TECTONIC SETTING AND PROVENANCE STUDY OF LOWER JURASSIC DATTA FORMATION POTWAR BASIN, PAKISTAN

By

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CERTIFICATE

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Dedication

My current research work is dedicated to my beloved parents as well as my teachers whose endless encouragement make it possible to complete the project.

ACKNOWLEGEMENT

Most humbly, we express my thanks to **Almighty Allah**, whose divine help made us able to complete this dissertation successfully and has always blessed with more than what we deserve.

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ABSTRACT

The tectonic setting and provenance study of the sandstone of the Datta formation, Early Jurassic of age, has been established under the current research work. The project area located in western part of Salt Range famously known as Nammal Gorge in the district Mianwali. During the field work fourteen samples were collected for the purpose of petrography as well as XRF analysis. Fourteen thin-sections were prepared and studied under microscope. The frame work grains such as quartz, feldspar and rock fragments alongside with accessory minerals were observed under microscope. All the obtained data presented in tabular form for further utilization. QFL triangular plots were plotted to classify sandstone of the Datta Formation by using Folk's (1974) classification. Nine samples of the sandstone were geochemically analyzed (major elements) by Geo Advanced Research Lab (GARL), Islamabad. On the basis of the results, the discrimination diagrams are plotted to find out the provenance study of the Datta Formation. The petrographic studies reveal that the source area lies "Craton Interior" as well as in the "Recycled Orogen". The geochemical studies reinforce the petrographic results. The Aravalli Range or Indian Cratonic rocks of Precambrian age was source area that was weathered as well as eroded to deposit as the Datta Formation. This research is further reinforce by paleo-current analysis which show that the direction of sediment transportation was from ESE to WNW during the Jurassic time.

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1.1 Background

The Formation has surficial exposure in Salt Range and in the Surghar Range. It exhibit clastic facies assemblage having multi-color sandstone, carbonaceous shale, siltstone and fireclay. The sandstone of the Datta Formation acts as hydrocarbon reservoir in the adjacent and KPK areas and has been selected for provenance study to unearth the further hydrocarbon exploration in future. The sandstone present in the Datta Formation acting as a reservoir rock in Potowar basin, this study will help to explore further hydrocarbon potential in the Datta Formation. Silica sand and fire clay deposits can be found with the help of provenance studies.

1.2 Objectives

The objectives of the research work has given below:

- To find out the provenance of sandstone.
- Provenance study of the sandstone.
- Petrographic study of clastic sediments.
- Detrital Frame work of the sandstone.

1.3 Introduction to study area

The surface outcrops of the Datta Formation are located in Marwat, Sheikh Budin Hills, and Surghar Range in the Trans Indus Ranges and in the western part of Salt Range (Abbasi et al 2010). The Datta Formation has subsurface extension in Kohat as well as in the western Potohar (Figure 1.1).

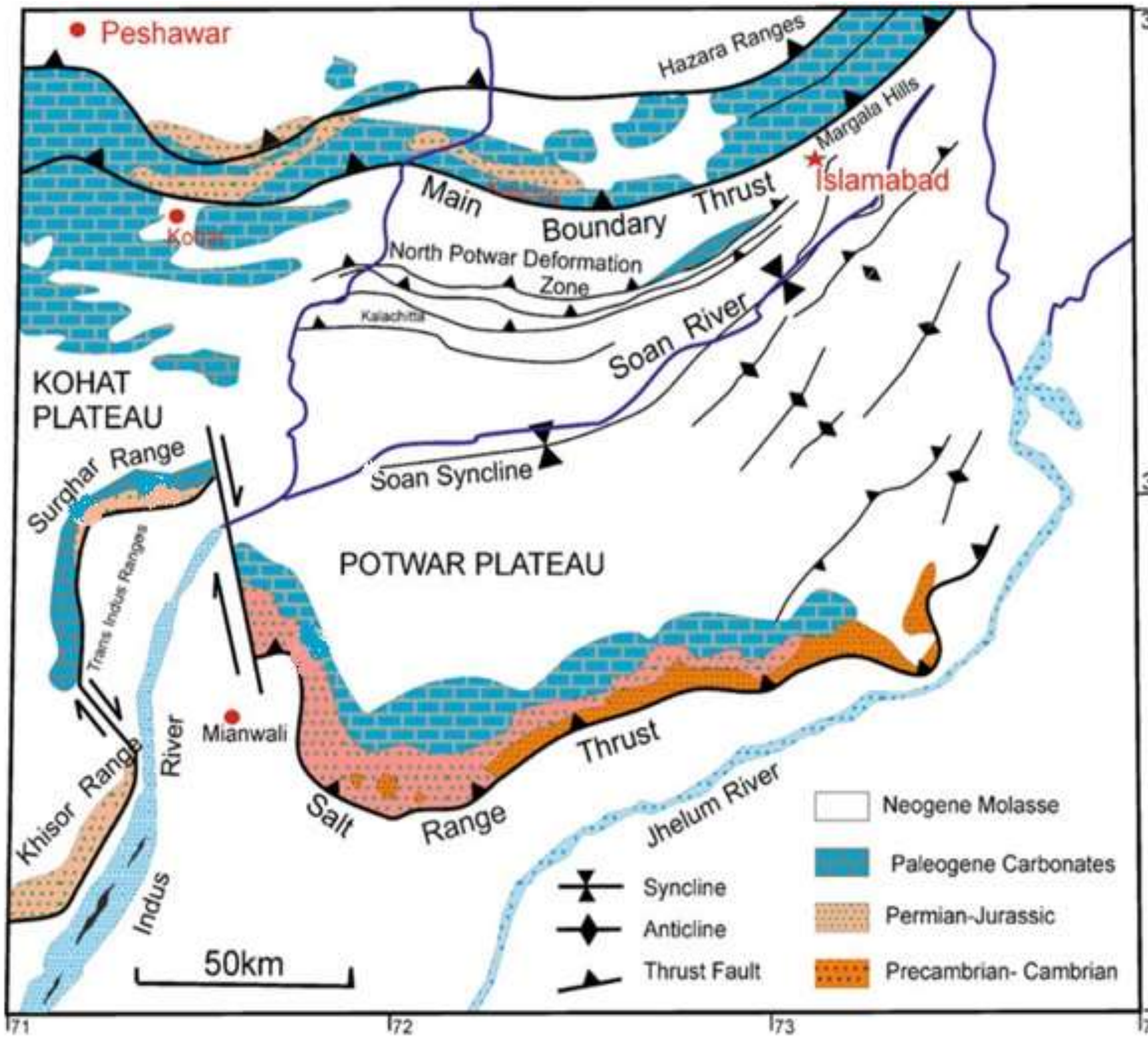


Figure 1.1 shows the distribution various litho-logical units in NW Pakistan (After Abbasi et al, 2010)

1.3.1 Location of the study area

Area lies near the town of Essakhel, in the district of Mianwali (Figure 1.2). The longitudinal value is 32^{o} 43'10" whereas the Latitudinal value is 71 ^{o}48'51".

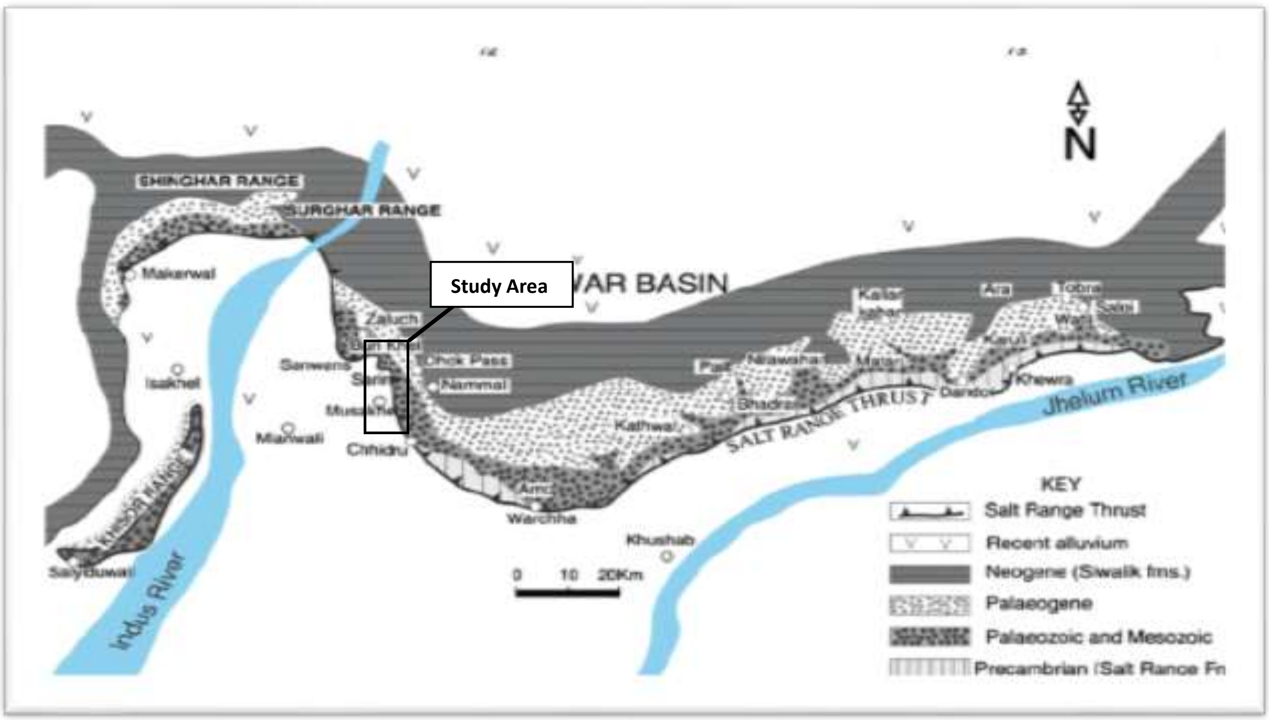


Figure 1.2 Geological map of the Northern Pakistan, area in rectangle showing the study area, (Modified after Jan and Stephenson, 2011).

1.3.2 Tectonics of the area

The thrust belts are formed due the tectonic collision of northward drifting Indian plate to the Eurasian plate. The effect of the ongoing collision continuously moved from north direction to the southward, that’s why, much younger faults are present in the southern side of the Indian plate. Himalayan range on the basis tectonics has been sub-divided into four categories

i) Tethyan Himalayan
ii) High Himalayan
iii) Lesser Himalayan
iv) Sub Himalayan

The Tethyan Himalaya

The Tethyan Himalayan lies between MKT to MMT. This region in terms of structural geology extremely complex.

The Higher Himalaya

The region lie between MMT in the north to the MCT has been known as Higher Himalaya. The rocks exposed in this region igneous complexes and high grade metamorphic rocks (Fig.3.1).

The Lesser Himalaya

The area between MCT and MBT is known as the Lesser Himalaya. This region is further subdivided by Panjal Thrust (PT) into categories that is sedimentary region as well as igneous metamorphic region.

The Sub Himalaya

The area lies between HFT and MBT is called as The Sub Himalaya. Himalayan Frontal thrust also known as Salt Range Thrust. The rocks exposed along this thrust ranges from Pre-Cambrian to Recent.

The Salt Range division

On the basis of structural deformation, Eastern, Western and Central Salt Range parts of the salt range have been named.

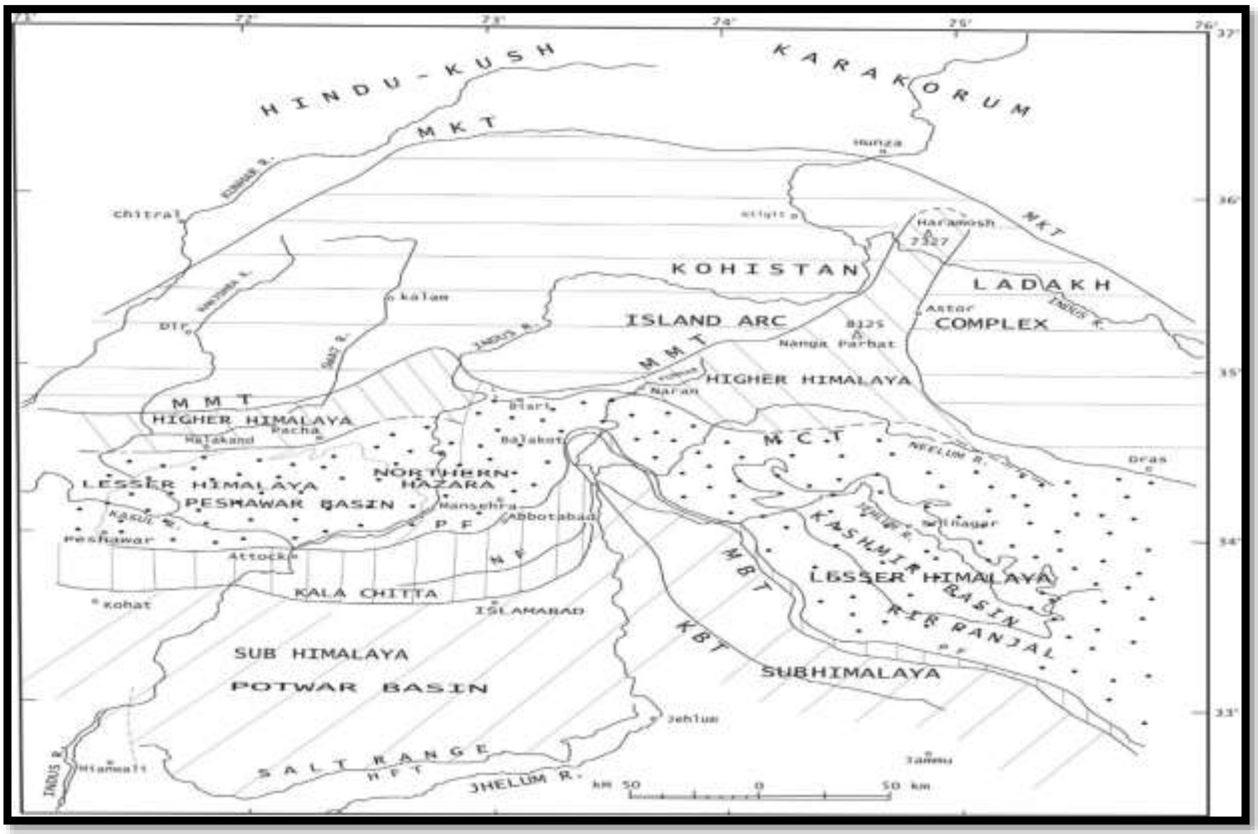


Figure 1.3 Map showing the division of NW Himalayas in Pakistan. (After Kazmi and Rana, 1982).

