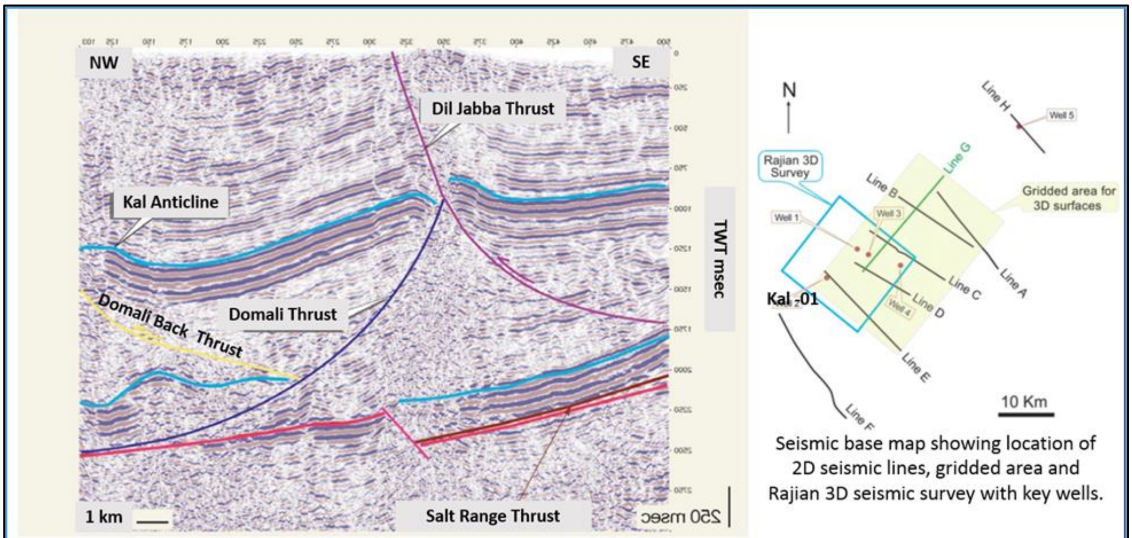
Figure 4.12 Time depth and velocity chart and lithological correlation of Daiwal well-01.

Kal Structure

The Kal structure is developed in the hanging wall against Domali back thrust and appear as rollover feature trending NE-SW in direction. This rollover has been mapped as an independent structural closure and bounded in the southeast by a structural low (syncline). The structure has been drilled down to Salt Range Formation residing below

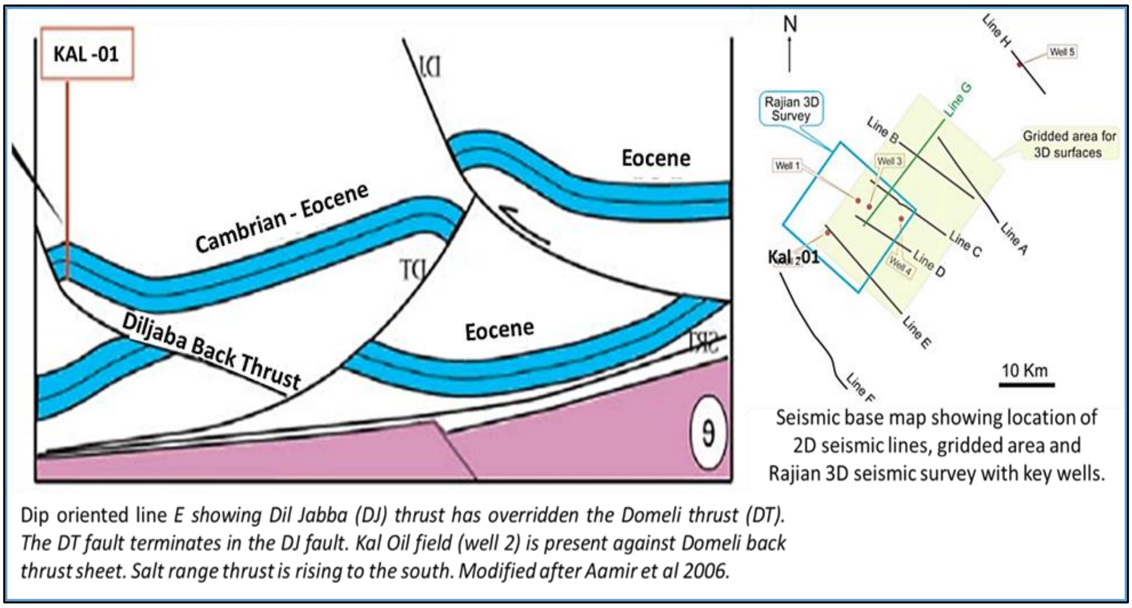
Cambrian - Lower Permian and Paleocene-Eocene clastic and carbonate lithologies. This entire succession is capped by Neogene molasse strata. The quality of seismic data is fair to good to yield its geometry for mapping. Structural repetitions by minor or major faults are not seen in this rollover feature at well bore location (Figures 4.15 and 4.16). Therefore, the stratigraphic thickness is considered valid for depositional cycles during Cambrian, Permian, Paleocene and Eocene times. The lithological and sequence boundaries pick has been plotted using time depth chart complied after correlation of sequence framework based on log data interpretation Figure 4.17.

The erosion truncation, downlapping of seismic event are seen in Kal seismic data between Cambrian and Permian strata and shallow levels and its link to system tract analysis and has been discussed in section 4.4.



Dip oriented line *E showing Dil Jabba (DJ) thrust has overridden the Domeli thrust (DT). The DT fault terminates in the DJ fault. Kal Oil field (well 2) is present against Domeli back thrust sheet. Salt range thrust is rising to the south. Modified after Aamir et al 2006.*

Figure 4.13 Dip oriented seismic section E showing Diljabba thrust overriding Domeli thrust (Modified after Aamir et, al. 2006).



Dip oriented line *E showing Dil Jabba (DJ) thrust has overridden the Domeli thrust (DT). The DT fault terminates in the DJ fault. Kal Oil field (well 2) is present against Domeli back thrust sheet. Salt range thrust is rising to the south. Modified after Aamir et al 2006.*

Figure 4.14 Sketch of seismic cross section E showing Diljabba thrust overriding Domeli thrust (Modified after Aamir et, al. 2006).

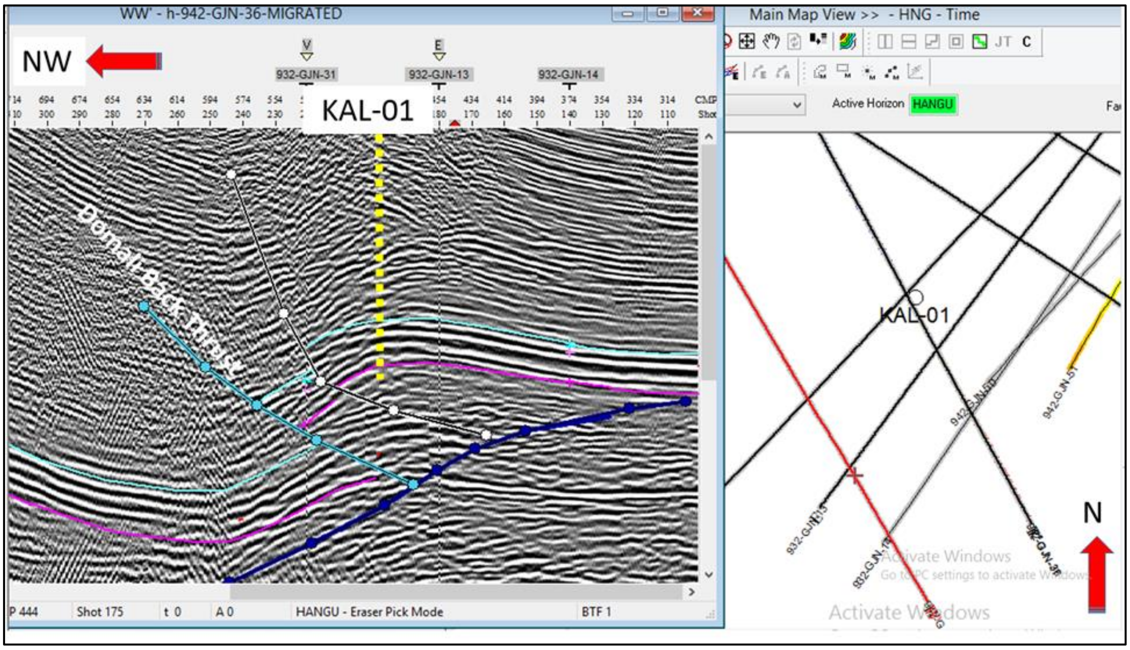


Figure 4.15 Seismic line (dip Direction) 942 GJN-36 showing Kal structural rollover bounded by a Domali Back Thrust. Blue is Top Eocene level. Purple is marking Top Salt Range Formation.

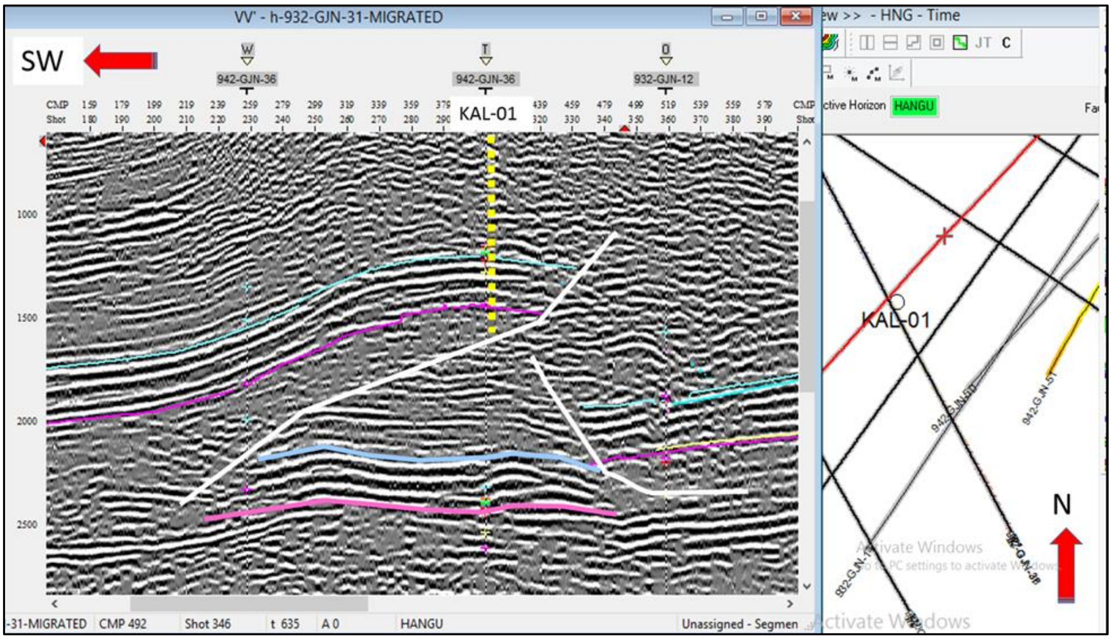


Figure 4.16 Seismic line (dip Direction) 942 GJN-31 showing Kal structural rollover bounded by a Domali Back Thrust. Blue is Top Eocene level. Purple is marking Top Salt Range Formation.

KAL-01								
Formations	Formation tops (KB) 495 M	KB	SRD	Formation tops (SRD) 350 M	Thickness (m)	Interval time (ms)	TVT (ms)	Velocity m/s
CHINJI	0	495	350	-145	860	577.2	1015	-286
KAMLIAL	860	495	350	715	210	140.9	1034	1383
MURREE	1070	495	350	925	1265	849.0	1074	1723
CHORGALI	2335	495	350	2190	35	23.5	1194	3668
SAKESSAR	2370	495	350	2225	84	56.4	1229	3621
NAMMAL	2454	495	350	2309	8	5.4	1276	3619
PATALA	2462	495	350	2317	12	8.1	1284	3609
LOCKHART	2474	495	350	2329	8	5.4	1288	3616
HANGU	2482	495	350	2337	5	3.4	1293	3615
SARDHAI	2487	495	350	2342	10	6.7	1298	3609
WARCHA	2497	495	350	2352	13	8.7	1303	3610
BAGHANWALA	2510	495	350	2365	7	4.7	1308	3616
JUTANA	2517	495	350	2372	48	32.2	1330	3567
KUSSAK	2565	495	350	2420	85	57.0	1370	3533
KHEWRA	2650	495	350	2505	132	88.6	1407	3561
SALT RANGE	2782	495	350	2637	-2637	-1769.80	1470	3588

Figure 4.17 Time depth and velocity chart and lithological correlation of Kal well-01.

