Procedures For The Investigation Of Dimension Stone Resources: The Suitability Of Jibal Aja And Jabal Salma Plutons, Near Hail, Saudi Arabia

A Thesis Submitted For The Degree Of Doctor Of Philosophy In

THE DEPARTMENT OF GEOLOGY AND APPLIED GEOLOGY

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BY

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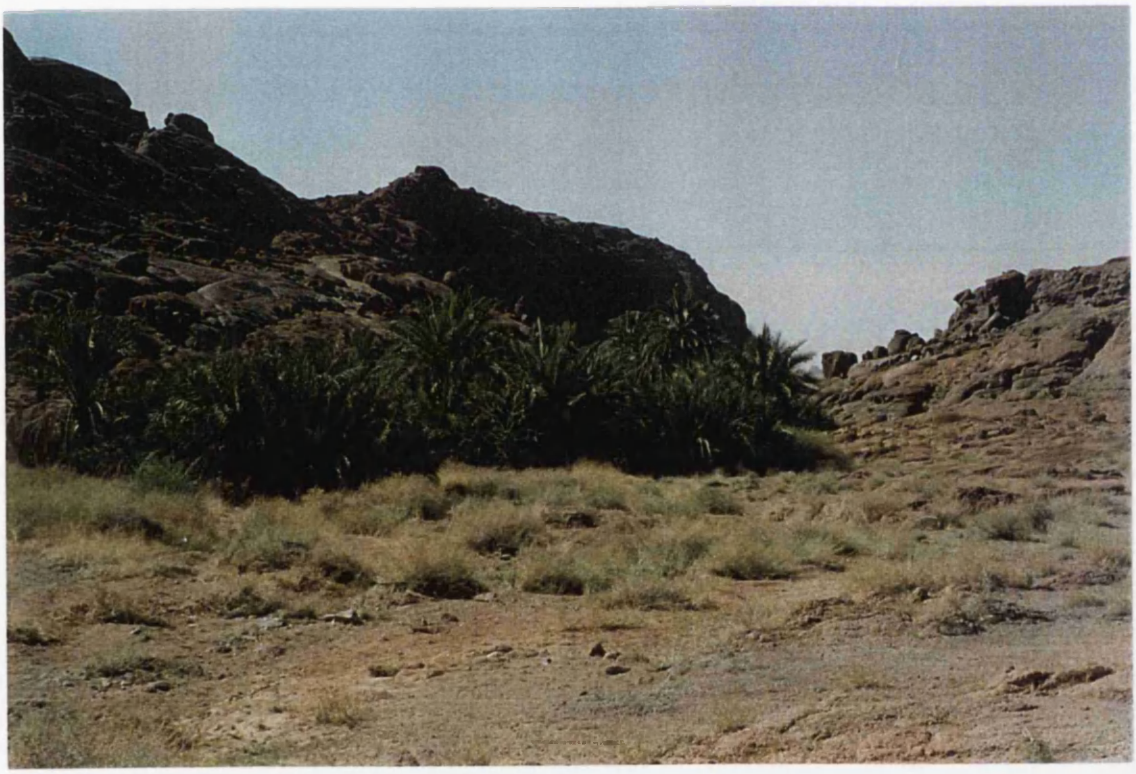

This thesis is dedicated

to my wife, to my mother, and to the father.

CONTENTS

Thesis Declaration

The material presented in this thesis is the result of research carried out between Jan. 1992 and June 1997 in the Department of Geology and Applied Geology, University of Glasgow, under the supervision of Dr. Gary Couples.

This thesis is based on my own independent research and any published material used by me has been given full acknowledgement in the text.

Abdullah R. Ghouth-Ali

June 1997

I certify that Abdullah R. Ghouth-Ali has undertaken the bulk of the work involved in this thesis. Specially, background geology, data collection, field study, mapping, laboratory investigation and analysis. I have assisted with advice and help of general, technical, conceptual nature, as would be expected in the course of normal Ph.D. supervision. Abdullah R. Ghouth-Ali has written the thesis himself, and he is responsible for its content.

G.D. Couples

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Abstract

This thesis describes a new set of procedures for evaluating dimension stone potential. It focuses on the granitic rocks of the Arabian Shield. In particular, two sites near Hail have been assessed in detail. Site 1 is in the Jibal Aja batholith, and site 2 is in the Jabal Salma pluton. Conventional investigation methods -- desk study, field and laboratory measurement -- have been applied, along with an analysis of satellite imagery. A key element in the new set of procedures is the use of Landsat (Thematic Mapper) data in the form of false-colour, CRC images. Many aspects of the sites which are related to the suitability of the materials for dimension stone can be recognized via the Landsat images; these include rock type, state of alteration and staining, rock colour, rock-unit contact conditions, and distribution of weathering. A new method of predicting in-situ block sizes has been developed which takes its input from conventional scanline data. From all of the geotechnical information collected, and the engineering geological maps which have been constructed, summary maps are prepared showing the distribution of potential dimension stone resources in the two test sites. Large potential reserves ($>10^8$ tonnes) of high-quality stone are present in the study areas. In general, there is a good correlation between the alteration and staining conditions of the granitic rocks and their geotechnical and geometrical properties. Application of the procedures developed in this thesis will enable new ground to be economically investigated -- by excluding poor areas early in the analysis, and focusing efforts on promising areas which will, nevertheless, require detailed laboratory and field investigations.

CHAPTER I

INTRODUCTION

I.1 *GENERAL*

Dimension stone is natural rock that has been selected, trimmed, or cut to a specified size or shape, with or without mechanically dressed surfaces (Laurent 1994). Dimension stone as a building material has been used for a greater period than has concrete. World-wide, dimension stone use has experienced rapid growth; consumption has risen from approximately 20×10^6 tonnes in 1981, to 25×10^6 tonnes in 1988, and there has been a further increase in production to over 36×10^6 tonnes in Napoli and Ragone (1996) (**Table I.1**). The increased demand is partly attributed to advances in quarrying and processing technologies, and partly to the superior durability of natural stone when compared to glass, steel, or concrete. Recent market trends in construction materials, combined with good resource availability, suggest opportunities for a much expanded building and ornamental stone industry, and a consequent increase in demand for dimension stone resources.

I.2 *REQUIREMENT FOR DIMENSION STONE RESOURCES IN THE KINGDOM OF SAUDI ARABIA*

The fastest-growing market in dimension stone products is for interior and exterior wall facing and flooring (Meyer & Dean 1988). This demand arises from both local and international consumer markets, and reflects the need for extraction of the dimension stone raw material. Plutonic rocks, marble and limestone are all used extensively for these applications.

Table I.1: International dimension stone production (tonnes) after (Napoli and Ragone 1996)

Countries	1981	1988	1994
Austria	25,000	40,000	21,000
Belgium	2,070,000	467,000	350,000
Brazil	850,000	970,000	1,600,000
China	na	na	4,750,000
Comecon Cont.	1,000,000	2,600,000	1,765,000
EC	13,534,850	14,214,000	15,990,000
Finland	200,000	256,500	550,000
France	734,000	920,000	1,140,000
Germany	na	137,000	250,000
Greece	900,000	1,700,000	2,100,000
India	400,000	700,000	3,000,000
Italy	6,700,000	7,480,000	7,500,000
Mexico	165,000	263,000	900,000
Norway	177,000	100,000	180,000
Portugal	400,850	640,000	1,100,000
South Africa	330,000	700,000	640,000
South Korea	na	687,000	900,000
Spain	2,730,000	2,155,000	3,100,000
Sweden	91,500	142,500	300,000
Turkey	150,000	485,000	750,000
UK	na	715,000	450,000
USA	875,000	1,062,000	1,100,000
Others	2,000,000	2,800,000	3,900,000
Total	**19,798,350**	**25,020,000**	**36,346,000**

In Saudi Arabia, dimension stone is desired for the construction of dams, buildings, retaining walls, sea walls, and as facing stone (Baghdadi 1986). To address these needs, the government established an extensive program of exploration for sources of dimension stone in 1965. As a result of successful exploration and development, the use of dimension stone in Saudi Arabia has greatly expanded, and local production is growing (Laurent 1994). Current sources of the dimension stone now used in Saudi Arabia are largely from abroad, but minor amounts are obtained from many locations in the country. Due to the high cost of materials from the current sources, particularly those from abroad, and due to increasing demand, there is, therefore, a need to investigate whether suitable large-volume resources exist in the country.

This project is intended to establish an appropriate methodology for exploring and evaluating possible dimension stone sites in the Saudi Arabian shield. These sites should provide attractive and good quality dimension stone. In the past, the exploration for dimension stone normally has been based on the experience of quarry operators. But the increasing demand for dimension stone means that a method needs to be found to increase the efficiency of exploration, particularly in light of the large areas involved.

I.3 *AIMS OF STUDY*

Geotechnical investigation of the rock is necessary in all disciplines of geomechanical works. This investigation includes evaluation of the intact-rock and rock-mass properties. For example, the rock-mass parameters are of significance for determining whether potential quarry sites are suitable for dimension stone production, while the intact-rock properties have important effects on the durability of the rock. It has been reported in many studies (for example, Jefferson 1993), that non-durability and stone failure is the result of misunderstanding the behaviour of geological materials, and the effects of the presence of adverse structural and mineralogical components.

This study is intended to establish an efficient exploration strategy for finding dimension stone resources in the Arabian Shield in Saudi Arabia with due regard to availability, supply capacity and quality standards. Two representative sites of plutonic rocks have been chosen: granitic rocks from Jibal Aja (Sihi pluton; site1), and Jabal Salma pluton (site 2). The study provides an opportunity to test the utility of Landsat remote sensing data as a preliminary site investigation tool by predicting rock properties, focused on the geotechnical aspects for dimension stone purposes. These predictions were correlated with data from field and laboratory investigations. The Landsat data have not yet been used to assess the geotechnical aspects of dimension stone resources generally in the Arabian Shield and particularly in the present study area.

The study has concentrated on determining the rock-mass characteristics, and intact-rock properties for dimension stone purposes. Therefore, the objectives of this project are as follows:

① To make maps showing the discontinuity spacing, fracture density and the distribution of weathering.

② To evaluate the physical and mechanical properties of the rocks, and to correlate these with the Landsat and field assessments.

③ To evaluate the ability of Landsat Thematic Mapper (TM) data to distinguish:

- Rock type.
- Weathering, alteration and massive vs. fractured nature of rocks.
- Rock boundaries.

④ To establish a method for exploring for dimension stone resources of granite in the large exposures of the Arabian Shield.

⑤ To draw conclusions as to benefits of Landsat as preliminary investigation predictive tool for locating and identifying potential dimension stone resource sites.

I.4 *METHODS OF INVESTIGATION*

Because programmes of dimension stone exploration in Saudi Arabia have been carried out for only a short while, there are few documented sites which could be used as test cases for evaluating exploration methods. Therefore, this study has had to both explore and evaluate simultaneously.

The two field sites have been examined individually; site1 has been extensively studied, and this site is then treated as a "lesson" case. Exploration predictions are possible based on study of site1, and the correlation of these results with Landsat images. These predictions are subsequently tested in the field at site2, and via Landsat interpretation. Although this division into "lesson" and "test" sites was made during the study, the bulk of this thesis will describe data from both sites together.

I.4.1 *Landsat data*

The great technology of high resolution satellite imagery of the Landsat system has established a new era in geological mapping. The present Landsat images have a resolution of 20m, but new developments in satellite imagery systems will enhance the resolution up to 1 to 4m by the year 2000 (Fritz 1996). This advance will produce huge and successive information for geological mapping and finding new resources, more efficiently and precisely.

The Landsat data (TM) of sites1&2 were analysed using digital image processing and this approach produces false-colour images. Predictions were made of site2 from the geological and geotechnical investigations made at site1. These predictions from Landsat data include: rock type, fracturing, weathering and alterations. These aspects are related to the geotechnical parameters such as rock geometry and its strength characteristics. Then the Landsat data were combined and correlated with the data from field study and laboratory investigations, to see the efficiency of the Landsat imagery to detect and locate suitable and specified rock areas for dimension stone potential.

I.4.2 *Air photographs*

The air photographs at scale of 1:15000 were used as a base map in field work and also as an aid to the Landsat images. The air photos were particularly useful in mapping the lineaments of the study area.

I.4.3 *Field work*

Field investigations were carried out to measure of structural features and to collect samples. More than three months were spent for the field study phase. Most of the work was concentrated in measuring discontinuity characteristics at number of locations. These include:

Field measurements		
	Characteristics	
Lithology	**Discontinuity**	**Weathering**
○ colour	□ type	● type
○ texture	□ orientation	● form
○ exposure description	□ spacing	● state
○ type	□ block size and shape	● distribution
○ boundary type		
○ hardness Schmidt hammer		

Inspection and correlation was undertaken between the Landsat image features and the geological aspects in the field. Collection of samples for petrographic study and laboratory investigation was also achieved.

Logistical parameters were also noted such as accessibility, electricity, water supply and settlement areas. Photographs were also taken at several locations to document the rock features of the study area.

As a separate study, the Mull Granite of Scotland was also investigated so as to provide a comparison with the granites from Saudi Arabia. The Mull Granite has been successfully used for dimension stone and the samples collected from there and subjected to testing permit the results for Saudi Arabian samples to be assessed against a proven supply of similar nature.

I.4.4 *Laboratory*

Thin and some polished sections were prepared from collected rock samples and studied petrographically under the microscope, including samples of Mull Granite. X-Ray Diffraction (XRD) analyses were also conducted on the samples from sites1&2 to investigate any alteration minerals present such as clays.

The physical and mechanical properties of the rocks were determined by laboratory testing. Density, porosity and water absorption data were obtained for samples representative of the rock units of sites1&2, as well as those samples from the Mull Granite. Cores were taken from the rock samples and subjected to mechanical testing. The uniaxial compressive strengths were determined, along with ultrasonic velocities. Soundness tests were also conducted on all samples.

I.4.5 *Data Analysis*

Lineament maps were constructed from air photographs at scale of 1:15000 for the selected detail study area (sites1&2). The lineament densities were determined manually and displayed as contour map. The rose diagram of the lineaments were also analysed and correlated with the field measurements.

The structural data have been analysed using stereographic projection methods in order to determine the main sets of the discontinuities in sites 1&2, and then correlated with lineaments of the study area.

The author has established his own method to determine and calculate the block size from the scan line measurements. This method is used to predict the block size distribution for sites 1&2 and for Mull Granite.

I.5 *THESIS ORGANISATION*

The thesis comprises nine Chapters. Chapter I serves as an introduction and addresses the requirement for local dimension stone resources. It also describes the aim of the research and the methods of investigation applied. Chapter II presents the background of rock quality requirements for dimension stone. Chapter III deals with the nature of the study area, and the general geological setting of the Arabian Shield. It also describes the local geology of the study area. Chapter IV is concerned with the lineament and discontinuity analyses, field investigation about rock masses, weathering classifications and the distribution of rock properties in the study area. Chapter V includes the engineering physical and mechanical properties of the rocks, such as density, absorption, porosity and the uniaxial compressive strength and the ultrasonic velocity. The soundness and the aesthetic features of the rocks are also included. Chapter VI is composed of the evaluation of these sites for potential dimension stone, the related geotechnical maps, and the extraction considerations according to the rock characteristics such as spacing and block size. Chapter VII discusses the satellite imagery techniques applied in the study area, including Landsat imagery system description, the Landsat image preparation method, and the geological aspects that were predicted from the Landsat images, such as rock units, rock boundaries, weathering and alteration, and fracturing. Chapter VIII is a general discussion of the thesis results from Chapter III to Chapter VII, describing the approach to exploring, identifying and assessing the dimension stone potential in the study area. The general conclusions are presented in Chapter IX.

CHAPTER II

REQUIRED CHARACTERISTICS FOR DIMENSION STONE

II.1 *QUALITIES AND TESTING OF DIMENSION STONE*

Natural dimension stone is one of the most extensively used materials for building purposes. It has been accessible to man for millennia; in ancient civilisations, i. e. Egyptians, Romans, Greeks, etc., stone was widely used for several purposes, including building and sculpture, and a high degree of technical skill and workmanship was gained in stone processing and transport. The use of stone ranges from walling, flooring and roofing, to statuary and coffins (Kukal *et al.* 1989).

In recent times the high cost of stone quarrying, processing and transportation has decreased the demand for dimension stone, and construction has shifted towards the use of relatively cheaper materials such as bricks. Despite this fact prestigious buildings continue to be built using natural stone. Economic constraints, and the desired appearance of stone-faced buildings, have led to the use of cladding sheets for High Street and government buildings (Jefferson 1993).

Research on conservation and restoration of building stone (Winkler 1973; Bortz *et al.* 1993; Attewell & Taylor 1990) has shown the need for a thorough investigation of the properties of dimension stone, primarily those related to its durability and in-service behaviour. Only a few ASTM standard tests are designed for building stone quality assessment: notably, durability and strength. These tests include water absorption, density, abrasion resistance, and compressive and flexural strength. In Britain, no BSI standard is yet established for dimension stone, but the Building Research Establishment uses some durability tests, such as saturation coefficient and porosity, the acid immersion test, and petrographic investigation.

The modern use of stone dimension frequently involves cladding sheets that are larger and thinner than ever before, sometimes with special types of finish for aesthetic purposes (Sims 1991). Nowadays, due to good transportation and supply facilities, a great range of rock types is available for use as dimension stone from sources world wide. For many of these materials, there are often no records of performance in certain environmental conditions. These new circumstances impose new requirements, such that the important characteristics for dimension stone have to be assessed and documented in advance. This change of approach should ensure that the user can be confident about the quality and durability of the material when selecting it for a project. In order to move towards this new arrangement, material quality assessment should begin at the exploration stage. During this stage all important stone characteristics, the quality variation, and potential reserves should be evaluated.

II.1.1 *Exploration*

Before any site investigation practice the engineering geologist carries out a desk study or inventory aimed at minimising the exploration target area. As is the case for any other mineral resource, the desk study phase should include a search through geological resources, aerial photographs, remote sensing images and archaeological information (Jefferson 1993). The initial estimate of the deposit's dimensions allows a calculation of the material reserves which is important for the future development of the quarry. In term of dimension stone, the rock mass properties are obviously of great interest to the engineering geologist as they determine the feasibility of production of large blocks (Priest 1993). The maximum size or volume of block that can be obtained from a quarry, as determined by the structural geology, can be important information when sourcing dimension stone. For example, the maximum discontinuity spacing will determine the yield and the maximum course height when sawing the rock blocks into slabs. In general, the primary potentiality for dimension stone is that sites can provide large blocks, which are as large as possible and yet can be handled. Normally, the suitable block size which can be processed effectively is 10 tonnes in weight, or 3 to 4 cubic meters in volume. These sizes can be produced naturally when the rock mass has well developed widely-spaced joints (Smith 1996).

II.1.2 *Dimension Stone Quality*

The quality of a dimension stone is mainly judged on its durability, strength, and appearance. West (1996) mentioned that physical properties such as density and compressive strength of the stone are most commonly used in assessing the quality of dimension stone, particularly at the exploration stage. Therefore the testing programme usually includes tests which assess these attributes. Other relevant properties such as mineralogy and petrography, to which quality and durability indices are closely related, should be considered in the material choice process.

In service, dimension stone is required to withstand the effect of weathering, water, acids and the imposed load. The effect of these factors can to some extent be reproduced in the laboratory and hence an estimate can be obtained of the likely in-service behaviour of the material. The effect of weathering has been dealt with using the accelerated weathering experiment (Cawsey & Mellon 1983). The effect of water has been a subject of intensive research and its effect is well known (Turk & Dearman 1986a; Johnson *et al.* 1990; Keller 1978; Attewell & Taylor 1990). The stone's resistance to load, or its mechanical properties, are directly related to secondary mineral content and distribution, volume of cracks and cavities, and their distribution and orientation. In practice the above factors do not work independently but in concert, and one influences the other.

❶ Aesthetic aspects

Although not amenable to laboratory testing, the geologist can predict the variation of colour and texture which may be encountered in a given deposit. The judgement of "beauty" cannot (as yet) be quantified.

Uniformity of colour through a large stone is highly desirable. For example, a granite may become widely known for a certain colour, and this factor may determine its choice by users over a long period of years. The uniformity in texture is another requirement. Not only the grain size, but also the distribution of minerals, must be uniform (Bates 1969).

❷ Durability

Durability is the ability of a material to endure loads and to maintain its essential and distinctive characteristics of strength, resistance to decay, and appearance in relation to a specific manner, purpose and environment of use (ASTM C615 1990). The resistance of the stone to the destructive effects of the environment such as weathering, freeze-thaw, wetting-drying, differential thermal expansion, and cracking due to imposed load, depends largely on the inherent geological characteristics of the stone (porosity, fabric, proportion and distribution of soft minerals) at the time of its use. For these reasons the durability assessment programme should include a number of tests which simulate the effect of these agents. It has been demonstrated that accelerated weathering experiments, such as wetting-drying and heating-cooling, significantly reduce rock properties such as Young's modulus and the uniaxial compressive strength. Bortz *et al.* (1993), using exposed and non exposed (protected) panels of marble from a building in New York, have shown that the strength of the exposed material has decreased considerably compared to its non-exposed counterparts.

For durability assessment, the Building Research Establishment (Ross and Butlin 1989) uses a number of tests such as the crystallisation test, saturation coefficient and porosity. Petrographic examination of the material is often carried out. The ASTM durability tests include index properties such as bulk specific gravity and water absorption. Modulus of rupture and abrasion resistance are also used to assess the likely behaviour of the material under stress and rubbing.

❸ Petrographic examination

In the context of dimension stone resource assessment, a petrographical examination is intended to determine the rock components which may have an adverse effect on durability, strength and appearance. Macroscopically the rock should be free from vents, fissures, cracks, cavities and all features which may impair the durability. Under the microscope (thin section), other durability related components can be observed and even quantified. These are secondary minerals (their nature, volume and distribution), cracks, cavities and texture. These data are of great importance in dimension stone selection since they directly influence the behaviour of the stone in service and can be used as a guide to where the stone is going to be best used. For instance, a rock containing swelling clay or clay-like secondary minerals, if used, should be always above the water table. Cracks in rocks are a potential site for water freezing or gypsum growth; therefore, if its strength is acceptable, the rock can be used safely in a place free from these two phenomena. If present, iron ore can be oxidised and cause discoloration and damage to the aesthetic properties of the building, and may have a strength effect.

❹ Crystallisation test

The crystallisation test is widely used by the BRE (Ross and Butlin 1989) mainly for sandstone and limestone, but other rock types can also be tested. It is used to simulate the damaging effect of freezing water and other mineral growth within the stone porespaces and cracks. When water freezes within the stone porespaces it exerts a force which pushes apart the two sides of the crack or cavity, tending to disaggregate the material. The disaggregation occurs when the crystallisation force exceeds the local tensile strength of the stone. For this test small cubes of the stone are soaked in a solution of sodium sulphate for a period of time then rinsed and oven dried. For the test to be completed this cycle is repeated 15 times. The weight loss after the 15th cycle expressed as a percentage of the original weight, is used to assess the material durability (Fookes *et al.* 1988).

❺ Strength test

The importance of building stone strength comes from the fact that in service, these materials are subject to different types of stress. They are, in general, subject to foot stress, wind action and static load coupled with other weakening agents such as water. Thus in order to withstand the rigours of the above stresses without failure, the building stone must have adequate strength.

The ASTM C615 (1990) includes two strength tests especially for granite building stone. These are the compressive strength and flexural strength tests. Other tests such as point load strength, Schmidt rebound and ultrasonic velocity tests can also be used, especially since they are cheap and easily carried out during the site investigation phase. The most common strength test is uniaxial compressive strength.

❻ Uniaxial Compressive Strength (*UCS*)

The uniaxial compressive strength is the most used test in rock mechanics. It has the advantage of being simple and requires minimal sophistication in equipment. Despite its widespread use, it is only considered as an index property for strength assessment and classification. As defined by Krynine & Judd (1957), the uniaxial compressive strength is the load required to break a loaded sample that is unconfined at the sides.

The uniaxial compressive strength has a very poor reproducibility. Jaeger & Cook (1984) explained this fact by the presence of Griffith cracks in any rock material. Griffith cracks of different lengths and orientation start to propagate at different magnitudes of stress, causing a scatter in the strength values and hence poor reproducibility and durability. Although several factors affect the UCS values, it is a very good index test for material strength assessment and classification. Among the non geological factors are rate of loading, specimen length to diameter ratio, and specimen preparation techniques especially the flatness of the specimen ends. The geological factors which are directly related to this study are material density, porosity, water content, grain size and above all, the state of weathering of the material.

CHAPTER III

GEOLOGICAL SETTING

III.1 *GEOGRAPHIC SETTING*

III.1.1 *Location*

The study area focuses on two granitic plutons located close to Hail city, within the northern part of the Arabian Shield (**Figs III.1** and **2**) (Sihi pluton (site1) is in the southern part of Jibal Aja; Jabal Salma is the other pluton (site 2).

Site1 covers an area of about 200 km^2 as does Site 2. The selection of these two sites was based on the excellent exposure of the massive younger granites (Ekren *et al.* 1986), a clear structural pattern, and the availability of previous geological studies. The study areas are easily reached, being close to the main city Hail and other towns. Both plutons are easily accessible for the most part, via asphalt roads and/or desert tracks.

III.1.2 *GEOGRAPHY*

Sites 1 & 2 lie within an area underlain by resistant granites which form rugged mountainous areas reaching up to 1300m in elevation. These high regions are surrounded by high desert plains at 850 to 1000m elevation above sea level. The climate is desertic; annual rainfall reaches only a few tens of centimetres and occurs mostly between November and March. The winter temperatures are less than 10°C and overnight temperatures sometimes drop to about 0°C. In summer (April to October) the temperatures exceed 40°C.

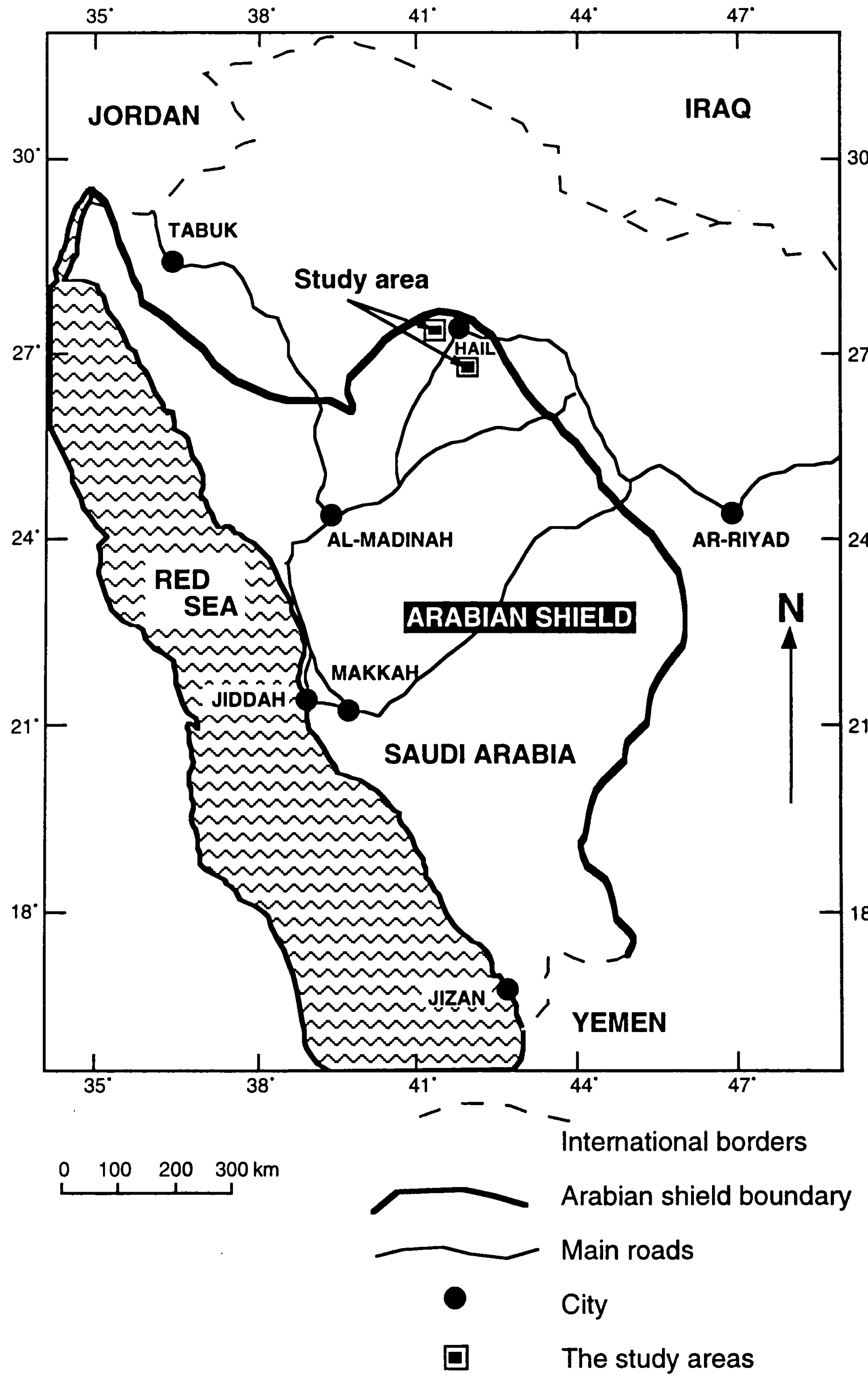


Fig. III.1: Location map of the study area

Natural vegetation in the region is restricted to perennial shrubs and seasonal grasses. Agricultural activity is increasing in the northern part of the Hail area. The drainage pattern consists of dry valleys which run in all directions, but which are related to the rugged mountains such as created by the Jibal Aja batholith and Jabal Salma pluton.

Sihi pluton appears to be nearly circular but slightly elongated in a N-S direction. The pluton is dissected by a number of dry valleys (locally called wadis) making it appear as a small group of hills. These hills are individually elongated in an E-W direction and have the typical domal and blocky forms of granitic bodies.

The Salma pluton is a mountainous area of 1300m in elevation with some of the constituting hills of about 150–200m above the local ground. The pluton is dissected by wadis of E-W direction. Some of the wadis are accessible while others are not due to accumulation of rock blocks within them. Most of the wadis are structurally controlled with very steep and high flanks.

In general wadis in sites1&2 contain sand and alluvial deposits. The deposits usually grades into rough, fragmented material close to the highly fractured and weathered parts of the granite outcrops.

III.1.3 *TRANSPORT*

Hail city lies at the foot of the Jibal Aja massif, at an elevation of about 980m above sea level. It is one of the largest cities in north central Saudi Arabia and is an expanding administrative centre. Four major highways radiate from the city. One connects it to Al-Madina (Southwest) and passes near-by site1, the second connects Hail to Qasim and Ar-Riyad (capital city), passing by site 2. The two other roads connect Hail with Jubbah to the north, and Baqa to the Northeast (**Fig. III.2**).

III.2 *GEOLOGICAL SETTING OF ARABIAN SHIELD*

The Hail area represents the northern part of the Arabian Shield. The Shield contains rocks ranging in age from Pre-Cambrian to Tertiary; these consist of basement complexes. At the margin, of the shield, the basement is overlain by sedimentary and volcanic rocks of younger ages (Ekren *et al.* 1986).

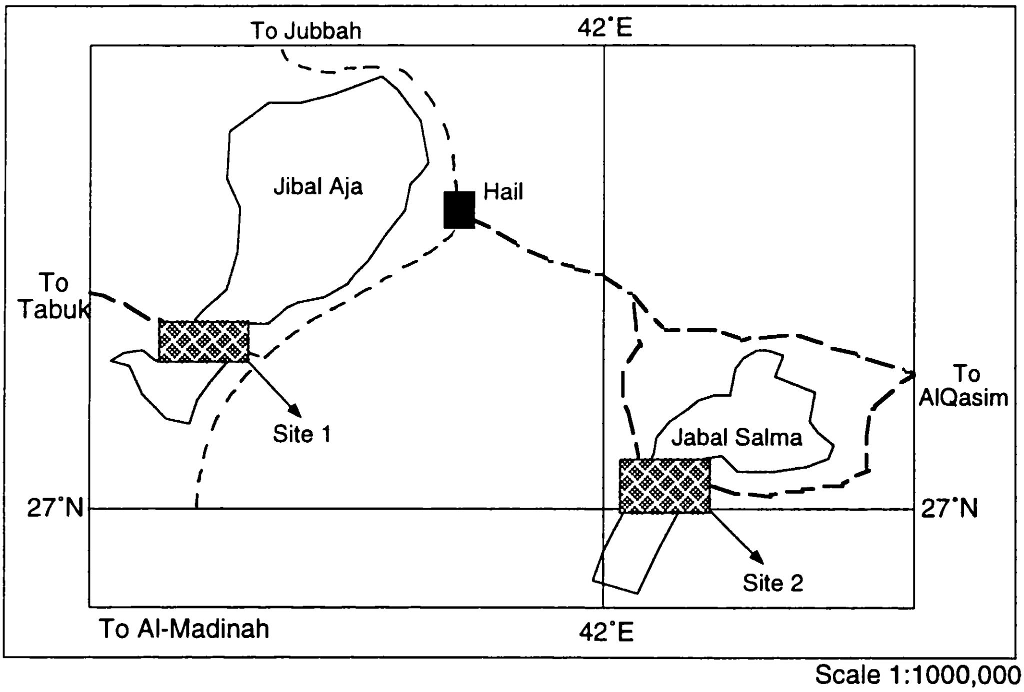


Fig. III.2: Transportation net map

III.2.1 *Lithologies*

The Arabian Shield is located in the western and the southern portion of the Arabian peninsula. Approximately 700 000 km^2 of the shield area lies within the Kingdom of Saudi Arabia.

This Precambrian basement comprises volcano-sedimentary successions and associated plutonic complexes that have been deformed and metamorphosed, and which have been intruded by numerous granitic plutons. The majority of the rocks are younger than 900 Ma. The volcano-sedimentary successions have ages in the range of 900-680 Ma, and are calcalkaline to tholeiitic in composition, and probably formed in oceanic island arcs (Greenwood *et al.* 1976). Those successions of 680-550 Ma are calcalkaline to alkaline and grade into clastic formations and ignimbrites; they are of mature island arc or continental origin (Roobol *et al.* 1983). Linear zones of ultramafic and associated basic complexes represent tectonically emplaced oceanic crust (Bakor *et* *al.* 1976; Claesson *et al.* 1984). These latter rocks represent sutures formed as a result of microplate accretion between 680 and 630Ma (Stoeser & Camp 1985). Granitic and granodioritic plutons are emplaced at relatively high structural levels during a culminating phase of intrusive activity between 610Ma and 570Ma. These late plutons are the focus of this study.

The studies undertaken on the Arabian Shield by several researchers (Brown & Jackson 1960; Schmidt *et al.* 1973; Greenwood *et al.* 1976) concluded that this region consists of metamorphic and plutonic complexes. The metamorphic rocks were mainly volcano-sedimentary successions and associated plutonic intrusions. The oldest rocks in the shield are metamorphic belts which are more than 1000 Ma old. The plutonic rocks, which intrude the metamorphic rocks, constitute a major part (55%) of the shield and vary in composition from ultrabasic (peridotite, dunite) through basic (gabbro), intermediate (diorite and tonalite) to acidic (granite). Their age is between 900-560 Ma. These plutonic rocks were classified into three units; these units are related to tectonic movements: syn-kinematic plutonic intrusions, late-kinematic intrusions, and post kinematic intrusions.

The syn-kinematic intrusions have ages between 1000 -900 Ma and stand as batholiths containing xenoliths of the older metamorphic belts. The composition of these intrusions varies from calcalkaline to trondhjemitic, and these intrusives are more deformed than the other two groups which are younger. The late-kinematic intrusions are in general slightly deformed massive bodies. They are mainly acidic rocks with ages between 700 to 620 Ma. They develop both gneissic and porphyritic textures.

The post-tectonic intrusions occupy limited areas in the Arabian Shield. These rocks represent circular or elliptical intrusions into the older rocks, and they are not affected by metamorphism. However these rocks are subjected to fracturing by rejuvenation of the old Najd fault systems and Hijaz tectonic cycle (Al-Shanti 1993). The post-tectonic intrusion rocks consist mostly of acidic plutons ranging in age from 620 and 560 Ma. These post-tectonic plutons form the focus of this study.

III.2.2 *Structural history*

The structural history of the Arabian Shield is complex. The rocks are affected by at least two major tectonic deformations. These tectonic episodes have been named by different authors who worked on the Arabian Shield. For example, the Hijaz cycle, which represent the oldest tectonic movement in the Arabian Shield, and which has major trends of N-S to NNE-SSW, affects the metamorphic belts whose age is >1000Ma (Greenwood *et al.* 1980). The other tectonic movement is along the NW-SE Najd fault system (Brown 1972), and affects all rocks of the Arabian Shield. This direction was rejuvenated by the Tertiary movements concordant with the opening of the Red Sea.

The Arabian Shield was affected by later regional tectonic movements which lead to the formation of the Gulf of Aden, Red Sea, Gulf of Aqaba, Dead Sea and the African Rifts. The trends of these events are well recorded in the Shield (Powers *et al.* 1966) by linear structures (probably faults).

III.3 *CHOICE OF THE STUDY AREA*

The study area, sites 1& 2, have been selected for the following reasons:-

1- The Arabian Shield contains large amounts of granitic rocks (**Fig. III.3**), and the study areas are representative samples of this geology.
2- The Aja complex (Sihi pluton) and Salma pluton contain un-metamorphosed, post-tectonic granite, and are well jointed.
3- Sihi pluton (site1) and Salma pluton (site 2) are highly accessible through wadis which are mainly structurally controlled.
4- The Sihi pluton and Salma pluton have various granite rock units in terms of grain size and colour.
5- The Sihi pluton and Jabal Salma pluton have various conditions of rock mass, ranging from massive to fractured, and from sound to weathered. These conditions provide good test sites for exploring and investigating about the suitability of these granite as dimension stone resources.