1.3.3 Generalized Straitigraphy

The rocks exposed in the study area from Permian age to the recent deposits (Table 1.1).

Wargal Limestone

Teichert (1966) introduced the name “Wargal limestone”. The formation is comprised of massive limestone of grey color. In the middle part it exhibit thin to medium bedded limestone with high fossil contents. It forms a gradational contact with above lying Chhidru formation whereas lower contact is not exposed (Shah 2009).

Chhidru Formation

The Chhidru Formation was formerly known as middle part of the “Productus Limestone”. The formation consists of arenaceous limestone as well as calcareous sandstone (Shah 2009). The formation also has some sedimentary structures such as ripple marks. The formation is rich fossiliferous content (Shah 2009). The formation belongs to Late Permian age on the basis of fauna present there.

Time Units			Rock Units	Description
Cenozoic	Tertiary	Pliocene	Dhok Pathan Foramtion	The formation consists of sandstone and clays
			Nagri Formation	The formation consists of sandstone and clays
			Chinji Foramtion	The formation comprises of sandstone and clays
		Miocene	Kamlial Foramtion	The formation consists of sandstone and shale
		Unconformity		
		Eocene	Sakesar Limestone	The formation consists of nodular limestone
			Nammal Formation	The formation consists of nodular limestone and shale
			Patala Formation	The formation consists of black shale
		Paleocene	Lockhart Formation	The formation consists of limestone
			Hangu Formation	The formation consists of sandstone and shale
Unconformity				
Mesozoic	Cretaceous	Late	Lumshiwal Formation	The formation consists of thick bedded sandstone
		Early	Chichali Formation	The formation comprises of black shale
	Jurassic	Late	Samana Suk Formation	The formation consists of mainly limestone
		Middle	Shinawari Formation	The formation consists of limestone with nodular marl
		Early	Datta Formation	The formation comprises of mainly sandstone with limestone and clay
	Unconformity			
	Triassic	Late	Kingriali Formation	The formation consists of mainly dolomite
		Middle	Tredian Formation	The formation comprises of micasous sandstone and shale
		Early	Mianwali Formation	The formation comprises of limestone, dolomite, shale and sandstone
Unconformity				
Paleozoic	Permian	Late	Chhidru Formation	The formation consists of mainly sandy limestone
			Wargal Formation	The formation consists of thick to massive bedded limestone

Table 1.1 Generalized description of the rock sequence in Nammal Gorge. (Shah 2009)

Mianwali Formation

The Formation consists of limestone, dolomite and sandstone (Shah 2009). The formation has been divided into three members. This formation demarcates the boundary between Permian and Triassic age which is also known as P-T boundary, along this boundary a major mass extinction has been taken place. The age on basis of fauna has been assigned is Early Triassic.

Tredian Formation

The Formation comprised of sandstone, the sandstone shows a non-marine environment of deposition. It has a few sedimentary structures like slump structure and ripple marks. On the basis of fossil content the Formation is known as Middle Triassic (Shah 2009).

Kingriali Formation

The formation consists of multiple lithologies such as sandstone, dolostone, shale minor part and limestone (Shah 2009). The age on the basis of fauna is Middle to Late Triassic.

Jurassic

Datta Formation

The formation is widely exposed in Trans Indus as well as Salt Range (Abbasi et al 2010). The Datta Formation has subsurface extension in Kohat as well as in the western Potohar. The Formation is correlated with Loralai Formation in the Sulaiman range. The Loralai Formation is of same Jurassic age.

Shinawari Formation

The Formation consists of limestone with nodular marl and ferruginous sandstone (Shah, 2009). The Middle Jurassic age is designated on the basis of fauna.

Samana Suk Formation

The name Samana Suk after the name of mountain peak in Samana Range. The formation lithologically comprises of limestone in bulk with a minor part is shale, limestone is thick to massive. Late Jurassic age is designated of the formation (Shah 2009).

Chichali Formation

The “Chichali Formation” was given by Danilchik (1961). Lithologically, it is comprised of glauconitic sandstone with glauconitic shale. The contact with Samana Suk formation is disconformable whereas that of with Lumshiwal Formation is conformable (Shah 2009). On the basis of fauna, the Early Cretaceous is designated age of this formation.

Lumshiwal Formation

The formation comprises of thick bedded to massive sandstone with minor glauconitic shale (Shah 2009). On the basis of fossil content, the Late Cretaceous is age of this formation.

Paleocene

Hangu Formation

The “Hangu Formation” after “Hangu Sandstone” from Davies (1930a). The formation consists of sandstone of various colors (Fatmi 1977). Early Paleocene is the designated age of Hangu Formation (Shah 2009).

Lockhart Limestone

The formation mainly consists of grey colored limestone. The limestone consists thin to thick bedded with high fossil content. The limestone in Salt Range exhibit nodularity. On the basis of fossil content, Middle Paleocene is designate age of the formation.

Patala Formation

Formation consists of mixed lithologies such fossiliferous shale, little marl. The shale is highly fossiliferous. In the eastern part of the Salt Range, it contains coal seams. On the basis of fossil content, the age the formation is Late Paleocene (Shah 2009).

Nammal Formation

The formation consists of limestone, shale with minor marl (Shah 2009).The limestone bears nodularity, with high fossil content. On basis of fossil content, the age of the formation is Early Eocene.

Sakesar Limestone

The formation consists of limestone and marl. It exhibits nodularity and highly fossiliferous. (Shah 2009). The formation is given as the Early Eocene, on the basis of fauna.

Kamlial Formation

The formation mainly consists of dark brick red sandstone. The sandstone consists of thin to thick bedded with alternating shale (Shah 2009). On the basis of fauna, the age of this formation is designated Late Murree.

Chingi formation

The formation consists of alternating sand and clay. The vertebrate fossils have reported in this formation. On the basis of fossils, the age of The Early Pliocene.

Nagri Formation

The lithological units of the formation contains of massively thick bedded sandstone with minor clay beds and conglomerate (Shah 2009). On the basis of fossils, the age of The Middle Pliocene.

Dhok Pathan Formation

The formation consists of alternating sand and clay. The sandstone medium to thick bedded whereas clay is fossiliferous. On the basis of fossils, the age of The Late Pliocene.

LITERATURE REVIEW

A lot of literature have been reviewed for the current study, some of which has narrated below

1. Hilmary, V.E et al., (2003) made a new approach to study the provenance of different formations. This scheme is devised for sandstone of synorogenic origin in the Alps region. Petrographic and geochemical (both the trace as well as major elements) methods are used to find out the origin. Furthermore, a few statistical parameters also applied to cross check the results.
2. Vermeesch, P., (2004) used single grain geochronology as well as statistical techniques to study provenance. Vermeesch used various mathematical equation to analyze the frequency of the data required for provenance study. Statistical techniques used to calculate p-max that helps to limit the density of the data.
3. Tykot, R.H., (2004) studies provenance studies different archaeological objects such pottery, glass, metals and a few other things. Analytical methods were used to study the physical properties such color, hardness, density and refractive index. The instruments were used are Neutron Activation Analysis (NAA), XRF, Proton induced X-ray/gamma ray (PIXE/PIGME) and optical emission spectroscopy (OES). On the basis of the results acquired through various instruments, dates has been established.
4. G.J Weltje et al (2004) has reviewed previous techniques of provenance study. After reviewing previous techniques, two classes has been formed, one is petro-facies analysis of sandstone composition and the plate tectonic environment, the second one. Weltje et al devised Quantitative Provenance Analysis (QPA) of sediments by using computer simulation model.
5. Morton, A.et al, (2004) used garnet mineral for the provenance study of North Sea Formation present in Norway and Scotland, because of the reason diagenetic processes have potential to alter the chemical makeup of the rocks. In this research adopted the

scheme to link between the source areas to the depositional site on the basis of garnet mineral group. The garnet compositions were determined by using XRF energy dispersive systems. Furthermore, a few analytical methods were also used to verify the results.

6.Datta, B., (2005) studied petrographic studies Chandarpur sandstone of Proterozoic age Chhattisgarh basin. Datta used petrography as a methodology and plotted various QFL diagrams to analyze the provenance as well as paleo-climatic conditions. Furthermore, histogram has been made to show the roundness of the detrital grains. Metamorphic rocks proved to be the source rocks for sediments.

7.Osae, S. et al (2005) used petrographic as well as geochemical studies to find out the provenance of Buem Sandstone of Late Proterozoic age exposed in the South east of Ghana. The sandstone was classified on basis QFL plots, various discrimination plots were made using XRF data.

8. Banco, G.,et al (2006) adopted relatively advance technique to study the provenance of Black Sands Early Cambrian rocks of Fish River Formation having outcrops in Namibia. The methods were used U-Pb Zircon Radiometric dating, petrographic studies and geochemical studies. The radiometric dating provided absolute geochronology or absolute age of the rock formation.

9. Jafarzadah et al (2008) has studied Ahwaz Sandstone member of Asmari Formation of early Miocene in the Zagros Mountains Iran. Petrographic as well as geochemical methods are adopted to study the provenance study. On the basis of thin-section studies sandstone is classified into quartzarenite and sublitharenite. Geochemical data reinforces the results of microscopic studies. Numerous plots has been plotted to analyze the paleo-climate and maturity of the sediments. Moreover, various discriminant diagrams show that the provenance are from the Quartzose sedimentary region.

10. Martinek et. al (2009) has studied the Permian sediments of the Krkonse Piedmont basin. Pebbles of near basin margin underwent heavy mineral association (HMA). HMA reveals that the sediment have gone repeatedly recycling and Vrchlabi formation acted as provenance for these detrital sediments. The garnet compositions in sand point out the leuco-granites and pegmatites situated in the North Eastern side.

11. Hazarika, S., (2011) studied the diagenetic history and the provenance of the Tertiary

formations having hydrocarbon potential in Assam Basin of India. The petrographic studies were used to study the provenance and burial diagenesis of the formation.

12. Abbasi, I.A et al (2010) used to various lithological correlations to study the different litho-facies of the Early Jurassic Datta Formation in Western Salt Range, Potowar, Kohat Basin and Hazara Basin of Northern Pakistan. After correlating the various facies at different localities, a detailed and comprehensive depositional model has been prepared.
13. Pizarro,C., et al., (2011) used analysis based on multivariate parameters to study the provenance of limestone. NAA or Neutron Activation Analysis and SLDA or stepwise linear discrimination analysis were used on various limestone samples. Different discrimination diagrams are made using SLDA techniques. These techniques produced high quality results on relatively low density data.
14. Durrani, R.A.M., et al, (2012) studied Loralai Formation of Jurassic age, in the Sulaiman Fold-Thrust Belt, Pakistan. Durrani conducted fieldwork in various areas for section-measurement. Thin-section of selected samples were prepared for petrographic studies. On the basis of the microscopic studies, sandstone of the Loralai Formation is classified by using QFL diagrams. Indian Cratonic rocks are proved as the provenance study for the sandstone of the Loralai formation.
15. Jalal, P et. al (2012) studied Siwaliks sandstone of Late Neogene age in Kumuan Himalayan Foreland Basin by using petrographic studies. Metamorphic rank has been calculated by studying phyllo-silicates such as illite-smectite minerals. Afterwards, metamorphic ranks classified into rank Rm1, rank Rm2, rank Rm3 and rank Rm4 to analyze the metamorphic grades. Abundance of Rm2 and Rm3 show presence of a thrusted sheet of crystalline body 07 Ma ago. That particular thrust sheet Main Boundary Thrust (MBT) placed a crystalline body.