Missa Kasswal Structure.

The Missa Kaswal structure has drilled down to Salt Range formation by well-1, 2 and 3. This feature is a tightly folded anticline bounded by frontal and back thrust faults.

The wells encountered Cambrian and thin sequence of Permian level below Paleogene strata (Figure 4.19, 4.20 and 4.21). Structurally this is salt cored anticline as proven by seismic and well data. The detachment can be placed between basement reflector and within Salt Range Formation.

The structure shows a four-way dip closure bounded by faults in NW and SE at multiple mapping levels from Top Salt Range to Top Eocene reflectors (Figure 4.21). This structure is proven for hydrocarbons presence and which flowed from Cambrian reservoir (Khewra Sands) beside Eocene carbonates. The 2d seismic data across this structure show popup feature with steep flanks. The axial trend of this tightly folded feature is NE–SW in direction. The seismic data has issues of very poor quality for QZN vintage while the quality appears better on GNA vintage lines. The imaging of this structure might have been deteriorated due to inadequate stacking velocities, elimination of high angle noise and statics. Structural crest represents offset on reflections corresponding to Eocene Carbonate events by low angle fault. There may be a possibility of repetition of strata at Eocene level. However, at the deeper Cambrian level of reflections appear continuous at drilling locations of Missa Kaswal wells 1, 2 and 3.

The lithological and sequence boundaries pick has been plotted using time depth chart complied after correlation of sequence framework based on log data interpretation (Figure 4.1). Therefore, the stratigraphic thickness is considered valid for depositional cycles during Cambrian, Permian, Paleocene and Eocene times. Structural repetition by minor or major faults at well bore location are not seen.

The erosion truncation, downlapping of seismic event are seen in seismic data between Cambrian Juttana levels. The wedge of lower Permian stratigraphy cannot be demonstrated due to very thin stratigraphic sequence and which could not be resolved in terms of reflectors due to low frequencies of data. The details of this in context of system tract signatures has been discussed in section 4.4

MISSA KESWAL-01						
FORMATION	Formation tops (KB) 462.7 M	KB	SRD	Formation tops (SRD) 350 M	TVT (ms)	Velocity m/s
CHORGALI	1802	462.77	350	1689.23	1071	3365
DANDOT TOBRA	1946	462.77	350	1833.23	1145	3399
BAGHANWALA	1964	462.77	350	1851.23	1168	3363
JUTANA	1980	462.77	350	1867.23	1180	3356
KUSSAK	2001	462.77	350	1888.23	1204	3324
KHEWRA	2062	462.77	350	1949.23	1230	3353
SALT RANGE	2181	462.77	350	2068.23	1278	3413

Figure 4.18 Time depth Chart Missa Kaswal 1, used to pick Cambrian-Permian boundaries along strike line.

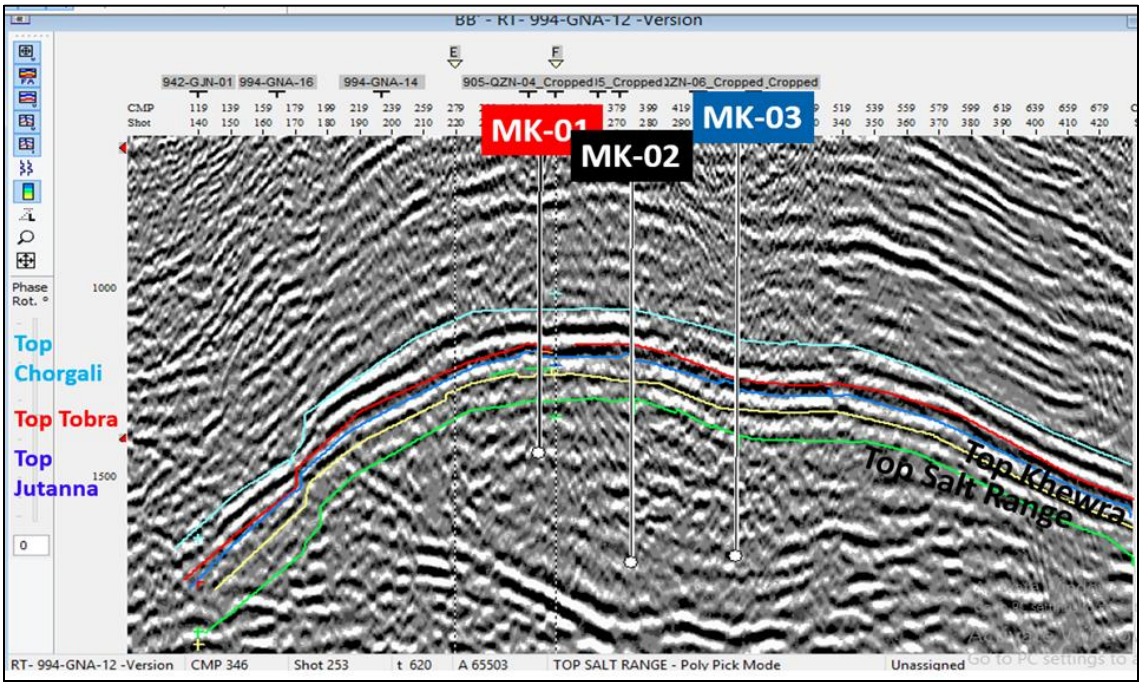


Figure 4.19 Strike line 994-GNA-12 across Missa Kaswal wells 1, 2 and 3 showing correlation of reflected horizons. This structural feature is showing doubly plunging anticlinal geometries across strike direction.

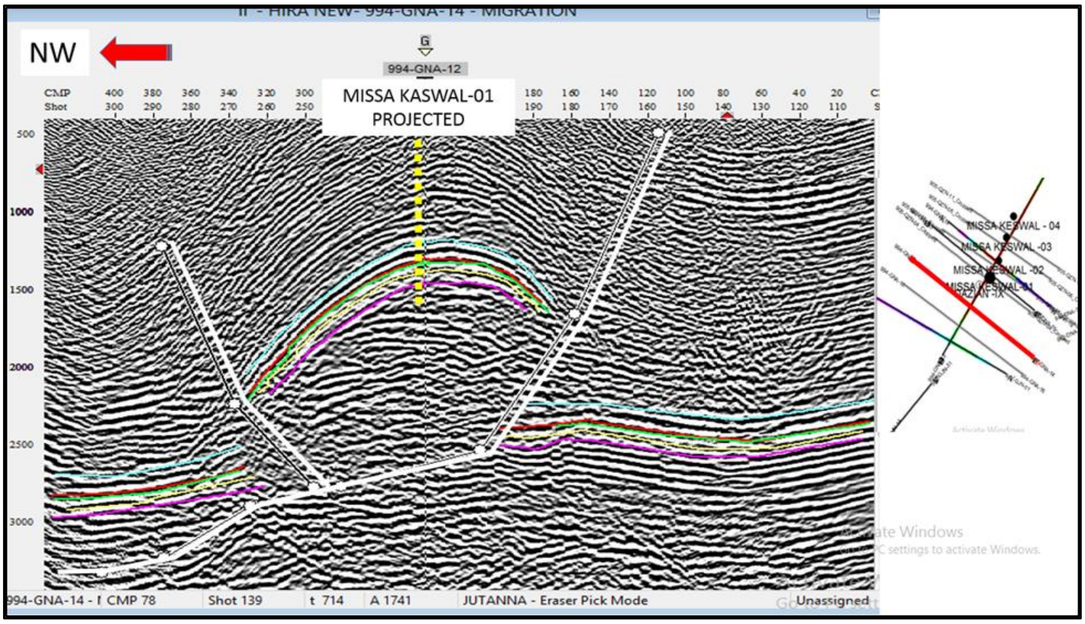


Figure 4.20 Dip line 994-GNA-14 across Missa Kaswal wells 1 showing correlation of reflected horizons. This structural feature appears as an asymmetrical popup bounded by frontal and back thrust. The Purple color is marking Top salt Range formation, Yellow Top Khewra Sandstone event, Green Top of Jutana/Baghanwala formation, Red Top Tobra Formation, Blue Top Eocene level.

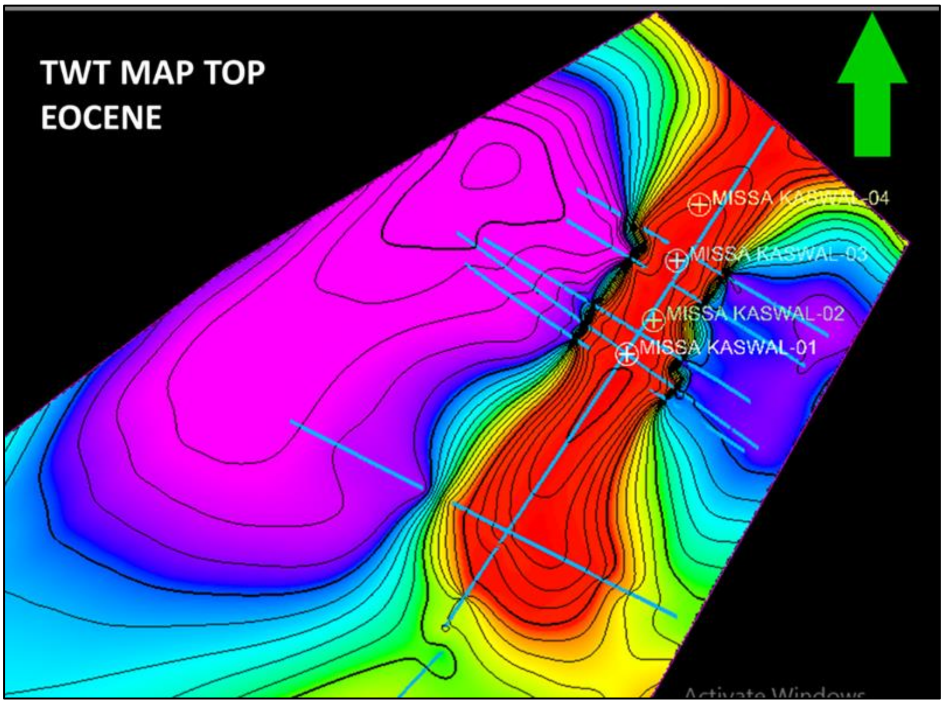


Figure 4.21 Two-way time map top Eocene level showing doubly plunging pop up anticlinal closure of Missa Kaswal structure trending NE-SW in direction.

4.4 Signatures of Depositional and Erosional Features.

This part of discussion will cover to address picking of truncations, onlaps, downlap and off lap geometries from seismic data used as a supporting evidences of system tracts. The available seismic data delineated traces of startal geometries which can be related to depositional and erosional surfaces. The data also delineated presence of onlapping, progradational and aggradational patterns already indicated by well data using GR log correlation across the study area. However these evidences are not very obvious due to quality of seismic data as the coherency of seismic reflections is not excellent. The frequency of data set is the key issue for resolving the features related to system tracts like on-lapping, down-lapping, top-lapping and etc. Following observations has been inferred from the seismic data set used to evaluate the features of sequence geometries for Cambrian and Permian levels.

