DIAGENETIC ALTERATION RESULTING FROM DOLERITIC INTRUSIONS IN THE LIMESTONE OF ATTOCK-CHERAT RANGES AND GANDGHAR RANGES, PAKISTAN

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BY

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This thesis is dedicated to
my beloved Parents for their
endless love, Support and
encouragment

APPROVAL CERTIFICATE

This is to certify that the dissertation entitled “Diagenetic Alterations Resulting from Dolerite Intrusions in the Limestone of Attock-Cherat Ranges and Gandghar Ranges, Pakistan” submitted by Muhammad Asim is accepted in its present form by the Department of Earth Sciences, Quaid-I-Azam University Islamabad, Pakistan, as satisfying the dissertation requirement for the M.Phil. Degree in Geology.

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ABSTRACT

Utch Khattak limestone (late-precambrian) is exposed in Southern Gandgher Range, in district Haripur having East-West extension. It is intruded and altered by dolerite dykes that are present throughout the formation in the study area. These igneous intrusions have mostly occluded the pore spaces and fractures in the host limestone. Fluids interaction with host rock change the mineralogy of the host rock and this phenomenon is least studied. Current study focuses on the diagenetic alteration in the host lithology due to igneous intrusion using field observations, petrography, mineralogical studies and stable isotopes analysis. These studies helped to generate a detailed paragenetic history of the altered carbonates and its relationship with the igneous intrusions. Field observations show numerous dikes (having basic composition) and thickness generally 2m are present at regular interval throughout the Utch Khattak limestone. These intrusions have altered the carbonates in the study area result in contact metamorphism (resulted in marble), recrystallized limestone and dolomites. Fracturing due to intrusions is apparent in the vicinity of dikes. Brecciation has occurred in the host lithology due to cataclastic deformation. From petrographic study (Cross-cutting relationship) it can be revealed that the dolomites are formed after the host lithology intruded by the dikes. The alteration in the host limestone is also clear from the petrographic study. Hydrothermal fluids coming along with dikes have invaded the country rocks through fractures and joints present in the strata and has caused alterations. Marble in the contact zone has partially acted as a barrier for the hydrothermal fluids to invade the country rocks. This is apparent in the field, where this marble cover is missing or crosscut by fractures, dolomitization has occurred in those area in the host strata. XRD analysis of the dike sample shows the mineralogy and alteration products of the dolerite dikes minerology. Altered carbonates mineralogy show dolomite along with clays minerals and some alteration products of dolerite dikes. This shows that the alteration in the host lithology occurred due to dolerite intrusions. These alteration products have affected the porosity of the host carbonates. In addition, fractures due to cataclastic deformation have also affected the porosity.

Results from different studies helped to conclude that the interaction of hydrothermal fluids with the rock resulted in the substitution of different minerals in the host rock and the formation of different types of rocks. Such alteration shows the effects on the porosity and permeability of the host rock and affecting its reservoir properties.

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CHAPTER 1

INTRODUCTION

According to geological research these magmatic intrusions helps in thermal maturation of organic matter present in those sedimentary basin rising its geothermal gradient and helps in promoting the hydrocarbons generation (Jones et al. 2010). In many sedimentary basins the sills and dykes are present which are the main the sources of igneous intrusions in those sedimentary basins, these dykes and sills are present both vertically and laterally and form an interconnected network (Planke et al., 2005; Holford et al., 2009; Jackson et al., 2012). The effect on maturation and over maturation in petroliferous basin is directly related to the these intrusions interaction with source rock facies (Schutter, 2003). The thermal effect seems to be more significant in the case when thick and multiple dikes and sills are present in organic rich sediments in a sedimentary basin (Aarnes et al., 2011). The release of magmatic fluids during igneous intrusion and the expulsion of pore water are the main agents for transportation of the heat. This heat can be transported both vertically and laterally in a sedimentary basin and cause the maturation of source rocks (Einsele, 1982). The circulation of hydrothermal fluids activated by dikes and sills is crucial while estimating prospects because these hydrothermal fluids maybe mineralizing to a greater extent and can decrease the quality of a potential reservoir, this cementation of minerals is temperature controlled (Parnell et al., 2010). Distinctive source rocks, accelerating fluid maturation, facilitating fluid migration, creating traps and seals and producing reservoirs, all these aspects of a petroleum system can be affected by the intrusions up to some extent (Holford et., 2012).

The reservoir characteristic of carbonate rocks can be affected through intrusion present in those rocks because it affect the porosity and permeability of carbonate rocks as it has been reported (Farooqui et al., 2009; Holford et al., 2010; Jacquemyn et al., 2014; Petford & McCaffrey, 2003; Schutter, 2003). Mafic intrusions alter the composition of the host carbonate rocks due to deep seated magmatic fluids which contain magnesium and cause the dolomitization of the host carbonate rocks (Blomme et al., 2017; Farooqui et al., 2009). Dolomite produced due to hydrothermal activity can be a good reservoir (Davies & Smith , 2006; Lapponi et al., 2014; Machel & Lonnee, 2002; F. Nader et al., 2012; Ronchi et al., 2010; Shah et al., 2010; Sudrie et al., 2006; Swennen, 2012; Vandeginste, 2005; Zhu et al., 2015). All over the word there are many carbonates successions where igneous intrusions are present and has affected that carbonate successions and the studied analogues of these are mostly present in Italy e.g. Sella (Antonellini & Mollema, 2000), the Pale di San Lucano (Blendinger & Meißner, 2006), the Roengarten (Emmerich et al., 2009) , Latemar buildups (Jacquemyn et al., 2014). Some of these intrusions help in providing migration pathways, seals and traps (Jacquemyn et al., 2014; Schutter, 2003; Sruoga & Rubinstein, 2007). Igneous intrusions in the host limestone result in the formation of marble due to contact metamorphism. Because of igneous intrusions hydrothermal alteration of limestone occur giving rise to dolomite phases and contact metamorphism. Dolomite is one of the enigmatic lithology and its precise origin in sedimentary strata is always been difficult for geologist to interpret. Different workers have proposed different dolomitization models for dolomites.(Gasparrini et al., 2006).

In present studies, diagenetic features from outcrop to thin section scale will be emphasize based on field observations, petrographic studies and geochemical investigation.

Carbonate reservoirs properties depend mostly on the diagenetic alterations and the primary sedimentary textures of the carbonate rocks. Digenesis is a very complex phenomenon and depend on the depositional settings and alterations. It depend on the compaction, dissolution, cementation, grain fracturing, authigenesis, replacement etc.(Lapponi et al., 2014). But the mechanical and chemical alterations, due to igneous intrusion have been given very less attention although these processes play a significant role in the reservoir properties of the carbonate rocks. These alterations either increase or decrease the porosity and permeability depend upon the nature of the intrusions and the depositional fabric (diagenetic minerals) (Farooqui et al., 2009)

The association of dolomites with three main processes as described by (Burgess, 1964) are (i) unconformity dolomitization (ii) dolomitization controlled structurally (iii) stratigraphic dolomitization (both i and ii occur late in the history of carbonate rocks and are hydrothermal dolomites). Hydrothermal dolomites due to its hydrocarbons reservoirs prospect have gained the attention worldwide (Davies & Smith, 2006; Lapponi et al., 2014; Shah et al., 2010; Swennen, 2012). This type of dolomitization occurs, because of the magmatic bodies located deep seated having Mg- rich hot fluids. When these fluids come in contact with the host lithology can also change the mineralogy of the host rocks (Nader et., 2008)

Igneous intrusions which have affected the carbonates rocks are reported from many areas of the Pakistan. The Khyber Agency and the areas of the Nowshera are the examples of carbonates rocks in Peshawar Basin which have been affected by the igneous intrusions. In the carbonate succession of Kaghan group, fractured restricted igneous intrusions are found in the Burawai village (Shah, 2009). In the northwestern boundary of the Indian plate due to Paleozoic rifting both acidic and basic intrusion are found in the Peshawar region, Kashmir and Hazara region (Kazmi & Jan, 1997). In the Early Jurassic Shirinab formation thin bedded limestone (with small amount of shale) are intruded by group of small sills, dykes and plugs of lamprophyres (Ahmed & McCormick, 1990).

Gandgher Range is located in northern Pakistan having lithology that is transitional between Plutonic and highly metamorphosed rocks in the north and sedimentary and un-metamorphosed strata in the south (Yeats & Hussain, 1987). Utch Khattak Formation (studied rocks) is located in the southern Gandghar Range. Southern Gandghar Range has marine starata succession, the base of which has been marked by argillacious rocks of Manki formation and overlain by Shahkot Formation, Utch Khattak formation, and Shekhai Formation having lithologies mostly consist of limestone and shale (Hylland, 1990). The lithology of Utch Khattak formation consists of black, grey, Stromatolite crystalline limestone with some argillaceous streaks and laminations (Iqbal & Shah, 1980).

Utch Khattak Formation is intruded by dikes and sills (Tahirkheili, 1970, Shah 2009). These dibasic sills and dikes can be correlated with the Panjal volcanoes (Honegger et al., 1982; Hylland, 1990).

1.1 Location and Accessibility

The study area is located near Gudwalian Dam, located in Gudwalian village; district Haripur, Khyber Pakhtunkhwa, Pakistan (Fig 1.1). The outcrop is located about 2 km away from the main road (Haripur-Sirikot road) toward the eastern side. To the north of the study area is Abbottabad, to the south lies Taxila, to the east lies Swabi district and to the west lays Murree and Islamabad. The outcrop has E-W extensions having approximate location 34^0 00' N latitude and 072^0 47' E longitude.

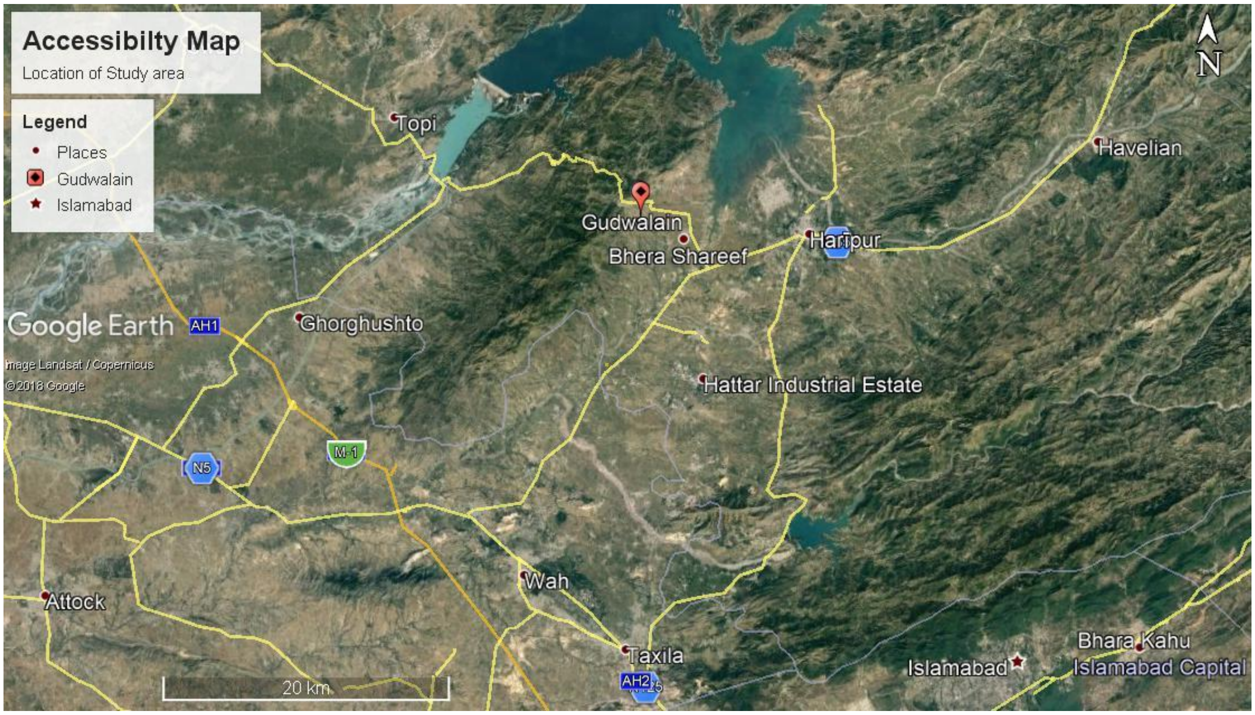


Fig 1.1 Location and Accessibility map of the study area

1.2 Aim and Objectives

The aim of this study is to investigate the effects of igneous intrusions on host limestone, interaction with carbonates, focusing on dolomitization process in the Utch Khattak limestone (Gandgher Range) due to these igneous intrusions, nature of dolomitization due to hydrothermal fluids and to note its effect on the porosity and permeability of the rock. The objectives of this research work are as followed.

- To carry out petrographic study of the affected zones of Utch Khattak Formation by Igneous Intrusions in the Gandghar Range.
- To evaluate different minerals assemblages due to igneous dikes, sills and the related hydrothermal fluids in the host rocks.
- To know about the digenesis and various diagenetic changes such compaction, dissolution, cementation, grain fracturing and replacement.
- To establish different diagenetic phases and to note the porosity variation
- To develop a paragenetic sequence based on the thin section study and field observations.
- To understand the phenomenon and the effect of igneous activity and hydrothermal fluids in the Utch Khattak limestone of the selected area.

CHAPTER 2

GEOLOGICAL SETTING

2.1 Regional Geological Setting

Indian plate is located on the eastern part of Gondwana super land continent (Valdiya, 1977, 1980). This name (Gondwana) was named after a city located in India because of a fossil plant that discovered in that region named Glossopteris (Krishnan et al., 1970; Smith et al., 1973; Wadia et al., 1964). Gondwana landmass constitutes continental crust and crystalline at its base, this information came from the seismic data in many wells. Crystal base consolidated in Pre-Cambrian age and in Paleozoic time Indo-Pak plate was formed.

Geologically Indo-Pak plate consists of three main divisions. From north to south these divisions consist of;

1) The Himalayas
2) Himalayan Fore deep
3) The Peninsular region (Searle, 1986)

In the world the most active and the largest collision has taken place in the Himalayas. The western extremity of the Himalayan platform and the Himalayan thrust belt begin from Burma (eastern part) to India, Nepal, Tibet (southern part), Pakistan (northern part), and expand to Afghanistan and Iran (central part). In the south the Himalayan thrust belt has its erosional products in Punjab plains (Pakistan) and Ganga Basin (India i.e. active Fore deep zones) and also these erosional products transported in southward direction (Ray, 1982). The peninsular region which is characterized by granite green earth is indicated by the Indian shield rock. It consists of gneiss, granite and magmatic rocks. Cretaceous basalt of Deccan Plateau has covered almost the entire peninsular region.

2.2 Major Tectonic Events

Le Fort, (1989) described the geodynamic tectonic setting of the Indian Plate. According to him, in the late Cretaceous time the Himalayan orogeny started, which ended in the late Cenozoic time. He divided the orogeny in the Himalayan region into three major events;

a) Movement of the Indian Plate towards the north caused intra-oceanic subduction in the Tethyan Ocean. Due to this subduction an island arc formed called Kohistan-Ladakh island arc. After the formation of this island arc the Tethyan Ocean was divided into two parts called Paleo Tethyan Sea and Neo Tethyan Sea.
b) After the division of the Tethyan Ocean, the oceanic-continent convergence started leading to the Paleo Tethyan sea subduction under the Karakorum Plate. As a result, Rakaposhi Ophiolites are abducted, and Karakorum Batholiths emplacements occurred due to this phase of orogeny. This phase completed in the Late Cretaceous.
c) In the third phase, Neo Tethyan Sea subducted beneath Kohistan-Ladakh island arc, and by the direct contact of the Kohistan Island Arc and the Indian Plate this phase was mark completed (late Eocene). Shangla Ophiolites are the products of this phase of orogeny.

2.3 Sub-divisions of the Himalaya (Pakistan)

The Himalayas are spread over a vast area of Pakistan. Himalayas are divided into the following divisions according to (Gansser, 1981)

2.3.1 Sub-Himalayas zones

Sub-Himalayas are the area having Main Boundary thrust toward north and Main Frontal Thrust towards the south, in between these two suture zones, the deformed foothills exposed are called Sub-Himalayas in the Geology of Pakistan. It is a peripheral zone of Himalayan Orogeny where sedimentary sequences having age from Pre-Cambrian to Neogene are included in this deformation. This deformation further extended in east-west direction divided into Punjab in the west and Azad Kashmir in the east while in north-south direction it has been divided in Potwar north deformed area and Potwar south deformed areas.

Sub-Himalayas are further divided from north to south in the following zones

a) Northern Potwar Deformed Zone
b) Soan Syncline Zone
c) Punjab Platform Zone

2.3.2 Lesser Himalayas

The deformed area located between MMT (Main Mantle Thrust/Indus Suture Zone) toward north and MBT (Main Boundary Thrust) toward the south are called Lesser Himalayas. In this zone high grade metamorphic (deformed) and igneous intrusions are present. Lesser Himalayas include the Hill Range, KalaChitta Range, Nizampur Basin, Hazara Kashmir Basin, Plio-Pleistocene Basins (Haripur and Cambelpur) and Southern Kohistan (Seeber & Armbruster). Precambrian sediments and volcanic rocks of Paleozoic age are present in the western part of Lesser Himalayas mountain ranges. High degree of overlap formed from the Crystalline central Axis target these sediments (Valdiya, 1977, 1980). Sedimentary area in the south expand from lower Himalayas, in the east from PirPanjal (Kashmir), through Kaghan, Hazara Kashmir syntaxes, Kohat and running through Kala Chitta ranges and ACR (Attock-Cherat Range).

2.3.3 Higher Himalayas

Higher Himalayas are a thick massive Sequence (10-15 km) of highly metamorphosed rocks superimposed over the lesser Himalayas. Its base can be marked from Central Crystalline thrust Sheets and MCT (Gansser, 1981). These Himalayas are situated between MCT (Main Central Thrust) to the south and MMT (Main Mantle thrust) to the north.

2.4 Geological setting of the Study area

Gandgher Range is North-East and South-West trending range at the northwest of Islamabad some 40 km away. Between Peshawar basin and Haripur (Plio-Pliestocene) this range forms a limited barrier Fig (2.1). It is a transitional zone between foreland strata (unmetamorphosed) to the south and plutonic, highly metamorphic rocks in the north. It has the record of transition between Himalayas and foreland strata and structurally continuous with the Northern Block of Attock-Cherat Range(Yeats & Hussain, 1987)

The study area is situated in the fold thrust belt along the southern margin of the Himalayas near to the Cambelphore Basin.

