RESERVOIR CHARACTERIZATION AND PROVENANCE STUDY OF THE EARLY CAMBRIAN KHEWRA SANDSTONE IN EASTERN AND CENTRAL SALT RANGE, PAKISTAN: AN INTEGRATED APPROACH BASED ON OUTCROP AND CORE DATA

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2021-2023

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ISLAMABAD

A thesis submitted to Quaid-I-Azam University Islamabad in partial fulfillment of requirement for the degree of Master of Philosophy in Geology

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ABSTRACT

The present study is aimed to evaluate the reservoir characterization and provenance analysis of the Early Cambrian Khewra Sandstone based on integrated approach of surface and subsurface (core cuttings) data from the Eastern and Central Salt Range, Upper Indus basin, Pakistan. The data set used during this research work is from two outcrop sections (Khewra Gorge & Nilawahan Nala) and two wells (Amirpur-01 & Daiwal-01). The methodology followed for the desired study is comprised of petrographic interpretations as well as core plugs tests. Petrographically the sandstone is classified into various compositional nature based on framework constituents (quartz, feldspar and lithics) among which the major portion from the outcrop samples are divided as sub-arkosic arenites with few samples into arkosic arenites, while the intervals from both the wells are classified to be sub-arkosic arenites entirely. The provenance origin for the Khewra Sandstone interpreted by petrographic observations is craton interior with few outcrop samples from transitional continental region. The estimated visual porosity from Khewra Gorge Section is in range 1 to 18.5 % with the average value of (8.02 %), from Nilawahan Nala Section the range is 0.5 to 17.2% with the average value of 6.51% and the reservoir properties (porosity and permeability) calculated by core plugs method for the Amirpur- 01 well is in range 10.27 to 13.37% (average 12.44%) and 0.58 to 217.57 mili Darcy (average 85.4 mD) while from Daiwal-01 well is 14.64 to 18.14 % (average 16.41 %) and 15.50 to 58.33 mili Darcy (average 42.59 mD). The increasing trend observed for porosity across the sections from lower beds to upper portion indicates the coarsening upward sequence, comparatively good sorting pattern of grains, decrease in matrix contents and also the negligence of overburden pressure. From these detail analysis this formation can be encountered as good reservoir for petroleum exploration especially the upper horizons at outcrop exposure while at the subsurface, the Daiwal-01 well due to its high porosity values (16.41 %) can be focused for future discoveries. The findings of this study can be used as reference material academically as well as helpful in developmental phase of these wells in future.

ACKNOWLEDGMENT

First of all I am very much thankful to Almighty Allah for His special blessings during this journey and for enabling me to accomplish my research work in a better way and letting me through all the tough time. I would like to express my feelings of gratitude to my supervisor **Dr. Mutloob Hussain (**Associate Professor), Department of Earth Sciences, Quaid-I-Azam University Islamabad, for his dynamic supervision and guidance during my research work that was full of sincere assistance.

I am also grateful to Dr. Amir Ali (Head of Department) and to all the teaching staff who have given me the motivation, help and facilitation during my study session.

I would also like to give special thanks to the professionals and supporting staff of all those laboratories which I have used for my analysis, especially to Syed Waqas Haider and Ihtisham Ul Haq (MS scholars) at HDIP, Islamabad for their co-operation and to Mr. Amir Jadoon (Sr. Petroleum Explorationist) Ministry of Energy (Petroleum Division) for his support and encouragement.

I am highly thankful to my beloved parents and family who encouraged, supported and motivated me at each step of my life.

At the last, I am expressing my special thanks to study colleagues (Tausif Javed, Arshad Jan, Zia Ul Islam and Rehan Ullah) and to all those with whom I spent time and learnt during all my academic career and also to Higher Education Commission (HEC), Pakistan for providing research fund through RGMS program.

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CHAPTER – 01

INTRODUCTION

1.1 Introduction

Petroleum is the most important energy source which is a trending market product in order to carry out routine works. The main components of any petroleum system are source rock, reservoir body and trap/seal which is the most important portion of the entire system. For the speedy and effective production Scientists develop technologies and new methods worldwide routinely for the exploration and evaluation of the hydrocarbon reservoirs. Most of the time Petrophysical approaches are more reliable initially to know about any reservoir but now a day more advanced techniques are used to avoid any inconveniences. A "reservoir" is any sub-surface sedimentary rock that has sufficient porosity and permeability and can hold exploitable/producible quantity of oil or gas. A reservoir rock can either be a carbonate or clastic in nature depending upon its origin and environment of deposition. Clastic reservoir can be defined as "A siliciclastic sedimentary body of rock having sufficient porosity and permeability to store and transmit fluids". Khewra Sandstone of Early Cambrian age is also one of the clastic sedimentary rock bodies in the stratigraphy of Pakistan. The nomenclature "Khewra Group" was assigned by Noetling (1894) initially, while the Stratigraphic Committee of Pakistan (1973) finalized the name Khewra Sandstone for this formation and type locality assigned is Khewra Gorge (32° 40′ 00″ N, 73° 00′ 00″ E) near Khewra town, Jhelum Punjab. The dominant lithology comprised of purple to brownish massive sandstone in the upper portion while reddish flaggy shales interbedded with sandstone in the lower part at type section. The maximum thickness reported for this formation at type section is about 150m (Shah, 2009). In the stratigraphy of Pakistan, Khewra Sandstone is the first oldest clastic reservoir body which is the important target zone of Exploratory companies for hydrocarbon reserves. In order to investigate further about this formation in detail I also tried to work and find some facts which could be a helpful material in future mostly for academic purposes. This research work is based on both the surface and subsurface data approach for which two outcrop sections each from Eastern and Central Salt Range is marked and also two wells (Amirpur 01 & Daiwal 01) from Potwar Basin are selected to study their available intervals (core cuttings) for Khewra Sandstone and collect the desired data.

1.2 Previous work

From the literature review, it is investigated that multidimensional research work is available on Khewra Sandstone mostly on outcrop scale that focuses on, Facies and Depositional environment (Shahzad, 2014), Clay minerals analysis of Khewra Sandstone (Baqri and Rajpar, 1991), Quantitative estimation of abrasion loss of Khewra Sandstone (Arslan et al, 2014), Reservoir characterizations based on petrographic approach and also some researchers have done a good work on its Provenance, Paleogeography and Lithofacies investigations mostly at its type section. While in the subsurface the same formation is encountered and studied by Petrophysical methods (Ghazi et al, 2016).

1.3 Objectives of the research

As from the previous work it is concluded that, there is no such integrated published work (both surface and subsurface) available on Khewra Sandstone so that it can be studied easily by comparing the acquired results and know all about this in detail which is the most important aspect to evaluate this formation as a reservoir body. That is why the aim of this research work was to accomplish the combine comparative surface and subsurface investigations of reservoir properties of Khewra Sandstone and for that the current idea was designed and work was initiated.

This research wok is aimed at evaluating the "Reservoir characterization and Provenance study of the Early Cambrian Khewra Sandstone" based on the available data which could be achieved through the Integration and comparative results from surface and subsurface possible approach and the objectives will be specified as,

- ➢ Detailed Petrographic analysis of surface and subsurface samples for,
- Sandstone classification
- Provenance analysis
- Reservoir characterization (Porosity and Permeability estimation)

1.4 Location of the study area

The data obtained for this research work is both from surface (outcrop sections) as well as from subsurface (well data). So in order to locate the study area i have mentioned both of them as per their exact locations while mentioning their coordinates also.

1.4.1 Outcrop sections: The surface data is collected from the two outcrop sections which are located in the Eastern and Central Salt Range, Upper Indus Basin, Pakistan and shown in the study area map (Figure 1.1b).

a) ***Khewra Gorge Section*** (32° 40′ 00″ N, 73° 00′ 00″ E) located near Khewra Town Jhelum, Eastern Salt Range, Pakistan.

b) ***Nilawahan Nala Section*** (32° 36′ 13″ N, 72° 37′ 15″ E) located near Nurpur Village, Khushab Road Chakwal, Central Salt Range, Pakistan.

1.4.2 Wells locations: Also the subsurface data from these wells i.e, Amirpur 01 and Daiwal 01 are used in this research work so the respective wells locations are shown (Figure 1.2) with their exact coordinates.

a) ***Amirpur 01:*** it is located at the south eastern part of the Potwar basin in Chakwal District Punjab. The coordinated location is (32° 57′ 34.37″ N, 73° 00′ 46.51″ E).

b) ***Daiwal 01:*** This well is also located in Chakwal District Punjab and the coordinates are **(**33° 01′ 11.82″ N, 73° 11′ 08.19″ E).

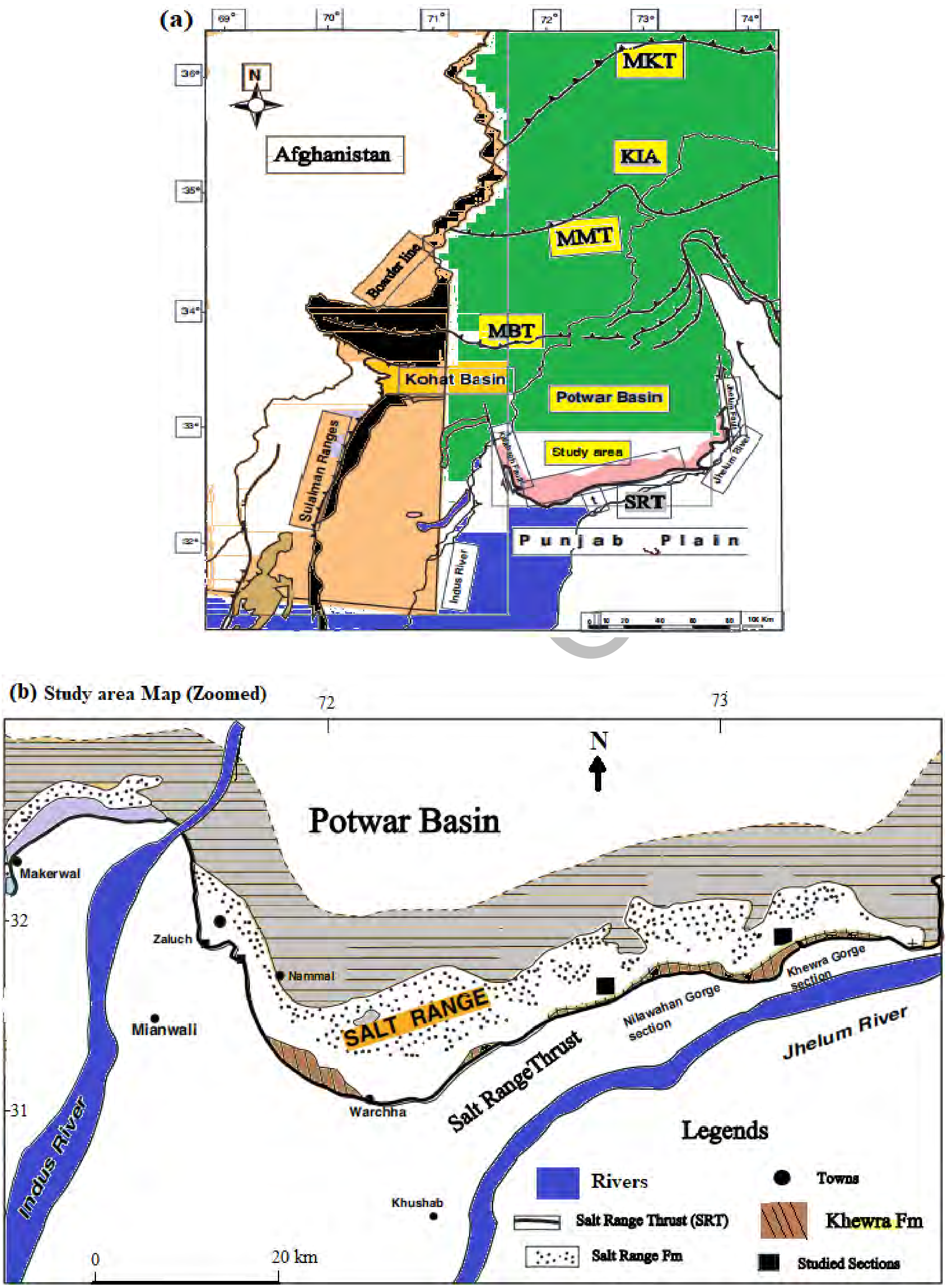


Figure 1.1: Location map of the study area (Salt Range). **(a)** Generalize tectonic map of Pakistan showing the study area zone also **(b)** zoomed map of the study area showing the outcrop sections of Khewra Sandstone, modified after (Ghazi et al, 2012).

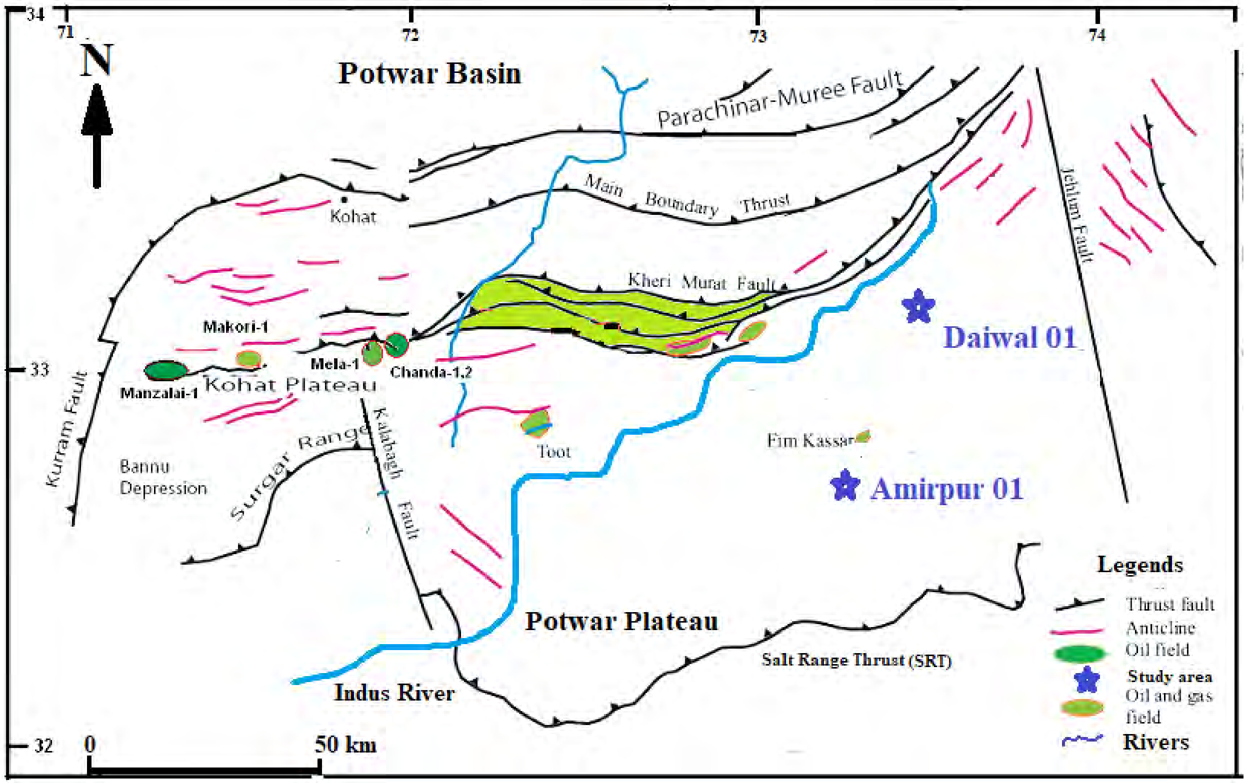


Figure 1.2: Location and accessibility map of the study area (Amirpur 01 & Daiwal 01) wells, modified after (Khan et al 2012)

1.5 Methodology for research work

The following research work was started with the initial steps of data collection and was put forward stepwise till finalization.

1.5.1 Data Collection

Both the surface and subsurface preliminary data was acquired by the following methods.

1.5.2 Field work

For the surface data, initially a reconnaissance field work was done to mark the targeted sections and know much about the area (Accessibility routes, weather conditions and desired research data package) so that during the final data collection errors and blunders are minimized possibly. Finally a detailed field work was conducted to these two outcrop sections and they were measured in detail for the required data which was obtained by using the conventional Geological field methods. The measured sections were "Khewra Gorge Section" (32° 40′ 00″ N, 73° 00′ 00″ E) Eastern Salt Range and "Nilawahan Nala Section" (32° 36′ 13″ N, 72° 37′ 15″ E) Central Salt Range. In these outcrop sections initially the strata was visually observed and the targeted formation was marked for the field features and samples collection.

1.5.3 Mode of Sampling

For the accurate data collection, the mode of sampling followed was such that total of 22 outcrop samples were collected from these two sections on the basis of features variations (texture, color and sedimentary structures) as well as at random interval from sandstone beds across stratigraphic column (vertically) from bottom beds to top most part. All the sampling was done with the help of geological hammer and field photographs were captured from the sampled locations along with the GPS points of the same location (outcrop) to display the data in the possible scientific manner.

1.5.4 Field Instruments

A GPS device was used for the exact coordinates of the samples location and a high resolution camera (DSLR) was used for the field photographs and a notebook for drawing sketches/ lithologs. Geological hammer for sampling and also sophisticated sample bags marked with the specific IDs for the collected samples.

1.5.5 Subsurface Data (Wells data)

For the collection of well data, initially the application approval was given by the Directorate General of Petroleum Concessions (DGPC) and then forwarded to the Hydrocarbon Development Institute of Pakistan (HDIP) for the final approval and recommendation of those wells which were in public domain.

1.5.6 Procedure for data collection

In order to collect the data from these core cuttings, some instruments like measuring tape, hand lens, camera, log sheets and notebook were used. The available core intervals of Khewra Sandstone were studied from top to bottom (left to right in boxes) and the required data was logged in the available sheets and also photographs were captured in order to display that data in future for the better observations.

1.6 Laboratory Analyses

After the samples collection from outcrop sections and core cuttings, they were subjected for laboratory analyses to acquire the useful results. The laboratories used were,

(1) Departmental Rock cutting lab (Quaid-I-Azam University), Islamabad

(2) Departmental Petrographic lab (for Microscopy)

These two laboratories were used for thin sections (slides) preparation and also for Petrographic analysis (microscopy).

(3) Pet core lab (Hydrocarbon Development Institute of Pakistan), Islamabad

(4) Reservoir lab (HDIP)

At the Pet core lab, the core cuttings of Khewra Sandstone from the available intervals of Amirpur 01 and Daiwal 01 wells were studied respectively and the visual data and pictures of the features observed were noted down while the Reservoir lab was used for the Plugs porosity and permeability tests and the following instruments were used for the porosity and permeability determination.

a) Helium Porosimeter: This device is used for the estimation of porosity of core samples taken from hydrocarbon reservoirs. The working principle is based on Boyle's Law and is designed to measure the effective porosity of a sample with different length and diameter but mostly the range of diameter is from 1 to 1.5 inch.