RESEARCH METHODOLOGY

During the research work, three research methods were applied, which are listed below.

- Geological field work of the project area
- Lab Work
  - i) Petrography
  - ii) X-Ray Fluorescence (XRF)

3.1 Geological Fieldwork

Geological fieldwork was carried out in the project area which is situated in Nammal Gorge in district Mianwali Figure (3.1). During the fieldwork, a reconnaissance traverses were completed to understand the local geology of the area (Figure 3.2).

Figure 3.1 shows panoramic view of the Nammal Gorge

3.1.2 Sample collection

Samples of sandstone in Datta Formation was collection from the fresh surface. Sampling bags were used to preserve the samples. Fresh samples as well as neat and clean samples were collected. Geological hammer were used to break the samples from the formation.

3.1.3 Field Photographs

Field photographs were of the various lithological units taken (Figure 3.3). These lithological units consist of sandstone, carbonaceous shale, siltstone, conglomeratic bed.

(a)

(b)

(d)

©

(e)

(f)

(g)

Figure 3.2 shows (a) Shale unit (b) Carbonaceous shale (c) Ferruginous sandstone (d) Conglomeratic bed (e) Siltstone unit (f) Siltstone with Carbonaceous shale (g) Fractured sandstone with black shale

3.1.4 Preparation of Litho-Log

A detailed and comprehensive litho-log has been prepared to demarcate the various lithological units, sedimentary structures. On the litho-log various spots has been marked to point out lithological units where samples has been taken for petrographical studies. Each lithological units has been briefly explained.

3.2 Lab Work

In lab work, preserved samples were analyzed by two methods that is given below

3.2.1 Petrography

14 thin-sections were prepared from the collected samples for the purpose of petrographical studies. Various triangular plots were drawn to study the provenance area of the sandstone. Petrographical data also arranged in tabular form with respect to their percentages. QFL Diagrams were plotted to show the provenance area.

3.2.2 XRF

Nine samples were sent to Geoscience Advanced Research Lab (GARL) Islamabad, to investigate the chemical make-up (only for major elements) of the minerals in the sandstone. After sometime, results were received from Geosciences Lab. Different plots were prepared using the various ratios. Chemical Index of Weathering (CIW) as well as Chemical Index of Alteration (CIA) were also calculated from the received data.

RESULTS AND DISCUSSIONS

4.1 Datta Formation

The outcropic exposures of the formation are found in Marwat, Sheikh Budin Hills, and Surghar Range. There is also some surficial exposures of the formation Western Salt Range (Abbasi et al 2010). The Datta Formation has subsurface extension in Kohat as well as in the western Potohar.

The formation exhibits clastic facies assemblage having multi-color sandstone, carbonaceous shale, siltstone and fireclay in western salt range as well as in Surghar range (Abbasi et al 2010). The sandstone bears whitest silica sand along with hematitic beds. Both silica sand and fireclay have economic utilization. Moreover, the Datta Formation act as reservoir rock. Whereas, in the Hazara and Kala Chitta area, the Datta Formation has marly carbonate facies (Qureshi et al, 2005). Datta Formation is 200m in its type locality in Datta Nala in Trans-Indus ranges, whereas150m in the Nammal Gorge and decreases in the eastward direction (Shah 2009).It is about 20m in the Kalachitta area (Choudhry and Ahsan, 1999) and 15 to 30m thick in the Hazara area (Qureshi et al, 2005). In the Pre-Tertiary uplift, Jurassic rocks has been eroded in the eastern, central Salt Range and in the eastern Potohar (Kazmi and Abbasi, 2008).In the most parts of the Northern area, the Datta Formation has unconformable contact with underlying Triassic Kingriali Formation, whereas in Hazara region it has unconformable contact with the Precambrian, Paleozoic and Triassic rocks as well (Kazmi and Abbasi, 2008). The Early Jurassic age is assigned to the formation, on the basis fauna, Classopollis classoides has been found in the Datta Formation. (Fatmi, 1977).

Thickness of Datta Formation is 100m in the project area. Various units of the Datta Formation with distinguished features show in Stratigraphic-Log (Figure 4.1).The Datta Formation is correlated with Loralai Formation in the Sulaiman range. The Loralai Formation is of same Jurassic age.

4.1.1 Importance of Litho-Log

Litho-log is a detail description of rock unit. The detailed description includes sedimentary structures like cross-bedding, ripple marks. Litho-log provides lithological variation like sandstone, shale, limestone which leads to interpret the environment of deposition. Sedimentary structures like cross-bedding assist to deduce the paleo-current analysis. Furthermore, accurate

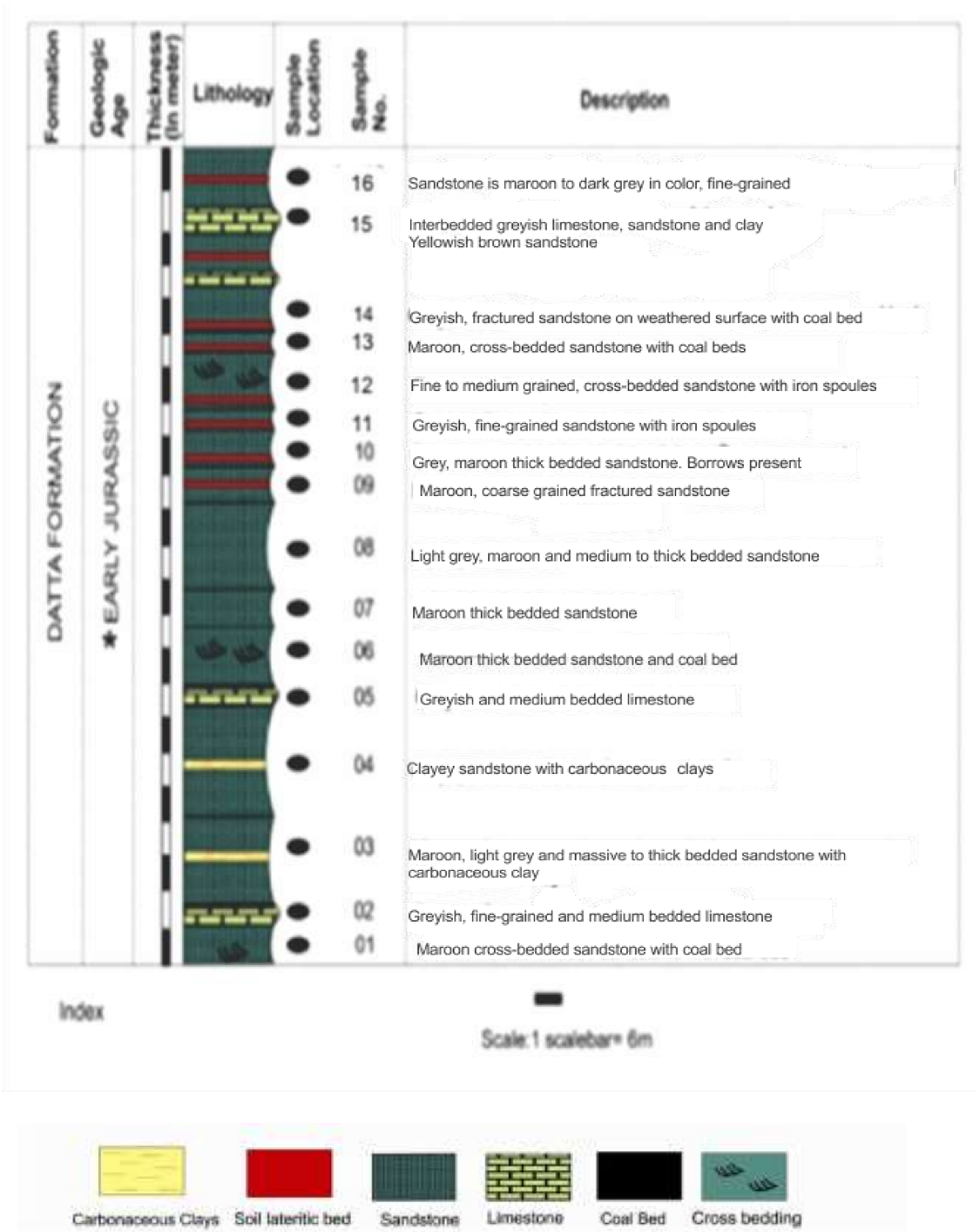


Figure 4.1 Litho-Log of Datta Formation in the project area

Thickness of rock helps in interpreting the depo-center during the time of deposition. Litho-log also useful for regional surface and subsurface correlation on the basis of age as well as lithology. Moreover, Litho-log provides deep insight into economic minerals like in Datta Formation, it is renowned for its economic deposits of fireclay, silica sand etc. (Shah 2009).

4.2 Petrographic Analysis

There are 14 thin-sections were prepared to analyze under the polarized microscope to study the detrital framework of the formation. Sandstone of Datta Formation is mainly composed of quartz arenite which grades into sublitharenite minor (Table 4.1). In quartz arenite quartz occurs around 90% whereas other constituents such feldspar, rock fragments contribute minor parts up to 3% and 2 % respectively. In the case sub litharenite rock fragments share goes up to 5 % similarly with feldspar 3 to 4 %, whereas quarts contribution decline to 70 to 80 %.

4.2.1 Mineralogical Assemblage

The formation mineralogical assemblage has been summarized in a table 4.1. From the table 4.1, it has been noted that the percentage of the silica ranges from 70% to 90%. Whereas minor percentages of K-feldspars, microcline, plagioclase, lithic fragments, micas (muscovite and biotite), and some opaque heavy minerals. Micas, zircon, monazite and tourmaline are the accessory minerals found in the thin-section studies. These reported accessory minerals make up the around 1 % of the total grains.

4.2.2 The Matrix

The percentage of the matrix ranges from 3-4%, the reason the behind the low percentage of the matrix is that the sandstone has been travelled a lot during its deposition due to which small sized grains got cleaned.

4.2.3 The Cement

There are four types of cement found in clastic rocks that are calcareous, siliceous, ferruginous and argillaceous. Here it is found that the siliceous cement which is recognized by the rims on the quartz grains also known as silica overgrowth (plate 1). Quartz, lithic fragment, feldspar, Datta Sandstone Classification

Thin Section #	Quartz %			Feldspar %				Accessory %			Rock Fragment %	Dolomite %	Total Grain %	Clay cement %	Chert/Silica %	Carbonates %	Iron oxide %	Folk`s (1974) Classification
								Micas %	Tourmaline %	Monazite %								
	Q_m	Q_p	Q_t	F_o	F_{pg}	F_{mi}	F_t					-						
01	83	01	84	-	01	01	02	01	01	-	-	-	88	09	-	-	03	Quartzarenite
02	77	02	78	-	01	01	02	01	-	01	-	-	82	10	01	01	05	Quartzarenite
03	80	02	82	-	01	02	03	01	-	-	03	-	89	01	09	-	01	Sublitharenite
04	75	01	77	-	01	-	01	01	-	-	05	-	83	01	01	01	14	Sublitharenite
05	70	01	71	-	01	-	01	01	-	-	01	30	94	-	-	04	02	Sublitharenite
06	89	01	90	-	01	0	01	-	-	-	02	-	92	-	-	02	07	Quartzarenite
07	74	01	75	-	01	01	02	01	01	0.5	01	-	80.5	15	-	02	03	Sublitharenite
08	80	01	85	-	0.5	0.5	01	01	-	-	02	-	89	08	01	0.5	02	Quartzarenite
10	79	01	80	-	01	01	02	01	01	0.5	02	-	84.5	10	01	01	02	Sublitharenite
11	88	02	90	-	0.5	0.5	01	-	-	-	-	-	91	-	-	-	09	Quartzarenite
12	79	01	80	-	01	01	02	01	01	01	02	-	87	01	-	-	12	Sublitharenite
13	79	01	80	-	01	01	02	01	01	01	05	-	90	10	-	-	-	Sublitharenite
14	73	02	75	-	0.5	0.5	01	01	01	01	01	-	79	15	01		05	Sublitharenite

Table 4.1. Detrital modes of selected samples of the Datta Formation, Western Salt Range, Pakistan Cn- Common, Re- Rare, Q-Quartz, m-Monocrystalline, p-Polycrystalline, F-Feldspar, o-orthoclase, pg-plagioclase, mi-microcline, t-total Fe- Ferruginous

calcite and hematite has been observed (plate 2). The presence of argillaceous sediments, dolomite, hematite, quartz, plagioclase, mica has noticed (plate 3&4).

There are two types of quartz grain that is monocrystalline and polycrystalline. Here it is found that quartz is of monocrystalline nature. The monocrystalline quartz typically show both undulatory extinction as well as non-undulatory extinction. These both type of extinction can be referred as strained as well non-strained quartz (Figure.4.1). The presence of strained quartz in a thin-section show that the origin of this quartz from the igneous as well as metamorphic rocks.

