MINERALOGICAL, TEXTURAL AND WEATHERING IMPACT ON THE PHYSICO-MECHANICAL PROPERTIES OF SELECTED PLUTONIC IGNEOUS ROCKS FROM NORTH-WEST, PAKISTAN

By

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ABSTRACT

The mineralogy, texture, and weathering grades of the plutonic igneous rocks from the Salarzai region (Bajaur), N-W Pakistan, as well as their effects on physico-mechanical attributes, are investigated. Field relationships together with petrographic investigations lead to the distinction of Salarzai plutonic igneous rocks into (i) fine-grained gabbronorites (F-GN), (ii) medium-grained gabbronorites (M-GN), (iii) coarse-grained quartz diorites (C-QD) and (iv) coarse-grained anorthosites (C-AN). Essential minerals including Plagioclase, quartz, pyroxene and olivine with minor to accessary amount of biotite amphibole, quartz, epidote, chlorite, garnet and sphene were found.

In contrast to acidic rocks, intermediate and basic rocks has lower percent abundances of felsic minerals and greater specific gravity (S.G), ultrasonic pulse velocity (U.P.V), strength includes unconfined compressive strength (U.C.S) and Schmidt rebound (R-value) values. Likewise, sample having irregular grain geometry, uneven surfaces and fine-medium grained (F-GN, M-GN) shows higher strength with unconfined compressive strengths values of 115 and 86 MPa and R-values 59 and 51 correspondingly. The physical parameters of the studied samples are in good accordance with the weathering grade given to the sample, like fresh (W.G-I), slightly weathered (W.G-II), and severely weathered (W.G-III). As the grade of weathering increases from W.G-I to W.G-III, the values of porosity (P) as well as water absorption (W.A) increases from 0.264 to 0.642% and 0.208 to 0.552% correspondingly, whereas the specific gravity and ultrasonic pulse velocity (U.P.V) decreases from 2.934 to 2.755, 6597 to 2660 respectively.

In comparison to coarse-grained anorthosite the coarse-grained quartz diorite variety have greater values of specific gravity, ultrasonic pulse velocity, unconfined compressive strength and Schmidt hammer rebound and reduced values of porosity and water absorption even though the quartz diorites are highly weathered. It is due to the fact, quartz diorite variety have comparatively more amount of mafic minerals and recrystallized quartz which are responsible for slightly greater values of specific gravity, ultrasonic pulse velocity, unconfined compressive strength and schmidt hammer rebound and lower values of porosity and water absorption.

CHAPTER 01
INTRODUCTION

1.1. General Introduction

Rocks of igneous, metamorphic and sedimentary nature have been utilized as dimension stone and construction supplies through human ages. However, in the present engineering projects these rocks needs a detailed geotechnical analysis before being used as an engineering supplies. The physico-mechanical properties, also known as engineering consideration of rocks are governed by various inherent and environmental parameters. The inherent parameters can be influenced by the inbuilt properties of rocks, such as mineralogy and texture while the environmental parameters can be influenced by the rocks exposure to various environmental condition including moisture and temperature (Hartly, 1974; Irfan, 1996; Tugrul and Zarif, 1999; Akesson et al., 2001; Miskovsky et al., 2004). As per petrology, texture refers to the size, form, and spatial placement of mineral grains (Mc Phie et al., 1993; Bucher and Frey, 1994).

Igneous rocks are formed when molten rock (magma, lava) crystallizes and solidifies. Magma forms at depth within the Earth, close to active plate margins or hot spots. Igneous rocks are divided into two categories, depending upon where the molten rock crystallizes solidifies. Plutonic igneous rocks originates when molten rocks remains within the Earth's crust where it cools and solidifies in chambers present in pre-existing rock. Magma within the Earth cools and takes thousands or millions of years until it solidifies. During slow cooling, the individual mineral grains have a very long time to grow, results a rock with large visible grains. Felsic (granites), intermediate (diorites) and mafic (gabbros) are the examples of intrusive igneous rocks. Igneous rocks especially granites are commonly used as building material in many engineering projects worldwide. These rocks have a range of engineering properties that makes them suitable for construction projects. Several research have been carried out to build the relationships between the petrographic features, and engineering properties of rocks (Howarth and Rowlands, 1987; Shakoor and Bonelli, 1991; Akesson et al., 2003; Sajid et al., 2009).

The strength and enduringness of rocks are adversely influenced by the weathering and alteration of the mineral grains (Arif et al., 1999; Tugrul, 2004; Coggan et al., 2013). The extent of twinning and the calcic composition of plagioclase, which together lead to alteration, determine the strength of gabbronorite, which is primarily comprised of pyroxene and plagioclase (Sajid et al., 2009). Further, the ferromagnesian minerals, orthopyroxene and clinopyroxene, which are high temperature and comparatively less hard, are susceptible to weathering that ultimately lowers the strength of rocks (Takahashi et al., 2007; Sajid et al., 2009; Rigopoulos et al., 2010).

Granitic rocks that are exposed at different location in the north-western Pakistan are investigated for their strength properties. Din et al. (1993) and Din and Rafiq (1997) have studied the strength properties of rocks from various location, such as granites from Malakand and Ambela, NW, Pakistan. Likewise the Mansehra granite, as well as amphibolite and gabbronorite from Dir Lower and granites from Utla area of Swabia, were studied for their strength properties by Arif et al. (1999), Sajid et al. (2009) and Sajid et al. (2016), respectively.

In the current study, petrographic, physical and strength properties of compositionally and texturally different plutonic rocks from the north-west Pakistan were investigated. In the past, researcher from all over the world have looked into the physical and strength properties of a single variety of rock at a time. But the current study include plutonic rocks that are minerologically and texturally different are investigated in term of mineralogy, texture, weathering grade, alteration and their relationship with the physical and strength properties. The investigated rocks includes quartz diorite, gabbronorite and anorthosite taken from the Chilas complex, western K.I.A., north Pakistan.

1.2. Literature Review

Evaluation of the physical and strength properties of rocks like granite, diorite, gabbronorite, dolerite, marble, limestone and sandstone are essential when considering the utilization of rocks as construction or dimension stones. The strength properties of rocks are adversely affected by weathering and alteration, therefore their characteristics are radically changed under several settings. Various researchers have studied the weathering effect upon the physical and strength properties of granitic rocks from Pakistan (Din et al., 1993; Arif et al., 1999; Sajid et al., 2009; Sajid and Arif, 2015; Sajid et al., 2016) and all over the world (Irfan, 1996; Tugrul and Zarif, 1999; Tugrul, 2004; Rigopoulos et al., 2010; Coggan et al., 2013). The strength behavior of granites has been observed to have an inverse relationship with increasing degree of alterations. Besides the importance of textural features the alteration has a significant impact on the strength and geotechnical behavior of granite. The possible cause of preferential fracture growth during compressional stress can be altered mineral and petrological features, like exsolution in mineral phases (Willard and Mc Williams, 1969; Coggan et al., 2013). Tugrul (2004) has investigated several types of rock from Turkey to know the effects of alteration on their physico-mechanical properties. According to him, the changes in their physico-mechanical properties in relation to rock weathering were largely caused by micro-texture.

Four different types of granitic rocks from northern Pakistan have been studied by Sajid et al. (2016). Details regarding the petrographic, mineralogical and strength tests and their relationships suggested that textural variation play an important role in the strength performance of granites. The research further finds that the average size of feldspar, quartz, and plagioclase together with the cleaved minerals have an inverse relationship with the rock's strength. They also observed an inverse relationship between the quartz concentration and UCS, in contrast to research done by Tugrul and Zarif (1999) and Sajid and Arif (2015), which revealed a positive correlation between the two. In comparison to the concentration of quartz itself, the textural characterization of quartz and its relationship to other minerals is somewhat more important (Shakoor and Bonelli, 1991).

The overall trend is that rocks with finer grains of the same variety tend to be stronger, although distribution of the grains is equally significant as grain size (Tugrul and Zarif, 1999; Lindqvist et al., 2007). Malanga et al. (2004) demonstrated how fractures originate and develop along grain boundaries in marble and limestone. Size and alignment of mica have a stronger influence on its strength properties, however randomly oriented small micas, particularly sericite in feldspar, possess fractures with high hardness (Lindqvist et al., 2007). However, if the grain size of the mica is larger than the separation between the triple points in the mineral matrix, the mica will provide a route for the cracks to develop (Akesson et al., 2001). Additionally, only a very small portion of the effect of mica concentration actually exists (Akesson, 2004). Coggan et al. (2013) observed the strength loss caused by changes in chemical composition in altered granites from south-west England. The strength of a rock is also significantly influenced by the shape of the minerals present. The surface energy and physico-chemical condition in which grains crystallized have a considerable impact on the grain's shape. According to Akesson at al. (2001), minerals with high surface energy typically evolve their crystal shape at the expense of adjoining minerals. According to Lindqvist et al. (2007), minerals that produce euhedral grains are thought of as discontinuities in rock structures where fractures easily originate as a result, the strength of the rock increases with an increase in the degree of complexity in grain shape and boundaries. In comparison to the normal idioblastic texture, where grain boundaries are regarded to be straight, the uneven xenoblastic texture has more strength and resistance to disintegration (Akesson et al., 2003). Such textural fluctuations have also impact on some other properties like thermal wear and resistance to drilling penetration (Howarth, 1986).

Sajid and Arif (2015) have studied different textural varieties of Utla granites from north-west Pakistan with respect to their physical and strength properties. They observed that significant recrystallization and related mineralogical shifts are caused by enhanced porosity and water absorption that can be account for lowering the strength of granites. Many researchers have used the ultrasonic pulse velocity test as an easy, reliable, and non-destructive approach toward investigating the strength behavior of various standing concrete and rocks (Hassan et al., 1995; Fernandes and Lourenco, 2007; Vasconcelos et al., 2008). Several correlations between ultrasonic pulse velocity and the modulus of elasticity and compressive strength have been made for the purpose of estimating elastic and strength parameters (Uchida et al., 2000; Kaharaman, 2001; Yasar and Erdogan, 2004). Fractures found in granites have a negative impact on the UPV, and a correlation between the two was proposed by Kaharaman (2002).

Ultrasonic pulse velocity can also be used to monitor the development of cracks in concrete (Selleck et al., 1998; Wu and Lin, 1998; Mirmiran and Wie, 2001). The shape, size and minimum width of the rock grains as well as the transducers' inherent resonance frequency have a significant impact on UPV (ASTM, D2845-08). The amount of moisture present has a considerably impact the ultrasonic pulse velocity. According to Binda et al. (2003), the difference in pore fluid present in the rock affects P-velocity measurements. Fort et al. (2011) reported similar outcomes for pore fluid present in a rock and its saturation. Two conditions, that are saturated condition and dry conditions, were proposed for all samples to solve this variable (Vasconcelos at al., 2008).

1.3. Location of the Study Area

A large body of plutonic rocks that extend from village Malkana to Batwar is exposed in Salarzai area of district Bajaur just west to the Jandul, NW Pakistan (Fig.1.1). The study area constitutes the north eastern portion of Salarzai, district Bajaur. The study area is closed to the Afghan border and easily accessible by a link road that runs through Mulakali, Tabai and Malkana, connects the study area to the Khar to Munda main road.

1.4. Topography and Climate of the Area

The Bajaur district is located at a high altitude to the east of the Kunar Valley, Afghanistan covering an area of 1,290 square kilometers. The land mass is located at a height of 1133 m/3717 ft., between latitudes of 34°30' and 34°58' N and longitudes of 71°11' and 71°48' E. About 45% area of the District Bajaur is hilly with plantation made by the Forest Department and having some natural forests in the area of Salarzai. About 47% land is plain/ agricultural on which houses are constructed. Approximately 8% of land is covered by the local rivers. Various springs and streams of fresh water flow throughout the area, and act is a potential source for drinking and irrigation.

The Bajaur has an extreme climate. The winter season lasts from November to March. This season is extremely cold and freezing. Most of the time, the temperature drops below the freezing degree. The summer season is quite brief. It starts in June and lasts until August. June through August are considered the hottest months in Bajaur.

1.5. Previous work

The Bajaur and surrounding area has a very complex set up in the context of geology and tectonics. The very first insight into the area had made by Badshah (1979). During his investigation, he investigated an area of about 1000 square km, reporting several types of

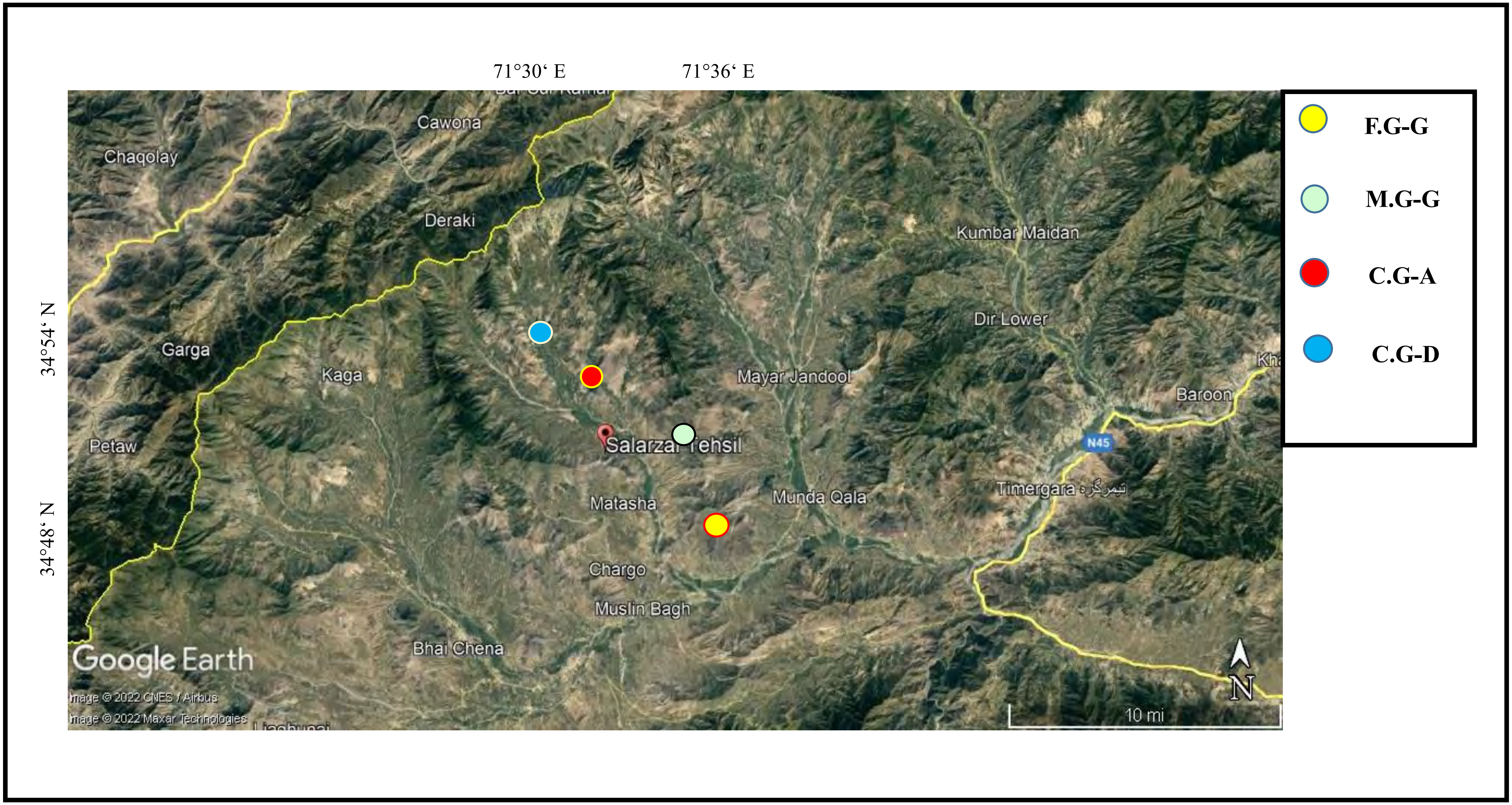

Fig. 1.1. Location map of the study area (Google Earth), the colour solid filled circles represent samples location.