To the south of study area in Kala Chitta ranges and northern Potwar plateau molasses are thrusted over by tertiary marine strata along the MBT. At the Southern edge of the Potwar plateau there is salt range thrust (Baker et al., 1988)

To the north of the studied area there is main mantle thrust consist of shelf strata of the northern side of the Pak-Indian plate. These shelf strata have various grades of metamorphism and also intruded by granitic rocks (Maluski & Matte, 1984). The MMT which is also know for emerald deposits of Pakistan is formed when Tethyan ocean lithosphere got consumed between Kohistan Island arc and Indian plate (Lawrence, 1989)

To the east of the study area in the southeast Hazara late Precambrian to Holocene strata are exposed along the fold thrust belt (Tahirkheli, 1970). To the west of the study area Peshawar Basin and Attock-Cherat ranges are present. Peshawar Basin fill mostly composed of lacustrine silt with interbedded river sand, gravel and clasts of Kohistan origin showing the deposition by Indus River and Kabul River (Burbank, 1983). To the south of Peshawar Basin three faults separated structural blocks of Attock-Cherat ranges are present. In the northern block, late Precambrian metaclastic strata and limestone are thrust over unfossiliferous flysch toward south. These are overlain by the middle block Cretaceous and Tertiary rocks (Yeats & Hussain, 1987). These are again thrust southward and thrust upon the southern block. The southern block consists of Paleozoic limestone (unfossiliferous) quartzite and argillite (Yeats & Hussain, 1987). The Paleozoic sequence exposed in the vicinity of Nowshehra in the south of Peshawar basin can be related to that of Attock-Cherat ranges on lithological basis. The southern bock of Attock-Cherat is thrusted over KalaChatta ranges and Margalla Hills, Triassic to Eocene foreland sequences (Yeats & Hussain, 1987).

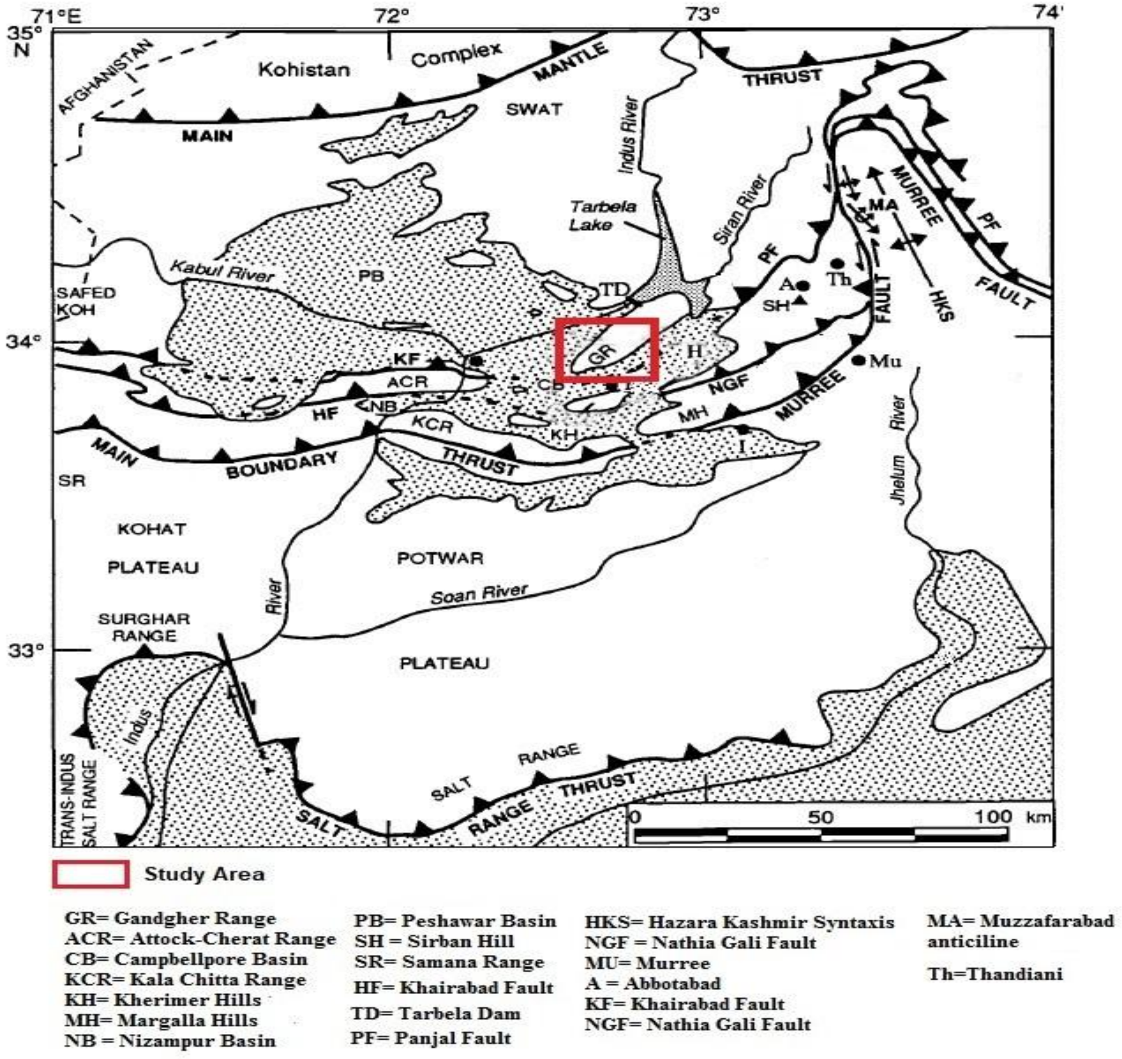


Fig 2.1 Generalized tectonic map of Northern Pakistan, location of study area encircled in the middle. Map is compiled from (Hylland, 1990).

2.5 Structural Geology

The structural geology of the study area consists of faults and folds. The faults in the study area are dipping toward the north, having three thrusts faults and a normal fault. Two sets of distinct folds are present in the study area.

2.5.1 Gudwalian Fault

This small fault is in the Gudwalian village, exactly where our study area located about 14 km from the Haripur toward the east. Previous workers (Calkins et al., 1975) mapped this fault. It is a normal fault having contact between Tanawal Formation and Shekhai Formation.

The fault is not distinctly visible as a line or zone but there are enough positive indications of having a fault. For example, the contact there is very sharp and the veins (Calcite and quartzite) present in the Shekhai Formation are truncated by the Tanawal Formation in some places. Also from the thin section study of the samples from the contact zone between Tanawal formation and Shekhai Formation the calcite grains show crushing and shearing, the shearing present can be seen with naked eyes also within the contact zone (Riaz et al., 1991).Similarly, striations and drag folds present also show the indications of a fault.

2.5.2 Baghdarra Fault

Another fault in the Gandgher ranges is called Baghdarra fault, named after Baghdarra, a village near Southern Gandgher area located 3 km away from Pirthan (highest peak) in Southern Gandgher range.

This fault juxtaposes Tanawal Formation, Shekhai Formation with Manki Formation. The Hanging wall of this fault consists of the Manki formation while Tanawal and Shekhai formation are in the footwall of Baghdarra fault. Drag fold in the fault zone shows reverse Sense of slipping in this fault (Riaz et al., 1991).The reverse slip displacement was also suggested by (Hylland, 1990).

2.5.3 Sirikot Fault

This fault got its name from Sirikot village, a village in the northwestern side of Haripur, some 19 Km away from Haripur.

Most part of this fault is in Manki Formation and the northern part of this fault juxtaposes the basal conglomerate unit of Tanawal Formation with the Manki Formation. In the Turbela Dam Lake water, the northern part of this part is better exposed. On the Haripur road this fault can also be seen in about 4 km east of Sirikot Village. The drag folds associated with this fault show that is a reverse slip fault.

2.5.4 Darrah Fault

In the Gandgher Range toward the northwest side this fault is located, in the Darrah village which is about 4 km away from Sirikot toward northwest.

This fault juxtaposes Tanawal Formation (basal conglomerate member) with Manki Formation. In the Darrah stream striations on the quartzite bed shows dip-slip movement in this fault and drag folds in the strata below the fault zone shows reverse sense of shearing. Slickensides in both the footwall and hanging wall shows dip slip movement. It is a back thrust fault (Riaz et al., 1991).

2.6 Previous work

(Verchere, 1866-67) in geological reconnaissance of northwest Himalayan ranges made the first reference to the study area. Extensive stratigraphic interaction was developed by (Waagen & Wynne, 1872) during mapping of the area near Sirban Hill in Abbotabad. Wynne (1879) present a detailed study of the Gandgher range developed cross sections of the Gandgher Range and also a map of Hazara area having a scale (1in = 8mi). A more developed sketch map was given by (Middlemiss, 1896) for the Hazara region at a scale of ½ inch = 1 meter. Both the workers Middlemiss and Wynne describe the limestone of the Gandgher Ranges but both of them were not sure about its age and also the stratigraphic position. (Cotter, 1929) described the hills near to Hasan Abdal in some detail.

From 1961 to 1965 the Gandgher ranges at its northern Part was mapped by Geological Survey of Pakistan in collaboration with U.S Geological survey (Calkins et al., 1975) during the detailed geological study.

(Tahirkheli, 1971) mapped all of the Gandgher range who were on the idea that Gandgher ranges are a lateral extension of Attock-Cherat Ranges.He described all the lithologies of the Gandgher Ranges to be Paleozoic and has correlative lithological units that are similar to Attock cherat ranges and southeast Hazara region.

(Riaz et al., 1991)described the stratigraphy and structure of the Northern Gandgher Ranges. He correlated the stratigraphy of the both northern and southern Gandgher ranges and marked different types of faults present in the Gandgher range.

2.7 Stratigraphy of the Study Area

The stratigraphy of the Gandgher ranges consist of thick, lower argillaceous formation i.e. Manki formation and it is overlain by the algal limestone and shale of Shahkot, Utch Khattak and Shekhai Formations.

(Talent & Mawson, 1979) suggested Proterozoic age for the succession based on fossils lacking and the correlation of Manki and Hazara Formations (Hazara formation being of Proterozoic age). Also, mostly the contacts are gradational all over succession. Igneous intrusions of basic nature are intruded throughout the succession which maybe of late Pennsylvanian to early Permian age

Two significant differences between the stratigraphic succession of Gandgher range as mentioned above and the one given by (Tahirkheli, 1971) are;

Firstly, bedrock unit with different names were used. (Tahirkheli, 1970), originally used the names as Manki slate, Shahkotbala, Khattak limestone and Shakhai limesone to the Attock Cherat ranges lithostratigraphic units. Then he used the name Sirikot slate, Mohat Nawan limestone, Baghdarra limestone and Pir than limestone to the Gandgher ranges lithostratigraphic units and correlates it with that of Attock Cherat ranges given above respectively. Manki Formation, Shahkot Formation, Utch Khattak Formation and Shekhai Formation of Attock-Cherat ranges are those modified from that of (Tahirkheli, 1970) and are now used by the Geological Survey of Pakistan. The reasons why these modified names are now used for Gandgher ranges succession is because of the correlation of (Tahirkheli, 1971) and to produce a more constant stragrahpic nomenclature instead of local names.

Second difference is that the stratigraphic position of Gandgher ranges given above and that given by (Tahirkheli, 1971) for the oldest bedrock is reversed. In Gandgher and Attock Cherat Range (Tahirkheli, 1970) the Shahkot is the oldest formation, however study by (Yeats & Hussain, 1987) and (Hylland, 1990) shows that Manki Formation is the oldest in both of these areas.

2.7.1 Manki Formation

Nomenclature of Manki formation has a long history. It consist of the oldest bedrock of the area having argillaceous unit was primarily named “Attock Slates” by (Waagen & Wynne, 1872) after it exposure at Attock near the junction of river Kabul and Indus. In Sirban Hill (Abbotabad) Waagen and Wynne extended the same name “Attock Slates” for argillaceous strata exposed at the bottom of a sedimentary sequence. Then (Middlemiss, 1896) used the name “Slate series” for all the argillaceous sequence exposed at the base all over Hazara region. (D. Wadia, 1931) correlate Hazara sequence with a similar argillaceous succession exposed in Kashmir area and called it “Dogra slates”. (Marks & Ali, 1961) pointed out that although slate is one of the lithologies present still they named “Hazra slate formation” and retained the name slate. (M. Latif, 1970) gave it a group status by dropping the slate and elevated it to a group status, he used the Lower Formation, Middle Formation, Langrial Limestone and Upper Formation to the different lithological units in Southeast Hazara. The name Hazara Formation was given by Calkins and other (1975). (Tahirkheli, 1970) called the Attock Slates of Waagen and Wynne as the Manki Slate because of Manki Ghar type section near Nowshehra. Manki Slate, Shahkotbala and Khattak limestone which are restricted to Attock Cherat ranges was named “Attock Formation” in “Stratigraphy of Pakistan” (Yeats, Khan, & Akhtar, 1984). To include other lithologies along with slate Hussain (1984) called “Manki Slate” as Manki Formation. (Tahirkheli, 1971) called it Sirikot Slate in Gandgher Ranges, a local name.

Manki formation is exposed in Gandgher Ranges along Baghdarra fault. Gradational contact with overlying Shahkot formation, base is less clear.

Manki Formation contains slate, phyllite and argillite. The rock color are dark grey, reddish brown or olive grey for weathered surface and dark grey to dark greenish grey for fresh surface. To the north grade of metamorphism increase indicated by petrological variation from slate and argillite to phyllite have abundant quartz veins. Bedding parallel cleavages set may show bedding fissility suggested by (M. A. Latif, 1969)

Lack of fossils and correlation with Hazara formation are the two factors that age of the Manki Formation is probably Proterozoic

2.7.2 Shahkot Formation

Mapped by (Tahirkheli, 1970), in Attock Cherat Ranges, as “Shahkotbala Formation” a unit of shale, limestone and slate. Shah (1977) place Shahkot, Manki and Khattak limestone in one unit named “Attock Formation”. (Tahirkheli, 1971) called it “Mohat Nawan” in Gandgher Range and made a comparison of it with Shahkotbala Formation in Attock Cherat Ranges. (Hussain, 1984) made a map for Attock-Cherat Range and called it Shahkot formation.

In Gandgher Ranges it is exposed in Southeastern Gandgher along Baghdarra fault footwall. In Gandgher Ranges its thickness is 300 m approximately, and its lower contact with Manki formation and upper contact with Utch Khattak Formation are conformable.

Shahkot Formation is composed of limestone, shale and argillite. Fine to medium grained and thin to medium bedded limestone having 100 m thickness approximately. Weathered surface is brownish gray and fresh surface is yellowish gray. Small amount of metamorphic minerals i.e. epidote and the deformation of crystals show low grade of metamorphism. Dark greenish gray argillites are found above the limestone having similar appearance as that of Manki Formation argellite. On the top within the argillite bed there is a thin and discontinuous bed of algal limestone.

(Tahirkheli, 1970) due his work on Attock Cherat ranges reported fossils which he uncertainly called as bryozoans of probably Paleozoic or maybe late Ordovician to early Silurian in the Shahkot Formation. However work by (Hussain, 1984) and (Yeats & Hussain, 1987) on Attock Cherat Ranges and later (Hylland, 1990) during his work on Gandgher ranges found no such fossils.

It has gradational contact with below lying Manki Formation and itself lying below other unfossiliferous strata suggest of late Precambrian age probably by (Hussain, 1984).

2.7.3 Utch Khattak Formation

(Tahirkheli, 1970) during his work on Attock Cherat ranges was the first to map this unit of distinctive limestone, argillite and shale as “Khattak Limestone”. Shah (1977) grouped Manki slate and Shahkotbala Formation with Khattak Limestone and all these as Attock formation. (Tahirkheli, 1971) during his work on Gandgher Range referred one limestone unit as Baghdarra limestone and make a correlation of it with the Khattak limestone of Attock Cherat Range. It was later called as “Utch khattak Formation” due to other lithologies present along with limestone by

(Hussain, 1984). In the study area Utch Khattak Formation is exposed in southeast Gandgher Range in the Baghdarra Fault footwall. It has conformable contacts both with the underlying Shahkot Formation and above lying Shekhai Formation and has thickness about 200-250 m.

Utch Khattak Formation consists of limestone, shale and argillite. The limestone of Utch Khattak Formation is very much distinctive and is at the bottom of the formation. The limestone is bluish gray and dark grey, medium grained and thin bedded. In places stromatolites are also well developed. Thickness of the limestone is 10 m to 70 m. The limestone is overlain by some argillite and some thinly bedded shale. Utch Khattak Formation has no fossils reported. The Utch Khattak limestone is younger than Manki and Shahkot formation because clasts of both Manki formation and Shahkot formation are found with an intraformational conglomerate in the Utch Khattak Limestone.

The Utch Khattak Formation being unfossiliferous and has a local gradational contact with Shahkot Formation lying below and also lies below unfossiliferous strata startigraphically, suggest of late Precambrian age probably by (Hussain, 1984).

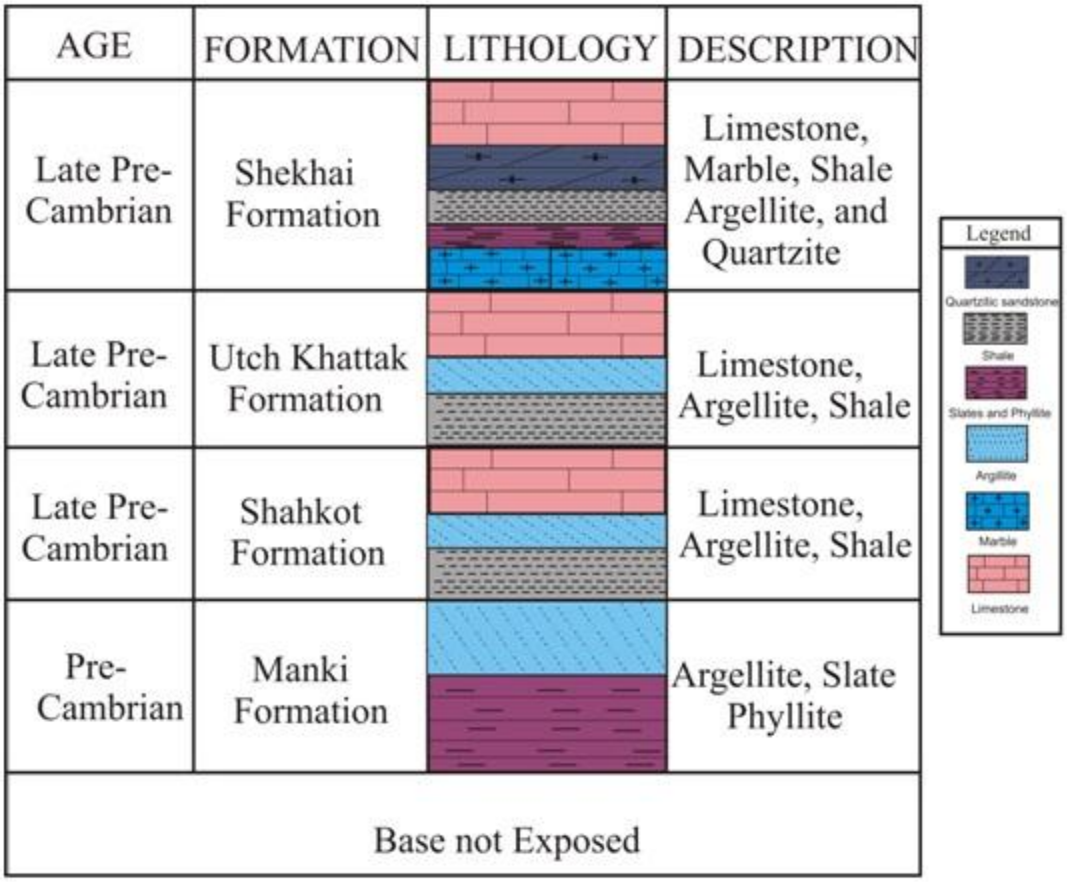
2.7.4 Shekhai Formation

(Tahirkheli, 1970) originally mapped Shekhai Formation during his work on Attock-Cherat range and named it as “Shakhai[sic] limestone. The (Tahirkheli, 1971) correlated a limestone unit in Gandgher Range which He named as “Pir Than Limestone” with the Shakhai Formation in Attock Cherat range. To reflect other lithologies with limestone in this unit (Hussain, 1984) used the name “Shekhai Formation”.