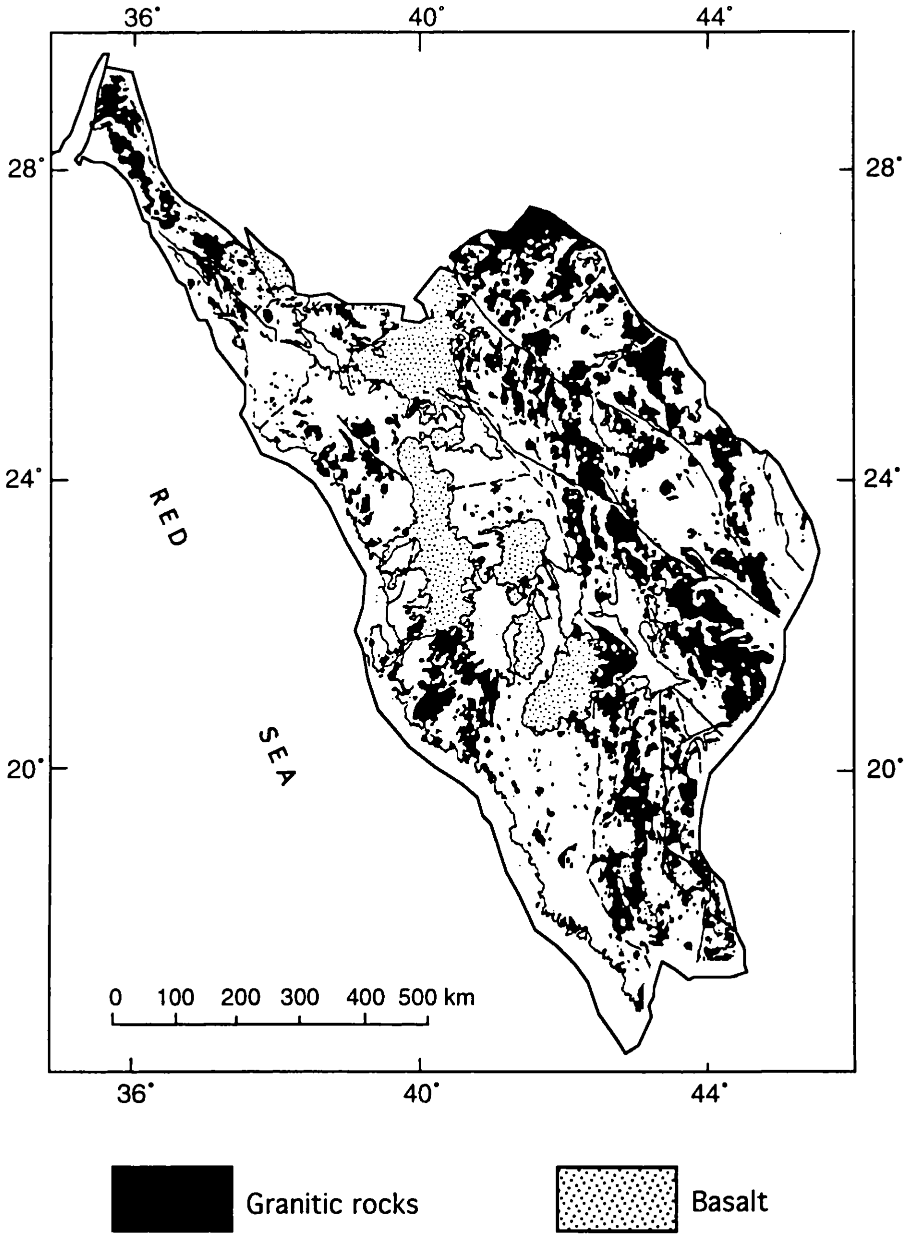


Fig. III.3: Map of the Arabian shield showing igneous rocks (after Stoeser 1985)

6- The availability of data such as aerial photographs and Landsat images.

7- The Arabian Shield is one of the well exposed basement rock areas in the world (**Fig. III.4**), and it provides a good opportunity for Landsat data to be tested and evaluated as a tool in resource exploration strategy.

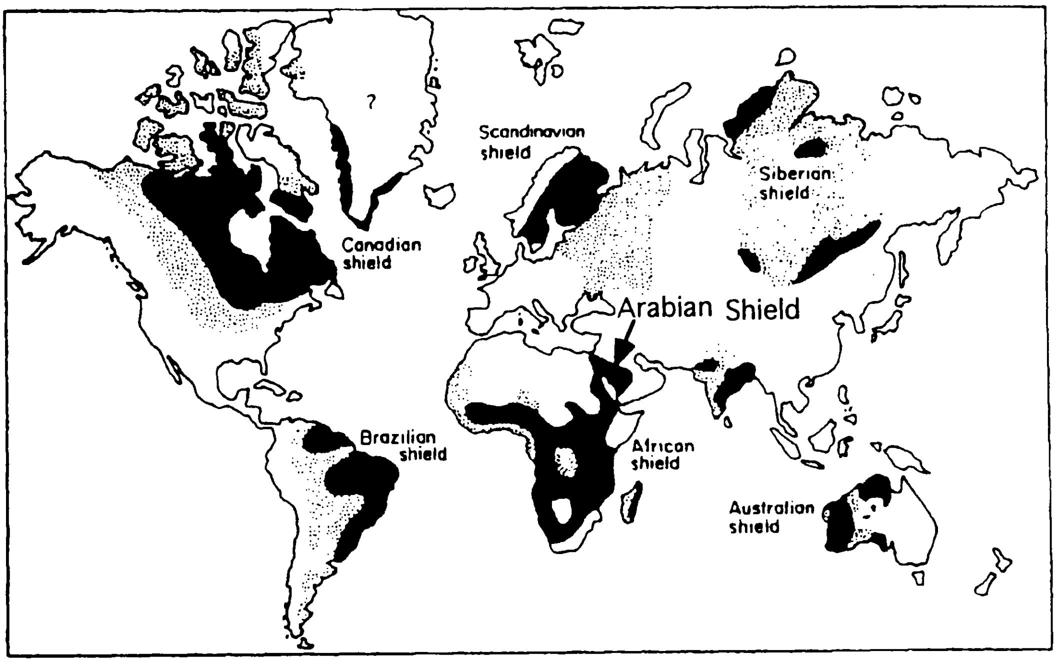


Fig. III.4: Shield regions of the world (from Blyth & de Freitas 1984)

III.4 *GEOLOGY OF THE STUDY AREA*

The Hail area is at the northern limit of exposure of the Proterozoic Arabian Shield and spans the boundary between the shield craton and the Palaeozoic succession of the Northern Arabian basin. The Proterozoic rocks were formed in response to activity along the Nabita mobile belt, a major north-trending suture zone between converging crustal plates. The Hail area is underlain by late Proterozoic volcanic, sedimentary and intrusive rocks, and a Cambrian to early Silurian succession of essentially sedimentary rocks. The Palaeozoic rocks, mostly sedimentary, in the Hail area are gently warped about the north trending, north plunging Hail arch (Powers *et al.* 1966). Burek (1969) suggests that the Hail arch is formed as the result of folding related to the opening of the Red Sea (N-S) and Gulf of Aden rifts (E-W). However, the Hail arch did not exist as a recognisable structure in the Hail area during early Palaeozoic time (Ekren *et al.* 1986). The Proterozoic rocks are part of the Arabian -Nubian Shield, a region of complex geology formed during a major episode of late Proterozoic crustal accretion, and constituted a stable basement on which the Phanerozoic sedimentary rocks were deposited. The Proterozoic rocks in the area consist of relatively young granite intrusions that include monzogranite and more evolved alkali-feldspar granites of the Abanat suite; the latter named rocks occur chiefly as a large batholith, where they form topographically conspicuous mountains such as the Jibal Aja massif (Ekren *et al.* 1986).

III.4.1 *Aja Complex*

The Aja complex, first named by Stoeser and Elliott (1980), is exposed in the Jibal Aja massif, also known as Aja batholith, which is a large composite body about 35 km by 85 km in extention. The southern part of the massif, the Marma Granite, is renamed into the Sihi pluton in the present study.

The Aja complex is the youngest member of the Abanat suite in the Hail area with an age of 566 to 570 Ma (Stuckless *et al.* 1984). The complex intrudes other units of the Abanat suite, and probably encloses them as roof pendant, and is largely free of dykes (Ekren *et al.* 1986). The intrusive rocks of the Aja batholith are divisible into a peripheral zone and a core zone. The peripheral zone consists mainly of peralkalic granites. The core zone comprises mostly granophyre. The zoning in the complex probably represents zoning in the magma chamber as it existed just prior to crystallisation because most contacts within the pluton are gradational or vague (Ekren *et al.* 1986).

The Sihi pluton as described by Ekren *et al.* (1986) is very similar to Jibal Aja batholith. It is fairly homogeneous and tends to form very massive, smooth, rounded, dark pinkish to red weathering faces, and consists of an alkali feldspar granite. Sihi pluton is located in a very accessible area between two asphaltic roads connecting to Hail city. However, the northern and central part of Aja batholith is rugged and less-accessible, it has very high and sharp peaks, and it would be difficult to construct a quarry in this area. In addition to its closeness to the city, the southern part of Aja batholith (which is Sihi pluton) is selected as the best test site in the present study.

III.4.2 *Jabal Salma*

The Jabal Salma granitic pluton represents the last major pulse of magmatism in the Hail area. This event resulted in the emplacement of large oval plutons of highly evolved post-orogenic granite dated about 580Ma (Aldrich 1978 and Stuckless *et al.* 1984). These granites constitute prominent highlands with rugged relief and deep valleys (Vaslet *et al.* 1986). The Jabal Salma pluton is very similar to the Jibal Aja batholith and it is located also in a very accessible area connected to Hail city.

III.4.3 *Description of sites* 1&2

In sites 1 and 2, granite occurs as five distinctive types, grey, pink and red granite, microgranite and granophyre and together with a separate type of mixed between the above lithologies. Another type of granite called orbicular granite occurs in site 1, but in very small amount.

The granites are surrounded by country rocks of mainly volcanic type with no exposed contact and intruded by aplitic, basaltic or doleritic dykes, but these are volumetrically not important.

III.4.4 *Structure*

Both sites 1 and 2 are at high elevations, bounded by straight lineaments of N-S direction and surrounded by lower-elevation areas consisting mostly of volcanic terrain. The Sihi and Salma plutons have been dissected by at least three lineaments of different trends (ESE-WNW, NE-SW and N-S) which are very obvious on the aerial photographs. In addition to these trends a weak trend appears on the aerial photographs and it is NW-SE. The valleys (wadis) in both plutons are mostly controlled by major faults or lineaments, particularly those aligned NE-SW.

From field study, it is clear that both sites are affected by a later stage of extension faults which have steep dips. These faults could be associated with the opening of the Red Sea and they form rugged, very steep scarps. Sometimes these scarps make some localities inaccessible either by walking or by driving a vehicle.

The other important structures are joints which are associated with all the trends recognised from the aerial photographs. The coarse granites are fractured and dissected by three sets of joints which are widely spaced, while the fine granites have more than three sets of closely spaced joints. Some of these joints are filled with silica in the form of opal; other minerals, such as fluorite and pyrite , are also observed. All the joints echo the major structural trends in the area. The dips of joints are mostly vertical in the range of 80°-90°. In addition there is a sub horizontal joint set **(Plate III.1)**.

III.4.5 *Dykes*

The Sihi and Salma plutons are intruded by dykes of varying trends and different composition. The area is also affected by younger volcanic rocks, especially the volcanic cones **(Plate III.2)**. These dykes are not numerous, and pose little difficulty for dimension stone.

III.4.6 *Wadi deposits*

Most of the wadis (dry valleys, locally called wadis) in both sites are structurally controlled and run in several directions. The most accessible wadis have NE-SW and NW-SE directions. These wadis are filled with sandy and gravely materials including angular to subangular pebbles, cobbles, and boulders, in addition to some large rock blocks (**Plate III.3**). Most of these materials originate from hills in the area, although some of the material has travelled very long distances from its source. Cobbles and the coarser sizes were derived mostly from the highly fractured and weathered exposures.

III.5 *PETROGRAPHICAL DESCRIPTION*

The study area (site 1 & 2) is composed mostly of granitic rocks of similar composition. The granites occur in different colours, primarily due to alteration and staining discoloration. Based on their colour and textures, the granites of the study area have been named into five rock units. These rock units are grey, pink, and red granite, and, microgranite and granophyre; the latter two rock units occur only in site 2.

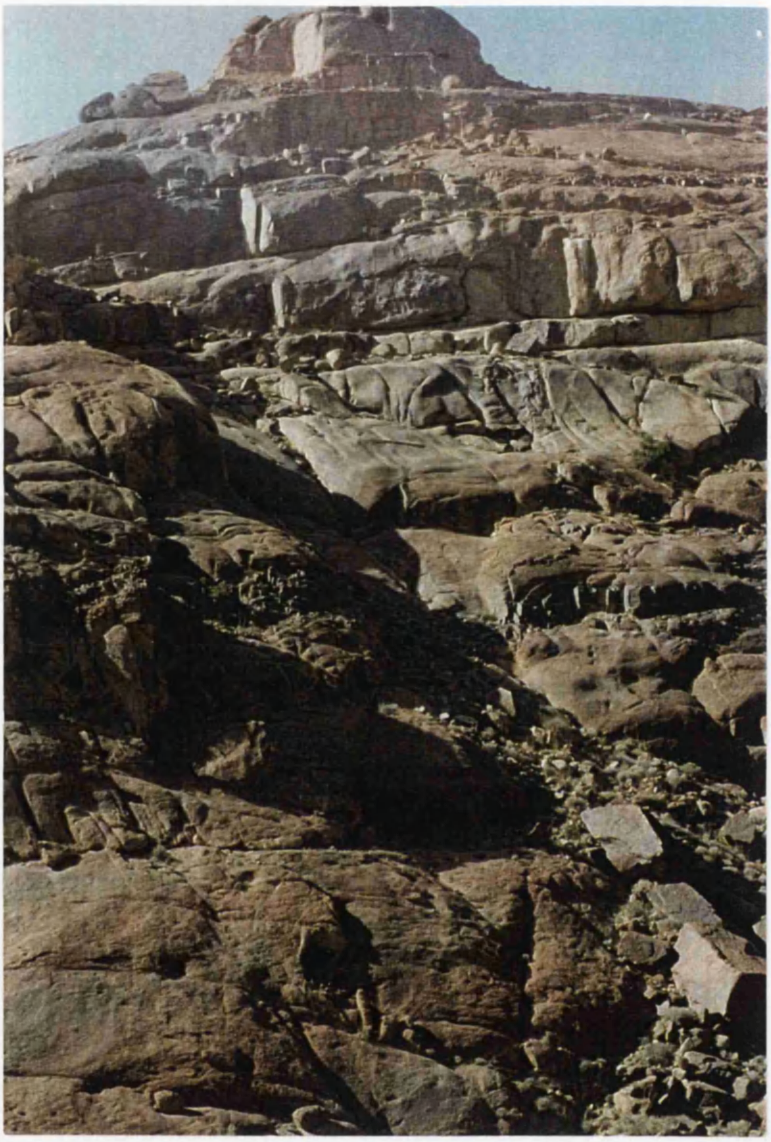


Plate III.1: The main Joint sets in the study area (site1)

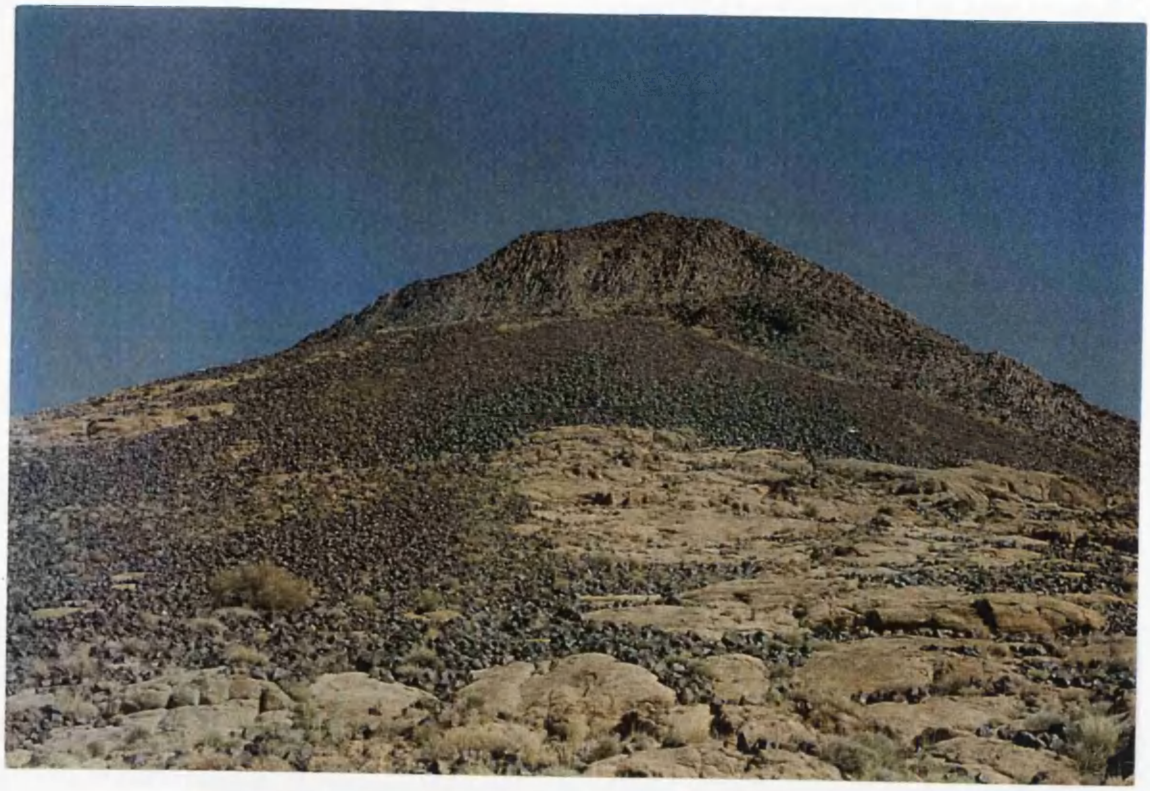


Plate III.2: The volcanic cones in the study area (site 1)

Plate III.3: Wadi materials in the study area

III.5.1 Sihi *pluton*

The granite in Sihi pluton (site 1) is texturally fairly homogeneous and tends to form very massive, smooth rounded hills. The rocks show in various colours, from grey to pink and red granites. Samples of the rock types from Sihi pluton have been collected and described. A geological map is constructed to show the distribution of the rock units in site1 (**Fig. III.5**). From this map the most dominant rocks are the pink and red granites, while the grey granite occurrs in limited areas.

(i) Grey granite

The rock occurs as small hills of maximum height of about 50m. It is well exposed in rounded massive bodies. The rock is coarse grained, and there is no evidence of a sharp contact with the pink granite. The grey granite occupies 10% of the map area

Petrographically the rock is phaneritic, coarse to medium crystalline. Inequigranular, graphic texture is the dominant appearance of the rock. Potassium Feldspar comprises 65% of the rock and occurs as large crystals (more than 4mm in size) of subhedral shape. Two sets of cleavage are recognised in the feldspars. Generally the feldspars are stained, either slightly, to considerably, in some specimens **(Plate III.4),** particularly close to cracks, cleavage and voids. Some feldspars are partially altered to sericite, typically along the cracks and cleavages. The grain boundaries are mostly clear and tight, but some are stained, sutured and filled by aggregated quartz crystals, sericite and opaque minerals. The alkali feldspar contains both orthoclase and microcline in perthitic composition. There are some tiny crystals of euhedral plagioclase which may have been enclosed by the potassium feldspar.

Quartz comprises 25% of the rock. The quartz crystals are mostly subhedral, and are about 5 mm and larger. They occur in graphic texture as a result of the simultaneous crystallisation of alkali-feldspar. The quartz crystals have some microcracks like hair. The quartz is clear and less stained (than feldspars) except along some cracks and some grain boundaries. The quartz also occurs as filling along the boundaries of the feldspar crystals and cracks.

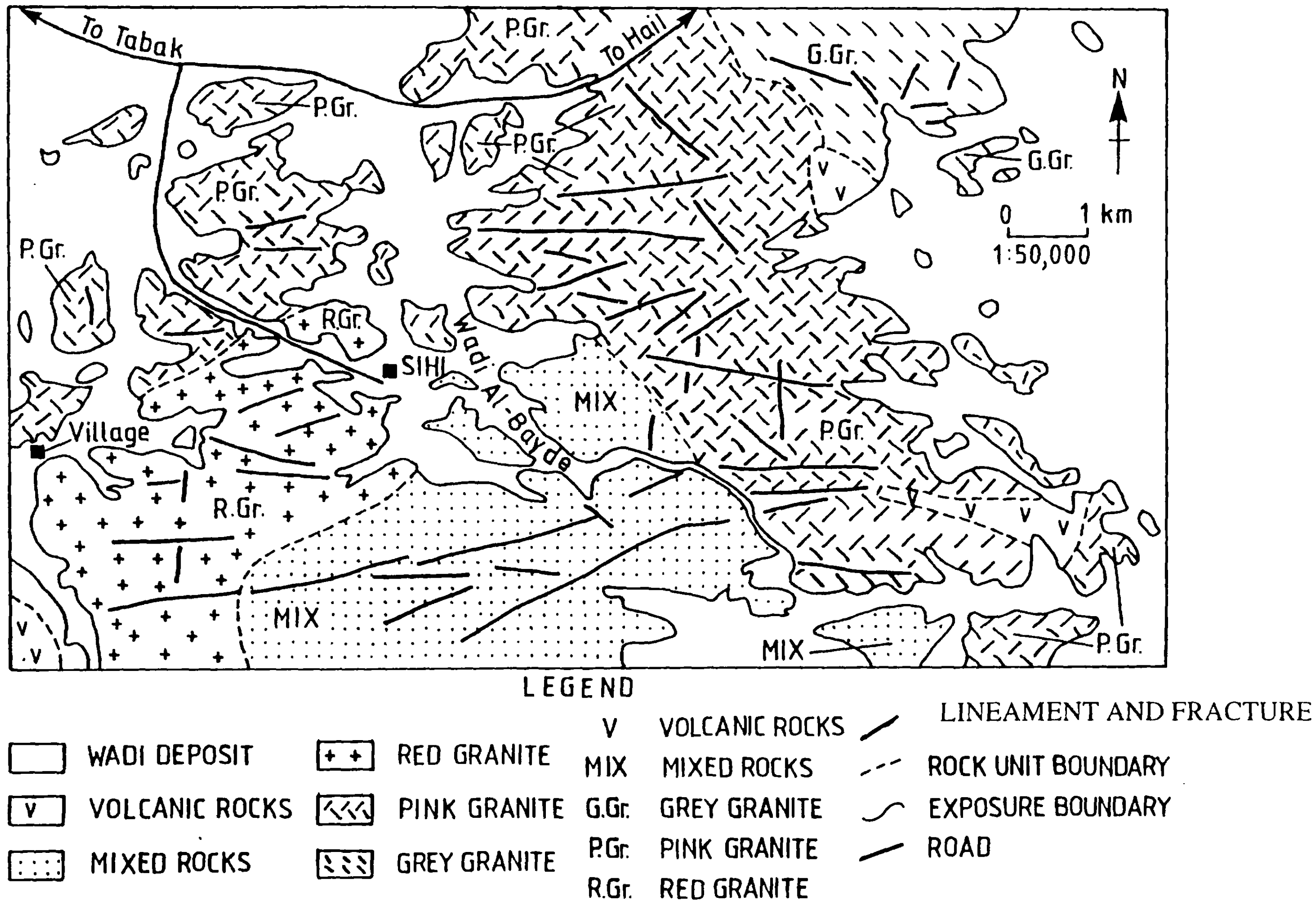
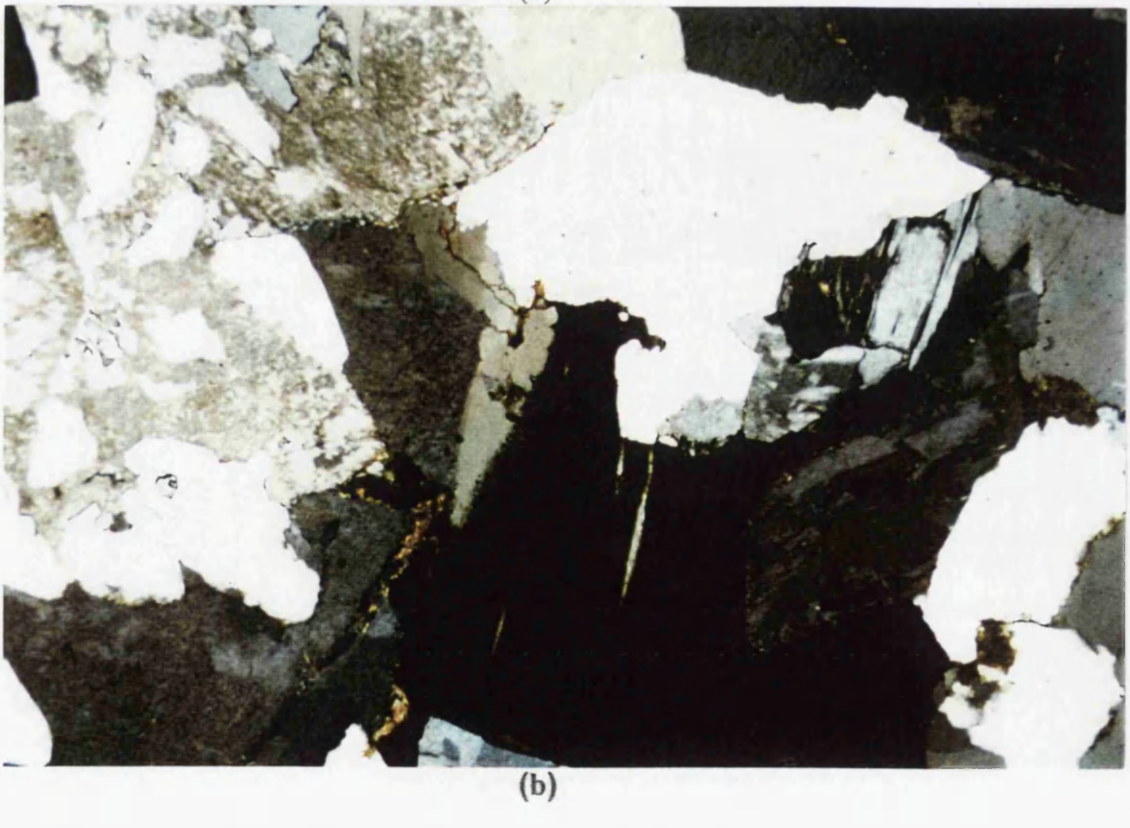


Fig. III.5: Geological map of site 1

(a)



(b)

Plate III.4 : Grey granite from site 1

a) Rock surface appearance

b) Photomicrographic showing a slightly altered grey granite, scale ×2.5.

Biotites occur as scattered grains that constitute less than 5% of the rock. They are dark brownish in colour, with one set of cleavage with high pleochroism. The biotite is largely unaltered, but some grains are affected by partial alteration, ranging to opaque iron oxides, but mostly as staining and chloritization. Some cleavages are filled with quartz and are also heavily stained by iron oxides. Lenses of quartz, chlorite and secondary white micas are included along the cleavage of the biotite. Zircon grains also appear as inclusions in these biotite crystals.

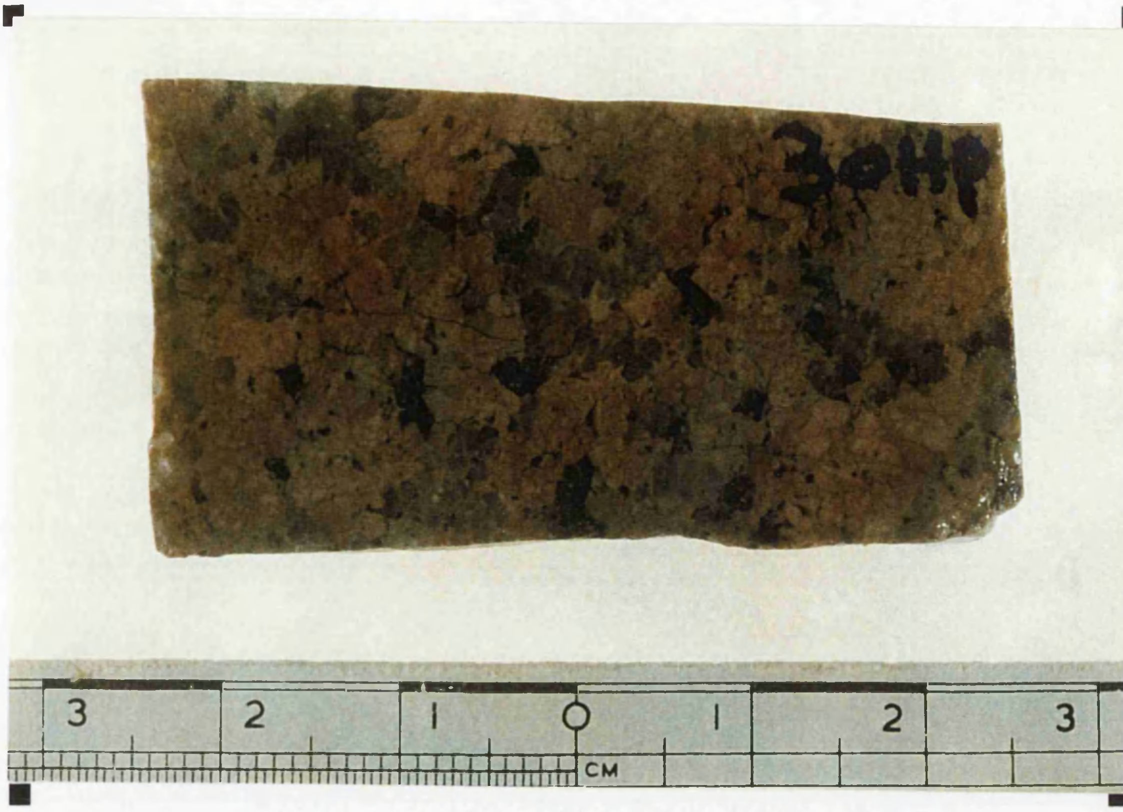
The whole rock is slightly affected by staining and alteration, and the alteration products are mostly of chlorite, clay minerals after biotite, and mica after potash feldspar. Such alteration occurs as complete replacement of primary minerals or as partial replacement along the crack and cleavage trends. The main accessory minerals are zircon and fluorite.

(ii) Pink granite

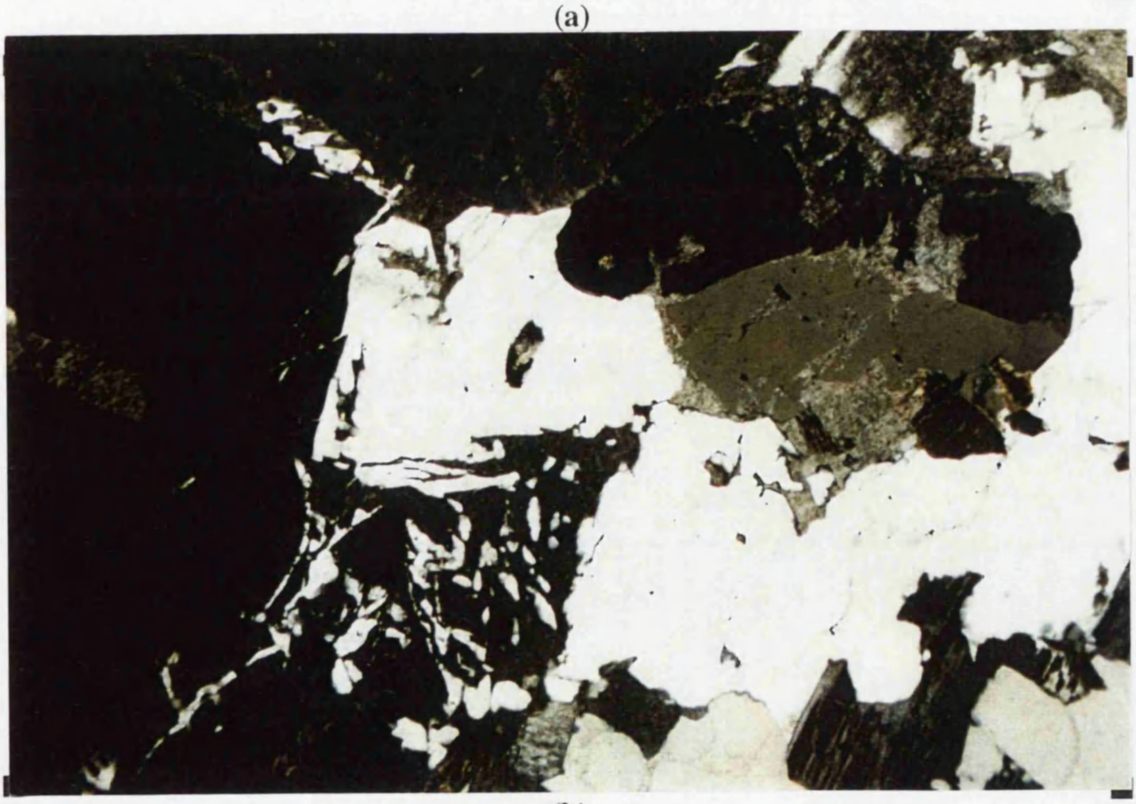
The pink granite is widespread in the area, covering 55% of the exposed ground. It occurs as massive and rounded body forms of pink to reddish weathering surface colour. The rock is found in topographically small hills with maximum heights of 40 to 50m.

Petrographically the rock is coarse to medium crystalline, and is composed of alkali-feldspar, quartz and biotite, with alteration products such as chlorite, sericite and hematite. The rock is substantially affected by alteration (**Plate III.5**) which introduces clays. These appear as cloudiness in the feldspars and as stains along the cracks and voids, which are otherwise completely or partially filled with the opaque minerals such as iron oxides as hematite.

The major constituent of the rock is potassium feldspar in the form of orthoclase and microcline. The feldspar crystals are large (>4mm) and subhedral, and they form more than 60% of the rock. The feldspars are highly perthitic, strongly altered and generally cloudy, the alterations is particularly intense close to the fractures. As a consequence of the alterations the rock develops a pink to red colour. There are albite



(a)



(b)

Plate III.5: Pink granite from site 1

a) Rock surface appearance.

b) Photomicrographic showing the alteration mineralogy and textures of the pink granite scale ×2.5.

laths enclosed in patches of potassium feldspar (mostly microcline). As in the grey granite, the feldspar is partially altered to sericite, and is also somewhat cloudy and stained, typically at the margin of the crystals, but also in the core and also adjacent to cracks, cleavage and voids. The grain boundaries are stained with opaque minerals, probably hematite. Quartz also occurs as interstitial material between crystals of alkali-feldspars.

The second dominant mineral in this rock is quartz, which constitutes about 25% of the rock. It occurs as large subhedral to anhedral crystals of greater than 5mm size. Most quartz has wavy extension. The crystals are apparently clear, but with stained internal cracks that are often filled with what appear to be clay materials and white mica. The grain boundaries are generally clear but some are stained and filled with opaque minerals. Much of the quartz has graphic intergrowth with the potassium feldspar. Some large crystals of quartz have been segmented into small crystals due to deformation.

Biotite occurs (6%) as scattered irregular flakes which are reddish brown in colour. Some of them display perfect cleavage, and they usually enclose small grains of zircon. Mostly the pleochroism is weak due to alteration of such biotite into chlorite, some sericite and partially into iron oxides. The accessory minerals are zircon, apatite and fluorite, with zircon usually appearing as inclusions within a major constituent (biotite, feldspar and quartz, and between the grains). The rock is also affected by late stage veining of quartz, fluorite, and chloritization of minerals along the vein path.

(iii) Red granite

The rock has various expressions of colour ranging from pinkish, to pink-reddish to mostly red. Although the rock sometimes occurs as small scattered masses, mixed with the grey and the pink rock units, the red granites usually occur in the highly fractured areas associated with disintegration and weathering. But locally some parts of the exposures appear to be hard.

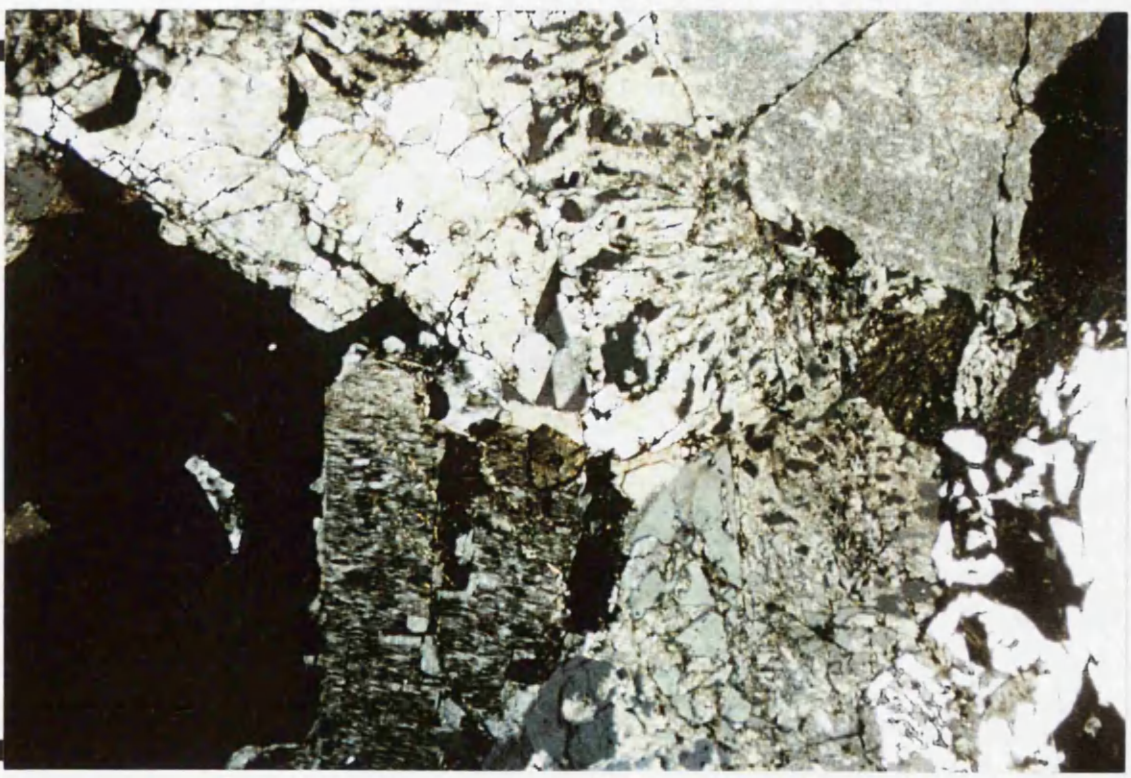
Petrographically the rocks are coarsely crystalline of more than 5mm in size. The rock is highly discoloured by staining; this is more than the pink unit, and much more than the grey unit (**Plate III.6**).