The overall method is designed with some important machine parts which includes,

Helium diaphragm valves, pressure transducers, three reference volumes and micro cups for measuring cuttings. The device is also composed of two cells one is sample cell while the other is expansion cell and the three valves are designed for controlling the gas (He) flow through the system. The working domains for these valves are,

- V1 is used to connect the sample cell to the helium containing tank
- V2 is used to expel the gas outside from the system
- V3 is used to control the flow behavior between the expansion cell and samples cell

The Boyle's law equation applied during this analysis states that under the conditions of constant temperature and fixed quantity of gas, the product of pressure and volume remains constant as,

$$P_1V_1 = P_2V_2$$

b) Air Permeameter: This particular device is used to measure the core plugs permeability in the lab. The working principle is based on Darcy's law which states that "flow of any fluid across a rock with constant viscosity is only a function of its pressure difference while the rock property (permeability) remains constant with time".

Mathematical equation is given as, $Q = -KA\, dh/d$

Gas is injected into the rock samples and a computer connected control system is used to monitor the pressure continuously.

CHAPTER- 02
REGIONAL TECTONICS AND STRATIGRAPHY

2.1 Introduction

The planet Earth in the solar system after formation from the nebular matter contracted for a period of time. There was a single continues landmass and a super continent on the Earth known as Pangea (Wegner, 1924) that remained intact up to 100 Ma. The Pangea was surrounded by a single body of water known as the Panthalassa Ocean. The Paleozoic rifting took place in the Pangea and divided it into two super continents the Laurasia to the north and Gondawana Land to the south. These both super continents were separated by an arm of the Panthalassa Ocean known as the Tethyas Ocean (Young et al, 2019). Laurasia continent is comprised of most of the Europe and Asia, and the Gondawana land got split into the South America, Antarctica, India, Australia, and Africa. The Indian plate (Indo-Pak) plate is the part of Gondawana landmass that separated as island continent started drifting toward north about 130 million years ago (Chatterjee et al, 2013). According to the Chaterjee, the estimated rate of drifting/movement of this plate between 130 Ma and 80 Ma was about 3 to 5 cm/year. This fast northward movement was facilitated by sea floor spreading along the Mid Indian Ocean Ridge. During its journey towards north it has divided the Tethyas ocean into paleo-tethyas ocean lying in between the Laurasian and Indian plate and the neo-tethyan ocean lying in between the Indian plate and the remaining part of the Gondawanian landmass. This drifting of Indian plate was accompanied by the creation of a number of island arcs in the Tethyas Ocean in between Indian plate and Laurasian plate such as Karakoram block and Kohistan island arc (Du Toit, 1937). The first island arc was the Karakoram Plate that collided with Laurasian Plate forming a boundary the Main Karakoram thrust (MKT) in cretaceous age. The Karakoram Block collided with the Indian plate or the Kohistan Island Arc in Eocene time at a boundary known as the Main Mantle Thrust (MMT). A number of tectonic features were formed during the complete collision of Indian and Eurasian plate in the north such as the MBT, MCT, MFT, SRT from North to South respectively and Himalayan Orogenic Belt. After collision in the North, since about 50 Ma Indian plate has steadily rotated counter clockwise which caused convergence in Baluchistan, complete closure of small basins like Seistan and Katawaz, crustal blocks collisions in Iran-Afghan regions and finally the formation of Baluchistan fold and thrust belts (Kazmi & Jan 1997).

2.2 Regional Tectonic Setting of Pakistan

Tectonics plays an important role in the configuration of basins. The geological setting of Pakistan in the sense of modern concept of plate tectonics is quite unique in the world. Which are described as;

Two types of plate boundaries are present in geology of Pakistan;

1) Convergent plate boundaries: It is characterized by intracontinental collision; obduction and thrusting such as in Himalayan region and by oceanic crust subduction with a volcanic arc in Chagai in Makran margin.

2) Transform boundary: it is characterized by strike-slip fault and obduction such as Chaman transform zone. The Chaman transform zone connects the Makran convergent zone, where the oceanic lithosphere is being subducted beneath the Lut and Afghan microplates and the Himalayan convergent zone where the Indian lithosphere is under thrusting Eurasia. The geological setting of Pakistan shows Atlantic type (spreading) plate boundaries are present since early Mesozoic until the late Cretaceous and the Andean type (subduction, obduction, collision) boundaries are present with the transform zone since (early Eocene to Oligocene) connecting the Makran and Himalayan zones (Shah, 2009).

A large number of models showing the evolution of the tectonic framework of Pakistan with large details have been published in the literature. A gist of the sedimentary basins of Pakistan is presented here. It consists of

A) Indus Basin*:* it is the largest and most studied basin of Pakistan. The trending direction is NE-SW over 1600 km long and width of the basin is almost within the range of 300 km. Sedimentary sequences ranges from Precambrian to tertiary age are present with some age missing i.e, Ordovician, Silurian, Devonian and Carboniferous (Shah, 2009). This basin is also characterized by syntaxes, irregular ridges and also promontories of the Indian Shield. The Indus basin can be divided into two parts based on their stratigraphic and structural conditions which are,

a) Upper Indus Basin: This Basin lies at the foot hills of lesser Himalaya which is bounded by Main Boundary Thrust (MBT) in the north while the Kurram Fault in the west, Sargodha Highs In south and Jhelum River in the East. Upper Indus Basin is subdivided into two sub basins. This part of the Indus Basin covers almost 50,000 km^2 area and stratigraphically it is divided into

(1) Kohat sub-Basin, (2) Potwar sub-Basin

The study area lies in Potwar sub-Basin which will be discussed in detail for the best tectonic and stratigraphic approach.

b) Lower Indus Basin: This part of the entire basin covers an area of almost 250,000 km^2 area having the excellent potential of hydrocarbon bearing strata from Jurassic to Tertiary sedimentary sections. The maximum part of this basin is covered by marine sequences (Shah, 2009). It can also be stratigraphically divided into Sulaiman-Kirthar Province.

Potwar Sub-Basin: The collision of Indian plate and Eurasian plate is producing a variety of active fold- and-thrust Belts in Pakistan. These zones extend from Kashmir fold-and-thrust belt southwestward to Salt Rang-Potwar fold-and-thrust belt, the Sulaiman fold belt and Makran accritionary wedge. The Salt Range-Potwar fold-and-thrust belt of north is an active fold belt (Lillie et al, 1987). Potwar platue is located in the South-West at the foot hills of Himalaya. Tectonically Potwar basin in north is bounded by Main Boundary Thrust (MBT), in east bounded by Jhelum strike-slip fault, in south bounded by Salt range thrust (SRT) and in west bounded by Kalabagh fault. Regional Soan syncline extends from north- east to south-west of the Potwar basin

Tectonic of Potwar basin is controlled by the following factors;

(1) Slop of the basement (Steeper in Western Potwar)

(2) Thick Eo-Cambrian evaporites beneath sedimentary cover

(3) Basement fragile tectonic (More in Eastern Potwar)

Potwar Sub-Basin is composed of the Northern Potwar deformed zone (NPDZ), Central Soan Depression and Southern Salt range belt (Jadoon et al, 2015). The northern part of the Potwar basin lies between the MBT and the Soan Syncline has been named as the Northern Potwar

Deformed Zone (NPDZ) and southern Potwar is less deformed as compared to Northern Potwar Deformed Zone (NPDZ) which is severely deformed. As the Potwar plateau moves nearer the collision zone, tight fold nappes develop which has been thrusted over the North Potwar Deformed Zone (Moghal et al, 2003).

2.3 General Stratigraphy of the Potwar Basin

The Potwar basin is characterized by sedimentary sequence ranging from Precambrian to Recent having evaporites (Salt Range Formation) and shallow marine to terrestrial Cambrian sequence of carbonates, shales and sandstone (Jhelum Group) (Kazmi & Jan, 1997). The thickness of strata varies according to the locations. The general exposed stratigraphy of the concerned basin can be divided into Paleozoic, Mesozoic and Cenozoic sequences which are shown in (Figure 2.1) and are discussed as.

2.3.1 Precambrian succession

It is the oldest succession reported in the Geology of Pakistan with continues exposure from east (Kussak) to west in (Kalabagh) area all along the Salt Ranges (Shah, 2009). The thickness of the formation at type section is almost 830 m.

2.3.2 Cambrian Succession

The following formations can be categorized in to this succession on the basis of prominent features, among which the oldest one is Khewra Formation and is mostly composed of purple to brownish massive sandstone in the upper portion while reddish flaggy shales interbedded with sandstone in the lower part at type section. The overlying formation here is Kussak Formation which has dominant lithology of greenish to grey glauconitic sandstone, siltstone interbedded with dolomites and age assigned is middle Cambrian (Teichert, 1964). After this the Jutana Formation is exposed with the dominant composition of light green massive sandy dolomite while in the upper horizon consist of light green to dirty massive dolomite. And the last formation of this age is Baghanwala Formation that is comprised of red shale and clay with some beds of flaggy sandstone.

2.3.3 Permian Succession

In this succession the oldest formation is Tobra Formation which is mostly composed of Tillites that grades in to marine sandstone, also siltstone and shale are dominant in this formation. Age is early Permian (Shah, 1977). This formation is followed by Dandot Formation which has a dominant lithology of gray to olive green sandstone with thin pebble beds and splintery shales. While the overlaying Warcha Sandstone is composed of medium to coarse grained cross-bedded sandstone, conglomerates interbedded with shales and are followed by Sardhai Formation dominantly containing bluish to greenish clay with some sandstone and siltstone beds. While the upper Permian age is comprised of Amb Formation followed by Wargal Limestone and Chidru Formation in the concerned area.

2.3.4 Triassic Successions

This succession is comprised of 3 Formations in this area among which the oldest is Mianwali Formation which is composed of marl, limestone, sandstone, dolomite and siltstone. The overlying formation is Tredian which is dominantly composed of micaceous sandstone and shale with some dolomite beds in the upper part. The youngest formation of this age is Kingriali Formation which is comprised of thick massive dolomite and dolomitic limestone with interbedded shale and marls in the upper part.

2.3.5 Jurassic Succession

The Jurassic strata is comprised of Datta Formation which is entirely composed of sandstone, shales, mud stones with minor amount of calcarious, dolomitic, carbonaceous glass sand & fireclay horizons. The overlaying strata is named as Shinawri Formation composition of this formation according to Fatmi (1977) is well bedded grey to brownish limestone with nodules containing marl, calcareous dark shale and reddish brown quartzose sandstone. While the upper most one is the Samanasuk Formation that is composed of limestone with minor amount of marl as well as shale beds.

2.3.6 Cretaceous stratigraphy

In this succession the oldest formation is Chichali Formation containing sandstone and siltstone with some minor amount of fossils. The overlying formation is Lumshiwal Formation with the dominant composition of glauconitic sandstone and shale followed by the last Kawagarh Formation of this age having dark marl, thick bedded sandstone, calcareous shale and nodular limestone.

2.3.7 Paleocene stratigraphy

Paleocene strata are composed of Hangu Formation with the dominant lithology of sandstone, shale and minor amount of argillaceous limestone with major fossils including Forams, gastropods, bivalves and corals (Davis, 1971). The upper contact of this formation is with Lockhart Limestone with dominant lithology of limestone which varies in color from grey to bluish. Minor amount of shale and marls are also present. The upper most stratum is Patala Formation which consists of shale and marl with subordinate limestone and sand stone thin beds at type locality.

2.3.8 Eocene stratigraphy

The Eocene stratigraphy in Pakistan is mostly the target of petroleum industry for their discoveries and is comprised of carbonate succession having the Nammal Formation with dominant composition of bluish limestone with greenish shales (Cheema et al, 1977). The second formation is Sakesar Limestone which is composed of composed of cream to light grey nodular limestone and marl beds and is followed by Chorgali Formation in which the lower part consists of shale and limestone while the upper is composed of entirely limestone.

2.3.8 Miocene Stratigraphy

In this succession the older formation is named as Murree Formation composed of dark red to purple clay purple greenish sandstone with subordinate conglomerate (Shah, 2009) and is followed by Kamlial Formation with the lithology of grey to dark red sandstone with inter-beds of purple shale and conglomerate. It is distinguished from Murree Formation by its spheroidal weathering and heavy mineral contents. A number of mammals' fossils have been recorded from this formation including Trilophodon, angustidens, Dinotherium indicum, Anthracotherium sp. Pentapotamiae cf.

2.3.10 Pliocene Stratigraphy

This stratum is composed of Chinji Formation which is comprised of red clay with subordinate grey sandstone which is fine to medium grain and occasionally gritty. Conglomerate and quartzite are also found in places (Pilbeam et al, 1977). The upper contact is with Nagri Formation containing sandstone with subordinate clay and conglomerate with rich assemblages of vertebrate remains recorded by (Pilgrim, 1913). It is followed by Dhok Pathan Formation and the last one is Soan Formation with composition of massive conglomerate with subordinate inter-beds of sandstone, siltstone or clay beds.

2.4 Stratigraphy of the study area

As this research study area lies in the Potwar Basin so the general stratigraphy of this basin is explained in the upper portion while this specific part will indicate the detail stratigraphic approach of the selected study area.

In both the outcrop section within the Eastern and Central Salt Range, both the lower contact of Khewra Sandstone and also its upper contact were observed so the following formations and its detail from literature are discussed as.

2.4.1 Salt Range Formation (Pre-Cambrian age)

The name Salt Range Formation was given by Asrarullah (1967) after the idea from Salt Range area. The type section assigned to this formation is Khewra Gorge (Eastern Salt Ranges) Jhelum, Punjab. After the detailed study of this formation, Asrarullah has divided it into three members based on dominant lithology which are,

1) Sahiwal Marl Member: it is composed of bright red marl beds with some irregular gypsum beds and Khewra Trap and also dull red marl beds with salt seams having 10 m thick bed of gypsum at the top.

2) Bhandar Kas Gypsum Member: It has massive gypsum alternating with minor beds of dolomite and clays.

3) Billianwala Salt Member: it is mostly composed of iron containing marls with thick seams of salt.

The following formations can be categorized in to this succession on the basis of prominent features,

2.4.2 Cambrian Succession

The following formations can be categorized in to this succession on the basis of prominent features and their respective ages which are,

2.4.3 Khewra Sandstone

The stratigraphic committee of Pakistan (1973) has formalized the name Khewra Sandstone to this formation. The type locality assigned is Khewra Gorge (32° 40′ 00″ N, 73° 00′ 00″ E) near Khewra town, Jhelum Punjab. The dominant lithology comprised of purple to brownish massive sandstone in the upper portion while reddish flaggy shales interbedded with sandstone in the lower part at type section. Thickness of the formation at type locality is about 150m (Shah, 2009). Sedimentary features like, ripple marks, mud cracks and cross laminations are reported from the formation. The age of Khewra Sandstone is Early Cambrian according to Shah (2009). The interpreted depositional environment of the formation is deltaic according to Baqri and Baloch (1991). The lower contact of Khewra sandstone is unconformable with Salt Range Formation while the upper contact is with Kussak Formation at Type section.

2.4.4 Kussak Formation

The name of this formation is formalized by Stratigraphic Committee of Pakistan (Fatmi, 1973). While the type locality assigned is nearby Kussak Fort in the eastern part of Salt Range. Dominantly the formation is composed of greenish to grey glauconitic sandstone, siltstone interbedded with dolomites. At the top some lenses of gypsum are also reported. Thickness of the formation at type locality is reported as 70 m having variation at other places. Kussak Formation is considered to be the fossiliferous strata having the following fauna, Neobolus warthi, Hyolithes wynnei etc. The age assigned to the formation is Early Cambrian (Shah, 2009). The lower contact of this formation is with Khewra Sandstone while upper is with Jutana Formation at Type section.

2.4.5 Jutana Formation

Initially Fleming (1853) has given the name "Magnesian sandstone" to this formation but finally Stratigraphic Committee of Pakistan has approved the name Jutana Formation. Type locality of the formation is near to Jutana village in the eastern Salt Range. The composition of formation at type section is light green massive sandy dolomite while in the upper horizon consist of light green to dirty massive dolomite.

2.4.6 Baghanwala Formation

The name Baghanwala Group was initially given by Noetling (1894), while Holland (1926) has modified the name as "Salt Pseudomorph beds". The composition of this formation is red shale and clay with some beds of flaggy sandstone. Also some sedimentary structures like ripple marks and mud cracks are reported. The diagnostic features of this formation include pseudomorphic casts of salt crystals.

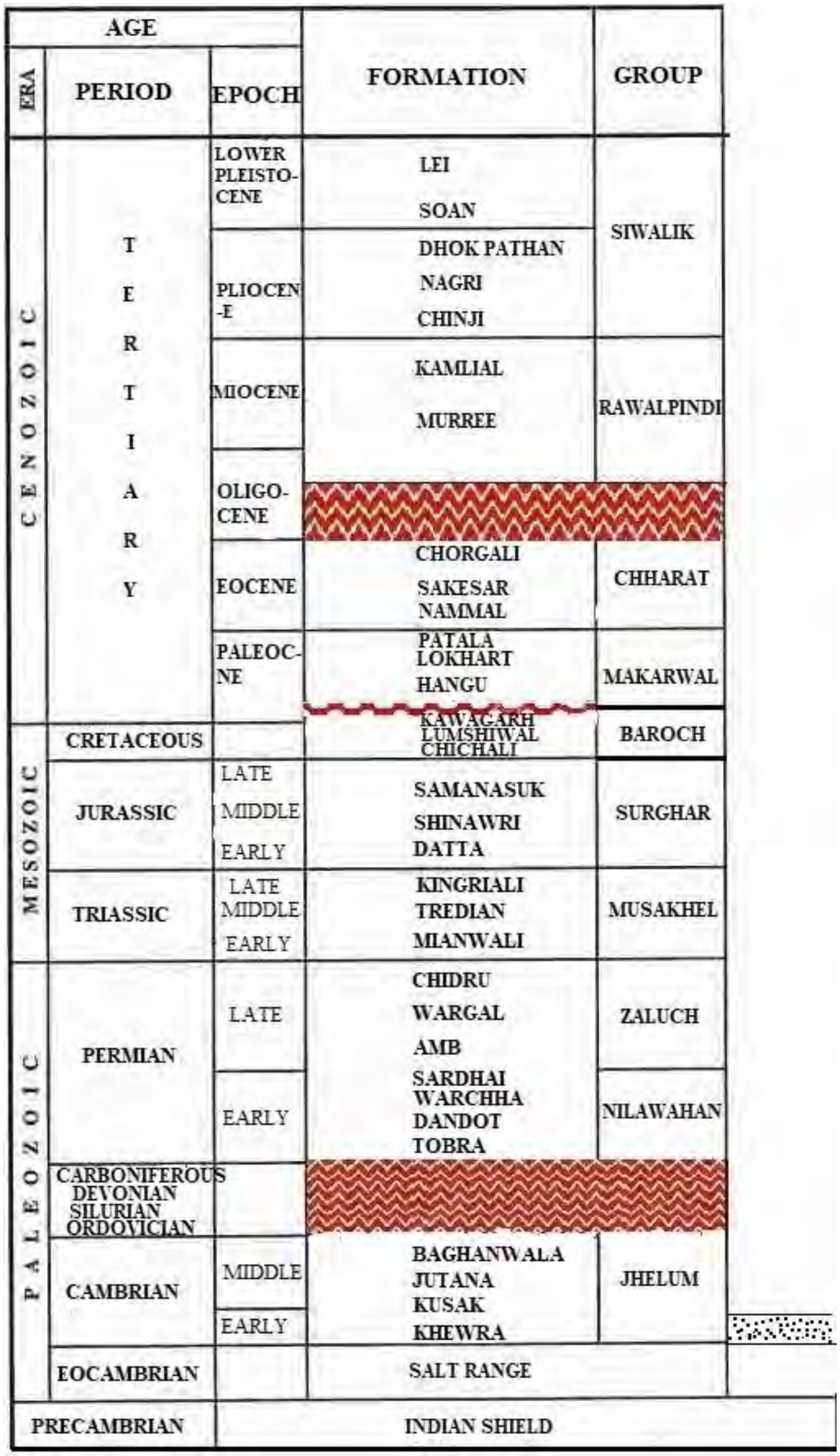


Figure 2.1: Generalize Stratigraphic column of Salt Range modified after (Fatmi et al, 1977).