In the study area Shekhai Formation is exposed in the Baghdarra fault foot wall. Thickness is uncertain because of the truncation by the Baghdarra fault. However minimum of 300m thickness can be implies from the outcrop. It overlies Utch Khattak Formation conformably.

Lithology of the Shekhai Formation consists of Limestone, Marble and some amount of shale, argillite and quartzite. Limestone is massive, fine grained to medium grained, and has various colors like dark gray, light brown, pink and light gray. The weathered surface of the formation is light grey, light brown and comparatively smooth. In some places the limestone is oolitic too. White marble in small areas are due to thermal metamorphism because of the association with the igneous dikes. Quartzite bed of almost 1 m at the Formation base and argillite and shale occur throughout Shekhai Formation.

The Formation is unfossiliferous. Due to conformable contact with Utch Khattak formation and because of no fossils (Yeats & Hussain, 1987) assigned that Shekhai formation of probably early Cambrian.



AGE	FORMATION	LITHOLOGY	DESCRIPTION
Late Pre-Cambrian	Shekhai Formation		Limestone, Marble, Shale Argellite, and Quartzite
Late Pre-Cambrian	Utch Khattak Formation		Limestone, Argellite, Shale
Late Pre-Cambrian	Shahkot Formation		Limestone, Argellite, Shale
Pre-Cambrian	Manki Formation		Argellite, Slate Phyllite
Base not Exposed			

Fig 2.2 Stratigraphy column of the study area adopted from (Hylland, 1990).

2.8 Intrusive Rocks

Almost all of the Gandgher Range have intrusions, i.e. sill and dikes which are basic in nature (Riaz et al., 1991). Same nature of intrusions are there in Attock-Cherat Range (Hussain, 1984; Karim & Sufyan, 1989), in the Hazara Ranges (Shams & Ahmed, 1968) and also in the Peshawar Basin (Pogue, 1993). The thickness of these dikes and sills are generally less than 5 meters. Its deformation has been caused structurally along with the country rocks. These sill and dikes are diabasic. Chemically these intrusions are tholeiites of continental flood basalt (Karim & Sufyan, 1989). Panjal Volcanics has also the same type of origin (Honegger et al., 1982) which are basic to intermediate rocks. These diabasic dikes and sills of Gandgher Range maybe correlated with those of Panjal Volcanics. Age of these intrusions is unknown but the intrusions of similar nature found in the strata of Peshawar Basin are of Carboniferous age (Pogue, 1993) thus these intrusion maybe of Permian age or younger.

CHAPTER 3

MATERIAL AND METHODS

To study the effects of intrusions on Utch Khattak Formation, a reconnaissance field was arranged to the Southern Gandgher Ranges.Utch- Khattak formation is also exposed in the Attock- Cherat Ranges but the intrusions are not that well exposed. Moreover, the type section is cut near Gudwanian Dam, so the intrusions are very well exposed and easily accessible. The variation in the country rocks can be noted through naked eyes as fresh surfaces of the lithologies are exposed due to cutting of the type section. After reconnaissance, a detailed field work was arranged to collect samples, field observations, field photographs, diagenetic features and field description.

3.1 Sampling

During the geological field work more than 50 rock samples were collected from the outcrop. As the intrusions were present vertically through the cut gorge so all the variations due to the intrusions were the same from top to the bottom. A systematic way of collecting samples was carried out as, to left side of the dyke first sample was taken at dyke-host lithology contact (Chilled zone), second sample was taken where there was change in the host lithology by naked eyes and third sample taken when again there was a change in lithology. Same process repeated to the right side of the dyke. 11 dykes were covered in this way. The distance of every sample from the dyke was noted down and the picture of every sample was taken exactly at its location. The samples were marked through a marker and GPS location and field description for every sample was noted down. The width of every dyke was noted down and few samples of the dykes were also collected for XRD analysis. Some random samples of the Utch Khattak limestone were also collected which was away from the dykes and was not affected by the intrusions. Dilute HCl was used in the field to differentiate between calcite and dolomite phases.

3.2 Macroscopic Analysis

First the rocks samples were cut to form the slabs of the rock samples in the lab. These slabs were polished and Dickson, (1965) method for the staining of the slabs was used to stain the slabs. These slabs were etched and then stained with Alizarin Red S and K- ferricyanide. Staining helps to differentiate between calcite/ dolomite phases, Fe rich/ Fe poor carbonates phases. Other than that porosity information, texture and cross-cutting relationships are easily observed from stained samples compare to the unstained samples.

3.3 Microscopic Analysis

15 samples were selected for the petrography based on features with naked eyes. The thin sections were then prepared in the Hydrocarbon Development Institute of Pakistan (HDIP). First all the thin sections were studied unstained. Then (Dickson, 1965) method was used and stained all the thin sections. According to this method all the thin sections were stained using Alizarin Red-S and Potassium Ferricynide. This staining of thin section helps us to differentiate between calcite and dolomite phases and also between Fe rich and Fe poor carbonates.

In Geological Laboratory of Earth Sciences Department, Quaid-i-Azam University Islamabad, analysis and photographs of thin sections were taken by Olympus Digital Camera (Model C-5000) connected to the Olympus compound microscope (Model Bx 51) and Pentium 4 computer using magnifications of X4, X10 and X40 magnifications achromatic objectives. (Sibley & Gregg, 1987) classification was used for crystal size and shape. Plane polarized transmitted and incident light microscopy gives us information about facies composition, micro-texture, diagenetic phases. Both plane polarized light (PPL) and Cross polarized light (CPL) were used to note the plane and cross light properties.

3.4 Minerological Study

3.4.1 X-ray diffraction analyses (XRD)

For analyzing Ca-Mg carbonates X-ray diffraction analysis is used. Composition of the carbonates (both biogenic and inorganic) is calculated through X-ray diffraction by comparing their $d104$ values with the empirical curves of those carbonates. For this, anode made of copper (Cu) is bombarded with high energy beam of electrons, which results in X-rays emission. These rays are then directed on the powder sample rotating in XRD apparatus at constant speed. X-rays diffraction according to Bragg's law is caused by the different mineral's phases present in the sample at an appropriate angle. Diffract meter gives the output result in the form of a chart. This chart has diffraction pattern of the minerals with vertical axis shows the maximum intensities of the diffracted peaks and horizontal axis is calibrated in 2ɵ degree. These peak intensities of different minerals are then compared with the standard pattern of the "Joint Committee on Powder Diffraction Standards (JCPDS).

Stoichiometric dolomites have equal number of Ca and Mg ions Ca: Mg = 50:50, called ideal dolomites, which are very rare in nature. Dolomites are mostly non-stoichiometric in nature having excess of Ca ions mostly (Ca: Mg =68:32) or less commonly excess of Mg (Ca: Mg =38:62). This variation of the ratio from ideal state is called non-stoichiometry and is measured as mol % of CaCO3. Ca^{+2} substitution by Mg^{+2} increase the cation lattice spacing and XRD are used to measure this and determine Ca/Mg molar ratio by d^{104} values and compare with the standard. Classical method of Ca excess can also be calculated from (Lumsden, 1979) equation which compares d^{104} values with molar % of (N $CaCO_3$) in angstrom units (d). The equation is given below;

N $CaCO_3$= Md +B

Where;

M=333.33 and B= -911.99

5 powder samples for XRD analysis were in the Geological Survey of Pakistan (GSP) laboratories, Islamabad.

3.5 Stable Isotopes Analysis (O & C)

Stable isotopes analysis gives us information about environmental variability in temperature, isotope composition of the host water, salinity and carbon cycling. In carbonates studies $\delta^{13}C$ and $\delta^{18}O$ are commonly used. Isotopic composition of $\delta^{13}C$ and $\delta^{18}O$ are determined using mass spectrometer. Standard isotopes are concerned with bulk isotopic composition of a sample (carbonates in our case), and expressed as a difference (delta or δ) between the sample and an international standard (VPDB, “Vienna Pee-Dee Formation Belemnite” standard for carbonates).Both standard isotopes are ($\delta^{18}O$, $\delta^{13}C$) are disciplines in the field of stable isotopes (i.e. isotopes that are stable and do not decay). The stable O and C isotopes result is expressed in permil or % and tell us how the $^{18}O/^{16}O$ ratio is different than the $^{18}O/^{16}O$ ratio of the standard. However, it provides no information how the various stable isotopes are organized within the lattice of carbonate crystals.

10 samples of carbonates having different phases from petrographic study were processed for isotopic studies. These analyses were carried out in PINSTECH institute, Islamabad.

3.6 Atomic Absorption Spectroscopy

AAS is a type of chemical analysis used to determine chemical composition of the whole rock. It is frequently used in the determination of major and minor elements such as Mg, Ca, Si, Fe, Al, K, Ti, Na and is also used for the analysis of trace elements such as Pb, Zn, Mn, Sr, Cd and Cr. Absorption of radiations by the atoms of an element demonstrates itself as a spectrum that is characteristic of the element. For the purpose of AAS analysis Aqua regia solution is prepared. 1 gram of powdered sample is dissolved in 5ml of HNO_3 and HCL i.e 1:3 proportion. The solution is placed for 24 hours and then the sample is heated and dried is then dissolved in 10 % HCL to make 100ml solution is then placed for AAS analysis. The analysis are performed at Chemistry Department of Quaid-i-Azam University, Islamabad.

CHAPTER 4

FIELD OBSERVATIONS

Study area (Utch Khattak Formation) lies in the Southern Gandgher Ranges, district Haripur. Detailed field work was carried out to study the effects of intrusions on the carbonate lithology of Utch Khattak limestone. The outcrop is exposed near Gudwalian Irrigation Dam having East-West trending. Utch khattak Formation has been cut in the middle to make a pathway for the extra amount of water of the Gudwalian Dam making a gorge. On both sides of the Gorge the fresh surface of Utch Khattak Formation is exposed.

Utch Khattak Formation is intruded by the dikes on both sides of the gorge where thin to medium bedded limestone, recrystallized limestone; dolomites and marble are exposed in the vicinity of the dikes (Fig 4.1). The dikes present in the Utch khattak formation are mostly responsible for the diagenetic changes in the host limestone. These diagenetic alterations were noted in the field and matched with the petrographic studies later on.

Igneous intrusions cross-cut the host limestone, almost at regular interval in the gorge. 11 dykes were covered in this gorge by increasing the samples collection in the vicinity of the dykes. During field studies it was observed that dark greenish color dikes having sharp and clear contact with the host limestone intruded the strata. The width of the dikes varies from 10 inches to 185 inches (Fig 4.1). Almost every dike has same pattern of contact zone (which are either marble, or marbleized limestone) followed by Recrystallized limestone or dolomite. Marble or marbleized limestone form due to contact metamorphism (Fig 4.2). Stresses in the study area is quite evident, because as we go toward north of Pakistan stresses increases because of the tectonically active area in the north. Also due to igneous intrusions fractures are present in the vicinity of the dikes. Heavily jointed and fractured limestone found in the study area (Fig 4.3). In the field, folded strata with cross-cut and vertical joints were also observed (Fig 4.4). Vuggy porosity with algal stromatolites was found in the dolomite (Fig 4.5). Some of the hydrothermal dolomites (Saddle dolomites), were found right at the contact zone just after the intrusions (Fig 4.6). In some places patches of calcite was found within the dolomite (Fig 4.7). Special type of weathering called Butcher Chop weathering, which is the characteristic of dolomite, was observed in the field (Fig 4.8). Association of white calcite veins with dolomites, visible to the naked eyes is present in the altered limestone of Utch Khattak Formation (Fig 4.9). The strata in the contact zone are heavily fractured making a way for hydrothermal fluids to cause dolomitization in nearby strata (Fig 4.10). Small intrusions of dikes intercalated with shale are observed in the field (Fig 4.11) and interbedded marly, shaly limestone is also present (Fig 4.12). Due to recrystallized nature of the limestone, some of the original limestone features/textures are uncommon (Fig 4.13). The strata away from the dikes which are not altered by dikes, dolomitization is not evident in those strata.

Marble and recrystallize limestone can be differentiated by color in the field. Dilute HCl was used in the field to differentiate dolomite from recrystallized limestone. Recrystallized limestone gives a little more effervescence with HCl than the dolomite. Most of the Recrystallized limestone has black color compared to the original precursor limestone having different color.

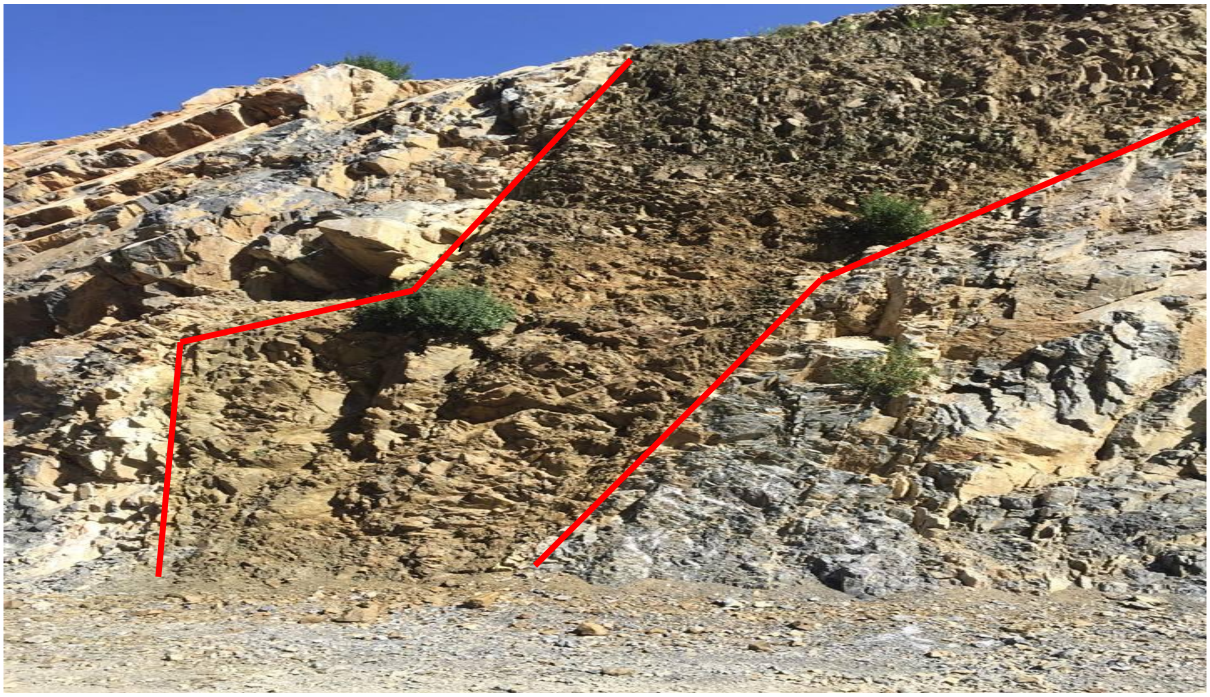


Fig 4.1 Cross sectional view of the strata showing the dolerite dyke within the Utch Khattak formation (The thickness of the dyke is 165 inches).

Fig 4.2 Field Photograph of dyke (left side), Contact zone (middle) and Recrystallized limestone (right). Width of the contact zone 100 inches

Fig 4.3 highly fractured sandy dolomites with two sets of joints, cyclic/ rhythmic bedding, and length, 20 inches.

Fig 4.4 Folded limestone, with Cross-cut and Vertical Joints.

Fig 4.5 Highly fractured, jointed, porous limestone, showing vuggy porosity. Algal stromatolites are also visible in the picture. This is the unaltered limestone away from the dyke.

Fig 4.6 Hydrothermal dolomites (Saddle dolomites), with altered calcite at the contact of the igneous intrusion.

Fig 4.7 Dolomite having patches of calcite

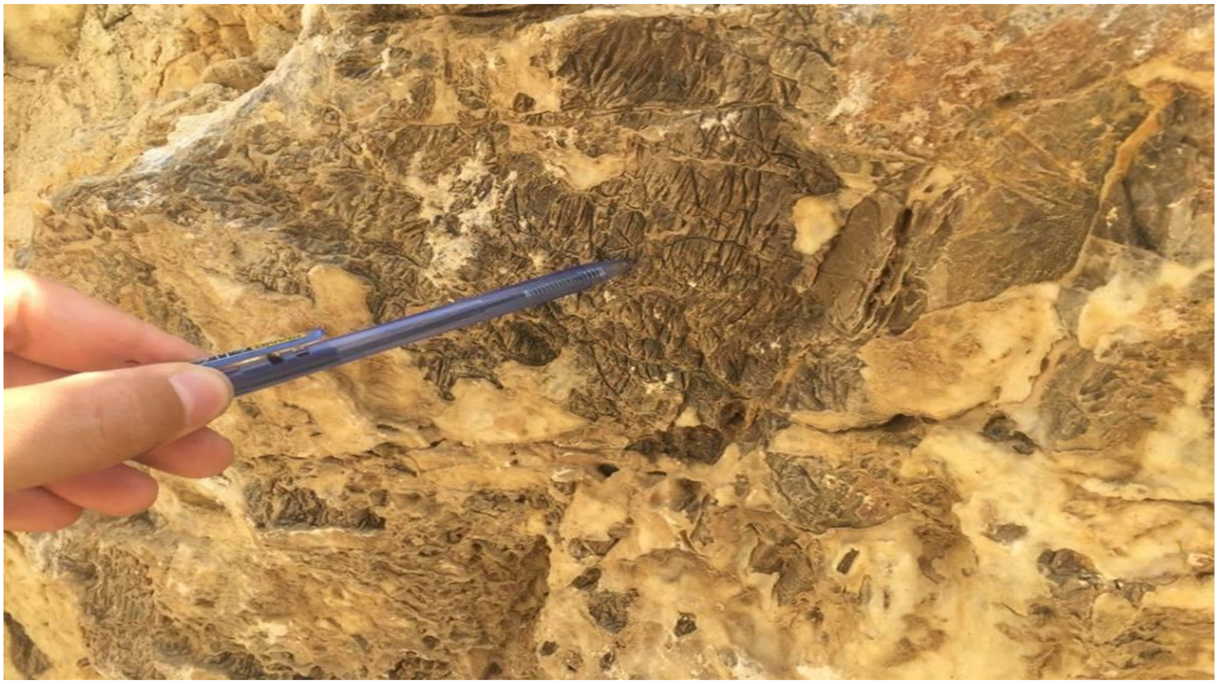


Fig4.8 Vuggy porosity, secondary dolomitization with butcher chops weathering. Layers of calcite crystallization from hydrothermal fluids. On this side marble was absent; the effect of the intrusion was less on this side, evident from outcrop

Fig 4.9 Late calcite filled veins associated with saddle dolomite. Calcite veins coming along the open space.

Fig 4.10 Highly fractured limestone, at the contact of the dyke. Dolomitization has occurred along the fractures. Mostly cementing dolomites are present in this sample from petrographic study.

Fig 4.11 Small intrusions intercalated with shale. Sandy and marly limestone are present. Carbonaceous matter is present in small amount

Fig 4.12 Thin to medium bedded limestone with interbedded marl and shale.

Fig 4.13 Recrystallized limestone present next with marble (contact zone). Fractured are not present, so dolomitization is absent on this side.