Sedimentary and meta-sedimentary rocks from the Paleozoic age and igneous rocks of Mesozoic to Tertiary age. Based on his finding, he came to the conclusion that the area constitutes the western part of K.I.A. Asrarullah and Hussain (1985) have studied marble deposits of Paleozoic age exposed in different location to the south-west of the study area. These deposits were found at Nawagai, Bar Kamangara, and Kharai Kamangara. Hussain et al. (1989) have worked on emerald mineralization at Amankot Barang, district Bajaur. His study revealed that the talc carbonate schist, that is part of the Indus suture melange, is the host rock for the emerald mineralization.

Bilqees et al. (2014) investigated the manganese ore deposits from Charmang and Takht area of Bajaur. His study revealed that 230 m long and 2 m thick bed of manganese ore is found in the metamorphic sequence of green schists. Recently, the radioactivity of plutonic igneous rocks has been analyzed (Younis et al., 2021). The findings of this investigation showed that the rocks are low radioactive norites.

1.6. Present Investigation

The Salarzai area of district Bajaur contains huge masses of plutonic rocks that are well exposed and easily accessible. The rocks present to north-east in Jandul have been studied in reasonable detail in the past. However, the plutonic rocks found in the Salarzai area have received very little attention. There is considerable controversy among the researchers regarding the composition and origin of Salarzai plutonic rocks. The purpose of this research study is to provide field and petrographic information about the plutonic igneous rocks of Salarzai so that the conflicts and misunderstandings regarding their composition and origin could be clarified. The physico-mechanical properties of these rocks have not been properly studied, hence need to be investigated.

1.7. Aims and Objectives

The main objectives of the present studies are outlined as under;

- ❖ Determination of weathering grade of the selected rocks by using different standard techniques.
- ❖ Petrographic examination of the Salarzai plutonic igneous rocks to determine their modal mineralogy and to discuss their genesis based on these petrographic details.

- ❖ Determination of physical and strength properties of the investigated rocks to assess their suitability being used as building material and dimension stone.
- ❖ Determination of possible relationships between petrographic details and physico-mechanical properties.

1.8. Methodology

Four representative fresh and fracture free bulk samples from different textural varieties of plutonic igneous rocks from Salarzai area were collected. Geographic coordinates of each sample were properly recorded during the field. Naked-eye observations and microscopic studies together were used for the determination of weathering grades for each variety. The petrogenetically important field features were also noted and photographed. Three thin sections from each bulk sample were prepared for detailed petrographic observations. Thin section were prepared in the thin section Laboratory while the petrographic investigations were carried out in the petrography laboratory, National Center of Excellence in Geology, university of Peshawar. For the determination of physical and strength properties six cubes were prepared from each sample according to the ASTM specification. These bulk samples were cuts into cubes in the rock cutting factory (Bajaur Marble Factory) nearby and properly polished to the required size in the thin section Laboratory of National Center of Excellence in Geology, university of Peshawar. Details regarding the sample preparation and testing procedures are present in the concern chapters.

CHAPTER 02
REGIONAL AND LOCAL GEOLOGY

2.1. Regional Geotectonic Frame Work of Northern Pakistan

Indian plate, Kohistan island arc (KIA), and Eurasian plate are the three separate tectonic zones that make up northern Pakistan. In the Late Jurassic, Tethys was intra-oceanically subducted beneath the Eurasian plate, creating the Kohistan island arc. A suture known as the Main Karakoram Thrust (MKT) or Shyok suture is developed during the Early Cretaceous period as a result of the collision of the Kohistan island arc with the Eurasian plate (Tahirkheli, 1979; Sajid and Arif, 2015). Another suture zone known as the Main Mantle Thrust (MMT) or Indus Suture Zone (ISZ) was created in the Early to Middle Eocene as a result of the collision of the K.I.A. with the Indian plate (Treloar et al., 1989; Sajid and Arif, 2015). Tahirkheli (1979) proposed the name Main Mantle Thrust (MMT) and established its significance as a plate boundary that separates crystalline shield rocks of the Indian Plate from the ultramafic and mafic rocks of the Kohistan island arc.

MMT is not the name of a single fault; rather, it refers to a series of faults of varying ages and tectonic histories (Kazmi, 1984; Lawrence et al., 1989). The basal fault of the MMT which is in direct contact with Indian Plate rocks known as the Kishora thrust (Lawrence et al., 1989). A roof fault known as the Kohistan Fault separates the Indus suture zone from the Kohistan island arc (Tahirkheli et al., 1979; Tahirkheli and Jan, 1984). According to Dipietro et al. (2000) MMT extends from Afghanistan eastward through Bajaur, Swat and Babusar, turns northward, and circle the Nanga Parbat-Haramosh massif on its way to Ladakh. The MMT suture has a variety of discontinuous fault slices that are separated into Shergarh, Kishora, Dargai, and Nawagai melange units, which collectively represent the Indus Suture melange group.

2.2. Geology of Kohistan Island Arc

The Kohistan island arc, covering an area of about 3600 km2, was created in the Late Jurassic as a result of the intra-oceanic subduction of Tethys beneath the Eurasian plate (Tahirkheli et al., 1979). K.I.A is one of the best-preserved oceanic island arc section worldwide that is sandwiched between the Eurasian plate to the north, and Indian plate to the south (Searle and Cox, 1999; Ahmad, 2004). Amphibolites, diorites, meta-norites, and related volcanic rocks make up the majority of the rock types in K.I.A (Tahirkheli et al., 1979; Bard et al., 1980; Bard, 1983). K.I.A consist of the following six geologic units (Fig.2.1) as we move from the south to the north (a) Jijal Complex, (b) Kamila amphibolites, (c) Chilas complex, (d) Kohistan batholith and Gilgit gneisses, (e) Chalt volcanics and (f) Yasin group metasediments (Jan and Howie, 1981; Ringuette et al., 1999; Dhuime et al., 2007).

The Jijal Complex, having an area of about 150km, is the southernmost and deepest part of the K.I.A. The two separate units that make up this complex are garnet granulite and ultramafic rocks. Ultramafic rocks includes clinopyroxenites, dunites, harzburgite and websterites. Two types of granulite have been recognized within this complex one having plagioclase and the other is plagioclase free (Jan and Howie, 1981). The Kamila amphibolites is located to the south of the Chilas complex and mostly separated into fine grained and medium to coarse grained verities. Geochemical study reveal that the fine grained verity is formed at the expense of volcanic protolith while the medium to coarse grained verity is derived from plutonic gabbro norite protolith (Jan, 1988). In the southern region of K.I.A, next to the Kamila amphibolites, is the Chilas complex. The complex measures around 300 km in length from east to west and 40 km in width from south to north. Mostly gabbronorite and pyroxene-diorite made up this complex. Additionally, there are a few anorthosite, gabbro, peridotites, dunite, and mafic dykes (Khan et al., 1985; Hameedullah and Jan, 1986; Khan, 1989; Khan et al., 1993). Tahirkheli and Jan, (1979) initially described the Kohistan Batholith, which represents the northern portion of K.I.A. This unit was later given the name Kohistan batholith. This unit stretches for 300 km east-west and 60 km north-south. It is thought that three stages of magmatic intrusions resulted in the formation of the Kohistan batholith. Diorites, granodiorites, lecugranite, hornblendite, and hornblend gabbro made up this batholith.

The Chalt volcanic group created a narrow, arcuate, long, and linear belt that is located to the south of the Northern suture zone (NSZ). This unit comprised of basalts, rhyodacites, and andesites, stretched for about 300km following the east west direction. These volcanics

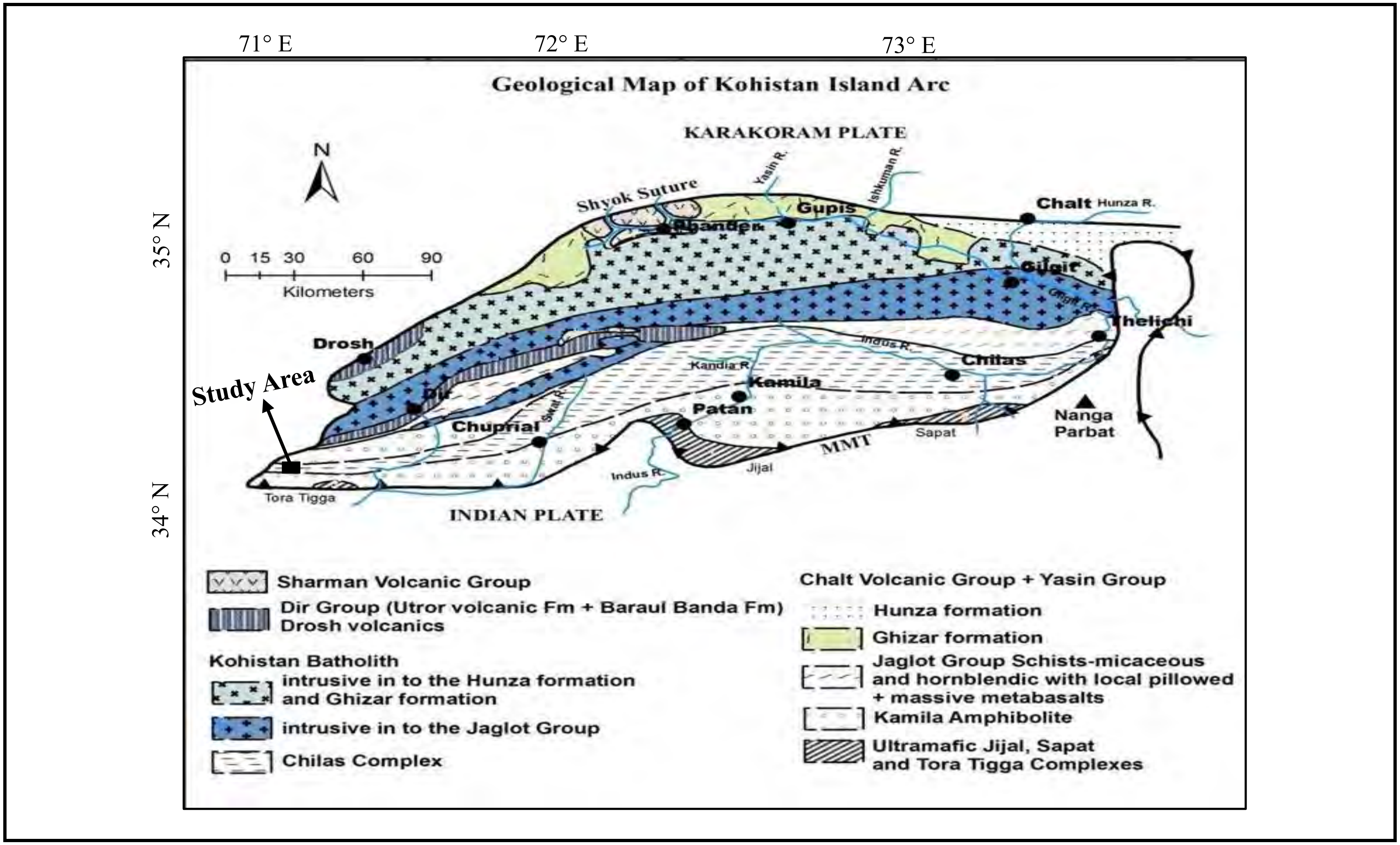

Fig. 2.1. Geological map of Kohistan island arc showing major divisions and study area (After Tahirkheli et al., 1979; Khan et al., 1993; Searle and Khan, 1996).

These volcanics are severely deformed, showing metamorphic grade from greenschist facies in the west to amphibolite facies in the south (Petterson and windley, 1985; 1991). Yasin group meta-sediments are recognized as the youngest Tethyan remains lies in northern part of K.I.A. The principal rock types in this unit are volcanics, limestone, slates, basal conglomerates, and volcanoclastics. As a result of the collision of the two plates, volcanic rocks underwent metamorphism, giving rise to the greenschist facies. Variation in lithology is found as the eastern part of this group along the Hunza valley contained volcanoclastics, terrigenous clastic, slates and limestone but the western part along the Ishkoman valley comprised of slates, silty quartzite and conglomerate with no limestone present.

2.3. Geology of Bajaur and Surrounding Areas

The area under investigation lies in Tehsil Salarzai, district Bajaur. Geologically, the area is located in the western part of K.I.A., within the Chilas complex, with MMT running EW, following the course of Bajaur Khwar. According to Kakar et al. (1971), the entire region, comprising Jandul-Bajaur and the surrounding areas, can be considered as one large fold, having axis that runs parallel to the Bajaur stream with a south-westerly pitch. Furthermore, it is believed that the region has gone through several structural deformation phases, including local and regional faulting and folding. These assumptions are supported by the repetition of similar lithologies at intervals. Rocks exposed locally are classified into meta-sedimentary and sedimentary of Paleozoic age, and igneous of Mesozoic to Tertiary age (Bilqees et al., 2014).

2.4. Paleozoic Rocks

Detailed description of Paleozoic rocks found in various locations are as follow.

2.4.1. Metasediments

Badshah (1979) has provided a detail description of the metasediments exposed in the Bajaur and northern Mohmand. These metasediments comprised of epidote-chlorite schists, phyllitic schists, slates, talc-carbonate schists, graphitic schists and piemontite schists. These rocks generally have an E-W extension, but in the Mamun area, they tend to have a NW-SE extension. These metasediments have different contact relationships in different parts of the area. A well-define contact with the diorites is seen in the eastern Mamund but in the north of the Sarkari-Qila the contact is transitional. Partly sheared and highly disturbed contact has also been observed at Shinai and Takht Kandao. In the eastern foothills of the Mamun Mountains and at the exposed limbs of the ridges to the north of the Khar-Bajaur-Main Kali road, the amphibolite facies, particularly the banded ones, are exposed. A few of the amphibolites are also exposed in the plains of Khar at Trakai and Baba-Ziarat, as well as on a few ridges at Kuhai, Kharashah, and Kharai in Ambhar Utmankhel. In the rest of the country rocks they are exposed in the form of scattered sheets and lenses. Plagioclase, hornblende, quartz, minor amounts of epidote, chlorite, biotite, muscovite, sericite, and occasionally garnet and an opaque ore, most likely magnetite, make up this species' mineral composition.

The epidote chlorite greenschist facies are exposed at Kamangara, Inayat Kili, Sara Mena, the Bajaur-Ambhar pass and at certain ridges in Ambhar Utmankhel. This facies has a medium-to-fine-grained texture with well-defined lineation, but the lineation is disturbed close to the contacts with intrusive. This species consist of minerals quartz, chlorite, epidote, plagioclase, and some hornblende, carbonate, sericite and opaque ore.

Phyllitic schists are exposed at Batai and the surrounding area of Alizai, the Amankot area of Barang and at certain ridges in Ambhar Utmankhel. In most of the exposure this facies is interbedded with limestone and volcanics. Two varieties of slates, one light green and the other dark grey, have been studied. The light green slates are exposed at Mukha, Kitkot and Gabarai while the dark variety, which has pegmatites and quartz veins, is exposed at a few ridges in Alizai and Barang areas. The light green variety of slate resembled the green rocks of Baraul valley of Upper Dir in appearance that lies close to the northern area of Salarzai, Bajaur. It is believed that the light green variety is most likely of volcanic origin.