1. Reflector corresponding to Top of Salt Range Formation is not a higher amplitude event. It may be the issue of impedance contrast not existed among the fining upward facies at the contact of Top Salt Range Formation and base Khewra Sands stone. The reflection data corresponding to Kherwa facies (change from fluvial to Aolian to Marine cycle) is not able to resolve contact definitions as the log data show most of the sands are aggradational bodies thus difficult to reveal any reflection due poor impedance contrast and by the low frequency factor. The reflected interval shows consistent frequency and very poor traces of changes of facies corresponding to Khewra sands.
2. The reflection criteria corresponding to Kussak lithologies (shale at top of Khewra and sand in upper part could not be resolved due to limited thickness and low frequency contents of seismic data. However, this reflection appears parallel to top Khewra marker and vanishes in west of study area. In addition, this reflection does form a surface where onlapping signatures has been noticed in the seismic data that may corresponds to Jutanna facies. Such signatures have been picked on seismic lines between Missa Kaswal and Balkassar Oxy wells, (seismic lines- GJN-08, 31, and 37 and Figures 4.22 to 4.24).
3. The reflections corresponding to Juttana cycles appear as an onlapping progrades at reflector near top Kussak level in the area of study. These progrades are well developed in Missa-Kaswal, Rajian, Daiwal, Kal and Balkassar area (Figures 4.22,

4.23, 4.24 and 4.25). The seismic data in these are showing prograde features stepping SE in direction indicating probability of shelf region. However, these progrades are arranged tilted and verging SW in direction where its relation with overlying reflections from Baghanwala is not clearly understood.

4. It can be interpreted at this stage that Jutana progrades developed under forced regression cycle and onlapping of progrades suggest retrogradational and aggradational pattern that related to FSST tract both in GR logs, field data (Khewra-Choa road section, Figure 3.47) and the present seismic data set. The tilting of progrades might be related to uplifting of shelf region in NW or subsidence in SE. Subsequent to this tilting the cyclic deposition of Baghanwala formation took place in shallow environments where tidal cycles from open marine involved into multiple transgressions and regressions on the tilted Jutanna progrades.

5. The reflection data corresponding to Baghanwala formation may have been mingled with Jutana data set as this unit also deposited in early falling stage of Eustasy. However the SW tilted culminations of Jutana progrades might be intercepting the Baghanwala reflections close to Tobra marker and cannot be resolved by the seismic wavelets for the geometry definition due to insignificant thickness of Baghanwala and Tobra formations. But this reflector can be picked at well bore after tie and nearby areas having good quality data. In the eastern area (Missa-Kaswal) the tilted prograding geometries are not obvious and may be eroded during Permian glaciation.

6. The seismic marker near base Permian surface is characterized by mingling of wavelets and clean pick of the erosional contact is dubious (see blue marker in Figures- 4.22, 4.23, 4.24 and 4.25). This behavior also marks erosional surface which is a sequence boundary at top of Cambrian level.

7. The seismic data also demonstrate wedge response along with updip truncation of reflectors corresponding to Lower Permian stratigraphy. These truncations are obvious in Balkassar and Kal area and may relate to erosional removal of Lower Permian lithologies (Figure 4.26 and 4.27). The internal stratal geometries representing features of system tract could not be resolved by the existing capacity of seismic data due to low frequency response and the small preserved thickness factor in the area of study for Lower Permian level.

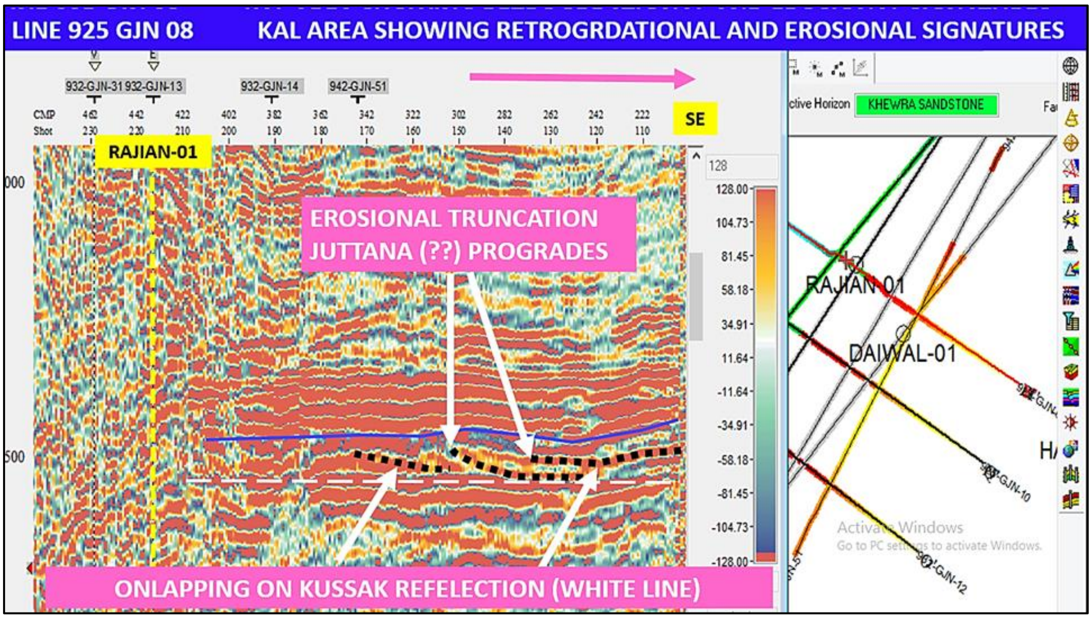


Figure 4.22 Seismic line 925 GJN 08 showing prograding reflections of Juttana Formation (??) which are onlapping on Kussak level at base and erosionally truncated by base Tobra Formation, Rajian area.

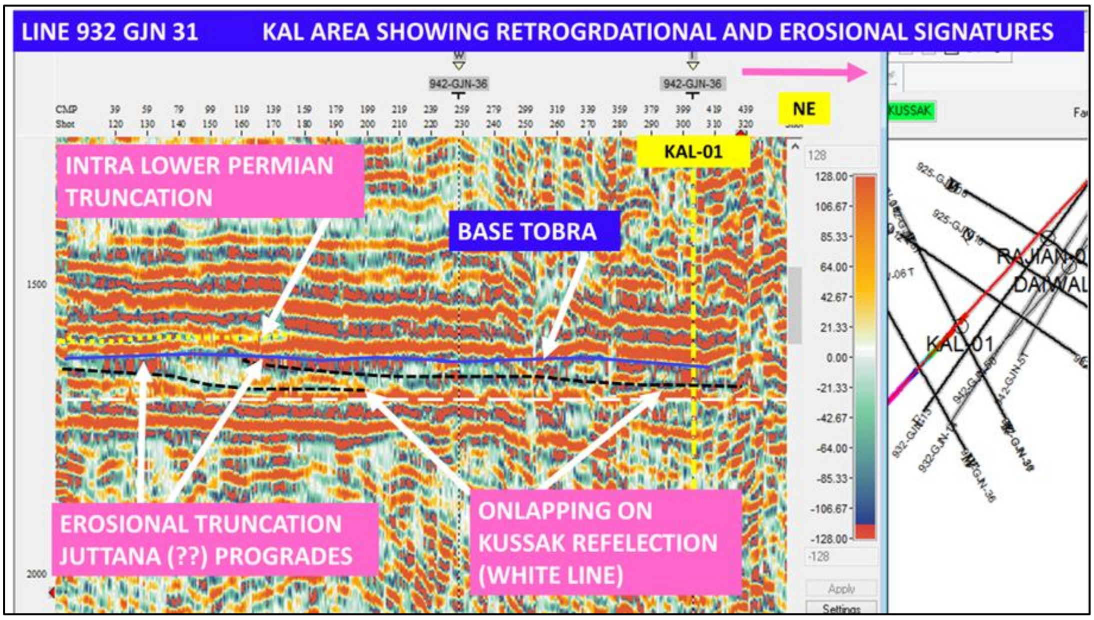


Figure 4.23 Seismic line 925 GJN 31 showing prograding reflections of Juttana Formation (??) below base Tobra Formation, Kal area.

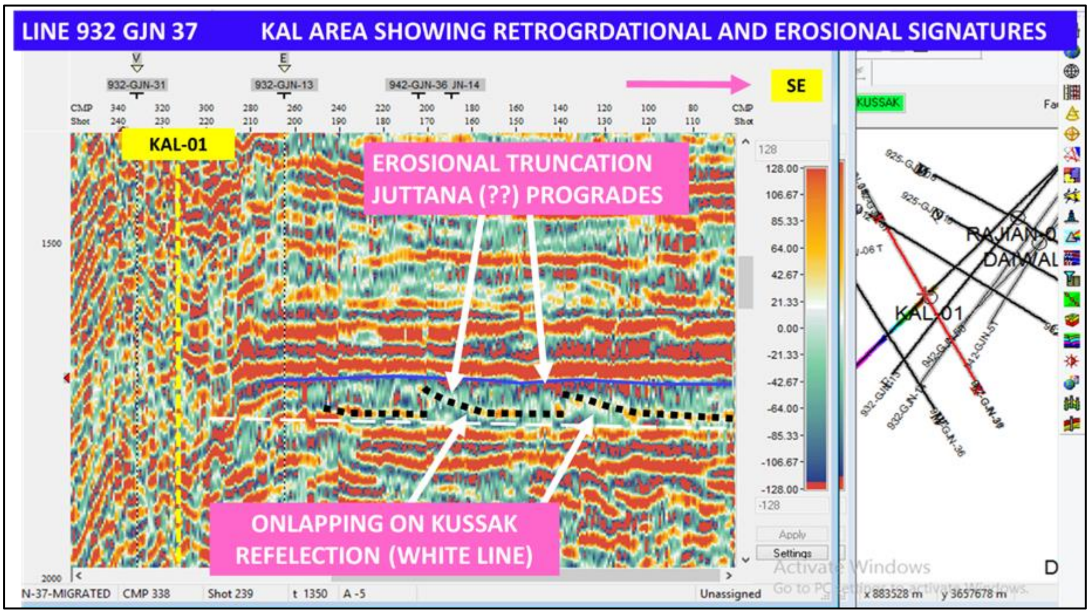


Figure 4.24 Seismic line 925 GJN 37 showing prograding reflections of Juttana Formation (??) below base Tobra Formation, Kal area.

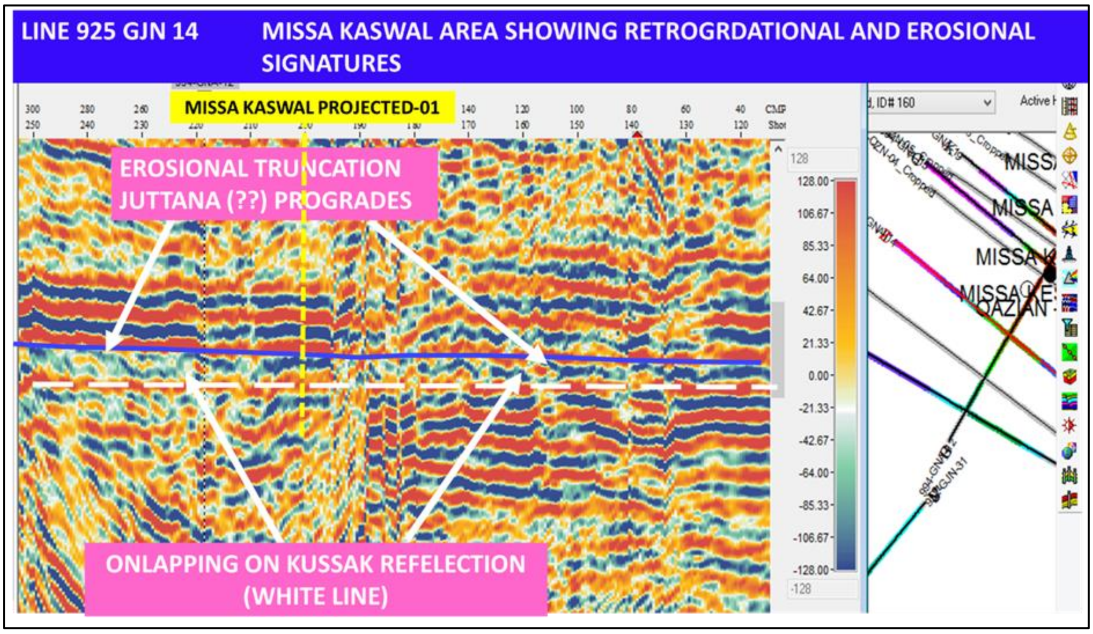


Figure 4.25 Seismic line 925 GJN 14 showing prograding reflections of Juttana Formation (??) below base Tobra Formation, Missa Kaswal area.