C HAPTER - 03

OUTCROP OBSERVATIONS

3.1 Introduction

For the complete data set collection all along the field work, the prominent features were observed in Early Cambrian Khewra Sandstone and were noted down for the systematic logging of data in each section.

3.2 Khewra Gorge section, Eastern Salt Range

In this section the Early Cambrian Khewra Sandstone has a lower conformable contact with Precambrian Salt Range Formation and upper disconformable contact with Kussak Formation marked by a thin conglomerate bed shown in (Figure 3.2). The entire thickness of this formation reported in literature is about 150 m (Shah, 1980) shown (Figure 3.1). So the samples and the required data were collected on that behalf to avoid any inconveniences.

3.2.1 Features observed

In the current section the lithological behavior was such that at the bottom there were red color, thin bedded, fine to medium grained sandstone with some light reddish mudstone beds while at middle portion there were somewhat medium grained massive sandstone beds with clay intercalations and shales were exposed. The differentiated feature among clays and shale was its fissility property for shale and also the color variation among both (shale is red to purple and clay is light greenish). The uppermost portion of the strata is entirely purple to reddish brown, massive bedded sandstone with the texture variation from medium to coarse grained all along while some prominent sedimentary structures like ripple marks, cross laminations, ball and pillow structures and thin planar laminations were observed at the bottom and middle part shown in Figure 3.2.

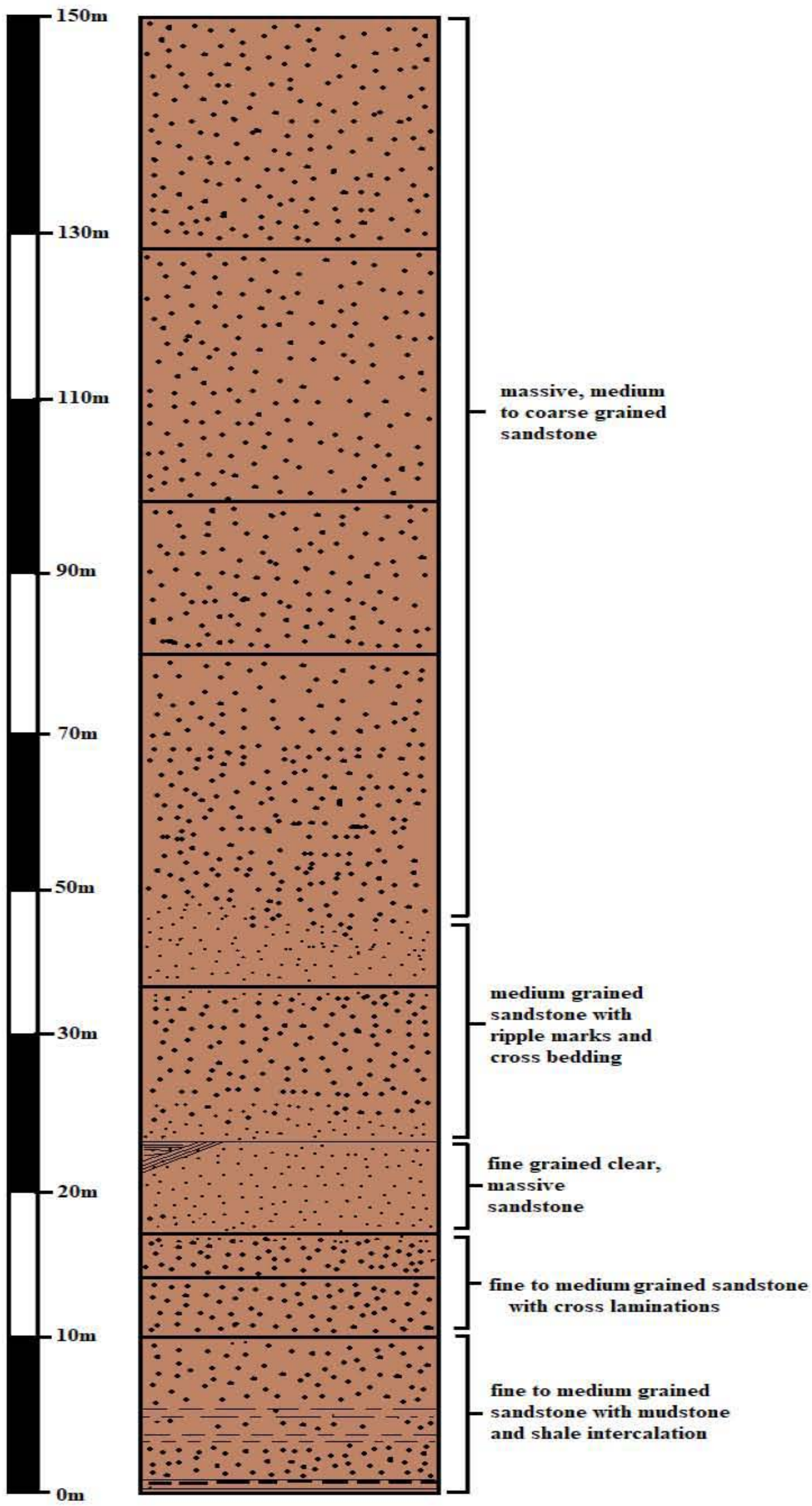


Figure 3.1: Litholog of the Khewra Sandstone based on observed features from Khewra Gorge Section, Eastern Salt Range.

Figure 3.2: Field photographs showing prominent features like, **A)** lower contact of Khewra Sandstone with Salt Range Formation. **B)** upper contact with Kussak Formation **(C)** alternate shales and sandstone beds **(D)** Thin low angle cross laminations **(E)** low angle climbing ripples in the lower portion **(F)** thin laminated beds in fine to medium grained sandstone **(G)** Thin dark and light color planar laminations in sandstone **(H)** Ball and pillow structures **(I)** Symmetrical Ripples

3.3 Nilawahan Nala Section, Central Salt Range

In this section the observed contacts behavior of Khewra Sandstone is such that, the lower contact is conformable with Precambrian Salt Range Formation while the upper is also conformable with Kussak Formation. The reported thickness of Khewra Sandstone in the present section is 70 m (Ghazi et al, 2012).

3.3.1 Prominent Features

At visual scale the entire vertical stratum of Khewra Sandstone was studied as, at the bottom there were thinly bedded brownish to maroon color sandstone concentrated with clay and shale beds alternatively. There were also few beds of light greenish mudstone intercalated between massive beds of sandstone. While going to the top vertically the textural behavior of sandstone changes from fine to medium and then to coarse grained at the top with color change from maroon to dark red and light brown. The shale beds at the bottom and middle portion were comparatively denser than that were in Eastern Salt Range. The observed sedimentary structures were ripple marks, ball and pillow structures, planar thin laminations, cross laminations and also a low angle monocline in this stratum shown in (Figure 3.3).

Figure 3.3: Field photographs showing outcrop features (**A)** lower contact of Khewra Sandstone with Salt Range Formation **(B)** Panoramic view of the whole section **(C)** low angle monocline in the lower part **(D)** maroon to brownish massive beds of sandstone **(E)** light and dark planar laminations in massive sandstone beds **(F)** alternate thin beds of mudstone, shale and sandstone **(G)** thin planar laminations in red fine grained sandstone **(H)** tabular low angle cross bedding **(I)** planar thin laminations **(J)** low angle climbing ripples and saturated thin laminations in massive sandstone bed **(k)** slumps structures in the light brown sandstone

CHAPTER-04

CORE STUDIES

4.1 Introduction

Core studies are actually a non-destructive technique which is used to know about any rock layer sampled from the subsurface with special drilling and recovering methods through sophisticated equipments like, a hollow-stem auger with diamond drill bits. Core samples are the solid cylinders of rocks taken from holes with 4-5 inches in diameters and about 30 feet in length. These samples are mostly studied by companies and researchers for their respective purposes among which depositional environment, porosity, permeability, mineralogy and structural features of the strata are seen and marked thoroughly by Geologists and Petrophysicists.

The study targets were to note down the visual features as well as porosity and permeability of the Khewra Sandstone from the two exploratory wells mentioned and discussed in detail in this chapter.

4.2 Wells Data

As the objectives of this research work also comprised of subsurface data for which the core cuttings of two wells mentioned below with their respective features in HDIP labs were studied. The formations tops in each well are shown in (Table 4.1a and 4.1b). The observed features are shown as;

4.2.1 Amir Pur 01 (core cuttings)

During the study of this well data, some defining features were studied from top to bottom in the available interval of 9 meter core (2956 m to 2965 m) of Khewra Sandstone which is entirely composed of fine to medium grained massive sandstone with color variation from dark brown to light gray. Clay intraclasts of greenish color and micro fractures filled with clay lenses are the most prominent features of this friable sandstone. Also oil imprints/residue saturated in the upper part dark brownish part was observed. In some intervals, dark grey silt and also cross beddings were present which are shown in (Figure 4.1).

4.2.2 Daiwal 01 (core cuttings)

This well is also studied for the concerned formation (Khewra Sandstone) in order to visualize the important features in the available interval of 9 meter core cuttings (2358 to 2367 m). The lithology observed was fine to medium grained massive micaceous sandstone with the color range of reddish maroon to dark brownish appearance. The features observed were light greenish clay intraclasts and micro fractures filled with clay lenses all along these intervals with some thin laminations at the middle potion shown in (Figure 4.2).

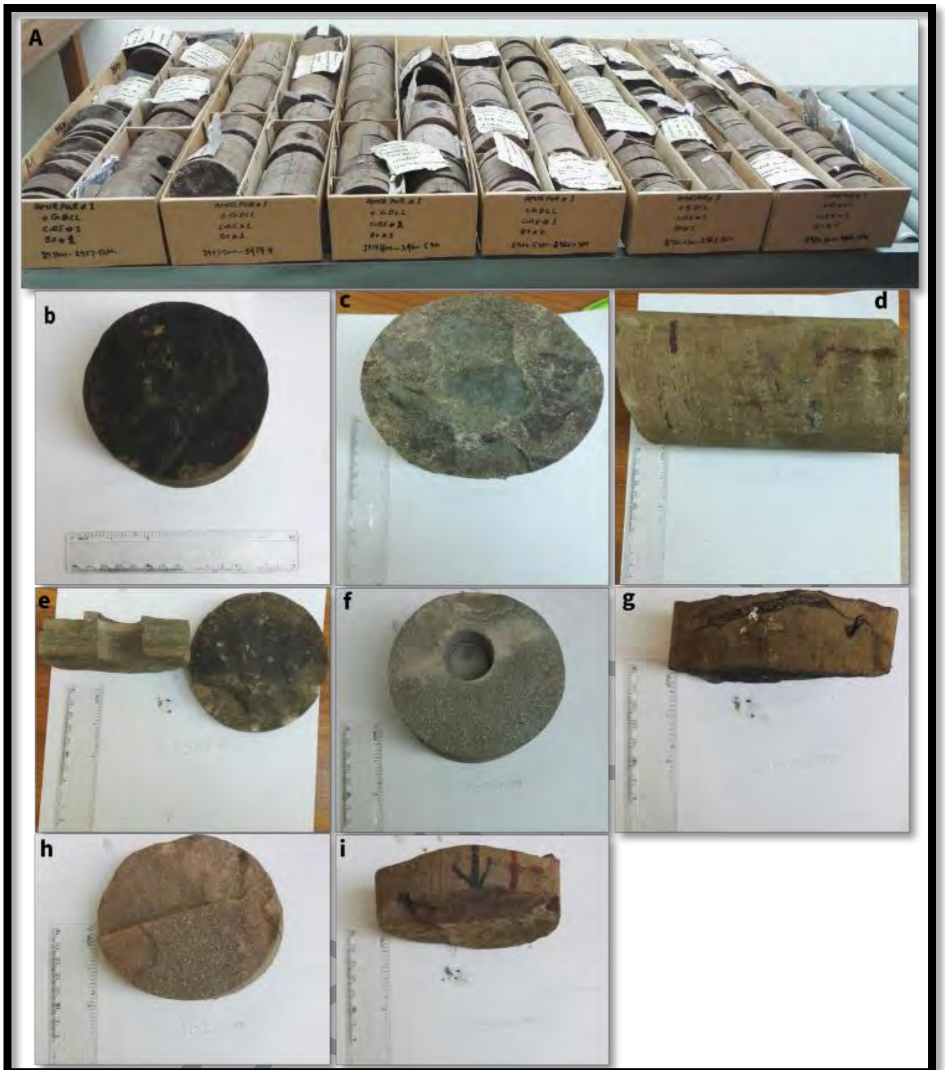


Figure 4.1: Photographs showing the observed features during study **(A)** Panoramic view of all core boxes (from left to right) display the entire available interval **(b)** dark brown medium grained sandstone with saturated oil imprints **(c)** greenish clay intraclasts within light gray sandstone **(d)** nearly horizontal filled micro fractures with clay lenses filled **(e)** thin laminations with oil imprints in a medium grained sandstone **(f)** light greenish micaceous sandstone interval **(g)** low angle inclined clay lenses and filled micro fractures **(h)** light brown micaceous sandstone bed **(i)** greenish clay contents at the bottom portion of interval.

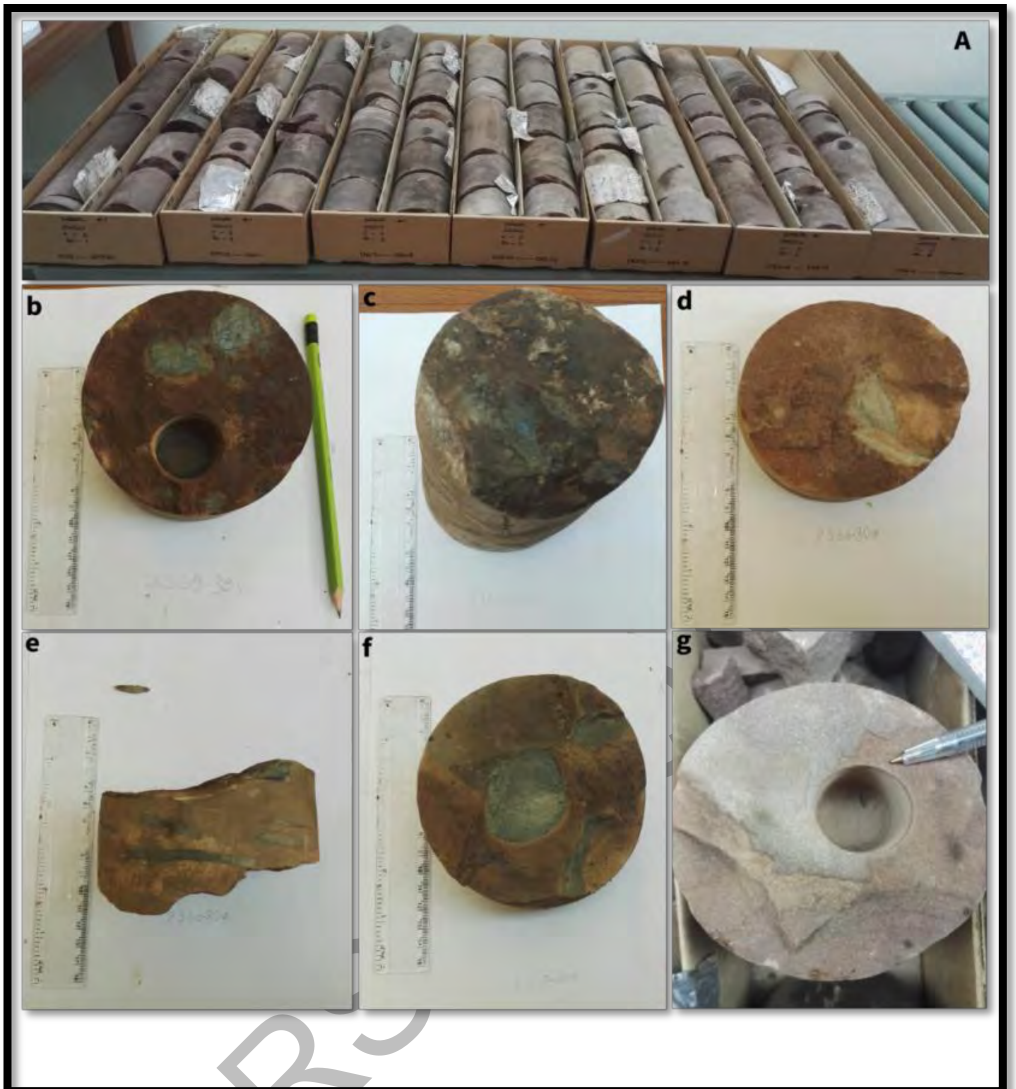


Figure 4.2: Photographs of visual observed features from the core cuttings study **(A)** Panoramic view of Khewra Sandstone in available core boxes **(b)** greenish clay intraclasts in a reddish maroon fine grained sandstone **(c)** clay contents in the same interval **(d)** reddish brown medium grained sandstone with clay intraclasts **(e)** nearly horizontal clay lenses in sandstone beds **(f)** visible greenish clay content in maroon sandstone **(g)** light gray micaceous sandstone bed in the middle portion of available interval.

Table 4.1: Formation tops of the **(a)** Amirpur 01 and **(b)** Daiwal 01 wells, Potwar Basin, Pakistan

(a)

Formation	Depth (m)	Thickness (m)
Nagri	0000	543
Chinji	0543.0	942
Kamlial	1485.0	120
Murree	1605.0	1003
Chorgali	2608.0	28.5
Sakesar	2636.5	78.5
Nammal	2715.0	9
Patala	2724.0	14
Lockhart	2738.0	9
Hangu	2747.0	5
Sardhai	2752.0	29
Warcha	2781.0	25
Dandot	2806.0	27
Tobra	2833.0	10
Baghanwala	2843.0	10.5
Jutana	2853.5	24.5
Kussak	2878.0	78
Khewra sandstone	2956.0	10

(b)

Formation	Depth (m)	Thickness (m)
Chinji	0000	395
Kamlial	0395.0	640
Murree	1035.0	162
Chorgali	1197.0	841
Sakesar	2038.0	36
Nammal	2074.0	79
Patala	2153.0	6
Lockhart	2159.0	8
Hangu	2167.0	8
Sardhai	2175.0	7
Warcha	2182.0	7
Dandot	2189.0	11
Tobra	2200.0	10
Baghanwala	2210.0	8
Jutana	2218.0	37
Kussak	2255.0	103
Khewra sandstone	2358	9

CHAPTER- 05

RESULTS AND DISCUSSIONS

5.1 Petrography

Petrography is actually the detail micro level study of rocks in thin sections with the help of polarized microscope for the textural and mineralogical trend of any rock and is useful for the classification of rocks in a systematic and scientific way.