CHAPTER 5

PETROGRAPHY

Sedimentary rocks petrography tells us about its mineralogy and chemical composition, from which we can interpret the rock geological setting (Tectonic setting), weathering, erosion and provenance of the rocks etc. (Cox & Lowe, 1996; Nesbitt & Young, 1989). After deposition of the sediments it is affected physically, chemically and biologically by the diagenetic processes which in turn control its porosity and permeability, texture and minerals (Richard, 2003). Therefore diagenetic processes and products are essential to understand because it has an important role in sedimentary basin evolution, and also has the key role to enhance, destroy or preserve the porosity and preservation of some economic minerals (Richard, 2003).

Fifty samples collected from the study area for thin sections. The thin sections were stained (Dickson, 1965) using solution of K-ferricyanide and Alizarin Red S. This staining enable to differentiate between calcite and dolomite phases and also between Fe-poor and Fe-rich carbonates (Jacquemyn et al., 2014)

For dolomites in the thin sections dolomite classifications of (Randazzo & Zachos, 1984) and (Sibley & Gregg, 1987). According to the first classification scheme crystal size of dolomites can be (very fine size, fine size, medium size, coarse size), crystal texture maybe (inequigranular or equigranular), crystal distribution (floating, patches, isolated, loosely or tightly packed). According to (Sibley & Gregg, 1987) dolomite are classified as unimodal, polymodal, planer, non-planer, euhedral, subhedral, and anhedral.

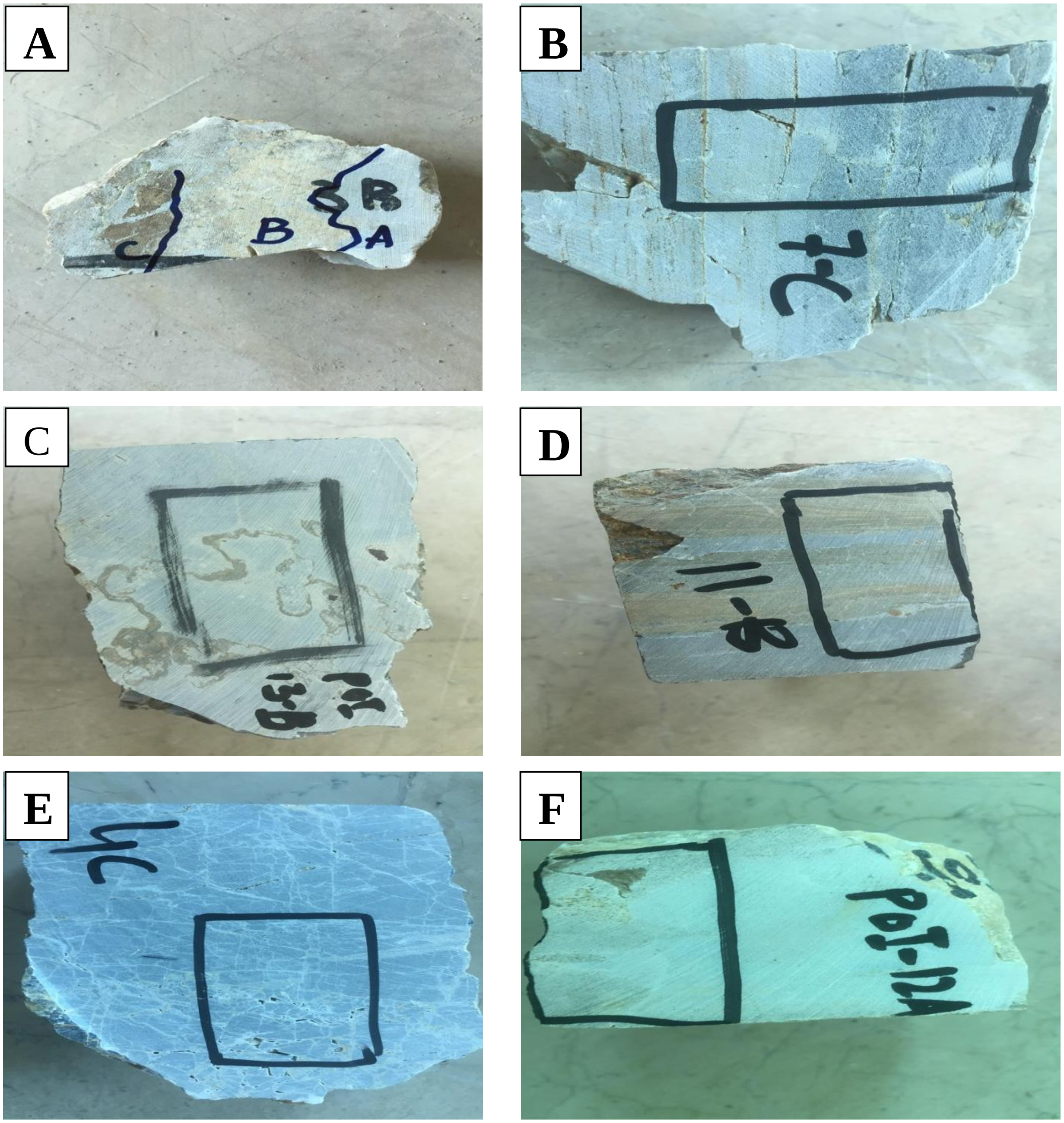


Fig 5.1 Photographs of some selected slabs for the thin sections showing different diagenetic features (A) Slab showing three phases of Precursor limestone, hydrothermal dolomites and altered Calcite (B) Showing highly fractured Recrystallized limestone, along the fractures, calcite and dolomites cements have invaded.(C) Showing slab of limestone where hydrothermal fluids have cause dolomitization (D) Hard Compacted limestone having band of Matrix replacive dolomites (E) Brecciated limestone having late calcite veins (F) Marble slab having both calcitic and dolomitic marble.

5.1 Texture

Thin sections prepared from the samples of altered carbonates of Utch Khattak Formation for petrography. These thin sections were studied in order to cover all the textures (altered, diagenetic and primary). Carbonates of Utch Khattak Formation are fine, medium, and coarse grained, compacted and altered as evident from our observations of thin sections study, field observations and hand specimen study. Dolomites found in thin sections are fine grained matrix replacive dolomite (Fig 5.2 A), fine grained cements dolomites (Fig 5.2 B, F), and both fine- and coarse-grained saddle dolomites (Fig 5.2 C, D). Most of the dolomites from thin sections are non-planer and anhedral to Subhedral dolomites. Dolomites cements are also present in the thin sections having white appearance, occupying the pore spaces (Fig 5.2 B, F). Quartz crystals are also present along the veins (Fig 5.2 A). These quartz grain shows undo lose extinctions and having fractures which shows stresses in the study area. Quartz grains bear moderate to sharp edges and mostly present in cluster having inetercrystalline porosity. This inetercrystalline porosity is filled by calcite. Due to contact metamorphism because of intrusions, marble is also present in the thin sections (Fig 5.2 D). Marble present in the thin sections mostly shows banded appearance and are fine and coarse grained as well. Calcite is present in the form of late calcite veins and Teleogenetic calcite (Fig 5.2 E, F). Some heavy minerals are also present in some thin sections in appreciable amount Fig 5.2 E)

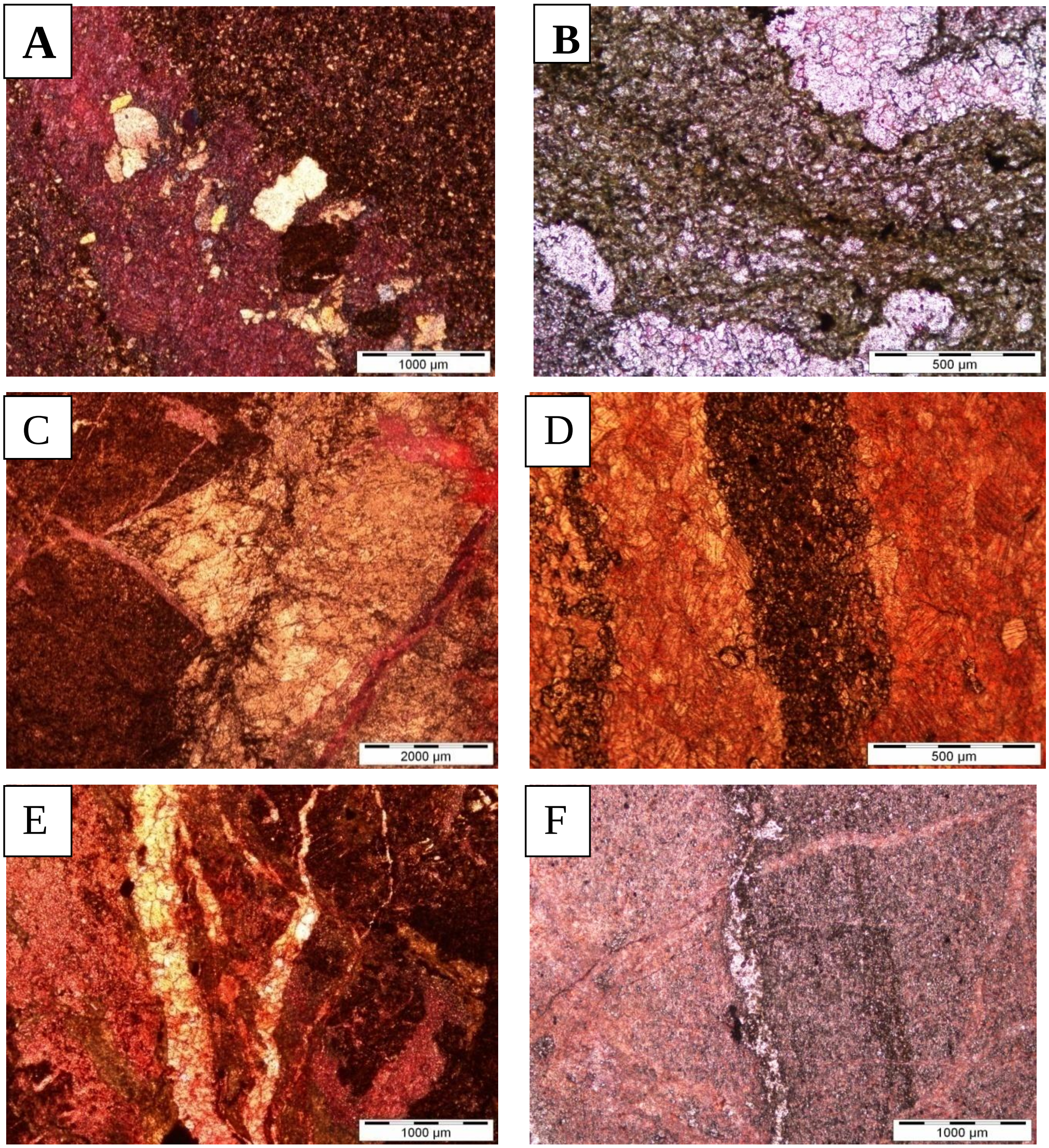


Fig 5.2 Photomicrographs of different textures (A) Fine grain black color matrix replacive dolomite associated with quartz grains coming along with calcite veins (B) white color cementing dolomite, in the open pore spaces along the contact of Saddle dolomite and precursor limestone (C) Non-planer Saddle dolomite with altered calcite (D) Marble having both black color dolomitic marble and calcitic marble differentiated by staining (E) Late stage Teleogenetic calcite veins along with saddle dolomites (F) Late stage calcite veins cut by fracture with white dolomite cement

5.2 Characteristics of different Phases

5.2.1 Dolomite

In the altered carbonates of Utch Khattak Formation dolomite is one of the dominant rocks forming mineral. Dolomites present in phase one are matrix replacive dolomites (Fig 5.3 A, B, C, D). They are dark grey in color. These dolomites are also present in the banded marbleized zone as dolomitic marble. In the stained thin sections, they have got no staining. These dolomites are present both fine grained size and in coarse grain size and are anhedral. Dolomites present in phase two are Saddle dolomites (Fig 5.4 A, B, C, D). These dolomites are light brown in color. In some thin sections they are fine grained while in other thin sections they are coarse grained. In coarse grained thin sections, they have non-planer boundaries and anhydral crystals. These non-planer boundaries are the characteristic of elevated temperature (greater than 50 ^{0}C) and also show high super saturation (Sibley & Gregg, 1987). They show undulose or sweeping extinction in cross polarizing microscope upon the rotation of the stage. These dolomites are also present along the veins. In some thin sections these saddle dolomites are also present in patches. Third phase are dolomite cements (Fig 5.5 A, B, C, D). These dolomites are whitish in color and are abundant in the altered carbonates of Utch Khattak limestone. They have mostly occupied small fractures and vein as pore filling cements. Porosity created already by fracturing is destroyed by this cementing phase of dolomites. They are present in patches also, between the hydrothermally formed dolomites and precursor limestone, and are later cements.

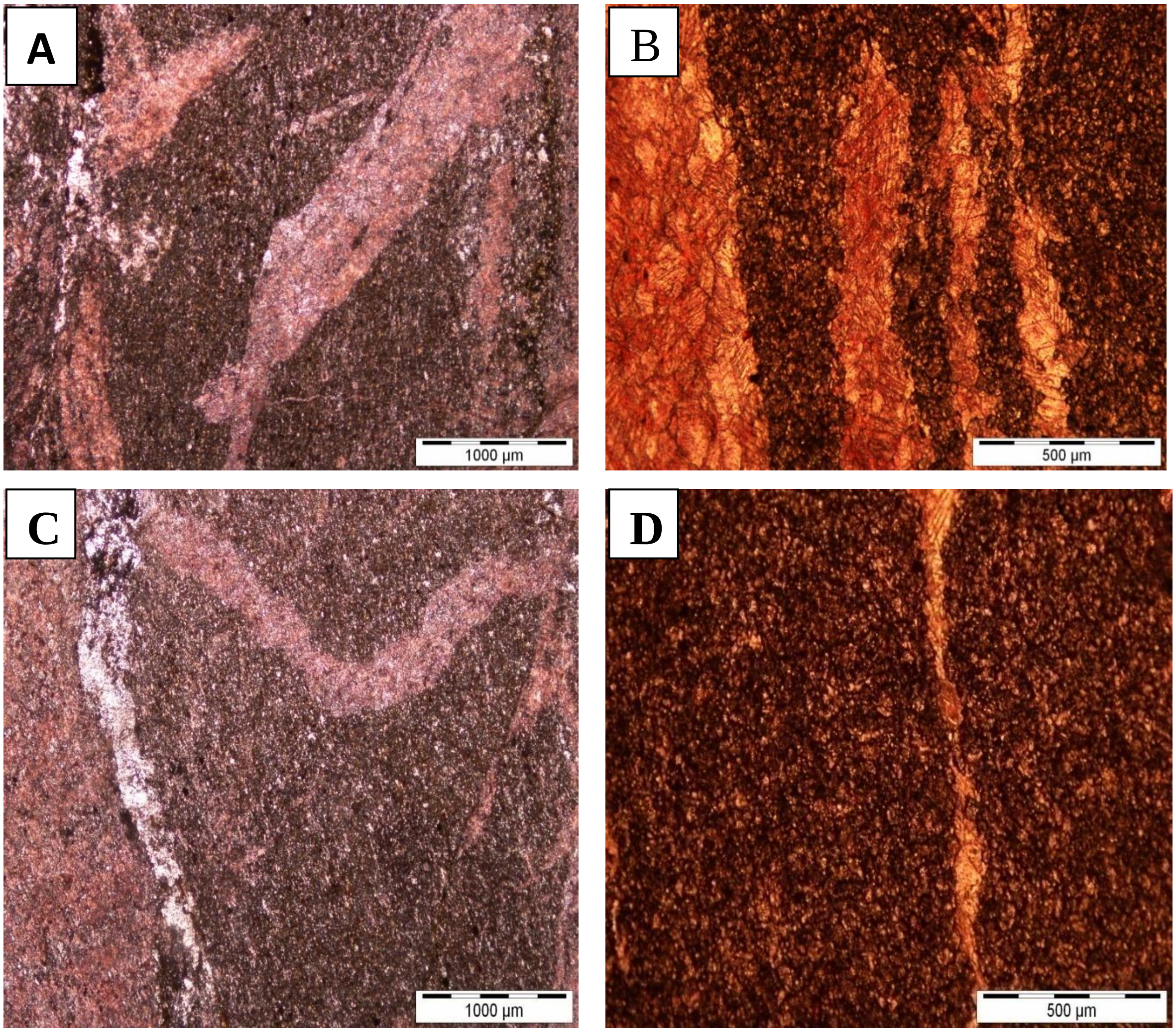


Fig 5.3 Photomicrograph of matrix replacive dolomites (A) Matrix replacive dolomite having Dedolomitization and later dolomite cements (B) Replacive dolomitic marble with calcitic marble (Recrystallized grains of calcitic marble are apparent) (C) Replacive Dolomite, with dolomite cements along the fracture (D) Matrix replacive dolomite with calcite vein.