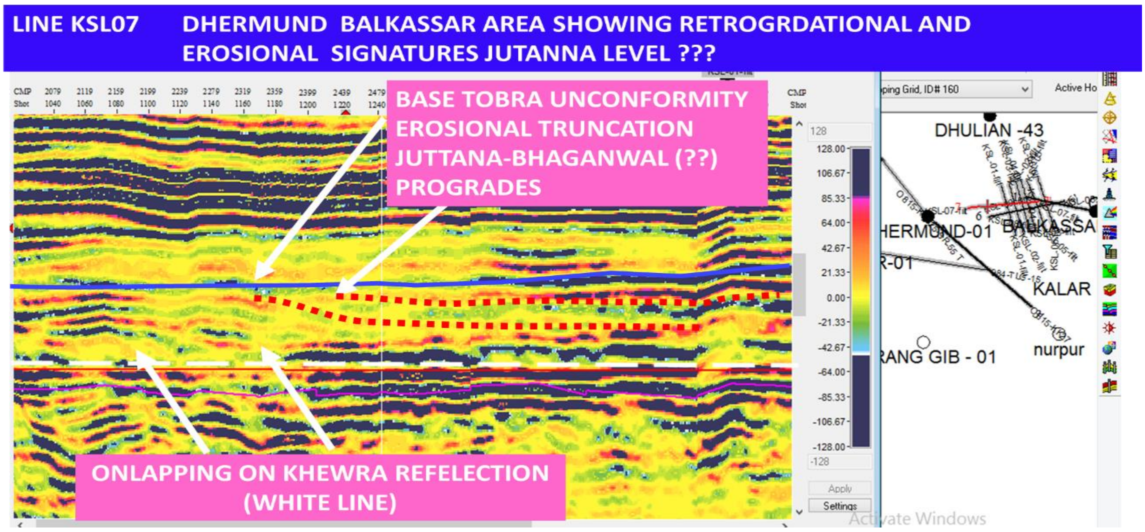


Figure 4.26 Seismic line KSL-07 showing prograding reflections of Juttana Formation (??) below base Tobra Formation, Balkassar area.

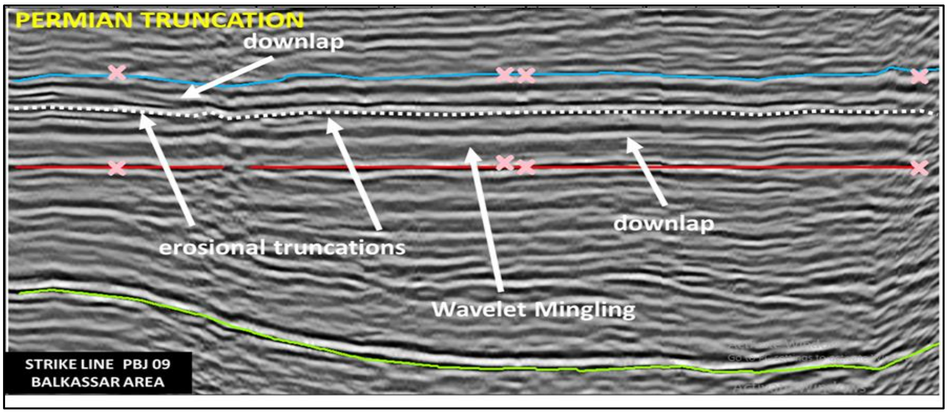


Figure 4.27 Seismic line PBJ 09 (strike direction) flatten on top Salt Range Formation onlapping, dwonlapping and erosional truncations at Cambrian and Permian Levels.

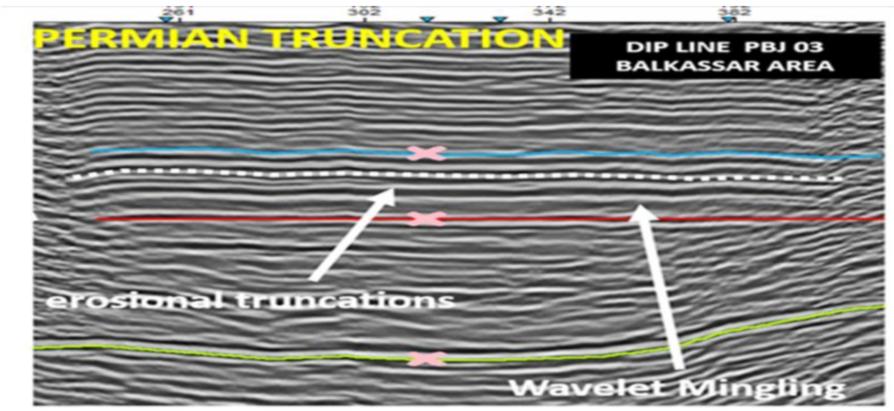


Figure 4.28 Seismic line PBJ 03 (dip direction) flatten on top Salt Range Formation onlapping, downlapping and erosional truncations at Cambrian and Permian Levels.

CHAPTER-5

SUMMARY OF DATA INTEGRATION FOR VALIDATION OF SEQUENCE MODEL BASED ON GR LOGS, FIELD OBSERVATIONS AND SEISMIC LINES

The sequence stratigraphic methodology can conclude reliable results when evaluation is derived and integrated from multiple data sets including outcrop, well log, core, seismic, biostratigraphic and geochemical (Figure 5.1). The data integration is important factor as it provides opportunity to validate and recognize depositional trends and stratal stacking patterns from multiple means (Figures 5.2). The integration stage may resolve reliability issues of results and this can be achieved by mutual calibration of multiple data sets as one data set may be more supportive than other in reaching firm conclusion. The integration of seismic data help to resolve sequence model within basin by providing continuous coverage, whereas outcrops, core and well logs provide and add reliable information for a fix location which is a support from sparse and discontinuous data base.

The study area required complete analysis of multiple datasets to dictate a sequence stratigraphic model which for present work was not available due to certain limitations like option of using more than four wells and the specific data like dip meter logs, biostrtigraphic studies, core and well ties / checkshots. And the option of using additional seismic lines (2d and 3d) more than seven or eight was not grated by regulator (DGPC). The project area resides in complex fold belt where such studies must be supported by additional and reliable data sets which should not be limited by the numbers due to certain limitations. Despite of these limitations the evaluation of available data set was conducted for construction of a framework of systems tracts and bounding surfaces leading to a model independent approach which could fulfill the practical purpose of sequence stratigraphy in the study area. The model-dependent choices (Figure-5.3 and 5.4) with respect to the selection of the ‘sequence boundary’ and framework could not be concluded to a full extent for any single approach. For present study the Depositional Sequence IV of Hunt & Tucker, (1992 and 1995) and Genetic Sequence (Galloway 1989) models (Figure-5.3) were considered valuable for developing correlation in the study area.

Data set	Main applications /contributions to sequence stratigraphic analysis
Seismic data	Continuous subsurface imaging; structural styles; lapout relationships; stratal stacking patterns; imaging of depositional elements; geomorphology; stratal geometries.
Well-log data	Vertical stacking patterns; grading trends; depositional elements; depositional systems; petrophysics; calibration of seismic data.
Core data	Facies; textures and sedimentary structures; nature of stratigraphic contacts; physical rock properties; paleocurrents in oriented core; calibration of well-log and seismic data.
Outcrop data	3-D control on facies architecture; insights into process sedimentology; facies; depositional elements; depositional systems; all other applications afforded by core data.

Figure 5.1 Figure showing contributions of different data sets to the sequence stratigraphic interpretation (Catuneanu, 2006). Integration of insights afforded by various data sets is the key to a reliable and complete sequence stratigraphic model.

Key: √√√ good, √√ fair, √ poor	Rock data			Geophysical data		
	Outcrops		Core	Well logs	Seismic data	
	Large-scale	Small-scale			2D	3D
Tectonic setting	√√	√	√	√√	√√√	√√√
Facies	√√√	√√√	√√√	√√	√	√√
Nature of contacts	√√√	√√√	√√√	√√	√√	√√
Stratal terminations	√√√	√	√	√	√√√	√√√
Depositional trends	√√√	√√	√√	√√	√√	√√√
Stratal geometries	√√	√	√	√	√√√	√√√
Depositional elements	√√√	√√	√√	√√	√	√√√
Depositional systems	√√√	√√	√√	√√	√	√√√

Figure 5.2 Figure showing utility of different data sets for building a sequence stratigraphic framework (Catuneanu, 2006). The seismic and large-scale outcrop data provide continuous subsurface and surface information respectively. In contrast, small scale outcrops, core, and well logs provide sparse data collected from discrete locations within the basin.

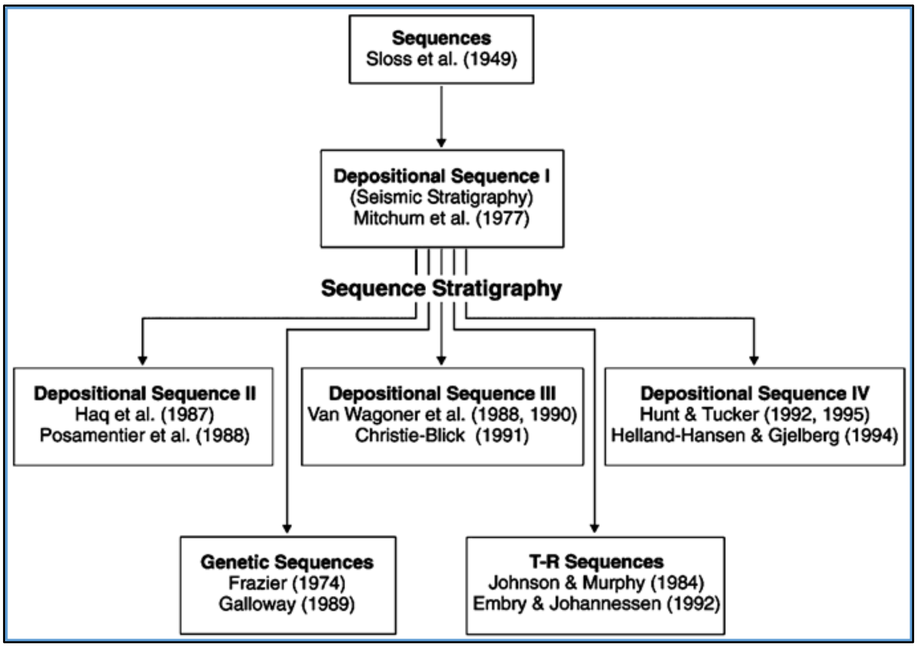


Figure 5.3 Figure showing sequence stratigraphic models (Catuneanu, 2006; modified after Donovan, 2001).