Orthoclase, microcline and perthite are the most common constituents, forming about 65% of the rock. The feldspars are highly cloudy and highly to completely stained to a dark brownish colour. Most of the feldspars exhibit cracks with perthitic texture which enclose small exsolved plagioclase. The potassium feldspar is altered into sericite, particularly in the margin of crystals, and also in the core of the crystals. The cleavage and cracks are mostly open and also altered, and thoroughly filled with sericite and opaque minerals such as iron oxides (hematite); this is similar to the grain boundaries. There commonly are voids in the feldspar (up to 1mm in size) and they are mostly completely filled with opaque minerals. This, of course, together with the staining of most of the feldspars, produces the red colour of the rock.

The quartz is the second constituent forming about 20% of the rock, usually intergrown with the potassium feldspar. forming graphic texture. The quartz appears to be stained and exhibits a high-density of cracks which are filled with opaque minerals, i.e. iron oxides. The grain boundaries are heavily filled with the same materials.

The rock does not contain any mafic minerals. Former biotite is completely altered and replaced by chlorite, clay minerals and iron oxides. The clay minerals occur as spots or/and as fillings in the cracks and the cleavage of feldspar. The chief effects of this alteration are to completely oxidise and destroy the mafic silicates in the rocks and to oxidise the iron into iron oxides in the form of hematite. The potassium feldspars are highly altered into sericite where they are densely cloudy; some pockets of sericite within the K-feldspar are usually combined and associated with highly staining feature, this probably due to the fact, that the feldspars are altered into sericite and clay minerals where the clays are susceptible to absorb any fluid percolating through the rocks, thus the iron oxides could be attracted and mixed with the clay materials

(a)



(b)

Plate III.6: Red granite from site 1

a) Rock surface appearance

b) Photomicrographic showing the alteration vugs, mineralogy and textures of the red granite scale × 2.5.

(feldspar alteration products) resulted as staining features on the feldspar. Due to this reason the rock is mainly discoloured into red colour. It is very common that the voids which may be formed mainly due to alteration of the feldspar have been filled with the iron oxides in form of hematite. There are some cracks which are filled with quartz and mica in the form of sericite, resulting from alteration of potassium feldspars. The accessory minerals are apatite, epidote and fluorite; zircon appears as an inclusion in biotite, quartz and feldspar. Generally the rocks exhibit more microfractures than the grey and pink granites.

III.5.2 *Salma granite*

The Salma granite (site 2) outcrops as two distinctive bodies. The first consists of coarse to medium grained, grey and pink granite. They form rounded massive hills. The second body has the form of standing cliffs and is likely to be a large sheet. It consists of pink to red, fine grained, microgranite and granophyre. The outcrops are mostly coated by rock varnish, particularly the fine grained one. The microgranite and granophyre are interfingering with each other; therefore they are mapped as one rock zone. **Fig. III.6** shows the distribution of the rock units in site 2. From this map, the microgranite and granophyre and pink granite are being seen as the main rock units in the area.

(i) Grey granite

The Salma grey granites appear to be fresh, light grey in colour when fresh and greyish to greenish when weathered. Petrographically the grain size is between 2 to 5 mm, with mostly inequigranular, subhedral and anhedral crystals. The texture is coarse to medium grained and cataclastic. The major constituents of the rock are potassium feldspar and quartz, which form approximately 90% of the rock, the rest is consisting of minor biotite, hornblende, plagioclase feldspar chlorite and opaque minerals.

Under polarised microscope, feldspar appears to be slightly cloudy and also some crystals are slightly stained. Potassium feldspar, which forms more than 60% of the rock, occurs usually as big crystals of exhibited breakage with perthitic composition.

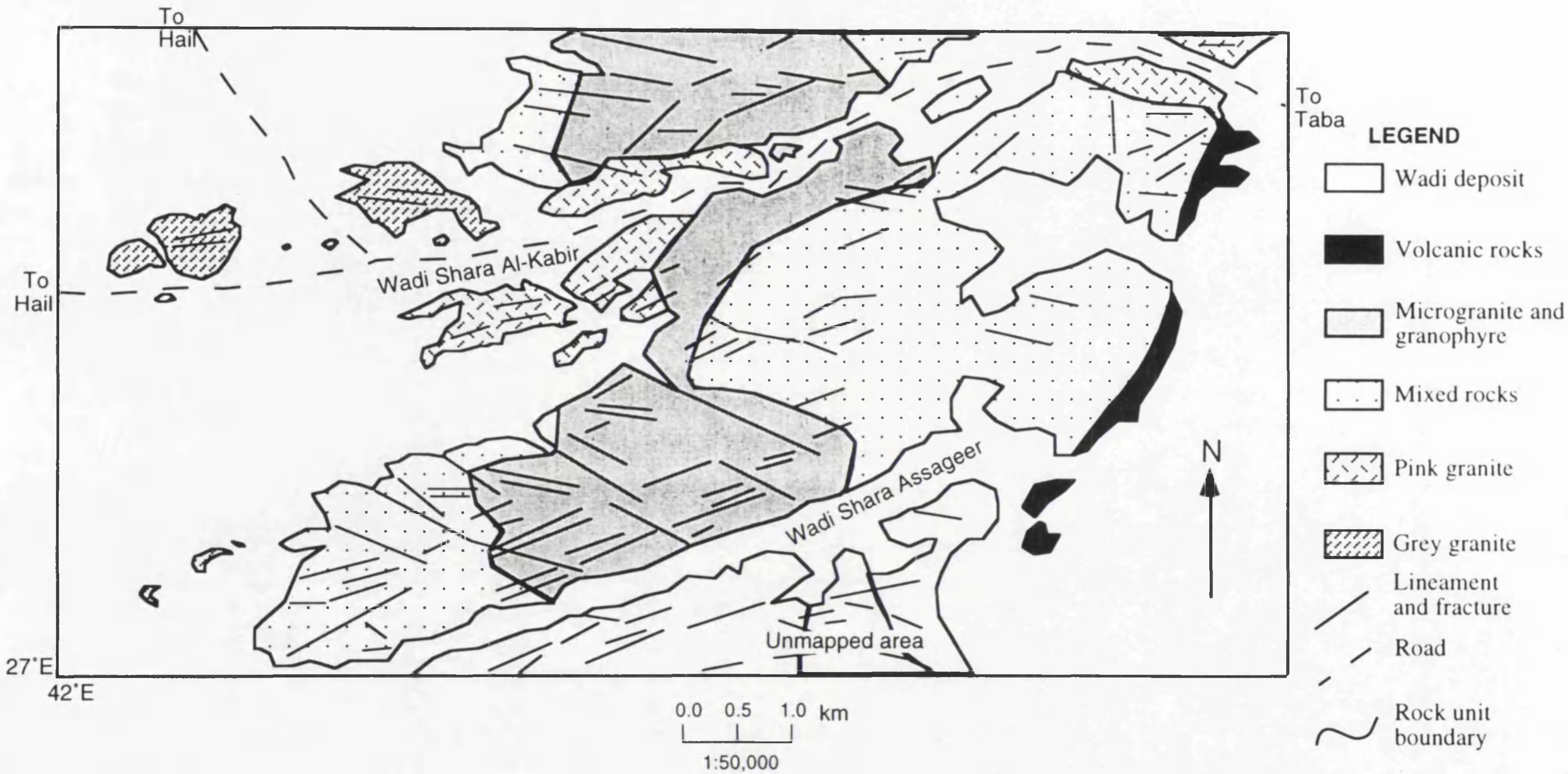


Fig. III.6: Geological map of site 2

Perthites have suture boundaries and they are marked by quartz. Very tiny crystals of plagioclase are also present with the albite twinning and mostly enclosed by potassium feldspar. Occasionally, the perthite is partially altered into clay minerals along cracks and cleavage.

Quartz is the second dominant mineral which forms 30% of whole rock and occurs as coarse to medium crystals varying between 1 to 5mm. The quartz crystals show breakage, exhibit hair-like microcracks and have undulose extinction.

Biotite is present but in small proportions. It occurs as small crystals and it is partially altered to chlorite and opaque minerals. The biotite occurs also as partial replacement of hornblende.

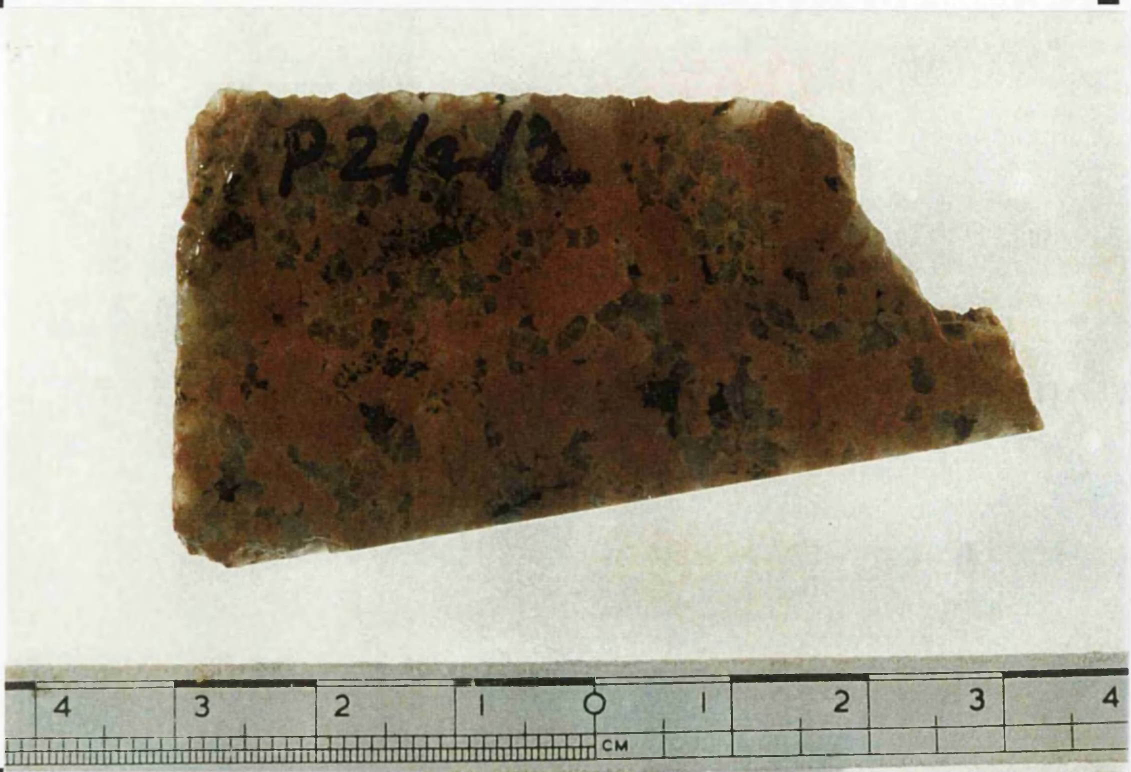
Hornblende is present as subhedral to anhedral crystals and is mostly associated with the biotite. It occurs as small crystals with two sets of cleavage. The hornblende is partially replaced by biotite, while some crystals are altered to chlorite and opaque minerals, particularly along the cleavage planes. Zircon is present in the rock as an accessory mineral.

The mineral composition of both Salma and Sihi grey granites is very similar, except that Salma granite has more microfractures, particularly within quartz crystals, and its texture is more cataclastic.

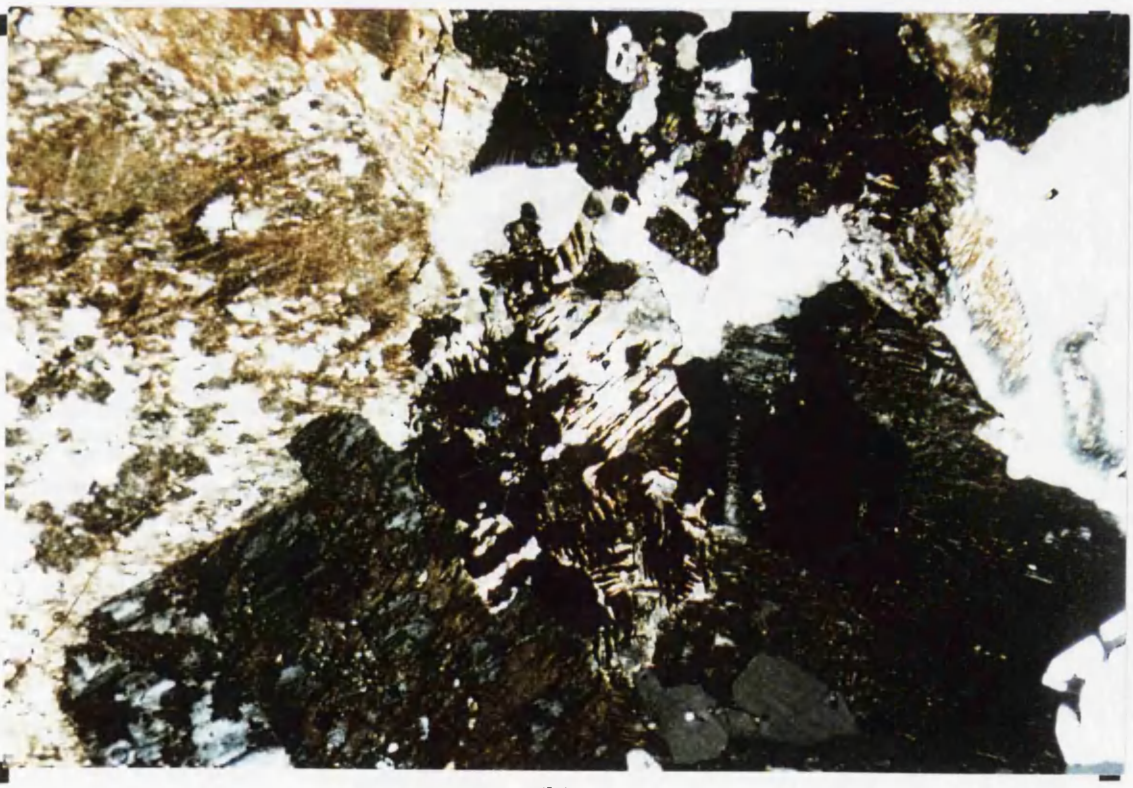
(ii) Pink granite

Salma pink granite is generally similar to Sihi pink granite. The rock is petrographically holocrystalline, coarse to medium ranging from 2 to 5mm in size. The crystals are approximately equigranular and subhedral in shape. There is slightly graphic texture due to the intergrowth of quartz and feldspar.

Feldspars, which form 60% of the rock, are slightly bigger than 5mm and subhedral in shape, composed mostly of perthite and microcline, mostly cloudy, corroded and highly altered to brownish to pinkish material **(Plate III.7)**. The grain boundaries are mostly stained and show two sets of open cleavage usually filled with opaque minerals and white mica. Feldspars have cracks and voids of dimensions greater than 1mm. They are partially to completely altered to clay minerals. The cores



(a)



(b)

Plate III.7: Pink granite from site 2.
a) Rock surface appearance
b) Photomicrographic showing the alteration mineralogy and textures of the pink granite scale ×2.5.

and margins of large amount of feldspar crystals are altered to sericite. Albite crystals fill the intergranular spaces. They are also corroded and have cracks filled with iron oxides.

Quartz is subhedral to anhedral, and forms about 25% of the rock. Its crystals are coarse to medium (4 to 6 mm in size). The crystals show microcracks that are mostly tight and clear except occasionally when they are filled with brownish material, mostly white mica. The quartz forms some sort of graphic intergrowth with feldspar in the form of graphic texture and has undulose extension. Some crystals include tiny spots of opaque minerals.

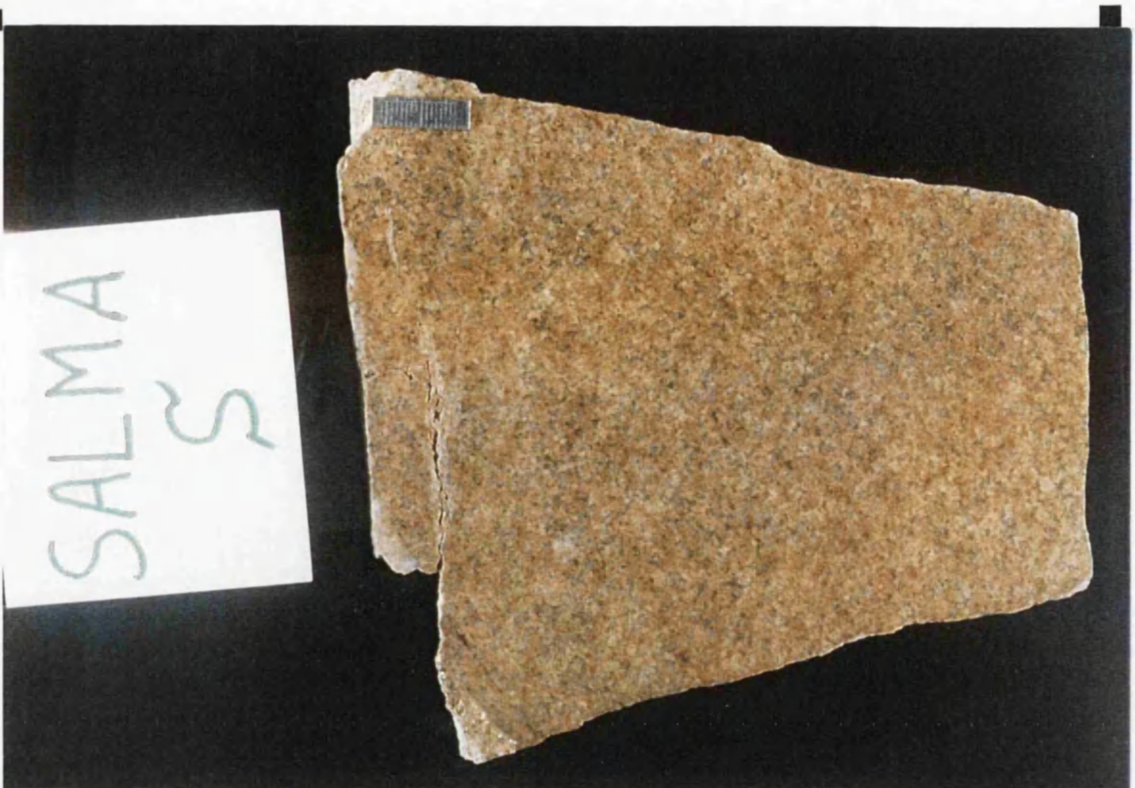
Generally, the rocks do not show any mafic minerals, but there are some exemptions. However the most of mafic minerals such as biotite are completely altered to secondary minerals such as chlorite or replaced by iron ore. Zircon, fluorite, and apatite are present as accessory minerals.

(iii) Granophyre

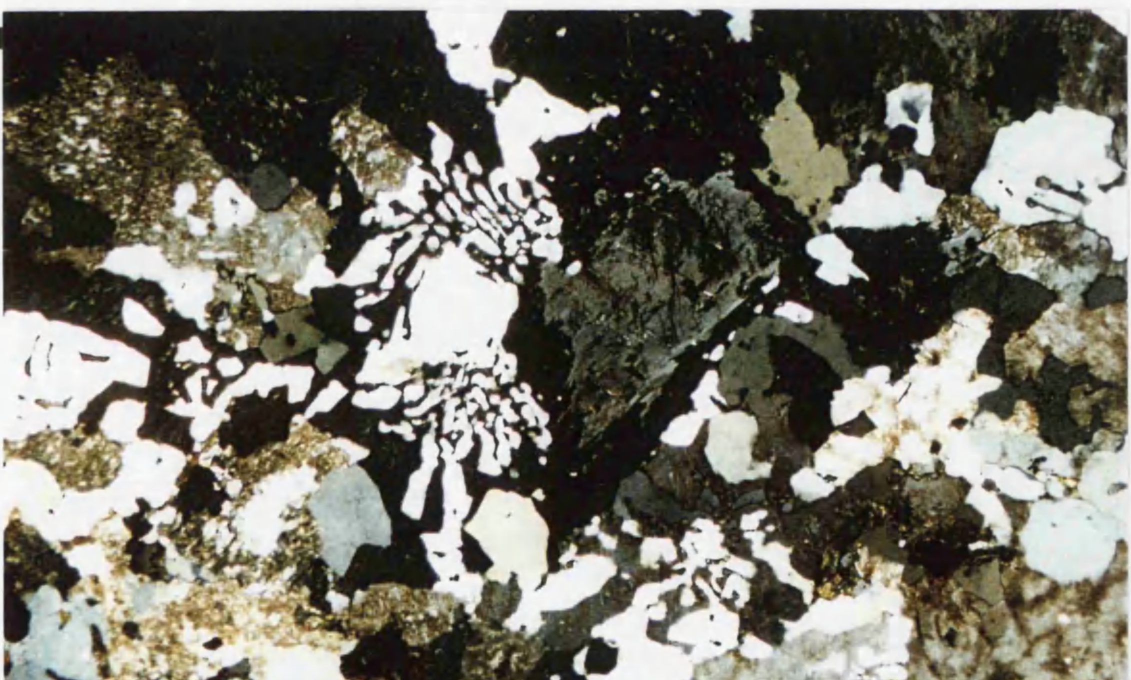
The granophyre is pink-red to pink-purplish in hand specimen and mostly similar to microgranite. Petrographically the rock is finely crystalline with interlocking and graphic texture. Potassium feldspar and quartz occur as subhedral crystals and show graphic intergrowth (micrographic texture). The feldspars are mostly cloudy and completely stained which give the rock its pink to red colour. The feldspars are mostly present as perthitic orthoclase and have small laths of plagioclase. The biotite occurs as small crystals which have been partially or completely altered to chlorite and iron staining. Fine grained quartzo-feldspathic veins occur in the rock. Zircon is also present as an accessory mineral.

(iv) Microgranite

The microgranite is fine grained, generally has graphic and interlocking texture and is composed of subhedral orthoclase and perthite, forming together more than 60% of the rock (**Plate III.8**). The alteration, corrosion and staining of the feldspar are intensively taking place along the cracks and cleavage planes and spreading in the grains as sericite



(a)



(b)

Plate III.8: Microgranite from site 2
a) Rock surface appearance
b) Photomicrographic showing the alteration mineralogy and textures of microgranite, scale ×2.5.

and clay minerals. Quartz forms about 30% of the rock. It is usually subhedral to anhedral in shape, and forms an intergrowth with potassium feldspar to give a graphic texture. There is plagioclase which is mostly enclosed in potassium feldspar. Biotite is partially to completely altered to chlorite and iron oxides. The grain boundaries are generally stained. The rock has some microcracks, particularly in the feldspar and they are stained and filled with alteration products of white mica and chlorite and opaque minerals such as iron oxides. The rock contains zircon as an accessory mineral.

III.5.3 *Rock unit boundaries*

The boundaries between different rock units in sites 1 & 2 are mostly gradational. They appear as zones of mixed granitic units in which it is difficult to map each rock units individually. The form of this kind of boundary zone may be due to the alteration variation or/and interaction between the rock units of the study area. Such boundary areas are called mixed rock units; however, they consist generally of an interfingering of the neighbouring rock units, i.e. mixed rock areas occur between pink and red granites, pink and grey granites, and also between pink-red and grey granites (**Plate III.9**). The mixed rocks are widely distributed between the grey-pink and red granites in site 1, and, between the grey-pink granite and microgranite in site 2.

III.5.4 *Alteration products*

The presence of alteration products such as clays and iron oxides are investigated in the study rocks (particularly the stained and weathered samples from the pink and the red granite) using the XRD method. The XRD results show the presence of clay minerals. The clay materials in untreated XRD samples show a symmetrical peak at 14.5Å. In glycolated samples, the clays expand to give a sharper and enhanced peak at 16.5Å. When the same sample is heated at 300°C, the clays tend to collapse to give a small peak or even none. The results of the XRD test shows that clay materials in the tested rocks are expandable. The XRD analysis charts are shown in **Figs. III.7,8** and **Table III.1** for the sample tested. Most probably, the clays in the studied rocks are of kaolinitic and illite-smectite type (Hall 1997).

Plate III.9: Mixed area of the rocks between pink and red granite

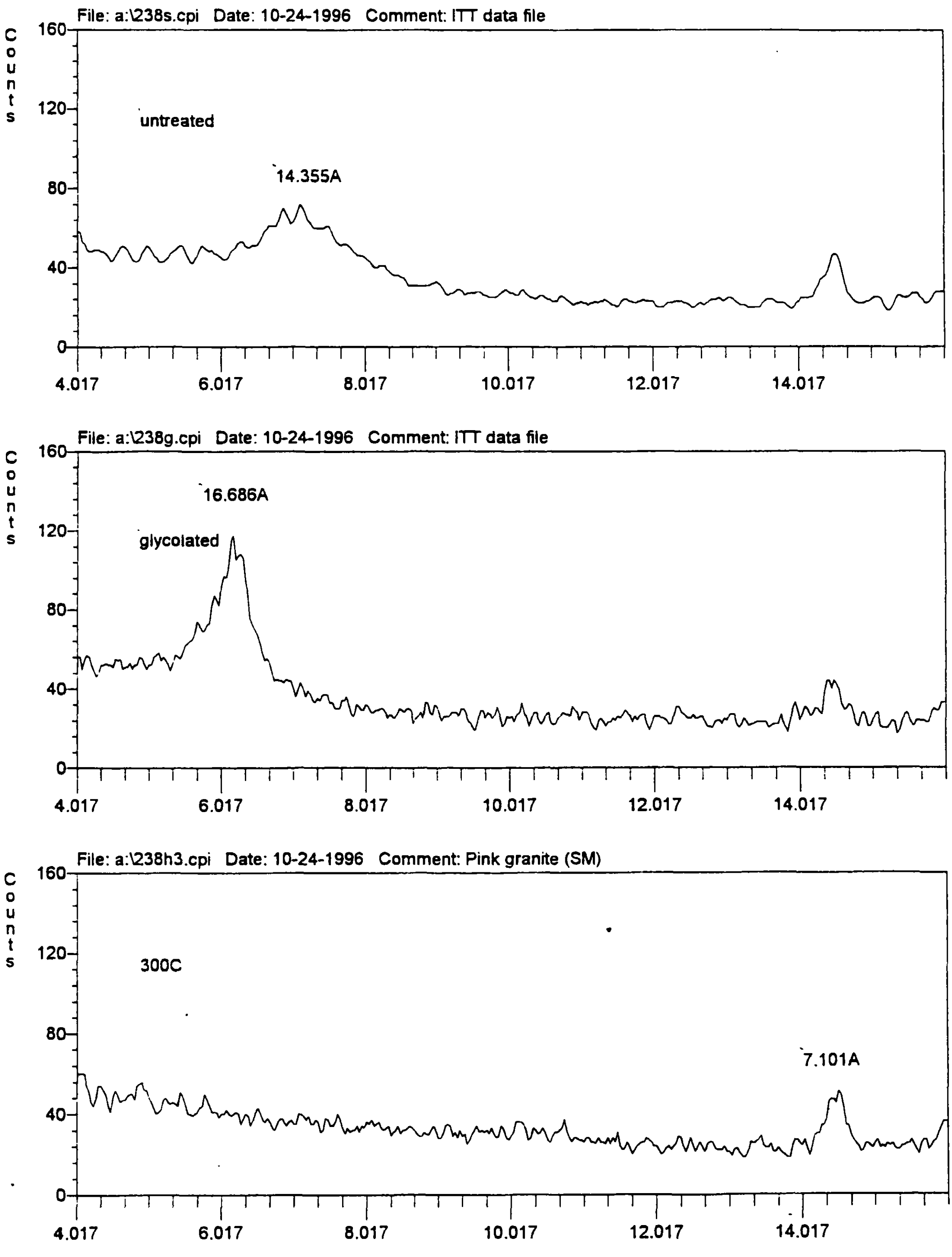


Fig. III.7: X-Ray diffraction traces of the clay in the pink granite
a) Untreated b) Glycolated c) Heated 300°C

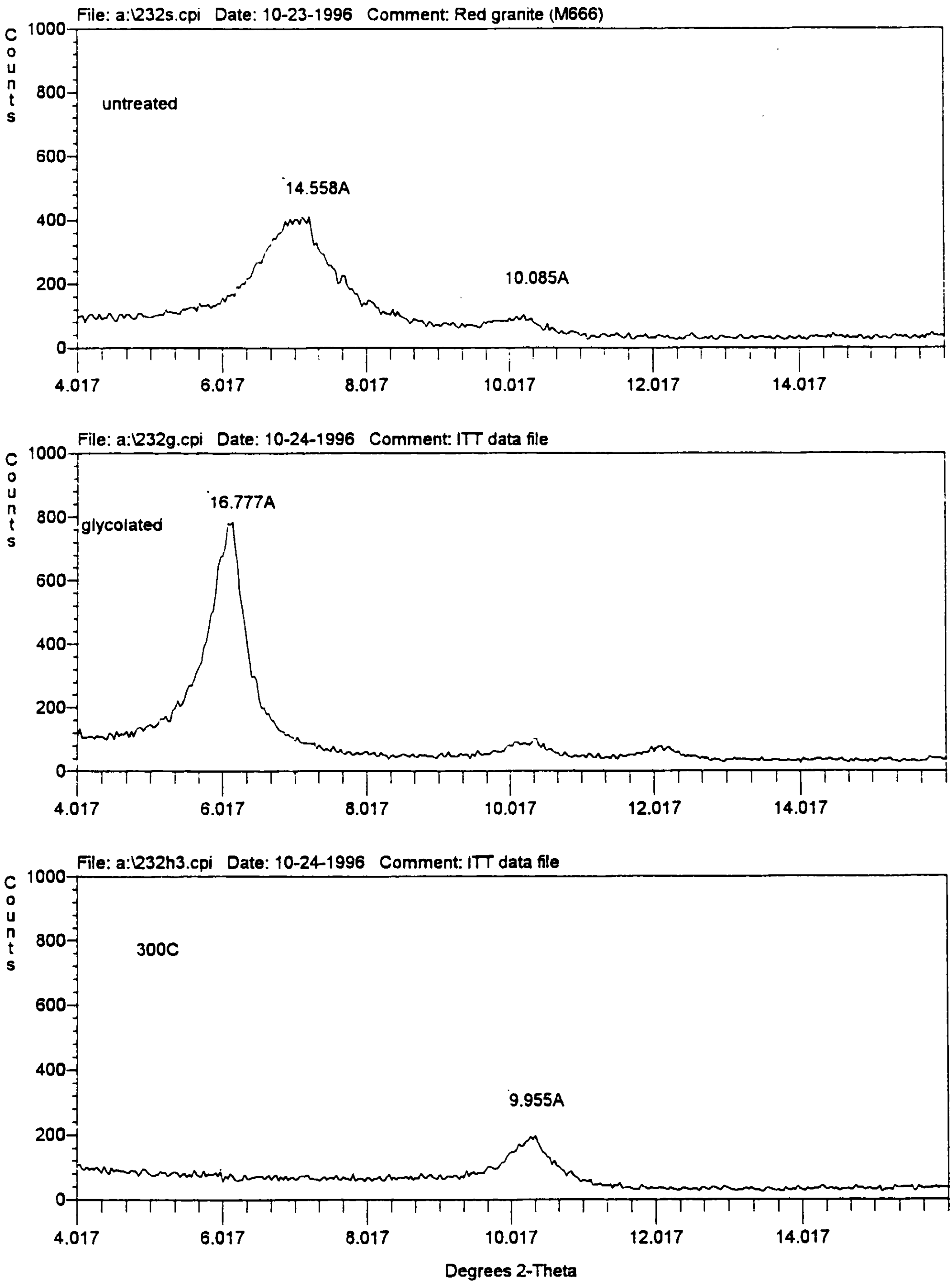


Fig. III.8: X-Ray diffraction traces of the clay in the red granite
a) Untreated b) Glycolated c) Heated 300°C

Table III.1: XRD analysis results of the clay materials in the rocks of the study area

Rock unit	Untreated (Å)	Glycolated (Å)	Heated at 300°C (Å)
Pink granite	14.355	16.686	–
Red granite	14.558	16.777	–

As noted above, the granites are composed mainly of feldspars, quartz and micas. The chemical weathering of these primary minerals results in the secondary alteration minerals clays and iron oxides. These are present especially along cracks, cleavages and in voids.

The alteration of the granites could be due to the penetration of meteoric water through cracks, or hydrothermal alteration due to the ascention of hot fluids. These possibilities will be evaluated later in this thesis.

III.6 *CONCLUSIONS*

① The study area, sites 1& 2, has five rock units of granite. They are of similar composition but have different colours, textures, grain sizes and alteration stages. These rock units are: medium grey granite, partially altered medium pink granite, completely altered medium red granite, microgranite, and granophyre (which are both fine grained and completely altered rocks).

② The rock staining is consistent with the alteration stages, as the degree of alteration increases the staining and microfractures also increase, a character that is typical in the red granite.

③ Although the microgranite and granophyre are completely stained due to alteration, they have fine and interlocking texture.

④ Sometimes fresh and slightly altered rocks exhibit microfractures which may be due to the deformation history. The grey granite of site 2 is a typical example of this condition.

⑤ The altered granites in the study area have expandable clay minerals.

⑥ The boundaries between the rock units in the study area are vague and seem to be gradational and appear as zones. This area has a mixture of rock units in the boundaries at various scales which are difficult to distinguish.

CHAPTER IV

SITE INVESTIGATION

IV.1 *GENERAL*

Site investigation is an essential element in any geotechnical work. In this process most of the geological and geotechnical parameters which concern the project are recognised and evaluated. There are three main stages of site investigation: the first is the feasibility stage, mostly done using published material, aerial and satellite image studies, and field work; this is followed by the evaluation and assessment stage, in which more concern is placed on analyses of experimental results and information obtained from the first stage, the third stage is ground investigation during construction (West 1986).

Each geotechnical discipline has special geological and geotechnical aspects which should be taken into consideration and investigated. In general, in most rock geotechnical work, the rock mass properties and intact rock material properties are investigated. The rock mass properties include the discontinuity characteristics and the rock mass weathering conditions, where the rock material properties include mineralogical, physical and mechanical properties. Some of the above parameters have more influence than the others depending on the type of project. For example, in rock slope stability analyses, the discontinuity characteristics are generally more important than the intact rock material properties. In the present study, which is concerned with the investigation of the dimension stone resources of the Arabian shield, the natural features and characteristics of the materials are most important, because it is the natural conditions and characteristics of stone success or failure of any such development.

A site investigation ideally requires an assessment of the physical and mechanical state of the rock mass (original strength and alteration) and the distribution (spacing, orientation) of discontinuities. In reality useful information is collected over a range of scales, from lineament analysis on the regional scale to joint analysis and weathering effects on the outcrop scale.

Two areas (sites 1& 2) have been used in this study. Sections 2, 3, and 4 below address lineaments, joints and weathering, respectively. Section 5 summarises the information.

IV.2 *LINEAMENT STUDY FROM AERIAL PHOTOGRAPHS*

IV.2.1 *General*

Lineaments are regional linear features that are caused by the alignment of regional or sub-regional morphological features, such as streams, escarpments, and mountain regions, and tonal features that in many areas are the surface expressions of fractures or fault zones. O'Leary *et al.* (1976) stated that lineaments can be defined as mappable, simple or composite linear features of a surface, whose parts are aligned in a rectilinear or slightly curvilinear relationship and which differ distinctly from the patterns of adjacent features and presumably reflect a subsurface phenomenon. Aerial photographs have long been used for lineament study, geological reconnaissance and field mapping. Although other forms of remote sensing imagery are available today, aerial photos still provide economical and easily used remote viewing of surface features. The black and white air photographs taken for topographical survey and mapping purposes still remain the most usual source for interpretation purposes. Air photograph interpretation can be used to map lithology, structure, physiography, ground water, and geological hazards. The technique is also very useful in investigating erosion, landforms and drainage patterns (Drury 1987).

Two types of information; lineament trends and lineament densities, have been used in this study to analyse lineaments and to correlate with the rock mass properties such as joint orientations and spacings. Because of the small scale of Landsat images, large-scale aerial photographs 1:15000 were chosen for use in this study. Aerial photographs are especially suited for lineament analysis, in this setting, because the fractures are highlighted by shadowing and appear on the photograph as sharp linear traces.

The lineaments were identified on the aerial photographs by visual inspection, and these were traced onto transparent overlays. Lineament maps (sheets **1** and **2**) for sites 1 & 2 have been constructed. The lineament trends have been determined from the above maps for both sites by selecting sampling windows on these maps, which are used as data-sets for further interpretation.

The density of lineaments (mainly joints in the study area) indicates the abundance of jointing in the area. Lineament density (as a proxy for joint density) can be measured and described in a number of ways: average spacing of joints, number of joints in a given area, total cumulative length of joints in a specified area, surface area of all given joints in a given volume of rock (Davis 1984). Only the number of lineaments per area is used in this study.

To determine the density of lineaments in the study area, the number of lineaments were counted per unit area. This was done by counting the lineaments shown on sheets **1** and **2**, on a 1-by 1-km. grid, and the total density was contoured for each site as shown on lineament density maps (sheets **3** and **4**). These maps were used to see the pattern of concentration of lineament density domains and to assess how these might relate to the other aspects of the study.