The talc chlorite schists are exposed at very few locations, including Gumbatai, Batomena, and Shinai in Ambhar Utmankhel, Nawagai, Doda, and Amankot in Barang, as well as in Targhao. Chromium mineral are rarely found in these metasediments in the form of fuchsite. Emerald has developed at Amankot while low to medium standard soap stone has developed at Doda and Targhao within these rocks.

The graphitic schists are severely weathered and mostly contain quartz, micas and carbonaceous matter. This species are exposed at eastern Pampokha in Ambhar Utmanikhel and also exposed at Targhao-Kandu-Gadamar line. Peimontite schist are exposed in some area of Sara Mena, Alizai and Batai.

2.4.2. Sedimentary Rocks (Nawagai Limestone Group)

These rocks are exposed at the Lakaro-Nawagai section and named as Nawagai Limestone group. In the southern-western part it occupies a limited area but extends over a vast distances to the Mohmand District and further west into Afghanistan. This limestone body is fine grained, unfossiliferous and medium to thick bedded having local folds and faults and intruded by dolerites, ultrabasic and porphyritic acidic rocks. This unit is measured 1000 m thick, having faulted contact with the metasediments. These rocks are light to dark grey in color and dolomitized at places. This unit of limestone is correlated with the Banna Formation of Allai area in Hazara Kohistan and stated as part of the Besham Group rocks (Tahirkheli et al., 1979). The Nawagai Limestone Group is also shown by Tahirkheli (1979) in a diagrammatic geological section across Mohmand, Malakand and Dir, showing the position of MMT with respect to the Indian Plate (Fig. 2.2)

2.4.3. Marble

The four major Marbles deposits identified in Bajaur and surrounding area, which are exposed at Nawagai, Doda, Bar Kamangara and Khari Kamangara. These marble units are estimated to have a capacity of 9 million cubic meters. Marbles of Bajaur having color ranging from grey to whitish gray with greenish grey and associated with meta-sedimentary rocks belonging to Paleozoic age (Asrarullah and Hussain, 1985). Among these exposures Nawagai Marbles has better access and extensive reserves. The general trend of these Marbles is N80°E with moderate to high dips in southern direction.

2.5. Mesozoic-tertiary rocks

The igneous masses comprised of diorite, gabbronorites, granite, granodiorite, anorthosites, ultrabasic and volcanic rocks. The geologic history of Bajaur and Jandul is closely related. The plutonic rocks of the Jandul valley are probably Jurassic-Cretaceous in age (Kakar et al., 1971). These rocks are divided into older group and younger group.

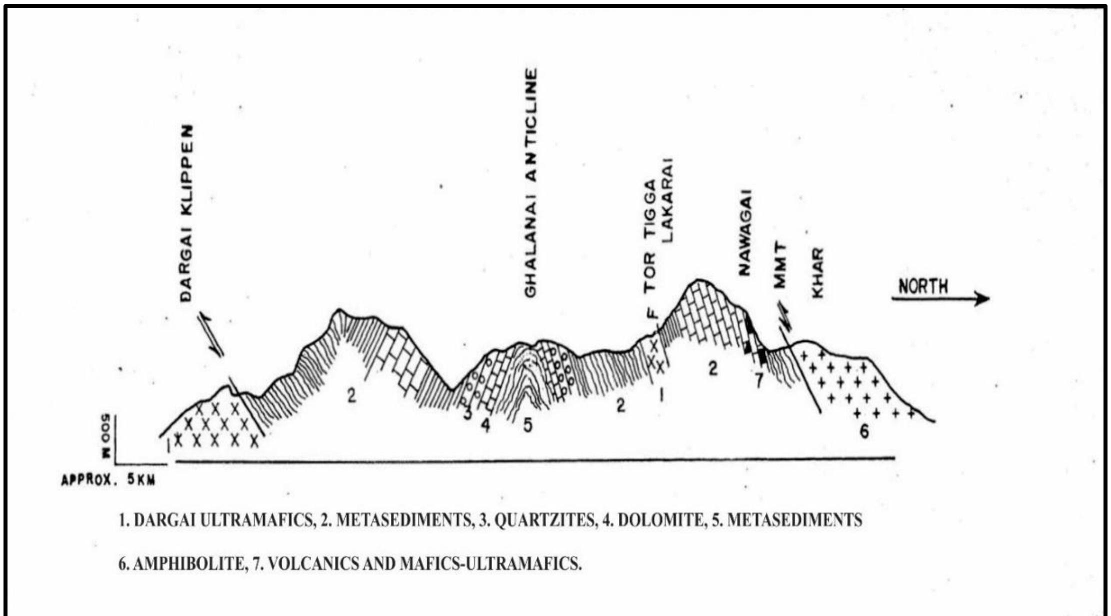

Fig. 2.2. Diagrammatic geological cross section across Mohmand, Malakand and Dir, showing the position of MMT with respect to the Indian mass (After Tahirkheli 1979).

The intrusion of diorites followed by gabbronorites began sometimes in the late Cretaceous, and the final phase of granitic stocks and dykes in the middle Eocene marked the end of the whole magmatism. Anorthosite and ultrabasic phases of serpentinites, peridotite and pyroxenite/hornblendite formed in the Late upper Cretaceous to Eocene-Oligocene, that lies interbedded with metasediments. Volcanic rocks of andesitic, rhyolitic and tuffaceous compositions of Eocene to Oligocene time are also found (Bilqees et al., 2014). The above mentioned igneous rocks are briefly described below.

Diorites are exposed in Salarzai, Kotkai, Gat and Asghar area of Bajaur. Some diorites are also exposed at certain ridges in Arang area. The Salarzai diorites is observed as quartz diorite that extends eastward through Jandul and further into Dir to discovered their continuity with the basic complex of Swat Kohistan. The Salarzai diorites were observed medium to coarse grained, hypidiomorphic and sub-equigranular. These diorites comprised plagioclase, hornblende, quartz and some pyroxene with biotite and epidote are common accessories. Minerals like apatite, sphene and garnet occurs as minor constituents. Plagioclase was observed intensely sericitized, saussuritized and epidotized, associated with the alteration of biotite to chlorite. Quartz was observed fresh and recrystallized.

Gabbronorites are exposed throughout the Salarzai and surrounding area. According to Badshah (1979) the Salarzai area is dominated by diorites but according to our field and petrographic observations and Younis et al. (2021), the area is dominated by gabbronorite. Petrographic observations of the studied sample reveals inequigranular, hypidiomorphic, fine grained and porphyritic texture at places. Anhedral to subhedral plagioclase and anhedral pyroxene are present as phenocrysts while the ground mass consist of quartz and biotite. Some of the plagioclase are sericitized at center and fresh at margins. The quartz grains are fresh and exhibit features of recrystallization.

Granites and granodiorites are collectively termed as granitic rocks that are exposed in the western part of the area. Baba Ziarat, Inayat Kili, Badan, Damadola Zagai, Gat and Tangai are the places that exposes these rocks. Some lecugranite bodies are also exposed at Bakaro in Mamun and at Maram Ghundai in Alizai. Gradual transition from granites to granodiorites is observed in these rocks. The modal minerology includes alkali feldspars, plagioclase, hornblende and subordinate biotite with minor amount of Epidote, chlorite, apatite, tremolite, garnet, sphene, rutile, leucoxene and iron ores. Alteration of feldspars into epidotes and biotite into chlorite is commonly observed.

Stocks of coarse grained anorthosites are exposed in the northeastern part of Salarzai. The minerology of these rocks includes plagioclase, hornblende and biotite with minor amount of quartz, chlorite, epidote and ores. Plagioclase was observed as equidimensional, subhedral to anhedral and coarse grained while medium grained to fine grained mass is comprised of anhedral amphibole and biotite. Some plagioclase were found zoned and very few was slightly sericitized. Some of the biotite altered to chlorite mineral was also observed.

The ultrabasic masses comprised serpentinites, peridotites and hornblendites that occurred in the southwestern part of the area. These are exposed at Ambar and Laman in district Mohmand and extends to Dargai-Malakand through Utmankhel, Prang Ghar and Skhakot. Isolated masses of ultrabasic rocks are also exposed at Gandao, Kudda Khel and Safi-Qandhari areas of Mohmand (Badshah, 1959). To the east peridotites were also exposed at Tora Tiga (Black hills) and Timergara, Dir Lower (Jan et al., 1969; Kakar et al., 1971).

Volcanic rocks of andesitic, rhyolitic and tuffaceous compositions are exposed to the south of the area at Bajaur Mohmand border. These are also exposed at Pak-Afghan border to the north-west. This belt of volcanics extends westward into Afghanistan and runs eastward into northern Jandul and Baraul through northern Mamun-Salarzai (Kakar et a1., 1971). Beside the above mentioned exposures, few volcanics are also exposed in Salarzai, Nawagai and at Mir Ali Baba, Mamun. These volcanics are hard, massive, vesicular, fined grained and porphyritic at places. In the porphyritic texture the Plagioclase, amphibole and clino-pyroxene makes the phenocryst while the minerals feldspars, epidote, hornblende, chlorite, sericite, calcite, magnetite, hematite, quartz, and in a few cases biotite and muscovite makes the ground mass. Chloritized ferromagnesian minerals and saussuritized, sericitized plagioclase are found.

CHAPTER 03
PETROGRAPHY

3.1. General Introduction

Petrographic study using a polarized petrographic microscope is required to determine the percentage volume of minerals present in a rock sample. The rock type is determined by the modal mineralogy and textural relationships within the rock, which are best described with the help petrographic studies. The petrographic studies comprised observation of field features and microscopic examination of rocks as well. Understanding the origin of the rock requires detailed microscopic studies of the minerals and their textural relationships in thin sections. The Salarzai area of district Bajaur contains huge masses of plutonic rocks that are well exposed and easily accessible. The rocks present to north-east in Jandul have been studied in reasonable detail in the past. However, the plutonic rocks found in the Salarzai area have received very little attention. Here in this chapter, a detailed petrographic examination of the Salarzai plutonic igneous rocks is provided.

3.2. Methodology

Four representative fresh and fracture free bulk samples from different textural varieties of plutonic igneous rocks from Salarzai area were collected. Geographic coordinates of each sample were properly recorded during the field. Naked-eye observations and microscopic studies together were used for the determination of weathering grades for each variety. The petrogenetically important field features were also noted and photographed. Three thin sections from each bulk sample were prepared for detailed petrographic observations. Thin section were prepared in the thin section Laboratory while the petrographic investigations were carried out by using plan-polarized light (PPL) and cross-polarized light (XPL) in the petrography laboratory, National Center of Excellence in Geology, university of Peshawar. Minerals were identified base on their optical properties. Modal abundance of minerals were determined based on visual estimation. Grain size, shape and their arrangement were observed for the determination of texture type.

3.3. Weathering

Weathering is defined as the disintegration and decomposition of rocks when exposed to moisture and other atmospheric conditions. The weathering grades for each variety were determined (Table3.1) based on texture, the color of weathered and fresh surfaces and impact sound produced when struck with hammer (Irfan and Dearman, 1978; Borrelli et al., 2007). The weathering grades for each variety were later confirmed by indicators including intra and inter granular fractures, recrystallization and alteration of different minerals during microscopy.

3.4. Petrography

Based on detailed field and petrographic observations, plutonic igneous rocks of the Salarzai area can be classified into three different rock types.

1) Diorites
2) Gabbronorites
3) Anorthosites

The petrographic description for each rock type is provided separately in the following sections.

3.4.1. Gabbronorites

The study area is dominated by gabbronorite observed medium to fine grained having greyish color on the weathered surface and typical grey on the fresh surface (Fig. 3.1) Petrographic observations of the studied sample reveals that the rocks under investigation are holocrystalline, inequigranular, fine to medium grained and porphyritic at places. The fine-grained variety of the present rock is observed as allotriomorphic. Most of the Anhedral plagioclase and pyroxene with few biotite grains are present as phenocrysts while some plagioclase and pyroxene with minor to accessory amount of other minerals including biotite, quartz, epidote, garnet, sphene and opaque mineral grains constitute the groundmass. The medium grained-variety of the present rock mass is investigated as hypidiomorphic. The phenocrysts comprised of subhedral to anhedral plagioclase and anhedral pyroxene and biotite while some plagioclase and pyroxene with minor to

Table 3.1. Weathering grade classification of the selected variety of rocks (after Irfan and Dearman, 1978; Borrelli et al., 2007)

Specimen	Outcrop & microscopic observations	Descriptive term	Weathering Grade
Fine-grained Gabbronorite	Typical grey on the fresh surface while greyish black on the weathered surface and fine-grained. Produced compact sound with hammer. Holocrystalline, inequigranular, fine and porphyritic at places. Fractures and Alteration of Plagioclase, pyroxene and biotite were observed during microscopy in some grains.	Slightly Weathered	II
Coarse-grained Gabbronorite	Medium-grained, hypidiomorphic appeared grey on fresh surface and slightly greyish black on weathered surface. Hard and produced compact sound. Major minerals appeared fresh with no visible alteration. Although very few grains were observed fractured.	Fresh	I
Coarse-grained Quartz Diorite	Inequigranular, allotriomorphic, coarse grained appeared greyish brown on the weathered surface and greenish grey on the fresh surface. Highly weathered, produced dull sound when struck with hammer. Plagioclase biotite and were observed severely weathered and fractured during microscopic examination	Highly Weathered	III
Coarse-grained Anorthosite	Appeared golden brown on the weathered surface and white milky grey on the fresh surface. Coarse-grained, produced fairly compact sound when hammered. Major minerals were observed fresh while fractures and alteration of minor minerals were seen during petrography.	Fresh	I

Accessory amount of other minerals including biotite, quartz, epidote, garnet, sphene and opaque mineral grains constitute the groundmass. The plagioclase is observed the most abundant mineral present in these rocks (Table 3.2) having range of modal abundance (45–50 %). During the petrographic examination, the plagioclase appeared cloudy exhibiting polysynthetic twinning and normal zoning. Some of the grains observed having myrmekite and poikilitic texture. The plagioclase of the fine-grained variety showed alteration that is largely sericitization and saussuritization. Some of the phenocrysts of this mineral are zoned with a saussuritized/sericitized core and fresh margin (Fig. 3.3 d) thereby indicating ‘normal’ zoning, i.e. the margins of the grains are more sodic and hence less susceptible to alteration than their respective cores. In the medium-grained variety, fresh, strained and tabular plagioclase (Fig. 3.2) was observed.

Pyroxene, including both clinopyroxene and orthopyroxene (Fig. 3.2) is the next most abundant mineral in these rocks and its modal abundance ranges from 34 to 41 % (Table 3.2). Petrographic examination revealed that Clinopyroxene is dominant over the orthopyroxene in these rocks hence classified as gabbronorites. This mineral is observed as anhedral, having garnet and opaque minerals inclusion and chloritized at places. Furthermore, this mineral is found as phenocryst and ground mass as well.