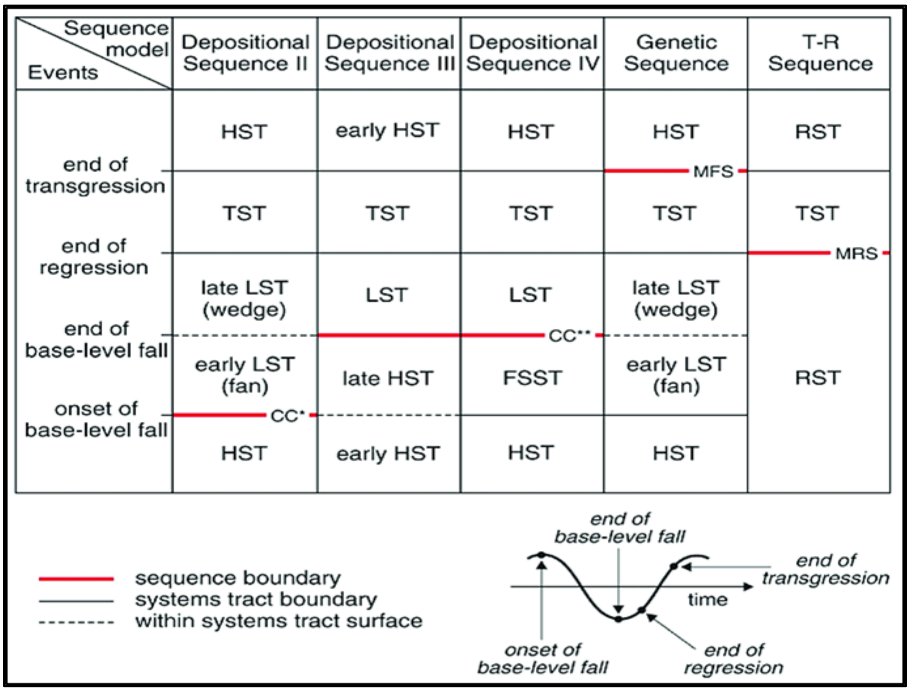


Figure 5.2 Figure showing nomenclature of systems tracts and timing of sequence boundaries for the existing sequence stratigraphic models (Catuneanu, 2006). Abbreviations: LST — lowstand systems tract; TST — transgressive systems tract; HST — highstand systems tract; FSST-falling-stage systems tract; RST — regressive systems tract; T–R — transgressive–regressive; CC * — correlative conformity sensu Posamentier and Allen (1999); Hunt and Tucker (1992); MFS—Maximum flooding surface; MRS—Maximum regressive surface.

The sequence stratigraphic framework specific to southern part of Potwar basin for Cambrian-Permian level of stratigraphy in terms of timing and scales of the stacking patterns and bounding surfaces show an interplay of global and local controls on accommodation and sedimentation. The tectonics, glaciation and Eustasy were major global controls beside localized activities of erosion. The Pre-Cambrian, Cambrian and Permian time period of Potwar Basin remain in affiliation with the entity of Gondwanaland and occupied geographic position along present day east African-Arabian Plate margin (Figure 5.5). The stratigraphic facies among Potwar Basin of Pakistan and Huqf area of Oman are correlateable to confirm affiliation of sedimentary terrain (Figure 5.7). The sedimentary cycles prevailed in the basin were primarily controlled by global tectonic position of the basin. The sedimentary cycle of deposition from end Cambrian to early Permian was missed by a presence of Late Paleozoic Glaciation (a non-depositional period) prevailed during that time frame (Ordovician to Carboniferous) and tectonic position of basin in southern hemisphere (Figure 5.6). It has been inferred that Paleogeographic setting of Potwar basin was within the north western terrain extending from Aravalli Ranges which remained a provenience of sediments supply during Cambrian-Permian time (Figure 5.8). The basin floor forming a landing ground in this area can be configured for a shelf slope setting dipping northwest and where river system might be transporting sediments towards Tethys Sea.

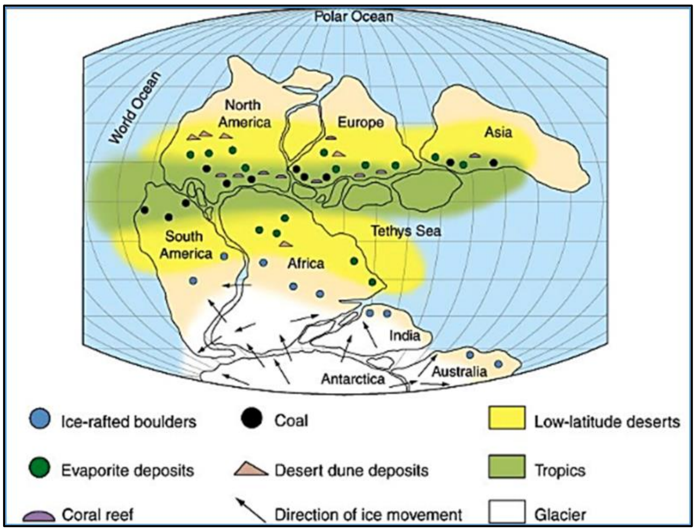


Figure 5.5 Figure showing global assemblage of continental blocks based on evaporitic basins, Aeolian deposits, coral reefs and coals deposits and paleo-climatic features (Glacial). Note that Potwar Basin in Indo-Pakistani Plate was in affiliation with east African-Arabian land masses.

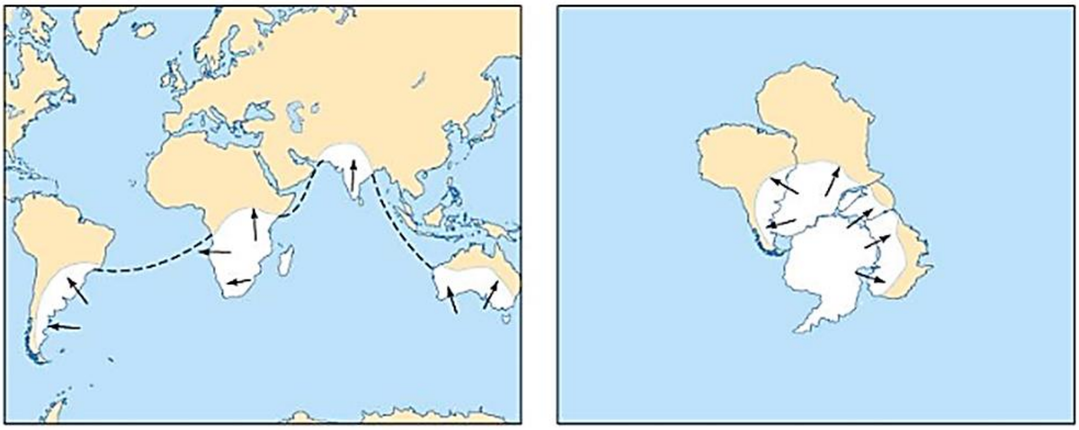


Figure 5.6 Figure showing Late Paleozoic glaciations which covered large portions of the southern part of Gondwana. Evidences of this event are reported as glacial deposits of Tobra Formation in Indus Basin. The glacial striations indicate direction of movement while no evidence for glaciation on northern continents at this time.

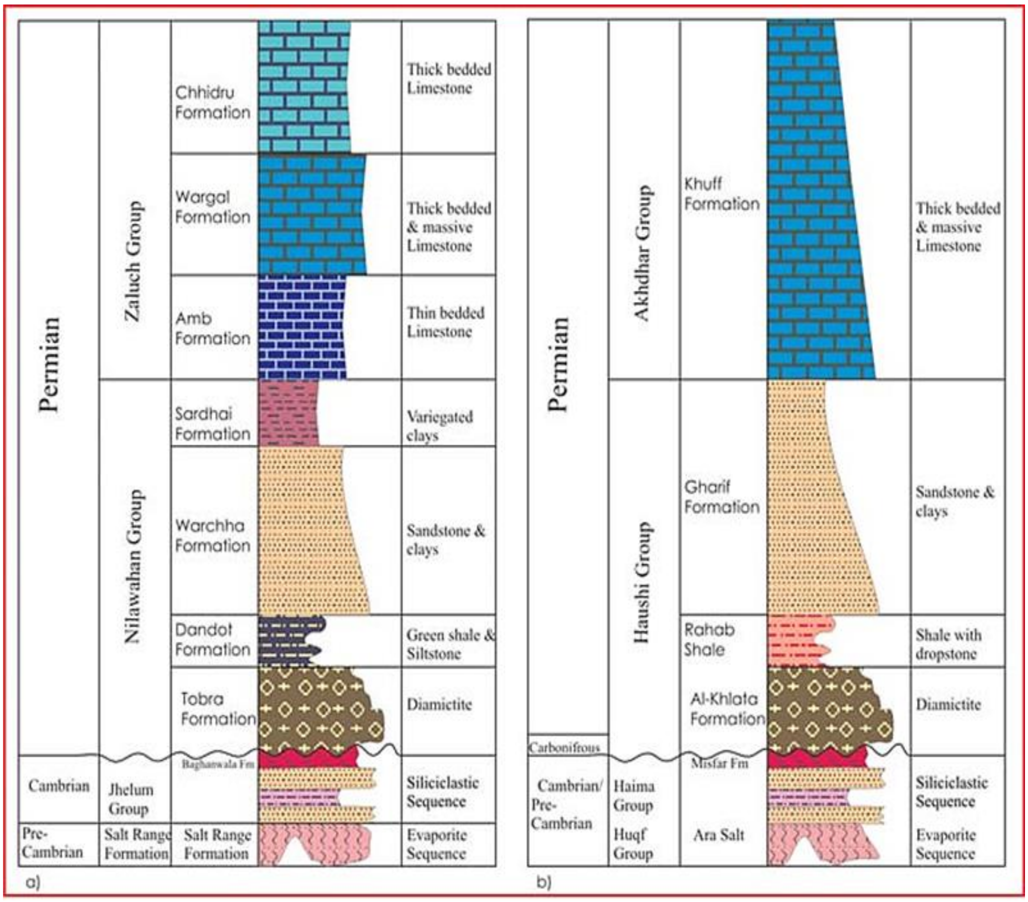


Figure 5.7 Generalized upper Paleozoic stratigraphy and its relationship with the lower Paleozoics of the Salt Ranges, (Figure 7a) and Huqf area (7b). Major unconformities mark the contact between the upper Paleozoic and lower Paleozoic sequences in the Salt Ranges and the Huqf area. (Abbasi et, al.2011).

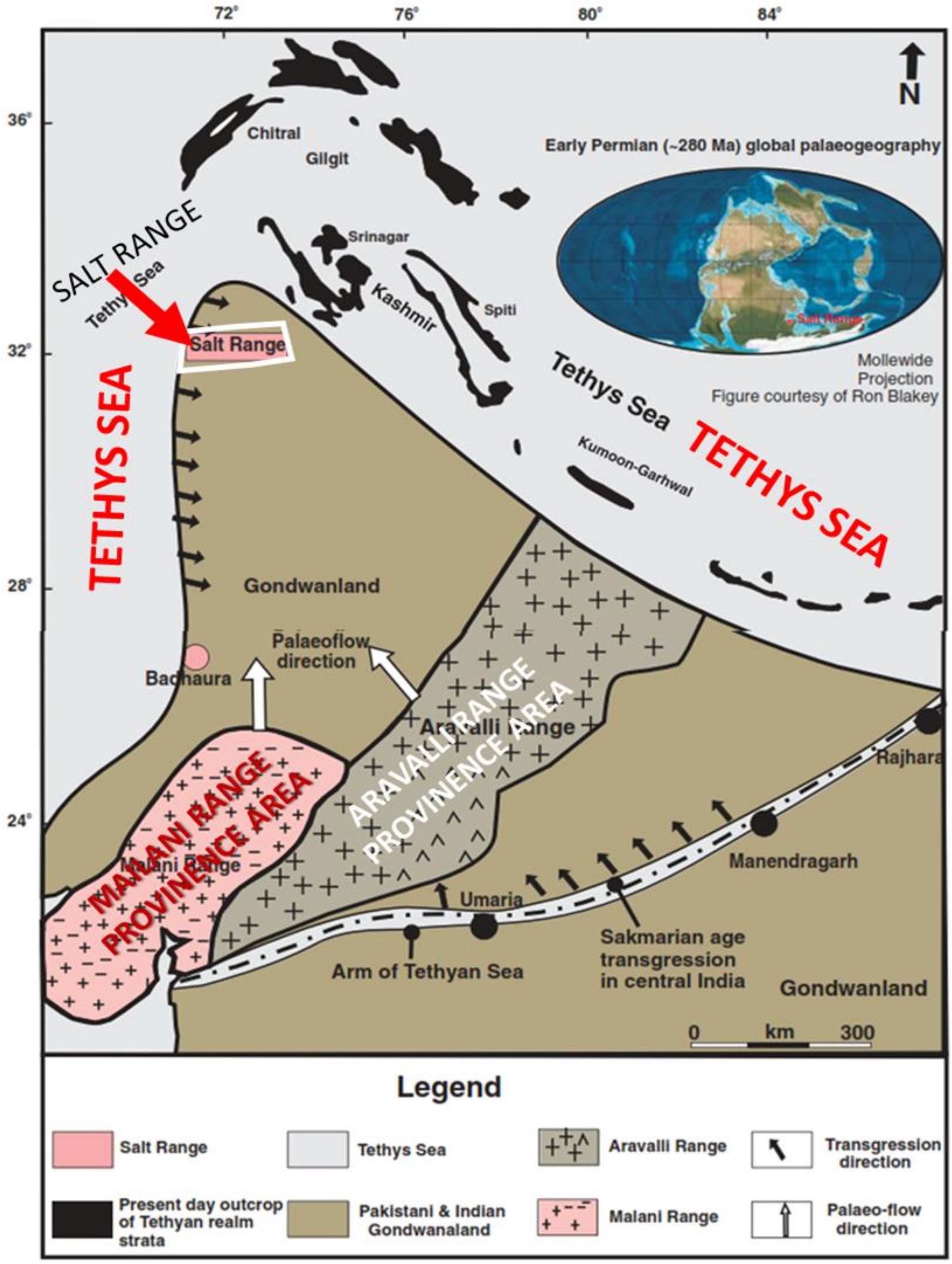


Figure 5.8 Palaeogeographic map (showing present day longitude and latitude) of the Pakistani and Indian parts of Gondwanaland during the Early Permian. The location of the Salt Range and main sediment source areas are shown (modified after Shah and Sastry 1973). During Permian times, the Pakistan region occupied part of Gondwanaland at a palaeolatitude of 50° –55° south of the equator and was bordered to the north by a large marine embayment that formed part of the Tethys Ocean. (modified after Ghazi et, al.2012).