In order to measure and study the above two sections for Khewra Sandstone in detail, total of 22 outcrop samples were collected from the Eastern and Central Salt Range sections and they were studied under polarizing microscope for the detail description and analysis. The results obtained are described as,

5.2 Khewra Gorge Section

From the type locality of Khewra Sandstone ten (10) representative sandstone samples were collected and were analyzed under polarizing microscope for mineralogical and textural composition. The results were such that the sandstone from the current section is entirely grain supported with the overall matrix content of about 0.5 to 3%. The framework grains are comparatively changing in size while tracing the section vertically from bottom beds to the top end with the average range of 67 to 320 um (from very fine to medium grain) and this trend is actually coarsening upward sequence respectively shown (Plate 1). The framework grains observed in this section also varies by proportion in samples which has a unique effect on mineralogical composition and sandstone classification also. The constituent components of sandstone are mostly quartz, feldspar and lithics with some amount of micas also. So the Khewra Sandstone has also these framework grains with the most abundant quantity of quartz followed by feldspar and then the other components shown in (Table 5.1). The calculated percentage of total quartz (Qt) in this section ranges from 72 to 83 % with the average value of 77% from the studied samples. The lowest value of quartz calculated from sample (KG-8) which is (72%) and is increasingly observed with highest value of 83%. The dominant portion here is moncrystalline quartz (Qm) with tiny portion of about 2% polycrystalline quartz (Qp) also. The second abundant component in this sandstone is feldspar with the average composition of about 9 % and range is

4-14% while the counted highest (i.e 14%) in sample (KG-2) in lower beds with the decreasing trend in the top portion. Plagioclase in minor portion is observed with dark and white strips. The third framework constituents are rock fragments (lithics) in the studied samples ranges from 1 to 4% with average of 2.4% and mostly observed are metamorphosed lithics (Lm) with some amounts of volcanic fragments (Lv) and broken sedimentary particals also. The mica part here is both muscovite and biotite having various colors due to its pleochroic nature and is proportionally 1 to 2% by volume in all section. Beside these some accessory minerals are also reported in few samples among them the most prominent are tourmaline grains of brownish color shown in (Plate 2). Finally after the complete analysis and observations of minerals and compositional texture, it is concluded that the framework grains of Khewra Sandstone has angular to sub rounded shape with the concave-convex and sutured contacted boundaries and is texturally mature and minerologically sub-mature. The sorting pattern of grains is moderate in the lower beds while well sorting nature is observed at the top portion of the section. The over all observed features of Khewra Sandstone in this section are shown in photomicrograph (Plate 2).

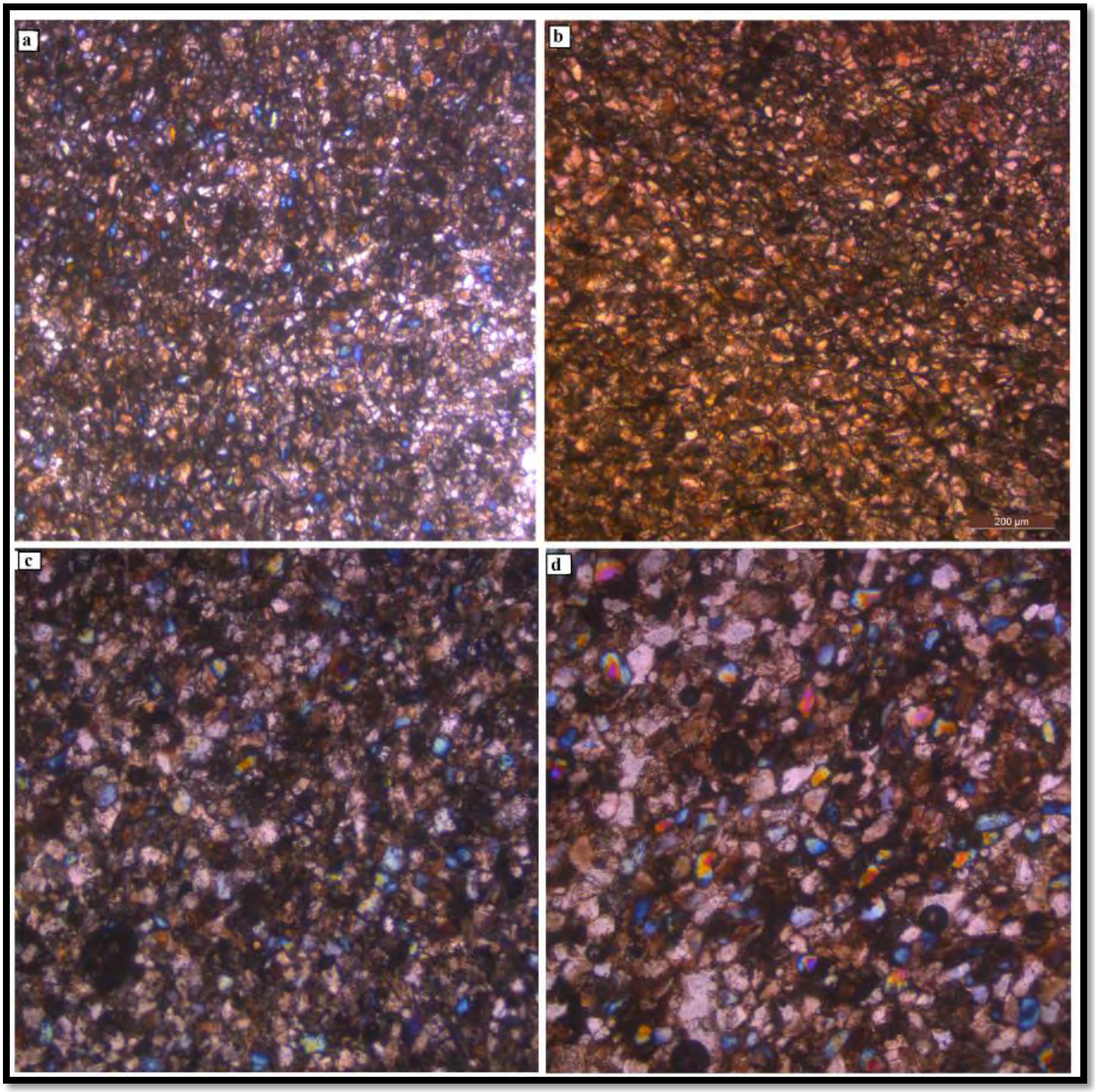


Plate 1: Photomicrographs of thin sections (Khewra Gorge section) showing the continous change in texture (coarsening upward sequence) from bottom beds **(a)** to top portion **(d)** comparitively.

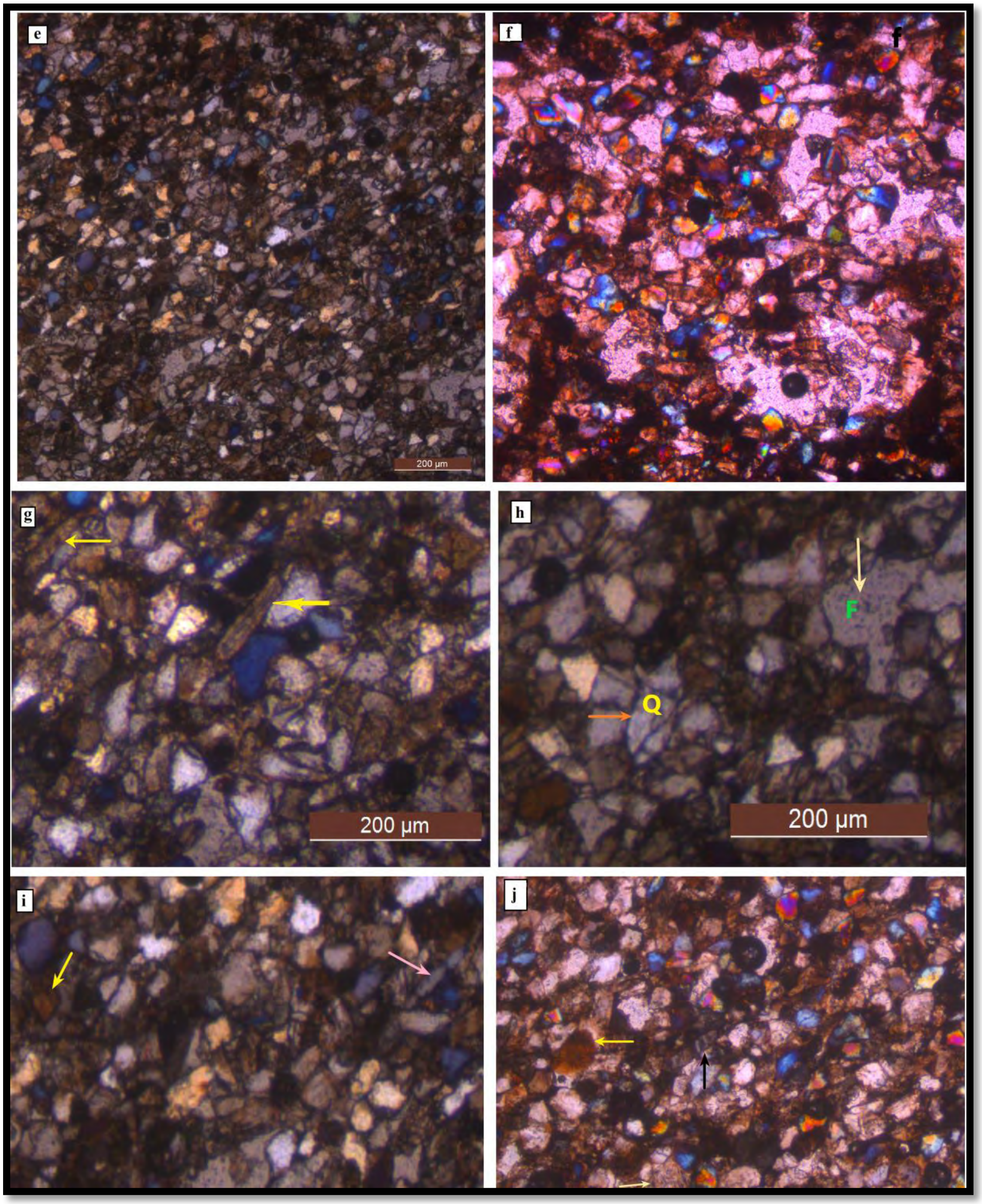


Plate 2: Photomicrographs of thin sections displaying various features observed in (Khewra Gorge section). Coarsening upward texture (from “e” to “f”), **(g)** elongated biotite flakes, **(h)** feldspar (F) shown with light yellow arrow and broken quartz (Q) pointed with dark yellowish arrow, **(i)** tourmaline grain shown with yellow arrow tip and streched quartz grain with pinkish arrow, **(j)** biotite component with yellow arrow, plagioclas having bands pointed with black arrow and feldspar with whitesh arrow.

Table 5.1: Estimated compositional compoenents in (% values) of Khewra sandstone from samples (KG-1 to KG-10), Khewra Gorge section, Eastern Salt Range.

Sample ID	Quartz (%)	Feldspar (%)	Lithics (%)	Matrix (%)	Micas (%)	Accessory minerals (%)	Porosity (%)
KG-1	79	12	3	3	1	0.3	1.7
KG-2	75	14	3	2	1.7	0.3	4
KG-3	83	8	4	2.8	1	N/O	1.2
KG-4	83	9	2	3	2	N/O	1
KG-5	77	14	3	2	1.7	0.3	2
KG-6	79	9	2	1.3	1	0.3	7.4
KG-7	73	8	2.5	1	1.5	0.5	13.5
KG-8	72	7	1.5	0.8	1	1	16.7
KG-9	73	8	2	1	1.5	0.3	14.2
KG-10	75	4	1	0.5	1	N/O	18.5

Table 5.2: Normalized values of frame work grains from (Point Counting) Khewra Gorge Section.

Sample ID	Quartz (Qt)	Feldspar (Ft)	Lithics (Lt)	Quartz (Qm)	Feldspar (Fn)	Lithics (Ln)
KG-1	79	17	4	77	18	5
KG-2	71	25	4	69	26	5
KG-3	85	11	4	83	12	5
KG-4	87	10	3	85	11	4
KG-5	77	18	5	75	19	6
KG-6	82	13	5	80	14	6
KG-7	72	24	4	70	25	5
KG-8	82	15	3	80	16	4
KG-9	82	14	4	80	15	5
KG-10	80	14	6	78	15	7

Nilawahan Nala Section

In order to study the Khewra Sandstone in this section total of 12 samples were analyzed petrographically and the results obtained are shown in (Table 5.3). The Khewra Sandstone in this section has grain packing of variable sizes that ranges from 30 to 77um for sample (NNS-1) at bottom bed with continuous coarsening upward sequence with 70 to 125um for (NNS-5 and NNS-6) at the middle part and finally for the top portion in (NNS-11 and NNS-12) this range of grain size is comparitevely coarser with 125 to 230um but for few samples this variation is inverse like (NNS-8 and NNS-9) represents fine particals with range of 67 to 102um.The observed shape of grains for the major portion of this section are angular to sub-rounded with few samples having well rounded grains and the contacts among the framework components are mostly concave-convex and sutured. The compositional pattern of sandstone at this section is such that mostly quartz is dominated with about 73.91% by average volume and has a range of 70 to 81% for entire samples. Like in the Khewra Gorge Section, moncrystalline quartz (Qm) here is dominant with the minor ratio (1% by volume) of polycrystalline quartz (Qp) also. The feldspar composition in this section is more than that of previous section with the average value of 13.5% and range is 9 to 18% for all samples. The lithics contents ranges from 1 to 4% with average value of 2.2% at all. The micaceous contents in this section are dominated with biotites with few muscovite flakes of stretched and bended nature also. While the accessory minerals with minor amount of about 0.2 % by volume are also present and mostly tourmaline grains are dominant. All the discussed features are shown in photomicrographs of thin sections (Plate 3 and Plate 4).

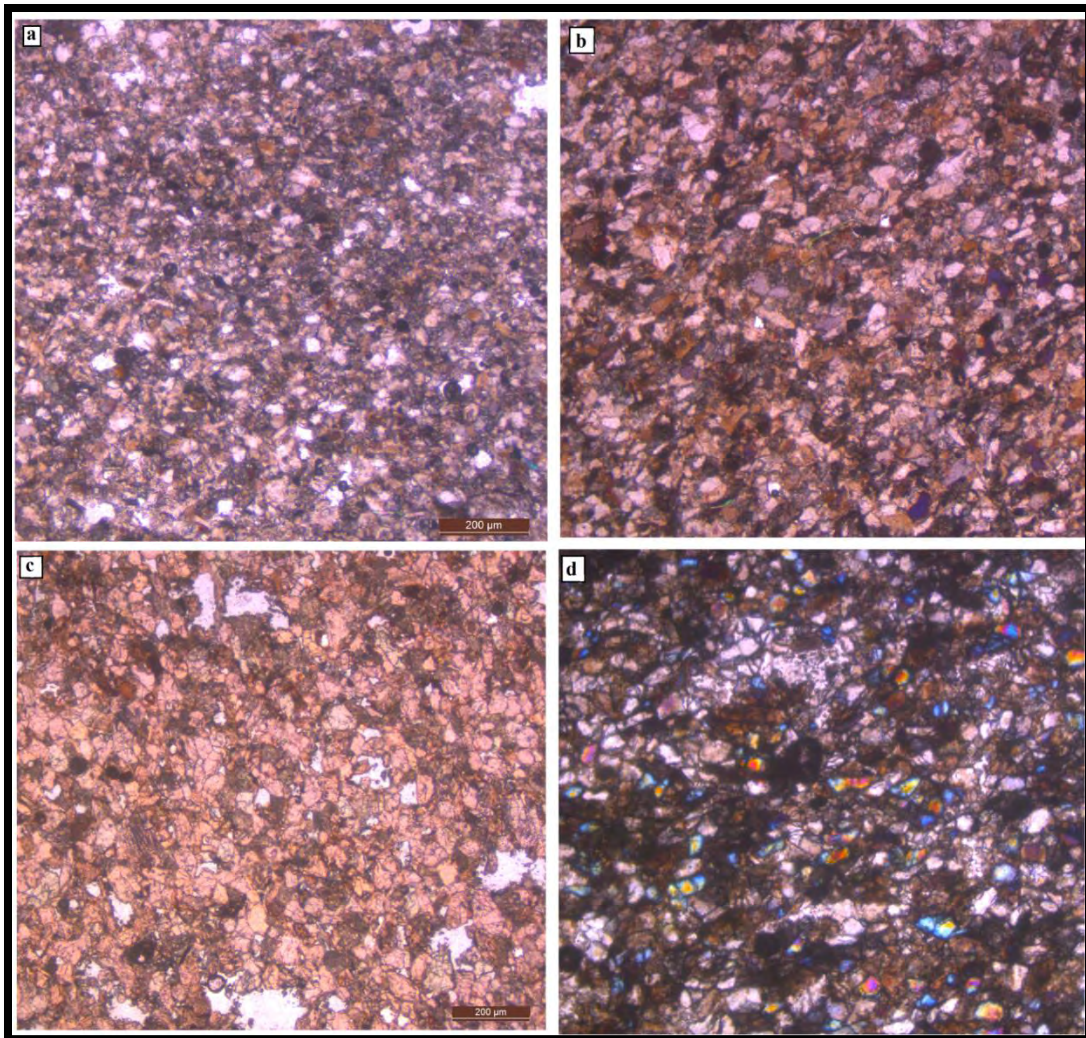


Plate 3: Photomicrographs of thin sections (Khewra Sandstone) showing the textural variation (i.e, coarsening upward sequence) from bottom beds **(a)** to top end **(d)**, Nilawahan Nala Section.