IV.2.2 *Lineament data*

The lineaments data have been collected in form of trends and numbers from sampling windows on sheets **1** and **2**. The trends of each window were plotted as rose diagram in order to see the main trends in sites 1& 2. The plot of each window was compared with each other. It is very obvious on the lineament maps (sheets 1 and **2**) and also from rose diagrams that the lineament trends of the grey and pink granites in sites 1& 2 are very similar, so their trends were plotted in the rose diagram together. The lineament trends in sites 1& 2 were presented in rose diagrams and also as bar diagrams (to see the frequency of the lineament trends) as in **Figs. IV.1, 2, 3, 4** and **5**, then the main trends were determined for further interpretations.

The lineament numbers were counted for whole area in sites 1& 2 as described above in order to see their density. The lineament densities were contoured on sheets **3** and **4**, for sites 1& 2 at contour intervals of 20 lineament per square kilometre, then the pattern of concentration or lineaments density domains were investigated and presented in **Figs. IV.6** and **7**.

IV.2.3 ***Lineament analysis results***

The conventionally constructed lineament maps (sheets **1** and **2**) include continuous (NE and NW trends) and less continuous (E-W and N-S trends) features. Visual inspection of the lineament maps of sites1& 2, suggests that there are distinct sets. This impression is confirmed by rose diagrams (**Figs. IV.1, 2, 3, 4** and **5**). Generally, the main lineament trends are very similar in sites 1& 2, this is also real between the rock units in the area with minor differences, particularly in the red granite, microgranite and granophyre. Therefore, the lineament trends data were gathered into groups and their rose diagrams were plotted. Grey and pink granites are grouped into one group and red granite as another group in site 1, and grey and pink granites in site 2 as one group and, microgranite and granophyre as another group. In both sites1&2, the E-W and N-S trends are dominant but are less continuous and of high frequency, while the NW and NE trends are of low frequency, although, they are more continuous.

The grey and pink granite mostly have similar major trends (NNW-SSE and E-W), while the red granite has major trends (N-S and E-W). Although the lineament trends in site 1 are very similar, they can be categorised into two lineament trends domains; grey and pink granite domain, and the red granite domain. In site 2, there are also two distinctive lineament trend domains. The grey and pink granite domain has major trends of N-S and E-W, while the microgranite and granophyre domain has three trends of lineaments.

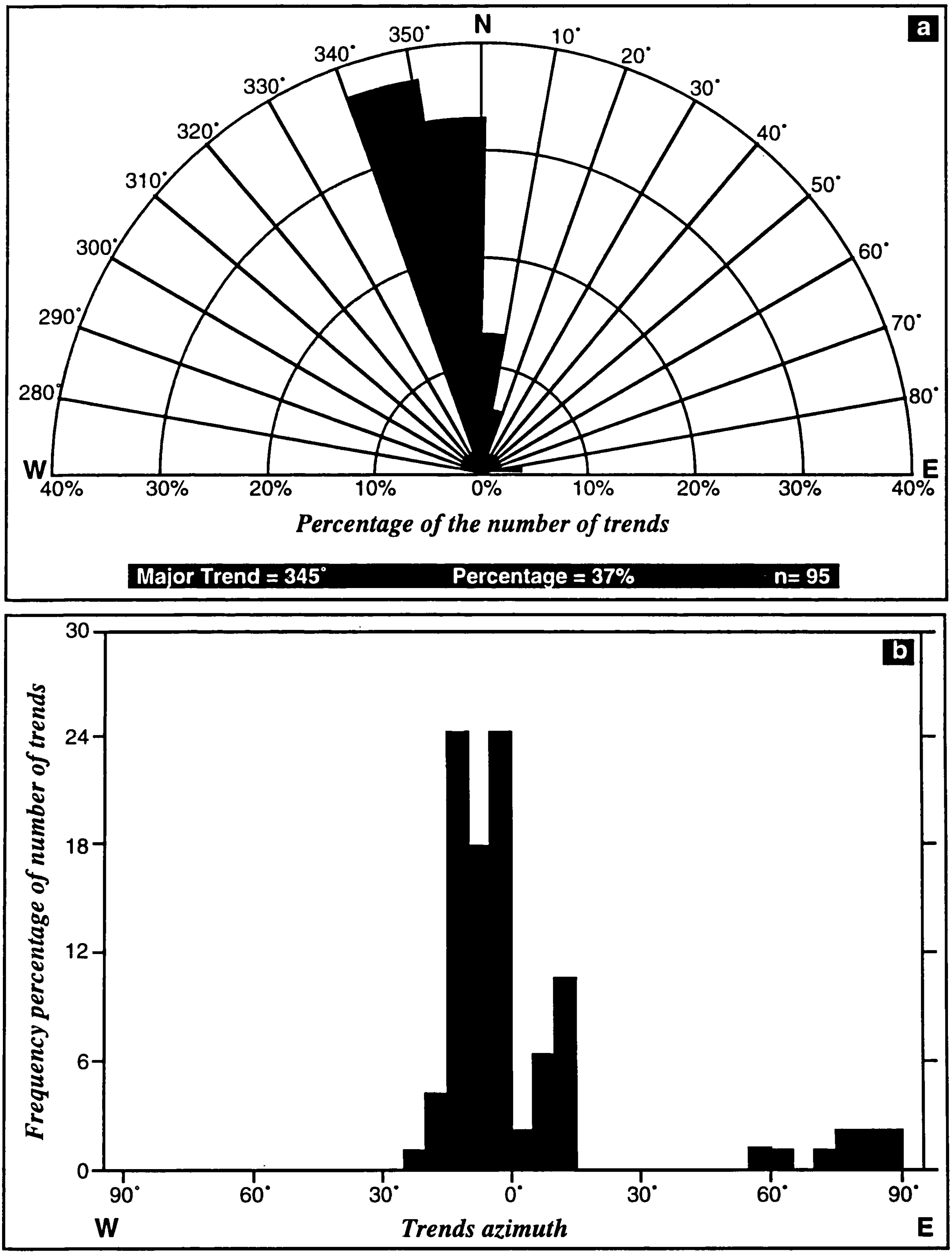


Fig. IV.1: Lineament trends of grey and pink granite in site1

a) Rose diagram b) Bar diagram

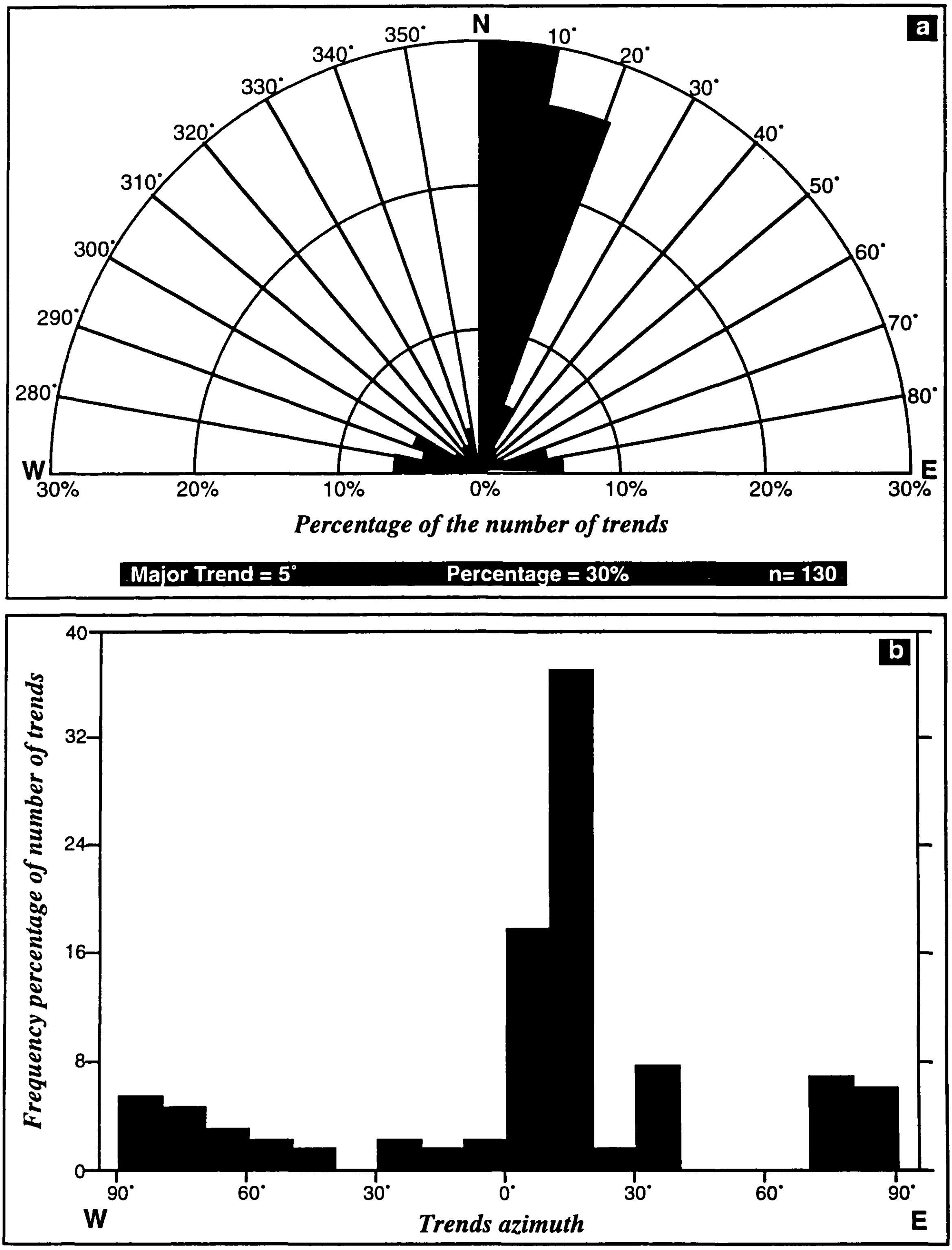


Fig. IV.2: Lineament trends of red granite in site1
a) Rose diagram b) Bar diagram

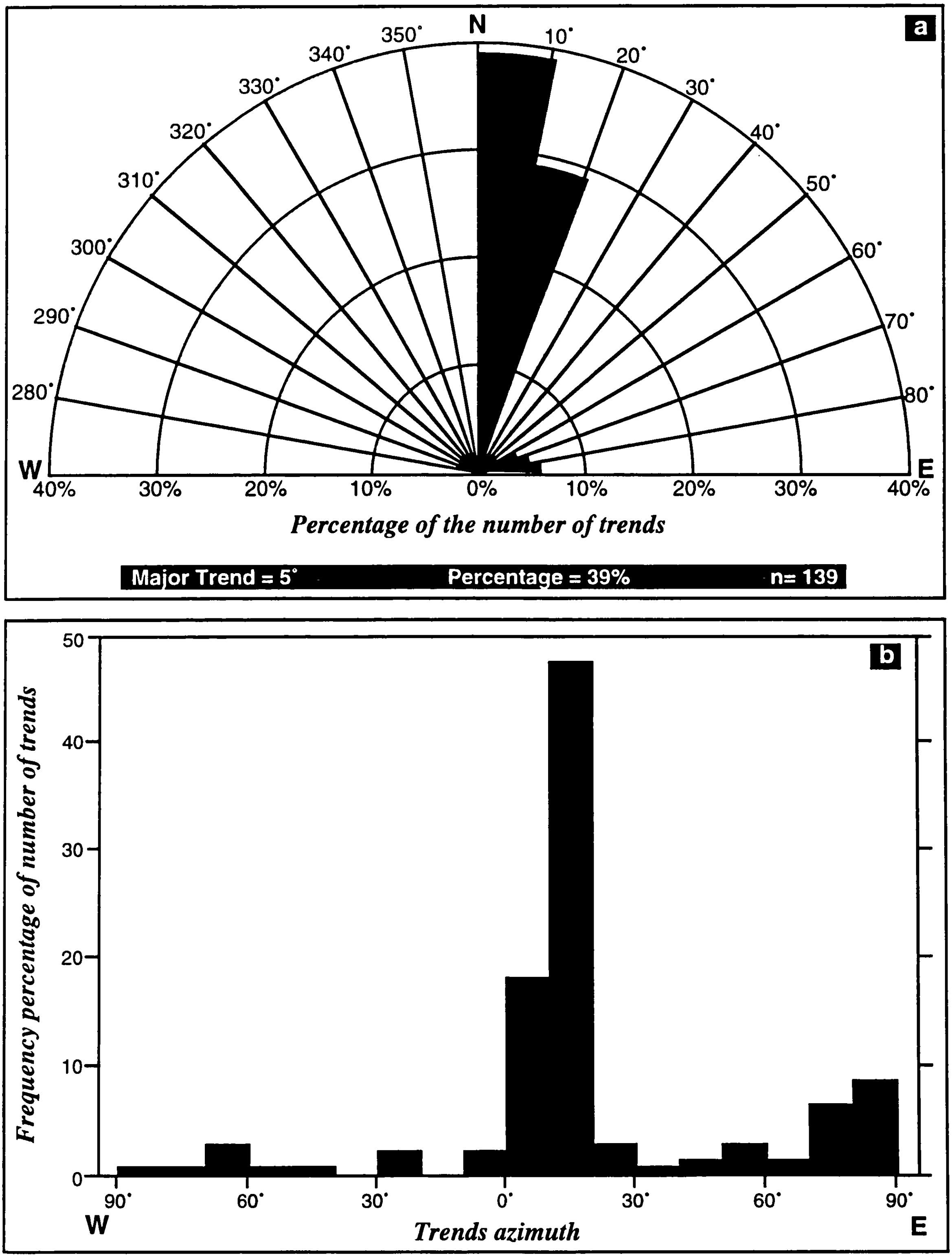


Fig. IV.3: Lineament trends of mixed area in site1
a) Rose diagram b) Bar diagram

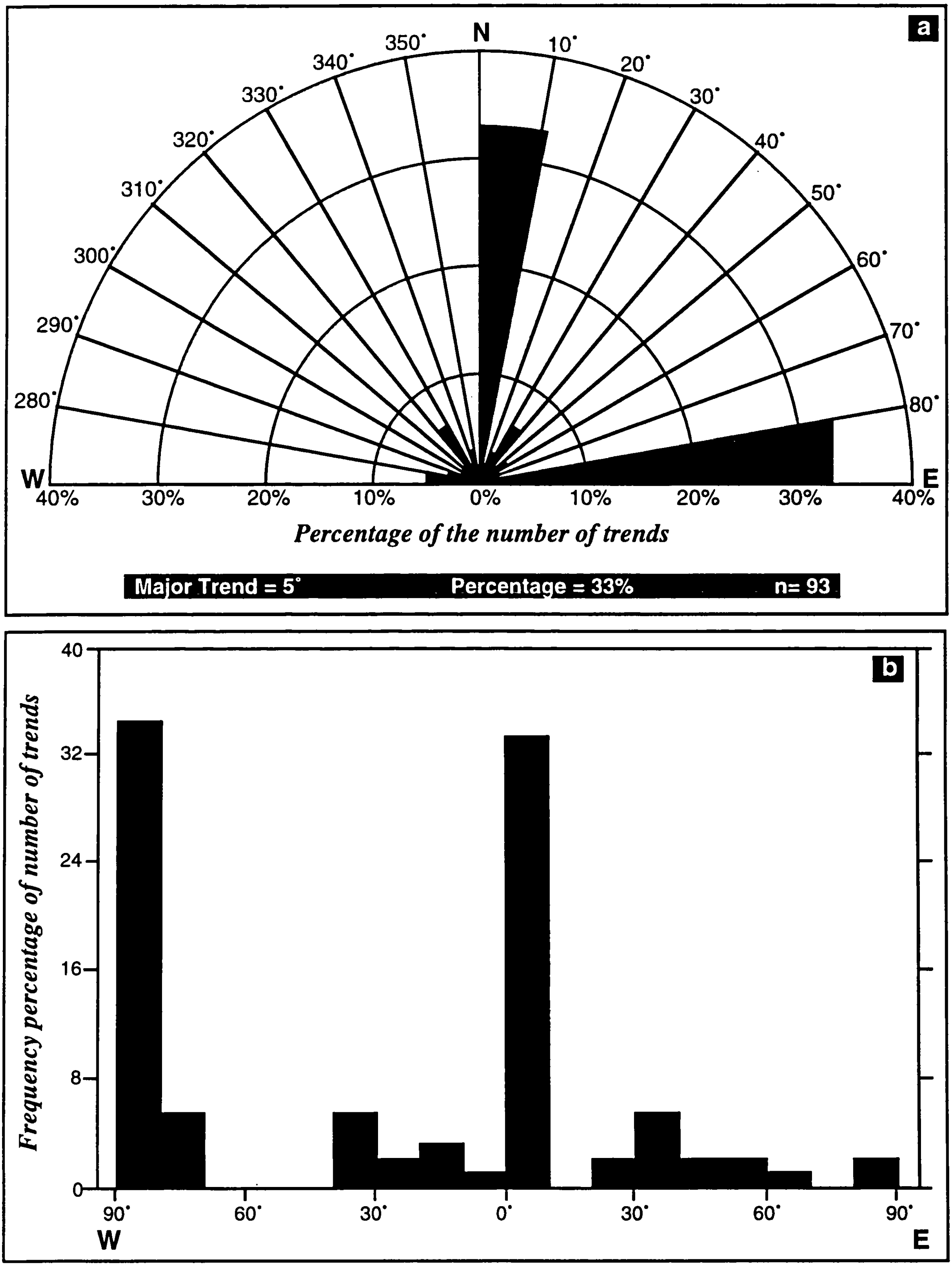
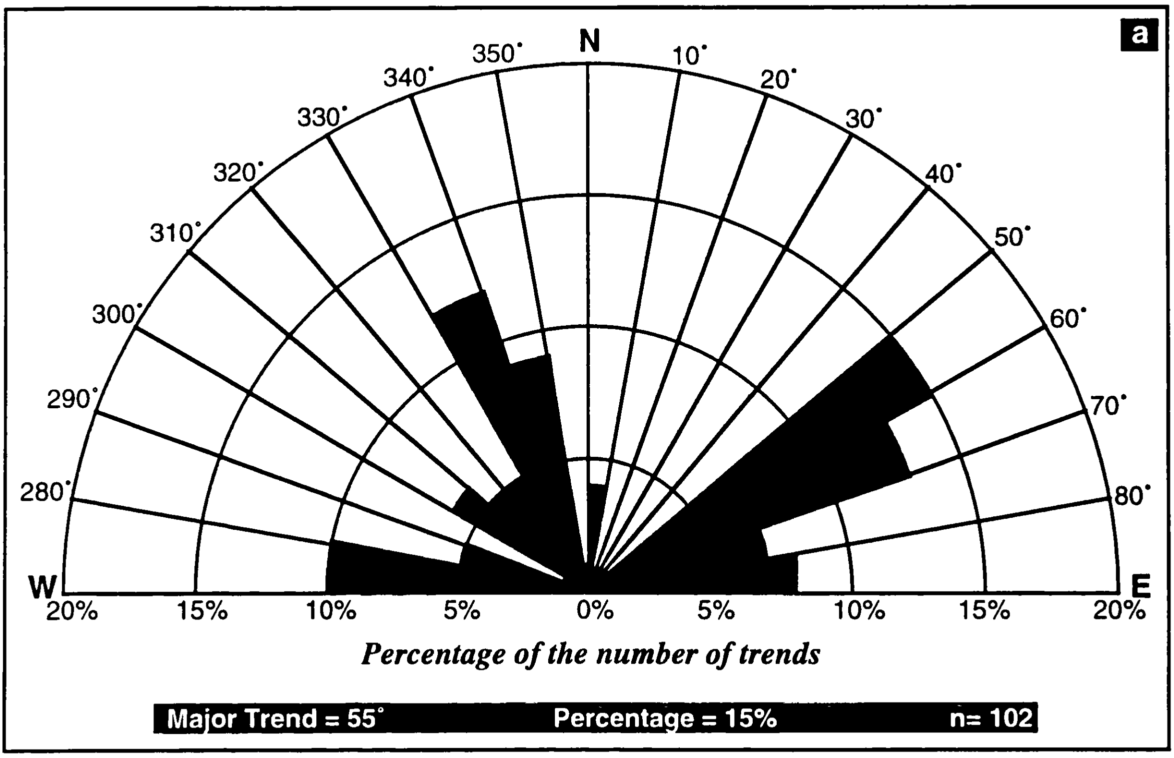


Fig. IV.4: Lineament trends of grey and pink granites in site2

a) Rose diagram b) Bar diagram



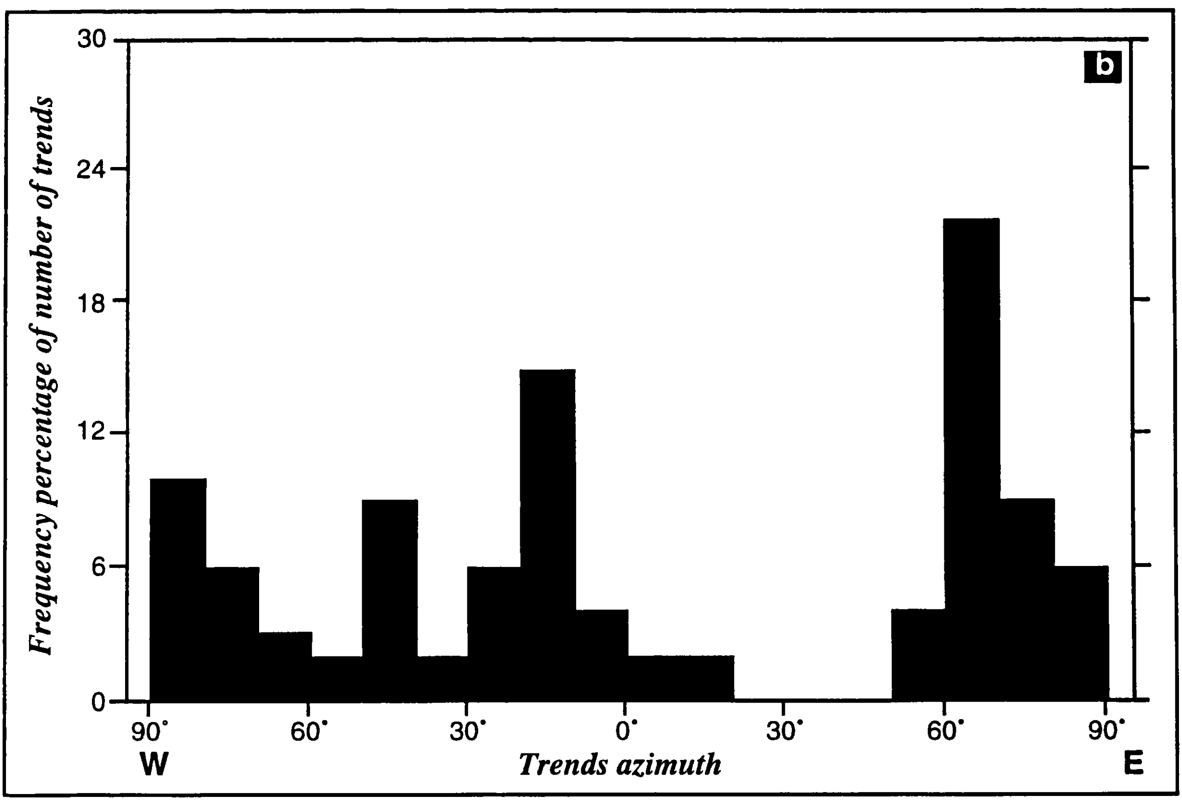


Fig. IV.5: Lineament trends of microgranite and granophyre in site2

a) Rose diagram b) Bar diagram

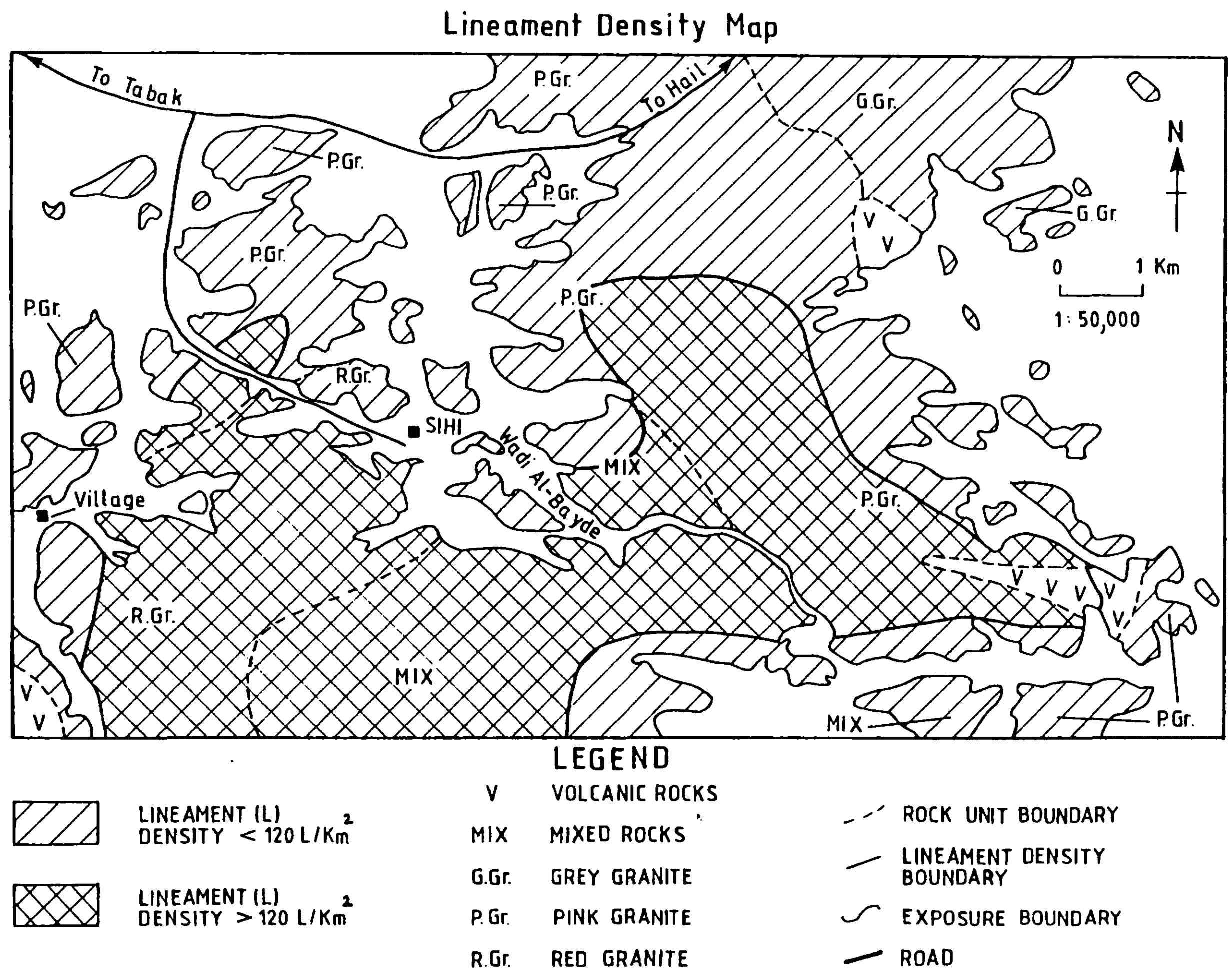


Fig. IV.6: Lineament density map of site 1

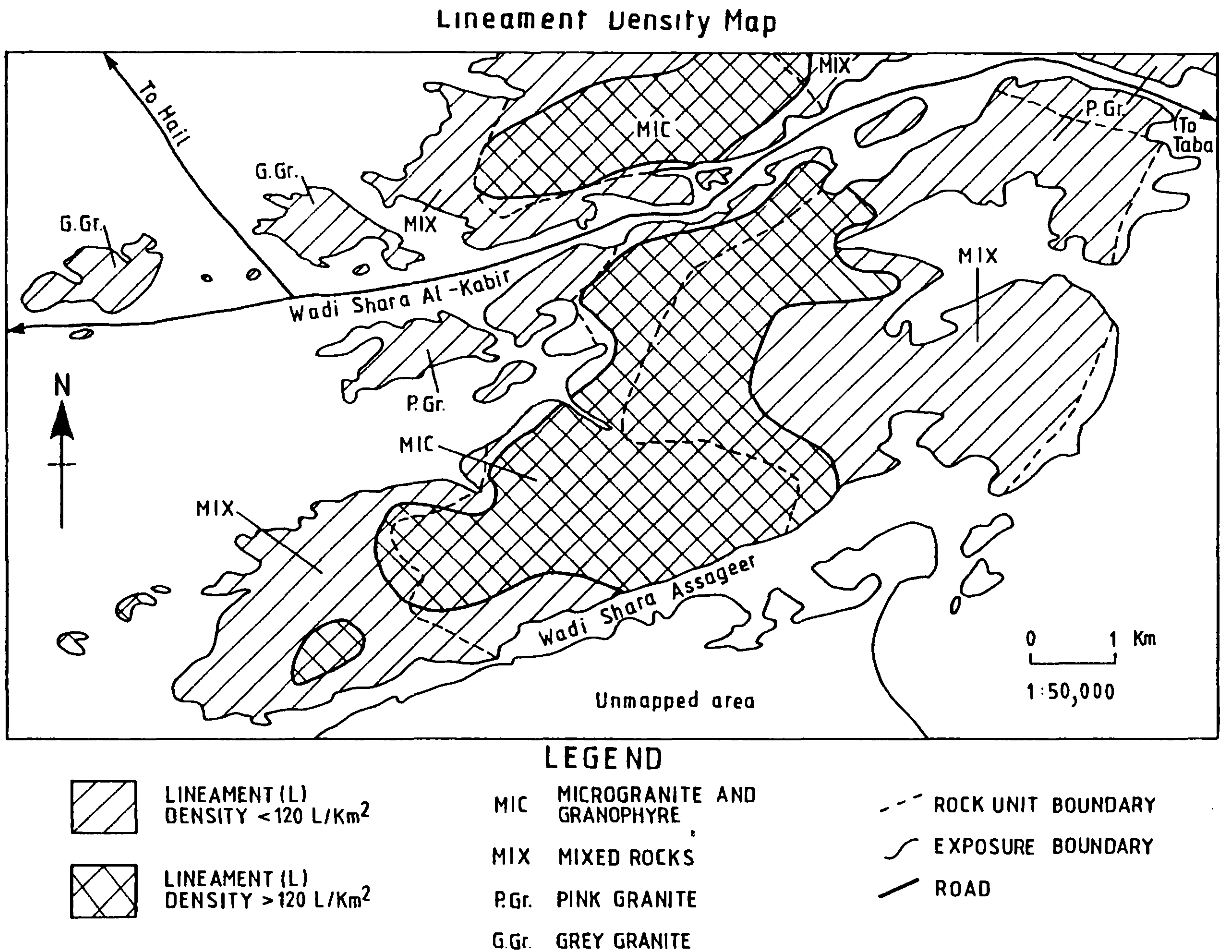


Fig. IV.7: Lineament density map of site 2

The lineament densities in site1 range from 20 to 220 lineament / km^2 (L/km^2) (sheet **3**). The red granite exhibits the highest lineament density (120– 220 L/km^2), the mixed areas of red, grey and pink granites have mostly moderate values of the fracture densities of site1, while the pink and the grey granite area exhibits the lowest values (20–100 L/km^2) (**Table IV.1**). Site 2 also shows variations in lineament densities (sheet **4**). The microgranite and granophyre areas of site 2 have high densities (120–248 L/km^2), while the pink and grey granites have lower values (40 and 120 L/km^2) (**Table IV.1**), particularly the grey granite.

Table IV.1: The main lineament trends and density in sites 1 & 2

Site No.	*Rock units*	*MLT*	*LD*
1	Pink and grey granite	NNW - SSE N–S and E–W	20 - 100
	Red granite		> 120 - 220
2	Pink and grey granite	N–S and E–W	40 - 120
	Microgranite & granophyre	E–W, NE and NW	120 - 248

MLT: Main lineament trend *LD*: Lineament density(L/km^2)

From both lineament and lineament density distribution maps (sheets **1,2,** and **Figs. IV.6, 7**), we can see that while the major trends and the lineament densities have good correlations in general, each distinctive trend has a particular lineament density. For example the grey and pink granite have major trends of NNW and E–W and density of less than 100 L/km^2, while the red granite has major trends of N-S and E–W and greater than 120 L/km^2. Based on this observation, the site1 has two distinctive structural lineaments areas, the first is in grey and pink granite and the second in the red granite. This is also the same with the site 2, where the microgranite has distinctive trends and densities that differ from the grey and pink granite.

IV.3 *LOCAL DISCONTINUITY CHARACTERISTICS*

Ideally, quarrying rock for dimension stone requires a knowledge of the distribution, geometry, and engineering properties of the discontinuities in the mass. The discontinuities are one of the most important geological aspects which control the suitability of the site to be quarried for dimension stone. The rock should be fairly massive, with a low fracture frequency, wide discontinuity spacing and favourable discontinuity orientations. These characteristics control the quarry development, and the size of the blocks which can be produced.

There are different parameters required for describing discontinuities and these include surface, block forming geometry, and the space between the blocks (Goodman 1976). These parameters are listed below:-

Discontinuity parameters		
Surface	***Block geometry***	***Space between blocks***
Orientation	Orientation	Aperture
Continuity	Number of sets	Filling
Roughness	Frequency	Seepage
Wall strength	Spacing	

The block geometry parameters such as orientation, number of sets, joint frequency and spacing are the most relevant to the dimension stone because they control the block size and shape (Goodman 1976). In the present study, the discontinuities are mostly continuous and well developed. For the purpose of dimension stone investigation, I have used only a selection of the discontinuity parameters which are concerned about block geometry, namely as follows:

Block geometry
Orientation
Number of sets
Frequency
Spacing

Field mapping is the only method to characterise some properties of discontinuities such as roughness and persistence. Hencher (1987) mentioned that often the best approach to surface mapping is a combination of statistical sampling and concentration on areas of particular importance. However, Piteau (1973) reports a case where despite good exposure and experienced personnel, structural domains were not recognised in the field and only become apparent after the statistical processing of the data.

Generally there are two methods for collecting discontinuity data, subjective and objective (Hencher 1987). The objective method is one in which the intersected discontinuity data is collected along selected lines in window set out on the exposed face. The data may be processed statistically and corrected for sampling bias due to the orientation of the sampling lines (Terzaghi 1965; Attwell & Farmer 1976; ISRM 1978a; Priest & Hudson 1981; Hudson & Priest 1983 and Priest 1993). The subjective method is where the data collected includes just those discontinuities considered to be of importance (Priest 1993). Hencher (1987) states that the most suitable method for collecting data for a particular project depends on the nature of the problem, the quality of the exposure and the experience of the investigator. It is to be noted that the most widely used methods in data collection are the scan line and window sampling methods.

IV.3.1 *Scanline sampling*

Scanlines themselves are simply measuring tapes, between 2 and 30 m long (Priest 1993) fixed on the clean planar rock face. Discontinuities intercepted along the scanline can be described under the headings of: number, distance from origin of traverse, orientation, type, length, spacing, filling, aperture, water flow, roughness, and waviness (Herget 1977). The rock face is generally large relatively to the size and spacing of the discontinuities exposed. Such exposures can be found on beach cliffs, in gorges, road cuttings, quarries, open pit mines and unsupported adits. The selected exposure should be representative of the site in terms of discontinuities and rock materials. A scanline should be set up on a second rock face approximately at right angle to the first scanline or at different orientations, to provide a three-dimensional sample of the discontinuity network.

The orientation of discontinuities such as joints or bedding is usually measured by means of a magnetic compass and clinometer device fitted with a water level (ISRM 1978a). The dip direction and dip angles of the discontinuities are recorded in addition to the scanline attitude: its azimuth, and its plunge angle. Wang *et al.* (1990) mention that a detailed scanline mapping can be carried out on rock exposures, so that orientation and location parameters of all discontinuities are recorded.

IV.3.2 *Discontinuity data collection*

IV.3.2.1 Joint orientations

Rock masses often have nearly parallel sets of discontinuities. The orientations of these discontinuity sets relative to each other are the most important structural features which relate to any engineering structure, or to the faces of an excavation. The discontinuity data can be represented on a rose diagram (Attwell & Farmer 1976) or by stereographic projection (Duncan 1981; Goodman 1976 and Priest 1993). As the number of joint sets increases, the rock mass becomes more irregular and jointed, but as the joint sets become fewer, the rock mass becomes more massive, and the blocks more regular in shape (ISRM1978a).