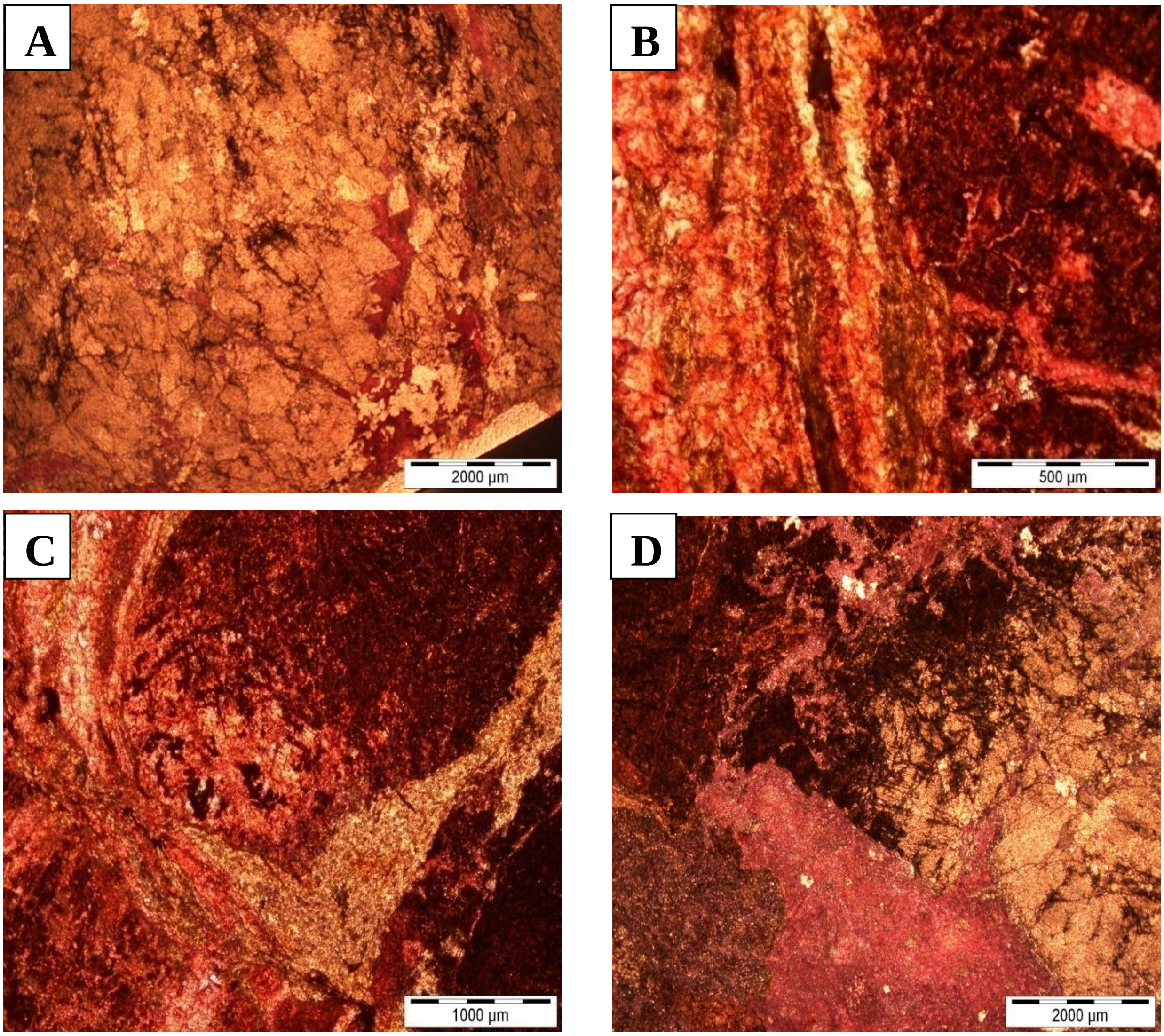


Fig 5.4 Photomicrographs of Saddle dolomites (A) Non-planer euhedral to subhedral saddle dolomites (B) Saddle dolomite in open pore spaces between calcite veins maybe replaced by later calcite (C) Saddle dolomite in open pore spaces between calcite (D) Association of Saddle dolomite with calcite, altered calcite and precursor limestone

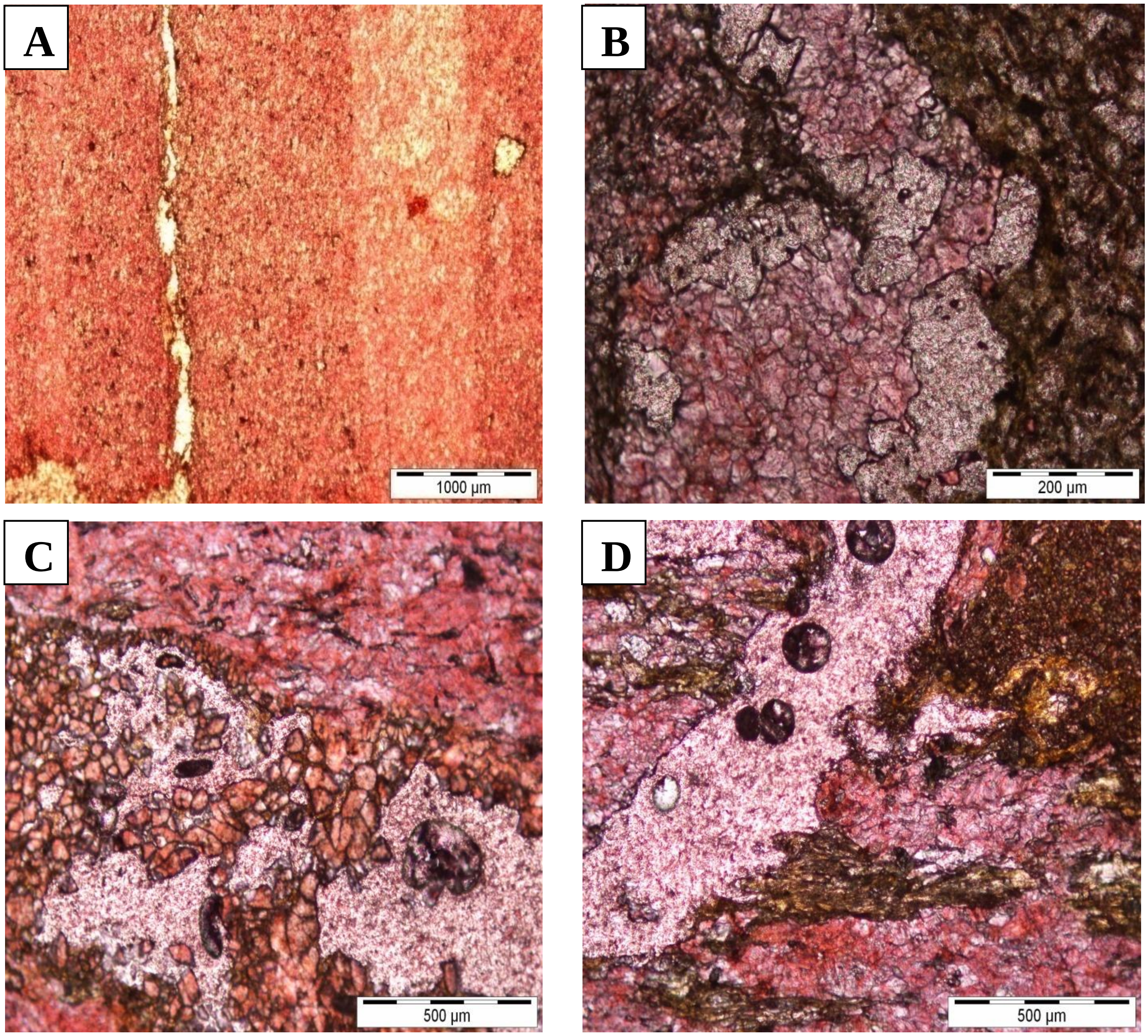


Fig 5.5 Photomicrographs of Cement dolomites (A) Cement Dolomites along a fracture in limestone (B) Cementing phase dolomites in between Saddle dolomite and later calcite cements (Saddle dolomite formed due to hydrothermal fluids along the veins in this thin section) (C) Dolomite Cements cross-cutting the precursor limestone (grain of later calcite cements are also visible) (D) Dolomite cements cross-cutting the saddle dolomite and precursor limestone.

5.2.2 Calcite

The other dominant mineral in the altered carbonates of Utch Khattak limestone besides dolomite is calcite. The precursor depositional calcite is well preserved, compacted having good welded grains. Calcite is also present in the form of Recrystallized grains due to contact metamorphism of the limestone, can be differentiated from dolomitic marble on the basis of staining (Fig 5.6 A). Calcite assemblage along with quartz crystals is also present in thin sections. These quartz crystals are precipitated from igneous intrusions and are coming along calcite vein (Fig 5.6 B). Calcite is also present as Teleogenetic transparent veins in some thin section replacing saddle dolomite (Fig 5.6 C). Calcite, as late calcite cements are also present in some thin sections (Fig 5.6 D).

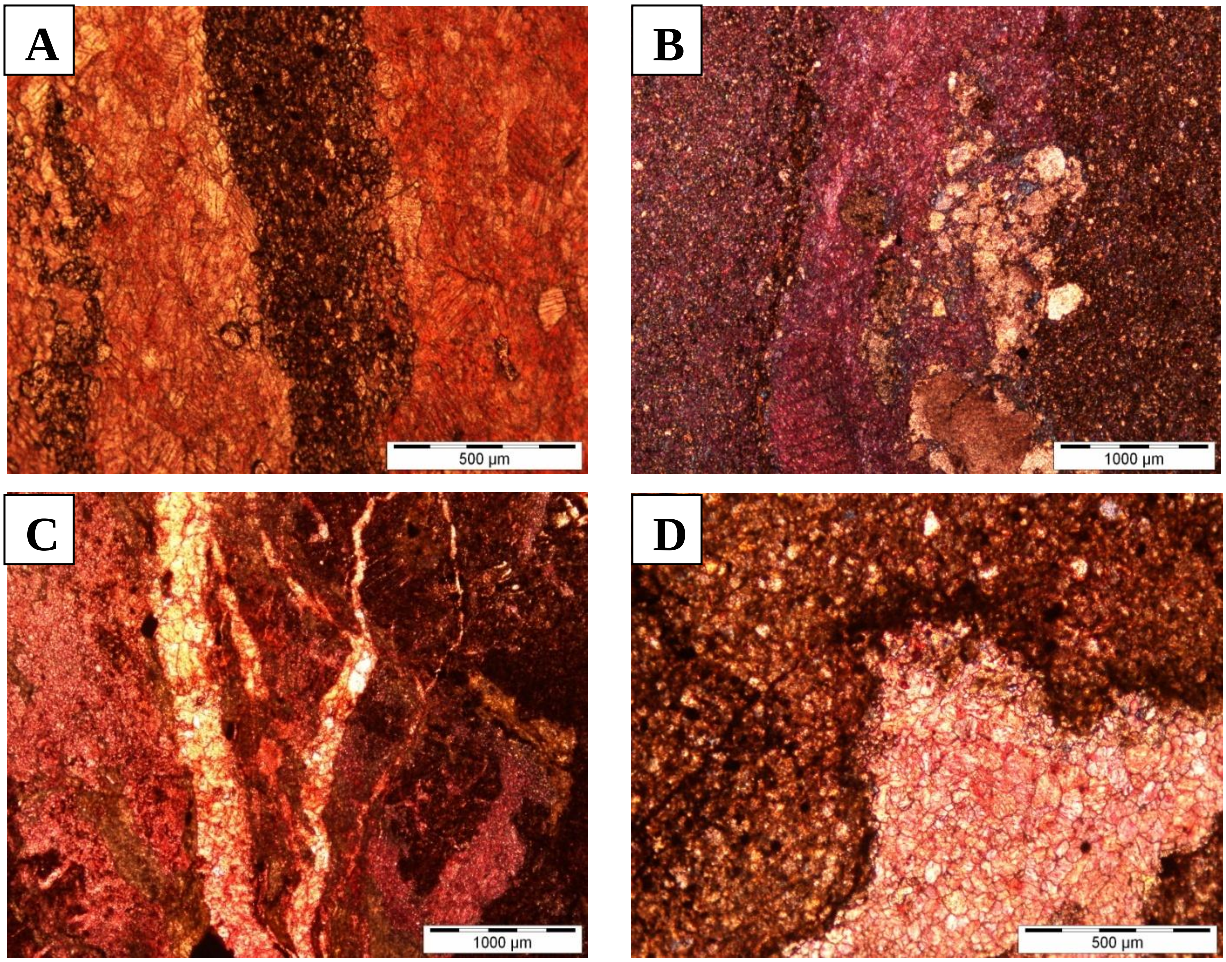


Fig 5.6 Photomicrograph of Calcite (A) Recrystallized calcite crystals of precursor limestone (B)Association of calcite with quartz (showing undulose extinction in cross-light) (C) Transparent Teleogenetic Calcite veins associated with saddle dolomites (D) Late calcite cements in open space associated with dolomites.

5.2.3 Marble

Marble is a metamorphosed limestone. The igneous intrusions present in the Utch Khattak limestone have caused contact metamorphism in the host limestone. The marble present in the Utch Khattak formation are in banded form as obvious from field observations, hand specimen and thin section study. The bands present in the marble are because of the contact metamorphism of both calcite and marble. Calcitic marble has well recrystallized grains and are stained, while the Dolomitic marble is unstained and are Dark grey in color. The marble present is both fine and coarse grained. Cataclastic deformation has caused fracturing in the marble. This fracturing later on provided pathways for dolomitizing fluids to invade the precursor limestone and cause dolomitization in these rocks (Jacquemyn et al., 2014).

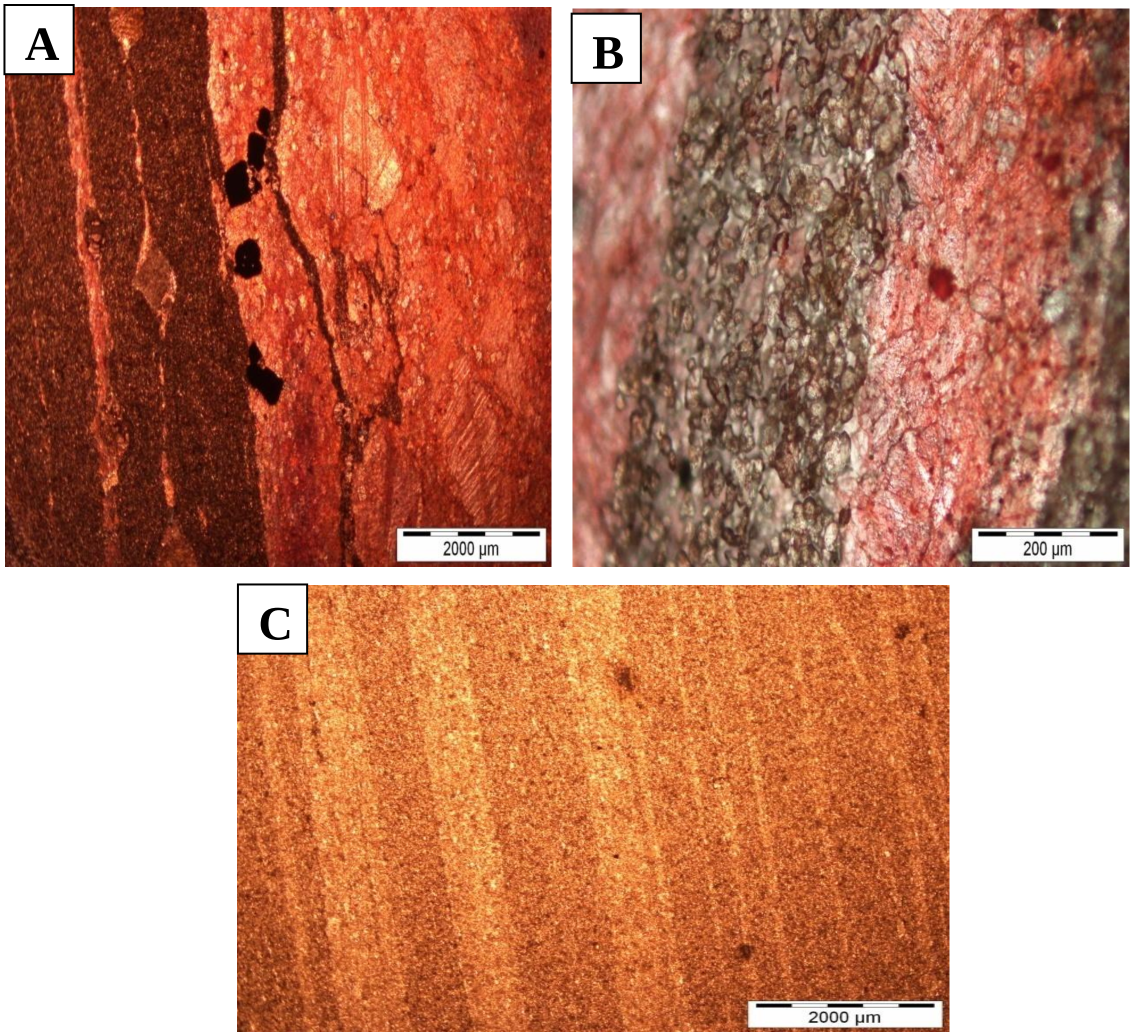


Fig 5.7 (A, B, C) Marbleized limestone having both calcitic and dolomitic marble, also associated with later coming heavy minerals

5.2.4 Quartz

Quartz crystals are also present as accessory minerals along with other diagenetic minerals in the altered carbonate succession of Utch Khattak limestone. These quartz grains are formed due igneous intrusion. Quartz grains present as white Quartz grains and are coarse grained. Most of the quartz grains are present locally in association with calcite. Quartz grains present shows sweeping extinction in cross polarized light. Fractures are presents in the quartz grains show tectonic stresses in the study area.

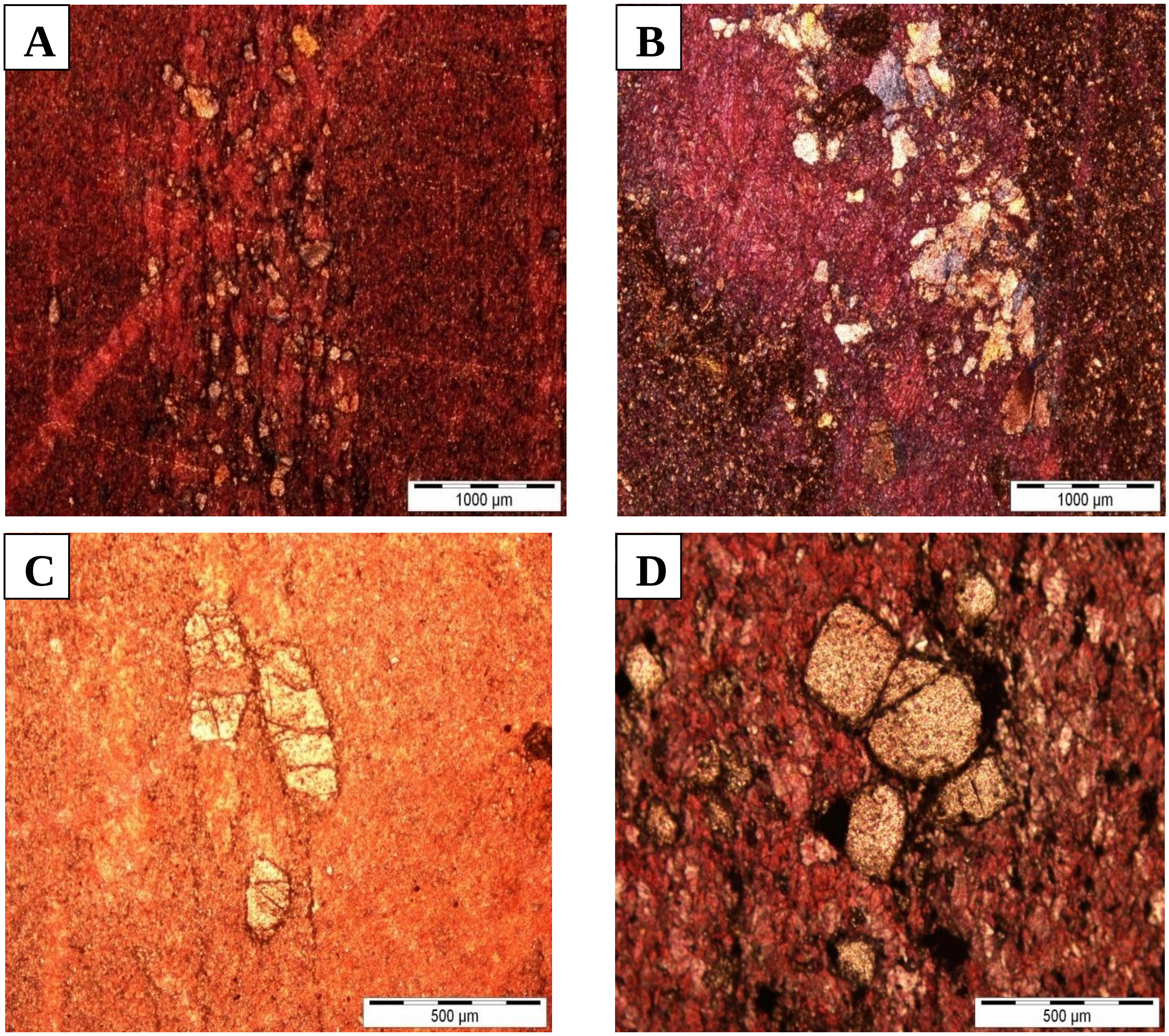


Fig 5.8 Photomicrograph of Quartz (A) Cross light view of quartz grains showing undulose extinction and coming along fractured open space (B) Cross light view of Quartz grains coming along calcite vein (C) Fractured Quartz grains embedded in the precursor limestone (D) Locally present quartz grains in the limestone.