The dip of paleoshelf and slope in upper Indus Basin including the study area is in NW direction as indicated by seismic reflection at basement level present below detachment of sedimentary cover. Therefore, consideration of NW dipping shelf slope setting from Aravalli range (the provenience area) to Tethys Sea as a Paleogeographic feature is reliable assumption during deposition of Cambrian - Permian facies and which has been also suggested by Ghazi et, al (2012) during Permian stage (Figure 5.8).

The objective of the present study was focused to evaluation of facies from Cambrian-Lower Permian clastic units therefore major contribution for stratal analysis and bounding surfaces were achievable through GR logs and on occasions was supported by SP and resistivity curves. Beside this stratal geometries were understood from limited 2d seismic data. As an essential first step for present sequence stratigraphic study the stratal stacking patterns were recognized based on GR log response from the preserved facies. Interpretation of GR values both high and low help in configuration of shape of curve. The significant features of curve helped to define coarsening or fining upward behaviors related to response of facies. The correlation of these features among the wells used in study area led to define progrdational, aggradational and retrogradational stacking system across the shelf slope area of Potwar Basin. These patterns indicates presence of normal regressive, forced regressive and transgressive types of facies representing three types of shore line shift in trajectories across shelf area. The geometric signature like up-stepping, fore-stepping, back-stepping and down-stepping, expressing three types of shoreline shift requires evaluation from regional seismic data which is not available for present study.

About all the lithological facies of Cambrian-Permian stratigraphy were analyses to interpret multiple surface that could be used to define the nature and geometry of building blocks leading to elaborate sequence stratigraphic framework. This analysis of stacking of stratal units has been discussed in chapter-3 for each lithological unit under caption of models. In general, the entire Cambrian-Lower Permian section is an assemblage of three sequences developed in response to change in Eustacy and accommodation space. The internal architecture of each sequence is shown in Tables (5.1-5.3). If we commence to follow the building blocks for Cambrian–Permian cycles of stratigraphy, the presence of Salt Range Formation at base led to assume a Paleogeography having a closed basin setting and the link of this closed basin to open shelf/slope might be bordered by marginal uplifts. However in either case the sea level can be considered at low.

Sequence-1

This sequence commenced during ongoing sea level rise stage (transgressive phase) since Late Proterozoic and continued to build up as a stacking progrades till Mid Cambrian time with a bounding surface as a type-1 sequence boundary. Two lithostratigraphic units (Salt Range and Khewra formations) are constituting the building blocks of this sequence. The boundaries at base and top are also marked by surface of unconformities (Table 5.1, Figures 3.9, 3.10, 3.25-3.26). The GR curve response across facies of Top Salt Range and basal Khewra units show fining upward profile. This suggest retrogradtional stacking pattern and landward shore line shift in SE direction can be marked for relevant geometries (back stepping) in the southeast of study area. A high gamma ray response during this transgressive phase suggest presence of maximum flooding surface (MFS KH). During this transgression phase the Eustatic cycle was intercepted by sudden fall and movement of shore line in NW and depositional cycle changed from marine to non-marine / Aolian environment leaving aggradational stacking pattern build by sandy progrades of Khewra Formation. The GR log response seen after correlation of well data represents this stage of aggradational and progradtional setting in the shelf slop region (Figure 3.24, Table 5.1).

The upper most part of sequence-1 is bounded by prograding sandy units of fluvial and marine in origin representing interaction of shore line across the shelf slope. The sudden and short phase of transgression indicate a sea level rise and then gradual fall to build prograding sandy facie at top. The top part shows this interaction of falling sea level where sandy facies are interbedded by conglomeratic facies deposited after fluvial incision and deposited among channels (Figure 3.21 and 3.22) marking unconformity as an upper sequence boundary (Table 5.1). The geometry of coastal onlap could not be marked as this might be preserved in SE of the study area. The configuration of this sequence yielded system tracts commenced from LST and then switched to TST. This stage was intercepted by forced regression and switched to FSST and then entre to short term flooding before LST stage.

Table 5.1 Showing internal architecture of sequence-1.

SEQUENCE-1 ARCHITECTURE - SALT RANGE-KHEWRA FORMATIONS SOUTHREN POTWAR BASIN						
LITHOFACIES	GENETIC RELATION	BOUNDING SURFACES	LOG SIGNATURE	SHORE LINE TRAJACTORY	GEOMETRY	SYSTEM TRACT
UPPER KHEWRA CLASTICS	REGRESSIVE FACIES	TOP SQ BOUNDARY T-1	COARSENING/PROGRDATION	BASIN WARD SHIFT (SE)	UNCONFORMITY FORE STEPPING	LST
UPPER KHEWRA CLASTICS	TRANSGRESSIVE FACIES	MARINE TRANSGRESSION	FINNING/RETROGRADATION	LANDWARD SHIFT (NW)	BACK STEPPING	FS
MIDDLE KHEWRA CLASTICS	REGRESSIVE FACIES	FR / FSST ONSET	COARSENING/AGGRADATION	BASIN WARD SHIFT (SE)	DOWN STEPPING	FSST
BASAL KHEWRA CLASTICS	TRANSGRESSIVE FACIES	MFS KH	FINNING/AGGRADATION	MAX LANDWARD SHIFT	BACK STEPPING	TST
		BASE KH/ SALT RANGE TOP				
TOP SALT RANGE CLASTICS	TRANSGRESSIVE FACIES	TR SURFACE	FINNING/RETROGRADATION	LANDWARD SHIFT (NW)		
SALT RANGE FORMATION	EVAPORITE FACIES	TOP SALT				LST
		BASE SQ BOUNDARY-1	PROGRADATION	BASE OF LOWSTAND WEDGE		
BASED ON GR LOG CORRELATION (DHERMUND-1, BALKASSR-01, KAL-01, DAIWAL-01, RAJIAN-01, MISSA KASWAL-01, 03						

Sequence-2

The sequence-2 commenced from top of sequence-1 surface of erosion as a basal boundary. There are three lithological units (Kussak, Jutana and Bhaganwala formation) which represents building of retrogradtional to progradational and aggradational stratal units configuring TST at base to FSST in middle and LST at top (Table 5.2). Well log data (GR and SP) in the study area demonstrated probabilities of flooding surface, maximum flooding surface at base and therefore suggest landward shift of shore line which is in southeast across the shelf slope setting of Potwar Basin and Salt Range. The outcrop facies in Salt Range are correlateable with retrogradational profile of GR logs recoded in wells. The signatures of back stepping may be preserved in SE area.

The eustatic rise in sea level has been culminated by normal regression after (sea level fall) from the shelf slope region. The section in middle part of this sequence show cyclic deposition of multiple clinoforms. Two of which are marked in field outcrops (Figure 3.41 and 3.45) and indicated by geometrical signatures of on lapping by seismic data (Figures 4.22 - 4.25). Each of these clinoform show progradation and coarsening upward profile. The cyclic repetition of eustatic fall to rapid rise and subsequent fall is indicator of tectonic control for uplift to sinking and then uplift in a succession during over all cycle of FSST. In the upper part this cyclic sedimentation continues under fluctuating controls of Eustacy generally settling for sea level fall. The signatures related to fluctuating shifting of shore line may be preserved in south east of study area. The top of sequence boundary is bordered by regional surface of erosion which is well developed across the Gondwanaland facies.

Table 5.1 Showing internal architecture of sequence-2.

SEQUENCE-2 ARCHITECTURE - KUSSAK-BAGHANWALA FORMATIONS SOUTHREN POTWAR BASIN

LITHOFACIES	GENETIC RELATION	BOUNDING SURFACES	LOG SIGNATURE	SHORE LINE TRAJACTORY	GEOMETRY	SYSTEM TRACT
BHAGANWALA CLASTICS	REGRESSIVE FACIES	TOP SQ BOUNDARY -2	COARSENING/PROGRDATION	BASIN WARD SHIFT (NW)	UNCONFORMITY FORE STEPPING	LST
UPPER JUTANNA CLASTICS	REGRESSIVE FACIES	CLINOFORM-3	COARSENING/PROGRADATION			FSST
	TRANSGRESSIVE FACIES	TR SURFACE	FINNING/RETROGRADATION	LANDWARD SHIFT (SE)	BACK STEPPING	
MIDDLE JUTANNA CLASTICS	REGRESSIVE FACIES	CLINOFORM-2	COARSENING/PROGRADATION	BASINWARD SHIFT (NW)	FORE STEPPING	
	TANSGRESSIVE FACIES	TR SURFACE	FINNING/RETROGRADATION	LANDWARD SHIFT (SE)	BACK STEPPING	
BASAL JUTANNA CLASTICS	REGRESSIVE FACIES	CLINOFORM-1	COARSENING/PROGRADATION	BASINWARD SHIFT (NW)	FORE STEPPING	
		TR SURFACE		LANDWARD SHIFT (SE)		TST
TOP KUSSAK CLASTICS	TRANSGRESSIVE FACIES	TOP KUSSAK	FINNING/RETROGRADATION		BACK STEPPING	
		MFS KUK-1,2,3		MAX LANDWARD SHIFT		
BASE KUSSAK CLASTICS		BASE SQ BOUNDARY-2		LANDWARD SHIFT (NW)		TST

BASED ON GR LOG CORRELATION (DHERMUND-1, BALKASSR-01, KAL-01, DAIWAL-01, RAJIAN-01, MISSA KASWAL-01, 03

Sequence-3

The definition of sequence-3 setting for basal boundary is clear but the provision of any surface for its recognition as upper boundary is not clear and could not be addressed due to limited data, extent of study area and scope of work confined to lower Permian succession). The upper part of this sequence even extending to include upper Permian level strata is truncated by regional base Tertiary unconformity which is a firm candidate for a sequence boundary at top. This base Tertiary unconformity removed Upper Permian and Lower Permian strata from west to east across the shelf slope setting of Potwar Basin. In western part of study area this unconformity resides as a sequence boundary above upper Permian section while in east this boundary resides above lower Permian progrades (Figure 2.4 and 2.5).