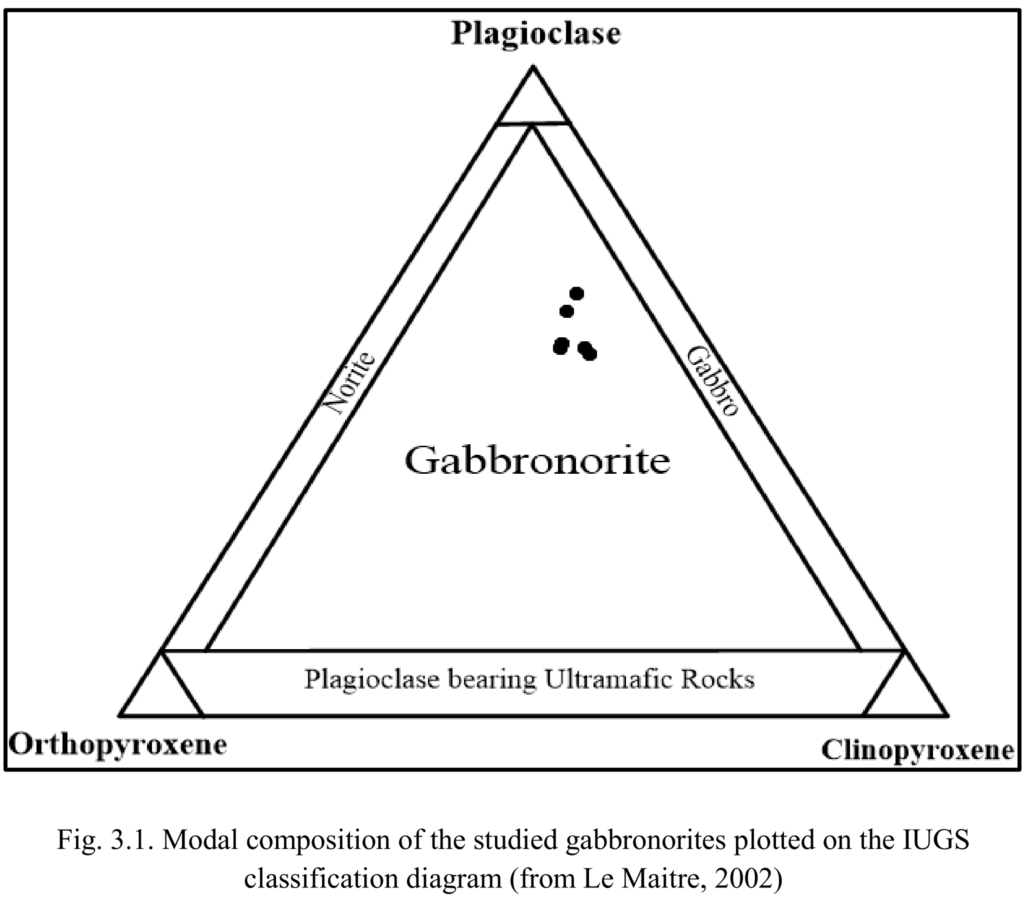

Fig. 3.1. Modal composition of the studied gabbronorites plotted on the IUGS classification diagram (from Le Maitre, 2002)

Biotite is seen to be the third most abundant mineral in these rocks (Table 3.2) having ranges of modal abundance (6.7-4.3 %). Anhedral biotite is occurred as phenocryst and groundmass, having opaque minerals inclusions (Fig 3.3 d) and chloritized at places.

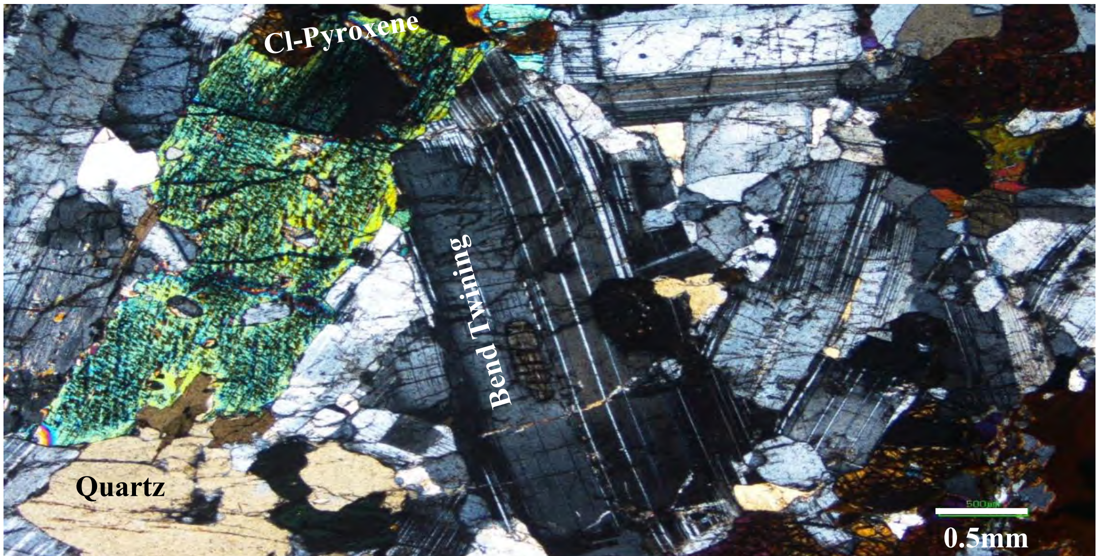

Fig. 3.2. Photomicrograph showing clino-pyroxene, bend twining in plagioclase and quartz in gabbronorite

Quartz is observed the fourth most abundant mineral in the present rocks. It occurred as anhedral in shape and was found as a groundmass constituent. Fresh and strained quartz grains, exhibiting features of recrystallization were also observed with the undoluse extinction that confirms their strained nature. During the fieldwork, quartz veins were found (Fig. 3.3 a) in addition to microscopic observations.

Few grains of epidote, chlorite, garnet, sphene and opaque minerals were found (Fig. 3.3 c) during the petrographic studies of the samples. Epidotes and chlorite were found to be formed at the expense of plagioclase and biotite respectively. Epidote were also found in association with quartz in the form of veins (Fig. 3.3 a). Garnet is observed clear in found associated with pyroxene. Opaque mineral most probably comprised ilmenite and magnetite were also seen in these rocks. It is primarily seen as an inclusion in biotite, however, some pyroxene also contains opaque minerals within its grains.

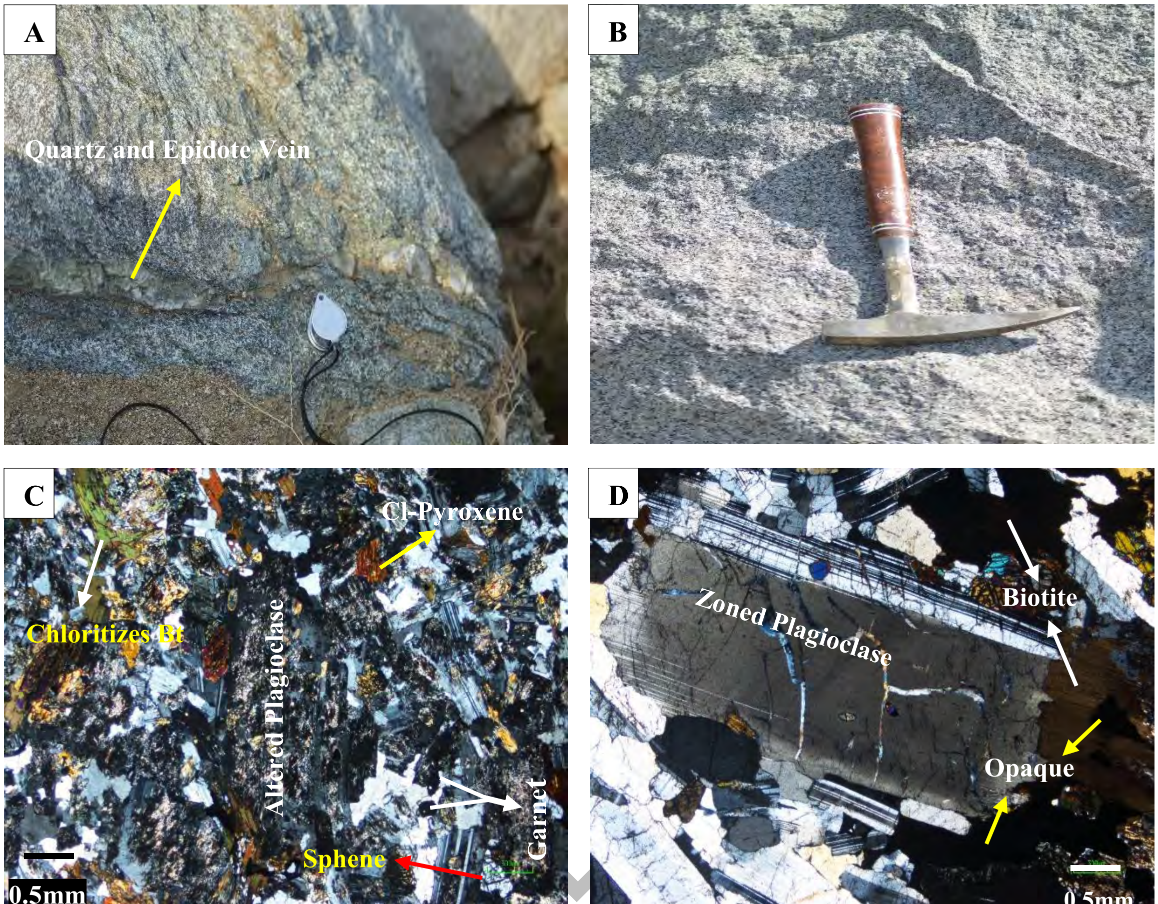

Fig. 3.3. Field & microscopic photographs: (A) Fine-grained gabbronorite having quartz epidote vien; (B) Fresh surface of gabbronorite; (C XPL) Chloritized biotite, altered plagioclase, clino-pyroxene, sphene and garnet; (D XPL) Zoned plagioclase and biotite having opaque inclusions

3.4.2. Diorites

The diorites are exposed in the north-eastern part of Salarzai at village Batwar appeared greyish brown on the weathered surface and greenish grey on the fresh surface. Based on field and petrographic observations, these diorites were regarded as quartz diorites that are cross-cut by aplitic veins. Petrographic studies revealed that the rocks are inequigranular, allotriomorphic, coarse grained and porphyritic at places. Anhedral plagioclase and amphibole are present as phenocrysts while some plagioclase, amphibole and quartz with minor to accessory amount of other minerals including biotite, epidote, chlorite and opaque mineral grains constitute the groundmass.

The plagioclase is found the most abundant mineral present in these rocks having range of modal abundance (69–72 %) (Table 3.2). During the petrographic studies, the plagioclase appeared cloudy exhibiting polysynthetic twinning that is hardly visible at the margins of grains because of intense sericitization and saussuritization (Fig. 3.5 c)

Quartz was observed the next most abundant mineral in these rocks and its modal abundance ranges from 9 to 12 %. (Table 3.2). It occurred as anhedral in shape and was found as a groundmass constituent. Fresh and strained quartz grains, exhibiting features of recrystallization were also observed with the undoluse extinction (Fig. 3.5 c), which is the diagnostic optical property of the quartz.

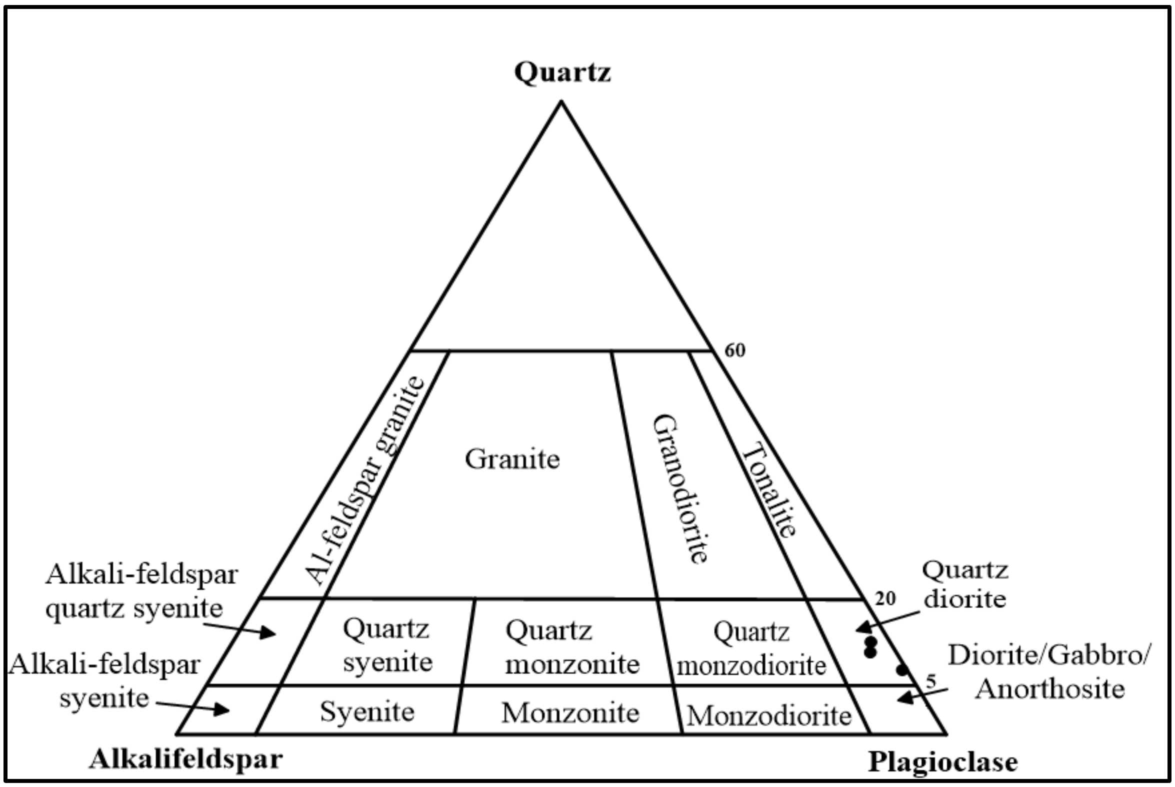

Fig. 3.4. Modal composition of the studied quartz diorites plotted on the IUGS classification diagram (from Le Maitre, 2002)

The third most abundant mineral, amphibole is present as phenocryst and groundmass, with a modal abundance of 6.8 to 9 percent (Table 3.2). The amphibole is observed as anhedral mostly hornblende exhibiting green and greenish yellow color (Fig. 3.5 a). Sphene and opaque minerals are seen as inclusions in amphibole.