During the petrography quartz was classified into two categories on the basis of undulose extinction and non-undulose extinction. In Figure 4.1 on the basis of monocrystalline quartz with non-undulose extinction, polycrystalline quartz with undulose extinction, as well as polycrystalline quartz with more than crystals and polycrystalline quartz with less than three crystals are the classifying factors. In this plot the data of the Datta formation fall in the domain of plutonic igneous rocks and low rank metamorphic rock (Figure 4.1a). Whereas data fall in the category of granites as well as mid and upper rank gneisses. The sandstone is classified using the Folk 1974 classification and shown as in the ternary diagrams (QFR). According to the Folk's classification, the sandstone fall into the category of arenite and sublitharenite (Figure.4.2) (Folk, 1974).

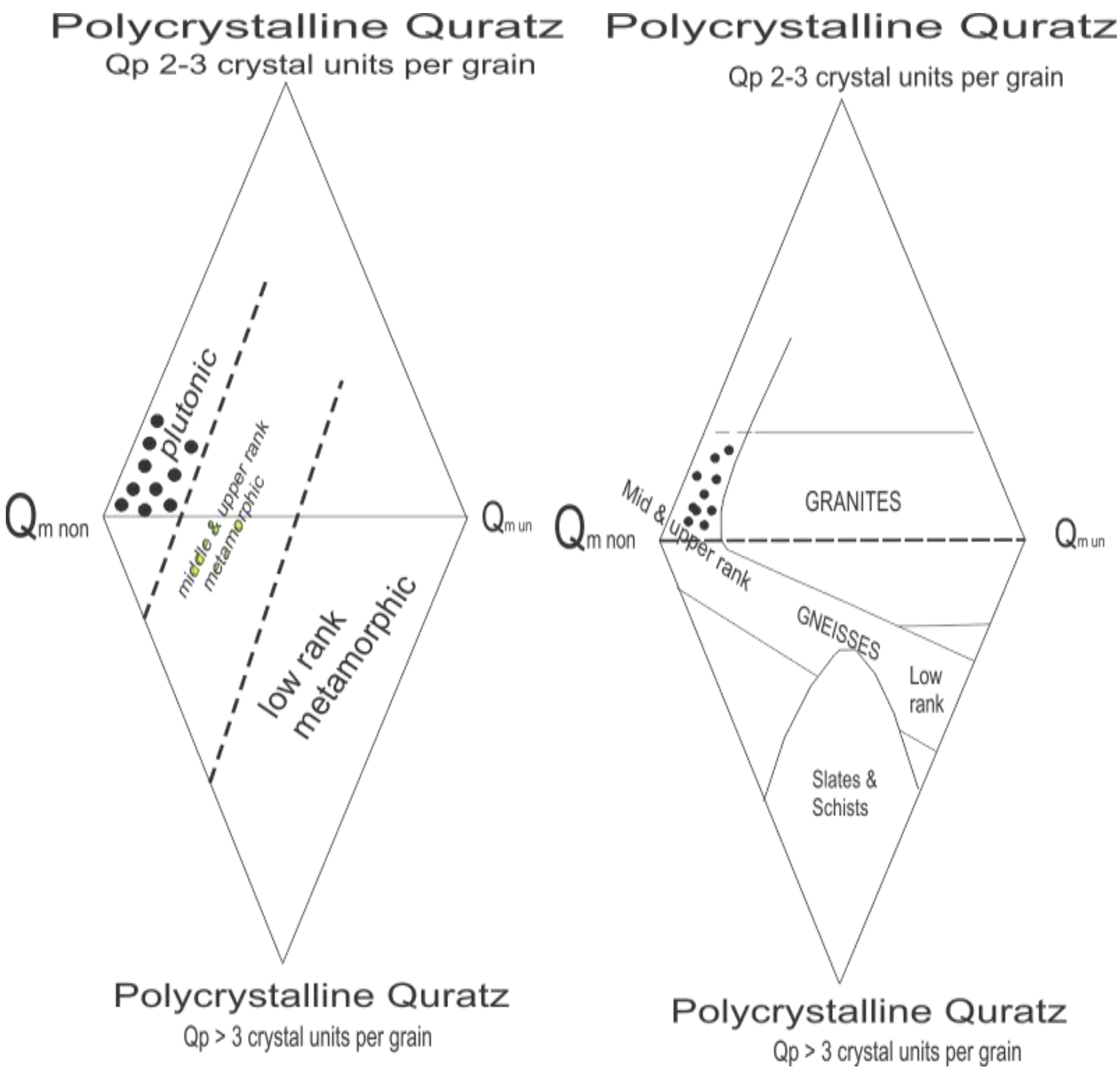


Figure 4.2 Varietal quartz diamond plot currently used to discriminate sands sourced by different types of crystalline rocks, on the basis of the extinction pattern and polycrystallinity of quartz grains

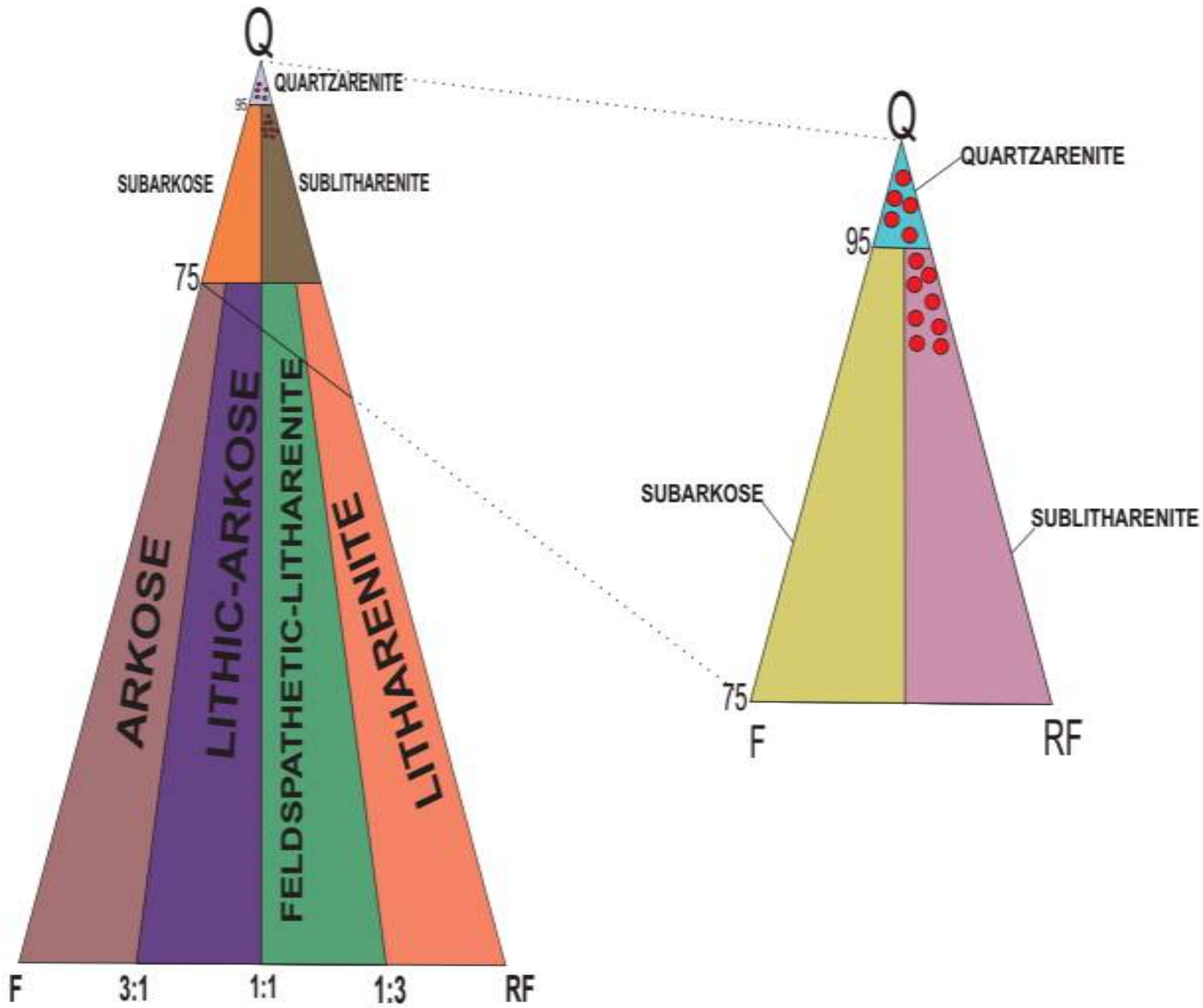
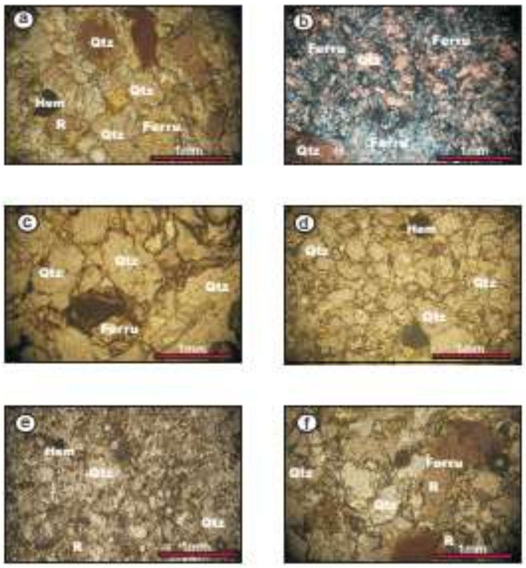


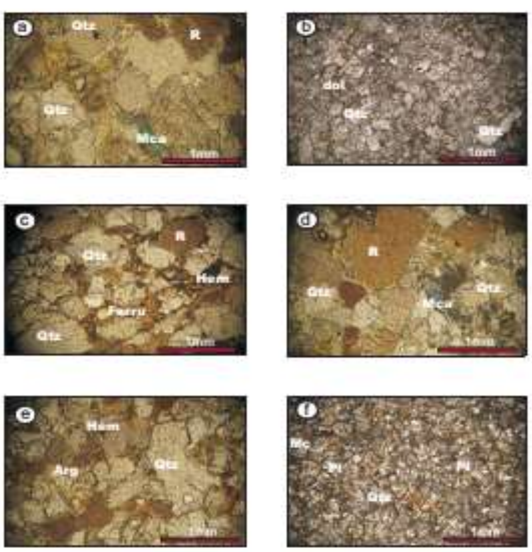
Figure 4.3 QFR triangular classification plot (Folk, 1974) of different sandstone samples from the Datta Formation

Plate 1



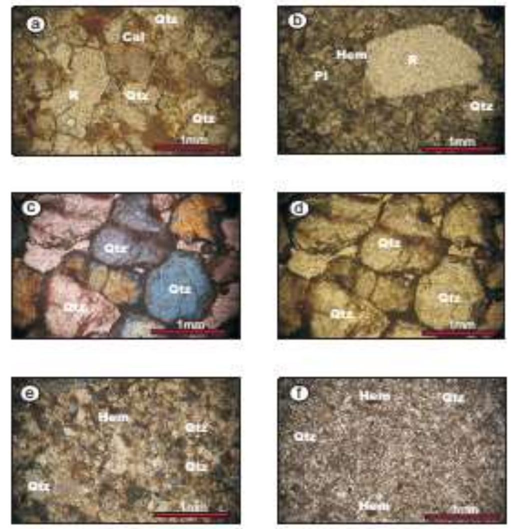
Sandstone of Datta Formation, Nammal Gorge Pakistan.(a),(c),(d) are Plane polarized views and (b),(e),(f), are cross Nickled views, Qtz: Quartz, R: lithic fragments, Ferru: Ferruginous cement and Hem: Hematite.

Plate 2



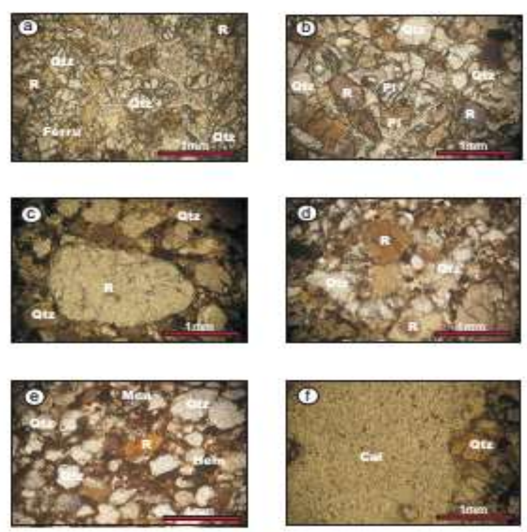
Sandstone of Datta Formation.(a),(c),(d),(b),(e),(f), are cross Nickled views, Qtz: Quartz, R: lithic fragments, Ferru: Ferruginous cement, Arg: Argillaceous material, Pl: Plagioclase, Mca: Mica, Mc: Microcline, dol: Dolomite, and Hem: Hematite.