Measurements of joint orientations were collected from the field survey, conducted during two field trips. The measurement locations in the study area are given serial numbers as M1...M9 etc. (**Fig. IV.8**) in site1 and from measurement locations in site 2 e.g. S1, S4, 2/2, 5R and R2/1 (**Fig. IV.9**). Detailed surveys have been carried out at the measurement locations using three (where possible) orthogonal scanlines, with length ranging from 5m to 30m. Two of these scanlines are essentially horizontal and orthogonal to each other and perpendicular to the main joint sets; the third scanline is taken in the vertical position. Joints of the several sets which are present intersect these scanlines at distances determined by the joint frequency. The joints are mostly perpendicular to the scanlines, so angle corrections are not necessary. An example of scanlines record is given in **Fig. IV.10**; all scanline data are included as **Appendix I.** In addition to the scan-line method, some data of joint orientations and spacings have been

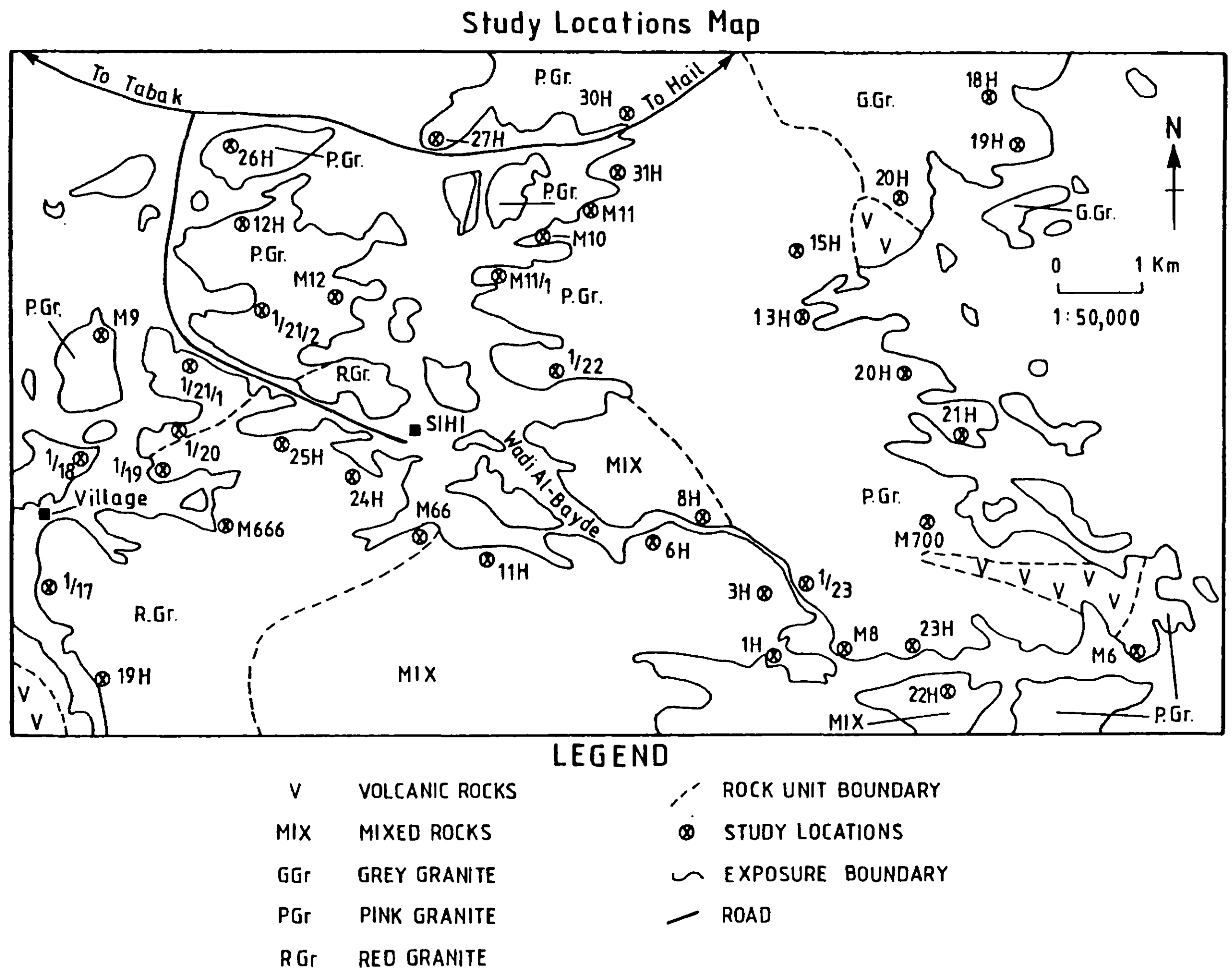
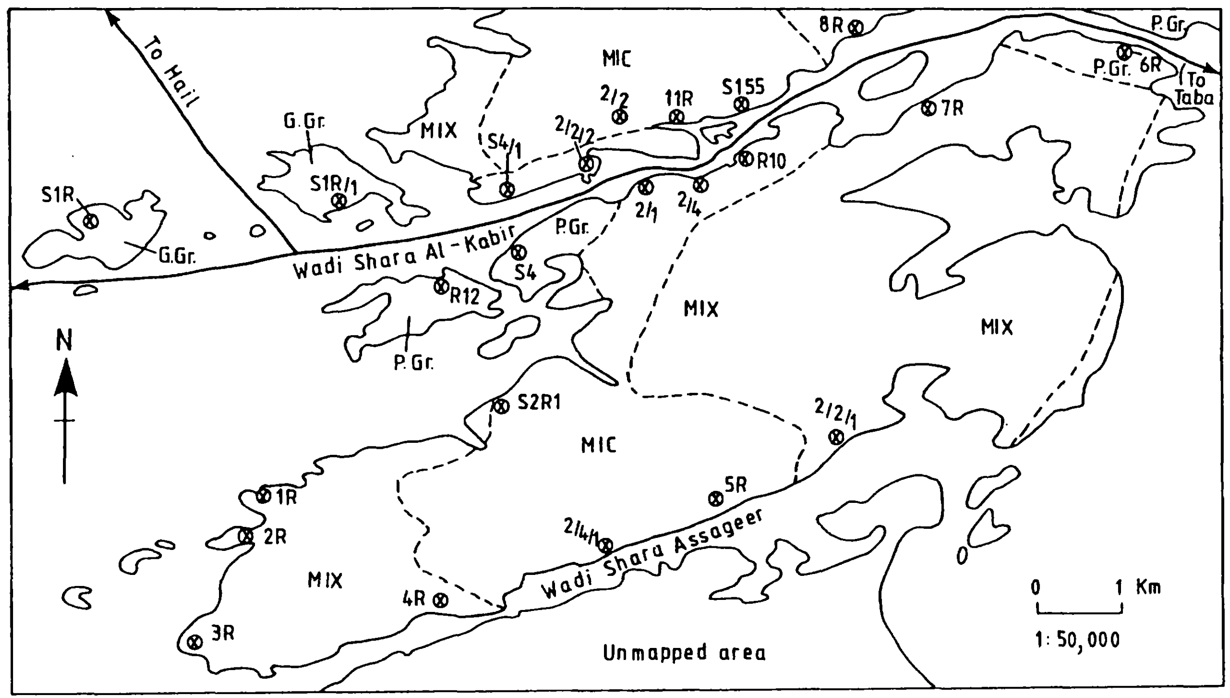


Fig. IV.8: Study and measurement locations map of site 1

Study Locations Map



LEGEND

MIC	MICROGRANITE AND GRANOPHYRE		ROCK UNIT BOUNDARY
MIX	MIXED ROCKS	⊗ 1R	STUDY LOCATIONS
P.Gr.	PINK GRANITE		EXPOSURE BOUNDARY
G.Gr.	GREY GRANITE		ROAD

Fig. IV.9: Study and measurement locations map of site 2

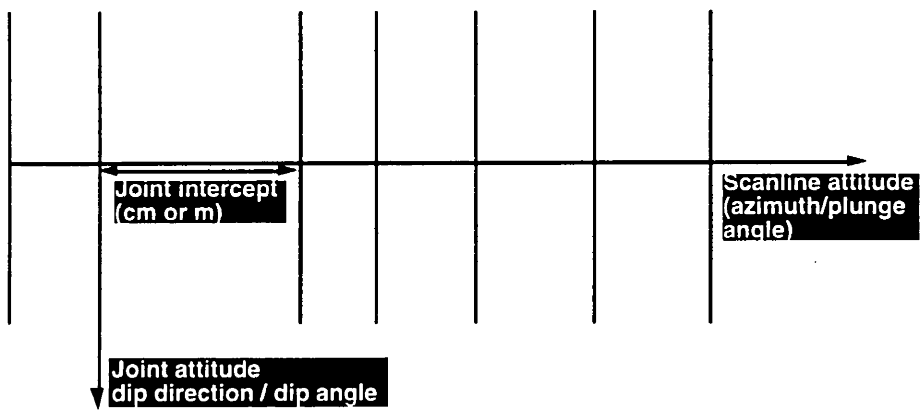


Fig. IV.10: Example of scanline survey method carried out on a possible exposure in the study area

recorded subjectively (main joint sets are orthogonal) in sites 1& 2. At each measurement location the rock unit was determined. Recording of joints crossing the scanline consisted of trend and plunge of dip direction and dip of the joint plane and the joint intercept (spacing), in addition , general information about opening, persistence and infilling of the joints. These were done in order to classify the joints in terms of sets, frequency and spacing. The joint orientations processing was carried out on the computer using stereographic projection methods, whose output showed the orientation of the joints in contour diagrams of the joint poles, used to determine the main orientations and the number of sets.

IV.3.2.2 *Joint frequency and spacing*

On a scanline, joint frequency is the average number of joints crossed per unit length. The joint frequency gives an indication of the intensity of fracturing of the rock mass, and it is also related to the block sizes (Franklin 1994; Priest 1993 and Hudson & Priest 1979). The joint frequency is determined in the study area using the scanline method.

For each scanline the joint frequencies are determined by dividing the number of joints of a set (as identified previously by stereographic projection) intersected by the scanline, by the total length of the scanline.

Spacing is the perpendicular distance between adjacent discontinuities of a set and it is taken as the mean spacing of a set of joints (Brown 1994). Spacing is widely used in predicting rock mass quality. The joint spacing in the study area is determined either by measuring the distance between the main joints at several locations (as mentioned above) or by dividing the total length of the scanlines by the number of the joints of a set intersected by those scanlines. According to the lineament results and field observations the spacings of grey and pink granites in sites 1& 2 were gathered as one group, and the microgranite and granophyre as another group. The means of the spacing values of each above groups were calculated and presented in **Table** IV.2.

Table IV.2: The mean joint frequency and spacing in sites 1&2

Site No.	*Rock unit*	**Mean values**	
		Fracture Frequency (Joint/m)	***Spacing (m)***
1	Pink and grey granite	0.28 – 1.59	0.63 – 3.50
	Red granite	1.85 – 3.13	0.32 – 0.66
2	Pink and grey granite	0.32 – 1.43	0.86 – 3.08
	Microgranite & granophyre	3.57 – 7.69	0.12 – 0.28

IV.3.3 *Interpretations of discontinuity data*

IV.3.3.1 Joint pattern

The discontinuities of the study area consist of joints, faults, dykes and veins. The major structures are faults, and many of them can be traced in the field; the remainder of them can be traced from aerial photographs. Joints are the most dominant structural features in the study area.

In the field these joints are mostly of three sets, two sets are sub-vertical and essentially orthogonal to each other, while the third one is almost subhorizontal (**Plate IV.1**). In addition, the joints have high persistence of more than 3 metres in distance. The apertures between the joints are variable depending on the weathering condition, the

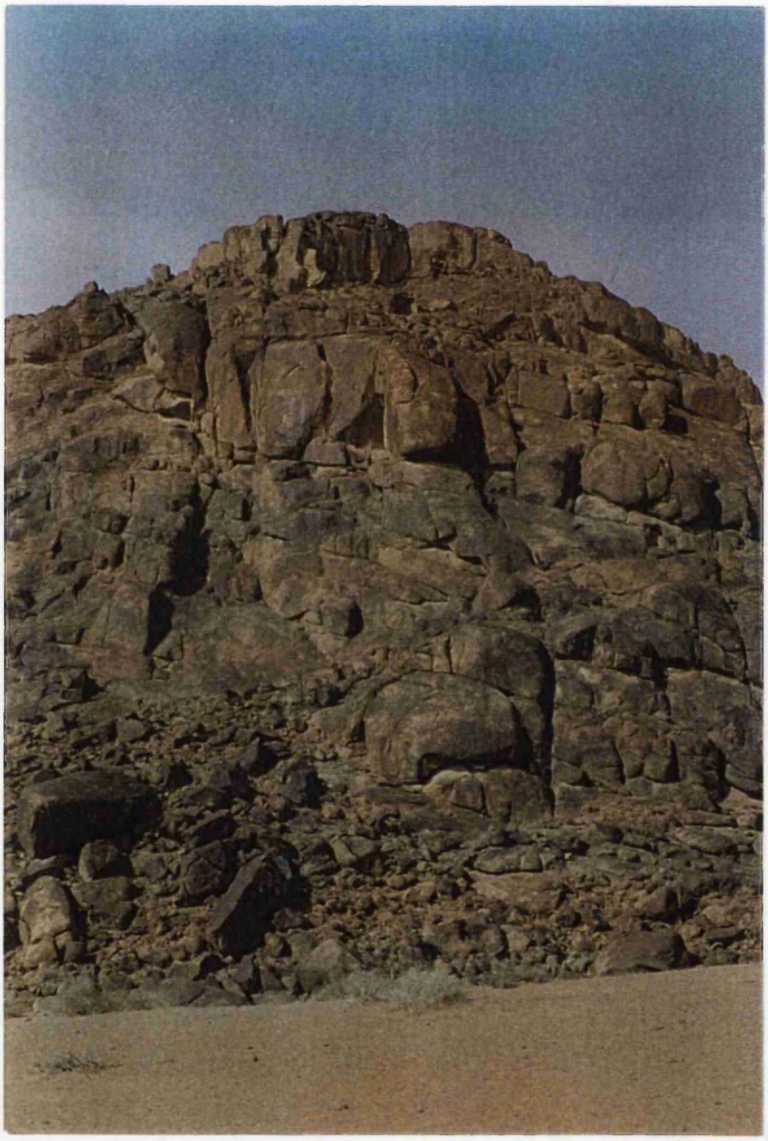


Plate IV.1: General view of joint pattern in study area (site1) weathered rocks have more open joints, with almost rough joint surfaces that are filled with sandy materials, probably in-situ weathered. The sound rocks have mostly tight and even joint surfaces. Some E-W joints are filled with vein material mostly quartz, with chloritized wall.

Data from each measurement location in each site were plotted in stereogram as poles to the joints, then contoured. The maximum concentration of pole plots were taken as main joint sets and their great circles were constructed. The plots were compared with each other. Generally, the pole concentrations show that the study area have mainly similar three joint sets (for example, **Fig. IV.11**): two subvertical of N-S and E-W trends, with a subhorizontal joint and the measurements in each rock unit are also very similar. Moreover the plots of the joint orientations between rock units in the study area are also very similar with minor differences (for example, **Figs. IV.11 and 12**). Therefore, data from measurement locations of the rock units in each site were gathered together into groups i.e. group of grey and pink granites and group of red granite in site 1, to see the main joint sets in each group, this grouping also is based on the results of the lineament density domains in site1 (**Figs. IV.6, 7**), grey and pink granites as one domain and the red granite as another domain.

As mentioned above, generally the first group of grey and pink granites of site 1 are very similar in structural styles as, those observations are based on the similarity of the joint poles plots. For example the joint orientations in measurement locations M9, M11, M8, 1/21/1 (pink granite locations) and H19 (grey granite locations) are very similar (**Fig. IV.11**, and have three main sets; two vertical sets of N-S and E-W trends and one subhorizontal joint set. The poles plots are highly scattered, particularly with the N-S trend.

The second group of red granite also has mainly three joint sets, N-S, E-W and subhorizontal one, as shown in the poles plots and contour diagrams of the joint readings in the measurement locations e.g. M12 and 1/19, (**Fig. IV.12**).

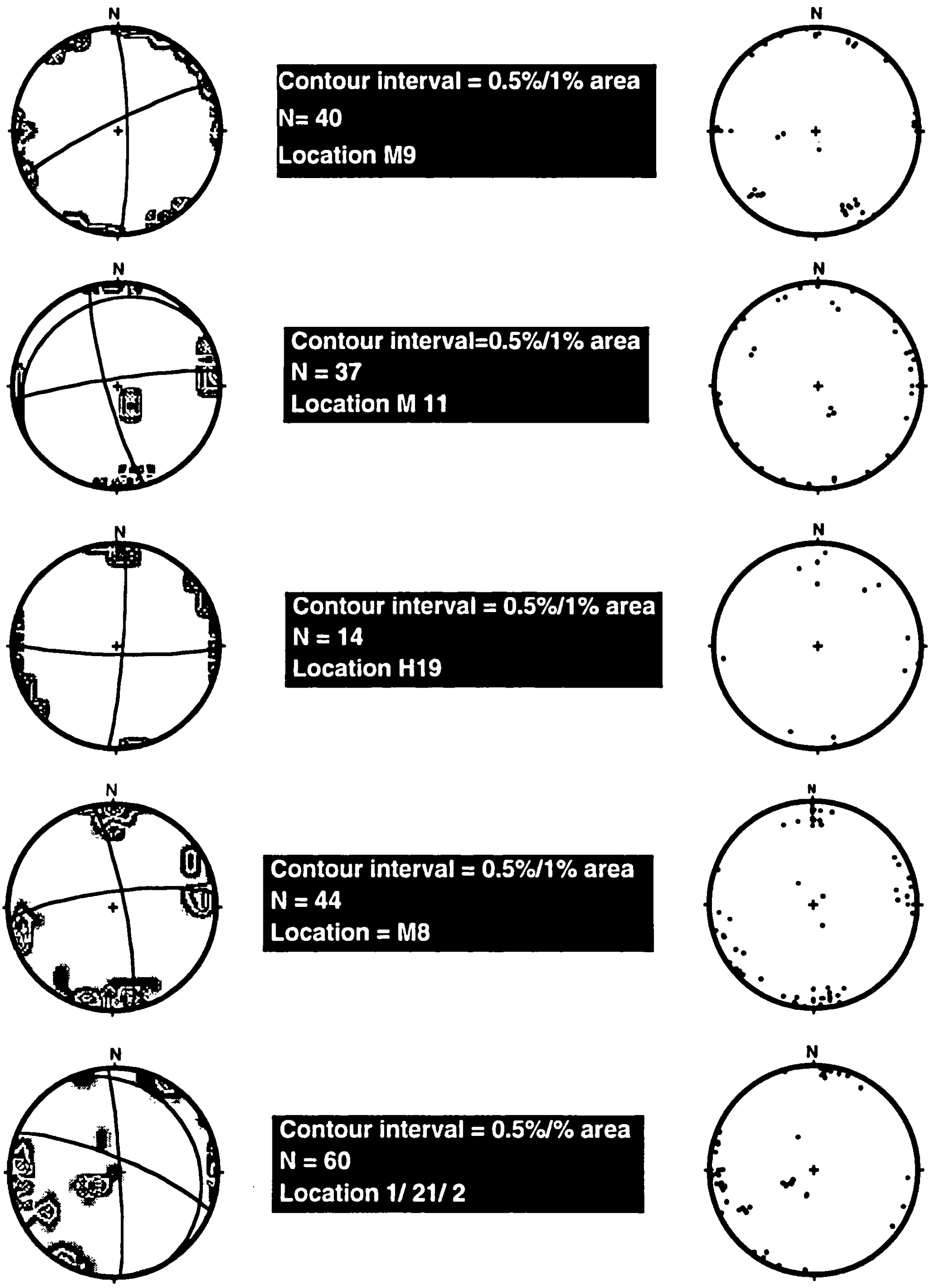


Fig.IV.11: Contour, scatter plot (equal area) and great circle of joints in site1 of grey and pink granites.

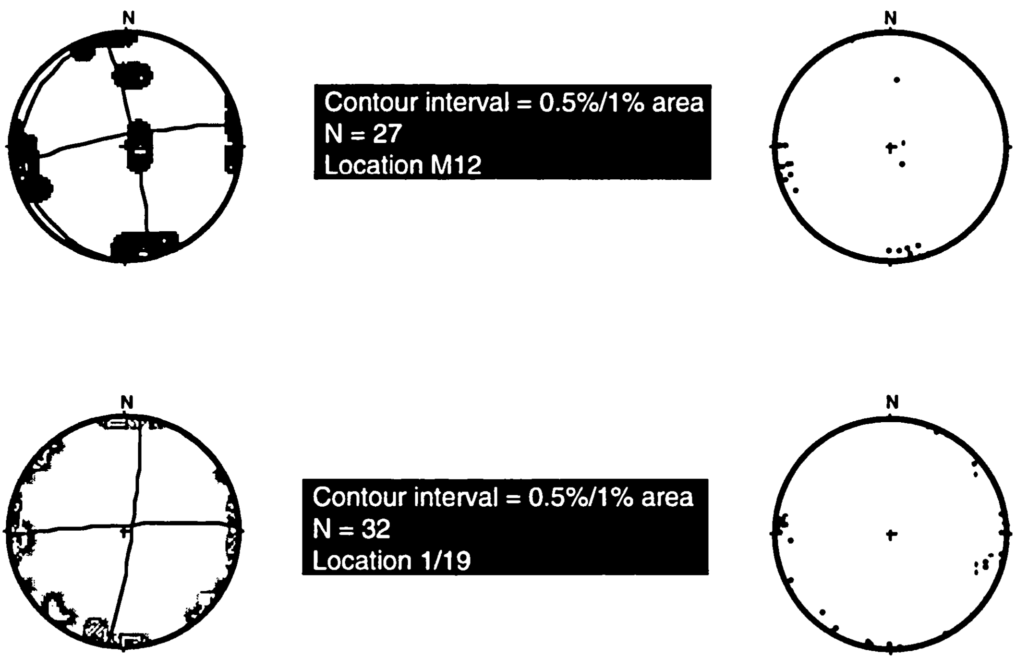


Fig. IV.12: Contour, scatter plot (equal area) and great circles of joints in site1 of red granite

There are minor differences in the orientations of the joints between the granites in site 1, These can be seen on the plots of the whole joints readings of grey-pink granites and red granite in site1 (**Fig. IV.13**). The similarities between the joint orientations may be due to a similarity in composition, age and deformation history. The minor variations may be due to differential uplifting, weathering and local effect by the deformations in the area.

Generally, the persistence and opening of the discontinuities in site 1 are also described. The E-W set is more persistent than the N-S joint set. The N-S set is more open, more frequent and more affected by weathering than the E-W set. Despite the lesser continuity of the N-S set, the rocks are more frequently dissected by this set than the continuous E-W sets. The greater continuity of E-W set makes the outcrop elongated and the N-S set makes the rocks dissected and sliced. This is more obvious in red granite where the outcrops are thinly elongated and tiny dissected and sliced.

The joint pattern in the grey granite of site 2 is very similar to the joint pattern in the pink granite as in site 1, therefore their joint data were gathered into one group. Similarly, the microgranite and granophyre joint data were also gathered together in another group. Generally, the plots of joint pole concentrations of site 2 indicate that the area has two joint patterns. The first one is mainly of three sets: two subvertical joints with N-S and E-W trends, and subhorizontal joints. This pattern is associated with the pink and grey granites (**Fig. IV.14**). The second group is of microgranite and granophyre. This pattern has three sets but with large scatter: mainly of two subvertical sets with one subhorizontal joint set (**Fig. IV.15**). This particular difference between the two groups (**Fig. IV.16)** is probably due to difference in rock type, weathering conditions and differential uplifting in the area.

Although there are some minor trends of NE and NW joint sets, both sites have three main joint sets, with N-S and E-W trends, and one subhorizontal set. Most of the joints in both sites are nearly vertical and the dips are greater than 80 degrees, (the trends swing from N-S to NE and NW directions). Those variations are probably caused by long term deformations.

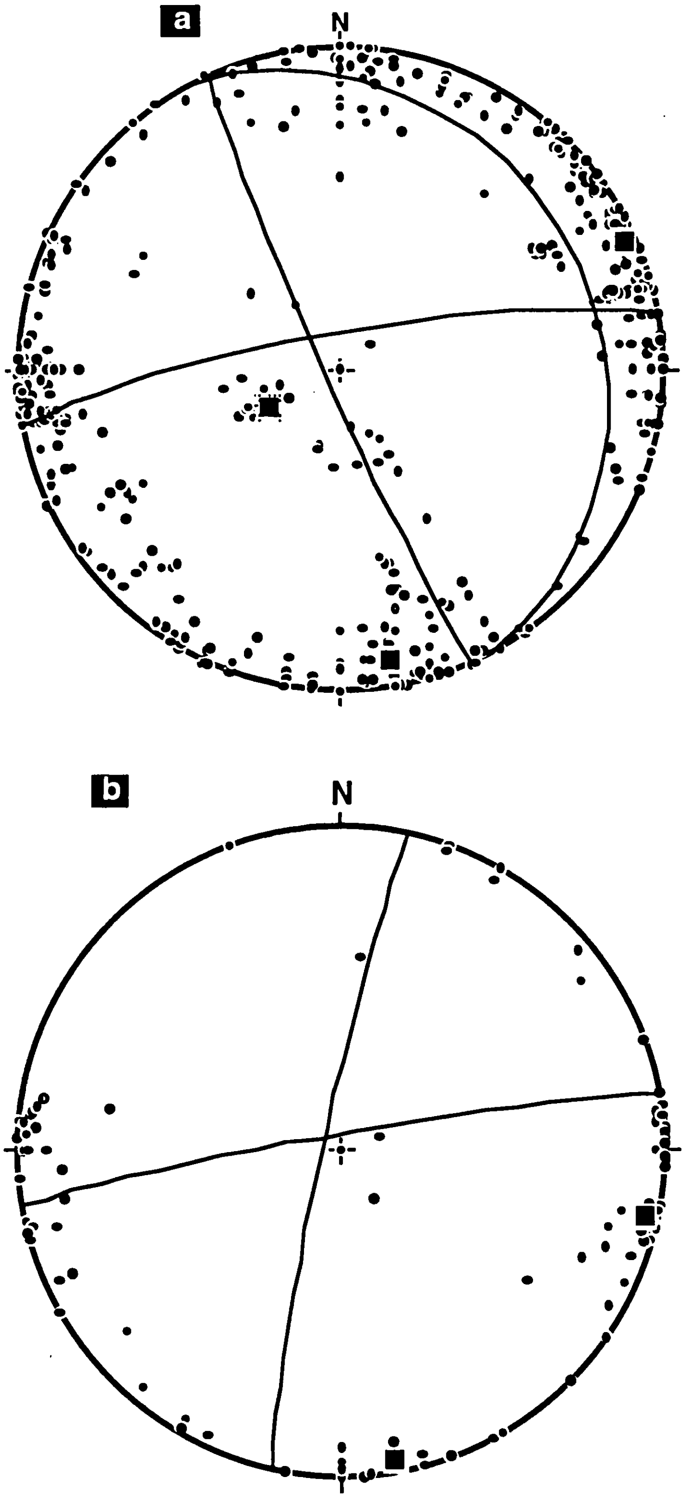


Fig. IV.13: Scatter plot and great circles of whole joint readings in site1
(a): Grey and pink granite. (b): Red granite

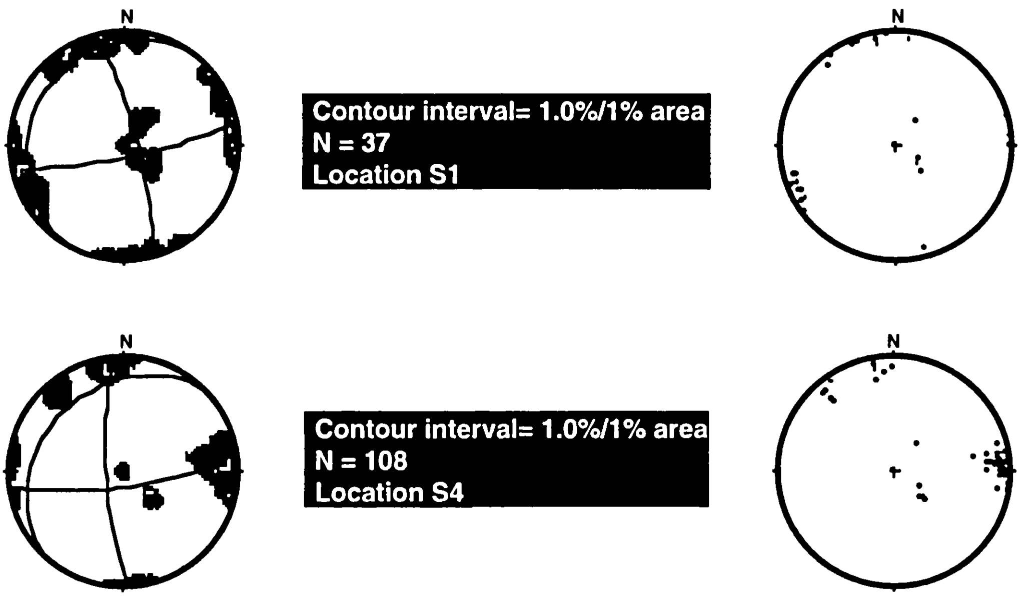


Fig. IV.14: Contour, scatter plot (equal area) and great circles of joints in site2 of grey and pink granite

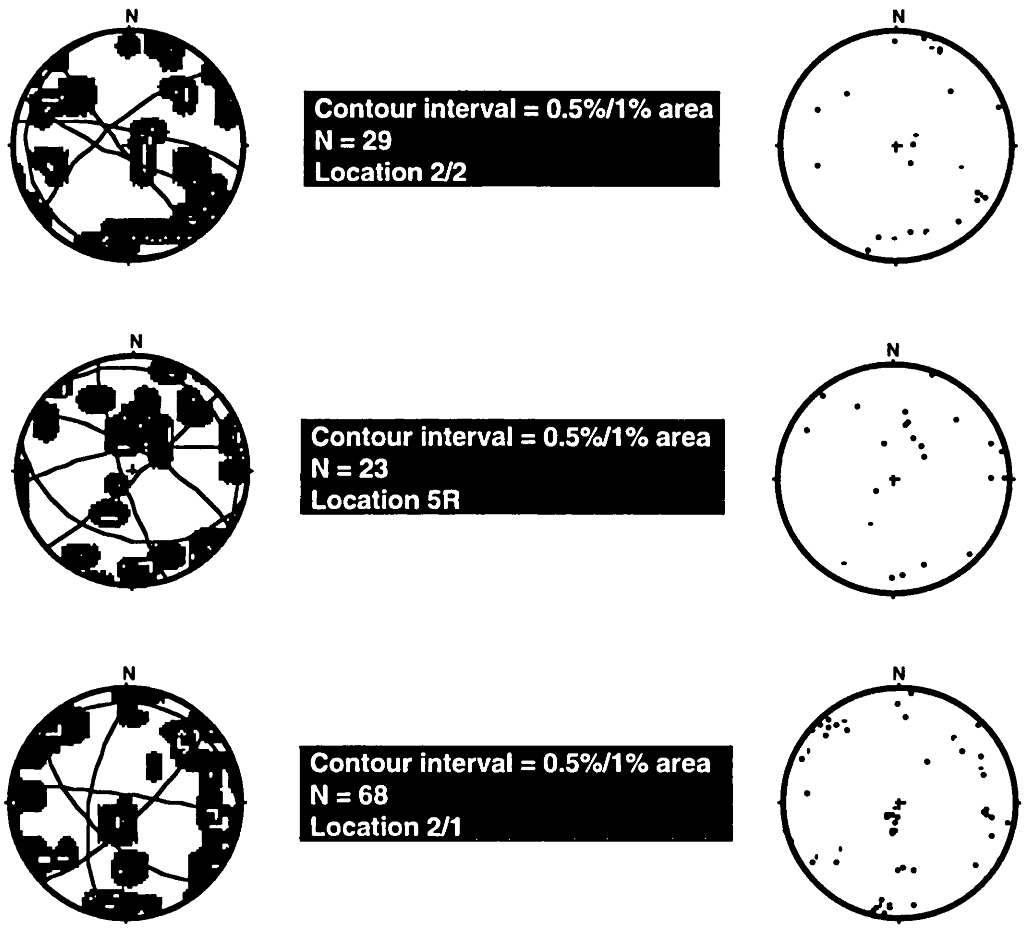


Fig. IV.15: Contour, scatter plot (equal area) and great circles of joints in site2 of microgranite and granophyre

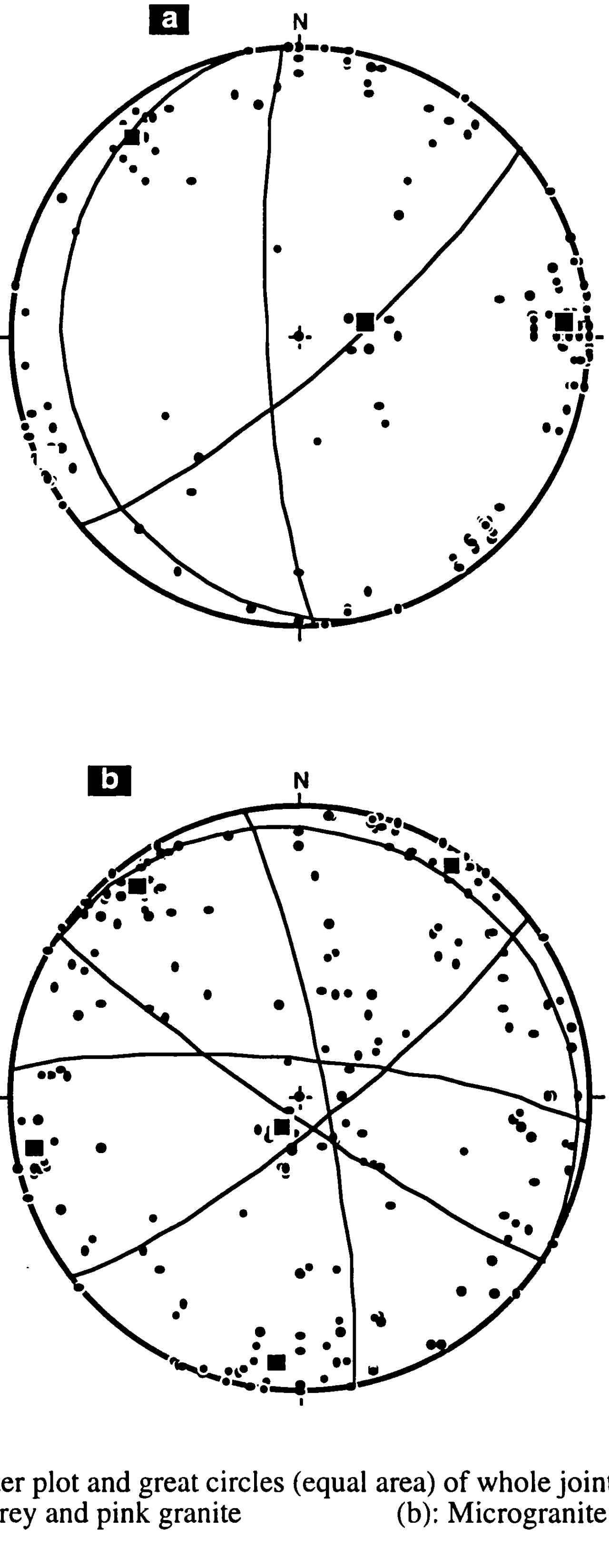


Fig. IV.16: Scatter plot and great circles (equal area) of whole joint readings in site2
(a): Grey and pink granite (b): Microgranite and granophyre

IV.3.3.2 Joint frequency and spacing

Generally, joint frequencies determined in the study area range from a low of 0.28 joints per meter (J/m) to high of 7.69 joints per meter. Both sites 1&2 exhibit similar joint frequencies. Grey and pink granite of sites 1 & 2 are mostly similar and have joint frequencies ranging from 0.28 up to 1.59 J/m. The red granite (site 1) and microgranite and granophyre (site 2) have higher joint frequencies than the pink and grey granites, ranging from 1.85 up to 7.69 J/m (Table **IV.2**). In the field joint frequencies noticeably increased in the pink granite closer to the boundary with the microgranites which mostly exhibits the highest values of joint frequency in the area.

From locations of the field measurements (**Figs. IV.17** and **18**), the joint spacing values in the study area were gathered into different groups based on the rock units, and also on the lineament and discontinuity analysis. These are grey and pink granites group, red granite group in site 1, and grey and pink granites group and microgranite and granophyre group in site 2. The mean spacings of each group were determined and presented in **Table IV.2.**

The grey and pink granite in site 1 have similar spacing values that range between 0.63m to 3.50m. The red granite exhibits the medium spacing values and ranges from 0.32m to 0.66m, with some exception in some localities of spacing values of 1.47m. Similarly, the spacing values of the grey and the pink granites in site 2 have range values of 0.86 to 3.08m, while the microgranite and granophyre exhibit the smallest (close) values of spacing of 0.12 to 0.28m. (**Table IV.2**).

IV.3.3.3 Discontinuity classification

To describe and classify the discontinuities, here I have used the geometrical parameters most relevant to dimension stone (as mentioned in the beginning of this chapter): joint orientation, number of sets and spacing. In this section the discontinuities are briefly classified, but they will be assessed more thoroughly in Chapter 6. Despite the minor joints, the study area are well jointed and have three main orthogonal joint sets: two vertical sets and one horizontal set.