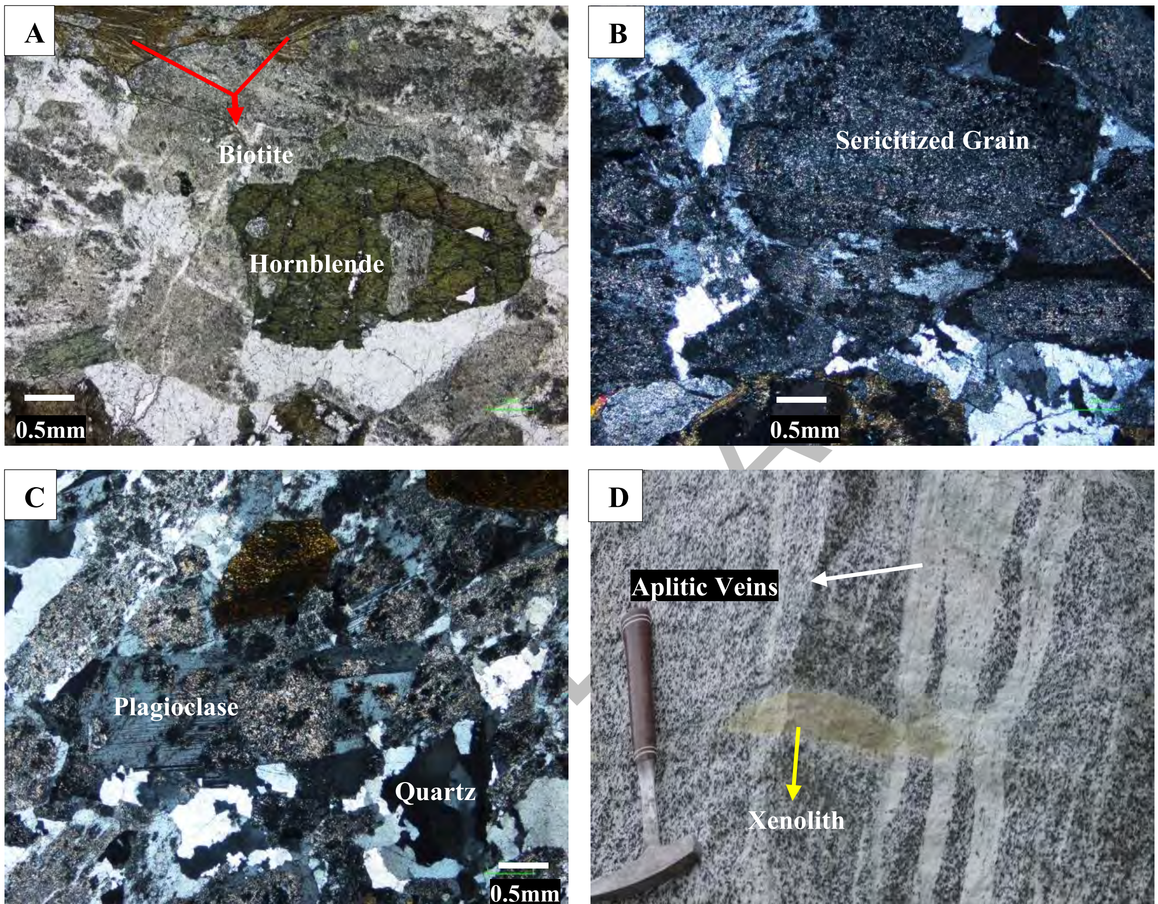

Fig.3.5 Photomicrographs (A) Hornblende and biotite in quartz diorite (B) Sericitized plagioclase grain (C) Plagioclase fresh at margin and sericitized at center and recrystallized quartz; (D) Field photograph showing aplitic vein and xenolith.

Biotite is seen to be the fourth most abundant mineral in these rocks and its modal abundance ranging from 3 to 4.5 % (Table 3.2). It occurred as anhedral and constitute part of groundmass and chloritized at places (Fig. 3.5 a).

Minor to accessary amount of epidote, chlorite and opaque minerals are taken into account in these rocks during the petrographic studies (Table 3.2). Epidotes were observed as primary and as a product of saussuritization while chlorites were seen to form at the expense of biotite. Garnet, sphene, and opaque minerals were found within the amphibole and biotite grains.

3.4.3. Anorthosites

The anorthosites are exposed in the form of stocks at village Atkai in northeastern Salarzai, Bajaur, which appeared golden brown on the weathered surface and white milky grey on the fresh surface. Field observations show that the rocks are coarse-grained, and porphyritic at places having parallel veins of epidote mineralization while petrographic studies confirms the holocrystalline, inequigranular, and hypidiomorphic nature. Subhedral to anhedral plagioclase is occurred as phenocrysts while some plagioclase and other minerals including amphibole, biotite, pyroxene, olivine and epidote makes the groundmass.

The plagioclase is observed the most abundant mineral present in these rocks having range of modal abundance (81 to 92 %) (Table 3.2). During the petrographic examination, the plagioclase appeared cloudy exhibiting polysynthetic twinning, multiple twinning, Carlsbad twinning and normal zoning. These mineral grains were observed fractured with no visible alteration (Fig. 3.8 a).

Fig. 3.6. Field photograph showing parrallel epidote veins

Amphibole was observed the next most abundant mineral in these rocks and its modal abundance ranging from 3.5 to 5 % (Table 3.2). The amphibole is seen to be anhedral, fractured, and mostly hornblende exhibiting light green and dark green colors (Fig. 1.3).

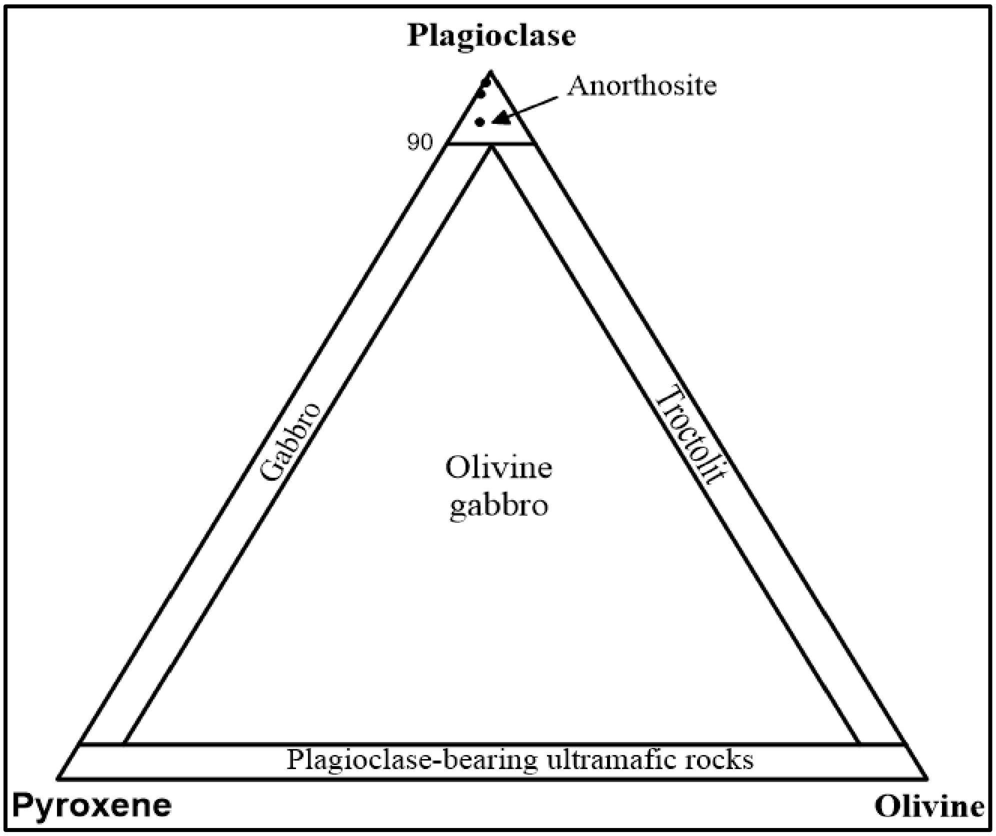

Fig. 3.7. Modal composition of the studied anorthosites plotted on the IUGS classification diagram (from Le Maitre, 2002)

Amphibole was observed the next most abundant mineral in these rocks and its modal abundance ranging from 3.5 to 5 % (Table 3.2). The amphibole is seen to be anhedral, fractured, and mostly hornblende exhibiting light green and dark green colors (Fig. 3.8 d).

The third most abundant mineral, biotite is present as groundmass, with a modal abundance of 1.2 to 4 percent (Table 3.2). It occurred as anhedral and chloritized at places (Fig. 3.8 b). Few grains of olivine, pyroxene, epidote, chlorite and opaque minerals were also noted during the microscopic studies of the present rocks (Table 3.2). Epidotes were observed as primary and as a product of saussuritization while chlorites were seen to form at the expense of biotite. Opaque mineral (ilmenite and magnetite) are mostly associated with amphibole and biotite.

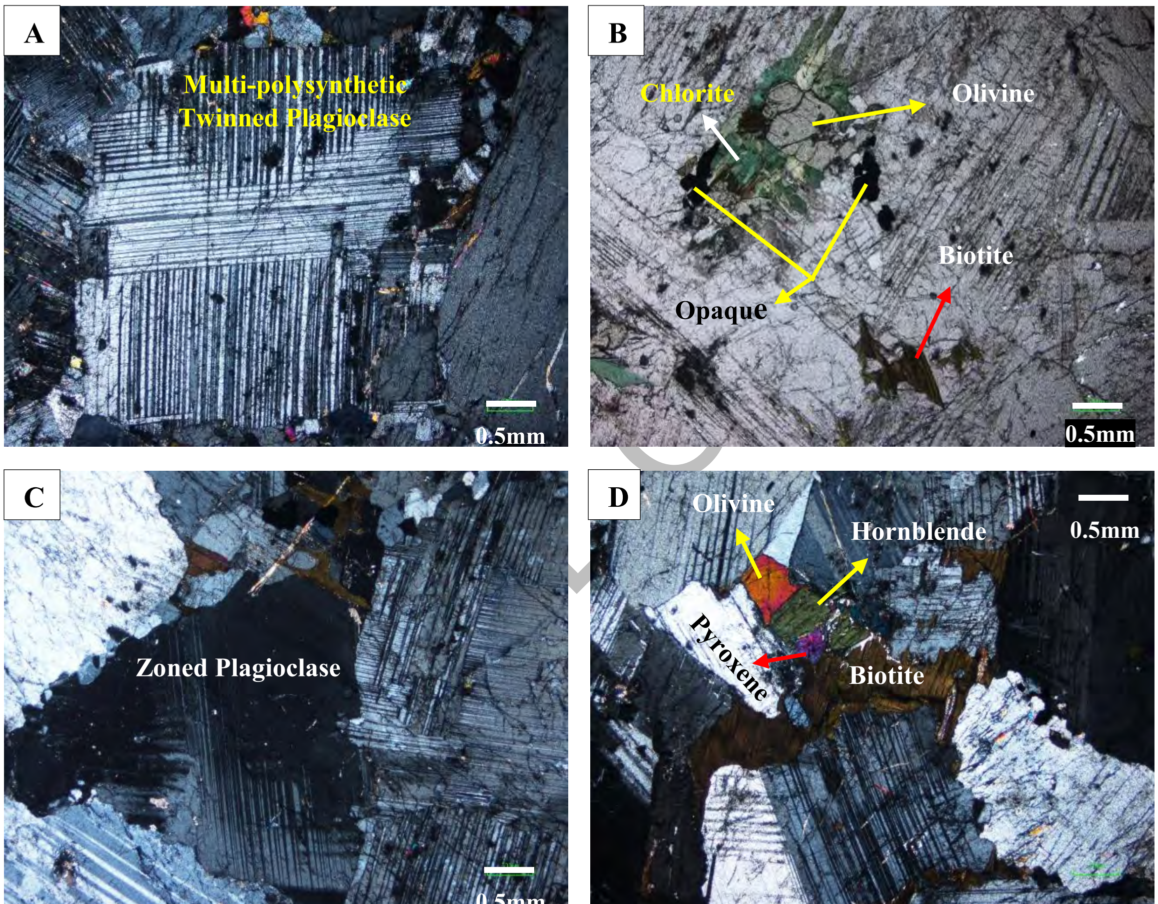

Fig. 3.8. Photomicrographs (A) Anorthosite having multi-polysynthetic twinned plagioclase; (B) Chlorite and opaque associated with olivine and fresh biotite; (C) Plagioclase zoned at the center; (D) Interstitial growth of Olivine, pyroxene, biotite and hornblende.

Table 3.2. Modal mineralogical composition of the studied rock types

Variety	Sample	Plg %	Cl-prx %	Or Prx %	Olv %	Al- F %	Bit %	Amp %	Qtz %	Epi %	Clt %	Grt %	Sph %	O.M %
Fine-grained Gabbronorite	F.GN-1	46.3	26.5	13.6	--	--	5.3	--	3.6	3.5	0.4	--	0.1	0.7
	F.GN-2	49.7	23.2	11.3	--	--	5.7	--	5.8	2.8	--	0.3	--	1.2
	F.GN-3	45.4	25.8	13.2	--	--	6.7	--	4.5	2.5	1	--	--	0.9
Medium-grained Gabbronorite	M.GN-1	49.6	25.7	13.3	--	--	4.8	--	2.6	2.5	--	0.2	--	1.1
	M.GN-2	46.8	27.6	13.5	--	--	6.5	--	3.3	1.4	--	--	--	0.9
	M.GN-3	50.5	24.6	16.4	--	--	4.3	--	1.8	0.8	--	--	--	1.6
Coarse-grained Quartz diorite	C.QD-1	70.3	--	--	--	--	5.9	11.1	10.3	1.3	0.7	--	--	0.4
	C.QD-2	74	--	--	--	0.2	4.1	7.7	12.5	--	1.4	--	--	0.1
	C.QD-3	71.6	--	--	--	1.5	3.8	8.6	11.8	0.8	1.6	--	--	0.3
Coarse-grained Anorthosite	C.AN-1	81	4	--	2.2	--	4.3	4.7	--	1.4	1.6	--	--	0.8
	C.AN-2	89.3	2.3	--	0.5	--	2.5	3.5	--	--	0.5	--	--	1.4
	C.AN-3	92	1	--	0.3	--	1.2	4.2	--	1.3	--	--	--	--

Plg= Plagioclase, Cl-Pyx= Clino-pyroxene, Or-prx= Ortho-pyroxene, Olv= olivine, Al-F= Alkali Feldspar, Bit= Biotite, Amp= Amphibole, Qtz= Quartz, Epi= Epidote, Clt= Chlorite, Grt= Garnet, Sph= Sphene, O.M= Opaque minerals

CHAPTER 04

PHYSICAL AND STRENGTH PROPERTIES

4.1. General Statement

A strong laboratory database of mechanical and physical properties of rocks is very useful for site characterization, construction of dams, tunnels, highways, railway ballast and mining engineering applications. Due to the discontinuous and variable nature of rock bodies, it is almost difficult for rock engineers to directly obtain the particular design parameters of interest. Physical and mechanical properties are the key geological factors that largely effects designing, construction, operation and maintenance of engineering works (Szlavin, 1974; Zhang, 2016). Igneous rocks are commonly hard and dense, hence mostly used in a number of engineering projects because of their stability in different conditions e.g. exposures to moistures, temperature, mechanical load etc. Many studies have been conducted on determining the engineering properties of granitic rocks (Tugrul and Zarif, 1999; Arif et al., 2013 Keikha and Keykha, 2013; Sajid et al., 2016). However, several authors have also conducted analogous studies in acidic-intermediate volcanic (Orhan et al., 2006), mafic (Sajid et al., 2009; Rigopoulos et al., 2010; Sajid, 2019), ultramafic (Rigopoulos et al., 2012; Undul and Tugrul, 2012; Petrounians et al., 2018) and metamorphic rocks (Sajid et al., 2009).

The study of the engineering properties of rock masses as well as their respective mineralogical and textural characteristics critically determines the strength of rocks and its durability from failure (Tugrul and Zarif, 1999; Giannakopoulou et al., 2018). In the petrologic sense texture is defined as the size, shape and mutual spatial arrangement of mineral grains (Mc Phie et al., 1993; Bucher and Frey, 1994). The engineering properties of igneous rocks are controlled by various inherent and environmental parameters. The inherent parameters can be controlled by the intrinsic properties of rocks including mineralogy and texture while the environmental parameters can be controlled by the rocks exposure to various environmental condition including moisture and temperature. Variation in environmental condition results the alteration of certain minerals. Sericites, epidotes and chlorites are alteration products of plagioclase and amphibole respectively, which negatively effects the physical and mechanical properties of rock masses. In the present investigations verities of plutonic igneous rocks exposed at various localities in the north western Pakistan are studied for their petrographic and physico-mechanical properties.