Plate 3



Sandstone of Datta Formation, Nammal Gorge western Salt Range Pakistan.(a),(d) are Plane polarized views and (b),(e),(c),(f), are cross Nickled views, Qtz: Quartz, R: lithic fragments, Pl: Plagioclase, Cal: Calcite and Hem: Hematite

Plate 4



Sandstone of Datta Formation. (a),(b),(c),(d),(e),(f), are cross Nickled views, Qtz: Quartz, R: lithic fragments, Mca: Mica, Pl: Plagioclase, and Hem: Hematite

4.3 X-Ray Flourosence (XRF)

4.3.1 Geochemical studies

09 samples have been sent to geo-science lab (GARL) Islamabad to evaluate by XRF, the results of these samples has been summarized and represented in table 4.2 Sandstones are categorized founded on their chemical makeup (e.g., PettiJohn, 1975). Table 4.2 points out oxides of major elements i.e. Si,Al, Fe, Mg, Mn, K, Ca, P, Ti. Moreover, Loss on Ignition (LOI), Chemical Index of Weathering (CIW), and Chemical Index of Alteration (CIA) has been calculated (Nesbitt and Young, 1982). Afterwards, the ratio between oxide of Al to that of Si, K_2O/ Na_2O and Fe_2O_3/ MgO has been calculated for the construction various plots which is given below.

Present study, sandstone was classified according to the system suggested by Herron (1988). A diagram was plotted against log (Fe_2O_3/K_2O) and log (SiO_2/Al_2O_3), according to aforementioned diagram the Datta formation fall in the category of quartz sandstone as well as Sublitharenite (Figure 4.3a). In the second diagram, plot was made weight percentage of K_2O and that of Na_2O. The data depicts in this diagram two categories that quartz rich to quartz intermediate and quartz poor as well (Figure.4.3b).

Sample Name	E-103 Sample-1	E-104 Sample-2	E-105 Sample-3	E-106 Sample-4	E-107 Sample-5	E-108 Sample-6	E-109 Sample-7	E-110 Sample-8	E-111 Sample-9
SiO_2	87.74	90.82	84.82	84.22	88.64	89.38	84.56	90.52	88.34
TiO_2	0.42	0.53	0.93	0.66	0.56	0.88	0.54	0.45	0.67
Al_2O_3	1.36	0.75	0.66	0.60	0.55	0.45	0.43	0.40	0.56
Fe_2O_3	4.68	2.92	8.71	4.78	4.23	3.12	7.19	2.17	4.76
MnO	0.04	0.004	0.03	0.04	0.004	0.03	0.04	0.04	0.004
MgO	0.20	0.24	0.22	0.21	0.22	0.24	0.22	0.20	0.24
CaO	1.01	1.39	0.40	1.20	1.12	1.47	1.32	0.49	0.87
Na_2O	1.78	1.84	1.85	1.86	1.83	1.80	1.79	1.68	1.78
K_2O	0.19	0.13	1.14	1.06	0.22	1.07	1.03	1.12	1.14
P_2O_5	-	-	-	-	-	-	-	-	-
LOI	1.58	1.37	1.26	1.30	1.34	1.33	1.23	1.45	1.23
CIW	43.3	28.95	24.29	28.23	29.21	34.22	32.82	34.65	28.27
CIA	40.8	27.57	18.1	34.48	22.64	20.13	38.34	32.67	34.34
Al2O3/ SiO2	0.015	0.0082	0.008	0.006	0.006	0.007	0.006	0.005	0.006
K2O/Na2O	0.11	0.07	0.62	0.88	0.56	0.67	0.08	0.71	0.45
Fe2O3/MgO	28.4	12.2	39.6	32.07	30.29	27.78	14.22	20.27	23.76

Table-4.2 shows the geochemical data of the Datta formation CIA = Chemical Index of Alteration), CIW = Chemical Index of Weathering (Culler, 2000)

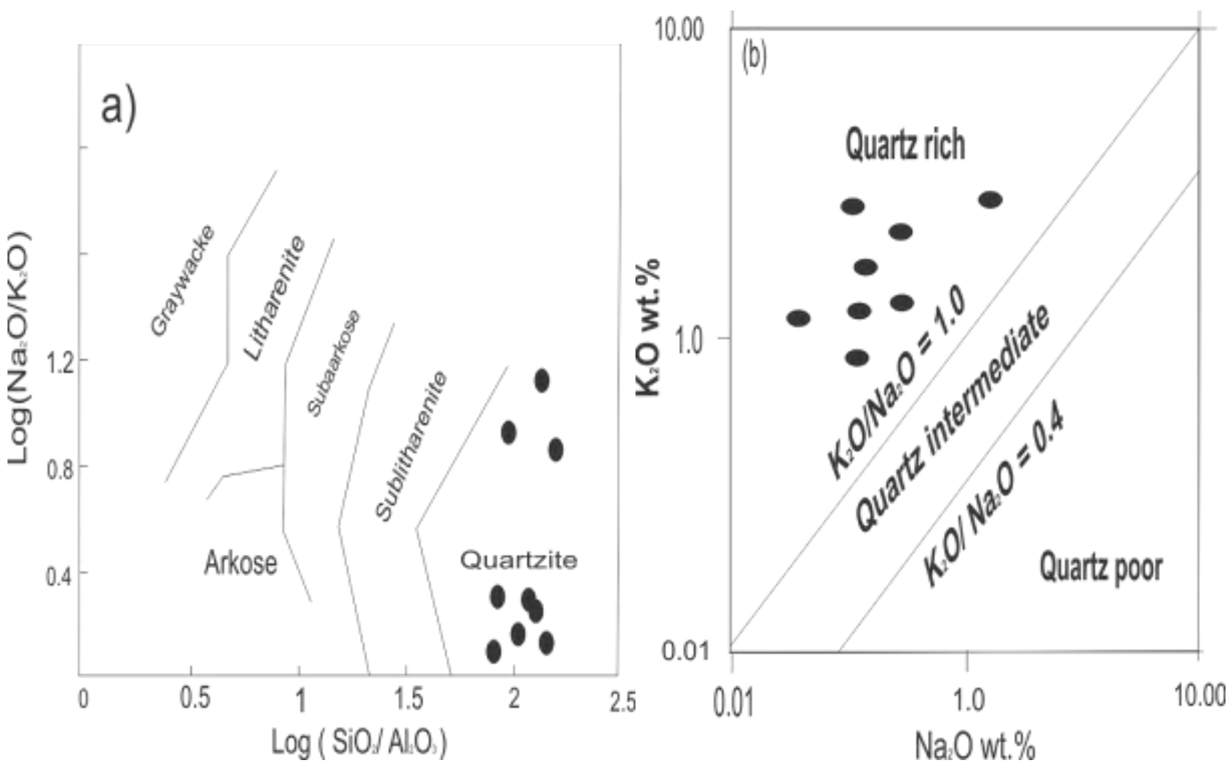


Figure 4.4 Geochemical classification of sandstones. (a) Log (Fe2O3/K2O) versus log (SiO2/Al2O3) bivariate diagram (After Pettijohn et al 1975) (b) K2O v Na2O (After Herron 1988).

4.3.2 Provenance studies

The tectonic setting for the purpose of provenance study of sandstone can be inferred by framework composition of sandstones. The ternary charts based on the detrital components of are extensively used to make the tectonic setting of the source area of sandstones (Dickinson 1985). Fourteen sandstone samples used for modal analyses of the present study (Table 4.1) and the Qt-F-L ternary diagram were formed by the obtained data of Dickinson et al., (1983). The provenance of the sandstone of the Datta Formation found as "Recycled Orogen" along with "Craton Interior" (Figure.4.4). Weltje et al (1998) designed a diagram to show the provenance of the a formation, According to Weltje Diagram, the Datta formation lies in the center of the diagram, which shows that source rocks were metamorphic as well plutonic rocks (Figure 4.6).

According to (Roser and Korsch 1988), mature continental provenance can be inferred from recycled sources along with that source area could have been consist of gneisses of granite rocks or already existed sedimentary occurs. The "Indian Craton" was the source of the detritus, where from sediments probably weathered, eroded and deposited as a Datta Formation (Abbasi, 2010) . Depending upon the geochemistry of analyzed samples (major elements) (Roser and Korsch 1988) the discrimination diagram for the purpose Datta formation provenance study reveals that Quartzose sedimentary region (Figure. 4.5).

These sedimentary rocks were consequent from extremely worn granitic-gneissic topography Laird, (1982) or from a sedimentary topography Nathan, (1976). The bulk chemical composition (in terms of SiO2 content) of the "ultimate" crystalline rock provenance of the sandstones can be inferred by using a simple equation provided by Hayashi et al., (1997). Hayashi et al., proposed the provenance discrimination equation (Figure 4.9).

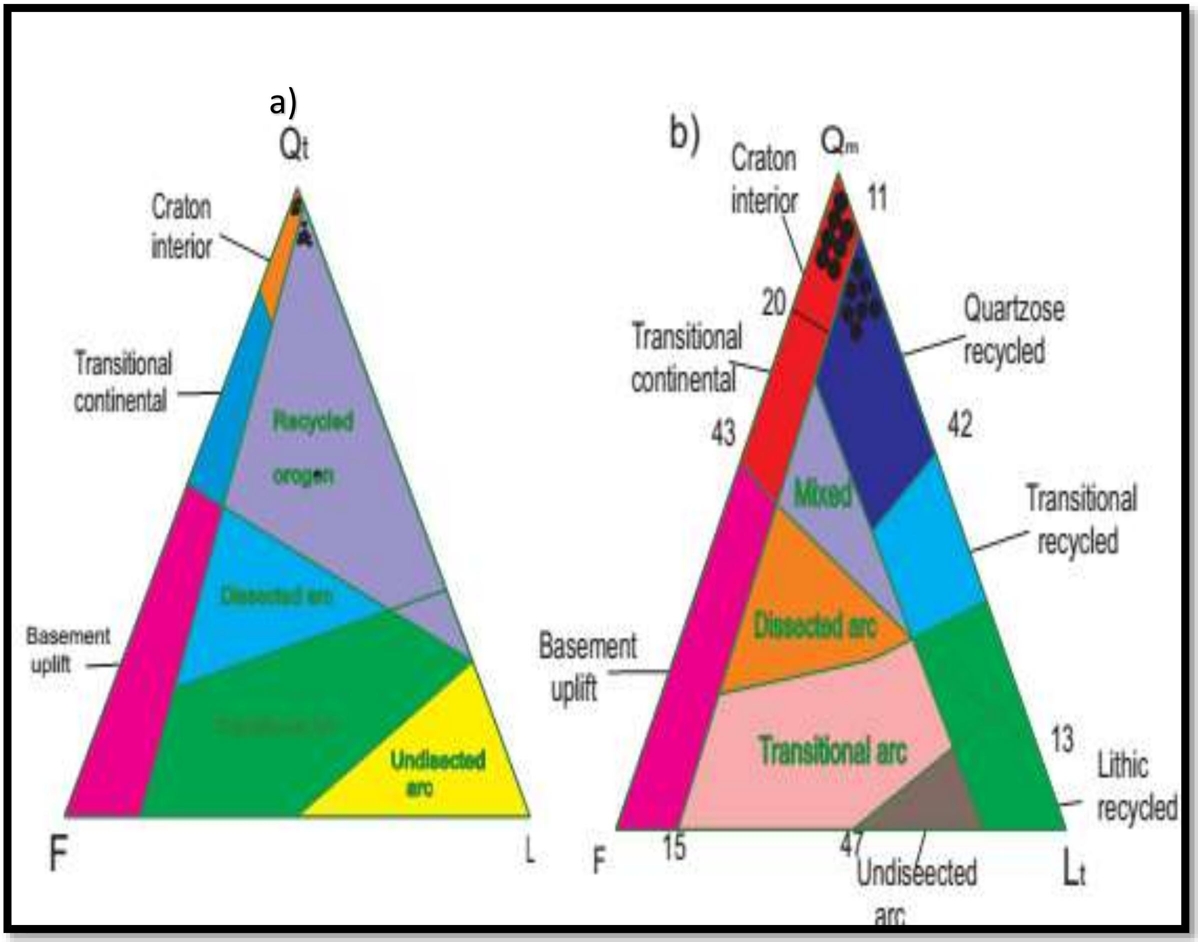


Figure 4.5 Qt – F – L tectonic setting discrimination diagram (after Dickinson et al., 1983). (b)QM = Total quartz, F = Feldspar = Lithic fragments including polycrystalline quartz.