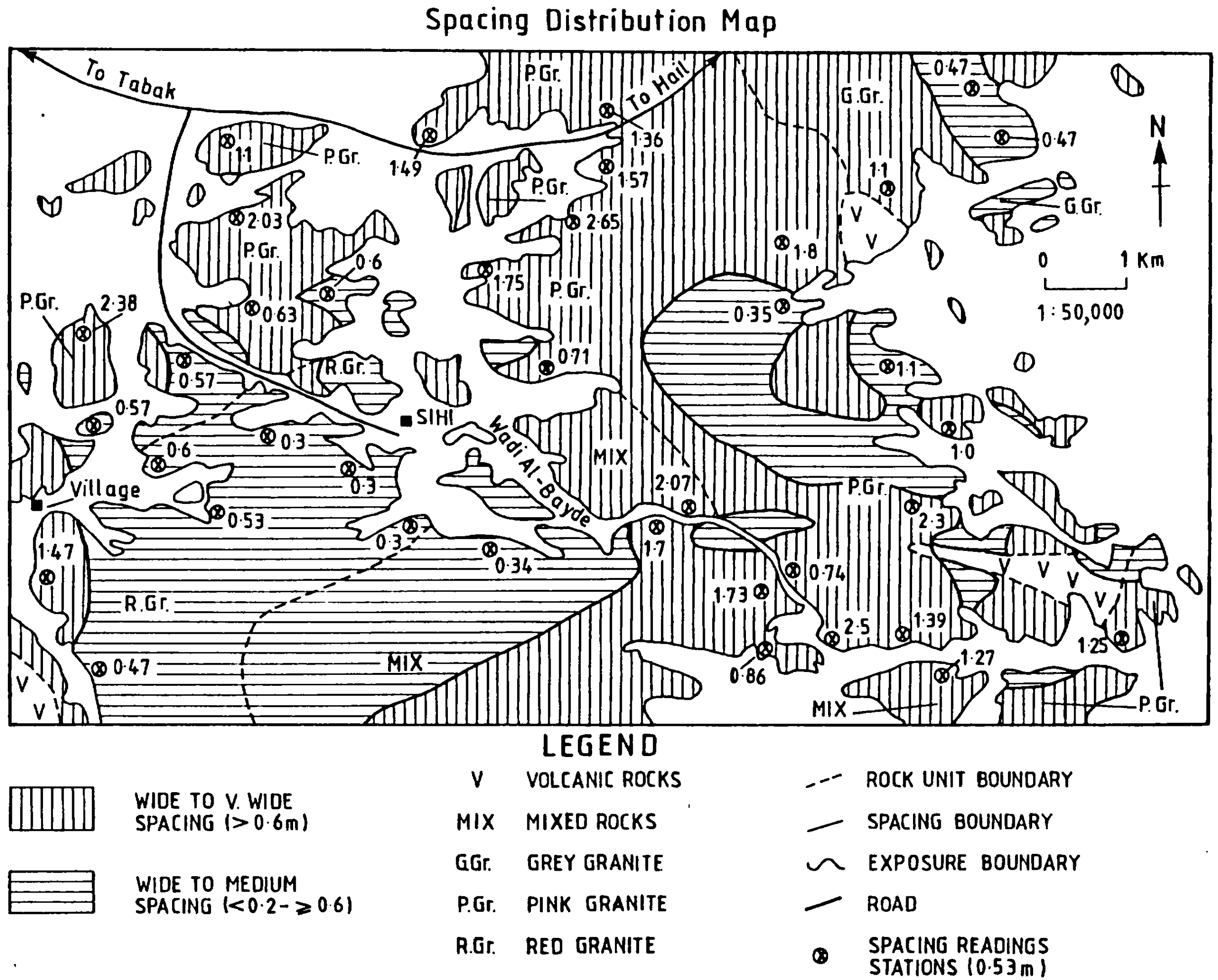


Fig. IV.17: Spacing distribution map in site 1

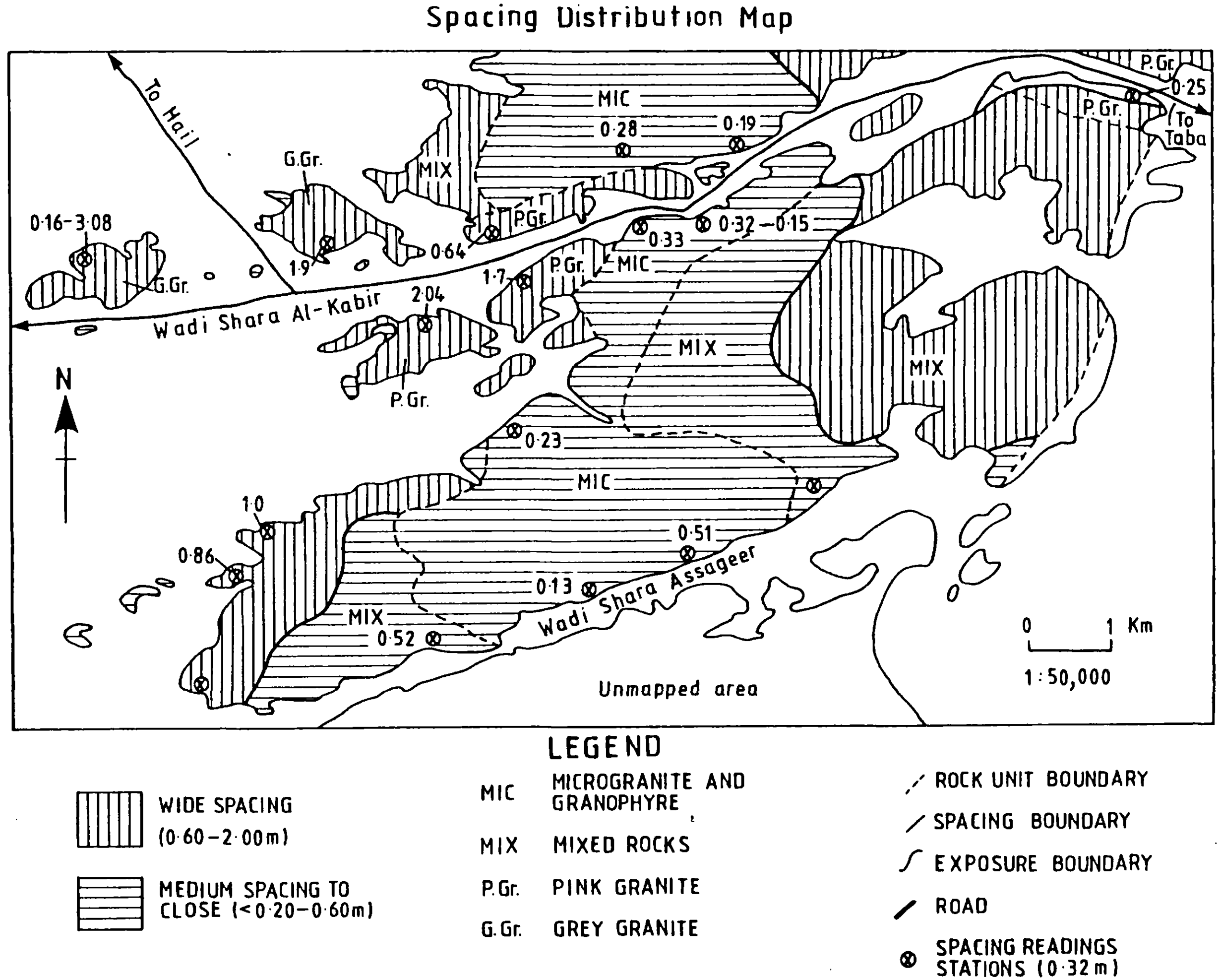


Fig. IV.18: Spacing distribution map in site 2

The spacing values in site1 are classified into two classes; wide and medium. The wide spacings are mostly greater than 0.6m. while the medium spacings are less than 0.6m (**Table IV.3**). Histograms of spacing values in the study area have been constructed, and these values have been classified according to the spacing classes after Anon (1995). The mean spacing values (**Figs. IV.19, 20**) show that the wide and medium classes of spacing are more dominant in site1, while site 2 (**Figs. IV 21, 22**) has more spacing classes (wide, medium and close) than at site1. The close spacing class (in site 2) is mostly associated with microgranite and granophyre rocks. It is noted in the field that the vertical spacing values are distributed quite similarly in all rocks in both sites. Therefore, the data from all rock are plotted in a single histogram to see the spacing classes (**Fig. IV.23**). From this histogram, the main class of vertical spacings in the sites 1&2 is medium class (0.3 – 0.6)m.

A spacing distribution map is constructed for the sites (**Figs. IV.17** and **18**) by grouping together locations with similar spacing class values. From these maps we can see that site1 (**Fig. IV.17**) has two spacing areas; the wide spacing class is mostly associated with the pink and grey granite, and the medium spacing class is mostly associated with the red granite, although, there are some wide spacing data for this lithology. Similarly, the spacing values in site 2 were classified into three classes; wide, medium and close. The wide spacings occur mostly in grey and pink granite while the medium and close spacing classes are mostly associated with the microgranite and granophyre (**Fig. IV.18**). From this map we can see that medium spacings occupy the largest areas in site2. Generally, the spacing distribution boundaries are not directly related to the geological boundaries; this can be seen clearly on both spacing distribution maps of both sites, although, occasionally the geological boundary is associated with the spacing distribution boundary (as in microgranite in site2).

By comparing the lineament density of site 1 & 2 with the joint spacings, it is found that a good correlation occurs between the distribution of the lineaments and the spacings. The areas of low lineament density less than 120 (L/km^2), are associated with the wide spacings (grey and pink granites), while the lineament density greater than 120 (L/km^2) is associated with the medium to close spacings (red granite, and microgranite and granophyre).

Table IV.3: Classification of discontinuity spacing

After Anon (1995)		**Site 1**		**Site 2**	
Measurement (m)	**Spacing (m)**	**Grey & pink granite (m)**	**Red granite (m)**	**Grey & pink granite (m)**	**Microgranite (m)**
> 2.00	Very wide	3.50		3.08	
0.60 – 2.00	Wide	0.63	0.66	0.86	
0.20 – 0.60	Medium		0.32		0.28
0.06 – 0.20	Close				0.12

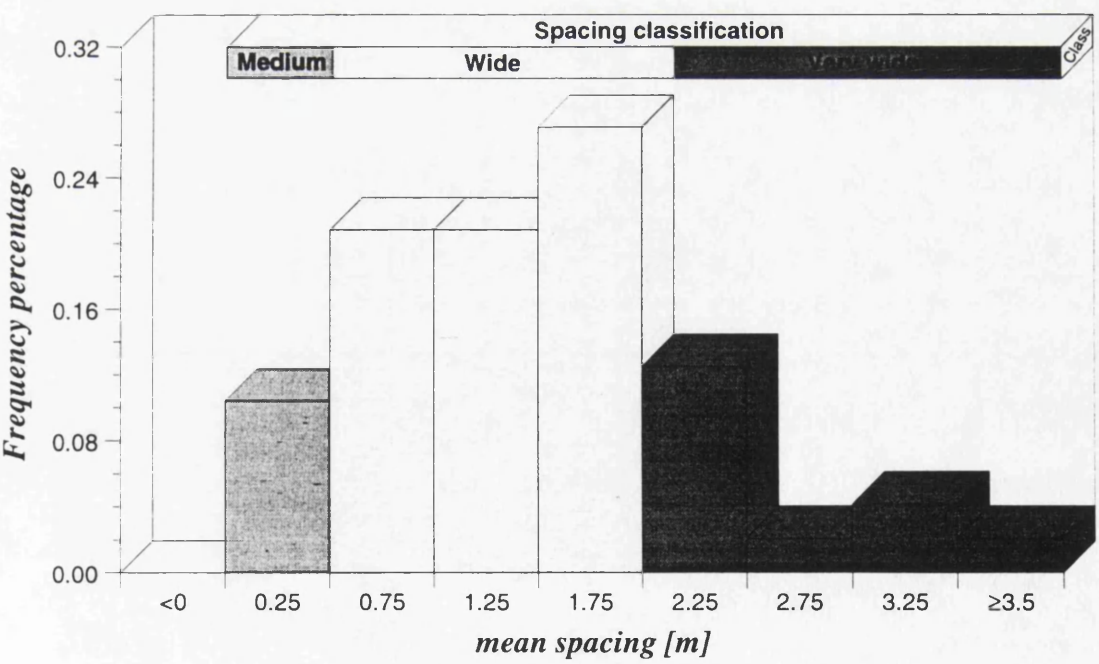


Fig. IV.19: Histogram of spacing classification of grey and pink granite in site1

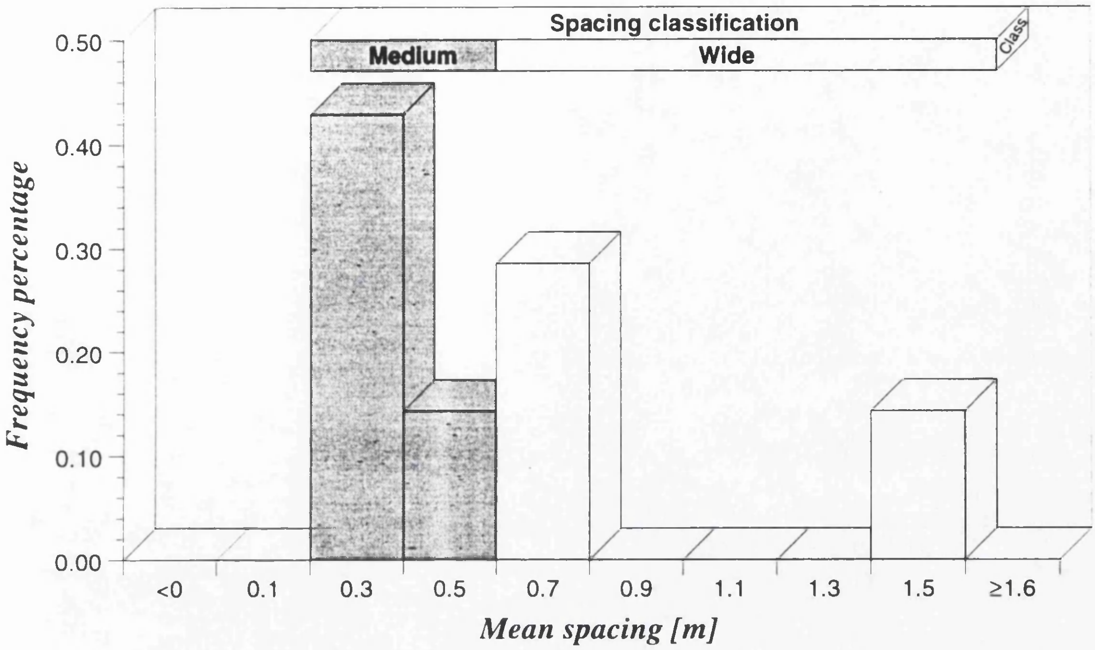


Fig. IV.20: Histogram of spacing classification of red granite in site1

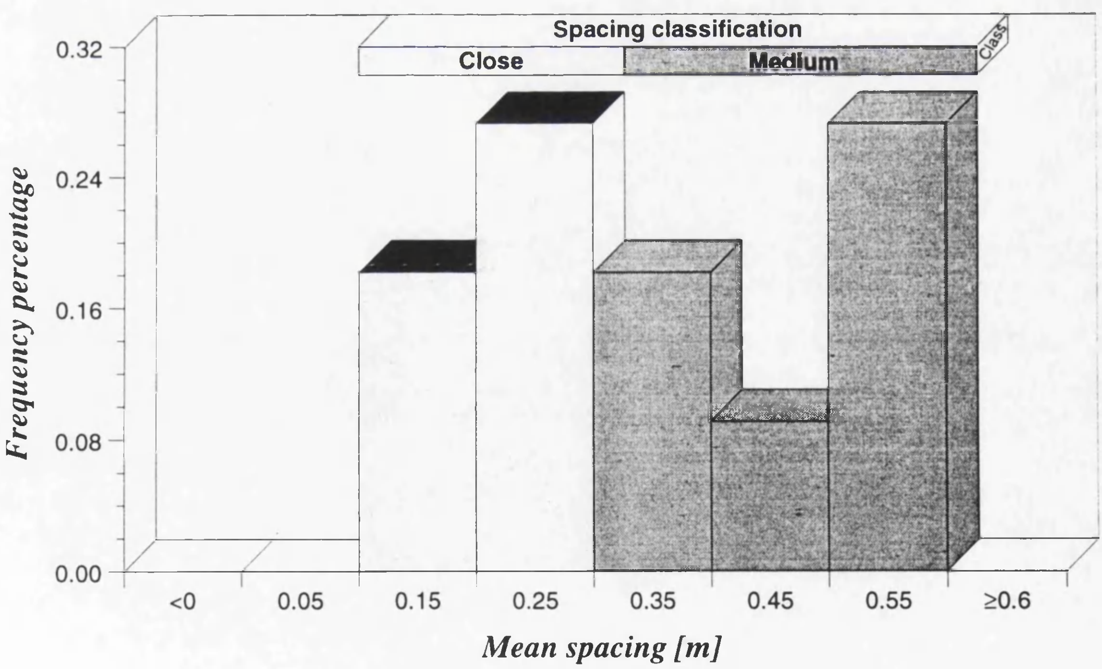


Fig. IV.21: Histogram of spacing classification of microgranite and granophyre in site2

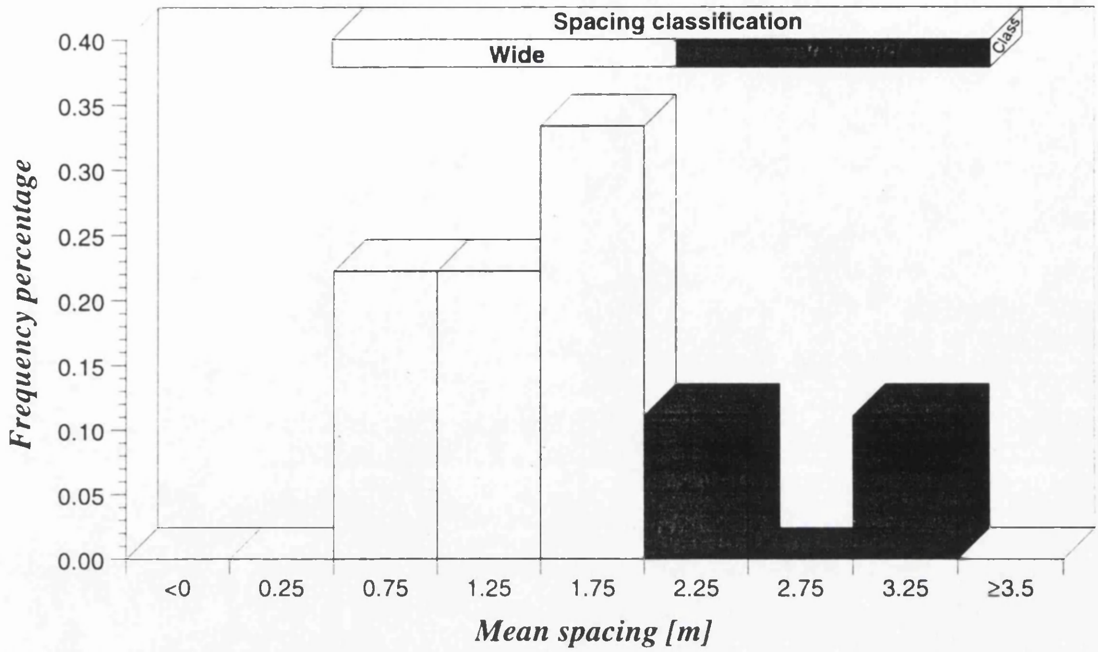


Fig. IV.22: Histogram of spacing classification of grey and pink granite in site2

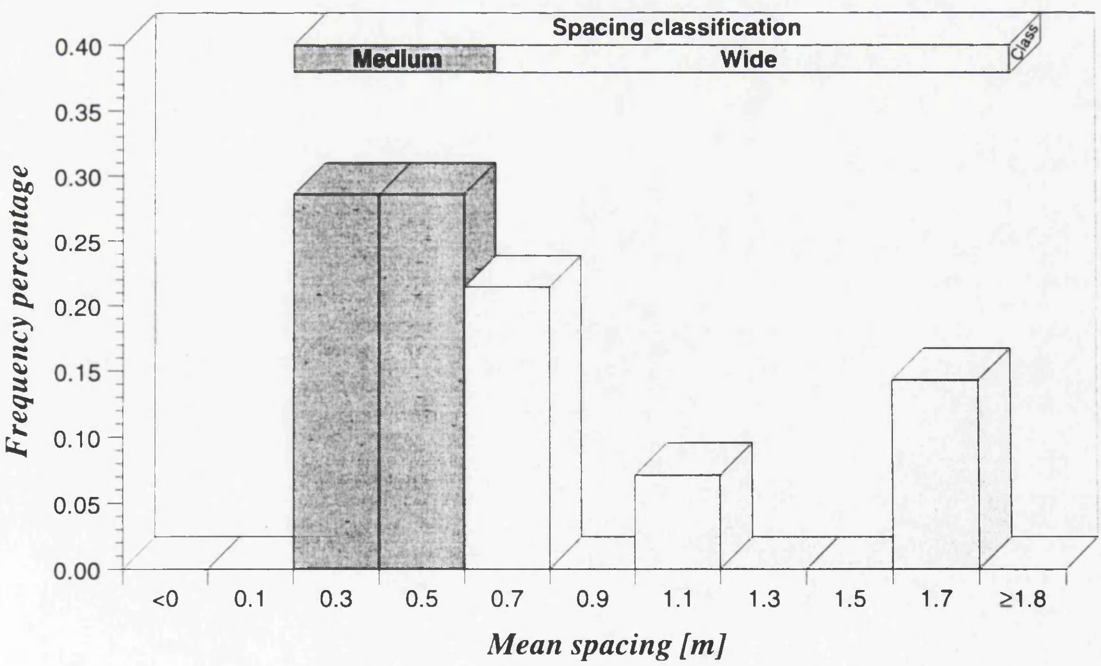


Fig. IV.23: Histogram of vertical spacing classification of granites in site1&2

IV.4 *WEATHERING*

Weathering is in general the result of two process acting together on the rock. These are physical weathering, which results in the disintegration of the rock by fracturing with minimal mineralogical changes, and chemical weathering, which results in a decomposition or alteration of the mineral constituents of the rock. Although the two processes may occasionally seem to act independently, their occurrence in isolation is extremely rare and most commonly one acts to enhance the other. Hydrothermal alteration, which results from the action of the hydrothermal fluids on the rock, can have effects which are similar to chemical weathering, leading to a change in the mineralogy. It forms secondary minerals which replace pre-existing components of the rock; these minerals are, generally, hydrous, and weaker than the mineral they replace.

IV.4.1 *Physical weathering*

Physical weathering can be defined as any process which leads to the disintegration of the rock. Actually, the fragmentation of the rock is mainly due to the change in stress level caused by many processes such as freeze-thaw, wetting-drying, or heating-cooling. The rupture of the rock material by these processes usually occurs along discontinuity surfaces and flaws within the material fabric (Fookes *et al.* 1988).

The freeze-thaw of water in the pore-spaces and open cracks can exert a stress up to 200 MPa (Ollier 1984 and Fookes *et al.* 1988). This magnitude of stress exceeds the tensile strength of most rocks. The repetition of the freeze-thaw process affects the rock integrity more than if the temperature is below zero and steady.

Salt crystallisation also causes disintegration of rocks. The process of crystallisation, thermal expansion, and especially hydration of salt within the pore-spaces of the rock builds up pressures of several tens of MPa, sufficient to disintegrate the rock (Winkler and Singer 1972 and Fookes *et al.* 1988). The process of crystal growth from saturated or supersaturated solution leading to rock disintegration is mentioned by Evans (1969).

Water is the most important agent of weathering. Alternate cycles of wetting and drying of rock material can lead to disintegration of the rock material, whether fresh or weathered. The fact is that clay minerals present in the rocks expand when wet and shrink when dry causing an opening and widening of microfractures within the rock (Ollier 1984 and Cawsey & Mellon 1983), presumably with stresses.

One of the main processes of physical weathering is disintegration following thermal expansion. This phenomenon is characteristic in arid environments. The mechanism of disintegration can be explained by the fact that rocks are generally a poor conductor of heat and the constituent minerals have different coefficients of thermal expansion, and the majority are anisotropic with respect to thermal expansion. Generally, the differential expansion of different minerals causes a development of stress along the grain contacts which can cause crack initiation and opening.

IV.4.2 *Chemical weathering*

The processes involved in chemical weathering or mineral decomposition are oxidation, hydration, hydrolysis, carbonation, and solution (Bell 1983b). Chemical weathering can be achieved by nothing more than the meeting of rock and water (Ollier 1984). Water is the most active agent of weathering, not just in hydrolysis, but also for the removal of soluble components allowing the reactions to proceed (Keller 1978). Decomposition of rock also results from the migration of chemically active solutions which are directly or indirectly caused by igneous activity (such as a nearby magma chamber or volcanic vent) as its thermal energy which causes movement of fluids, this hydrothermal alteration typically is more pervasive, as it may progress through the rock at depth where discontinuities are not present in large numbers (Johnson and DeGraff 1988). The end result of alteration of this sort or that from chemical weathering is essentially the same from the engineering standpoint, that is, a weakening of the rock mass (Johnson and DeGraff 1988).

In the chemical decomposition of granite, quartz remains largely unchanged. Biotite is bleached, and transformed to alteration minerals such as chlorite or other clay minerals.

The release of iron leads to a general brown or reddish staining of the rock. The feldspars alter to a variety of clay minerals (Loughnan 1969).

IV.4.3 *Effect of Weathering on Engineering Properties*

The engineering properties of rocks are closely related to their structural, textural, and mineralogical characteristics, and as a result, are affected by changes in weathering or alteration. Generally, these changes cause a decrease in the strength of the rock and make it more deformable. The permeability may increase or decrease depending on the nature of the rock, the presence and type of weathering products, and the stage of weathering. The weathering effect is reflected by a change in the index properties such as the relative dry density, seismic velocity, Schmidt rebound number, and clay content (Anon 1995).

Chemical weathering is associated with the growth of voids as well as the formation of secondary minerals such as clays. The potential for collapse of the framework of relic minerals, together with the influence of secondary minerals, are the factors that distinguish the engineering behaviour of weathered rocks. New fractures are created whether physical or chemical processes dominate. These new fractures are the result of a change in the state of stress within the material leading to its weakening (Anon 1995). Typically such fractures extend from grain boundaries but may also develop across grains. Incipient discontinuities such as cleavage may also become open. Therefore, the strength of the rock, as reflected by the such as uniaxial compressive strength, is reduced significantly as weathering increases. Ebuk *et al.* (1993) showed that the clay content of a weathered rock has an influence on its brittleness.

Intact rock strength and fracture spacing both change in response to weathering. Fracture spacing normally decreases with increased weathering grade (Beavis 1985).

IV.4.4 *Weathering classification*

Weathering has a great influence on the engineering properties of rocks. This influence may manifest in several aspects such as the reduction of strength, fracture, colour, fabric, and textures. The material's physical and mechanical properties are directly related to its state of weathering as expressed by the amount of secondary mineral content, the intensity of fracturing, the discoloration, the fabric, or the texture. Therefore, the purpose of a weathering classification is to provide a means to describe the geological condition of rocks and their associated engineering characteristics. Weathering grade classification is also beneficial in that it provides a framework within which test results can be interpreted and linked to the material's engineering performances. It also allows simple, field-determined index properties to be related to engineering properties such as strength characteristics.

Many weathering classifications have been developed. The earliest attempts to classify weathered rocks in a way which might be useful to engineering were by Moye (1955) and Ruxton & Berry (1957). The Moye classification used six grade classifications: fresh, slightly weathered, moderately weathered, highly weathered, completely weathered, and soil, while the Ruxton & Berry classification scheme used four zones of weathering for rock masses. Followed by many schemes of classification, the most important ones is Anon (1970) which is mainly based on the Moye (1955) classification. A brief review of weathering classifications has been presented by Anon (1995).

Recently, there have been new approaches suggested for the description of weathered rocks for engineering purposes (e.g. Anon 1995). The classification of rock weathering is controlled by the wide range of rock types, which will differ in their styles of weathering related to different weathering processes. Inevitably, therefore, different approaches will be required in different situations and at different scales, rather than trying to adopt one general scheme of weathering classification for rock. Five approaches for description and classification of weathering have been suggested depending on the geological conditions, the scale of the problem, the exposure available and the particular requirements of the engineering problem in hand. These approaches can be described briefly as follows.

Approach 1 covers the general description of weathering features in rock and is mandatory as it forms part of a full description. This description will not involve formal classification but might provide sufficient information for the user subsequently to classify for a particular purposes (see **Table IV.4**). This approach is applied where the full profile of the rocks is not seen.

Table IV.4: Approach 1: Factual description of weathering (After Anon 1995)

Standard description should always include comments on the degree, extent and nature of any weathering effects at material or mass scales. This may allow subsequent classification and provides information for separating rock into zones of like character. Typical indications of weathering include: ❊ Changes in colour ❊ Changes in fracture state ❊ Change in strength ❊ Character and extent of weathering products These features should be described using standard terminology, quantified as appropriate, together with non-standard 'English' descriptions as necessary to describe the results of weathering. At the mass scale, the description and proportions of the variously weathered materials (e.g. corestones Vs matrix) should be recorded.

Approach 2 classifies gradation of weathering of intact rock material. The classification is based essentially on strength as determined by a simple field test such as the Schmidt hardness test as suggested by Hencher & Martin (1982). The classification has six grades; Grade I (fresh); Grade II (slightly weathered); Grade III (moderately weathered); Grade IV (highly weathered); Grade V (completely weathered); Grade VI (residual soil) (**Table IV.5**). Hencher & Martin (1982) used the N (Schmidt rebound value) to distinguish between the grade of weathering, for example, N >45 is associated with Grade II, Grade III has N from 25 to 45 and in Grade IV, N ranges from 0 to 25. Moreover, examples given by Anon (1995) indicate that Grade III-IV has N = 20 to 30 and Grade V= 0 to 12. They also mention that this suggestion only applies to in situ materials, such as outcrop, not cores.

Approach 3 is for rocks which develop weathering profiles that consist of a mixture of relatively strong and weak material and for which a classification is concerned with distinguishing relatively large zones of different engineering classifications. The classification is based on a zone scheme, such as zone1 (zone 1 composed of 100% of rock material weathering grades (Grade I-III). Zone 2 composed of >90% material grades I-III and <10% material grades IV-VI (**Table IV.6**).

Approach 4 is for rocks in which the nature and scale of the heterogeneities developed during weathering is such that a simple classification scale incorporating both intact material and mass characteristics is appropriate. This classification is more suitable to rocks which are moderately weak in their fresh state, such as sedimentary rocks (**Table IV.7**).

Table IV.5: Approach 2: A prescriptive weathering classification for uniform materials (After Anon 1995)

Grade	*Classifier*	*Typical Characteristics*
I	Fresh	❖ Unchanged from original state
II	Slightly Weathered	❖ Slight discolouration, slight weakening
III	Moderately Weathered	❖ Considerably weakened, penetrative discolouration ❖ Large pieces cannot be broken by hand
IV	Highly Weathered	❖ Large pieces can be broken by hand ❖ Does nor readily disaggregate (slake) when dry sample immersed in water
V	Completely Weathered	❖ Considerably weakened ❖ Slake ❖ Original texture apparent
IV	Residual Soil	❖ Soil derived by in situ weathering but retaining none of original texture or fabric

Table IV.6: Approach 3: A prescriptive weathering classification for heterogeneous masses (After Anon 1995)

Zone	*properties of material grades*	*Typical characteristics*
1	100% G I–III (not necessarily all fresh rock)	Behaves as rock; apply rock mechanics principles to mass assessment and design
2	> 90% G I–III < 10% G IV–VI	Weak materials along discontinuities. Shear strength, stiffness and permeability affected
3	50 to 90% G I–III 10 to 50% G IV–VI	Rock framework still locked and controls strength and stiffness; matrix controls permeability
4	30 to 50% G I–III 50 to 70% G IV–VI	Rock framework contributes to strength; matrix or weathering products control stiffness and permeability
5	< 30% G I–III > 70% G IV–VI	Weak grades will control behaviour. Corestones may be significant for investigation and construction.
6	100% G IV–VI (not necessarily all residual soil)	May behave as soil although relict fabric may be still be significant.

Table IV.7: Approach 4: A prescriptive weathering classification for soft rocks incorporating material and mass features (After Anon 1995)

Class	*Classifier*	*Typical characteristics*
A	Unweathered	Original strength, colour fracture spacing
B	Partially weathered	Slightly reduced strength, slightly closer fracture spacing, weathering penetrating in from fractures, brown oxidation
C	Distinctly weathered	Further weakened, much closer fracture spacing, grey reduction
D	Destructured	Greatly weakened, mottled, ordered lithorelicts in matrix becoming weakened and disordered, bedding disturbed.
E	Residual or Reworked	Matrix with occasional altered random or "apparent" lithorelicts, bedding destroyed. Classed as reworked when foreign inclusions are present as a result of transportation

Approach 5 (**Table IV.8**) is for rocks whose weathering state do not follow the above approaches: for example, special landforms such as karst, or special rocks such as evaporites. The requirement is to give a full description (Approach 1), and then to apply a classification, if required, at a site specific level.

Table IV.8: Approach 5: Special cases (After Anon 1995)

For rocks whose weathering state does not follow the other patterns indicated here, such as karst in carbonates and the particular effect of arid climates.

IV.4.5 *Rock weathering index tests*

In the case of weathering classification, the purpose of using index tests is to provide definitive guidance as to the grade of weathering. Many studies have been conducted to provide useful index tests to describe the weathering, for example Lee & De Freitas (1989) and Irfan & Dearman (1978b). They adopt tests which can be used to identify the changes which occur during weathering, and the alteration of properties and aspects of rocks such as petrographic and chemical changes, changes in density, porosity and water absorption, and changes in the physical behaviour, including strength, friability and slaking.

Irfan & Dearman (1978b) stated that the Schmidt hammer, point load strength and quick absorption tests comply most fully with the requirements of index tests for classification purposes. Martin (1988) suggests that the ultrasonic velocity index and the consistency index are also useful. Irfan & Dearman (1978b) mentioned that dry bulk density can be used to estimate point load strength, uniaxial compressive strength and absorption index.

IV.4.5.1 *Schmidt Hammer as an tool for weathering classification*

(i) Rebound hardness test

The Schmidt Hammer measures the hardness of a rock exposure (Olivieira 1994). It is one of the index tests used to characterize the degree of weathering, as well as for indirectly estimating rock strength (Irfan 1996). The rebound hardness is determined from the rebound of an object that is dropped or impacted on the surface of the rock. The Schmidt hammer was developed in Switzerland for estimating the in situ strength of concrete by Schmidt (1951). Subsequently it was found to be a useful tool and convenient testing device for rock strength assessment, as it can be used in both the field and the laboratory. The popularity of the Schmidt hammer derives from its small size and weight, its use in the laboratory and field, and the simplicity of its operation. When used properly it yields consistent results.

The Schmidt hammer consists of a long, narrow solid piston (the hammer) held inside a steel cylinder. A spring allows the hammer to be primed inside the cylinder. It is pressed against a level spot on a rock surface with the hammer held at right angle to the surface, and a catch holds the hammer in position. When the piston is fully primed the catch is released and the hammer impacts the rock and rebounds from the rock surface to a height recorded either by a simple needle or on a graph recorder. The reading known as the rebound number *N*, depends on the elasticity of the material tested and the hardness of its surface. The recommended operation procedure is to conduct five sequential impacts at a selected spot without removing the plunger. This technique reduces data variations caused by small surface irregularities. By the fifth impact any surface roughness has been reduced and a repeatable reading should be obtained (Poole & Farmer 1980). The ISRM (1978a) recommended 15 impacts and the mean of the highest readings to be taken as *N*.

The strong correlation between *N* and the uniaxial compressive strength for a variety of rock materials enabled Deere & Miller (1966) to establish a correlation chart **(Fig. IV.24)** from which the uniaxial compressive strength can be derived if its dry density is

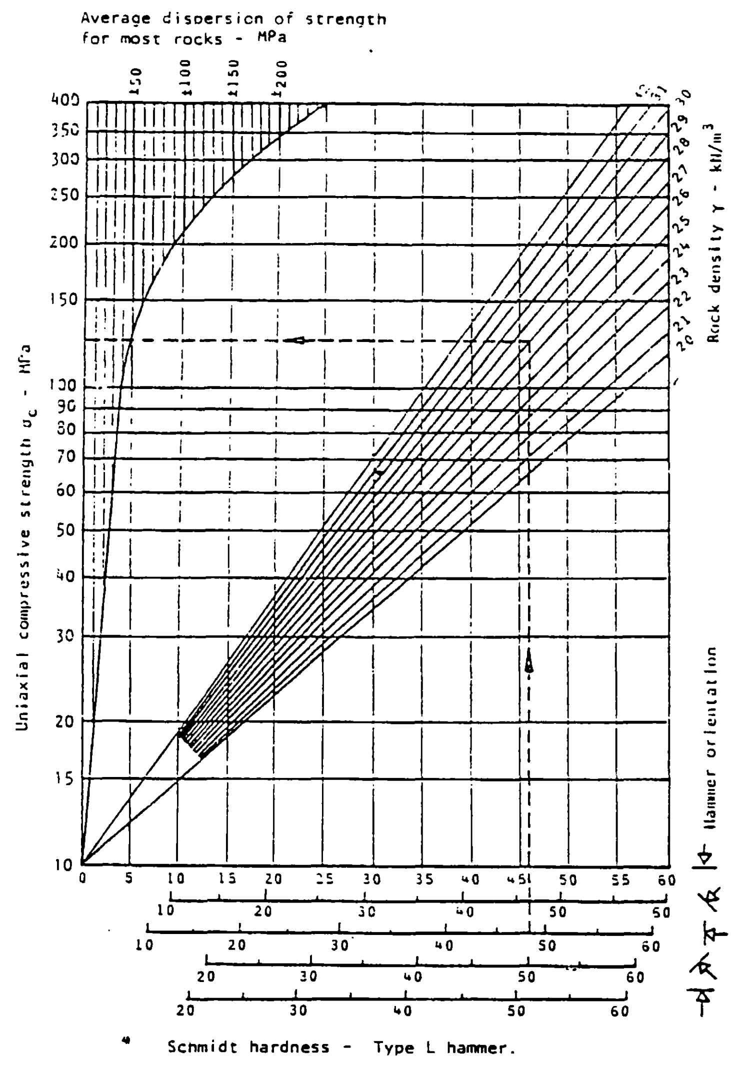


Fig. IV.24: Correlation chart for Schmidt hammer, relating unit weight of rock, compressive strength and rebound number (*N*) (after Deere & Miller 1966) known. The chart has been recommended by many authors such as Duncan (1969) and Dearman (1974), but Anon (1977) found that there is only 75% probability that the laboratory determined uniaxial compressive strength would fall within 50% of the strength derived from the Schmidt rebounds using the correlation chart of Deere & Miller (1966). They suggested however that the uniaxial compressive strength can be obtained by multiplying *N* by the dry unit weight of the rock.

(ii) Factors influencing Schmidt rebound number

Several factors are known to affect the rebound number, among them are:

1. The plunger of the hammer must be in good condition. It was reported when the plunger is worn the hammer can give variable energy of impact which leads to variable values of *N* (Poole& Farmer 1980).
2. The plunger should be tightly held perpendicular to the rock face in a vertical plane unless corrected.
3. The surface of the specimen should be flat and smooth at least over the area covered by the plunger.
4. If the specimen under test is in a wet condition the results can be unreliable especially if the material is weak.
5. It was found that the size of the specimen under test affects the rebound number (Carter & Mills 1976). The ISRM (1978a) recommended that the area under the plunger should be free from cracks or any localised discontinuity at least to a depth of 6cm under the spot.