4.2. Methodology

Four representative fresh and fracture free bulk samples from different textural varieties of plutonic igneous rocks from Salarzai area were collected. These bulk samples were cuts into cubes in the rock cutting factory (Bajaur Marble Factory) nearby and properly polished to the required size in the thin section Laboratory of National Center of Excellence in Geology, university of Peshawar. Six cubes samples were prepared from each bulk sample. Three thin sections from each bulk sample were prepared for detailed petrographic observations. Each cube samples were cut according to the ASTM specifications for the determination of mechanical properties including unconfined compressive strength (UCS), Schmidt Hammer (SH) test and ultrasonic pulse velocity (UPV). UCS was determined by subjecting each cube sample to increasing loading at a nearly constant rate with the help of a Universal Testing Machine (UTM) of 3000 KN capacity. Schmidt Hammer test was carried out by L-type hammer for each sample at five different points within the same sample. UPV was determined through direct method for each sample according to ASTM (2008). The instrument was first calibrated with the cylindrical standard, having transit time of 58.2 μs to check the accuracy of the used instrument. The transit time of ultrasound wave for each sample were noted in microsecond. UPV values for each sample were determined by dividing the length of the sample by the transit time.

Some of the physical properties including specific gravity, water absorption and porosity were also determined for each sample. For the determination of specific gravity, water absorption and porosity, each sample was weighted in air and regarded as weight in air denoted by (W1). The same samples were kept in water in weighted as weight in water and denoted by (W2). For the determination of Saturated Surface Dry (SSD) weight the samples were kept in distilled water for 24 hours. After 24 hours the samples were dried with the help of tissue paper and weighted as SSD weight denoted by (W3). At last the samples were kept in oven for 24 hours at 100°C. After 24 hours the samples were cooled at room temperature and weighted as oven dry weight, denoted by (W4).

The above physical and strength tests were carried out in the geotechnical laboratory of the National Center of Excellence in Geology, University of Peshawar. The details of these determinations and their correlation with petrographic observations through statistical analysis are presented here.

4.3. Petrographic Description

Based on petrography the studied rocks were classified into four distinct textural varieties (Fig.4.1). The geographic coordinates and petrographic details of the studied sample are given as follows.

4.3.1. Fine Grained Gabbro Norite (F.GN)

Petrographic observation of the studied sample reveals inequigranular, hypidiomorphic, fine grained and porphyritic texture at places. Anhedral to subhedral plagioclase and anhedral pyroxene are present as phenocrysts while the ground mass consist of quartz and biotite. Some of the plagioclase are sericitized at center and fresh at margins. The quartz grains are fresh and exhibit features of recrystallization.

4.3.2. Medium Grained Gabbro Norite (M.GN)

Plagioclase and pyroxene are present as medium grained while quartz and biotite constitute the fine grained mass. Plagioclase is present as elongated, subhedral to anhedral with no visible alteration. Very few plagioclase were zoned and strained. The amount of quartz present in this variety is slightly lesser than that of present in fine grained variety.

4.3.3. Coarse Grained Quartz Diorite (C.QD)

The coarse grained mass of the studied rock was observed to be comprised of anhedral to subhedral plagioclase and anhedral amphibole. Quartz, biotite and some grained of alkali feldspars constitute medium to fine grained mass. Plagioclase was observed intensely sericitized associated with the alteration of biotite to chlorite. Quartz was observed fresh and recrystallized.

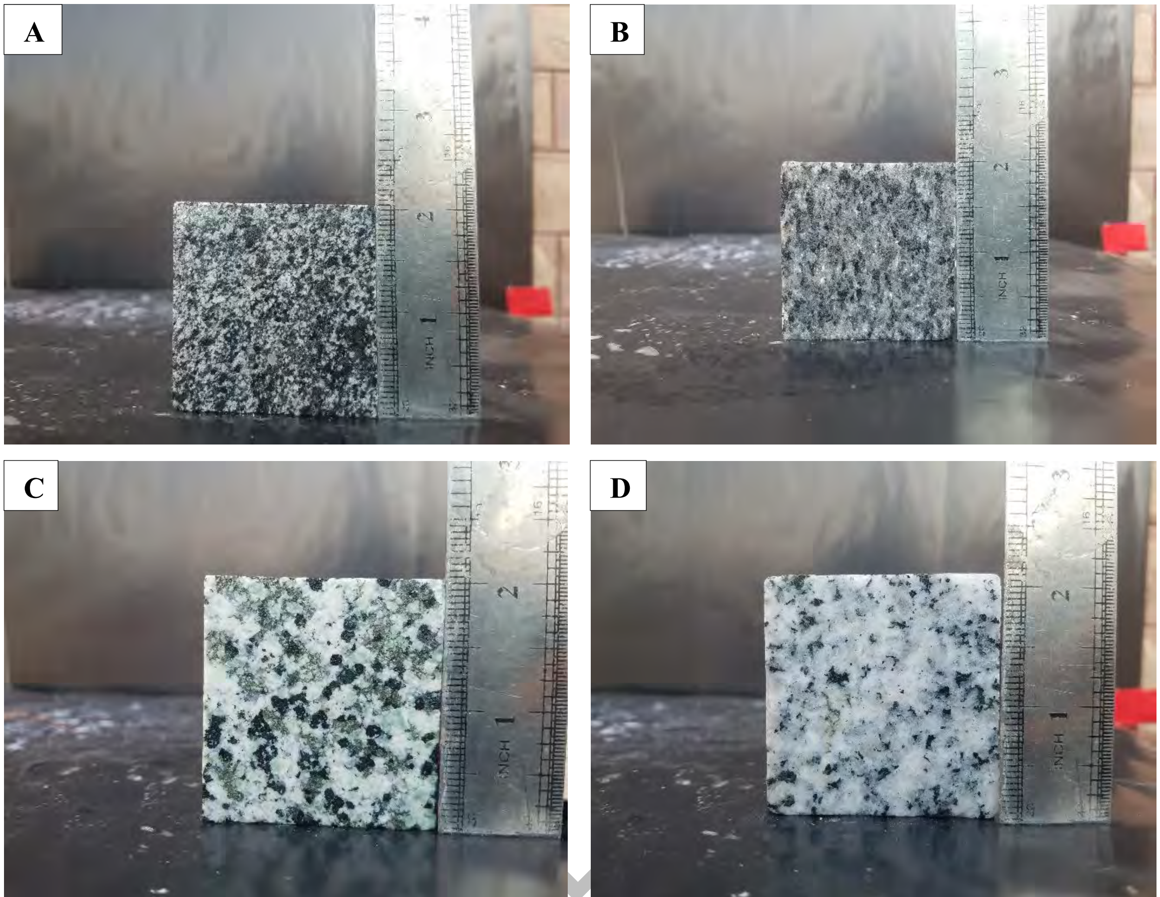

Fig. 4.1. Photographs: (A) Fine-grained gabbronorite; (B) Medium-grained gabbronorite; (C) Coarse-grained Quartz diorite; (D) Coarse-grained anorthosite

4.3.4. Coarse Grained Anorthosite (C.AN)

Plagioclase was observed as equidimensional, subhedral to anhedral and coarse grained while medium grained to fine grained mass is comprised of anhedral amphibole and biotite. Some plagioclase were found zoned and very few was slightly sericitized. Some of the biotite altered to chlorite mineral was also observed

4.4. Strength Tests

The strength tests including Uniaxial Compressive Strength (UCS), Schmidt Hammer test (SH) and ultrasonic pulse velocity (UPV) were carried out for selected cube samples. These are further discuses in the following sections.

4.4.1. Uniaxial Compressive Strength (UCS)

UCS is the highest uniaxial stress that a specimen can withstand when applied to its ends (Bell, 2007). UCS was determined by subjecting each cube sample to increasing loading at a nearly constant rate with the help of a Universal Testing Machine (UTM) of 3000 Kn capacity. The UCS of the tested samples are calculated by the following formula. Table 5.1 shows the details and results of the UCS of the studied cube samples.

$$UCS\ (Pa) = \frac{L\ (n)}{A\ (\mathrm{m}^2)}$$

Where,

L (n) = Failure Load in newton

A (m^2) = Area of the cube sample

4.4.2. Schmidt Hammer Rebound (R-Values)

Schmidt Hammer test was carried out by L-type hammer for each sample at five different points within the same sample. The five R-values for each sample are averaged (Table 5.1).

4.5. Physical Test

Physical tests including ultrasonic pulse velocity (UPV), specific gravity, porosity and water absorption were determine for the selected samples. Detail regarding these tests are presented in following sections.

4.5.1. Ultrasonic Pulse Velocity (UPV)

UPV measurement is a non-destructive geophysical method mostly used by engineers working in verity of fields such as mining, geotechnical, civil, underground engineering and minerals explorations as well. Due to the non-destructive nature, high precision and low cost, the UPV test is becoming more popular in rock mechanics. The test procedures is easy hence equally applied in laboratory as well as in field (Soroush et al., 2011; Ajalloeian et al., 2020). The key factor that influenced the UPV is density which intern influence by the rock nature and its texture. UPV can be used to evaluate the quality of homogeneity, to predict the strength and to find out the internal flaws and cracks within the rock sample. There are varieties of methods used for the determination of UPV. These methods include direct, indirect, and angle beam methods according to the placement of the transmitter and receiver (Hong et al., 2020). In the present study UPV for each sample was determined by direct method at three different points within the same sample using the following formula. The results obtained from each sample are averaged (Table 4.2)

$$\boldsymbol{UPV\ m/s = \frac{L}{T}}$$

Where,

L= Length of the sample (m)

T= Transit time (Sec)

Table 4.1. Results of tests including UCS and Schmidt hammer rebound values.

Variety	Sample	Area (m2)	Load (N)	UCS (Pa)	UCS (MPa)	R Values
Fine-grained Gabbronorite	F.GN-1	0.0026	299018.38	115007069.2	115.00	59
	F.GN-2	0.0026	266942.25	102670096.2	102.67	53
	F.GN-3	0.0026	289579.25	111376634.6	111.38	57
	F.GN-4	0.0026	270656.51	104098657.7	104.10	54
	F.GN-5	0.0026	280967.49	108064419.2	108.06	57
	F.GB-6	0.0026	273779.17	105299680.8	105.30	55
Medium-grained Gabbronorite	M.GN-1	0.0026	222344.38	85517069.23	85.52	51
	M.GN-2	0.0026	217953.98	83828453.85	83.83	49
	M.GN-3	0.0026	208924.09	80355419.23	80.35	48
	M.GN-4	0.0026	203141.4	78131307.69	78.13	45
	M.GN-5	0.0026	210454.28	80943953.85	80.94	48
	M.GN-6	0.0026	217509.16	83657369.23	83.66	50
Coarse-grained Quartz Diorite	C.QD-1	0.0026	176718.96	67968830.77	67.97	42
	C.QD-2	0.0026	188284.34	72417053.85	72.42	45
	C.QD-3	0.0026	180277.54	69337515.38	69.34	44
	C.QD-4	0.0026	185615.41	71390542.31	71.39	42
	C.QD-5	0.0026	169503.95	65193826.92	65.19	46
	C.QD-6	0.0026	175028.64	67318707.69	67.32	43
Coarse-grained Anorthosite	C.AN-1	0.0026	143530.78	55204146.15	55.20	38
	C.AN-2	0.0026	152680.77	58723373.08	58.72	43
	C.AN-3	0.0026	149051.02	57327315.38	57.33	42
	C.AN-4	0.0026	140234.65	53936403.85	53.94	41
	C.AN-5	0.0026	156399.49	60153650	60.15	37
	C.AN-6	0.0026	142147.38	54672069.23	54.67	39

4.5.2. Specific Gravity

Specific gravity is define as the ratio of the weight of a specimen having specific volume to the weight of water having same volume of that specimen is termed as the specific gravity of that specimen. Specific gravity of rocks mainly depends on the nature of mineral grains and its arrangement within the rock body. Increase in porosity results decrease in

Table 4.2. Results of ultrasonic pulse velocity test for the studied samples.

Variety	Sample	Length (Inch)	Length (m)	Time (µs)	Time (sec)	UPV (m/s)
Fine-grained Gabbronorite	F.GN-1	2	0.0508	10.7	0.0000107	4379.31
	F.GN-2	2	0.0508	11.6	0.0000116	4618.18
	F.GN-3	2	0.0508	11	0.000011	4456.14
	F.GN-4	2	0.0508	11.4	0.0000114	4576.57
	F.GN-5	2	0.0508	11.1	0.0000111	4495.57
	F.GN-6	2	0.0508	11.3	0.0000113	6597.40
Medium-grained Gabbronorite	M.GN-1	2	0.0508	7.7	0.0000077	6512.82
	M.GN-2	2	0.0508	7.8	0.0000078	6195.12
	M.GN-3	2	0.0508	8.2	0.0000082	6120.48
	M.GN-4	2	0.0508	8.3	0.0000083	6271.60
	M.GN-5	2	0.0508	8.1	0.0000081	6430.37
	M.GN-6	2	0.0508	7.9	0.0000079	3602.83
Coarse-grained Quartz Diorite	C.QD-1	2	0.0508	14.1	0.0000141	3681.15
	C.QD-2	2	0.0508	13.8	0.0000138	3628.57
	C.QD-3	2	0.0508	14	0.000014	3479.45
	C.QD-4	2	0.0508	14.6	0.0000146	3735.29
	C.QD-5	2	0.0508	13.6	0.0000136	3552.44
	C.QD-6	2	0.0508	14.3	0.0000143	2886.36
Coarse-grained Anorthosite	C.AN-1	2	0.0508	17.6	0.0000176	3155.27
	C.AN-2	2	0.0508	16.1	0.0000161	3005.91
	C.AN-3	2	0.0508	16.9	0.0000169	3078.78
	C.AN-4	2	0.0508	16.5	0.0000165	2659.68
	C.AN-5	2	0.0508	19.1	0.0000191	2822.22
	C.AN-6	2	0.0508	18	0.000018	4747.66

specific gravity and strength as well. The rocks are recommended to be use for heavy construction projects having specific gravity value greater than 2.55 (Yar et al., 2017). The specific gravity for each sample was determined by the following formula and the results are given (Table 4.3). The results of the studied samples suggest their favorability to be used in heavy engineering projects.

$$\boldsymbol{S.P = \frac{w4}{w4 - w2}}$$

Where,

S.P= Specific Gravity
W4= Oven dry weight
W2= Weight in water

4.5.3. Porosity

Porosity is defined as the ratio of pore spaces or voids volume to the bulk volume of the specimen i.e. it is a measure of the total void volume in a specimen. It is usually represented in percent. Porosity of the crystalline rock is the sum of the micro fractures, intergranular pores and pores and cavity formed as a result of chemical weathering (Tullborg and Larson, 2006). Grain size, grain shape and mineralogical composition especially the presence of clay minerals are the key factors that affect the porosity of the rock body. Determination of porosity is very important because the presence of porosity can negatively affect the rock strength (Bell, 1978; Jumikis, 1983). The porosity values (Table 4.7) for each sample was determined by the following formula.

$$\boldsymbol{P}(\%) = \boldsymbol{\frac{w1 - w4}{w1 - w2} * 100}$$

Where,
P= Porosity
W1= Weight in Air
W2= Weight in Water
W4= Oven Dry Weight

Table 4.3. Results of physical test including specific gravity, porosity and water absorption of the studied samples