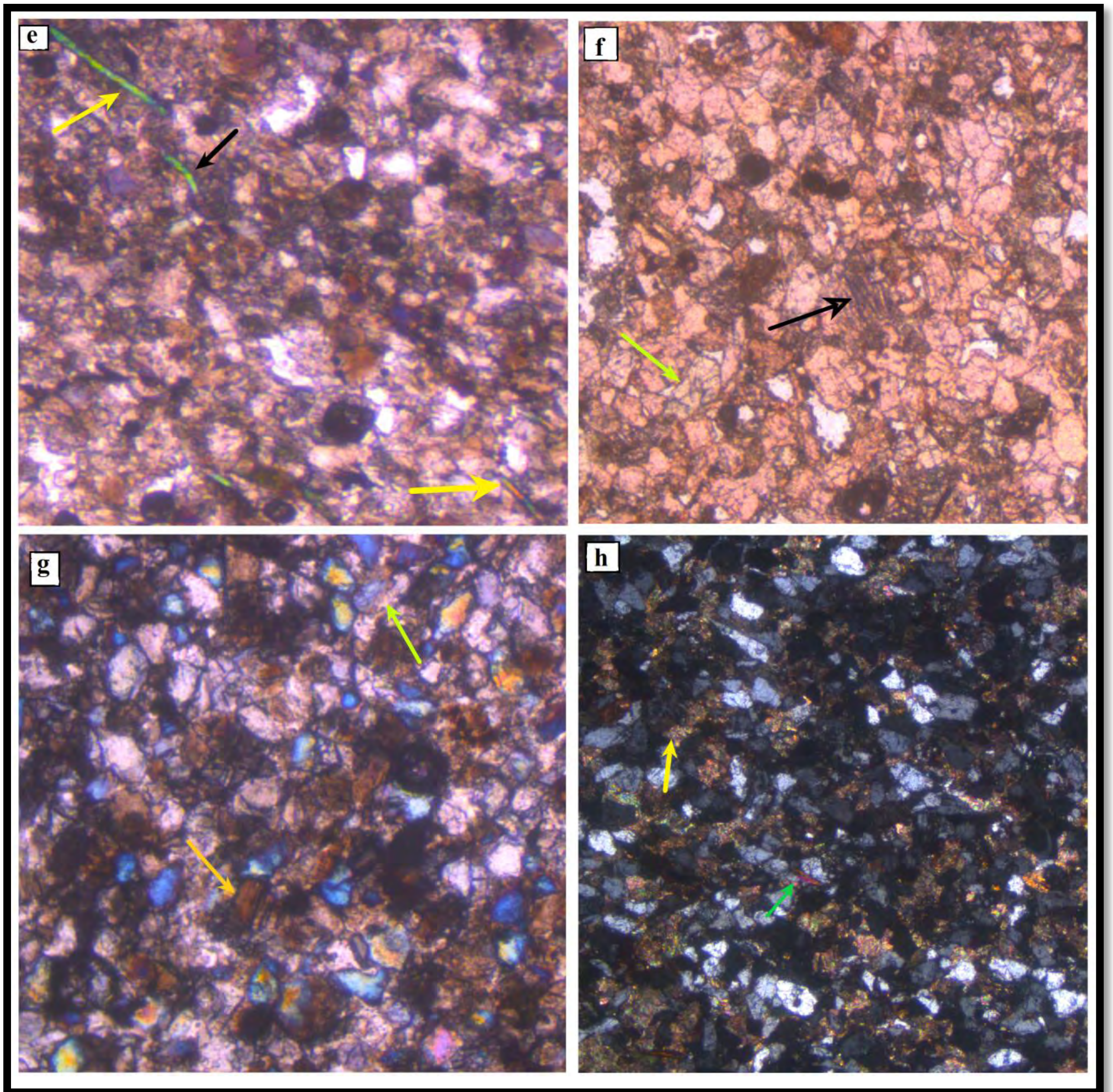


Plate 4: Thin sections photomicrographs showing the observed features in Khewra Sandstone samples (Nilawahan Nala Section), **(e)** green color muscovite (mica) flakes, **(f)** broken quartz grains and feldspar representing pressure regime, **(g)** dark brown tourmaline grain and polycrystalline quartz grain shown with yellow arrows, **(h)** Hematite cements (brownish) and polycrystalline quartz grain pointed with green arrow.

Table 5.3: Compositional model representation of Khewra Sandstone from samples (NNS-1 to NNS-2), Nilawahan Nala Section.

Sample ID	Quartz (%)	Feldspar (%)	Lithics (%)	Matrix (%)	Micas (%)	Accessory minerals (%)	Porosity (%)
NNS-1	77	13	3	3	2	N/O	2.1
NNS-2	78	13	2	4	2	0.5	0.5
NNS-3	72	17	2	2.5	2	0.2	4.3
NNS-4	77	10	2	1	2	P	8.1
NNS-5	70	18	3	2	2.3	0.2	4.5
NNS-6	81	12	2	2.8	1	P	1.2
NNS-7	71	14	2	1	0.8	P	11.2
NNS-8	71	9	1	0.5	1.3	N/O	17.2
NNS-9	75	15	4	2	2	P	2.0
NNS-10	70	14	2	1.7	2.6	P	9.7
NNS-11	72	15	2	1.4	1	N/O	8.6
NNS-12	73	12	3	1.2	2	N/O	8.8

Table 5.4: Normalized values of framework grains from (Point Counting) for sandstone classification and provenance analysis, Nilawahan Nala Section

Sample ID	Quartz (Qt)	Feldspar (Ft)	Lithics (Lt)	Quartz (Qm)	Feldspar (Fn)	Lithics (Ln)
NNS-1	81	15	4	80	16	4
NNS-2	80	16	4	79	17	4
NNS-3	75	21	4	74	21	5
NNS-4	83	14	3	82	15	3
NNS-5	75	21	4	74	21	5
NNS-6	84	13	3	83	14	3
NNS-7	75	20	5	74	21	6
NNS-8	75	19	6	74	20	6
NNS-9	75	20	5	74	21	5
NNS-10	77	17	6	76	18	6
NNS-11	78	17	5	77	17	6
NNS-12	81	15	4	80	16	4

5.3.1 Sandstone classification

Various researchers have proposed different classification schemes for sandstone but the mostly used and followed are those of Pettijohn et al (1987), Fischer (1961) and Folk (1954). According to these methods a triangle labeled with framework constituent (i.e Quartz, Feldspar and Rock fragments) as their end members is constructed and then the triangle is divided into different portions based on these end members percentage composition. Finally the complete analysis and model composition of sandstone samples are displayed by this constructed figure.

For the classification of Khewra Sandstone, the framework components are normalized to100% and then displayed in ternary plots shown in (Table 5.2) while the most prominent scheme of (Pettijohn et al, 1987) is used which represents different classes of sandstone in separate portion based on the respective matrix and framework constituents calculated from sandstone during petrography. The simplest way to differentiate the sandstone class is to know their respective compositional pattern. Those rocks which are comprised of more than 15% matrix are termed as “wackes” while those of less than 15% are “arenites” (Williams et al, 1954). They are further classified based on quartz, feldspar and rock fragments percentage presence. It may be “quartz arenites” with 95% are more quartz, “arkosic arenites” with 25% or more feldspar with minor volume of rock fragments and “lithic arenites” with 25% or more volume of rock fragments rather than feldspar by volume (Pettijohn et al, 1987). Also “wackes” are classified with the same procedure and compositional volumes for quartz (95% or more) is termed as “quartz wacke” but in case of feldspar and lithics the percentage value is 5% or more accordingly and are termed as “feldspathetic greywacke” and “lithics greywacke”.

According to the discussed scheme of Pettijohn et al (1987), the Khewra Sandstone is composed of about 0.5 to 3% matrix while the major portion is comprised of grain/framework components but the feldspar content her is high with the average value of 9.3% which classified it as sub-arkosic sandstone with few samples (KG-2 and KG-7) in arkosic portion also and is shown in (Figure 5.1).

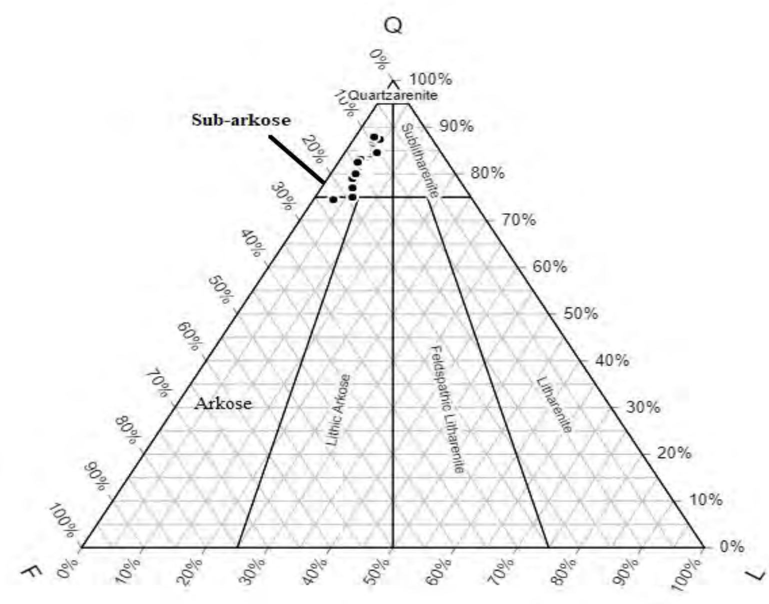


Figure 5.1: Ternary plot showing the classification of Khewra Sandstone from modal compositional values of samples (KG-1 to KG-10), Khewra Gorge Section.

For the classification of sandstone again Pettijohn et al (1987) scheme is used according to which the ternary plots with end framework members are displayed and the studied samples after compositional modal preparation are shown in their respective fields. The Khewra Sandstone in this section is classified also as sub-arkosic with few samples (NNS-5, NNS-8 and NNS-9) in arkosic field due to higher values of feldspar comparatively than that of lithics in these samples (Figure 5.2).

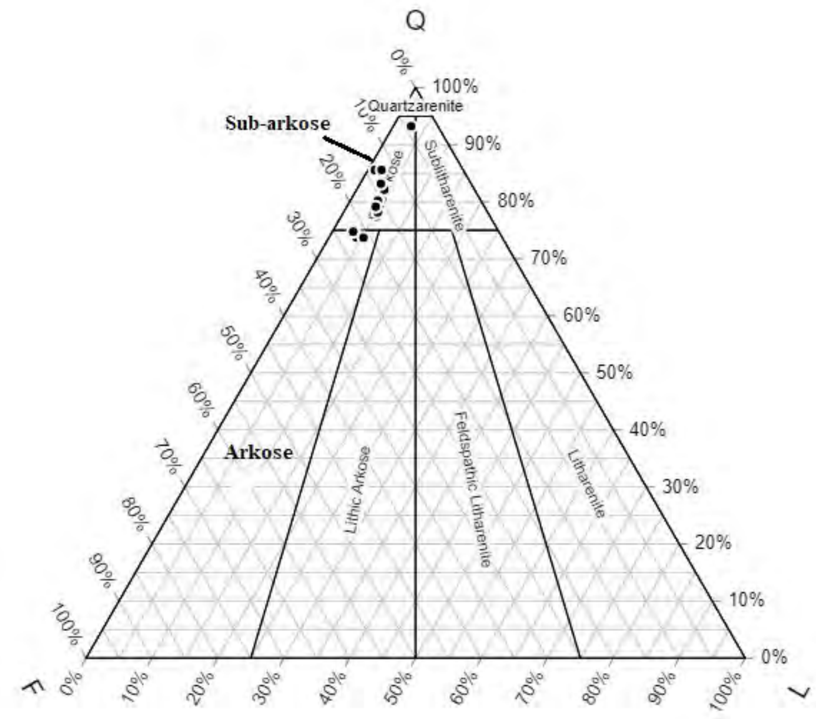


Figure 5.2: Ternary plot showing the classification of Khewra Sandstone from modal compositional values of samples (NNS-1 to NNS-12), Nilawahan Nala Section.

5.4 Provenance analysis (outcrop sections)

According to the Dickinson and Suzeck (979) statement, for the provenance of any sandstone a quantitative modal of framework grains obtained from point counting of thin sections during microscopy can be used and the desired results can be achieved easily. So for the provenance analysis of Khewra Sandstone in both the discussed sections, the calculated framework components from petrography are normalized to 100% (Table 5.2 & 5.4) and then they are plotted in ternary plots based on Dickenson et al (1983) classification which use the framework grains (Q,F, L) as an end members. Two ternary plots for each section (i.e, Q-F-L and Qm-F-L) are shown in (Figure a,b) and the samples classified for both these sections mostly fall in craton interior with few samples in Transitional continental field accordingly. It concludes that the major portion of Khewra Sandstone in both sections is derived previously from craton interior as its origin. The samples of Khewra Gorge section are almost compositionally different because they don't overlap each other (Figure 5.3a and 5.3b) while some samples from Nilawahan Nala section overlaps their margins displaying relatively same compositional pattern (Figure 5.4a and 5.4b) in the respective beds.

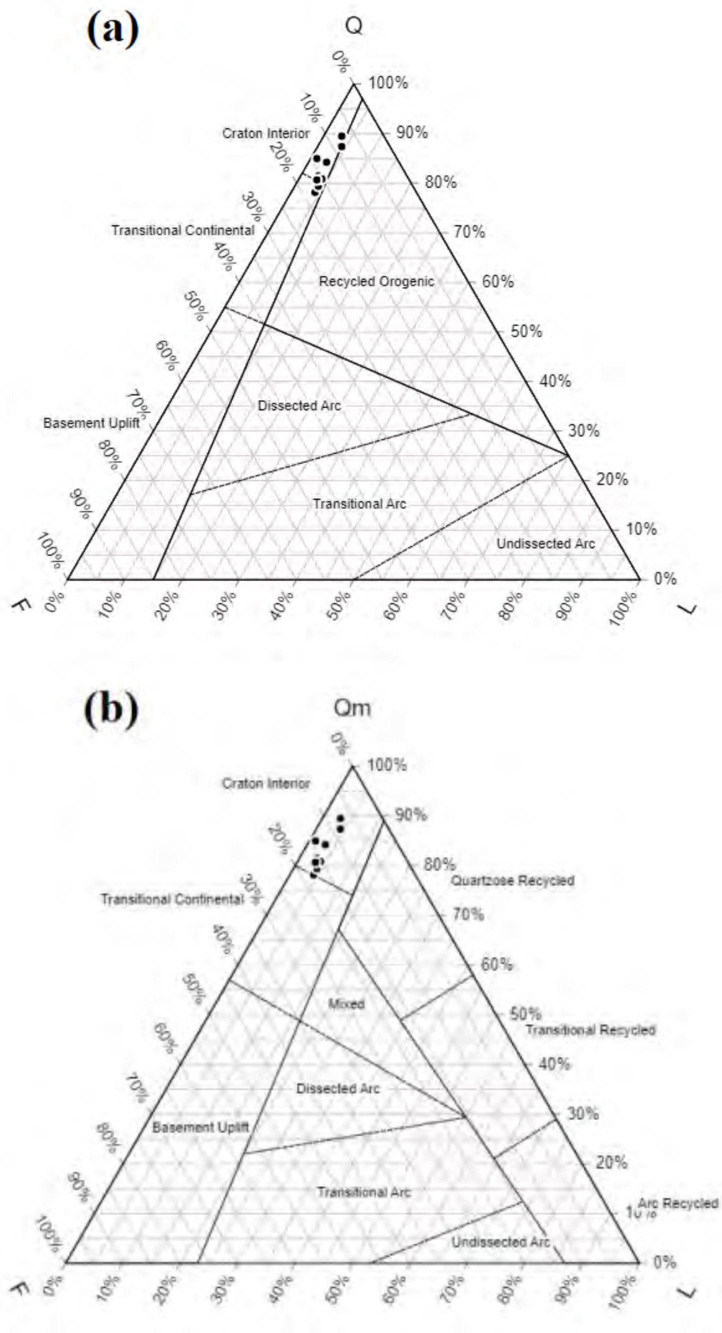


Figure 5.3: Ternary plots showing the provenance of Khewra Sandstone (Khewra Gorge Section), **(a)** end members as Q-F-L , **(b)** framework grains (end members) Qm-F-L

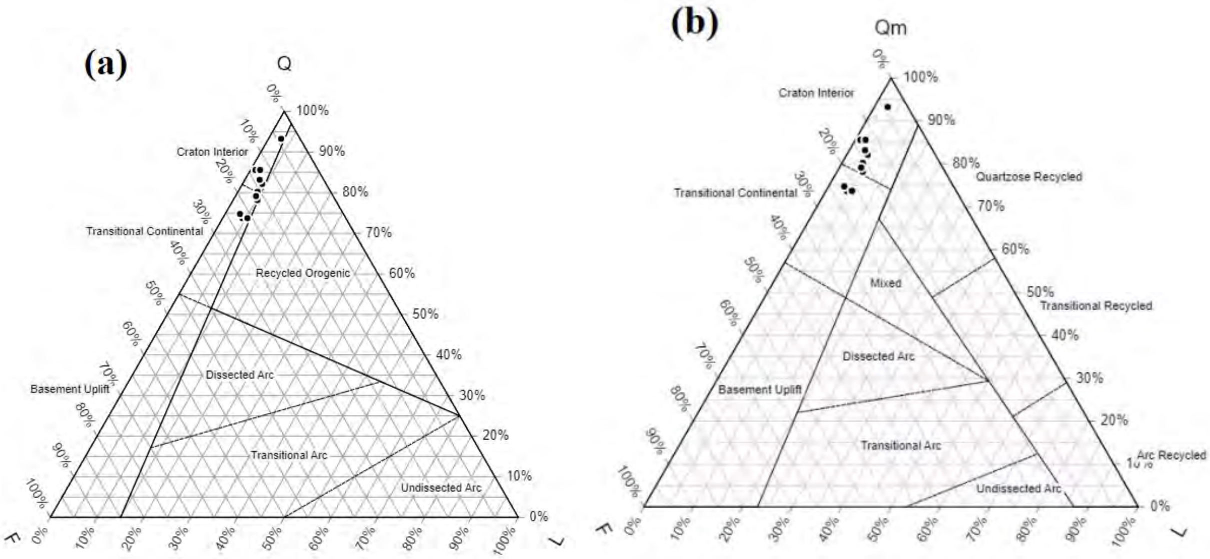


Figure 5.4: Ternary plots showing the provenance of Khewra Sandstone (Nilawahan Nala Section), **(a)** end members as Q-F-L , **(b)** framework grains (end members) Qm-F-L.

5.5 Petrographic results of core cuttings (Amirpur 01 & Daiwal 01)

To study the textural and mineralogical composition of Khewra Sandstone from the subsurface (core cuttings) of both these wells, total of 10 samples (5 from each well) were studied under polarized microscope and the petrographic results are shown in (Tables 5.5 & 5.6). In both wells, the sandstone has a matrix value of about 2% average while in Amirpur 01 it is in range of 1 to 4 % while dominated with grains packing having variable compositional pattern. The most dominant framework grain is quartz (Q) followed by feldspar (F) and thin lithics (L) respectively. The quartz range in Amirpur 01 well is from 80 to 84% with average of 82% having minor amount of polycrystalline quartz (2%) also. The second abundant mineral is feldspar within range of 9 to 13% and followed by rock fragments of about 2 to 4% by volume. Also some mica (muscovite and biotite) with a minor portion of about 1.9% (average value) is observed in these samples while accessory minerals like tourmaline are also present in some samples. The grain size measured from the available samples (AMP-1 to AMP-5) ranges from 55 to 182 um (average size) which display a coarsening upward sequence for the available interval of sandstone (Plate 5) while the framework grains observed are sub-angular to sub-rounded with a concave-convex to linear contacts between grains and the sorting pattern is not so developed (i.e, poorly sorted). The compositional modal of Khewra Sandstone in Daiwal 01 well is such that quartz is dominated with 82 to 84% in all samples (DW-1 to DW-5) followed by feldspar and then rock fragments with the same composition as discussed for (AMP-1 to AMP-5) above. The micaceous components (both muscovite and biotite) here with an average volume of 1.7% are observed and some samples also contain accessory minerals as well. The grains packing with a size range of 70 to 138 um is observed and is also a coarsening upward pattern (Plate 6) for sandstone in this available interval and the shapes of grains are sub-rounded to rounded with comparatively well sorted nature.