5.2.5 Heavy minerals

Heavy minerals are also present in some thin sections. They are in disseminated form and are present in some thin sections. From petrographic study, cross-cutting relationship shows that they have late origin. Most of them have square shape like pyrite. Iron leaching has also occurred from some heavy minerals.

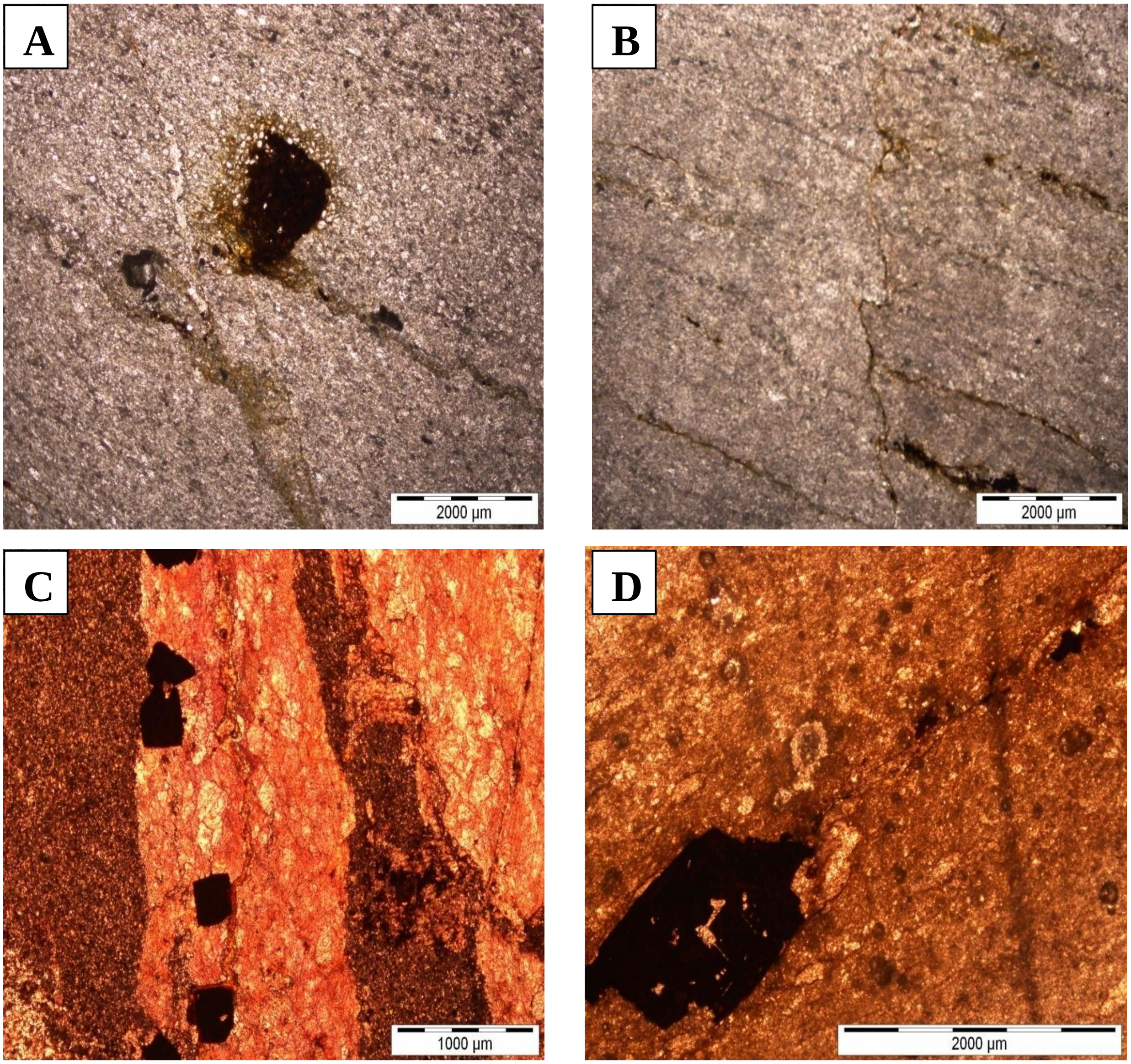


Fig 5.9 Photomicrographs of Heavy minerals. (A, B) Iron leaching from pyrite grains along the fractures. (B) Heavy Minerals in the dolomitized zone (C) Isolated heavy mineral

5.3 Diagenesis

Diagneseis refer to any chemical, biological or physical process that change/ alter the pre-existing rock after its deposition. Whenever environmental conditions change or migration of extrinsic fluid take place into the rock mass, radical changes occur in precipitation, dissolution and mineralogy. These are diagenetic changes and include compaction, infestation, cementation, replacement and recrystallization (Parker & Sellwood, 1994).

Carbonates of Utch Khattak Formation are altered carbonates and have faced both mechanical and chemical changes. Mechanical changes are due to tectonically active area toward the north of Pakistan, so the study area is heavily faulted, folded and fractured. Chemical changes are mostly due to intrusions which has caused alterations in the host limestone. Diagenetic changes were observed with the help of polarizing microscope and to support our microscopic study XRD and stable isotopic studies were carried out. Diagenetic alterations observed in the Utch Khattak limestone of Gandgher range are different types of dolomitization, different types of cements (both calcite and dolomite cements), Calcitization, Silica formation, fracturing, grain fracturing, stylolites.

5.3.1 Dolomitization

One of the major diagenetic changes in the altered carbonates of Utch Khattak Formation is dolomitization. Dolomites observed in Utch Khattak Limestone are matrix replacive dolomites, Saddle dolomites and cementing dolomites in fractures and open voids. Matrix replacive dolomites are mostly fine grained and first phase of dolomites from Cross-Cutting relationship. The second phase of dolomites is Saddle dolomites, confirmed from their sweeping extinction and high stable oxygen isotope value as compare to the first phase of dolomites. Magnesium source for this type of dolomites are hydrothermal fluids related to the intrusions, as obvious from their high oxygen stable data and XRD data. Third phase of dolomites are dolomites cements that are mostly present in the fractures and open spaces. They are last stage of dolomites.

5.3.2 Calcitization

Calcite present in the altered lithology of Utch Khattak Limestone in two ways. Telogenetic calcite as confirmed by stable carbon oxygen isotope analysis and cross-cutting relationship. This type of calcite is formed by the replacement or partial replacement of Saddle dolomite. They are in the form of bright veins and can be seen as twinned calcite veins. Partial or complete replacement of saddle dolomite by this type of calcite was observed in the petrographic study.

Second type of calcite present is in the form of cements. These cements are late stage of calcite and occur in open spaces created by dissolution and Dedolomitization. Thus, the already existing porosity is destroyed by these calcite cements. Calcite precipitation after dolomitization possibly indicate the depletion of Mg in the hydrothermal fluids (Jacquemyn et al., 2014)

5.3.3 Silicification

The solidification of the magmatic intrusion results in the formation of silica as quartz minerals. Quartz presents in the altered carbonate are present locally in cluster. They are mostly associated with calcite veins and fractures. Fractures present in the quartz crystals maybe due to the cataclastic deformation. Quartz crystals been resistant to dissolution are present as complete crystals. During petrographic study no dissolution or replacement of quartz grains were observed.

5.3.4 Fracturing

Altered carbonates of Utch Khattak Formation is heavily folded, jointed and faulted from field observations. Dikes and their damage zone act as pathways for the dolomitizing fluids. Surrounding the dikes; contact marble has locally stopped the dolomitizing fluids to invade the limestone. Dolomites occur mostly where this dolomite cover is absent or crosscut by fractures. Fractures in the limestone of Utch Khattak Formation near to the dikes are filled by the later phase of dolomite and calcite cements.

5.3.5 Stylolites

Bedding parallel stylolites are common in the altered carbonates of Utch Khattak Formation. These stylolites are pre-dolomitization stylolite’s and post-dolomitization stylolite’s. Pre-dolomitization stylolites are mostly clearly visible are not occupied by dolomite cementing phase while post-dolomitization stylolite’s are vaguely present and are filled by dolomite cements.

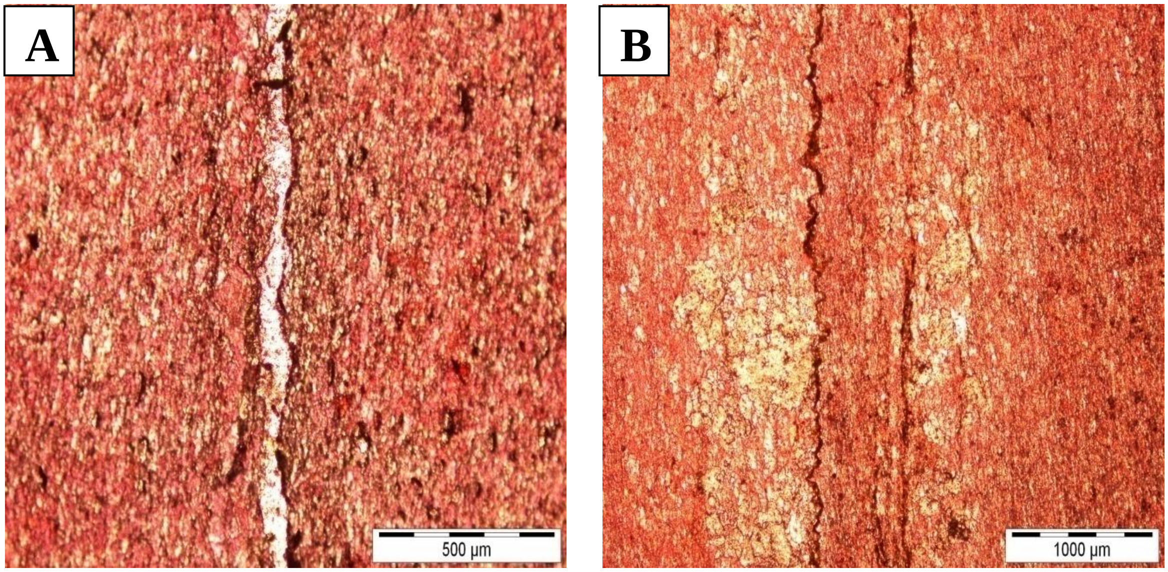


Fig 5.10 (A) Pre-dolomitization Stylolites filled by dolomite cements (B) Post-dolomitization Stylolites not filled by cements

CHAPTER 6

GEOCHEMISTRY

6.1 X-ray diffraction Analysis

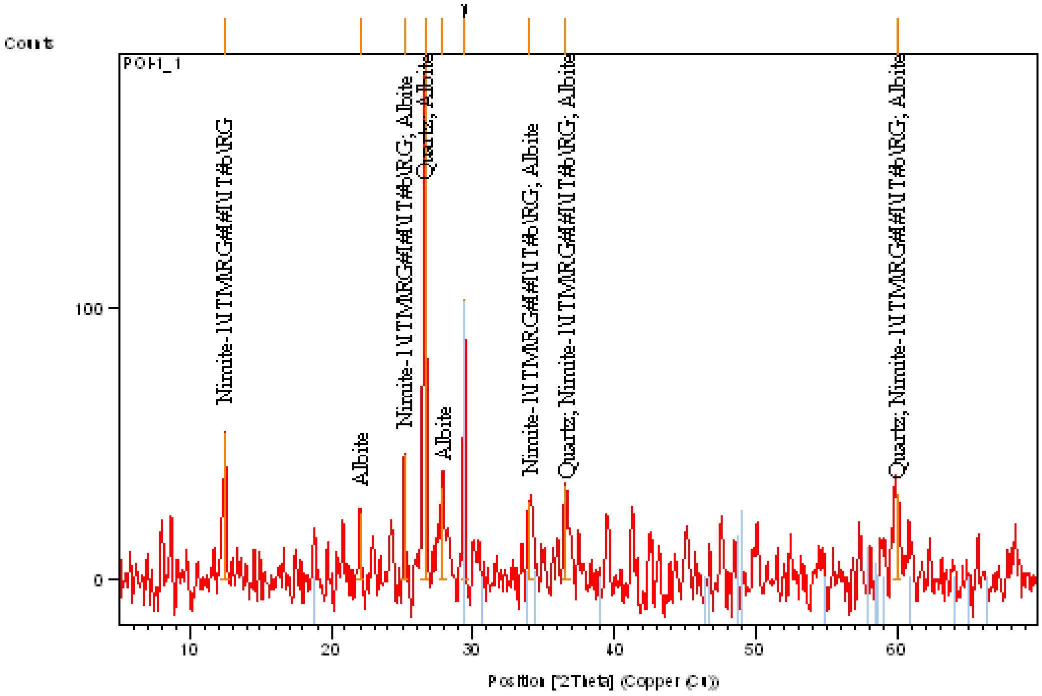
In order to find the bulk mineralogy of the samples, XRD analysis of 5 powder samples was carried out i.e. one dike sample and four altered carbonates samples of Utch-Khattak formation. XRD analysis helps in the identification of the minerals. Crystal structures are difficult to find from the powder samples because single crystal data is much easier to find out than to interpret the powdered diffraction data. Different crystals in the powdered samples give different X-rays intensities peaks but the orientation of planes causing diffraction can’t be revealed. Nowadays a new technique called Rietveld method can overcome these complications. However, the X-rays powder technique gives us peak intensities and a list of *d*-values used to identify the minerals in the powdered samples. The *d*-values of the powdered samples correspond to sets of planes and the intensity shows us how many atoms are in those planes. This is because each mineral in the powdered sample has different crystal structure that gives a different pattern. We compare *d*-values and intensities of different minerals to the reference data sets for identification of those minerals. X-rays diffraction analysis obtained from samples does not show the parent rock remnants.

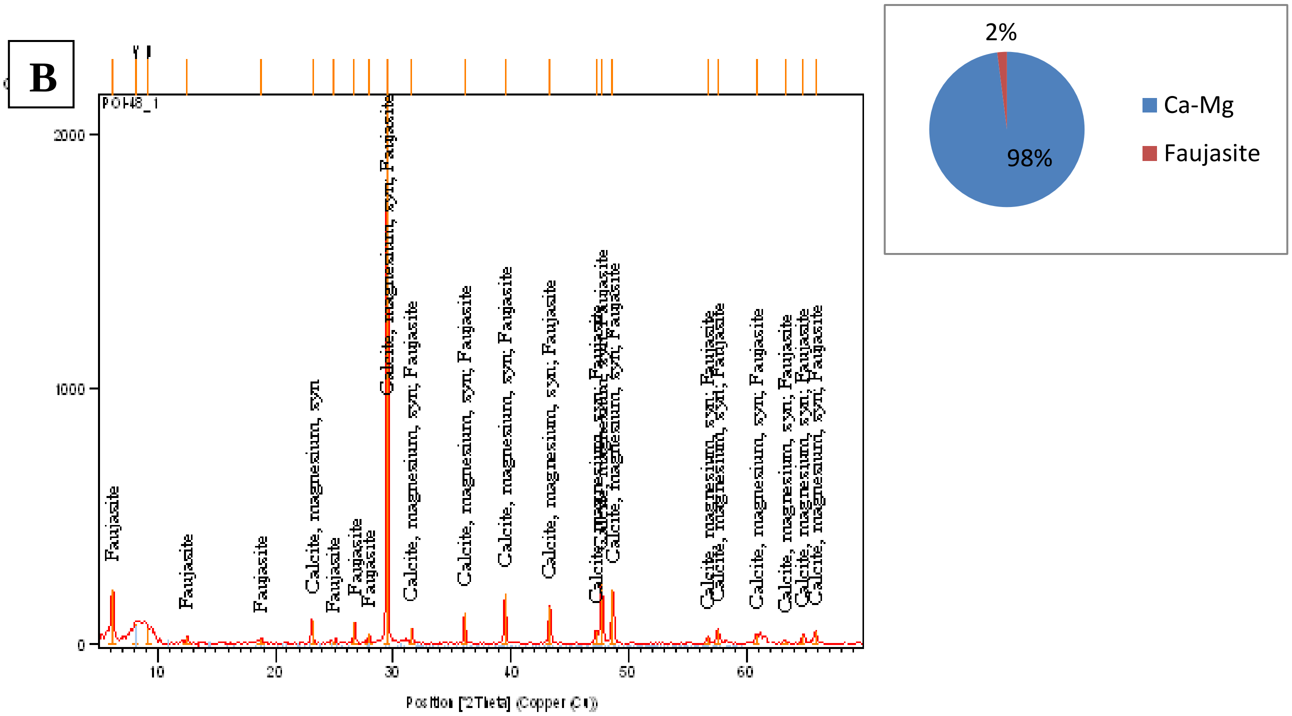
The diffraction peaks obtained for minerals, were analyzed for stoichiometric calculations especially for dolomites. The diffraction peaks obtained for the dike shows the mineralogy of the dike sample (quartz, nimite (chlorite) and albite) (fig 6.1 A). The dikes reported in the Utch Khattak limestone are Dolerite dikes (Hylland, 1990; M.Riaz et al., 1991). The mineralogy of dolerite rocks are diverse containing plagioclase, quartz, amphibole, chlorite, pyroxene. (Zahid Kraim Khan, 2009). The common alteration products in the dolerite rocks are the assemblage of chlorite, feldspar (Albite), epidote and clay minerals (Zahid Kraim Khan, 2009). Albite is plagioclase feldspar mineral. It is Na rich member of plagioclase solid solution while Nimite is one of the minerals of Chlorite. This composition is most compatible with dolerite rock. Albitization of Plagioclase has taken place as post magmatic changes in the dolerite dike (Macdonald et al., 1981). Nimite (Chlorite member), form by the replacement of ferromagnesium minerals in the dolerite rocks (Macdonald et al., 1981).

Diffraction peaks obtained for the altered carbonates are in (Fig 6.1 B-E). In (Fig 6.1 B and C) diffraction peak for clay mineral palygorskite is present along with quartz and dolomite. This clay mineral is associated with dolomite. Clay minerals are formed during evolution of silicate melt (Perkins, 1998). Presence of such clay minerals indicated that the hydrothermal fluids are from magmatic origin which has caused changes in the parent rocks. In (fig 6.1 E) Chamosite (Chlorite) peaks are present along with dolomite which means the ferromagnesian minerals coming along with the dikes invaded the host rocks, which are replaced by Chamosite as alteration product. This shows that the alteration in the Utch Khattak Formation is due to the dolerite dikes. In fig (6.1 B) Faujasite is also present which a member of zeolite family (Aluminosilicate). Most of the minerals in the altered carbonates are weakly metamorphosed minerals i.e. Chlorite and Albite which shows that's the metamorphism due to the dikes is weak.

Sharp diffraction peaks for Ca-Mg was obtained. The *d104* values shows little variations and most of the dolomites are nearly stoichiometric.