The internal architecture of sequence-3 (Table 5.3) demonstrate multiple transgressive events, maximum flooding surfaces, regressive progrades arranged in retogrdational, aggradational, and progradational patterns linking to number of costal shore line shifts across the shelf slope setting in the study area (Figures 3.62-3.63 3.69-3.70, 3.76-3.77. 3.82-3.83). The basal part of sequence-3 is surface of sequence boundary clearly showing erosional facies formed after glacial melting after a long span of time frame. The eustatic curve is mainly controlled by glacial melting and thus represents transgression cycles where clastics were occupied by channels (boulder beds) and flood plain of fluvial cycles (Sandstones and siltstones). The shore line shifts might be seen in SE of study area. The facies change from glacial tillite in east to fluvial sediments in west of study area can support the direction of transgression in association with glacial melting

(Figure 3.56-3.57). This cyclic transgressive episode during glacial flooded landward to a maximum level and its relevant event can be marked by maximum flooding surface (MFS Dandot). The back stepping signatures of this TST may be preserved in SE of study area.

The progradational staking geometries appear above retrogradational facies marking sea level fall and indicate basin ward shift of facies along with movement of shoreline in SW direction across shelf slope area. These prograding units belong to falling system tract (FSST) and seismic data do indicate fore stepping in the area of study (Figures 4.26-4.27). This cycle than culminated by sea level rise marking TR (transgressive) surface and this trsangessional episode reached to a maximum level as indicated by presence of maximum flooding surface (MFS Sardhai) in the GR logs of wells.

At the end of maximum flooding the highstand systems tract sediments prograde and aggrade along with a change from clastics to nonclastics facies. This change accumulated carbonate facies of three nonclastic units belongs to upper Permian stratigraphy (Amb, Wargal and Chiddru Formations). The top of this HST systems tract belonging to sequence-3 is marked by the eroded unconformity surface which develops during sea level fall and erosion of highstand system sediment. The Top Permian and Base Tertiary unconformities appeared commingle in the eastern part of study area and present at the top of sequence-3 and referred as top of sequence-3 boundary.

Table 5.2 Showing internal architecture of sequence-3

SEQUENCE-3 ARCHITECTURE - TOBRA-DANDOT-WARCHHA-SARDHAI FORMATIONS SOUTHREN POTWAR BASIN						
LITHOFACIES	GENETIC RELATION	BOUNDING SURFACES	LOG SIGNATURE	SHORE LINE TRAJACTORY	GEOMETRY	SYSTEM TRACT
PERMIAN NONCLASTICS			PROGRDATION/AGGRADATION	BASINWARD SHIFT (NW)	UP STEPPING	HST
BASE SARDHAI	TRANSGRESSIVE FACIES	MFS TR SURFACE	FINNING/RETROGRADATION	MAX LANDWARD SHIFT LANDWARD SHIFT (SE)	BACK STEPPING	TST
TOP WARCHHA BASE WARCHHA CLASTICS	REGRESSIVE FACIES	PROGRADES RS SURFACE	COARSENING/PROGRADATION	BASINWARD SHIFT (NW)	FORE STEPPING BASINWARD SHIFT	FSST
TOP DANDOT UPPER DANDOT CLASTICS BASE DANDOT CLASTICS	TRANSGRESSIVE FACIES	MFS	FINNING/RETROGRADATION	LANDWARD SHIFT(SE) MAX LANDWARD SHIFT LANDWARD SHIFT (SE)	BACK STEPPING	TST
TOBRA CLASTICS	TILLITE FACIES	TOP TOBRA BASE SQ BOUNDARY-3	COARSENING/PROGRADATION	BASINWARD SHIFT (NW)	FORE STEPPING	LST
BASED ON GR LOG CORRELATION (DHERMUND-1, BALKASSR-01, KAL-01, DAIWAL-01, RAJIAN-01, MISSA KASWAL-01, 03						

CHAPTER 6

IMPLICATION OF SEQUENCE STRATIGRPHY OF CAMBRIAN-PERMIAN LEVELS FOR PETROLEUM PLAY

6.1 Existing Petroleum System of the study area

The Potwar Basin is petroliferous region in upper Indus Basin and well known by many significant discoveries of oil and gas. At present this basin has produced 290 MMBO and 1.9 TCF of gas from 24 fields since 1915 (PPIS information 2019). The remaining estimated potential is about 1250 MMBO and 2.0 TCF of gas from known reservoirs in the basin. The major reservoirs belong from Eocene, Paleocene, Cretaceous, Jurassic, Triassic, Lower Permian and Cambrian levels. The source rock are from Paleocene and pre-Cambrian shales while shales from Cambrian, Permian, and other levels are contributing in trapping mechanism (Figure 6.1). The traps are mainly anticlines, fault bounded rollovers and uplifted fault blocks formed by thrusting. One of the major implication of present study is to add a valuable contribution in the petroleum system with respect to sequence stratigraphic frame work for Cambrian and Permian level.

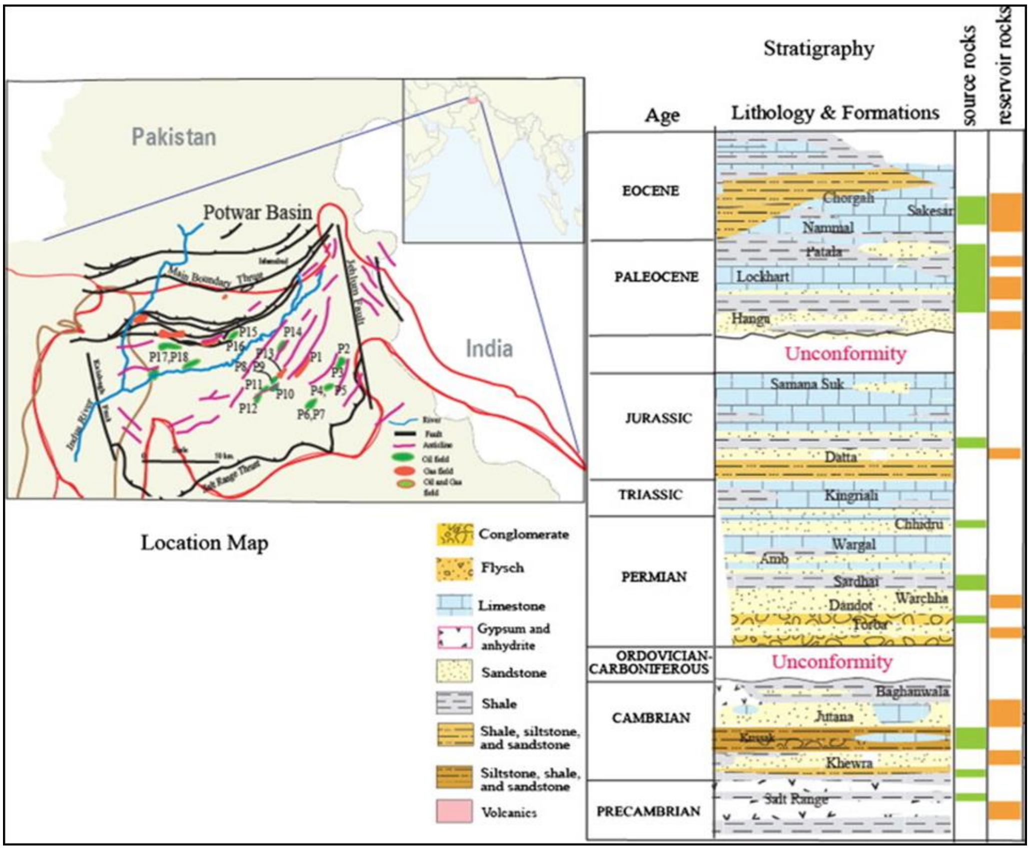


Figure 6.1 Figure showing Seal, Source and reservoir summary in Potwar Basin (modified after Asif et al, 2012).

6.2 Trap Nature

The study area is a part of southern Potwar Basin and thus belongs to foreland fold thrust belt verging south. The leading edge of foreland fold thrust belt is exposed Salt Range and adjacent ranges located south of the study area form a classical examples of salt-sediment interaction. The Salt intrusion due to halokinetic movement caused the shaping of trap geometries. The hydrocarbon accumulation that have been discovered in the basin are from the structure traps where anticlinal among the folded strata and the uplifted tilted blocks bounded by faults are salient features which has been drilled and tested successfully from the reservoirs.

In the study area of Potwar Basin a complete sequence of Eocambrian to Quaternary strata is preserved in outcrops and drilled in the fold belt which has been detached from the basement rocks. This entire sedimentary column can be divided into three units which are contributing as a stratigraphic and structural setting in the basin:

The unit of ductile layer of Eo-Cambrian evaporites that serve as a detachment and which is present above basement. This unit may have thickness more than 01 km and can be noticed from seismic data image showing core of anticline filled with salt (Figure 6.2). The unit of competent layer of Cambrian to Eocene platform sequence residing above salt layer and that is contributing source, reservoir and seal rock units (Figure 6.2). A unit of Miocene fluvial molasse lithologies residing about reservoir units serve as major seals (Figure 6.2).

The structural deformation in the Kohat-Potwar Plateau occurred in the Neogene due to ongoing Himalayan orogeny. It is believed that maturity of source rock to expel hydrocarbons happened contemporaneous to this phase of deformation. Later the migration of hydrocarbons could led to accumulate in suitable structural traps. This migration also charged Pre-Neogene structural traps at shallow levels in molasse strata in Potwar Basin.

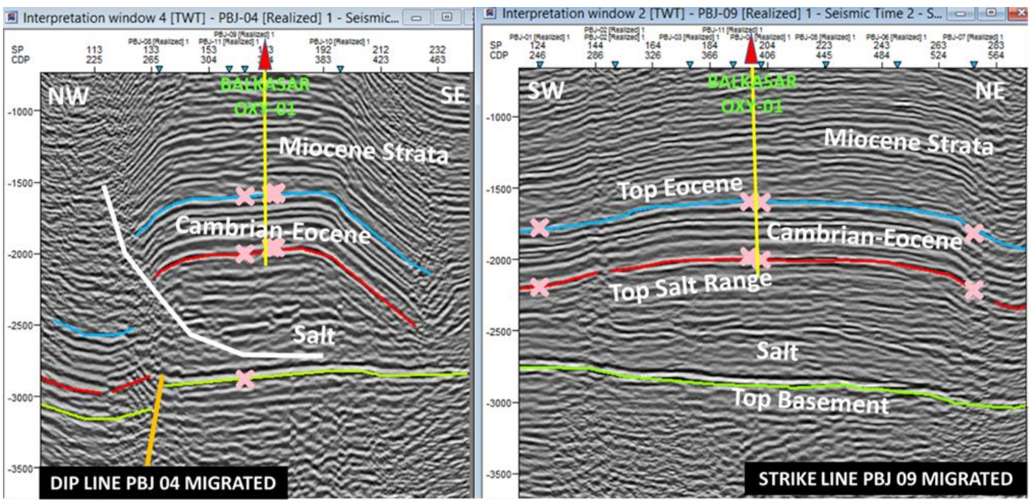


Figure 6.2 Major features of trap imaged from seismic line PBJ 04 and PBJ 09, Balkassar area.

6.3 Source Rock and Maturity

Potwar basin retained potential source rocks at multiple levels from Cambrian to Eocene age. These potential source rocks includes Pre-Cambrian Salt Range Formation, shales of Cambrian Khewra and Kussak Formations. The shales of Wargal and Sardhai levels from Permian age are also believed to retain source potential. However the major and well known contributor for hydrocarbons in Potwar is from the Paleocene Lockhart and Patala Formations (Wandrey et al. 2004; Moghal et al. 2007; Fazeelat 2010: Asif and Fazeelat 2012). The studies of Salt Range Formation in the upper and middle part show presence of up to 36% total organic content that has been developed. The TOC of Patala Formation of upper Paleocene age show an average of 1% TOC. Regional information on oil characterization (Ahmed and Alam 1990) suggest that all oils from producing fields in Potwar Basin are generally related and probably generated from same source rock. However the seep data from Kohat-Potwar basin yield different characterization and suggest generation from different source rocks. The seep provide evidence that there is more than one effective source rock in the area. In study area the eastern oil prone zone (Adhi, Missa Kaswal, and Qazian) the oil is being produced with three different characteristics based on API and GOR. The physical properties these three oils are not similar. The maturity of Tobra oil is high compared to Cambrian and Eocene levels. The Eocene oil is quite different than the Permian and Cambrian oils. The oils in this system could have been generated from different or same source rock at different levels of thermal maturity.