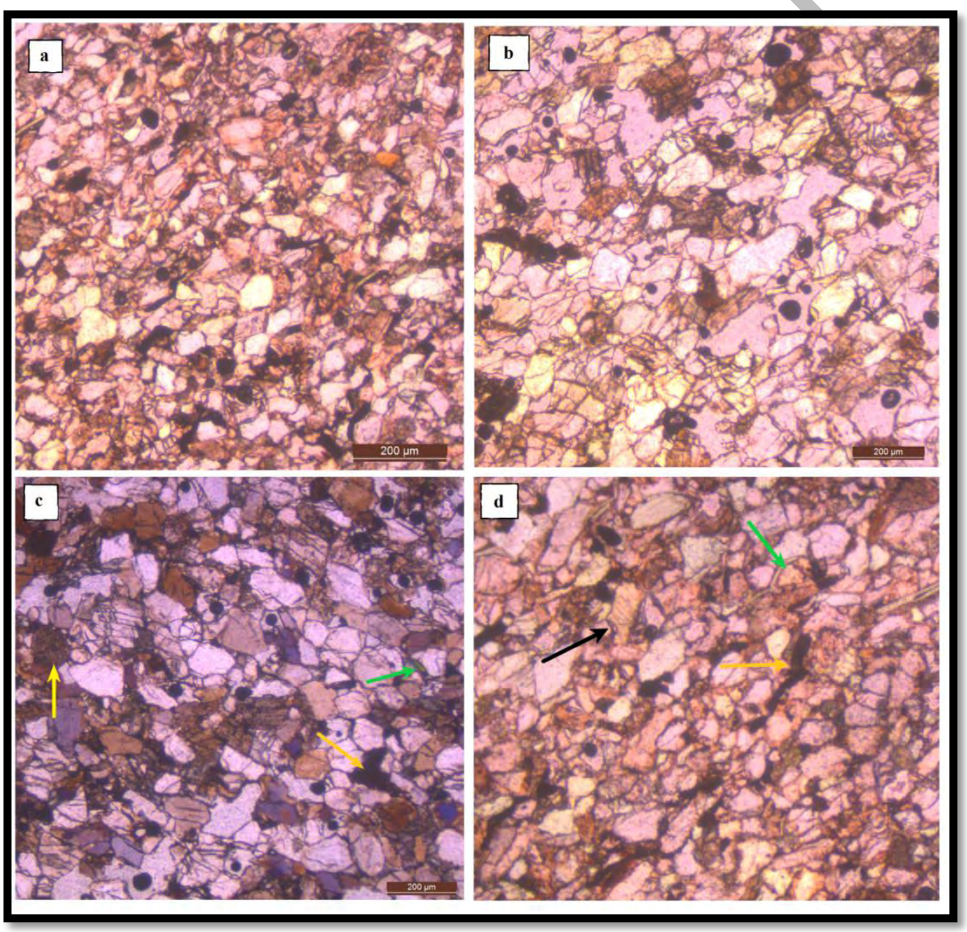


Plate 5: Photomicrographs of thin sections showing the observed features in Khewra Sandstone (Amirpur 01) well, coarsening upward sequence from bottom bed with high matrix contents **(a)** to top **(b)**, Shale lithics (brown color) shown with yellow arrow, organic contents (black) and muscovite shown with green arrow in **(c),** feldspar with black arrow, organic contents with black and micas with green arrow in **(d)**

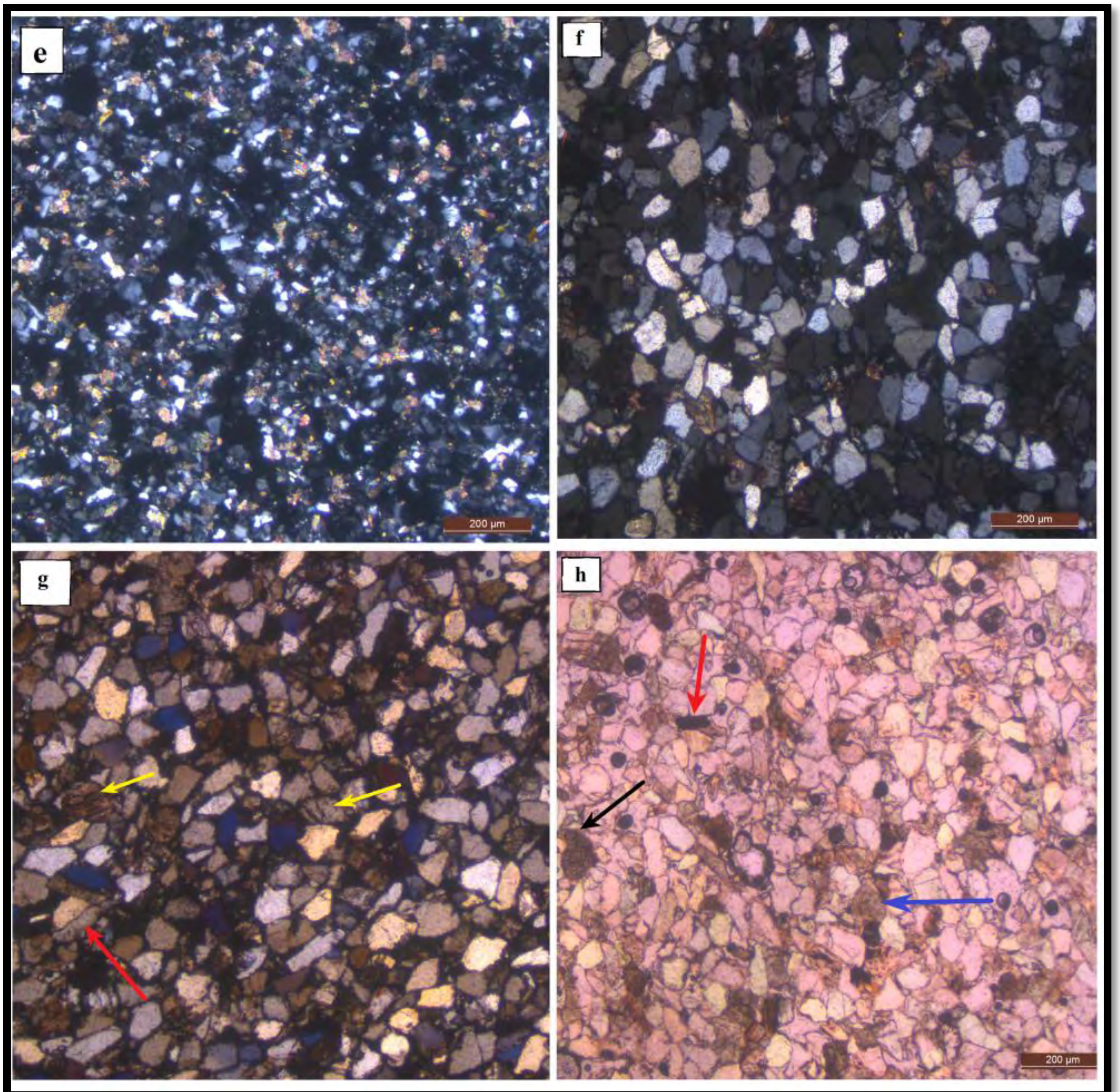


Plate 6: Photomicrographs of thin sections showing the observed features in Khewra Sandstone (Daiwal 01) well, coarsening upward sequence from bottom bed **(e)** to top **(f)**, feldspar lithics shown with yellow arrows and polycrystalline quartz with red arrow in **(g)**, Shale lithics shown with black arrow, organic contents with red arrow and feldspar with blue arrow in **(h)**

Table 5.5: Compositional model representation of Khewra Sandstone from samples (AMP-1 to AMP-5), Amirpur 01 well, Potwar basin, Pakistan.

Sample ID	Quartz (%)	Feldspar (%)	Lithics (%)	Matrix (%)	Micas (%)	Accessory minerals (%)
AMP-1	81	13	3	1	2	N/O
AMP-2	80	12	4	2	2	N/O
AMP -3	82	10	3	3	2	P
AMP -4	83	11	1.5	3	1.5	P
AMP -5	84	10	3	2	1	N/O

Table 5.6: Compositional model representation of Khewra Sandstone from samples (DW-1 to DW-5), Daiwal 01 well, Potwar basin, Pakistan.

Sample ID	Quartz (%)	Feldspar (%)	Lithics (%)	Matrix (%)	Micas (%)	Accessory minerals (%)
DW-1	83	11	3	1.5	1.5	N/O
DW-2	82	13	2	2	1	N/O
DW -3	84	9	3	2	2	P
DW -4	82	12	4	2	2	P
DW -5	84	10	3	1	2	N/O

5.5.1 Sandstone classification

For the classification of sandstone, the above discussed scheme of Pettijohn et al (1987) is used and based on that the Khewra Sandstone from the both wells are displayed in ternary plots each representing the various fields with the framework grains as an end members (Q-F-L). For this the calculated values of framework components are normalized to 100% (Table 5.7 & 5.8) and then according to their respective proportion they are shown in plots. According to this scheme, the Khewra Sandstone from both the wells encountered as sub-arkosic in nature (Figures 5.5a & 5.5b) with less amount of matrix and abundant amount of framework grains shown in (Tables 5.5 & 5.6).

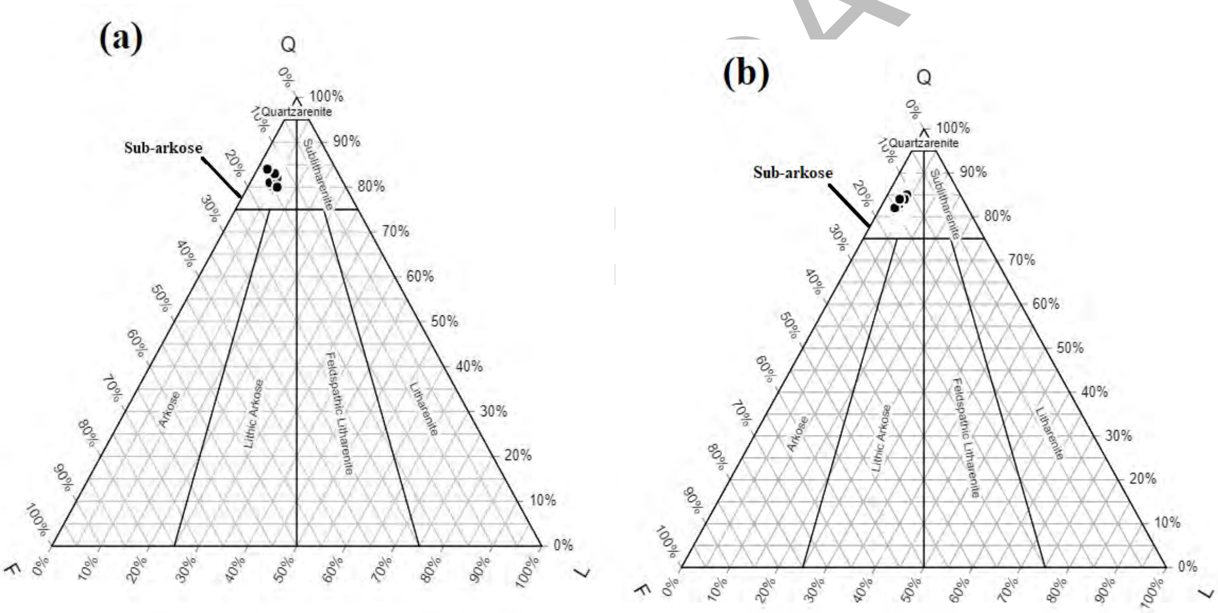


Figure 5.5: Ternary plots showing the classification of Khewra Sandstone from modal compositional values of **(a)** samples (AMP-1 to AMP-5) Amirpur 01 well, **(b)** samples (DW-1 to DW-5) Daiwal 01 well.

5.6 Provenance analysis from wells (core cuttings)

In order to investigate about the provenance of Khewra Sandstone, the normalized framework grains are displayed in ternary plots of Dickenson et al (1983) classification which is based on the end member's percentage composition and are shown (Figures 5.6 & 5.7). Based on the obtained results it is concluded that all the samples of sandstone from both the wells previously has a craton interior origin with one sample (AMP-3) falls in recycled orogenic region. This analysis is done with the ternary plots with an end members of quartz, feldspar and lithics (Q-F-L) and also monocrystalline quartz and the same other grains (Qm-F-L) shown in figures 5.6a &b, 5.7a &b.

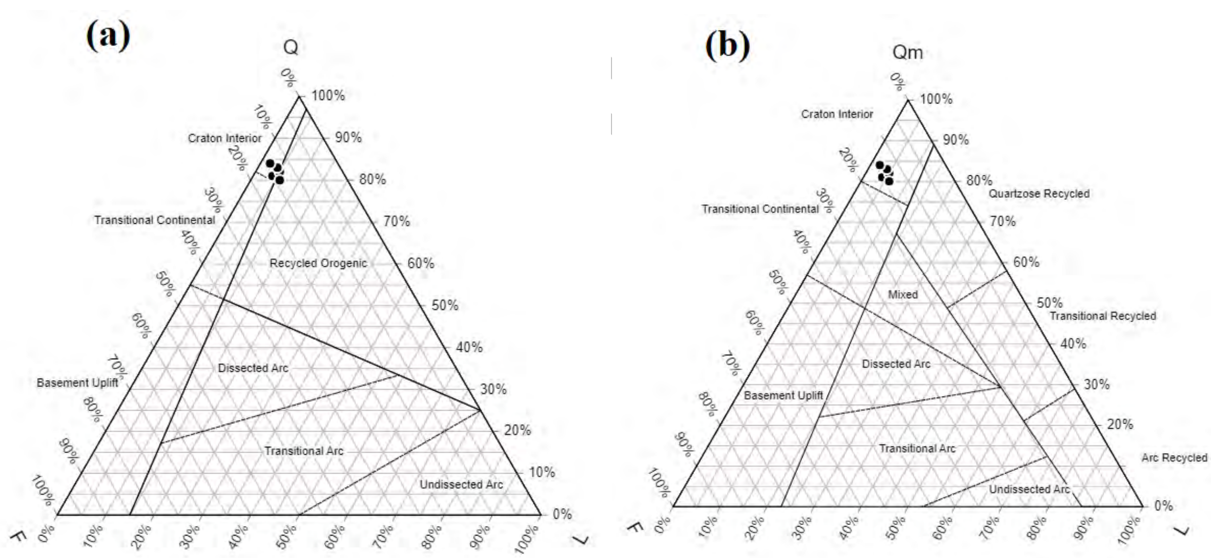


Figure 5.6: Ternary plots showing the provenance of Khewra Sandstone (Amirpur 01) well, **(a)** end members as Q-F-L , **(b)** framework grains (end members) Qm-F-L

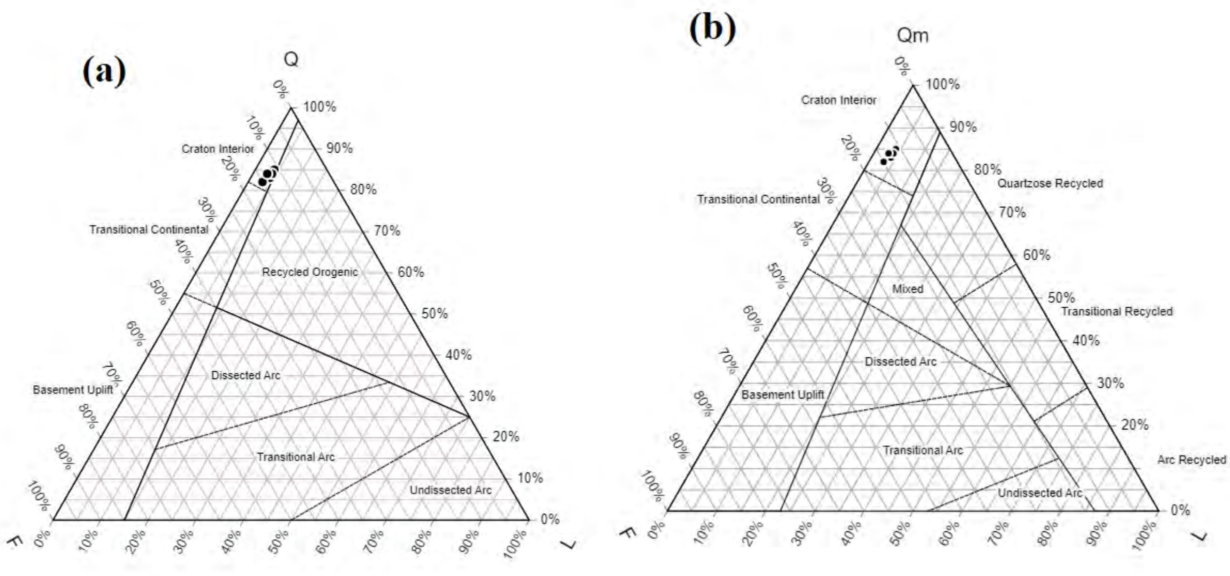


Figure 5.7: Ternary plots showing the provenance of Khewra Sandstone (Daiwal 01) well, **(a)** end members as Q-F-L , **(b)** framework grains (end members) Qm-F-L

Table 5.7: Normalized values of framework grains from (Point Counting) for sandstone classification and provenance analysis, Daiwal 01 well, Punjab.

Sample ID	Quartz (Qt)	Feldspar (Ft)	Lithics (Lt)	Quartz (Qm)	Feldspar (Fn)	Lithics (Ln)
DW-1	83	13	4	81	14	5
DW-2	85	11	4	83	12	5
DW -3	84	12	4	82	12	6
DW -4	82	15	3	80	16	4
DW -5	84	13	3	82	15	3

Table 5.8: Normalized values of framework grains from (Point Counting) for sandstone classification and provenance analysis, Amirpur 01 well, Punjab.

Sample ID	Quartz (Qt)	Feldspar (Ft)	Lithics (Lt)	Quartz (Qm)	Feldspar (Fn)	Lithics (Ln)
AMP-1	81	15	4	79	16	5
AMP -2	82	13	5	80	14	6
AMP -3	80	14	6	78	15	7
AMP -4	83	13	4	81	16	3
AMP -5	84	14	4	82	13	5

5.7 Reservoir characterizations

Any rock body that acts as a reservoir must possess the fundamental physical properties among which the most important are Porosity (Φ) and Permeability (K). These can be defined with their actual standards for sandstone as,

(a) Porosity (Φ)**:** it is actually the ratio of porous volume to the bulk volume within a rock and depends upon the grain size, grain shape, orientation and its sorting pattern. Two type of porosities are majorly present which effects the reservoir properties among which the total porosity (Φt) is defined as "the ratio of total porous volume to that of bulk volume within a rock body" while the effective porosity (Φe) is the interconnected pore spaces to the total bulk volume which is the actual portion to be considered for a good reservoir criteria.

(b) Permeability (K): it can be defined as "the ease with which a fluid can flow through a porous media and is proportional to the pressure gradient and is represented with the unit of mili

Darcy (mD). It is controlled by cementing material between grains, size of pores and degree of connectivity also. Mostly three types of permeability is encountered which are absolute, effective and relative in nature but for any reservoir body relative and effective portion are useful in conventional ways.