A

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60
Position [°2Theta] (Copper (Cu))
Faujasite
Faujasite
Faujasite
Calcite, magnesium, syn
Faujasite
Faujasite
Faujasite
Calcite, magnesium, syn; Faujasite
Calcite, magnesium, syn; Faujasite
Calcite, magnesium, syn; Faujasite
Calcite, magnesium, syn; Faujasite
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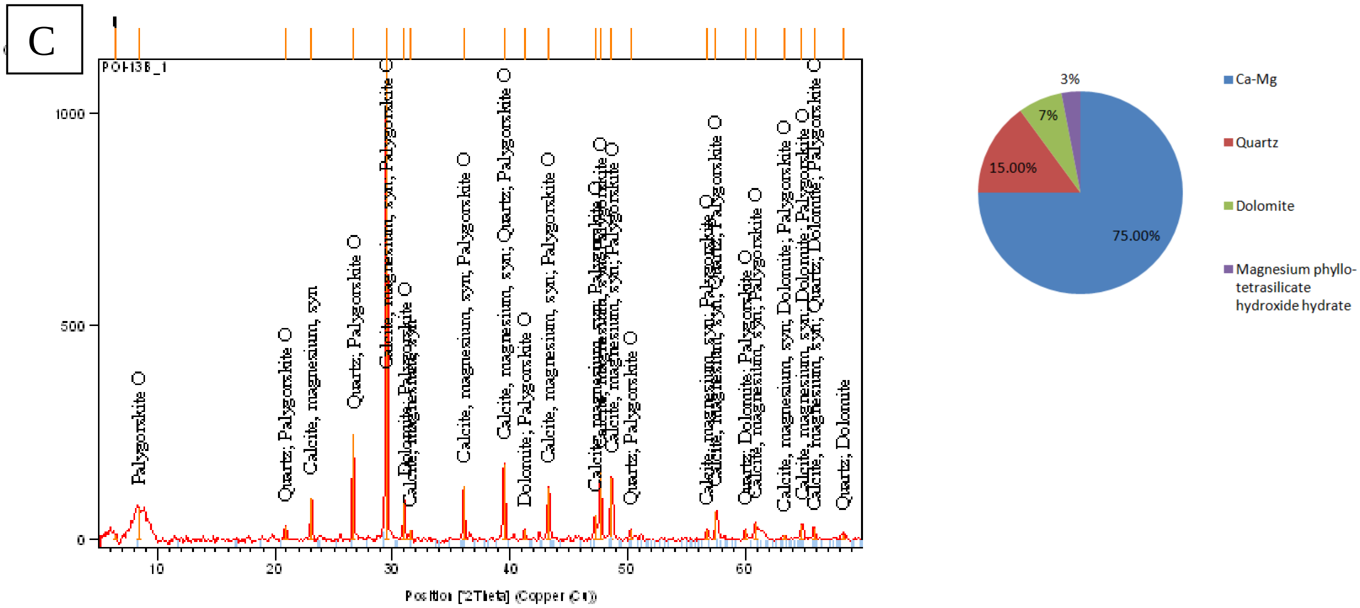
2%
98%
Ca-Mg
Faujasite


C
POH3B_1
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Position [°2Theta] (Copper (Cu))
Palygorskite O
Quartz; Palygorskite O
Calcite, magnesium, syn
Quartz; Palygorskite O
Calcite, magnesium, syn; Palygorskite O
Dolomite; Palygorskite O
Calcite, magnesium, syn; Palygorskite O
Calcite, magnesium, syn; Quartz; Palygorskite O
Dolomite; Palygorskite O
Calcite, magnesium, syn; Palygorskite O
Calcite, magnesium, syn; Palygorskite O
Quartz; Palygorskite O
Calcite, magnesium, syn; Palygorskite O
Quartz; Dolomite; Palygorskite O
Calcite, magnesium, syn; Palygorskite O
Calcite, magnesium, syn; Dolomite; Palygorskite O
Calcite, magnesium, syn; Dolomite; Palygorskite O
Calcite, magnesium, syn; Quartz; Dolomite; Palygorskite O
Quartz; Dolomite
3%
7%
15.00%
75.00%
Ca-Mg
Quartz
Dolomite
Magnesium phyllo-tetrasilicate hydroxide hydrate

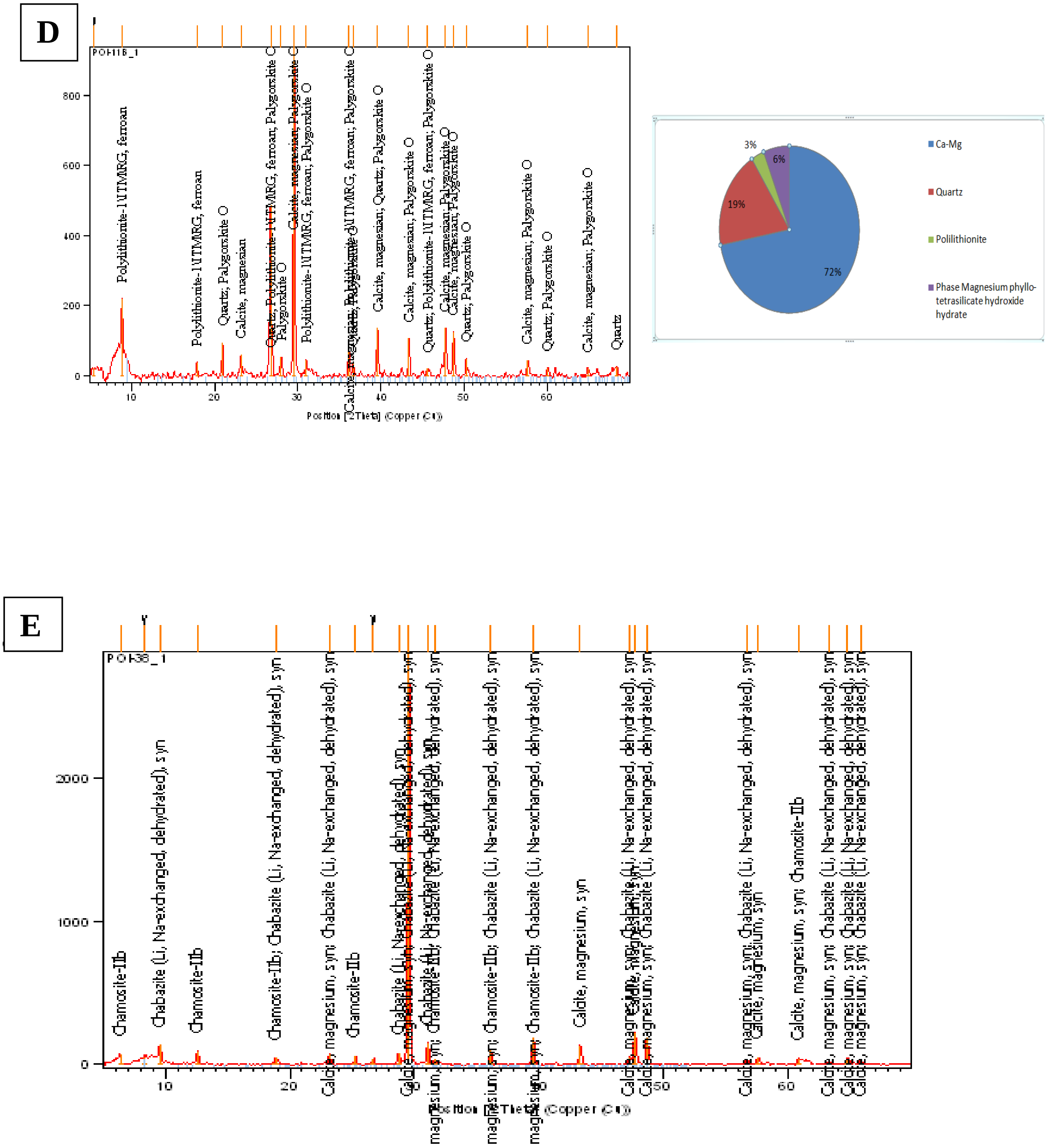
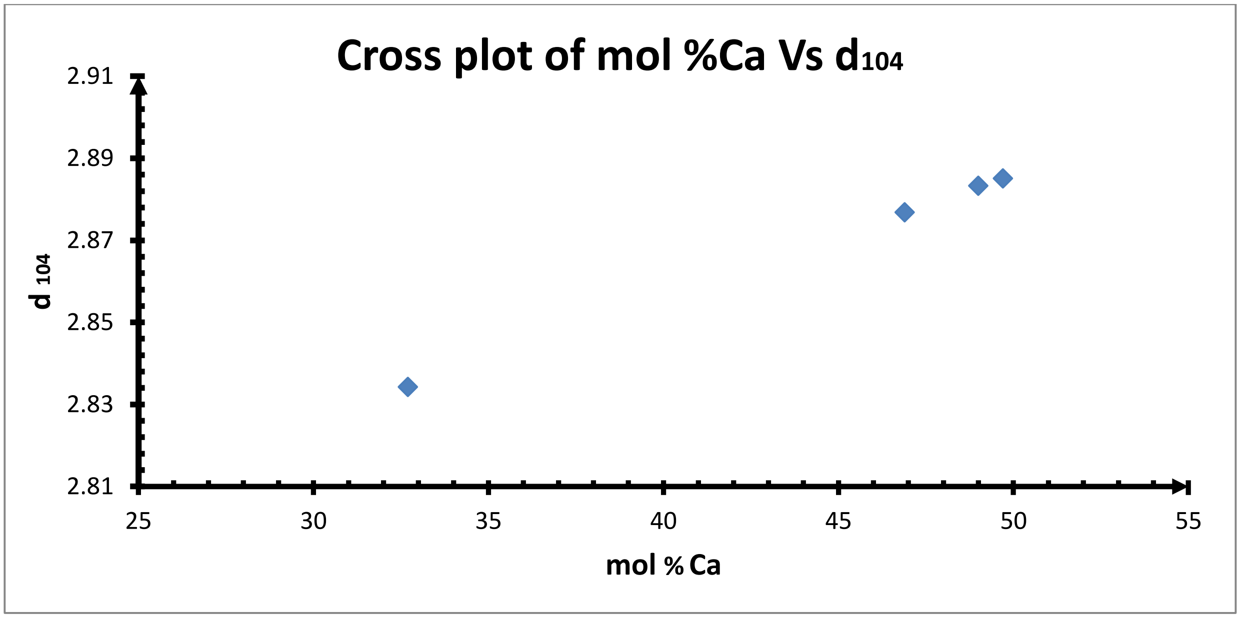


Fig 6.1. X-ray Diffraction peaks of Dike and altered carbonates of Utch Khattak Formation with pie-charts

S/No	Sample I.D	d-spacing (Angstrom)	Stoichiometry (mol % CaCO3)
1	POI-3B	2.87684	46.9
2	POI-13B	2.88329	49
3	POI-11B	2.88511	49.7
4	POI-4B	2.83426	32.7

Table 6.1. Dolomite stoichiometry, along with their d-spacing values. Dolomites are nearly stoichiometric.



Graph 6.3 Cross-plot of mol% Ca vs d^{104} showing most of the dolomites are nearly stoichiometric

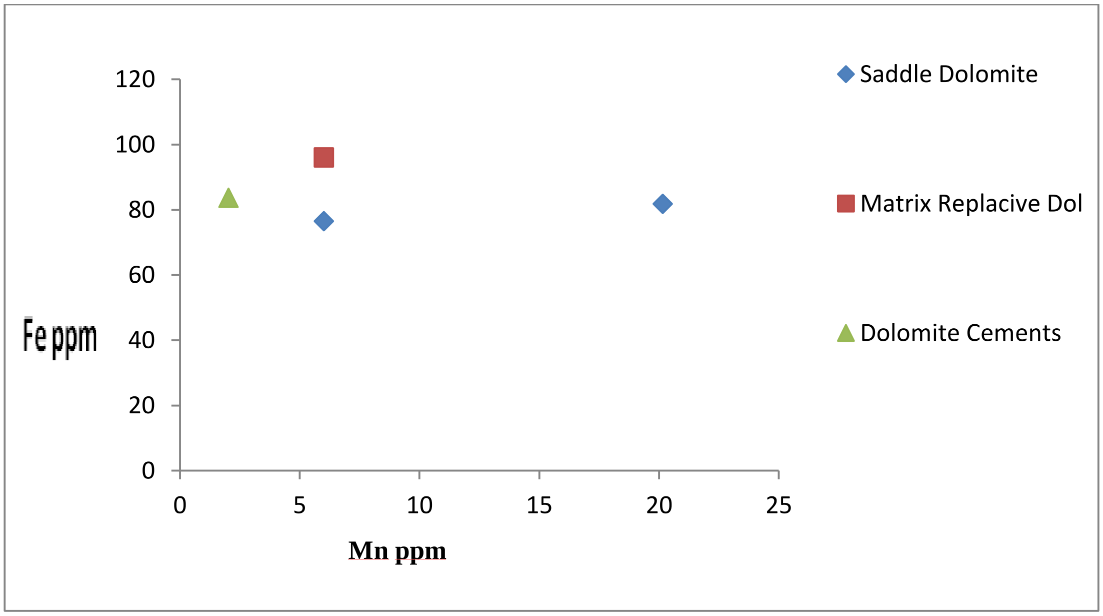
6.2 Atomic Absorption Spectroscopy

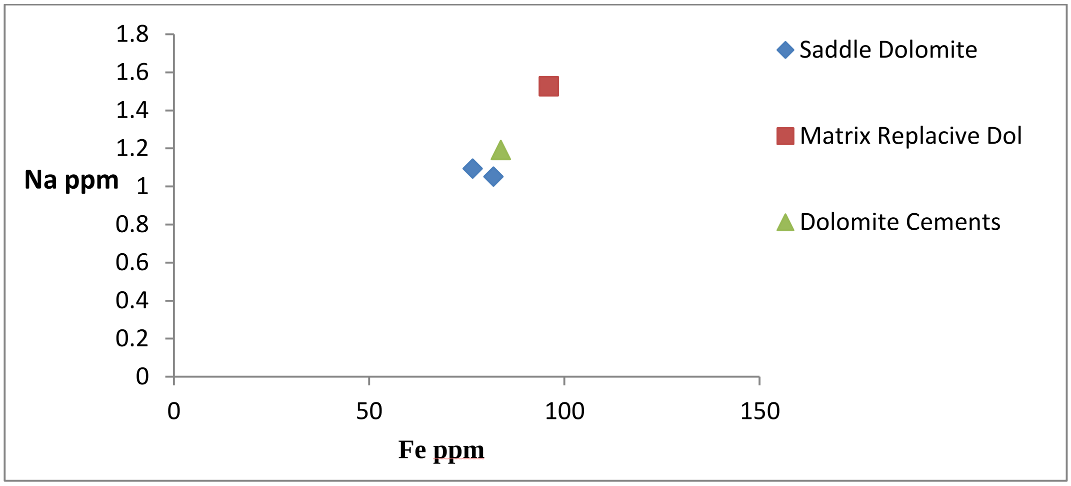
Geochemical analysis is used to find out the concentration, chemical composistion of specific mineral and its composition in a rock sample. About 60 to 62 elemental concentrations can be determined in a solution by using Atomic absorption spectroscopy.

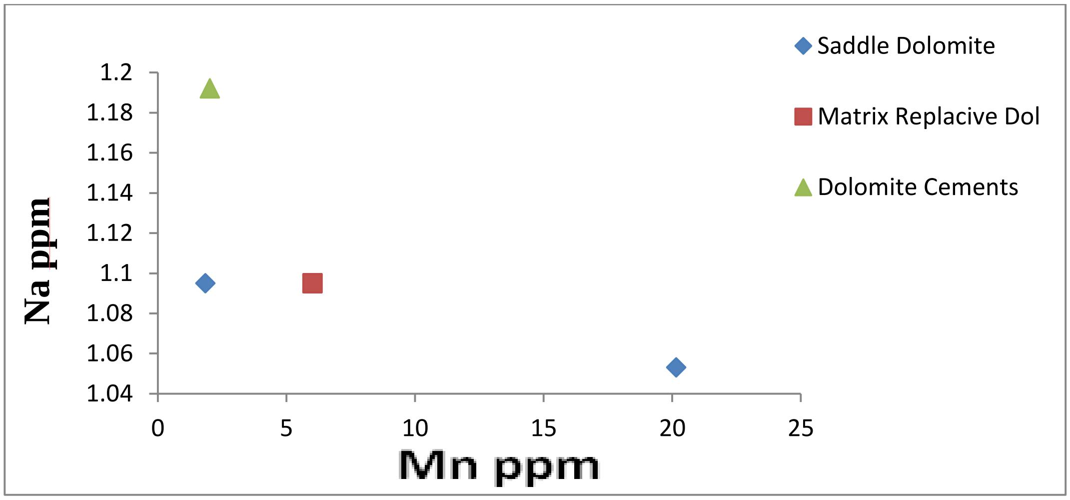
Trace elements were analyzed using atomic absorption spectroscopy. Representative trace elements concentrations of the studied samples groups are present in Table below.

S.No	Samples	Ca	Mg	Na	K	Fe	Mg
1	3-B	6856	114.9	1.053	0.635	81.89	20.16
2	11-B	5037	118.7	1.527	104	96.07	6.018
3	13-B	630.8	117	1.095	19.46	76.57	1.859
4	4-D	8355	112.1	1.192	6.89	83.75	2.03

Table 6.2 Geochemical Data base of Various elements







Cross-Plot between various elements

CHAPTER 7

STABLE ISOTOPES ANALYSIS

7.1 O and C stable isotopes Analysis

Ancient ocean water isotopic variations are largely measured through stable Carbon and Oxygen isotopes analysis. Foraminiferal Calcite, Oxygen isotope ratio is mostly used to study temperature variation and to reconstruct the paleo-temperature history which in turn gives us information about de-glaciations and glaciations in both the hemispheres (Zachos et al., 1999). To illustrate the different characteristic of carbonates, Carbon and Oxygen stable isotopes were analyzed from matrix dolomites, saddle dolomites, calcites and limestone. For purpose of stable isotopes analysis 10 samples were screened. These representative samples were selected from the record and description of petrography. 5 mg of powder from each sample was obtained through drill machine representing different phases of rocks under investigation. The data was divided into four groups as, (i) Matrix replacive dolomites (ii) Saddle dolomites (iii) Calcite and (iv) limestone. Powder from some cementing phases was difficult to get because of the contamination. Dolomites are abundant in ancient rocks record and generally comprise significant parts of carbonate succession. In some cases where limestone is absent, dolomites play an important role in carbon and oxygen stable isotopic studies(Bartley et al., 1998; Bartley et al., 2001; Calver, 1998; Derry et al., 1994; Fairchild et al., 2000; Gorokhov et al., 1998; Gorokhov et al., 1995; Hill & Walter, 2000; Kah, 2000; Kah et al., 1999; Kaufman et al., 1991; Kaufman et al., 1993; Kaufman et al., 1996; Kennedy et al., 2001; Knoll et al., 1995; Kuznetsov et al., 2003; Narbonne et al., 1994; Pelechaty, 1998; Podkovyrov et al., 1998). This is because diagenetically formed dolomites hold the carbon and often Strontium (Azmy et al., 2001) isotope ratio of the precursor carbonates and its coeval water.