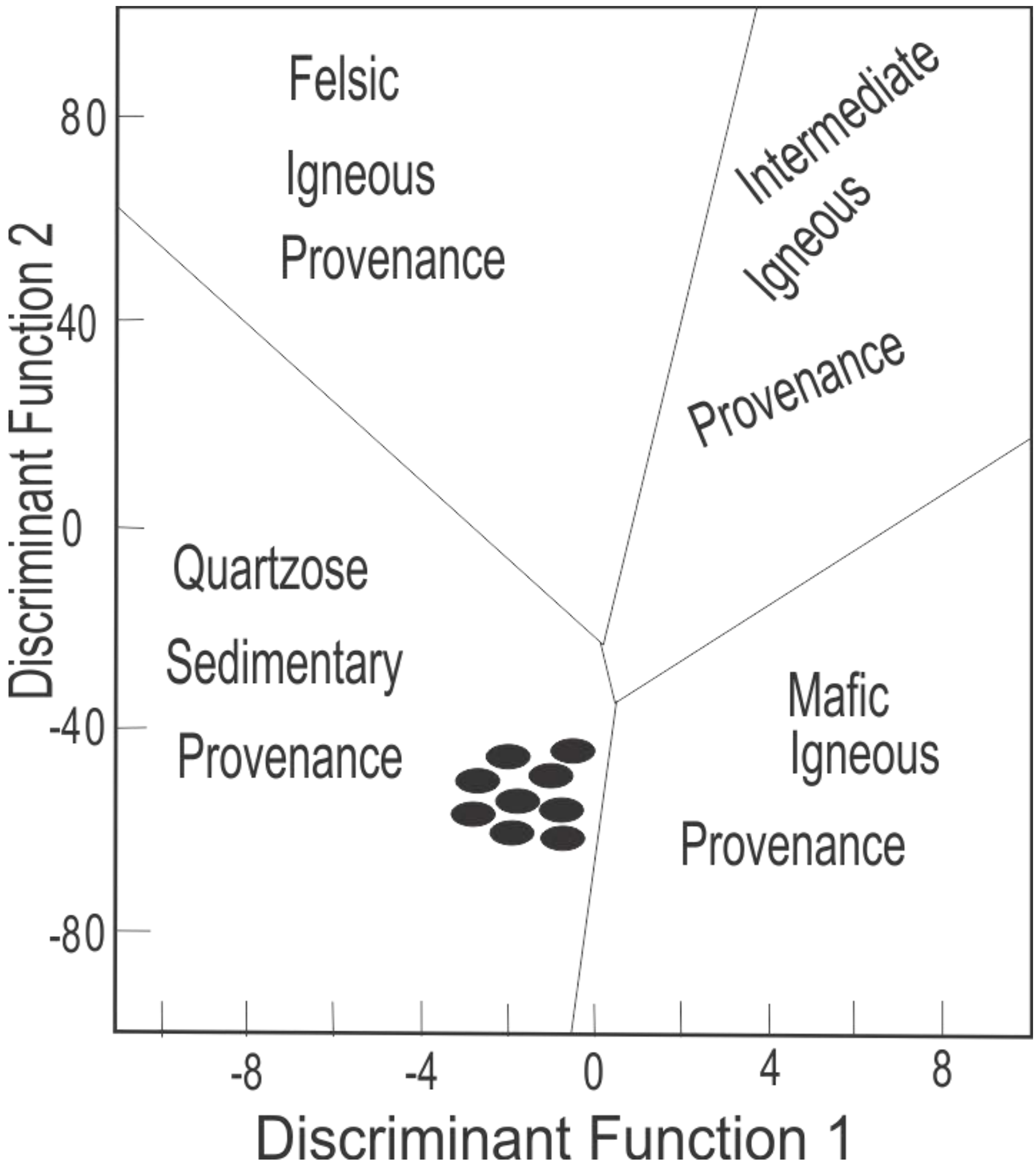


Figure 4.6 Provenance discrimination diagram for sandstones (after Roser and Korsch, 1988).

4.4 Weathering of the source area

4.4.1 Source indices

Roundness under the microscope, shows the range from sub-rounded to rounded having heterogeneity in roundness which implies that sediments underwent different episodes of physical weathering (Jafarzadah et al. 2008). The lacking of feldspar in the framework grains shows that the feldspar underwent intensive chemical weathering which implies hot and humid conditions prevailed during that particular time (Figure 4.5). Furthermore, the presence of quartz in the quartz arenite shows maturity both physical and chemical which implies that quartz has multiple episodes of weathering i.e. of recycled origin. The maturity of the quartz needs larger distances of transportation (Jafarzadah et al, 2008). The Weltje Diagram (1998) devised a table showing the physiography as well as precipitation (Figure 4.4). In plot field no 4 shows that the sediments underwent hot and humid climatic condition and deposited in low relief as well.

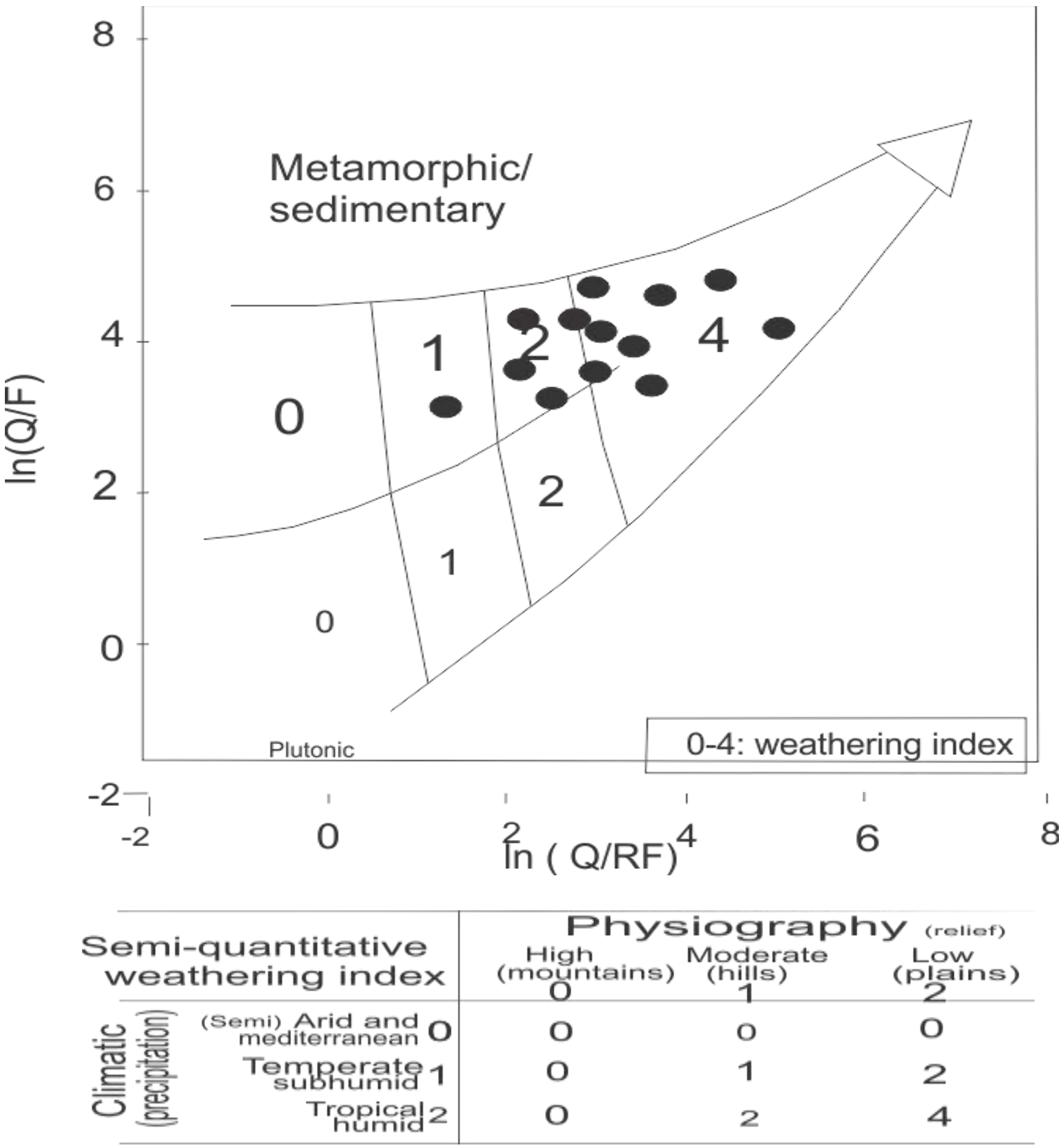


Figure 4.7 Log-plot after Weltje et al. (1998). Q: quartz, F: feldspar, RF: rock fragments, Fields 1-4 semi-quantitative weathering indices defined on the basis of relief and climate as indicated in the table.

4.4.2 Geochemistry and weathering of the source area

The percentage of the Alumina (Al2O3) range from 0.55 to 1.45 (Table 4.2) which implies that parent rock underwent intensive chemical weathering leaching out all the water soluble elements paving the way for the enrichment of Alumina (Jafarzadah et al. 2008). Moreover, Chemical Index of Weathering (CIW), as well as Chemical Index of Alteration (CIA) has been calculated to infer level of weathering (Culler, 2000). The values range from 26 to 43 marking the normal to high values of weathering. These CIA as CIW values implies that the hot and humid and intense recycling condition existed (Osae et al. 2006).

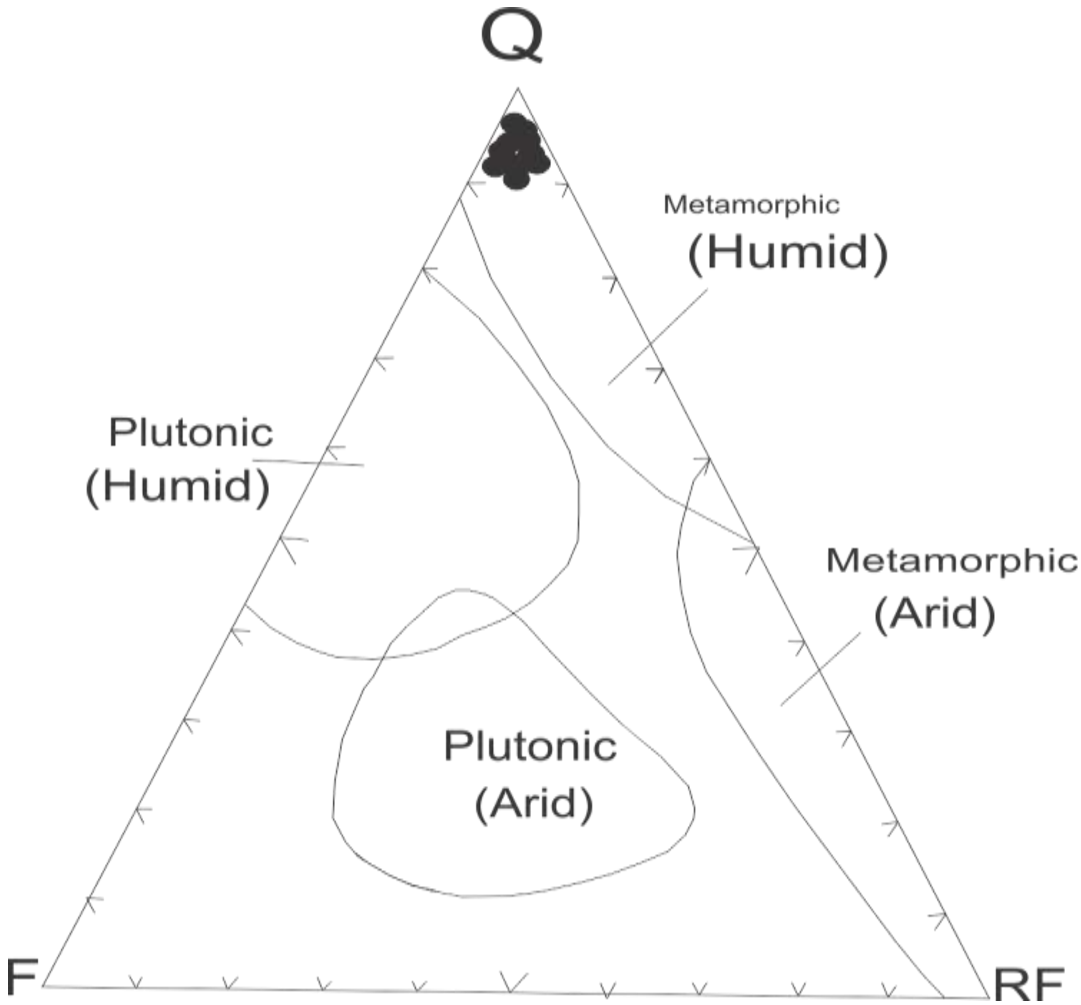


Figure 4.8 the effect of source rock on the composition sandstone of the Datta Formation using Suttner et al. (1981) diagram

4.4 Tectonic Setting

The discrimination charts for tectonic setting can deliver steadfast effects for detrital sedimentary rocks that have not intensely changed by weathering or any post depositional. According to The Discrimination Diagrams, there are eight types of tectonic settings (Bhatia (1983). These are i) Active Continental Margin (ACM) ii) Passive Margin (PM) iii) Continental Island Arc (CIA) iv) Oceanic Island Arc (OIA) are few examples. A diagram was plotted in which the weight concentration of TiO_2 placed in the y-axis and that of (FeO + MgO) placed in the x-axis. After plotting the data, it reveals two type of tectonic settings that is Passive Continental Margin (PM) as well as Active Continental Margin (ACM) (Figure 4.9 a) (Bhatia 1983). In the next diagram does not reveal anything particularly well. A plot was drawn against K_2O/NaO versus FeO + MgO, this plot shows the Oceanic Island Arc setting (Figure 4.9 c). The active continental margin (ACM) is indicated by the discrimination diagrams (Figure. 4.9 d). The plot between SiO % versus K_2O/ Na_2O % shows the similar tectonic setting that is the active continental margin (Figure. 4.9 e) (Roser and Korsch 1986). Furthermore, a triangular plot between the three quantities SiO/2, K_2O/Na_2O and TiO_2 + Fe_2O_3+ MgO shows the passive margin (PM) (Figure.4.9 g). Finally, a diagram was drawn between SiO_2/Al_2O_3 against K_2O/Na_2O. This diagram also suggest the tectonic setting was a passive margin where the sediments were eroded and transported (Figure.4.9 h) (Maynard et al.1982).