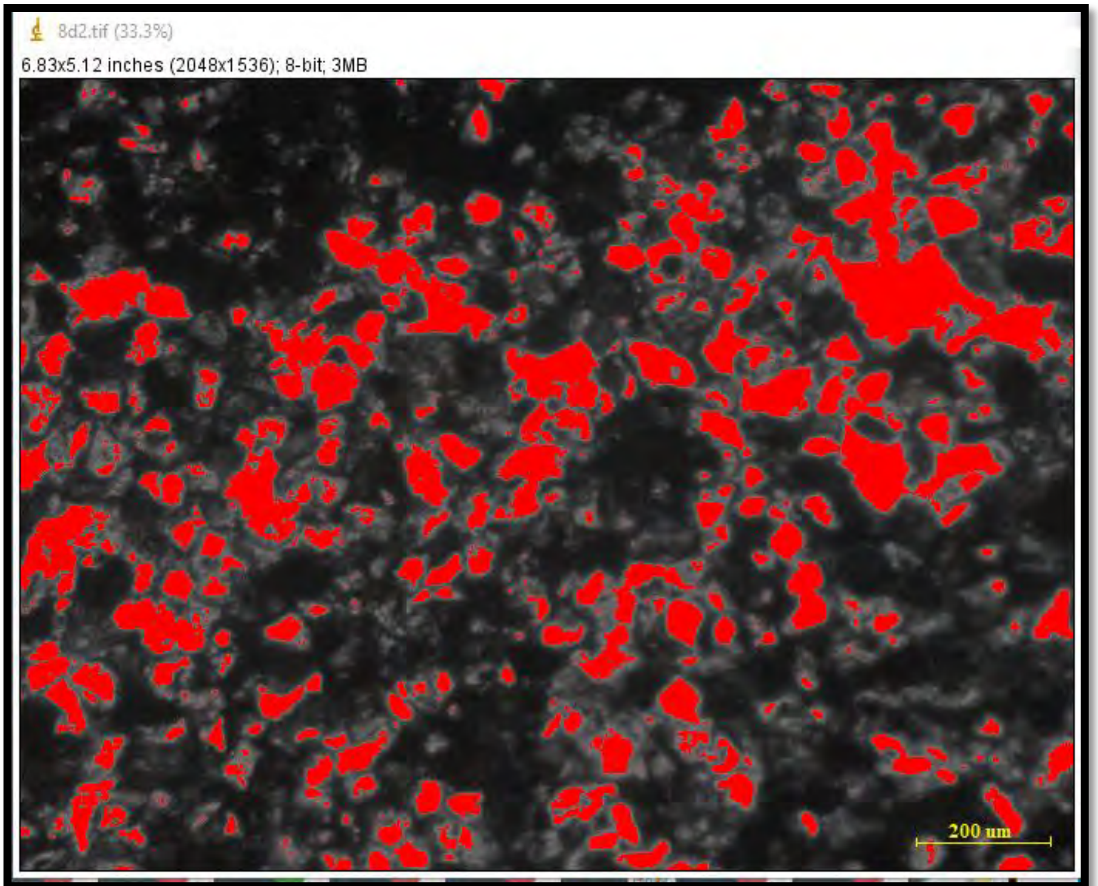
For the reservoir assessment and study many techniques are used among which petrophysical methods, visual estimation of properties and core analysis are mostly used. While this research work only focuses on visual estimation of porosity (Petrographic methods) and core analysis techniques. For that purpose the interpreted results and findings are shown as,

5.8 Visual estimation of Porosity (outcrop sections)

For the outcrop samples of Khewra Sandstone, a conventional method during petrography is used in which the thin section is visually estimated for porosity through microscope and then correlated with the obtained results from software image (Figure 5.8) and the values for each sample are given (Table 5.9 & 5.10). The visual estimated results for both the sections are exaggerated due to software and human imperfection but ultimate care is adopted during the point counting method.

5.8.1 Khewra Gorge Section (KG-1 to KG-10)

The porosity values calculated for Khewra Sandstone (Table 5.9) ranges from 1 to 18.5 % with the average value of (8.02 %) which indicates a good sign for the potential reservoir zone and the highest values in the upper region (16.7 & 18.5 %) proves this sandstone to be more clear in nature with low percentage of matrix contents, comparatively well sorted grains (texture), sub rounded to rounded shape and high porous zones as evident from the photomicrographs of thin sections (Plate 1 &2) in petrography portion as well as from compositional tables. This trend of porosity increase vertically (bottom to top) shown in (Figure 5.9) also proves the coarsening upward sequence for Khewra Sandstone with change in depositional environment. The low porosity values in (KG-1 to KG-5) are as an evidence for this sandstone to be tight sandstone in the lower portion while petroleum reservoir in the upper horizon. The results obtained during this research are almost close and comparable to those interpreted with wireline logs (8.76%) of Jamil et al (2005).



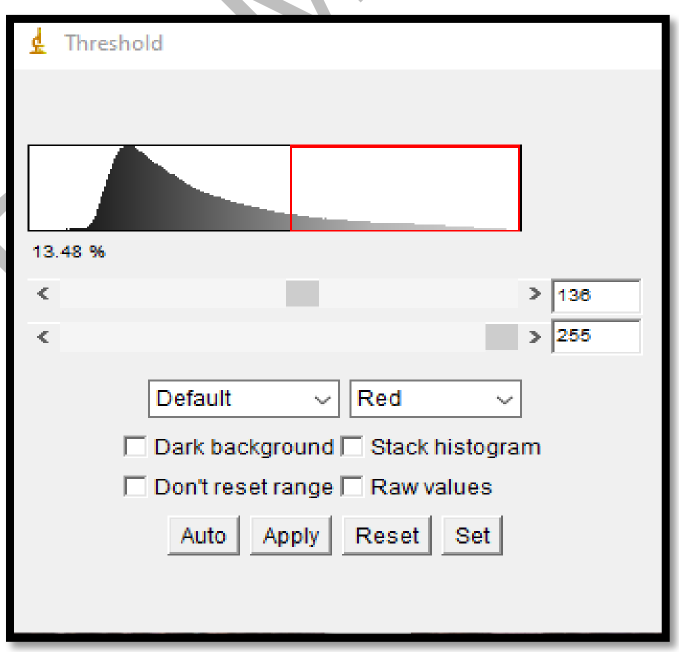


Figure 5.8: Photographs showing the porosity estimation (software value) of sample (KG-7), Khewra Gorge Section, Eastern Salt Range.

Table 5.9: Showing the Porosity (%) variation in samples (KG-1 to KG-10), Khewra Gorge Section.

Sample ID	Porosity (%)
KG-1	1.7
KG-2	4
KG-3	1.2
KG-4	1
KG-5	2
KG-6	7.4
KG-7	13.5
KG-8	16.7
KG-9	14.2
KG-10	18.5

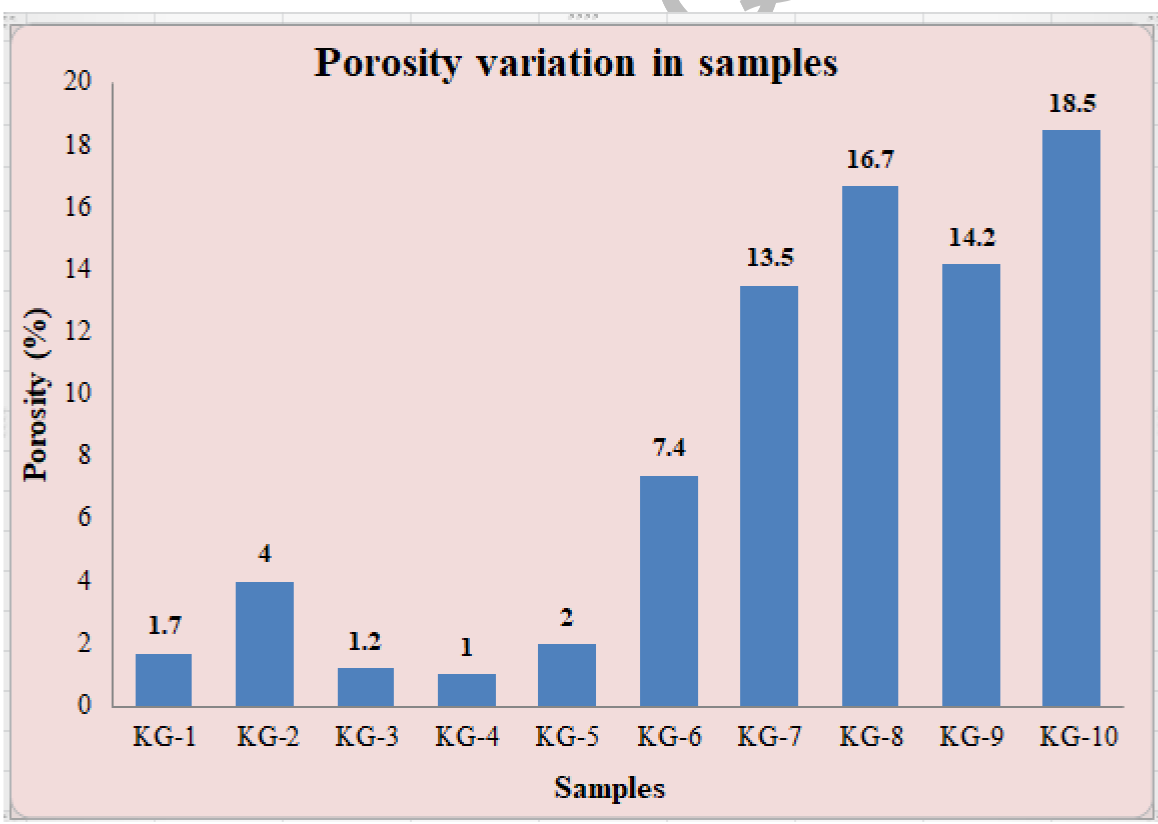


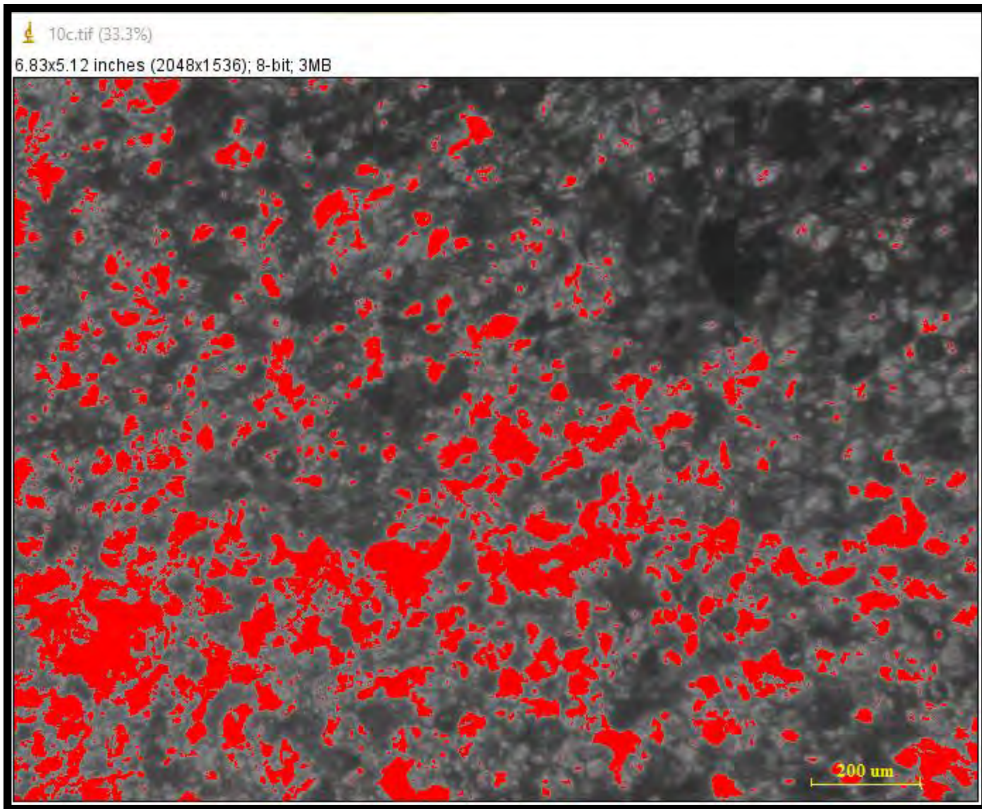
Figure 5.9: Graph representing the porosity trend of samples (KG-1 to KG-10), Khewra Gorge Section.

5.8.2 Nilawahan Nala Section (NNS-1 to NNS-12)

The range of porosity in this section is from 0.5 to 17.2% with the average value of 6.51% shown in (Table 5.10). The lower portion of this section is also observed with the low porosity values but the upper horizon is encountered as potential reservoir zone with the highest value of 17.2% (NNS-8) shown in (Figure 5.10) and actually this horizon is the target zone for hydrocarbon exploration. As the porosity trend increases vertically from bottom beds to top portion (Figure 5.11), it indicates the possible decrease in matrix contents as well as increase in texture size (coarsed grain) of sub-rounded to rounded nature which maximize the porous zone and inter-particals porosity also. These possible conditions are calculated from the petrographic observations and are shown in thin sections photomicrographs (Plate 3 & 4).

Table 5.10: Showing the Porosity (%) variation in samples (NNS-1 to NNS-12), Nilawahan Nala Section.

Sample ID	Porosity (%)
NNS-1	2.1
NNS -2	0.5
NNS -3	4.3
NNS -4	8.1
NNS -5	4.5
NNS -6	1.2
NNS -7	11.2
NNS -8	17.2
NNS -9	2.0
NNS-10	9.7
NNS-11	8.6
NNS-12	8.8



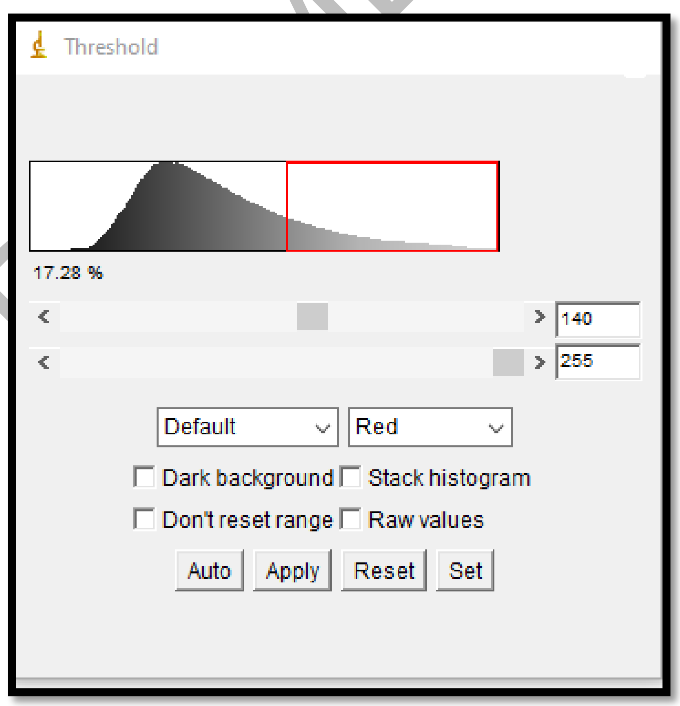


Figure 5.10: Photographs showing the porosity estimation (software value) of sample (NNS-8), Nilawahan Nala Section, Central Salt Range.

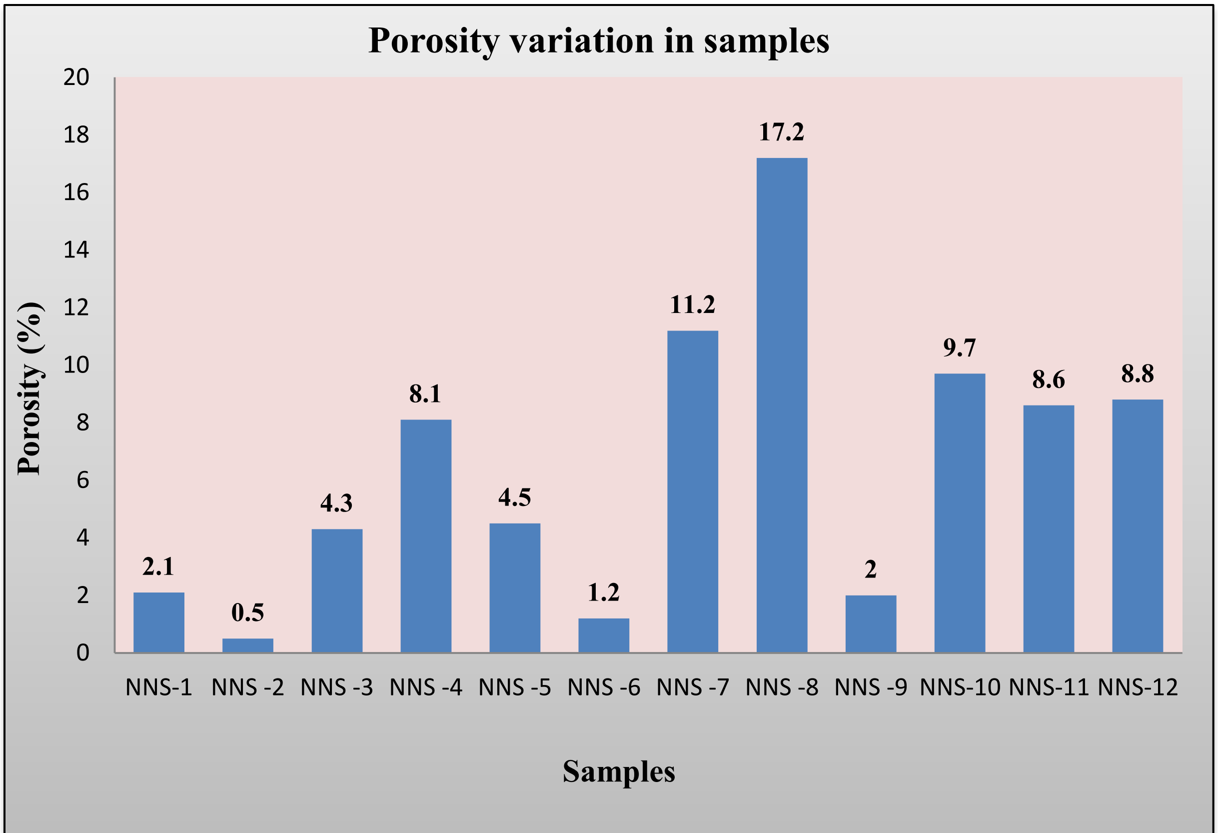


Figure 5.11: Graph representing the porosity trend of samples (NNS-1 to NNS-12), Nilawahan Nala Section.

The conventional range of porosities can be described as, Negligible (0-5%), Poor (5-10%), Fair (10-15%), Good (15-20%) and Very good (20-25%) given randomly in literature.

5.9 Core analysis (Plug Porosity results)

To know about the subsurface realities, core analysis is used as a tool to measure many important properties of the targeted formation. For this purpose the core intervals (cuttings) of a formation are transferred to the surface and are visualized as well as subjected to laboratories for knowing their porosity and permeability trends, textural variation, mineral composition and grain density also. These samples may be collected from conventional cores, sidewall cores or from cuttings of the concern well but mostly the analyses are done with the procured samples (core plugs) with an average length of 5cm (2 inches) and a diameter of 2.5 cm.