IV.4.6 *Weathering conditions in the study area*

IV.4.6.1 General

The weathering grades have been studied in site 1&2 at many locations (**Figs. 25,26**). In each location, data was collected of rock type, visual estimation of weathering grade and *N* Schmidt hammer reading of the outcrops were also determined. Also *N* readings on the rock samples have been recorded to compare with the in situ *N* values. The *N* readings were plotted on the measurement locations (**Figs. 25, 26**), then the whole *N* values of each rock unit were gathered together and plotted as histograms to see the overall

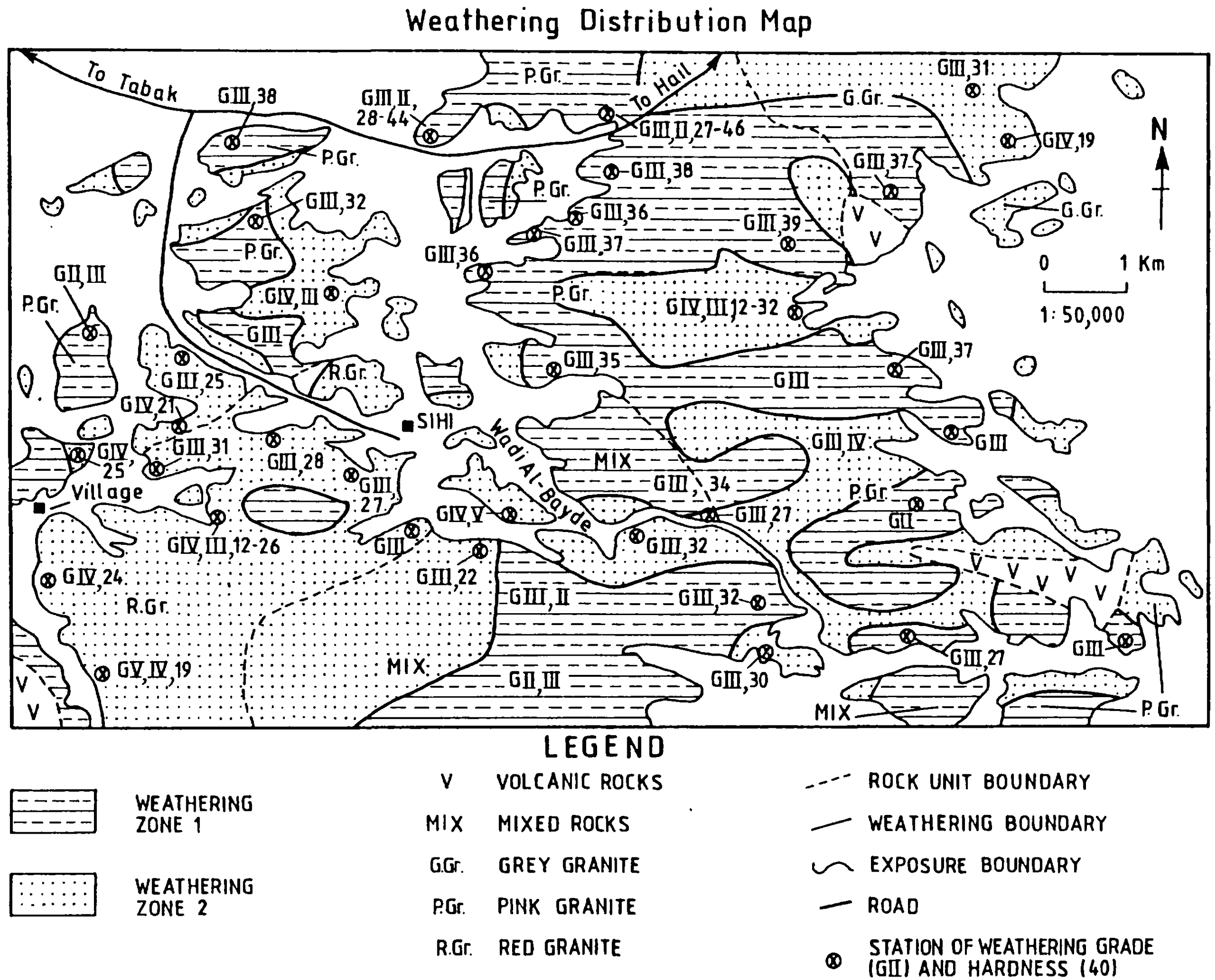


Fig. IV.25: Weathering distribution map in site 1

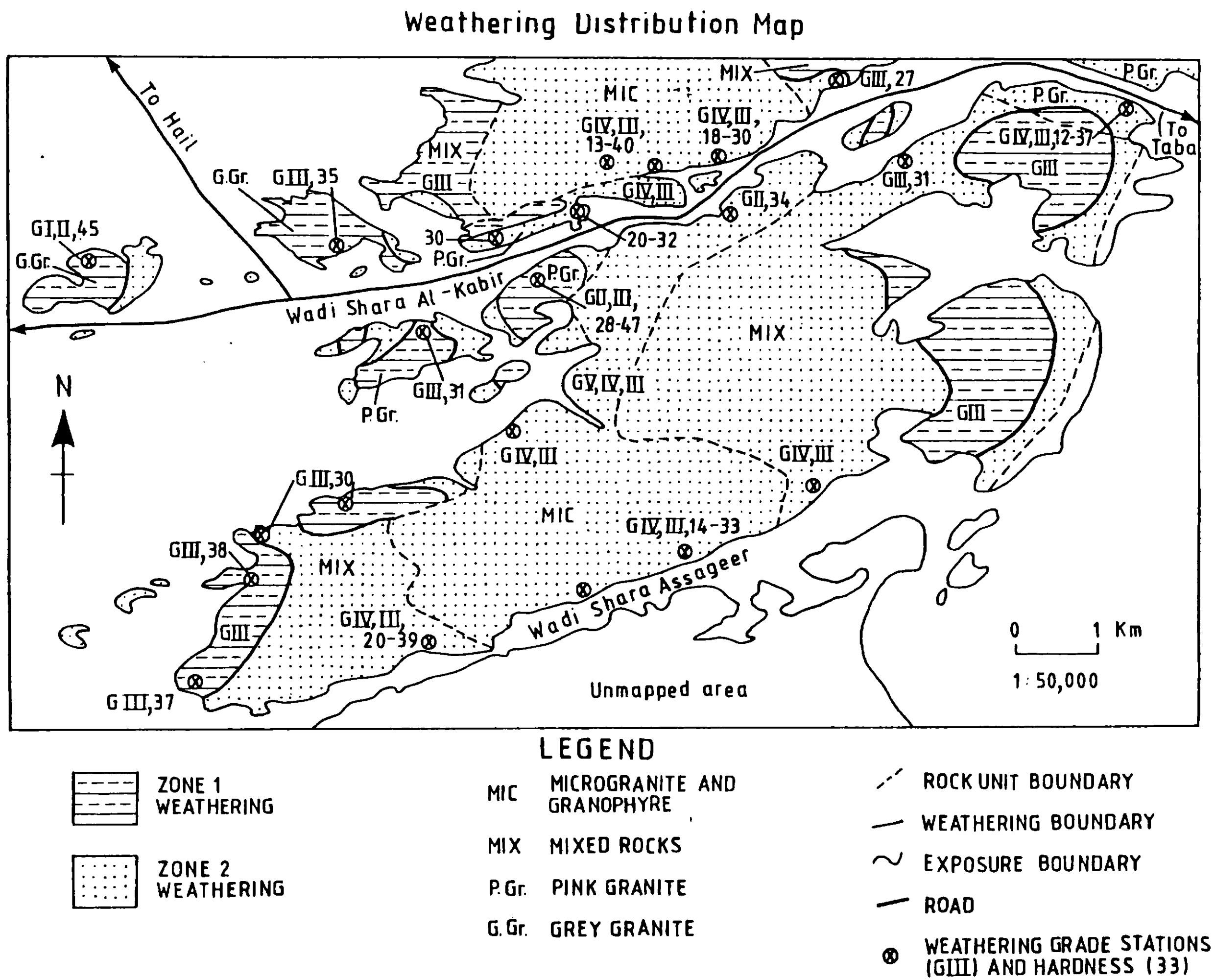


Fig. IV.26: Weathering distribution map in site 2 distribution of the N values. The minimum and maximum N values also for each rock unit have been plotted as histogram to see the range of N values. The rock grade weathering was estimated according to Approach 2 and correlated with the N values. Then due to the fact that the study area consist of a mixture of relatively strong and weak material, the Approach 3 was applied in order to see zones of rock material weathering grades, to produce the weathering distribution map. This map together with the spacing map produce the engineering geological map which is presented in Chapter VI.

IV.4.6.2 *Weathering features in the study area*

Generally, the rocks of study area (sites 1& 2) are affected by weathering to greater or lesser degrees depending on the location and rock type. The depth of weathering is variable and ranges from 5 to 15m in depth. Physical and chemical weathering processes occur together, with a possible hydrothermal alteration process which may have influenced the area. Several features of physical and chemical weathering were recognized in the area: these are described below.

(i) Physical weathering features

Physical weathering features, such as sheeting joints, exfoliation domes, rock fragmentation, development of columns and pillars (Monroe & Wicander 1995 and Montgomery 1990), are recognized in the area. In the field the granite bodies occur in domal shapes **(Plate IV.2)**, in which most of the top part of these bodies has been affected by skin weathering ranging in depth between several centimetres, and up to 5 to 15 m. These features mostly form in grey and pink granites, where sheeting joints are formed, and are associated with peeling and exfoliation surfaces with hole features.

Fragmentation (disintegration) of the rocks also occurs in the area, but it is more apparent in the red granite, and microgranite and granophyre areas **(Plate IV.3)**, This may be due to the fact that these areas are intensively fractured. The weathering products of red granite, and microgranite and granophyre are mostly characterised by shattering and brecciation of small blocks and sharp, angular lithic fragments which accumulate downslope of the mountains.

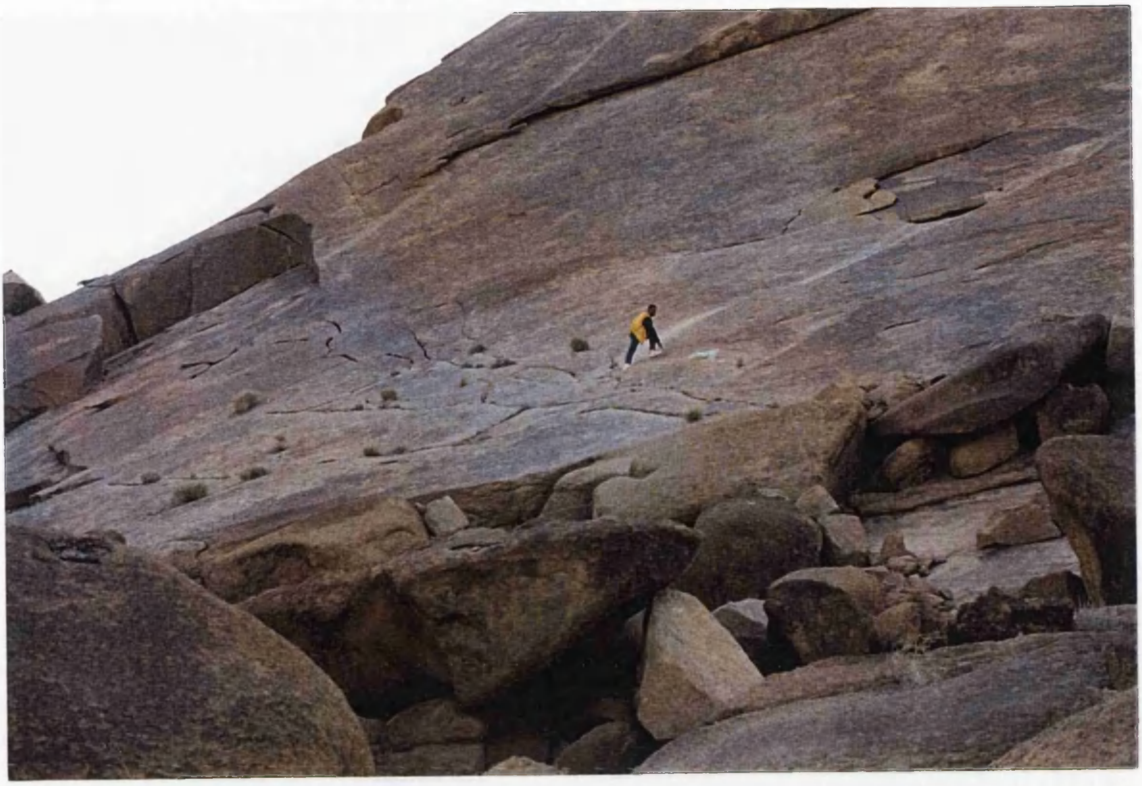


Plate IV.2: Domal weathering form in granites (site 1)

Plate IV.3: Fragmentation weathering in granites (site 2)

The development of columns occurs as result of weathering along fractures **(Plate IV.4)**, causing opening of these fractures. These features are generally associated with the fractures of N-S trends in the rock mass of the area, particularly in the grey granite and the pink granite.

Desert varnish is a common feature in the study area. particularly in the microgranite and granophyre. It is a material coating of up to about 70% clay minerals cemented to the underlying rock mainly by iron oxides (Oberlander 1994). Clays and oxides are intimately mixed, with the oxides cementing the clay minerals together forming the rock varnish (Oberlander 1994). Desert varnish shows in some rock blocks (particularly the stained ones) in the study area, when more densely coated by rock varnish **(Plate IV.5)**, the rock block is more sound and strong, at least at the surface.

Inselberg features occur in the area as isolated high ground of granitic bodies of dome and blocky shapes **(Plate IV.6)**. This feature is mainly associated with the grey granite in the study area, particularly in site2. Ollier (1984) mentioned that inselberg is formed from deeply weathered granite for long period and exposed by erosion. Most of the inselbergs are higher than the plain, and are mainly composed of massive and sound rocks.

(ii) Chemical weathering features

Spheroidal weathering is mostly associated with chemical weathering (Holmes 1972 and Monroe & Wicander 1995). The cores of these blocks are more sound than the outer parts. It is sometimes associated with the exfoliation, indicating that both chemical and physical weathering processes are present in the area. Holmes (1972) mentioned that the spheriodal weathering is best developed in well-jointed rocks. The study area is well-jointed, therefore, the water penetrates the intersecting joints and thus attacks the rocks to form the spheriodal weathered blocks. The red granite (site1) and microgranite and granophyre (site 2) are especially affected by spheriodal weathering **(Plate IV.7)**, where the rocks are intensely jointed.

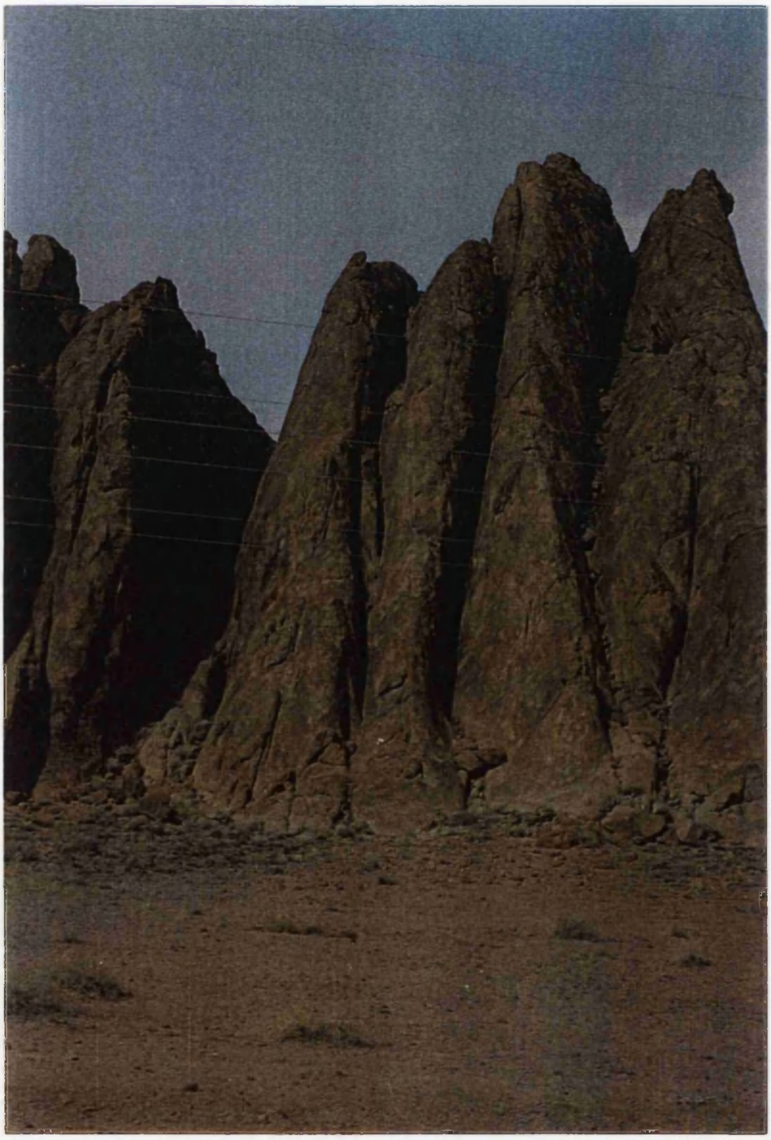


Plate IV.4: Column weathering features in granites (site 1)

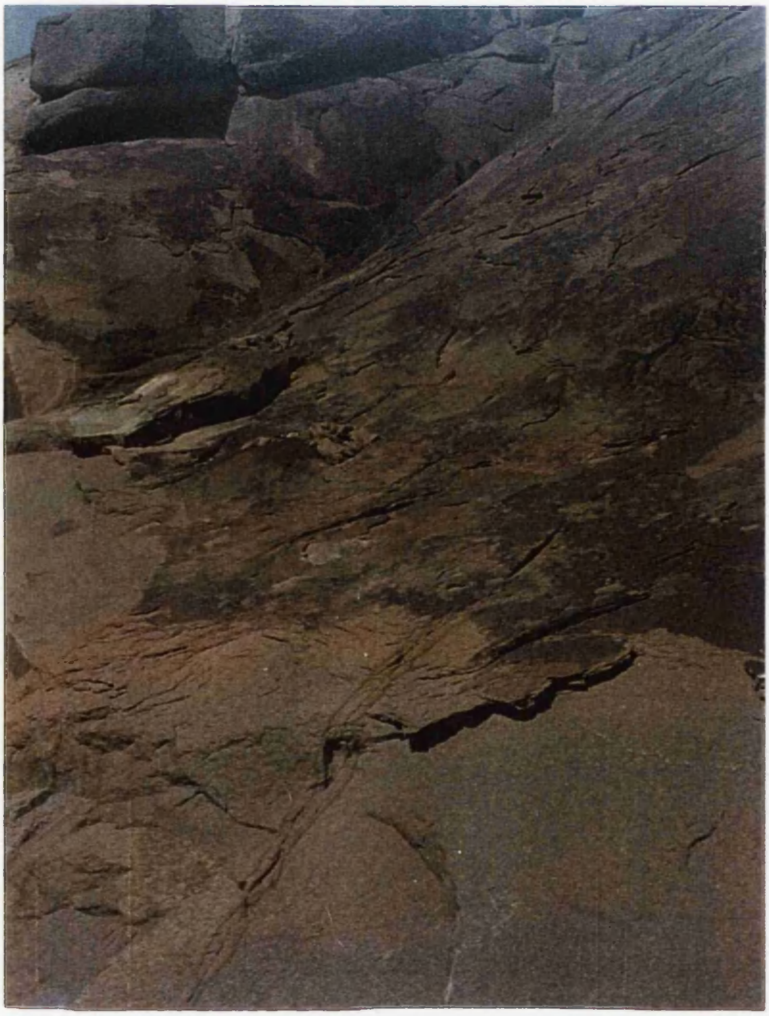


Plate IV.5: Rock desert varnish feature in granites (site2)

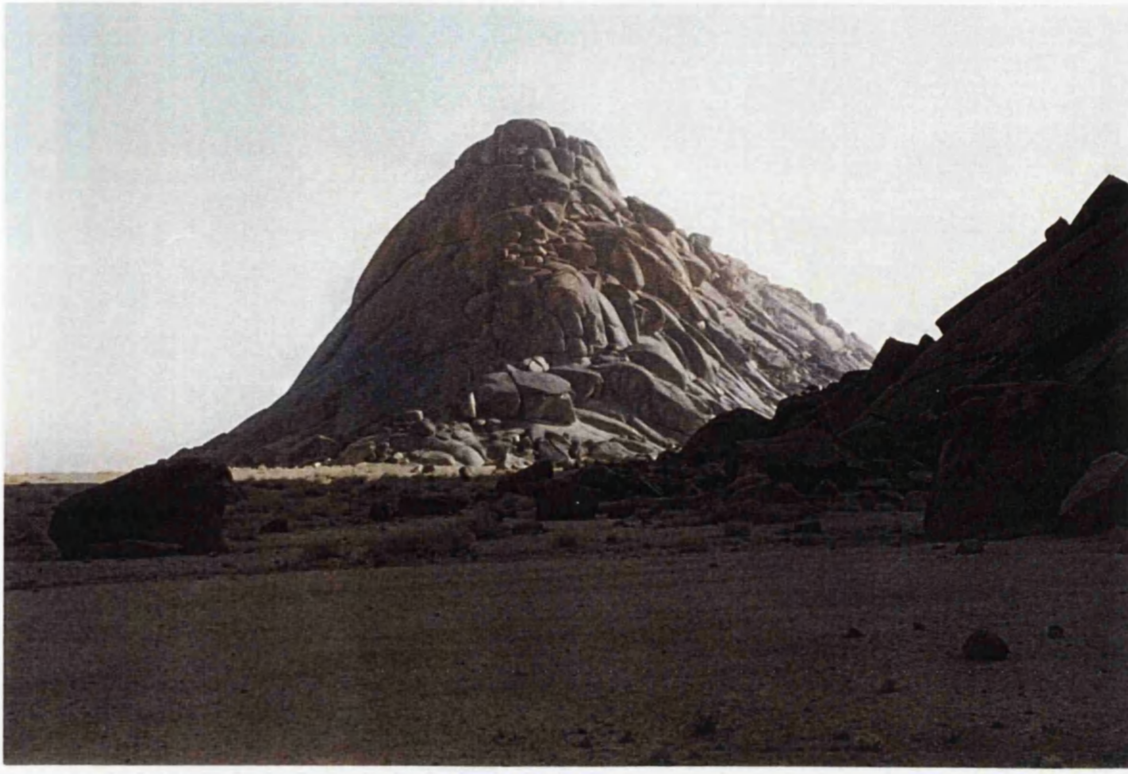


Plate IV.6: Inselbergs features in granites (site 2)

Plate IV.7: Spheroidal weathering features in granites (site 2)

The presence of clay minerals and staining (iron oxides) are the main products, and serve as an indication of chemical weathering of the common rock forming minerals (Plummer & McGeary 1993). The rocks of the study area have those products of weathering in various degrees. The grey granite is less affected while the red granite has more clays and highly stained features.

IV.4.6.3 *Mapping of weathering in the study area*

(i) General

The study area (site 1 and 2) has well exposed outcrops, therefore, the state of weathering could be described clearly in each measurement locations (**Figs. 25** and **26**). The Schmidt hammer test was also conducted in each location and the readings (*N*) were recorded in order to correlate with the weathering grades distribution. As most of the rocks could be described as strong, Approaches 2 and 3 of Anon (1995) are used to assess the weathering conditions of the study area. Each location is described using Approach 2 as grade material classification, then Approach 3 is applied to map zone distributions of weathering in the study area.

ii) Schmidt rebound hammer as index tool for weathering grades

More than 1800 readings of Schmidt Hammer were recorded from 55 studied locations on rock outcrops of sites1&2. Generally, 10 to 30 *N* value readings are taken in each site, with a type N hammer positioned vertically. The *N* reading in each location was plotted in the weathering map (**Figs. 25** and **26**). All *N* values in each rock unit were gathered together to see the overall weathering grades in these rock units. For each rock unit the mean, maximum and minimum of the obtained *N* values are calculated and plotted against their respective frequencies. The mode of the mean, maximum and minimum *N* values is taken as the representative *N* value for each category. The histograms of *N* vs frequency displays variations in each rock unit. The histograms of these readings show that the *N* values vary from 10 to 60, with the majority of readings occurring between 20 and 40 (**Fig. IV.27**). The mean values of each site are also plotted on histograms (**Figs. IV.28** and **29**). These histograms show that the *N* readings are similar, and this may indicate that the two areas have been affected by similar weathering processes.

At site1 the mean *N* values from all the stations in the grey granite fall into two categories: 30–40 and 50 – 60. These two categories of hardness (strength) indicate that the grey granite presents at least two major grades of weathering, according to the classification of weathered granite, related with the *N* values as suggested by Irfan (1996) (**Table IV.9**). The grey granite weathering state could be classified as moderately weathered (Grade III) to fresh grey granite (Grade I). The minimum *N* values, on the other hand, range between 10 and 25; the maximum *N* values are between 40 and 70 with a peak at 50 – 60 (**Fig. IV.30**).

The pink granite of site1 exhibits a minimum *N* value in the range 10 – 20, and a maximum between 40 – 60 with a peak between 50 – 60. The mean *N* values are between 20 – 40 with a peak at 35 – 40. Although there are mostly fresh (Grade I) exposures as indicated by the maximum *N* values and completely weathered (Grade V) ones indicated by the minimum *N* values, the bulk of the pink granite is moderately weathered (Grade III) (**Fig. IV.31**).

The mixed rocks of red, pink and grey granite area in site1 display a mean *N* value in the range of 20 – 45. The ranges of minimum and maximum *N* values are 10 – 30 and 20–70, respectively. These Schmidt hammer rebound readings suggest that this mixed rock are has generally all grades of weathering from completely (Grade V), to highly weathered (Grade IV), to moderately (Grade III) to slightly (Grade II), and fresh (GradeI).

Red granite has a mean *N* value of 20 to 30 with a peak of 25 to 30. The minimum readings of *N* are in the range of 10 –16, while the maximum readings are between 35 – 50 (**Fig. IV.32**). *N* values with the field and laboratory observations show that the red granite is completely (Grade V) to moderately weathered (Grade III) in general. The maximum *N* values obtained on the red granite suggest that it is not uniformly weathered (mixed mass weathered) but some places (locations) are only slightly weathered (Grade II) such as the core material in spheriodally weathered blocks.

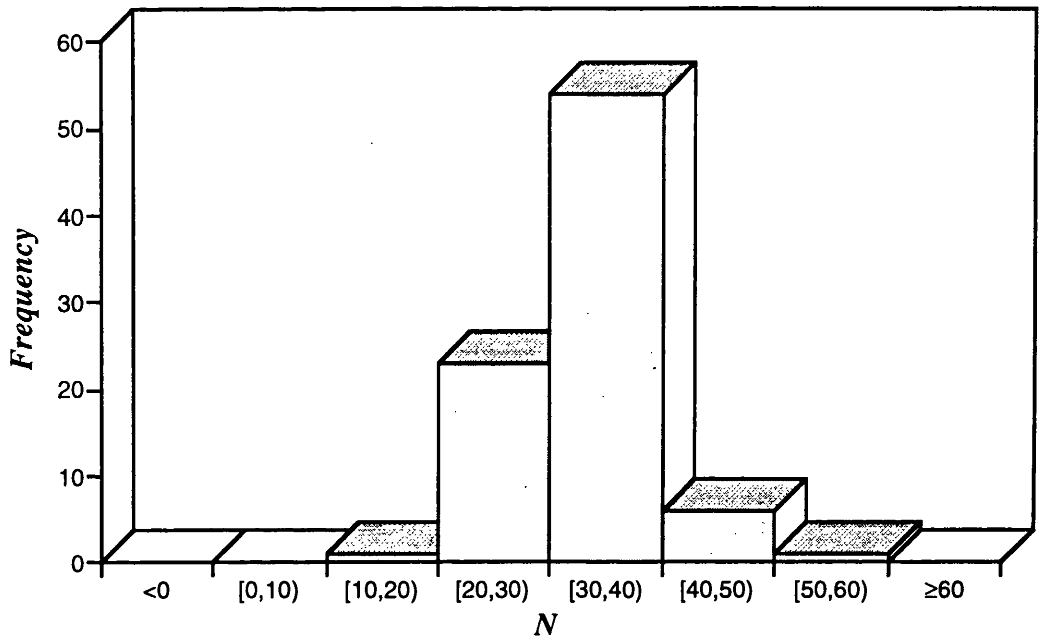


Fig. IV.27: Histogram of mean N ($\boldsymbol{R}$) values of sites1&2

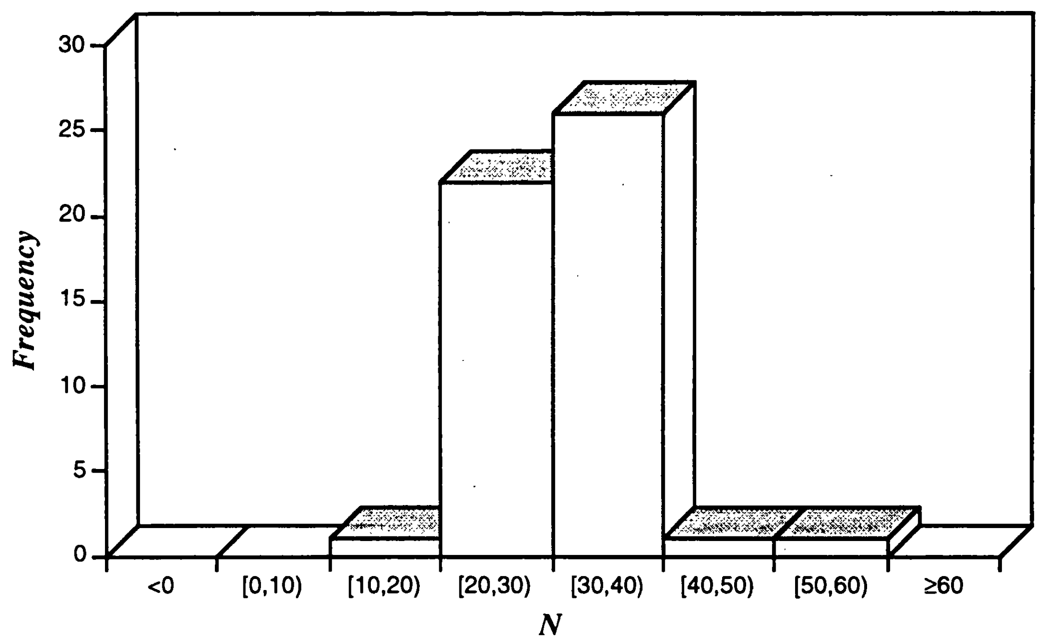


Fig. IV.28: Histogram of mean N ($\boldsymbol{R}$) values of site1

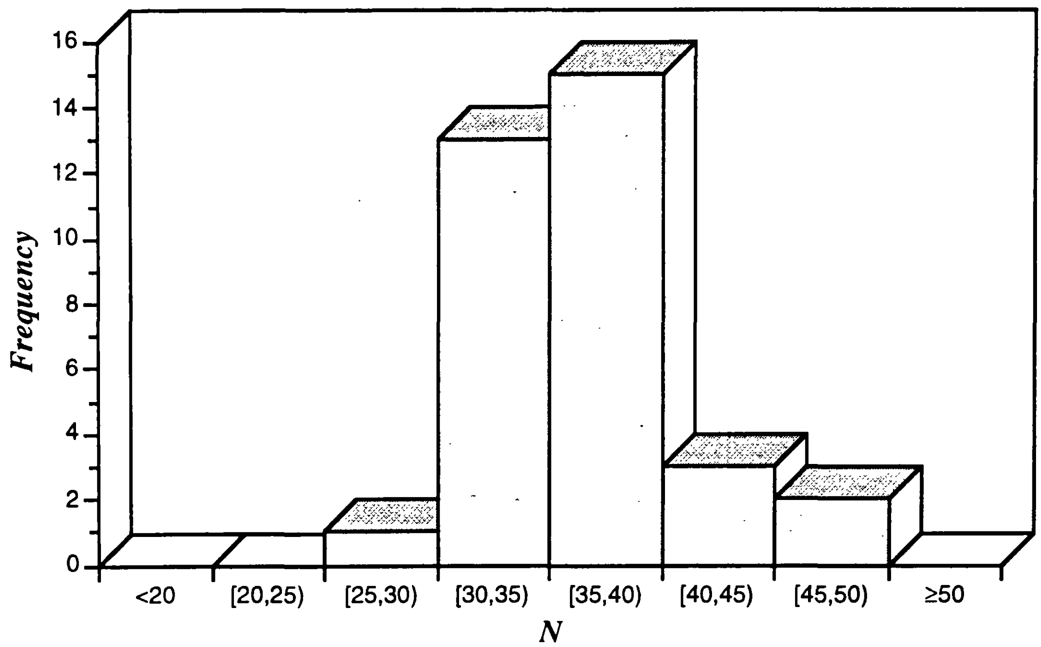


Fig. IV.29: Histogram of mean *N (R)* values of site2

In site 2 the mean *N* values of grey granite vary within two groups, between 30 – 40, and 45 – 50, the readings show that the grey granite is moderately to fresh weathering grades (Grades I to III). This distribution is quite similar to that exhibited by the grey granite in site1. The maximum and the minimum *N* values vary in the ranges of 40 – 60 and 20 – 30. respectively.

The pink granite of site 2 displays a mean *N* value in the range of 30 – 35. Some outcrops in this site are fresher (Grade I) and harder showing a rebound number varying in the range of 50 – 60. Other outcrops show rebounds of 10 – 25 which means they are more weathered (Grade IV and V), and eventually with lower strength. But in general the rock is moderately weathered (Grade III).

Microgranite and granophyre (as one group) display similar rebound values. The mean *N* values for these two rock types vary in the range of 35 – 40. The maximum *N* values are in the range of 50 – 60 while the minimum values ranges are 10 – 15 and 20 – 25. The field observations show that these two rock types are mixed mass weathering and completely stained rocks. According to the wide range of *N* values, the rocks have weathering grades of fresh Grade I (hard block pieces) to completely weathered material (Grade V).