Variety	Sample	W1	W2	W3	W4	S.P	P (%)	W.A (%)
Fine-grained Gabbronorite	F.GN-1	393.03	256.491	393.78	392.60	2.884	0.314	0.300
	F.GN-2	388.77	253.24	389.61	388.26	2.876	0.376	0.347
	F.GN-3	392.8	256.169	393.58	392.35	2.881	0.329	0.313
	F.GN-4	389.57	253.849	390.36	389.08	2.877	0.361	0.328
	F.GN-5	392.13	255.62	392.91	391.67	2.879	0.336	0.316
	F.GN-6	390.74	254.7	391.54	390.27	2.878	0.345	0.325
Medium-grained Gabbronorite	M.GN-1	399.23	262.911	399.7	398.87	2.933	0.264	0.208
	M.GN-2	397.74	260.657	398.22	397.37	2.906	0.269	0.213
	M.GN-3	395.17	258.919	395.66	394.79	2.905	0.278	0.220
	M.GN-4	393.38	257.633	393.88	392.99	2.903	0.287	0.226
	M.GN-5	395.96	259.438	396.45	395.58	2.905	0.278	0.219
	M.GN-6	397.01	260.141	397.5	396.64	2.906	0.270	0.216
Coarse-grained Quartz Diorite	C.QD-1	381.52	246.216	382.78	380.88	2.828	0.473	0.498
	C.QD-2	385.02	248.659	386.28	384.40	2.831	0.454	0.489
	C.QD-3	383.2	247.313	384.47	382.57	2.828	0.463	0.496
	C.QD-4	379.46	244.623	380.75	378.79	2.823	0.496	0.517
	C.QD-5	386.21	249.643	387.34	385.61	2.836	0.439	0.448
	C.QD-6	381.15	245.936	382.41	380.50	2.827	0.480	0.501
Coarse-grained Anorthosite	C.AN-1	377.12	239.9	378.2	376.29	2.758	0.604	0.512
	C.AN-2	379.18	241.434	380.2	378.42	2.762	0.551	0.457
	C.AN-3	377.17	240.069	378.19	376.38	2.761	0.576	0.480
	C.AN-4	379.1	241.367	380.04	378.32	2.762	0.566	0.454
	C.AN-5	375.88	238.918	377.07	375.00	2.755	0.642	0.552
	C.AN-6	376.63	239.429	377.78	375.77	2.756	0.626	0.534

W1= Weight in air, W2= Weight in water, W3= surface saturated dry weight, W4= Oven dry weight, S.P= Specific gravity, P= Porosity, W.A= Water absorption.

4.5.4. Water Absorption

Water absorption is defined as the amount of water that can be readily absorbed by a rock body. Greater the amount of water absorbed greater will be the loss in strength of the rocks. Hence Water absorption is a useful parameter in evaluating the durability of rocks to be used as dimension stone and engineering material (Shakoor and Bonelli, 1991). According to Blyth and De Freitas (1974) plutonic rocks having water absorption value less than 1% by weight are considered suitable used as dimension stone and engineering materials because of their high resistance to weathering. The water absorption for each sample was determined (Table 4.2) by the following formula. The obtained result of water absorption for each sample suggests their suitability to be used as dimension stone and engineering materials.

$$W.A\,(\%) = \frac{w3 - w4}{w4} * 100$$

Where

W.A = Water absorption
W3 = Saturated surface dry weight
W4 = Oven dry weight

4.6. Relationship among Petrographic, Physical and Strength Properties

The petrographic, physical and strength properties of the studied rock varieties are plotted against each other to explore the possible relationship among them. The relationship between modal mineralogical composition and physico-mechanical properties of the studied rock types was determined by plotting specific gravity, UPV, UCS and R-values against the ratio of felsic to mafic (felsic/mafic) minerals abundance in each variety. These parameter are found inversely related (Fig. 4.2).

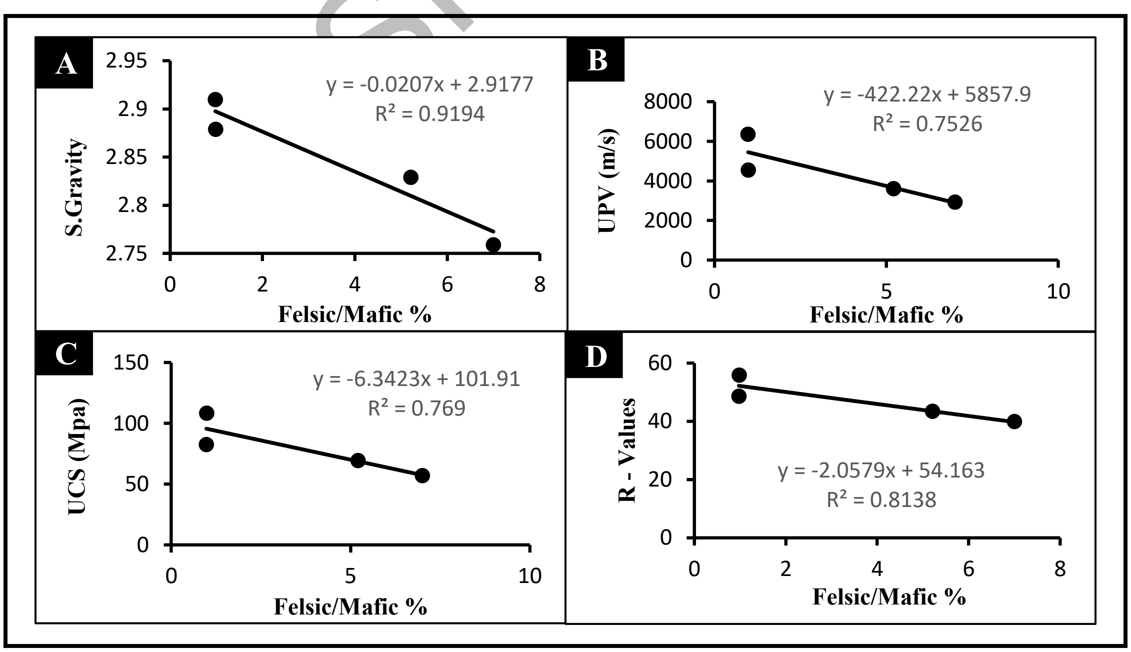

Fig.4.2. Correlation of felsic/mafic % with (A) Specific gravity (B) Ultrasonic pulse velocity(C): Unconfined compressive strength and (D) Schmidt hammer rebound values.

The presence of void spaces can also affect the strength of rocks. The physico-mechanical properties including UPV, UCS and R-values were plotted against the percent porosity within each sample (Fig.4.3, 4.4, 4.5)

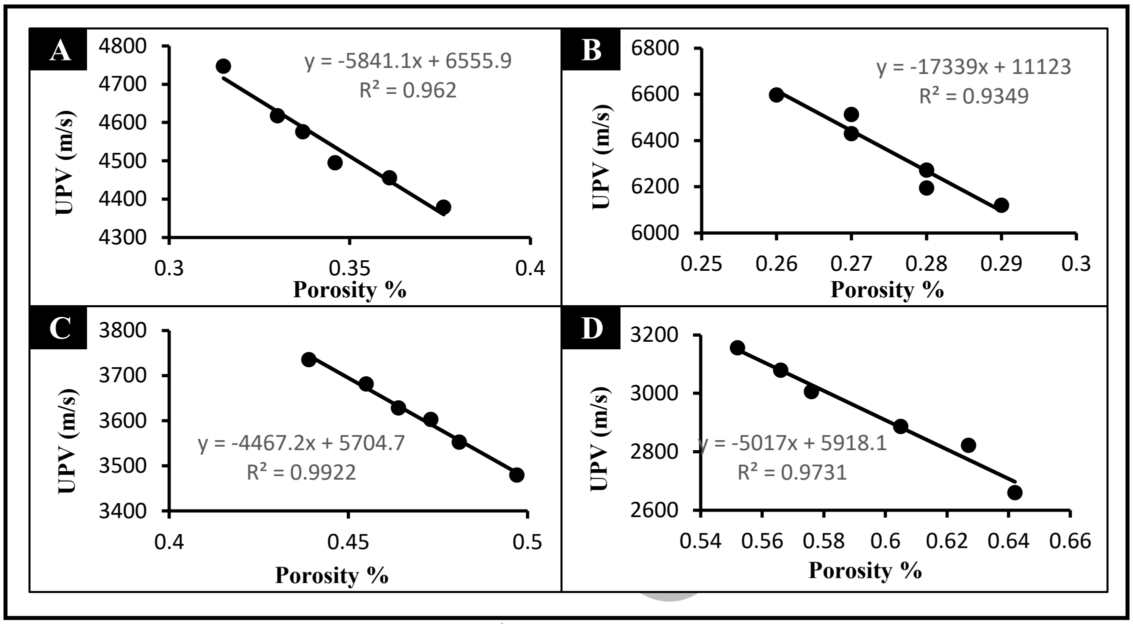

Fig.4.3. Correlation between Porosity % and ultrasonic pulse velocity (m/s) (A) Fine grained gabbronorites (B) Medium-grained gabbronorites (C) Coarse-grained quartz diorites (D) Coarse-grained anorthosites

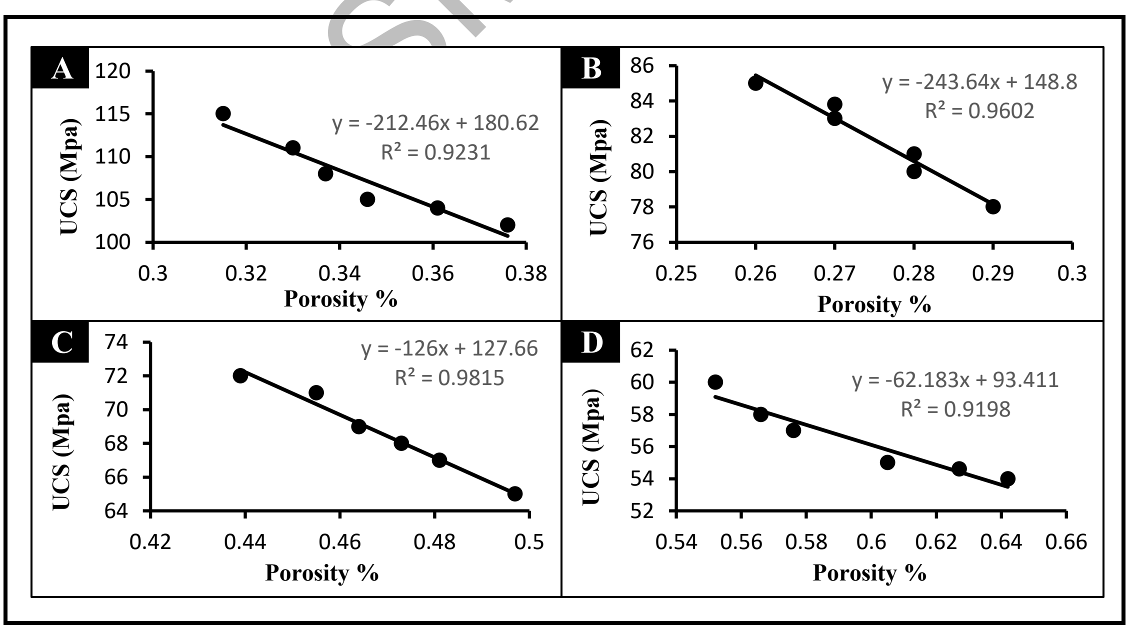

Fig.4.4. Correlation between porosity % and unconfined compressive strength (Mpa) (A) Fine grained gabbronorites (B) Medium-grained gabbronorites (C) Coarse-grained quartz diorites (D) Coarse-grained anorthosites

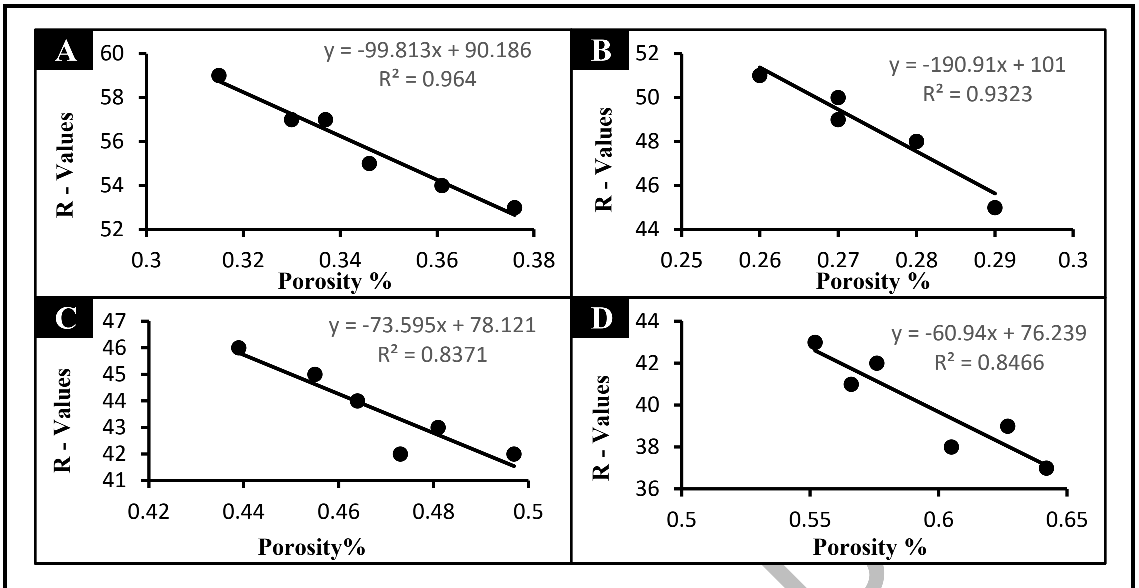

Fig.4.5 Correlation between porosity % and R-values (A) Fine grained gabbronorites (B) Medium-grained gabbronorites (C) Coarse-grained quartz diorites (D) Coarse-grained anorthosites.