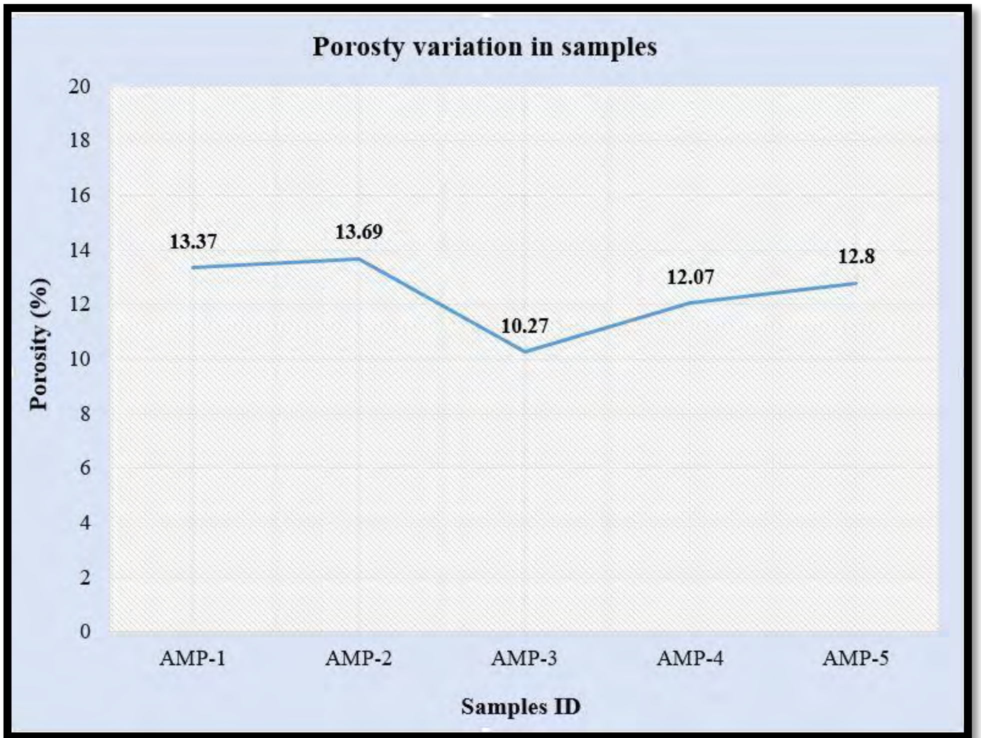
For the reservoir characterizations and assessment of Early Cambrian Khewra Sandstone, core intervals from two wells (Amirpur 01 & Daiwal 01) were used as a data material and were interpreted with different techniques in laboratories to get the desired porosity and permeability results as well as mineral composition and textural arrangement within the sandstone samples.

5.9.1 Amirpur 01 well results

A conventional core of Khewra Sandstone at a reservoir interval (2956 to 2965 m) of about 9m was studied and the porosity and permeability along with the other prominent parameters shown in (Table 5.11) were obtained with plugs analysis. The range of porosity is from 10.27 to 13.37% with the average value of 12.44 % while the permeability range shown is 0.58 to 217.57 mili Darcy with the average value of 85.4 mD. The lowest value of porosity at the bottom indicates that the grain packing is tight (fine grains) due to overburden pressure evidenced with the concave-convex and sutured contacts between grains as well as matrix abundance comparatively at the lower portion (AMP-3 and AMP-4) which has blocked the porous zone and minimized the porosity and permeability of beds, while the upper horizon acts as a potential zone with high porosity and permeability and low matrix contents, also the grain size is from medium to coarse with good sorting pattern and sub-rounded to rounded shape that enhanced the porosity trend (Plate 5). This interval has also proved to be a coarsening upward sequence observed from the petrographic analysis of all samples. The observed trend of porosity and permeability is shown (Figure 5.12).

Table 5.11: Showing various parameters from the core plugs analysis of (AMP-1 to AMP-5), Amirpur 01 well, Pakistan.

Sample (ID)	**Depth (m)**	**Length (cm)**	**Diameter (cm)**	**Dry weight (g)**	**Grain Density (g/cc)**	**Porosity (%)**	**Permeability (mD)**
AMP-1	2957	2.518	2.533	28.82	2.622	13.37	217.57
AMP-2	2959	2.531	2.548	29.16	2.618	13.69	120.22
AMP-3	2961	2.512	2.546	30.59	2.666	10.27	0.58
AMP-4	2963	2.514	2.537	28.88	2.672	12.07	82.52
AMP-5	2965	2.521	2.549	30.71	2.668	12.80	4.407



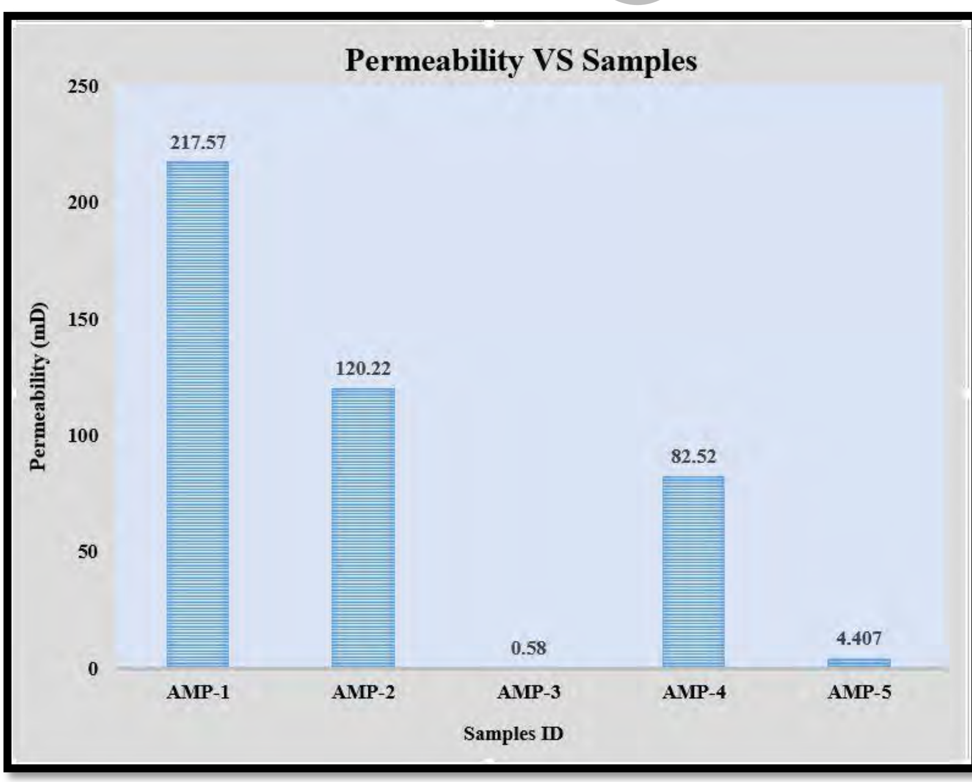


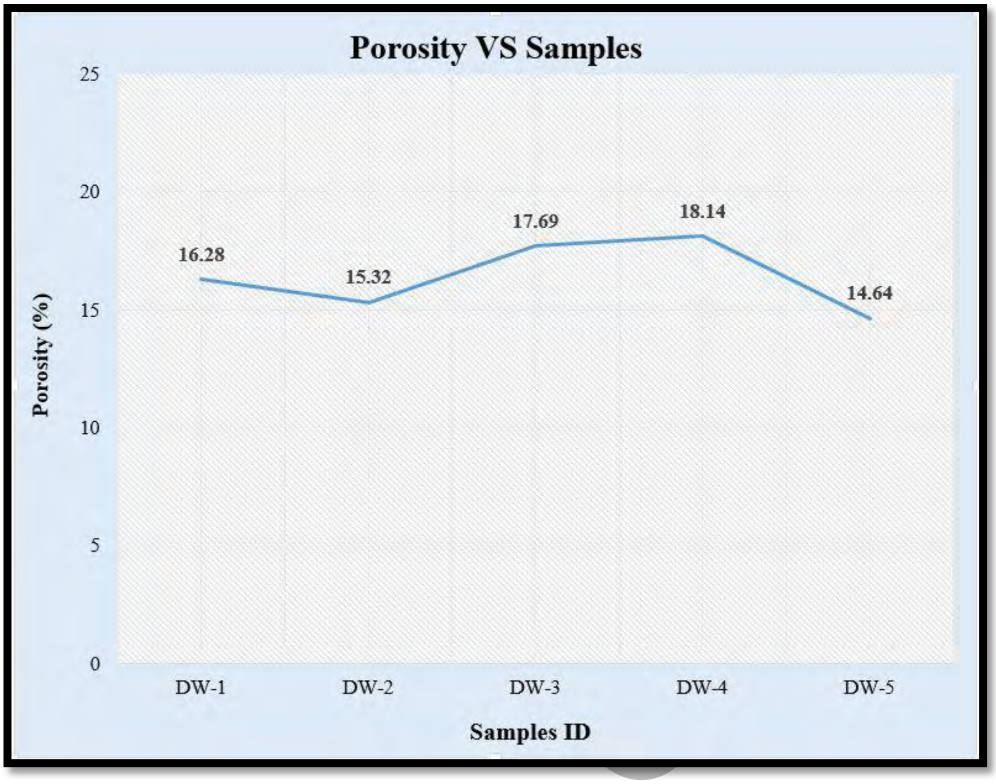
Figure 5.12: Graphs showing the Porosity and Permeability trends of samples (AMP-1 to AMP-5), Amirpur 01 well, Pakistan.

5.9.2 Daiwal 01 well results:

From this well, a core of Khewra Sandstone at a reservoir interval (2358 to 2367 m) was also studied and finally plug analysis was performed on selected samples from various depths and the obtained porosity and permeability results along with other parameters are shown in (Table 5.12). The acquired porosity range is from 14.64 to 18.14 % with the average value of 16.41 % while the permeability range is from 15.50 to 58.33 mili Darcy while the average is 42.59 mD. This interval of Khewra Sandstone has comparatively high porosity and is more than that of the Amirpur 01 well which is a good sign to be correlated with the petrographic interpretations shown in (Table 5.6) and photomicrographs of thin sections (Plate 6). Based on that correlation, it is concluded that matrix component here is comparatively low while the grains are of equal size with good sorting pattern. The variation in porosity and permeability is shown in (Figure 5.13).

Table 5.12: Showing various parameters from the core plugs analysis of (DW-1 to DW-5), Daiwal 01 well, Pakistan.

Sample (ID)	**Depth (m)**	**Length (cm)**	**Diameter (cm)**	**Dry weight (g)**	**Grain Density (g/cc)**	**Porosity (%)**	**Permeability (mD)**
DW-1	2358	2.843	2.555	32.20	2.639	16.28	58.25
DW-2	2360	2.823	2.523	29.41	2.643	15.32	56.12
DW-3	2362	2.621	2.541	30.34	2.656	17.69	24.79
DW-4	2364	2.827	2.546	31.26	2.653	18.14	58.33
DW-5	2367	2.526	2.539	28.86	2.644	14.64	15.50



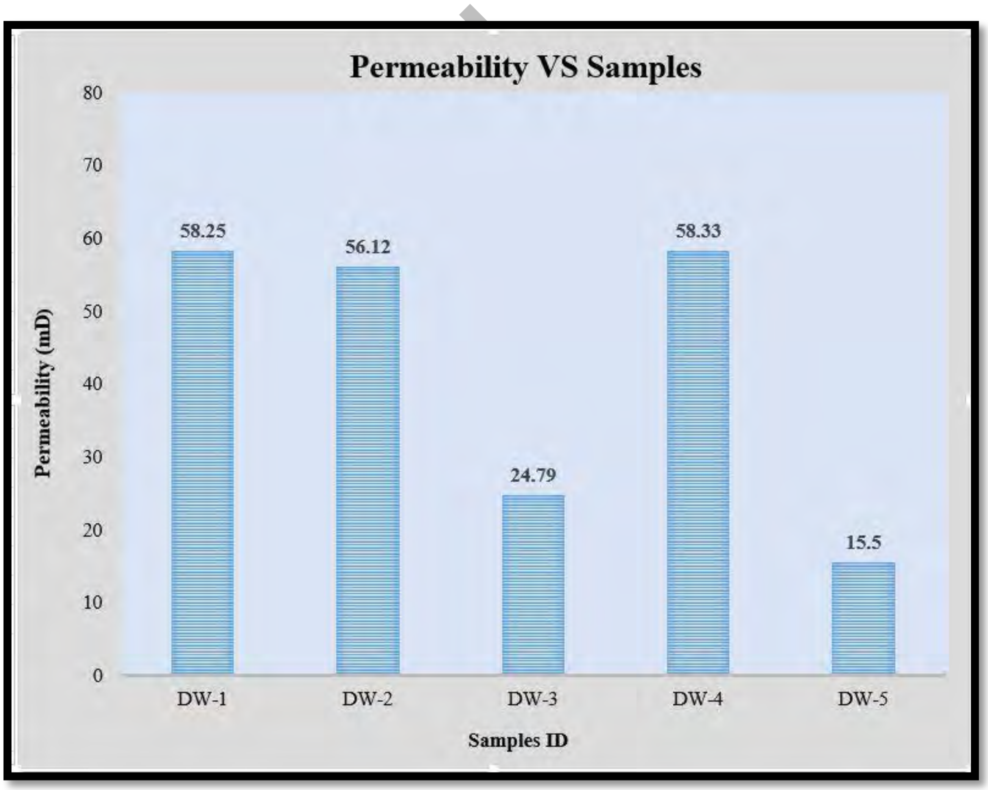


Figure 5.13: Graphs showing the Porosity and Permeability trends of samples (DW-1 to DW-5), Daiwal 01 well, Pakistan.

5.10 Discussions

The purpose of this section is to conclusively discuss the overall results and findings based on the analyzed data material.

5.10.1 Petrographic Interpretations

The major portion of this research work is based on petrography which has disclosed various facts about the interpreted data. From the detail analysis and observations, Khewra Sandstone from the outcrop sections as well as from the subsurface (well cuttings) is classified into its compositional nature and also its provenance is studied according to the standard classifications.

5.10.1.1 Outcrop Sections

From the Khewra Gorge section, it is interpreted that the sandstone in this section is classified mostly to the "sub-arkosic arenites" with some samples in "arkosic" domain based on Pettijohn et al (1987) classification while the provenance origin is "Craton interior" for the major portion while few samples also falls in "Transitional continental" field shown in (Figures 5.1 & 5.3) respectively. These all facts and findings were correlated with the standards reported in literature and used worldwide and finally these acquired results were plotted for the current section. The classification of sandstone is entirely based on the framework (Q-F-L) constituents whose percentage variation actually influences the nature of the classification. As the matrix contents are less than 5% and the sandstone is grain supported while the feldspar (F) values have actually choose the discussed classified fields for all the samples. The higher concentration of feldspar has divided the sandstone into arkosic nature while comparatively fewer amounts have divided the same lithology into sub-arkosic nature.

The Khewra Sandstone from Nilawahan Nala Section was petrographically studied and is classified based on the same standard criteria used for the above discussed section. The results are such that the sandstone is classified into "sub-arkosic and arkosic arenites" according to the framework constituent proportion while the provenance origin is "Craton interior" for the entire section with few samples from "Transitional continental" region shown in (Figure 5.2 & 5.4).

5.10.1.2 Well cuttings

The samples from Amirpur 01 and Daiwal 01 wells were also studied and classified according to the ongoing scheme based on that the major portion of Khewra Sandstone from these two wells is “sub-arkosic arenites” in nature with no arkosic samples while the provenance origin for both is “Craton interior” entirely shown in (Figures 5.5, 5.6 & 5.7).

This result is differentiated from the outcrop sections because of the framework constituents as well as matrix contents which are the influential substrate to affect the entire scheme of classification. The feldspar (Ft) grains in these samples are comparitevely less than those calculated from the outcrop sections while the quartz (Qt) composition is high which has differentiated the subsurface petrographic results of Khewra Sandstone from the surface (outcrop sections).

5.10.2 Reservoir quality

The reservoir parameters (Porosity & Permeability) for Khewra Sandstone were estimated visually from petrographic observations for the outcrop sections as well as from the core plug analysis for well cuttings which are discussed as,

5.10.2.1 Outcrop samples

The porosity values for Khewra Sandstone collected from the outcrop sections are shown in (Table 5.9 & 5.10) which are actually the visually estimated as well as software calculated results. These values after comparing with the porosity values of Khan et al (2012) calculated from plugs analysis (Khewra Gorge Section) and Siddique et al (2003) from Adhi oil field, concludes that the porosity values from upper horizons of both these sections are almost comparable to the discussed limits and are potential zones to be explored for petroleum while the Khewra Sandstone at the lower portion is said to be tight in nature because of overburden pressure and intense grain packing. Also the matrix contents calculated from petrography is high in the lower beds while the grains are fine to medium in size which has minimized the porous zones compare to the upper reservoir horizon (coarsed grains & low matrix).

5.10.2.2 Core plugs (well cuttings)

The subsurface samples of Khewra Sandstone from the two wells (Amirpur 01 & Daiwal 01) were also evaluated for the reservoir porosity and permeability trends through core plug analysis which has given more authentic and real results due to less chances of errors (machine) shown in (Table 5.11 and 5.12). These results were also compared with the discussed values of (Khan et al, 2012: Siddique et al, 2003) based on which the reservoir properties of sandstone from these core intervals are also good and are recommended for the exploration of hydrocarbon. Especially the values of porosity are much high (>15%) in Daiwal 01 (cuttings) than those reported from Amirpur 01 (10-15%) which is a positive sign for the said well to be focused more.

Also the type of reservoir from these results is evaluated based on Nabawy et al (2018a) classification shown in (Table 5.14). The average values of porosity and permeability from both the wells are compared with the discussed standard classification scheme (Table 5.13) and the estimated results are discussed as,

- The average porosity and permeability values calculated from Amirpur 01 well (core cuttings) are 12.4% and 85.04 mD which have classified this reservoir into different ranks i.e, based on porosity value the reservoir will be “Fair” with (Rank 4) while the permeability has classified the same reservoir into (Rank 3) with “Good” reservoir potentiality index.
- While the porosity and permeability values from Daiwal 01 well (core cuttings) are 16.41% and 42.59 mD which has ranked this reservoir into (Rank 3) with “Good” reservoir potentiality index.

- By comparing with the standard chart of (Nabawy et al, 2018) the obtained results are as under,

Table 5.13: Showing the standard chart of (Nabawy et al, 2018a) classification for reservoirs.

Porosity (%)	**Rank**	**Permeability (mD)**	**Rank**	**Reservoir Quality Index (um)**	**Rank**	**Reservoir Potentiality Index**
25 < Ø	1	1000 < k	1	5.00 < RQI	1	Excellent
20 < Ø ≤ 25	2	100 < k ≤ 1000	2	2.00 < RQI ≤ 5.00	2	Very good
15 < Ø ≤ 20	3	10 < k ≤ 100	3	1.00 < RQI ≤ 2.00	3	Good
10 < Ø ≤ 15	4	1.0 < K ≤ 10	4	0.50 < RQI ≤ 1.00	4	Fair
5 < Ø ≤ 10	5	0.1 < k ≤ 1.0	5	0.25 < RQI ≤ 0.50	5	Poor
0 < Ø ≤ 5	6	0 < k ≤ 0.1	6	0.00 < RQI ≤ 0.25	6	Tight

Table 5.14: Showing the type of reservoir for the studied wells based on Nabawy et al, 2018 classification.

Well name	**Porosity (%)**	**Permeability (mD)**	**Rank**	**Reservoir Potentiality index**
Amirpur 01	12.4 %	85.04 mD	4,3	Fair to Good
Daiwal 01	16.41 %	42.59 mD	3	Good

CONCLUSIONS

With the discussed integrated approach based on surface and sub- surface data set, it is concluded that how the reservoir quality and provenance origin of Early Cambrian Khewra Sandstone is evaluated and during this detail assessment , the following key outcomes are reported as,

- The petrographic interpretations of Khewra Sandstone has divided the major portion of this sandstone into "sub-arkosic arenites" with few samples from both the outcrop sections and core cuttings into "arkosic" domain as well based on quantitative compositional pattern of framework grains (Q-F-L).
- The provenance of Khewra Sandstone is evaluated as "Craton interior" with few samples from "Transitional continental" region also.
- Based on porosity and permeability trends, this sandstone is classified as good reservoir (specially the upper 35- 40 m portion) for hydrocarbon exploration.

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