The standard marine signature for the limestone of late proterozoic seawater have consistant δO 18 values of about -0.5% ~ +0.9% and C 13 values in the range of +5% ~ + 7% (Zempolich, Wilkinson, & Lohmann, 1988). Stable isotopes signatures for precursor limestone shows depleted values of O18 (-12.64 to -10.07% V-PBD) and depleted values for C13 (+1.45% to +3.16%V-PBD). This shows that this precursor limestone is affected by high temperature hydrothermal fluids than the normal temperature during the formation of the host limestone and also by diagenetic fluids. Various other phases (Replacive matrix dolomite, Saddle dolomite, Calcite) shows their separate values of isotopes signatures, which shows their origin relation to separate diagenetic conditions. First phase (Matrix replacive dolomites) in the dolomites shows less depleted values compare to the second phase having value of O18 (-9.37% to -7.06% V-PBD) and (-.95% to 3.1% V-PBD). Second phase of saddle dolomite shows more depleted values of O18 (-12.43% to -10.65 V-PBD) and C13 (+2.42%-2.75% V-PBD) which shows a significant shift from Proterozoic sea water signatures. The more the negative trend in the stable isotope of oxygen shows the higher temperature conditions (Vandeginste, 2005).Oxygen value for calcite associated with marble is more depleted compare to altered calcite while altered calcite has got much depleted carbon values compare to calcitic marble. The results are in per mill (%) values relative to V-PBD and are shown in table.

S.No	Sample I. D	Sub-Samples	Phases	δ 13 C	δ 18 O
1	3-B	A	Limestone	3.16	-12.64
2	3-B	B	Saddle dolomite	2.42	-12.43
3	3-B	C	Altered calcite	-1.08	-6.91
4	13-B	A	Saddle dolomite	2.49	-11.72
5	13-B	B	Limestone	1.45	-10.07
6	UK-3	A	Calcite	0.30	-10.57
7	UK-3	B	Matrix replacive dolomite	3.10	-9.37
8	11-B	A	Matrix replacive dolomite	-0.95	-7.06
9	4-D	A	Dolomite cements	1.26	-8.88
10	4-D	B	Limestone	2.75	-10.65

Table 7.1: C and O stable isotopes results in per mil (%) relative to V-PBD standard

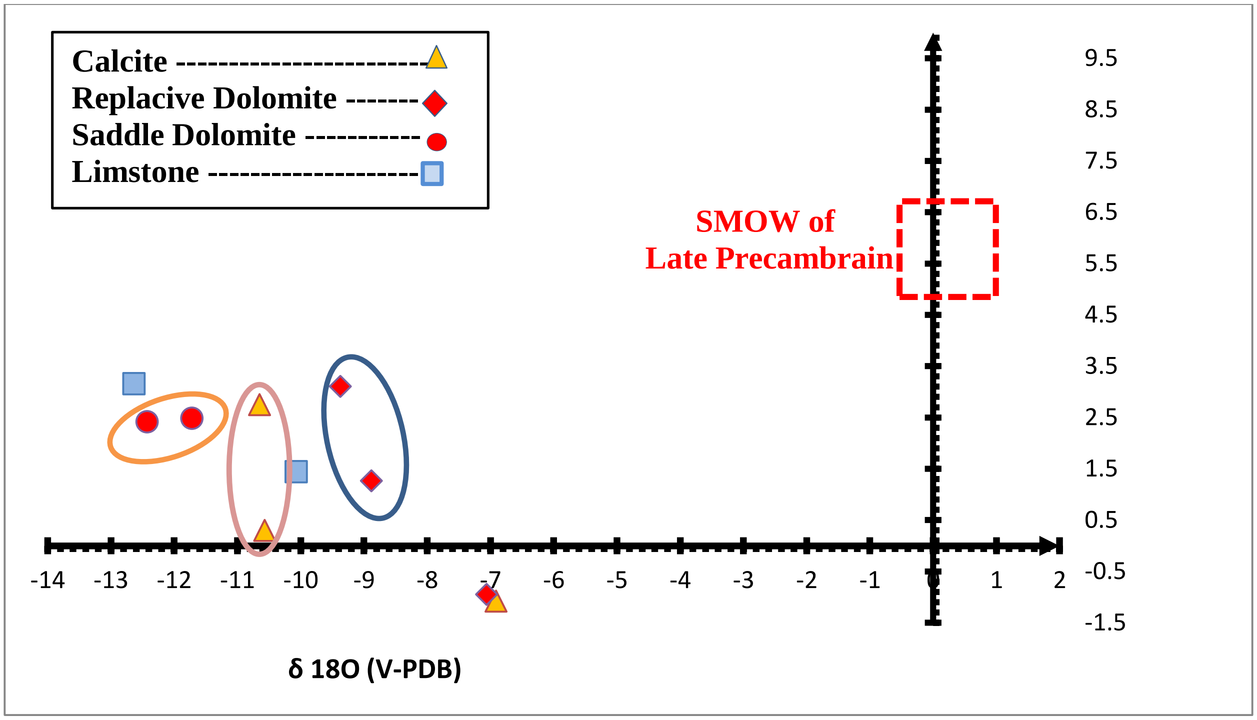


Fig 7.1: Cross plot of δ ^{13}C vs δ ^{18}O showing two types of dolomites form through different fluids.

CHAPTER 8

DISCUSSIONS

In the study area (Utch Khattak Formation), Southern Gandgher range, the only igneous rock that are present are the basic dikes and sills which has intruded all the strata exposed in the southern Gandgher range (Hylland, 1990) including (Utch Khattak Formation, Shekhai Formation, Shahkot Formation and Manki Formation). These dikes and sills have variable thickness but generally the thickness is 2m for most of the dikes and sills.

Investigations of the carbonates successions which are affected by the igneous intrusions (magma) shows vast mineralogical modifications due to the interaction of fluids and rocks (S. Holford et al., 2012; Rateau et al., 2013; Santos et al., 2009; Schutter, 2003; Sruoga & Rubinstein, 2007). Sharp contact between the dike and the host limestone shows that the interaction of the dikes with the host limestone is quite rapid (Fig 4.2).

Based on petrography and cross-cutting relationship the first phase of matrix replacive dolomite is formed just after the dike emplacement. This phase of the dolomite has low $\delta^{18}O$ as compare to the saddle dolomites. Later, dedolomitization has also take place in this type of dolomite. These dolomites are formed during first episode of dikes hydrothermal fluids. Dolomites formed in the second phase are saddle dolomites. This is evident from their high $\delta^{18}O$ depleted values compare to the first phase of dolomite. XRD values of these dolomites shows the alteration products of the dolerite dykes are associated with these types of dolomites. Saddle dolomites can be both void filling and matrix replacive (Davies & Smith Jr, 2006). Last phase of dolomites are white pore filling dolomite cements. Various authors (Boni et al., 2000; Davies & Smith Jr, 2006; Gasparrini et al., 2006; Mountjoy & Halim-Dihardja, 1991; Radke & Mathis, 1980; Spötl & Pitman, 1998) have suggested the origin for white, pore filling saddle dolomites in high temperature conditions.

Petrographic study revealed that calcitization has taken place later which replaced the saddle dolomites. Dedolomitization is also evident by the replacement of dolomites by calcite cements (Dorobek et al., 1993; F. H. Nader et al., 2008). Dedolomitization maybe due to the concurrent depletion of Mg^{2+} in magmatic fluids which caused the Dedolomitization (Jacquemyn et al., 2014) or it may be due to meteoric recharge which caused late stage de-dolomitization phenomena (Choquette et al., 1988; Meyers, 1991; Niemann & Read, 1988; Reeder, 1991). Along partially de-dolomitized dolomites, porosity related to dissolution can developed (Giles & De Boer, 1989) and such phenomena are also observed in the petrographic study. Based on above-mentioned studies, a detailed paragenetic sequence has been developed. It is evident from these studies that dolomitization in the Utch Khattak Formation is caused by Mg-rich fluids associated with hydrothermal fluids coming along igneous intrusions. Besides this the igneous intrusions have also caused low-grade contact metamorphism (as evident from low-grade metamorphic minerals in XRD), recrystallization of limestone and fractures in the dikes zone area. Porosity and permeability increased due to igneous dikes and brecciated limestone has formed in the study area. This study gives insights about the spatial and temporal relationship of various diagenetic phases caused by the hydrothermal fluids coming along the dikes in the altered carbonate of Utch Khattak formation.

XRD analyses of the altered carbonate samples and dike were carried out in order to find out the bulk mineralogy of the altered carbonates and to associate the diagenetic changes in the carbonates to the dikes, intruded the study area. The dike sample shows the mineralogy of dolerite rocks with some alteration products of the mineralogy of the dolerite rocks. The diffraction peaks obtained for the dike shows the mineralogy of the dolerite sample (quartz, nimite (chlorite) and albite). The mineralogy of dolerite rocks are diverse containing plagioclase, quartz, amphibole, chlorite, pyroxene (Zahid Kraim Khan, 2009). The common alteration products in the dolerite rocks are the assemblage of chlorite, feldspar (Albite), epidote and clay minerals (Zahid Kraim Khan, 2009). The XRD data obtained for the altered carbonates shows peaks of palygorskite, quatz,chamosite(chlorite). Most of these are the alteration products of the dolerite rock mineralogy. Clay and quartz present in the altered carbonates show the phenomena of authigenesis. Thus, it’s obvious that the diagenetic changes in the altered carbonates of Utch Khattak formation are due to the magmatic fluids of dolerite intrusions present in the Utch Khattak formation.

Variation of Carbon and Oxygen isotopes from ancient ocean water are used to reconstruct the paleo-temperature history during the formation of these rocks. More negative trend in the $\delta\ ^{18}O$ shows that the high temperature condition prevail and show depletion compare to the stable isotopes values of Late-precambrian sea water.

Based on field observations and paragenetic sequence, a conceptual model has been developed for igneous intrusions that have affected the Utch Khattak limestone in the study area during late Pennsylvanian –Early Permian (fig 8.1 B). This model explains both the phenomena before the intrusions and the effects of igneous intrusions after dikes emplacement. Basic magma has very high temperature as compared to acidic magma which has got lower temperature. The temperature of basic magma ranges up to 1200 ^{0}C. The high temperature of the magma and associated hydrothermal fluids has caused contact metamorphism in the chilled zone in the form of marble. The second phase of hydrothermal fluids has caused the formation of dolomites. Phases of intrusions, marble formation and dolomitization are purely based on the previous literature and the chronological order of the analyzed samples. The present-day scenario of the study area can be seen in the figure (8.1 C).

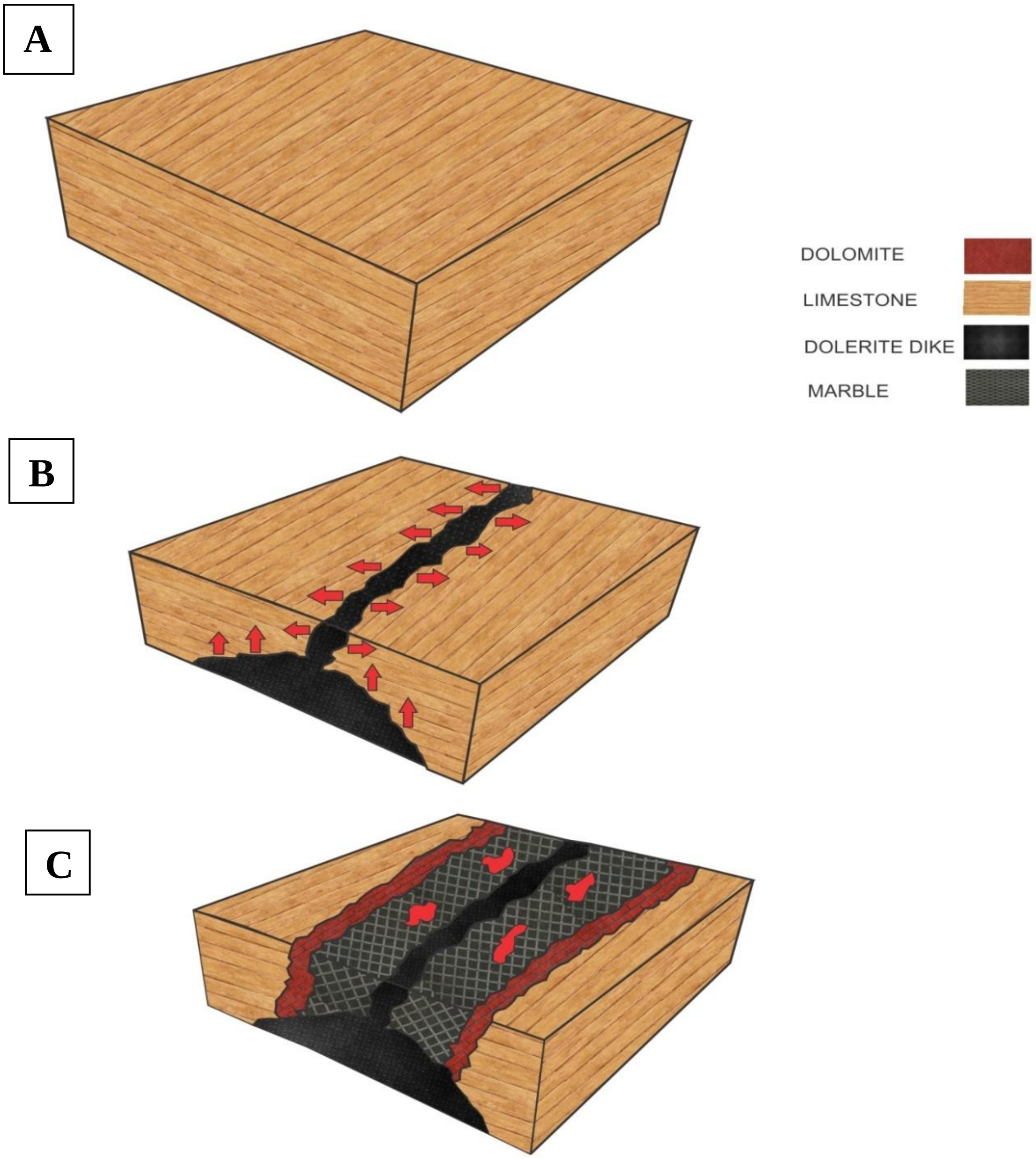


Fig 8.1 Conceptual Depositional for Utch Khattak limestone (A) Utch Khattak limestone in Late-Precambrian (B) Late Pennsylvanian- Early Permian dikes intrusions with hydrothermal fluids invaded the host limestone. (C) Present day situation of the altered carbonates of Utch Khattak formation.

5.4 Paragenetic Sequence

Petrographic studies along with geochemical analysis helped us to develop paragenetic sequence in the altered carbonates of Utch Khattak limestone. Paragenetic sequence helps us to determine the diagenetic history and changes that has taken place in relative time in the altered carbonates of Utch Khattak Formation. Diagenetic changes mostly occurred due to the intrusion and the related hydrothermal fluids that caused changes to the precursor limestone. Contact marble at the Dike and limestone interface locally shielded the hydrothermal fluids to invade the country rocks, but where this marble cover is missing, or fractured changes has taken place in the precursor limestone.

In relative time from early to late in the diagenetic history, diagenetic products and events are;

(1) Soon after Dyke emplacement, the limestone next to contact aureole (marble) recrystallized

(2) Dark grey colored matrix replacive dolomite is formed first, from cross-cutting relationship. This dolomite is later de-dolomitized in some thin sections. Also, fractures are present in these dolomites which are filled by dolomite cements. This mean the fractures are formed later. The stable oxygen isotope ratio for this dolomite is less compare to the saddle dolomites.

(3) After the emplacement of the dykes, fracturing provided pathways for hydrothermal fluids to circulate in the host rocks. These fractures maybe due to tectonic stresses or maybe due to intrusions.

(4) Due to circulation of fluids along the fractures and veins caused dolomitization along the rocks. Saddle dolomite formed along this phase.

(5) Dissolution / Dedolomitization of already formed saddle dolomite occurred during this phase. The dissolution of saddle dolomite produced Ca ions which along with other calcium sources caused the formation of twinned calcite.

(6) Next diagenetic event was quartz influx, along the veins formed from solidification of magma from intrusions.

(7) Dolomite Cements coming along the fractures, veins and open spore spaces.

(8) Calcite cements coming along the open pore spaces. This may be due to the depletion of Mg in the hydrothermal fluids which caused the formation of calcite cements rather than dolomite cements.

(9) Teleogenetic calcite as confirmed as confirmed by oxygen and carbon stable isotopes analysis and cross-cutting form during this phase.

10) Pyrite formed in the last stage. This may be due to the leaching of Iron from intrusions.

Diagenetic events Early Late

Limestone deposition …………………….

Fractures ……………………….

Pre-dolomite stylolites ....

Intrusions …………………..

Marble ……………………

Recrystallized limestone ……………….

Matrix Replacive dolomites ………………

Fractures …………………

Saddle Dolomites ………………….

Quartz Influx …………………….

Teleogenetic Calcite …………………….

Dolomite Cements ……………………

Calcite Cements ………. ………………….

Post dolomite stylolites ………………..

Heavy Minerals …………………

CHAPTER 9

CNCLUSIONS AND RECOMMENDATIONS

Igneous intrusions present in the study area have caused diagenetic alteration in the carbonate lithology of Utch Khattak limestone. Well exposed surface analogues of the dikes have caused modifications to the host limestone mineralogy due to the interaction of magmatic fluids with the host rocks. Some of the major conclusions are given below.

- From field observations and XRD analysis it’s revealed that the dikes present in the study area are of basic origin.
- Sharp contact of the dikes with the host lithology suggest that the interaction of the dikes with the host lithology is quite rapid
- Due to these dikes the contact metamorphism (marble) and dolomites are formed.
- Saddle dolomites have formed due to magmatic fluids interaction with the host lithology. Also, white colored cements dolomites are formed in the high temperature conditions. Saddle dolomites have inetrcrystalline porosity and developed crystals.
- Calcite in the later stage has replaced the Saddle dolomites and has caused Dedolomitization in the altered carbonates.
- The formation of quartz crystals in the host lithology is due to the magma delivered along the dikes and is present as authigenic mineral. Most of these quartz minerals are present along the veins and fractures and are formed due to the solidification of the magma.
- From field observation, in the vicinity of the dikes the limestone is heavily fractured compare to the unaltered limestone away from the dike shows that the fractures present are due to the intrusions of the dikes.
- Most of the fractures and open pore spaces are filled by later dolomite and calcite cements confirmed by cross-cutting relationship.
- Two stages of stylolite’s confirmed from petrography, pre-dolomitization stylolite’s which are vaguely present and are filled by dolomite cements and post-dolomitization stylolite’s which are visible clearly and are not occupied by dolomite cements.
- XRD analysis of Dike and altered samples was carried out to find the mineralogy of both and to find the association of magmatic fluids with the altered host lithology
- XRD analysis of the dikes obtained shows the mineralogy of the dolerite dikes.

- In the altered carbonates the minerals of dolerite dikes and its alteration products shows that the modification in the host rocks are due to magmatic fluids coming along the dikes and invaded the host rocks.
- From XRD analysis the major mineral present is dolomite along with some clay minerals, chlorites, quartz.
- Saddle dolomites present high temperature as compared to the matrix replacive dolomites.
- Comparing the late-Precambrian sea water signatures with the analyzed samples show that the samples have depleted $\delta\ ^{18}O$ values.

Recommendations

(1) Other formations present in the Gandgher range (i.e. Shekhai Formation, Shahkot Formation) are also intruded by igneous intrusions. So, this study should be extended to these formations also to cover the diagenetic effects of intrusions on these formations.

(2) In order to find out the nature of the fluids that caused the diagenetic changes and temperature during the precipitation of different diagenetic phases, fluid inclusion study is very necessary.

(3) In order to find out the exact age of the dolerite dikes present in the study area, age dating of the intrusions is recommended.

(4) ^{86}Sr analysis should be carried out in order to find out the composition of respective fluids from which different dolomite phases precipitated.

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