The strength parameters (UCS & R-values) and UPV values of the studied rocks were plotted against each other (Fig. 4.6)

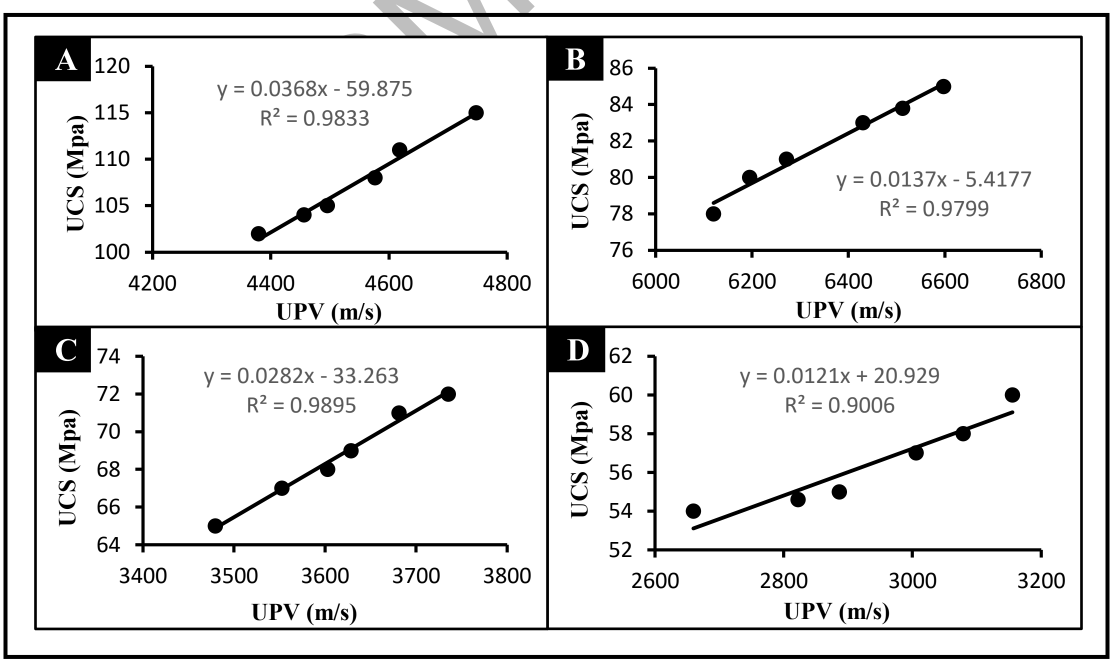

Fig.4.6. Correlation between ultrasonic pulse velocity and unconfined compressive strength (A) Fine grained gabbronorites (B) Medium-grained gabbronorites (C) Coarse-grained quartz diorites (D) Coarse-grained anorthosites

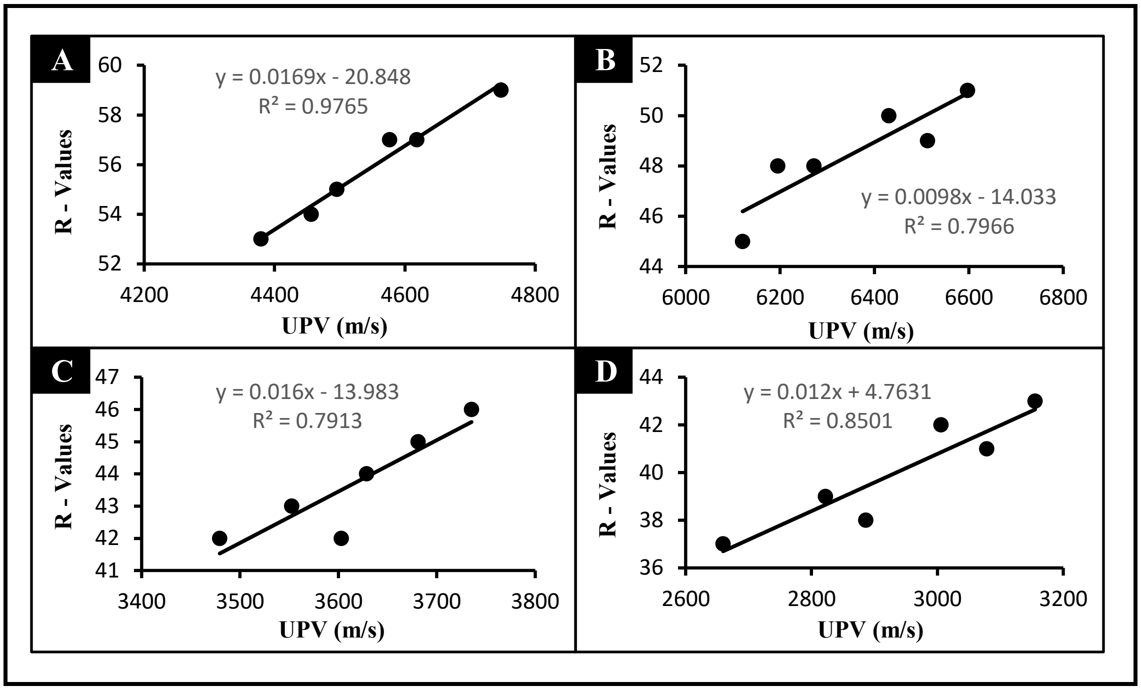

Fig. 4.7. Correlation between ultrasonic pulse velocity and Schmidt hammer rebound values (A) Fine grained gabbronorites (B) Medium-grained gabbronorites (C) Coarse-grained quartz diorites (D) Coarse-grained anorthosites.

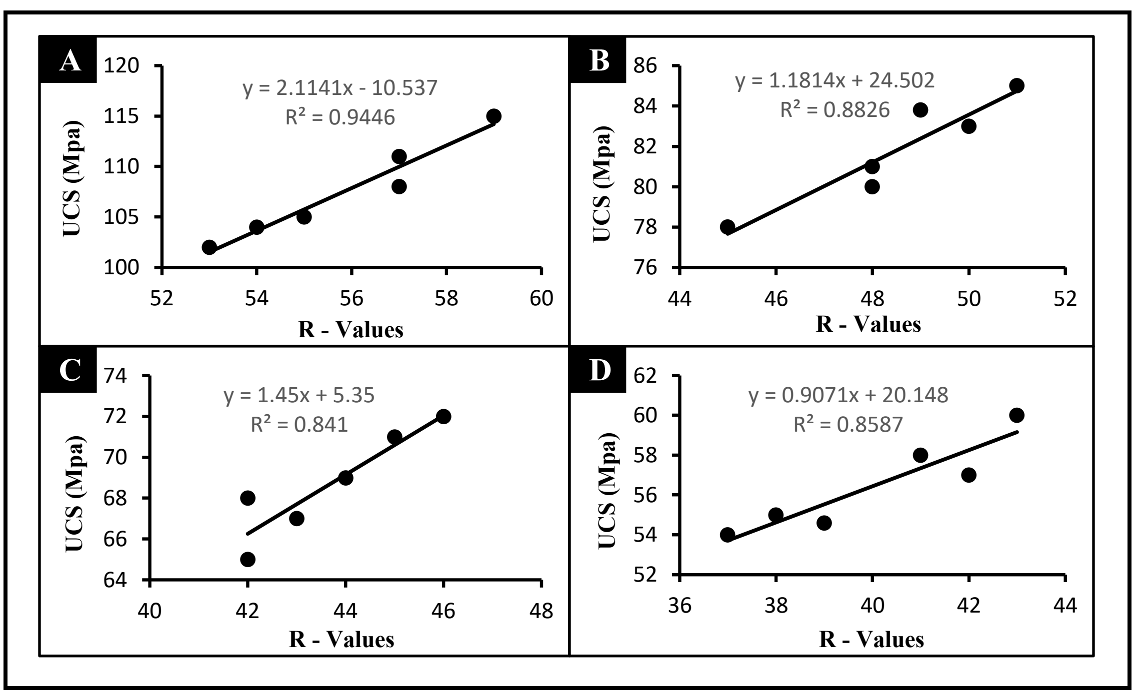

Fig. 4.8. Correlation between Schmidt hammer rebound and unconfined compressive strength values (A) Fine grained gabbronorites (B) Medium-grained gabbronorites (C) Coarse-grained quartz diorites (D) Coarse-grained anorthosites.

CHAPTER 05
DISCUSSIONS

The petrographic and physico-mechanical evaluation of the plutonic igneous rocks from the Salarzai area, Bajaur are the principle objectives of the current study. The obtained results from the present studies are utilized to identify different types of rocks and their strength potential to be used as dimension stone and construction supplies. Details regarding the various methods used and findings from these studies are provided in the previous chapters. The following sentences provide a brief discussion of these findings:

5.1. Weathering Grades

The weathering grades were given to the selected rock type's base on field and petrographic observations. Coarse-grained gabbronorites were recognized as fresh and given the weathering grade (WG-I). The fine-grained gabbronorite and coarse-grained anorthosite were observed slightly weathered and regarded as (WG-II), while the coarse-grained quartz diorite were recognized as highly weathered and given the weathering grade (WG-III).

5.2. Petrographic Description

Based on petrographic details the studied rocks are classified into gabbronorites, quartz diorites and anorthosites. Gabbronorites were observed holocrystalline, inequigranular, fine to medium grained and porphyritic at places that confirm the multiple episodes during their formation. The fine-grained variety of the present rock is observed as allotriomorphic. Most of the Anhedral plagioclase and pyroxene with few biotite grains are present as phenocrysts while some plagioclase and pyroxene with minor to accessory amount of other minerals including biotite, quartz, epidote, garnet, sphene and opaque mineral grains constitute the groundmass. The medium grained-variety of the present rock mass is investigated as hypidiomorphic. The phenocrysts comprised of subhedral to anhedral plagioclase and anhedral pyroxene and biotite while some plagioclase and pyroxene with minor to accessory amount of other minerals including biotite, quartz, epidote, garnet, sphene and opaque mineral grains constitute the groundmass. The plagioclase appeared cloudy exhibiting polysynthetic twinning and normal zoning. Some of the grains observed having myrmekite and poikilitic texture.

The plagioclase of the fine-grained variety showed alteration that were largely sericitization and saussuritization that indicates low grade metamorphism. In the medium-grained variety, fresh, strained and tabular plagioclase was observed. Pyroxene, including both clinopyroxene and orthopyroxene observed as anhedral, having garnet and opaque minerals inclusion and chloritized at places. Clinopyroxene is dominant over the orthopyroxene in these rocks hence classified as gabbronorites. The biotite and quartz were observed anhedral. Opaque minerals and garnet inclusion with chloritization seen in biotite while the Fresh and strained quartz grains, exhibiting features of recrystallization observed.

The diorites were regarded as quartz diorites that are inequigranular, allotriomorphic, coarse grained and porphyritic at places. Anhedral plagioclase and amphibole are present as phenocrysts while some plagioclase, amphibole and quartz with minor to accessory amount of other minerals including biotite, epidote, chlorite and opaque mineral grains constitute the groundmass. The porphyritic nature of these rocks confirm multiple episodes during their formation. The most abundant mineral plagioclase appeared cloudy exhibiting polysynthetic twinning that is hardly visible at the margins of grains because of intense sericitization and saussuritization. Fresh and strained quartz grains, exhibiting features of recrystallization with biotite alteration to chlorite were seen. Sericitization and saussuritization in plagioclase and chloritization in biotite confirm the associated metamorphism in these rocks.

Stocks of anorthosites were found intruded within the gabbronorites that were holocrystalline, inequigranular, hypidiomorphic and coarse-grained. Subhedral to anhedral plagioclase constitute the coarse mass while some plagioclase and other minerals including amphibole, biotite, pyroxene, olivine and epidote makes the groundmass. The plagioclase of this variety appeared cloudy exhibiting polysynthetic twinning, multiple twinning, Carlsbad twinning and oscillatory zoning. These mineral grains were fractured with no visible alteration. The anhedral amphiboles are largely hornblend and biotite were seen chloritized at places. The coarse nature of these rocks confirms their formation within the crust.

5.3 Physical and Strength properties

As part of the current study, some of the physical and strength properties of different rock types were analyzed to verify their potential as building materials. The physical properties including ultrasonic pulse velocity (UPV), specific gravity, porosity and water absorption as well as the strength properties including unconfined compressive strength (UCS) and Schmidt hammer rebound (R-values) were studied in reasonable detail in the previous chapters. According Blyth and de Freitas (1974) rocks with specific gravity ≥ 2.55 and water absorption less than 1 % and according Anon (1979) rocks having porosity less than 5 % are considered to be suitable for heavy building works. In the present studies all the rocks type studied having ultrasonic pulse velocity, specific gravity, porosity and water absorption values are considered suitable to be used as building materials.

The strength properties of the studied rocks types were determined by using UCS and R-values. With respect to USC the fine-grained gabbronorites were regarded as very strong and all the rest rocks type were regarded as strong (Table 5.1). The R-values within each sample were observed in good accordance with the UCS values.

Here, an effort is made to identify the possible relationships that may exist among the petrographic features, physical properties and strength of these rock types. The strength parameters of the investigated rock samples were plotted against their respective physical parameters and petrographic features. After careful comparison and detailed inspection lead to the suggestion that the following petrographic features are believed to be significant in determining and controlling the strength of the studied rock types:

- ❖ Modal mineralogical composition
- ❖ Grain size, shape and degree of variation
- ❖ Volume of pore spaces

The relationship between modal mineralogical composition and physico-mechanical properties of the studied rock types were determined by plotting specific gravity, UPV, UCS and R-values against the ratio of felsic to mafic (felsic/mafic) minerals abundance in each variety. These parameters were found inversely related. Studies in the past showed a positive correlation between quartz to feldspar ration and negative correlation for quartz to plagioclase (Tugrul and Zarif, 1999; Sajid et al., 2016). But there is no such relationship found in the present investigations.

It has been found that fine-grained rocks are stronger than their coarse-grained counterpart (Tugrul and Zarif, 1999; Bill, 2007; Lindqvist et al., 2007; Sajid et al., 2009). Similar relationships found in the present investigation as fined-grained gabbronorites were found stronger than the course grain gabbronorites, even though the fine-grained variety is weathered. Hence it was found that the grain-sized significantly affect the rock strength.

The coarse-grained gabbronorites, anorthosites and diorites were observed to have nearly equal grain sizes. Among these coarse-grained varieties, the anorthosites have the lowest strength values. It is due to the fact that the grains in anorthosites are identical and equidimensional having partially developed faces.

The presence of void spaces can also affect the strength of rocks. An increase in void volume results in increased absorption that may cause the alteration of present minerals and reduce its strength (Sajid et al., 2016). A little change in pore volume can have a considerable mechanical impact (ISRM, 1981). The UPV, UCS and R-values were plotted against the porosity values. The resulting plots showed that the plotted parameters are inversely related.

The strength parameters (UCS & R-values) and UPV values of the studied rock samples are plotted against each other. Strong positive correlation are found among these parameters within each variety.

Table 5.1. Grades of unconfined compressive strength.

Geological Society (Anon,1977)		*IAEG (Anon, 1979)		**ISRM (Anon, 1981)	
Term	**UCS (MPa)**	**Term**	**UCS (MPa)**	**Term**	**UCS (MPa)**
Very weak	<1.25				
Weak	1.25-5.00	Weak	<15	Very low	<6
Moderately weak	5.00-12.50	Moderately strong	15-50	Low	6-10
Moderately strong	12.50-50	Strong	50-120	Moderate	20-60
Strong	50-100	Very strong	120-230	High	60-200
Very strong	100-200	Extremely strong	Over 230	Very high	Over 200
Extremely strong	Over 200				

*International Association of Engineering Geologists **International Society for Rock Mechanics

CONCLUSIONS

The details of field and petrographic observation, physical and strength properties of the selected plutonic igneous rocks from northwestern, Pakistan in previous chapters. Based on the presented results and discussions the following conclusion are derived.

- The weathering grades were given to the selected rock type's base on field and petrographic observations. Coarse-grained gabbronorites were recognized as fresh and given the weathering grade (W.G-I). The fine-grained gabbronorite and coarse-grained anorthosite were observed slightly weathered and regarded as (W.G-II), while the coarse-grained quartz diorite were recognized as highly weathered and given the weathering grade (W.G-III).
- Based on detail petrographic observation the plutonic igneous rocks of Salarzai area are group into three rocks types.
    1) Gabbronorites: These rocks were observed fine to medium grained, holocrystalline, inequigranular and porphyritic. The fine-grained variety was observed allotriomorphic while the coarse-grained was hypidiomorphic.
    2) Diorites: These diorites are regarded as quartz diorites. Petrographic studies revealed the coarse-grained, inequigranular and allotriomorphic nature.
    3) Anorthosites: This variety was investigated coarse-grained, holocrystalline, idiomorphic and porphyritic at places.
- Physical properties including specific gravity, porosity, water absorption and ultrasonic pulse velocity and strength properties including unconfined compressive strength and Schmidt hammer rebound were determine for each sample. The obtained results of the above mention parameters suggested their use as dimension stone and construction supplies.
- After careful comparison and detailed inspection led to the conclusion that the petrographic features including modal minerology, grain size, grain shape, degree of variation in grains and volume of pore spaces appeared to have collectively contributed in determining and controlling the strength of the studied rock types.

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