The results of petroleum geochemistry based on hetero-cyclic and polycyclic aromatic hydrocarbons of this basin lead to indicate to generation from three different types of source rocks (Asif and Fazeelat 2012). The study suggest the influence of biodegradation of organic matter (OM) derived from a highly oxic/deltaic environment to suboxic marine environment. However there is no any effects of biodegradation happened on the organic matter derived to marine oxic depositional environment.

In the study area presence of source rock can be seen in Shawal unit where dark gray papery shales contain rich in organic matter and have faint kerosene smell when broken. These shales are considered as potential source rock with TOC of 30% in eastern salt range (Figure 3.6 B). The wells of study area intercept fine grained lithological units having higher GR values and the correlation of this signature across the well data of study area suggest presence of shaly strata in the area of interest (Figures 3.9 and 3.10).

6.4 Reservoir Rocks

The reservoirs in the study area of southern Potwar are well known from Cambrian, Permian and Paleocene-Eocene levels which has contributed in the fairway. The present study focused to Cambrian - Permian levels. The extent and lateral distribution of these clastic reservoirs has been studied through well logs (GR and SP) in order to address the correlation of lithofacies.

6.4.1 Khewra sands

The log signatures and its correlation suggest presence of Khewra sands in the area of interest and may retain good quality associated to upper most cycle where GR log response show coarsening upward profiles (Figures 3.25 and 3.26). This sand level has been proven viable after flow of hydrocarbons present in the oil field of eastern and southern Potwar. Adhi, Missa Kaswal, Qazian, Rajian, Chak Nurang, Daiwal and Kal are among those well known producing fields which have contributed from the upper part of Khewra sands. In the western part of study area the upper sand progrades are not well developed and lithofacies drilled in Balkassar oxy-1 and Dhermund-1 are lacking of reservoir properties.

The four lithofacies of the Khewra sandstone in Salt Range (Khewra Gorge and adjacent parts) show progradational stacking pattern of parasequences and a coarsening upward sequences. The Gamma Ray log data of the wells in the study area also indicate presence of same lithofacies in southern and eastern Potwar basin. The cleaning upward trend from GR log from the wells used in the study corresponds to presence of coarsening and upward building of clastic facies. The major curve signatures captured in Khewra reservoir changed upward from aggradation to progradation stacking of parasequences and such stacking may related to a change from Eolian to shallow marine sedimentation. The GR value ranges from high A.P.I. in the lower part to low A.P.I. in the upper part of the curve.

Core and log studies conducted by oil companies (PPL, OGDCL, POL) and also by individual workers in field location of Salt Range (Saqib et, al. 2009) indicated a range of porosities from 5% to 15% in the sandy section of Khewra Formation. The sand grains are of quartz in origin and are angular to sub rounded, medium to well sorted at certain levels. The upper most facie of the Khewra sands is most homogeneous and well sorted and retain better reservoir properties thus has been successfully tested by the oil fields in eastern part of the study area. The permeability in the Khewra sands are controlled by combination of original facies and presence of quartz overgrowth and clay minerals diagenesis effects. There is a vertical trend in Khewra Formation for increasing in porosity and permeability from the lower part of sequence (laminated and ripple Sandstones) to top part (poorly and well bedded sandstones) as the clay content decreased and is clearly indicated by GR log curve of the well data used in the study. The well reports from Adhi and Missa Kaswal and Rajin indicated a range of permeability from 0,4 to 67MD.

6.4.2 Tobra Formation

The Tobra is among a another oil contributor as a reservoir is eastern Salt Range. The facies of Tobra are distributes in the Salt and Trans-Indus range with a thickness varies from 10 m (Khewra area of the eastern Salt Range) to 150 m (Sarin and Zaluch areas of the western Salt Range). The isopach map compiled based on well data in the study area show relevant thickness (Figure 3.61). The major facies of this formation are tillites which are restricted to the eastern Salt Range. The glacio-fluvial facies alternating siltstone and shale is preserved predominantly in the central Salt Range. The glacio-marine facies consisting of diamictite, sandstone and boulder beds of marine and estuarine origin is located predominantly in the western Salt Range. The lithological characteristics were observed in the field along Salt Range (Choa-Khewra road, Motorway M-2, Nilawahan and Khata Pail sections. Pink granite, gneiss and quartzite in a poorly sorted sandy and olive-green-colored silty and muddy matrix appear as a pebble to boulder-sized clasts in these locations (Figure 3.58, 3.59 and 3.60 A and B). The greenish-grey to dark-grey, brown and black-colored conglomerate and sandstone also appear on Tobra Formation.

In the study area the deposition of the facies of Tobra Formation have been restricted to glacio-fluvial cycle which at later stage might have been impacted by fluvial and marine interaction phase. In order to set a correlation between facies reported in outcrop of Salt Range with subcrop of southern Potwar Basin the log data of the wells provided for the study were evaluated. Both GR and SP logs show response of regressive and transgressive nature to image facies relationship. The signatures of GR curve log from western part of southern Potwar basin to eastern part is not consistent and do show variation Figure-3.62 & 3.63. The correlation may be the trickier but suggest presence of multiple stacked lithologies. In Missa Kaswal, Rajian and Balkasar area the GR curve indicate a coarsening upward profile. This profile near upper level of Tobra also show finning upward behavior which is more obvious in Balkasar Oxy-1 location. Such signatures do represents relationship with facies of glacial deposits formed in association of fluvial and shallow marine environments. In general most of the facies like tillite, diamicite and sands, siltstone represents stacking and inter-fingering along lateral and vertical distribution which commenced from lowstand and continued till early transgression times, hence represented by both coarsening and limited fining upward cycles seen in log data.

The coarsening upward, blocky and finning upward behavior of the GR curves in the study area can be associated with the regression and transgression of Tethys Sea across the shelf slope area of Potwar Basin prevailed during Cambrian-Permian time. The behavior of eustatic curve during entire lower and upper Permian sedimentation indicate rise in sea level after glaciation time which later entre to falling stage and then subsequent rise to a maximum flooding level. Under these conditions the entire or part (?) of Permian stratigraphy represents a sequence having a lower boundary at the base of Tobra Formation while the upper boundary may be placed after a complete cycle near top Warchha Sands. The Top surface is again marked by unconformable contact with Sardhai shales. Within this sequence maximum flooding surface may present near Top Dandot level.

The Tobra formation as a reservoir has been tested in Adhi, Missa Kaswal, Rajian, Qazian and Kal structure where it flowed hydrocarbons and where both the porosity and permeability parameters are well developed between a range of 8 to 9 percent and 2,5MD to 0.50MD. respectively. The Tobra reservoir inhabits a lateral inhomogeneity due to variation in depositional environment, supply and dumping of erosional sediments. In the central part of study are the Balkasar oxy-1 well tested viscos oil from sandy facies of Tobra reservoir with a matrix porosity of 8%. The log data show presence of mobile hydrocarbons in the area. The operator (OXY) plugged and abundant the wells without any further testing and recovery of hydrocarbons.

6.5 Seal Rock

The major seal rocks which favored trapping to reservoir as a top and lateral seal includes Kussak Shales sealing effectively Khewra reservoir sands in eastern part of study area and Dandot shaly units which are sealing Tobra reservoir facies. The shaly lithologies of Kussak and Dandot are effectively contributing as a top and lateral seals in trapping hydrocarbons.

6.5.1 Kussak Shales

The isopach map of Kussak Formation compiled using well data of study area show thickness ranging from 5 to about 100 meters (Figure. 3.35). In north of southern Potwar Basin this formation is absent may be due to erosional removal. The GR log data of the wells show finning upward profile conforming presence of shaly section at basal part which belongs from retrogrdational stacking pattern. The signature of GR log curves of the wells drilled from west to east (Dhermund-1, Daiwal-1, Rajian-1 and Missa Kaswal-1 and 3) indicate uniformity in shape and thus indicate a consistency in lateral distribution and deposition of shaly facies above Khewra reservoir sands (Figure 3.36 & 3.37). The correlation of log curve signature from Daiwal-1 to Missa Kaswal wells in east is good and marks consistency for lateral distribution of facies. However, the correlation of GR log curve signature with Balkassar oxy-1 and Dhermund-1is trickier and fair due to a change in thickness, marking absence of facies. The event suggested by high GR response in upper part of Diawal-1, Rajian-1 and Missa Kaswal well is regarded as flooding surface (FS-2 KSK) and the section above this surface is believe to be absent in Dhermund-1 well.

A fair to good correlation of GR curves of well data from coarsening upward in Khewra sands to finning upward in Kussak shales has been also demonstrated in the outcrop area where Khewra sandy units are present below shaly facies in the outcrop locations (Ara Bashrat, Choa-Khewra section, Khewra gorge, Motorway section, Nilawahan and Katha Pail sections) Figures 3.29-3.34.

6.5.2 Dandot Shales

The shaly units of Dandot Formation act a top and lateral seal in the discovered fields present in the study area which are producing from Tobra reservoirs (Adhi, Missa Kasewal, Rajian, and Kal). The isopach map compiled based on well data form in the study area shows thickness ranging from 5 m to 50m (Figure 3.68). The Formation is about 50 m thick at its type locality in the Dandot area of the eastern Salt Range (Fatmi 1973; Shah 1977). The maximum thickness of this formation is about 70 m in the Sarin and Sanwans areas in the western Salt Range.

The gradational, transitional nature of the change from the underlying Tobra to the overlying Dandot Formation implies a gradual but significant regional rise in relative sea-level and a region wide transgression of the Tethys Sea, probably in response to deglaciation across many parts of the Gondwanaland at this time (Ahmad 1970; Shah and Sastry 1973; Dickins 1977, 1985; Dasgupta 2006). This evaluation of the rise in Eustasy has been reflected by the preserved facies of Dandot Formation seen in outcrop along Salt Range while the same has been reflected by the well data of the study area. The GR log response show consistency in curve signature when correlated across the wells from east to west (Missa-Kaswal-1 & 2 to Dhermund-1). A fining upward profile in general can be defined for all the wells used in study for Dandot level that also marks presence of shaly facies acting as a seal unit in the area of study (Figure 3.69 & 3.70). These shaly units form building blocks of retrogradational and aggradational stacking system developed during transgressive stage across the shelf slop region in this part of Potwar Basin. The facies observed in the west of the study area for Dandot Formation also indicate increase in water depth relevant to geometry of shelf slope setting beside rise in sea level. The eastern Salt Range during this time retained fluctuating sea level even during overall rising stage thus allow preservation of channels among sandy and shaly units.

CHAPTER 7

CONCLUSIONS

- The Cambrian – Lower Permian stratigraphic section show sands, shale and silt stone units in the study area.
- The upper Permian represents non clastic units and are present in western part of study area.
- This Cambrian – Permian stratigraphy has been folded and thrusted and has been detached from basement by Salt Range Formation.
- The sequence stratigraphy evaluation of Cambrian-Permian level suggest presence of three sequences in the study area.
- Cambrian stratigraphy show presence of two sequences each bounded by surfaces of erosion at top and base.
- The sequence-1 culminate at top Khewra by type-1 sequence boundary.
- The sequence-2 extends to base Tobra unconformity.
- The sequence-3 covers Permian stratigraphic interval from Base Tobra to Top Chiddru Formations.
- The geological field data supported in integration of sequence framework along with well data and subsurface seismic.
- The low frequencies of seismic data were not supportive to pick clear internal geometry of a sequence.
- GR log curve helped to define stacking pattern of lithological units based on coarsening or finning upward cycles.
- The building blocks of each sequence represented progradational, retrogradational and aggradational patterns.
- The geometry of stacking units helps to delineate transgressive (TR) regressive (RG), maximum flooding (MFS) and unconformities.
- The stacking of progrades helps to identify transgressive (TST), Regressive (LST, FSST), High stand (HST) system tracts

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