Present research suggest that the provenance of the sandstone in the Datta Formation is outcrops of Indian Craton. The subsurface rocks may differ from the surface exposure in terms of rock assemblage particularly in igneous rocks. The igneous rocks classify as volcanic and plutonic rocks. Plutonic rocks occur in the subsurface, don’t have the volcanic equivalent in case of ultramafic rocks. Moreover, volcanic rocks have surficial exposure that is why, they are more prone to weathering and erosion as compare to plutonic rocks.

The Datta Formation exemplifies a depositional environment deltaic facies of prograding sequence. Thick beds of sandstone normally related with lags deposits, siltstone and red clays, clays rich organic matter show a setting of fluvial dominated delta-plain. The Datta Formation contained coarser-grained sandstone strata with beds of granule that show the facies of channel belt, deposited during the meandering of sinuous channel. Features such as cross-stratification as well as lineation displays that the main fluvial system was flowing in the direction of WNW (Abbasi et al., 21010). The Datta Formation in lower part controlled by facies of flood plain like lateritic soil and siltstone, these horizons were deposited showing a depositional setting of broad flood plain region afterwards the channel was become distributary. The sedimentary structures just like, levee deposits, crevasse splays as well as channelized sandstone bodies recommend meandering stream. The deposits of channel belt are usually triggered by tinny carbonaceous clays or coal seams carbonaceous material, signifying presence of boggy conditions on the floodplain then forming fluvial channel system. The direction of prograding delta was WNW, the western boundary of the Indo-Pak tectonic plate with Neo-Tethys oceanfront. The source of the sediments for sandstone of Data Formation might be from Indian Craton. The coastline was present to the west of N-W in the direction prograding delta. The shell fragments of gastropod and pelecypod fossils, worm burrows as well as bioturbation, and the fragments of plants along with wood show a deltaic coast also present as well as other presence distributary channel system, swamps, marsh land, and lagoons (Abbasi et al., 2010).

In Salt Ranges especially in the central as well as in eastern and in some parts of Potwar Region, this sequence is has very shrill or absent because this region was have constructive relief. While in the western boundary of the Indo-Pak plate in Early Jurassic by a deltaic setting and the Ranges like the Salt as well as Trans Indus, varying gradually shows in the schematic depositional model for the Datta Formation showing major facies shift clearly seen from Hazara region to Kohat region, deltaic-facies to marine-facies (Abbasi et al 2010). The delta past marked as SW–NE prograding coastline (Scotese 2001).The source was a fluvial-dominated delta, sediments were transported by stream systems was charging from the Aravalli Ranges or Indian cratonic rocks. The direction of flowing river was from direction of ESE to WNW in the project area (Figure 4.10).

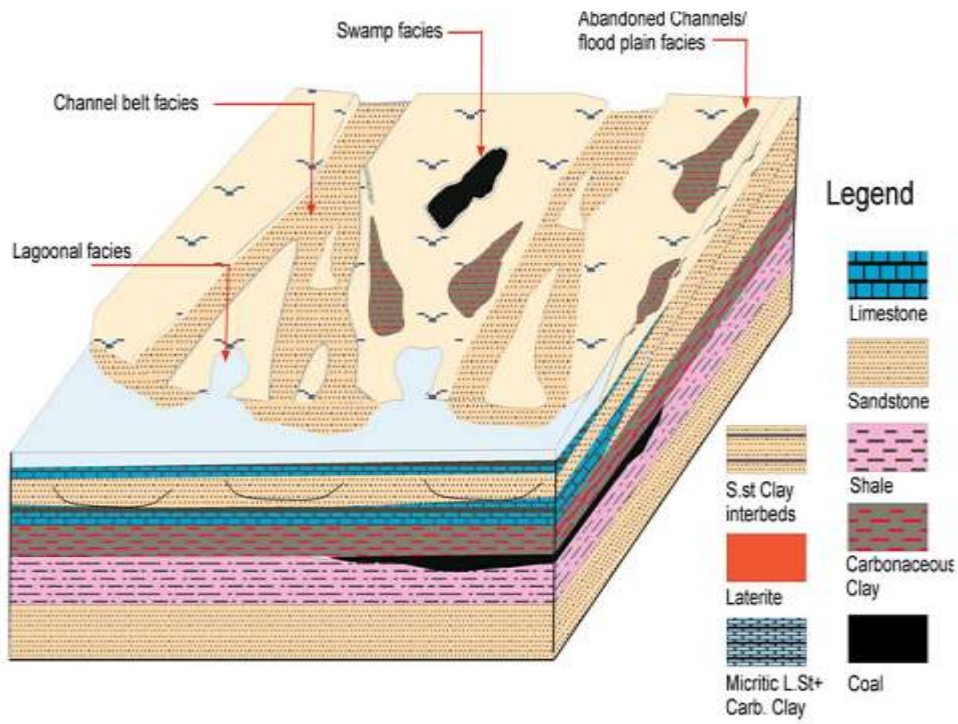
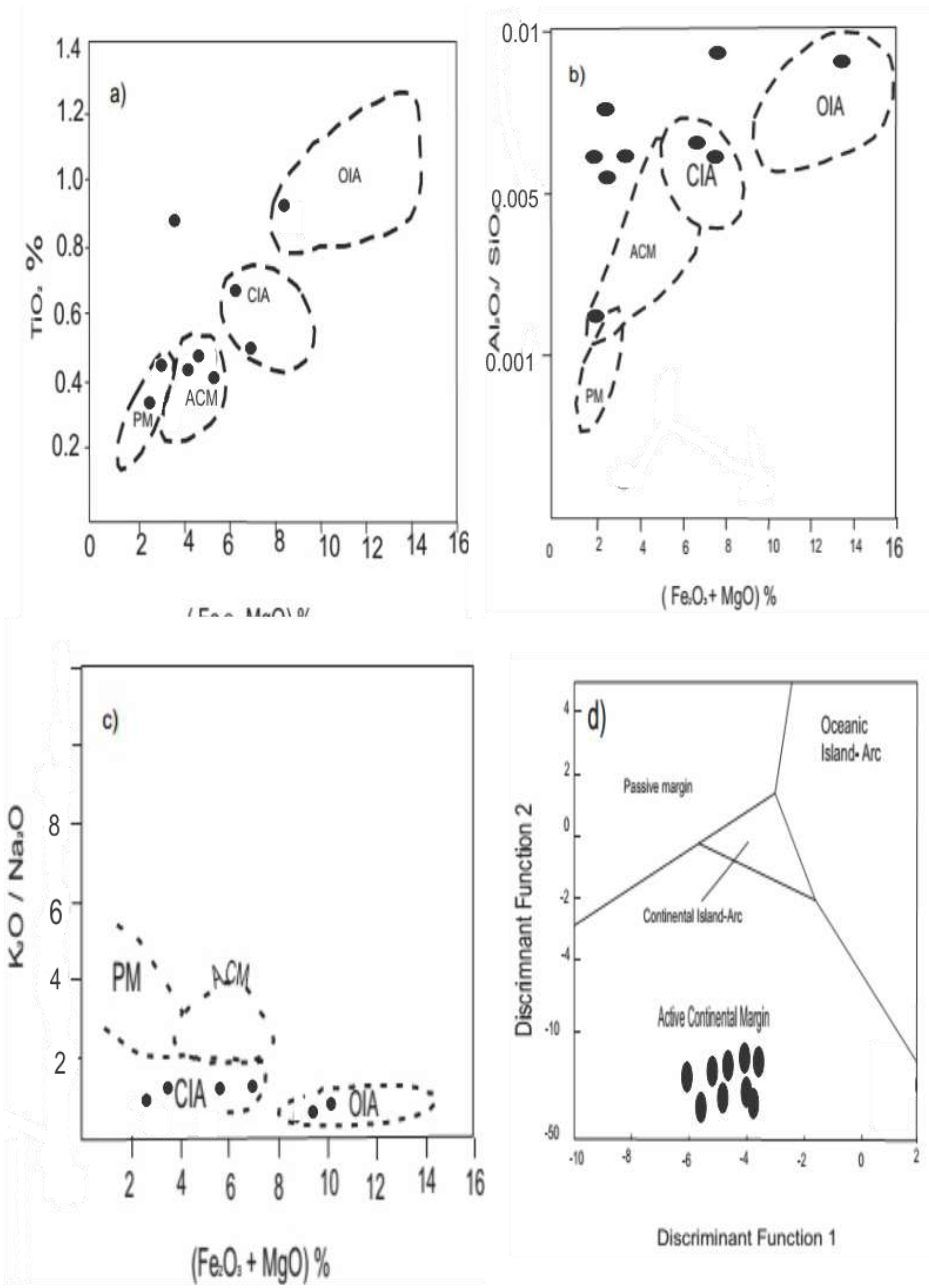
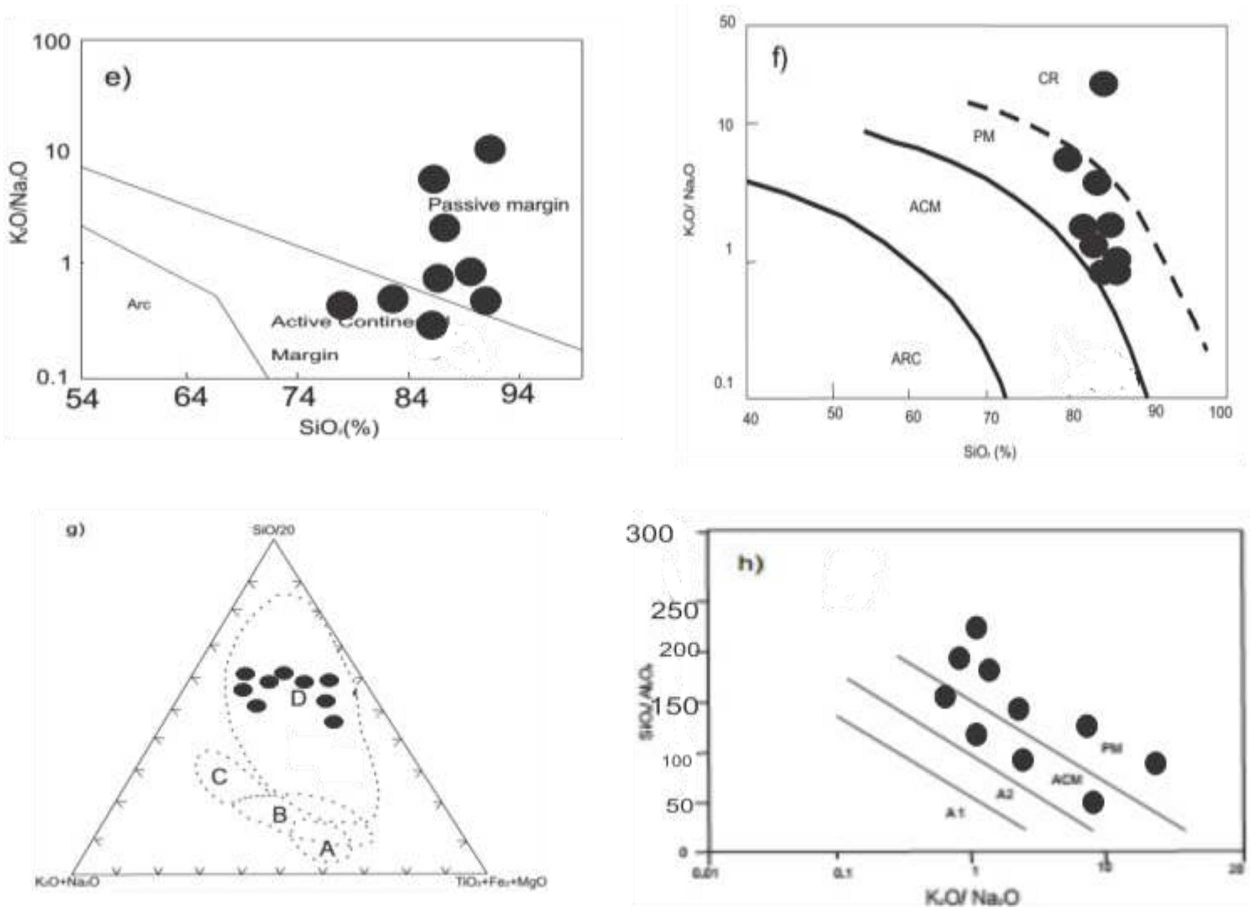


Figure 4.9 Schematic depositional model for the Datta Formation showing major facies types in deltaic setting (After Abbasi et al 2010)


a)
OIA
CIA
ACM
PM
b)
OIA
CIA
ACM
PM
(Fe₂O₃+ MgO) %
c)
PM
ACM
CIA
OIA
(Fe₂O₃ + MgO) %
d)
Oceanic Island- Arc
Passive margin
Continental Island-Arc
Active Continental Margin
Discrimnant Function 2
Discriminant Function 1



(Figure. 4.10 Tectonic setting discrimination diagrams based on major element composition of sandstones. (a) (Fe_2O_3T + MgO) wt. % versus TiO_2 wt. % diagram (Bhatia, 1983). PM: Passive Margin. ACM: Active Continental Margin. CIA: Continental Island Arc. OIA=Oceanic Island Arc. (b) (Fe_2O_3T + MgO) wt. % versus Al_2O_3/SiO_2 diagram (Bhatia, 1983). Field setting symbols as in Figure 9a. (c) (Fe_2O_3T + MgO) wt. % versus K_2O/Na_2O diagram (Bhatia, 1983). Field setting symbols as in Figure 9a. (d) Bivariate discriminant functions diagram (Bhatia, 1983). Discriminant Function 1 = (-0.0447×SiO_2%) + (-0.972×TiO_2%) + (0.008×Al_2O_3%) + (-0.267×Fe_2O_3%) + (0.208×FeO%) + (-4.082×MnO%) + (0.140×MgO%) + (0.195×CaO%) + (0.719×Na_2O%) + (-0.032×K_2O%) + (4.510×P_2O_5%). Discriminant Function 2 = (-0.421×SiO_2%) + (1.988×TiO_2%) + (-0.526×Al_2O_3%) + (-0.551× Fe_2O_3%) + (-1.610×FeO%) + (2.720×MnO%) + (0.881×MgO) + (-0.907×CaO%) + (-0.117×Na_2O%) + (-1.840×K_2O%) + (4.244×P_2O_5%). (e) SiO_2 wt. % versus K_2O/Na_2O diagram (Roser and Korsch 1986). (f) SiO_2 wt. % versus K_2O/Na_2O diagram (Roser and Korsch, 1986), modified after Murphy (2000) CR = Continental Rift. (g) SiO_2 / 20 wt. % - (K_2O + Na_2O) wt. % - (TiO_2 + Fe_2O_3 + MgO) wt. % ternary diagram (Kroonenberg, 1994). A: Oceanic island Arc. B: Continental Island. C: Active continental margin., D: Passive margin. (h) SiO_2/Al_2O_3 versus K_2O/Na_2O diagram (Maynard et al., 1982). A1 = arc setting, basaltic and andesitic detritus. A2 = evolved arc setting, Felsic-plutonic detritus.

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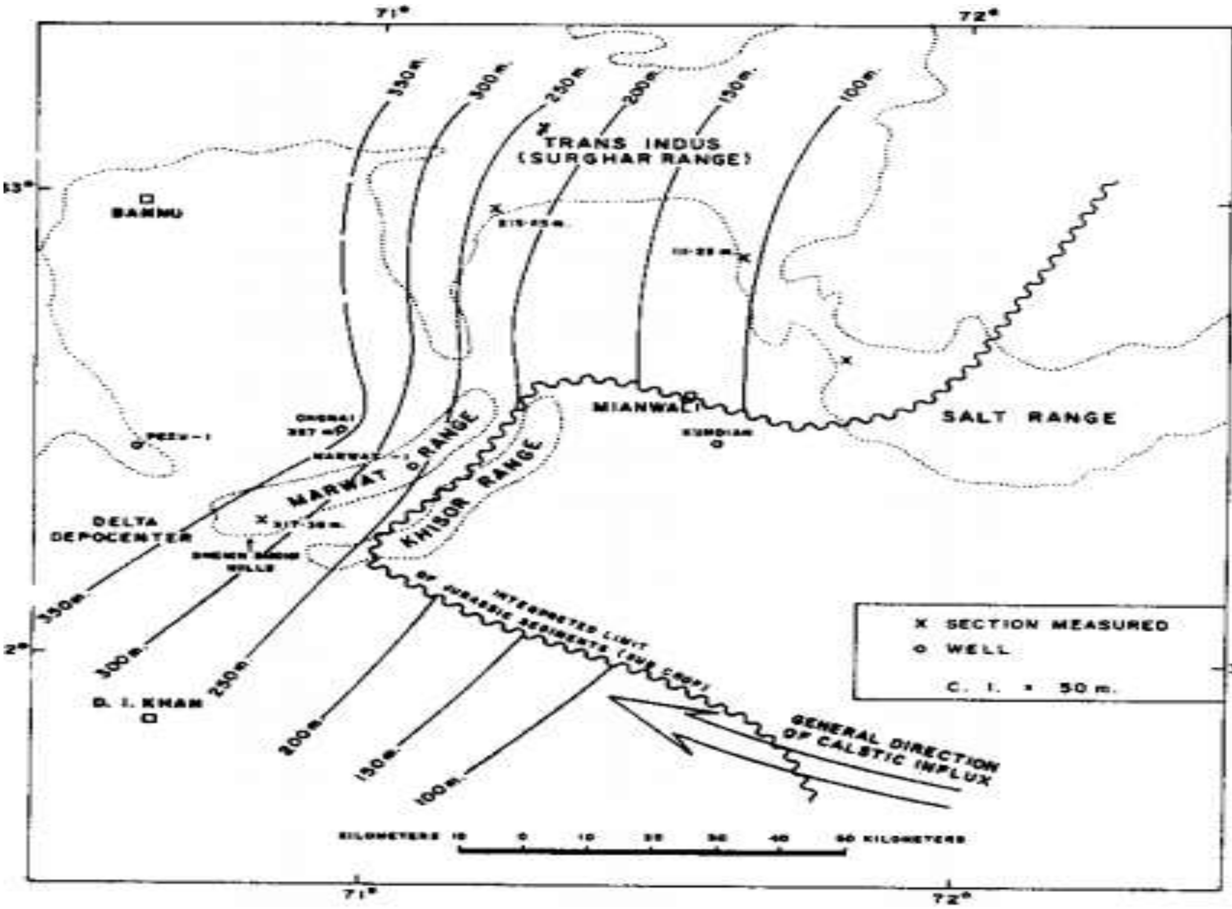

Figure 4.11 shows the direction of clastic input during the Jurassic time (After Kadri, 1995)

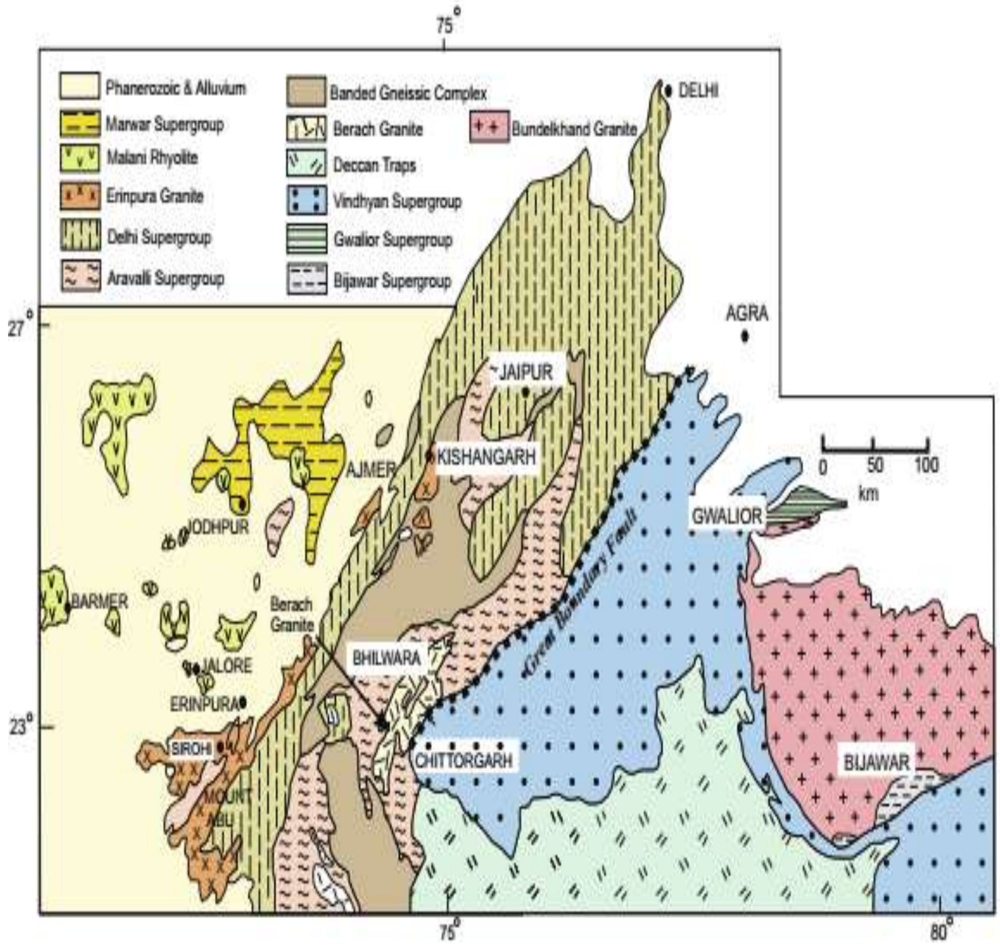

Figure 4.12 shows the sketch map of the Aravalli-Bundlekhand protocontinent, NW India (After Vaidyanandhan, 2008)

Aravalli Range consists rocks of both Precambrian and Phanerozoic ages but the emplacement started from 2.5 Ga years ago (Meert et al 2004) (Figure 4.11). In figure 4.12 map shows the ages of the rock units as well as the lithological variations in the rocks like granitoids, mafic dykes, and ultra-mafic rocks (Meert et al 2004). Aravalli Range is mostly composed of gneissic complex which is subdivided into migmatites, amphibolite, and metasedimentary rock units of 3.2 Ga age (Meert et al 2004). This Aravalli Craton was underwent into weathering and erosion and later deposited as the Datta Formation of the Early Jurassic age.

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusions

Petrographic studies besides with geochemical studies lead to the following conclusions

- From the petrographic studies reveal that sandstone can be classified into quartz arenite and Sublith-arenite, Quartz arenite is a matured sandstone both physically and chemically usually forms after repeated cycles of deposition, so as it is shown by QFL diagrams recycled origin. Similarly Sublitharenite is sub mature type of sandstone physically as well as chemically, which means it has transported less than 100 km from its origin. That's the same result shown by the QFL diagrams i.e. Craton interior. Moreover, geochemical data reinforce the petrographic results in terms of sandstone classification.
- The Datta Formation consists of some beds of laterite, laterite generally forms under intense hot and humid conditions for considerably longer period of time, this observation strengthen by XRF data shows that hot and humid climate during deposition
- QFL diagrams that Recycled as well as Craton Interior provenance. This result fortify by the results of Discriminant diagram based on geochemical data which shows similar origin quartzose sedimentary provenance
- Geochemical studies show that active continental margin as well as passive margin, whereas petrographic results show that sandstone of two types i.e. quartz arenite as well as sublitharenite which shows different type of origins one from stable part of craton whereas other from orogenic part. It is therefore, concluded that The rocks of Indian basement or Indian cratonic also known as Aravalli range was eroded and deposited as Datta Formation during the Jurassic time. Furthermore, the mighty Himalayan were formed after Cretaceous orogeny, there was nothing in the north of the Indian plate to contribute sediments.

- A similar study has been conducted on the Pab Sandstone of the Late Cretaceous age in the Rakhi Gaj area of the Suleiman Basin (Durrani et al 2012), the results shows the same Aravalli range acted as a source area even in the Late Cretaceous time. It is quite obvious now the sandstone of the Datta Formation was weathered and eroded from the Aravalli Range.

5.2 The Recommendations

There are some brief recommendations, which is given below

- The outcrops of the formation would be linked to infer the comprehensive depositional model. The outcrop of the Datta Formation from Trans-Indus Ranges to Kohat, Kala Chitta and Hazara area (Qureshi et al 2006).
- To broaden the scope of the project also assist in the delineation the economic deposits lie inside the Datta Formation like fireclay, silica sand (Qureshi et al 2006).
- Isotopic Studies, Heavy Mineral Association (HMA) and Rare Earth Elements (REE) will be helpful for precise results (Weltje, 2004). These advance techniques will bring more precision and accuracy to the results.
- Clay mineral investigation would be more precise and accurate to find out the climatic conditions during the process of sedimentation (Jafarzadah et al. 2008)

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APPENDICES

ACM= Active Continental Margin

CIW = Chemical Index of Weathering

CIA = Chemical Index of Alteration

CIA= Continental Island Arc

The **Gazzi Dickinson technique** is used to calculate components of sedimentary rock mainly sandstone. The basic purpose of this technique to separate the grains from cement as well as from matrix.

OIA= Oceanic Island Arc

PM= Passive Margin