Table IV.9: Classification of granite in terms of in-situ Schmidt hammer values

Schmidt hammer value (after Irfan 1996)					*Granites of study area (Mean N values)*					
					Site 1			*Site 2*		
Weathering Grade	**Coarse grained granite, Hong Kong**	**Granites, Hong Kong (Hencher & Martin 1982)**	**Granodiorite, Hong Kong (Irfan & Powell 1985)**	**Granites, UK (Dearman & Irfan 1978)**	**Grey**	**Pink**	**Red**	**Grey**	**Pink**	Microgranite & granophyre
Fresh (I)	57 – 60	nil	59 – 68	58 – 66						
Slightly (II) Decomposed	> 55	> 45	45 – 68	53 – 58	60			50		
Moderately (III) decomposed	30 – 58	25 – 45	25 – 50	45 – 58	30	40	30	30	35	40
Highly IV) decomposed	14 – 32	0 – 25	15 –30	20 – 45		35	25		30	35

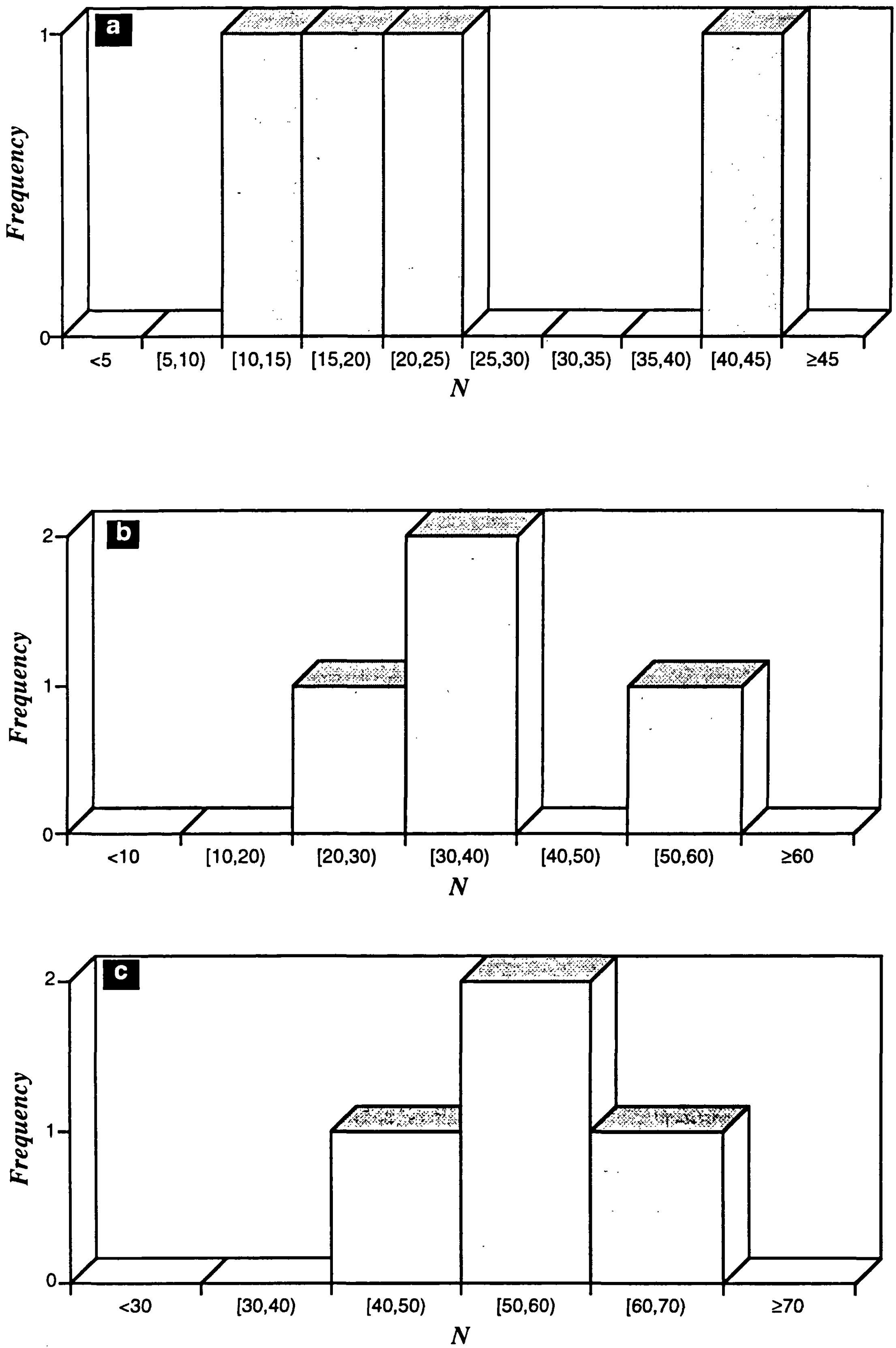


Fig. IV.30: Histogram of *N* (***R***) values of grey granite exposures in site1
a: Minimum **b:** Mean **c:** Maximum

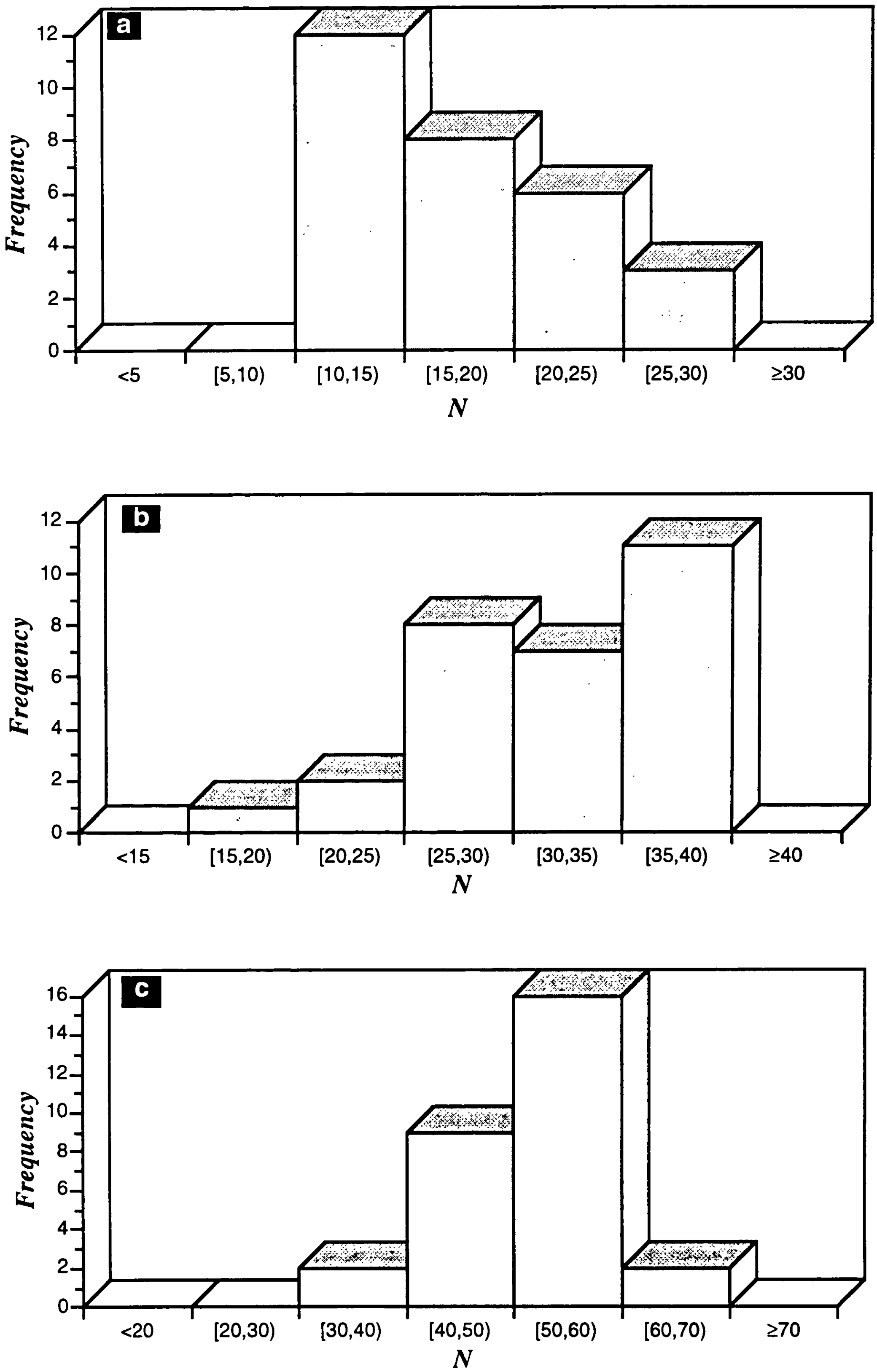


Fig. IV.31: Histogram of N ($\boldsymbol{R}$) values of pink granite exposures in site1
a: Minimum **b:** Mean **c:** Maximum

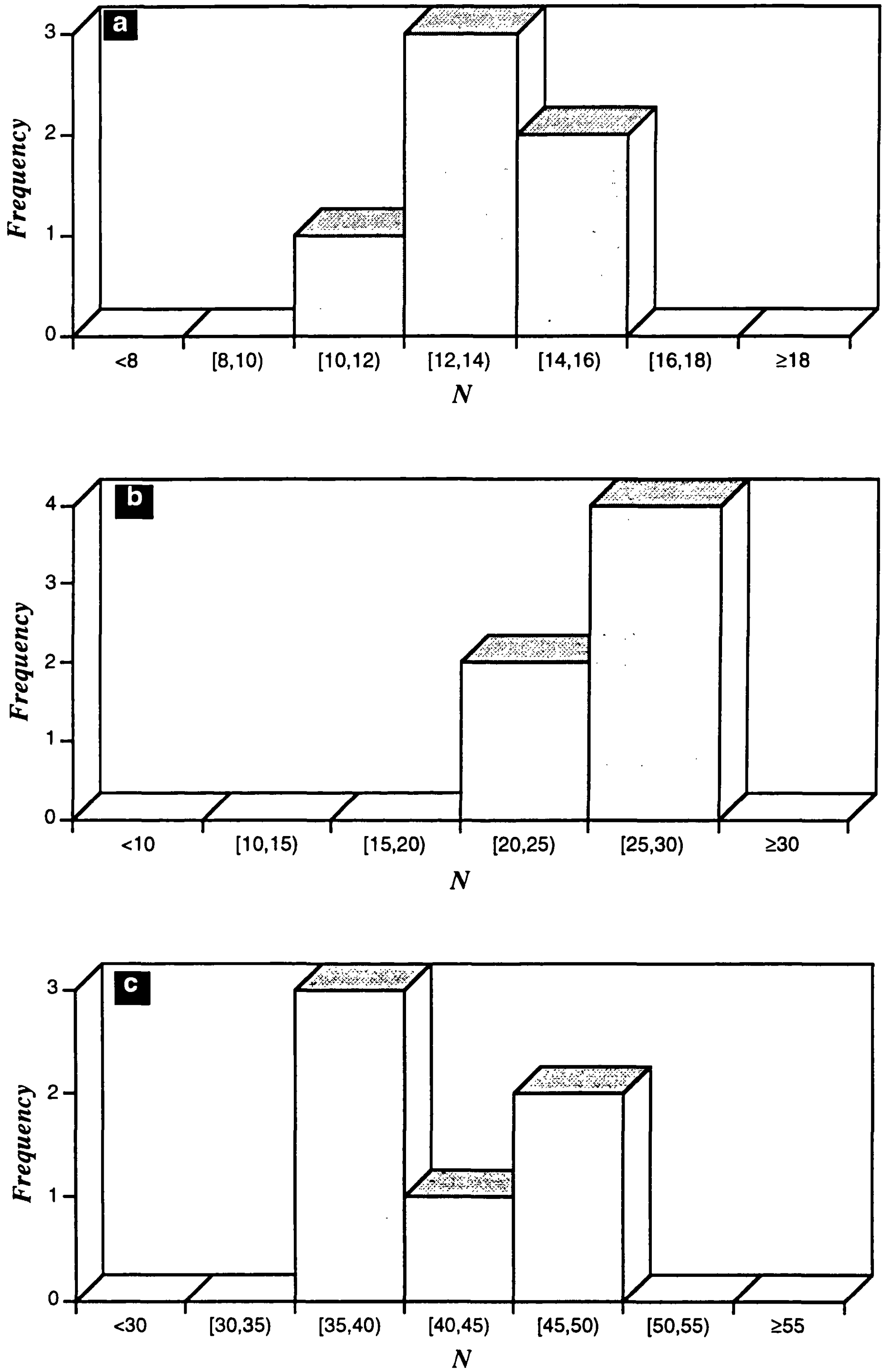


Fig. IV.32: Histogram of N ($\boldsymbol{R}$) values of red granite exposures in site1
a: Minimum **b:** Mean **c:** Maximum

The laboratory Schmidt rebound test is performed on rock samples (with dimensions 40:30:30 cm) from the same locations as the field stations. The *N* values obtained are in general higher than the field ones: in the range of 40–70. The tested rocks can, on the basis of their *N* values, be categorized into three groups. Category 1 with *N* values in the range of 60–70 and includes granophyre and Sihi pink granite. Category 2 with *N* values in the range of 50 – 60 and they are mainly microgranite, hard red granite, grey granite, mixed granite. Category 3 of *N* values from 40 – 50 includes site 2 pink granite and weathered red granite.

It has been observed that *N* for outcrops is usually lower than *N* from the laboratory. But for fresh or slightly weathered rocks the rebound numbers obtained from field outcrops and laboratory are very close, i.e. in pink granite site1, recent road cuts gives *N* values of 62 similar to those obtained from the same rock in the laboratory. Therefore, a ratio of *N* value in the field to *N* value in the laboratory is suggested to estimate the degree of the rock surface weathering, deterioration and weakening.

The variation in Schmidt rebound number is mainly an indication of the state of freshness, and surface hardness of the rock. Fresh and slightly weathered rocks are characterised by high rebound values from 45 up to 60. As the amount of alteration minerals and cracks increases, the rebound value decreases significantly.

Maps showing the distribution of weathering related with the *N* values have been constructed for sites1&2 (**Figs. IV.25 and 26**). From these maps it can be seen that the in-situ *N* values decreased when the zone of rock weathering is increased.

Generally, most of the rocks in sites1&2 have a rebound number within or close to the range of 30–40. This means that the outcrops are generally moderately weathered. The lower *N* values are with the weathered, slightly disintegrated and fractured rocks such as red granite, microgranite and granophyre. The depth of weathering for these latter rocks varies from 5 to 10 m. A classification of the weathering grades of the granites in sites1&2 in terms of Schmidt hammer values (*N*) is given in **Table IV.9,** based on the readings of field exposure testing. **Table IV.9** also shows the values reported by many authors for some granites for comparison.

(iii) General correlation between weathering grades and Schmidt rebound (*N*)

In site1, the grade of weathering is generally variable from one location to another (**Fig. 25**). However, the weathering is mostly of Grade I, II and III. The Grade IV and V are very limited and particularly occur in low ground and highly fractured areas such as the red granite. The rocks of grade I and II are mostly spatially associated. They are fresh to slightly discoloured. The *N* are > 45; more than one blow of the geological hammer is needed to crush the specimen; the joints are open to tight with wide spacing. The rocks exhibiting these grades are the grey and pink granites. The rocks falling in Grade III are considerably weakened. These rocks are more discoloured and stained. The rocks cannot be crushed by hand, and the *N* values are normally between 30 and 45. The Grades IV and V are significantly weak and can be crushed by hand; some grains can be picked up from the surface but mostly the original texture is apparent. The *N* values are less than 20. The rocks are strongly discoloured and stained, the joints are mostly open and medium to close spacing. These Grades mostly occur in red granite. More likely the same weathering condition occurs in site 2 as in site1. Grades I, II and III are the common grades of weathering in site 2, Grades IV and V do occur occasionally and particularly in microgranite and granophyre.

(iv) Weathering classification

By applying Approach 3, site1 has two distinguishable zones, 1 and 2. Zone 1 has rock materials Grades I-III. The rock mass in this zone is generally of good quality, with some weathering along discontinuities (mainly joints). Zone 2 is composed of >90% of material Grade I-III and <10% of material Grades IV-V with occasionally some of Grade VI. The rock masses have weak materials along the discontinuities. In this zone weathering features are more frequent such as rock disintegration, fragmented and spheriodal blocks, and exfoliated surfaces.

Zone1 is mostly related to areas of pink and grey granite, while zone 2 occurs in the red granite. However, some of the zone 2 weathering class occurs in the pink and grey granite areas, but only in limited areas. This spatial distribution of weathering zones has a good correlation with the lineament density map **(Fig. IV.6)** and spacing distribution map **(Fig. IV.17)**. For example zone1 of weathering in site1 is associated with the low lineament density areas and with wide spacing areas in general. Also as in spacing distribution map, the weathering zone boundaries are not coincident with the geological boundaries. The classification of weathering grades of the studied locations are presented in **(Fig. IV.25)**.

Similarly, a weathering zone distribution map for site 2 has been constructed (Fig. IV.26). From this map we can see that two zones occur here, as was the case in site 1. The characteristics of zone1 of site 2 are very similar to those of zone1 at site1. This weathering zone is related to the grey and pink granites, sheeting with exfoliation dome features (small hill size), as well as some rock disintegration features. Zone 2 is distributed in a large area and occurs in the microgranite and granophyre. The rock mass in this zone are mixed (rock type boundary area) with material too strong to be broken by hand (weathering grades I to III), and weak materials of weathering grades IV to VI. The joints are well developed, mostly medium to close spacing, open with weak materials along joints. These joints form quite loose and small, strong blocks (Grade I to III). However, these blocks generally are affected by spheriodal weathering, disintegration and fragmentation into tiny angular rock pieces as well as exfoliation weathering features. More general correlation between the N values and weathering grades in sites 1& 2 is in the following section.

IV.5 *CONCLUSIONS*

Lineament study shows that the study area has two main trends, N-S and E-W, and two lineament density domains: low density mainly in grey and pink granites and high density mostly in red granite, microgranite and granophyre.

The granite masses in site 1&2 are well jointed, of main three orthogonal joint sets: two vertical sets of N-S, E-W trends and a subhorizontal set, with some minor sets.

Generally, the granites in sites 1& 2 have three main classes of joint spacings: grey and pink granites are characterised with wide spacings, whereas red granite has medium spacings and microgranite and granophyre possess close spacings.

By comparing the Schmidt rebound values *N* in the studied locations with weathering distributions as in **Figs. IV.24 and 25**) of sites1&2, they showed good correlation between the *N* values and grades of weathering. As in weathering maps, the *N* values could be classified generally into two groups; group1 of *N* values greater than 30 and group 2 of *N* values less than 30. The group 1 occurred mostly in zone1 of weathering while group 2 occurred mainly in zone 2. It can be seen from weathering maps that the in-situ *N* values decreased when the zone of rock weathering increased. Generally, most of the zone1 and high *N* values occurred in grey and pink granites in sites 1&2, while low *N* values and zone2 were mostly associated with the red and microgranite and granophyre.

The study area has mainly two zones of weathering (Approach 3). Zone 1 mainly in grey and pink granites and zone 2 in red granite, and microgranite granophyre.

The mixed rocks area has various grades of weathering possibly inherited from parent rocks.

The results of this Chapter indicate that there is good correlation between the lineament trends, joint trends, lineament densities, spacings of the joints and the weathering zones in site 1& 2: Orthogonal trends of lineaments as well as joints; high lineament densities associated with medium to close spacing and zone 2 of weathering compared to the low lineament densities associated with the wide spacing and zone 1 of weathering. The impact of this conclusion on the assessment of the granites as dimension stone will be presented later.

CHAPTER V

ENGINEERING PROPERTIES OF ROCKS

V.1 *PREVIEW*

Generally, the engineering properties of the rock material is used to assess rock quality, in term of its suitability for use, and distinguishing characteristics of the rocks. The only method to evaluate the engineering properties of the rocks is by testing methods and the data obtained from these tests were used in the assessment of the rocks.

Geologically, rock, or in other terms, stone, is a heterogeneous substance characterised by wide ranges of mineral composition, texture, grain size, structure and weathering. Consequently, the physical, mechanical and chemical properties, i.e., the durability, density and strength, are extremely variable. Determining the suitability of a stone for a given purpose should be based upon various properties that may be readily tested in the laboratory (Winkler 1973).

In this Chapter I present the tests that are used to study the engineering properties as dimension stone of the granitic rocks units in site 1& 2:-

$\boxed{1}$ Physical properties tests

(*i*) Density (Υ) (*ii*) Water absorption (*iii*) Porosity

$\boxed{2}$ Mechanical properties tests

(*i*) Uniaxial compressive strength (*ii*) Ultrasonic Velocity

$\boxed{3}$ Durability (Magnesium sulphate soundness)

V.2 *BACKGROUND ON PHYSICAL AND MECHANICAL PROPERTIES*

V.2.1 *Density, porosity and water absorption*

The density of the stone of volume (V) is the ratio of its weight to an equal volume of water. It is calculated as A/(A–B); A is the weight of the dried specimen, B the weight soaked and suspended in water. The density of the stone has an influence on the other engineering properties of the rock such as porosity and strength. For example if the porosity of the stone is high, the density of the rock is relatively low. The strength of the rock is also related with the density of the rock; within one given type of rock, strength increases with density increase (Duncan 1969 and Irfan & Dearman 1978a).

The porosity is the ratio of the volume of the pore space in the rock (i.e., voids, vugs, microcrack, grain boundary, cracks and fissures) to its bulk volume, in percent. As indicated above, the porosity has a good direct relationship with the density. This can be explained by the fact that mineral alteration creates voids due to dissolution, and cracks due swelling. These transformations result in higher values of porosity and lower density (Baynes *et al.* 1978).

Water absorption value is expressed as a percentage of the ratio of the weight of water absorbed by a rock sample to the weight of the same sample after being oven dried (for 24h at 105°C). The ASTM standards (ASTM C97-83 1990) for the water absorption test for dimension stone suggest at least three smooth-surfaced specimens are weighed after soaking in distilled water at 20°C for 48 hours. It is recommended that the maximum acceptable value for granite dimension stone is 0.4% . Water absorption is an indirect measure of the porosity of the rock, which in turn, can relate to other physical characteristics such as mechanical strength, soundness and to its general durability potentials (Collis & Fox 1985). The water absorption test in particular may be useful in assessing the degree of hydraulic conductivity of a rock due to the presence of interconnecting networks of secondary minerals and microfractures, which are especially common where rock material is weathered (Fookes *et al.* 1988). The density and water absorption tests have been found to be useful indicators of material quality (e.g. Baynes *et al.* 1978 and Fookes *et al.* 1988).

V.2.2 *Unconfined compressive strength*

Intact strength is one of the primary components required for predicting rock performance for a variety of geological applications. (Gunsallas & Kulhawy 1984). The uniaxial compressive strength (UCS) test of rock is by far the most common laboratory test undertaken for geomechanical interests (Pells 1994 and Brook 1994). Uniaxial compressive strength test is standard for defining rock strength and recommended by (ISRM 1979) and widely used in engineering practice as a rock index property and in research programmes (Paterson 1978). The test is conducted by loading the rock sample that is unconfined at the sides, until it fails (Krynine & Judd 1957). It is a direct measure of the load carrying capacity of dimension stone in different uses, i.e. in walls, bridges and as cladding sheets used as facades. The uniaxial compressive strength is calculated as follow:

$$P = \frac{F}{S}$$

P stands for the uniaxial compressive strength.

F represents the load at which the specimen fails

S denotes the surface area under the applied load.

The mode of failure in uniaxial compressive strength has been described by Jaeger and Cook (1984) and Hawkes & Mellor (1970). Three modes of failure have been identified. First, cataclastis which consist of a general internal crumbling by formation of multiple cracks in the direction of loading. Generally when the specimen collapses two conical end fragments are left together with long slivers of rock from around the periphery. The second mode of failure is axial cleavage exhibited by a vertical splitting in which one or more major cracks split the sample parallel to the loading direction, i.e. in a principal plane of stress. The third mode of failure is shear fracturing of the specimen along a single plane oblique to the principal stress. In practice it is difficult to distinguish these three modes of failure in a failed specimen and occasionally all these modes may appear to be present.

V.2.2.1 Factors affecting uniaxial compressive strength

The uniaxial compressive strength is influenced by many factors geological and methodological, and the test will be misleading if these factors are not considered.

(*i*) *Methodological factors*

a) Specimen length to diameter ratio

The rock specimen tested in uniaxial compression are most often cylindrical. The height to diameter ratio of the specimen influences the measured strength. Typically the strength decreases with increasing height to diameter ratio, but it tends to become constant for ratios in the order of 2:1 to 3:1 (Obert & Duvall 1967). For higher ratios the specimen strength may be influenced by buckling (Lade 1994). Bieniawski (1968) stated that as this ratio increases the uniaxial compressive strength increases up to a length/ diameter ratio of 1.5 after which the compressive strength becomes independent (**Fig V.1**).

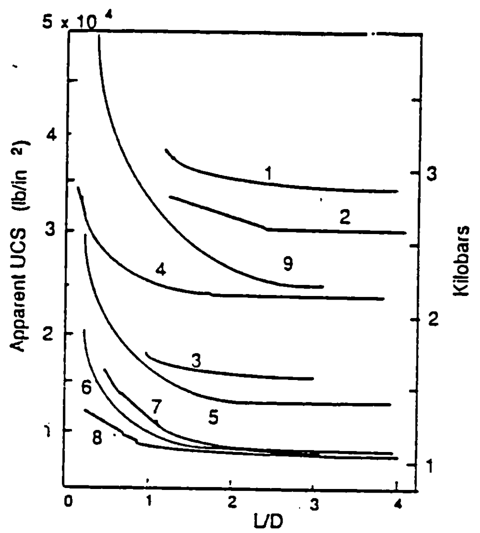


Fig V.1: Influence of length \ diameter ratio (L\D) on uniaxial compressive strength (after Hawkes & Mellor 1970)

1- Westerly granite; 2- Dunham Dolomite; 3- Muzo Trachyte;

4- Pennant Sandstone; 5- Kirkby Siltstone; 6- Ormonde Sandstone and Siltstone; 7- Darley Dale Sandstone; 8- Berea Sandstone;

9- Saturated granite.

b) Rate of loading

Experimental observations show that the strength decreases with decreasing rate of loading or strain rate (Goodman 1980). The uniaxial compressive strength also increases as the rate of loading increases (Vutukuri *et al.* 1974).

c) Sample preparation

The ISRM (1979) suggested that the end flatness of the tested core sample should be to the tolerance of 0.02mm. The end flatness distribute the stress induced at the platen core contact uniformly. The presence of asperities on the surface of the core can induce a premature failure of the rock sample.

(ii) Physical factors

a) Density and porosity

The density has a big role in the rock strength, when the density increases the strength of the rock increases (Duncan 1969 and Irfan & Dearman 1978a). The negative exponential relationship between porosity and strength was reported by (Hochino 1974). Attewell & Farmer (1976) mentioned that the overall magnitude of the grain bounding forces depends on the total area of contact between individual particles which is inversely related to the amount of pore spaces within the rock. Duncan (1969) stated that the extent of the voids within the rock material and the nature of the bond between the solid mineral aggregates have a strong influence on the strength of the whole rock. Therefore, in general when the porosity increases the contact between the grains which leads to an overall decreases in the bonds between the mineral grains, resulting at the end in a decrease in strength of the whole rock.

b) Water content

Generally water is present within the pore spaces and cracks of rocks, it has great effect on their properties. Pells (1994) mention that all rocks show a change in strength with change in moisture conditions. They recognised this effect due to a combination of the following physical or physiochemical effects:

- surface energy change (Rehbinder effect)
- pore pressure changes
- friction reduction
- corrosion

Generally it is found that the strength of the rock material decreases with the increase in water content Colback & Wild (1965).

c) Temperature

In general an increase in temperature causes strength to decrease (Hawkes & Mellor 1970 and Lade 1994). Being a polymineralic and heterogeneous body, rocks when heated exhibit a differential expansion (elongation) of it's constituent minerals. These conditions create an internal stress capable of opening and propagating cracks and fractures which are the major factor in strength reduction of the materials. Houpert (1970) showed that subfreezing temperature causes a dramatic increase in strength.

(iii) Geological factors

a) Effect of mineralogy and fabric

The mineralogical composition and fabric of a rock have a great influence on the mechanical properties of the rock material. Price(1966) found that a sandstone having a clay matrix is weaker than a calcite cemented one. He also mentioned that the strength is related to the mineralogical content of the rock. The bonding between minerals, the interlocking nature of grains contact, is usually reflected in higher strength. The strength of a rock is not only affected by it's mineralogical composition but also by it's texture grain size, grain orientation, grain shape, and structural defects (Marriam *et al.* 1970). Mineral alteration has a dramatic influence on the strength of the rock, when the mineral grain boundaries are slightly altered, the intergranular bonds are greatly reduced and as a consequence the strength is reduced. Therefore, engineering classification of rocks on mineralogy and petrology alone can be misleading (Farmer 1983). Thus, although strength can be related to mineralogy particularly quartz and clay mineral content, it is equally likely to be related to density, porosity, grain size and shape and much more likely to be affected by the presence of discontinuities on a micro or macroscale (Farmer 1983).

b) Grain size

Many studies have shown the effect of the grain size on the strength of rocks. It is, as the grain size decreases the ultimate strength of the material increases (Jaeger & Cook 1984; Stagg & Zienkiewcz 1968; Brattli. 1992; Hawkes & Mellor 1970; Paterson 1978; and Atkinson 1987).

c) Weathering

Generally the resultant of the rock weathering is in form of mineral alteration, crack formation and opening, void creation by leaching and the subsequent bond weakening and loss of cohesion. The change in the state of strength as weathering progress has been studied using several weathering indices, i.e. porosity, water absorption, and density (Hamrol 1961 and Irfan & Dearman 1978a). In all cases strength was found to decrease dramatically as weathering progress, especially in the initial stages. Similar results were obtained when cracks and or secondary minerals were used as a weathering index (Onodora *et al.* 1974 and Irfan & Dearman 1978a).

d) Anisotropy

Anisotropic material, in respect to strength, is when it's mechanical properties are not similar in all directions. The variation of compressive strength with the direction of loading is called strength anisotropy (Goodman 1980). Many rocks are anisotropic, especially sedimentary rocks. Their strength varies with the direction of loading (Lade 1994). Goodman (1980) found that the compressive strength parallel to the bedding is always less than the strength measured perpendicular to the bedding. Although the rocks studied in this programme are homogenous, the discussion of anisotropy here is just to show the different possibilities that may affect the strength of rocks.

V.2.3 *Ultrasonic Pulse Velocity*

The ultrasonic pulse velocity test is used to study the dynamic properties of rocks (Sutherland 1962). In the field, the ultrasonic velocity is influenced by a number of factors among which are depth of burial, degree of compaction and cementation, discontinuity, fluid saturation, texture, composition and degree of weathering (McLean & Gribble 1985).

The value of the longitudinal wave velocity, ϑ_p has been recognised as an indicator of rock mass quality; the higher the velocity the better the rock quality. Caterpiller Tractor Co. (1972) has given a range of velocity for different types of rocks. Fresh crystalline rocks usually have the higher velocities, i.e. igneous rocks. Illiev (1967) on monzonite, and latter Dearman *et al.* (1978) on granite have used the longitudinal velocity for weathering classification (**Table V.1**). The fresh material has the highest velocity, and as weathering increases the velocity of the material decreases.

Table V.1: Range of P-wave velocity (ϑ_p) in granites (after Dearman *et al.* 1978)

Weathering state	**ϑ_p (m/s)**
Fresh	3500 – 5500
Slightly weathered	2500 – 4000
Moderately weathered	1500 – 3000
Highly weathered	1000 – 2000
Completely weathered to residual soil	500 – 1000

V.2.4 *Durability and Soundness*

It is very important for dimension stone that the appearance characteristic (colour and texture) should be stable for a long period of time, and the rock be durable and resistant against alteration and weathering processes. The rock or the stone is composed of one or more minerals. Stone colours are therefore influenced by the constituent minerals, texture and grain size. Different rock has different durability and stability in terms of colour texture and grain size. The more durable and stable one is the igneous rocks such as granite, the generally highly variable and frequently unstable in colour and texture are the sedimentary and metamorphic rocks (Winkler 1973). Igneous rocks have the following common rock forming minerals which determine the rock colour: feldspars (orthoclase, plagioclase), quartz, mica (biotite, muscovite), ferromagnesian silicates (hornblende, augite) and pyrite. These minerals are quite stable in colour except the biotite and pyrite. The overall rock colour depends on mineral colours and on the texture and structure. Fine grained rocks appear to be more homogeneous than coarser grained varieties.

The dimension stone industry is more interested in the stability of the rock minerals, particularly in minerals containing iron and the rate of their oxidation to ferric oxide (hematite) and ferric hydroxide (geothite) which may show an undesirable discoloration of existing colour. The weathering of iron minerals and of minerals in which iron is in the crystal lattice, like the ferromagnesian silicates, releases iron to the immediate surrounding of the mineral grain. The process of oxidation and hydration forms nearly insoluble oxides and hydroxides of iron as rusty stains (Winkler 1973). Certain igneous stones change colour when weathered, for example, within several weeks some light grey granites may alter to various shades pink, red, brown, or yellow, caused by the hydration of iron oxides when they produce rusty surface stains. Winkler (1973) studied the physical damage caused by rust, he mentions that the damage is due to the expansion (physical effect) of rust such as in the form of geothite or to the common rust hematite.

Water in the porespaces and microcracks in the stone can also expand when warmed. For example water expand within granite from 0.0004 to 0.0009% of total volume (Bell 1993).

The presence of clay minerals can cause significant disruption of the rock. For example in the construction of the main runway of Sidney Airport, a slightly weathered dolomite was used as a rip-rap in that section constructed in Pootany Bay. Reactions between clay minerals, existed in this dolomite due to weathering, and sea water resulted in a very rapid disintegration and decomposition of the dolomite. Therefore the presence of clay, iron oxides, pores, vugs, and microcracks may lead to the disruption of the rock in term of changing colour, texture, strength, and cause an increase in the rate of in service weathering.

V.2.4.1 Magnesium sulphate soundness test

Magnesium sulphate soundness test (BS 812 1989) is used to simulate the effect of the crystallization process (physical effect). It assesses the ability of the rock to resist deterioration resulting from a change in the physical environment, such as wetting - drying, and thermal changes especially "freeze - thaw".

The freeze - thaw process commonly affects porous rocks. When the water freezes in the rock pore-spaces it develops an internal stress which can overcome the tensile strength of the rock leading to its disaggregation. Moisture-susceptible minerals such as clay swell in the presence of water and this leads to the built up of internal pressures able to open cracks and causes deterioration of the rock. For these reasons certain tests have been designed to simulate the effect of these destructive processes and allow the prediction of the likely in-service performance of the material. Among such tests is the magnesium sulphate soundness test. Fookes *et al.* (1988) found the magnesium sulphate soundness a useful test in distinguishing sound and unsound materials as well as an indicator of water adsorption capability.

The factors which affect the magnesium sulphate soundness are the temperature of the solution (Jackson 1930), and the solution concentration (Walker 1936), the temperature and the period of drying (Woolf 1956) and the period of immersion in the solution (Woolf 1956). The use of magnesium sulphate as a replacement of the sodium sulphate solution is established in many studies (Walker 1936).

V.3 *RESULTS*

V.3.1 Density, porosity and water absorption

The density and porosity and water absorption measurements in this study have been carried out according to the BS 812 (1975). The mean density (γ) values range between 2.52 and 2.59 g/cm^3 in the dry state, and 2.55 and 2.60 g/cm^3 in the saturated condition. This variation is more likely to be due to the alteration and weathering state of the rocks, the more weathered the rock the greater the difference in density between dry and saturated conditions. Water absorption varies in a range between 0.37 and 1.18%. Accordingly, porosity values have similar trends and range between 0.95% and 2.96% depending on the weathering condition of the rocks.

The grey granite of site1 exhibits the best physical properties. Generally, the density ranges between 2.61 and 2.57 g/cm^3 with absorption values of 0.33 up to 0.41% and porosity of 0.85 up to 1.06%. The pink granite of site1 exhibits density values between 2.54 and 2.57 g/cm^3 in the dry state. These values increase at saturated condition and ranges between 2.57 and 2.60 g/cm^3. The water absorption values for the pink granite are generally higher than the grey granite, and it varies in the range of 0.67 and 1.07%. Similarly, the porosity values for pink granite are higher than the grey one and vary between 1.73% and 2.72%. The differences in porosity and water absorption between grey and pink granite are due to the fact that, as the petrographic study shows, the pink granite is more altered than the grey granite. The red granite exhibits generally the lowest values of physical properties among the rocks in the study area. Its density values are between 2.47 and 2.55 g/cm^3; these values increases generally up to 2.57 g/cm^3 in saturated condition. The absorption values are between 0.86% and 2.22%, and the porosity ranges between 2.17% and 5.48%.

The physical properties of the rock units in site2 show similar pattern. The microgranite and granophyre exhibit higher values than the pink and grey granites. The density of the microgranite and granophyre rocks are between 2.56 and 2.58 g/cm^3 and these values do not show significant variations in saturated condition except when the rock is affected by stained veining, the density decreases by 0.01%. The absorption values are very low and mostly around 0.4% except when the rock is veined, the absorption values increased up to 0.69%. Similarly the porosity values are also low and it is around 1.07%. The density in the pink granite is mostly around 2.57 g/cm^3 in dry condition and 2.60 g/cm^3 in saturated condition, the absorption value is around 0.92% and the porosity is around 2.40%. The grey unit exhibits lower qualities material in terms of physical properties with density value of 2.51 g/cm^3 in dry condition and 2.55 g/cm^3 in saturated condition, the absorption value is around 1.63% and the porosity is around 4.08%. These physical properties of the grey granite may be due to the fact that this rock exhibits more open microcracks. **Table V.2** summarizes the physical properties in the study area.

Table V.2: Physical properties of the study rocks on sites 1 and 2

Site No.	Rock type	Sat density (γ sat) g/cm^3	Dry density (γ dry) g/cm^3	Absorption (%)	Porosity (%)
1	Grey granite	2.58 – 2.62	2.57 – 2.61	0.33 – 0.41	0.85 – 1.06
	Pink granite	2.57 – 2.60	2.54 – 2.57	0.61 – 1.07	1.73 – 2.72
	Red granite	2.52 – 2.57	2.47 – 2.55	0.86 – 2.22	2.16 – 5.48
2	Grey granite	2.55	2.51	1.63	4.08
	Pink granite	2.58 – 2.59	2.55 – 2.57	0.91 – 1.00	2.36 – 2.65
	Microgranite	2.57 – 2.60	2.56 – 2.58	0.25 – 0.69	0.63 – 1.77
	Granophyre	2.58 – 2.60	2.59 – 2.26	0.30 – 0.45	0.78 – 1.15

V.3.2 *Strength of the rocks in the study area*

The compressive strength of the rocks in the study area were carried out according to the ISRM (1979). More than 100 specimens of one inch diameter and an aspect ratio of 2 have been prepared from the available rock spectrum and uniaxially loaded to failure using an ELE 200KN digital compression machine.

Sample cores from Sihi and Salma granites (sites 1&2) were tested for uniaxial compressive strength under dry and saturated conditions. The Sihi granite samples were collected from different granite units. These samples vary in colour and alteration condition, and these variations are reflected in their physical and mechanical properties. According to the petrographical and field study, Sihi granite has been subdivided into three units, grey, pink, and red granites.

Sihi grey granite has an mean UCS of 198MPa in the dry state and 161MPa when saturated (**Table V.3**). In general the rock can be classified as having high strength (ISRM 1981).

The general relationship between the density, water absorption and the effect of water on the uniaxial compressive strength of the granite in this study is summarised in **Table V.3**.

Table V.3: The geotechnical properties of the granites in the study area

Site No.	*Lithology*	*Density (dry) g/cm³*	*Water absorption (%)*	*UCS (dry) (MPa)*	*UCS (sat) (MPa)*
1	Grey granite	2.57 – 2.61	0.33 – 0.41	198 (158)	161 (132)
	Pink granite	2.54 – 2.57	0.61 – 1.07	153 (127)	129 (103)
	Red granite	2.47 – 2.55	0.86 – 2.22	122 (103)	105 (82)
2	Grey granite	2.51	1.63	131	
	Pink granite	2.55 – 2.57	0.91 – 1.00	151 (120)	136 (108)
	Microgranite	2.56 – 2.58	0.25 – 0.69	198 (158)	174 (139)
	Granophyre	2.59 – 2.26	0.30 – 0.45	235 (188)	176 (141)

Note: Values in brackets represent minimum while the rest are mean values.

Sihi pink granite is more altered than the grey granite. It has more pores, vugs, and microcracks, it is also partially stained and display lower strength than the grey granite. The mean uniaxial compressive strength of the pink granite is 153MPa in the dry state and drops to 130MPa when saturated.

The Sihi red granite is more altered than the other two rocks. It is even more stained than the pink granite and has more pores, vugs, and cracks, and occasionally the rock is completely stained. The mean UCS is 122MPa in the dry state and about 105MPa in the saturated condition. The rock is of moderate strength. There are variation in UCS values in Sihi granite units. The red granite shows lower strength than the grey and pink granites. This low strength is due to the fact that the red granite is highly altered and completely stained with more microcracks, pores and vugs. The red granite also has the lower density, and higher porosity and water absorption. The grey granite has the highest values of strength among the rock units in site 1. This is due to the that the rock is more fresh with less amount of hair like microcracks than the other granites.

Salma pluton granites (site 2) has four units, grey granite, pink granite, microgranite and granophyre. The UCS values of Salma granites display ranges of variation like Sihi granite. The grey granite display an average strength of 130MPa, the pink one is 150MPa (**Table V.3**). The microgranite and granophyre exhibit the highest values of UCS of 198MPa and 235MPa respectively with mean value of 207Mpa. The reason that Salma grey granite display the lower strength is that it contains more hair like cracks especially on the quartz grains.

The Salma microgranite and granophyre have high UCS and lower absorption values. Although both these rocks are completely stained and altered, their fine grained and interlocking texture may give them the highest strength. Microgranite and granophyre are generally intruded by veins (mostly quartz veins). Specimens containing veins display, in general, higher absorption values and lower UCS. It has been observed that veined specimens, in compression, fail along the vein rock contact.

The variation of density, porosity, and absorption, as they are indicators of the state of soundness and freshness, are concordent with the strength variations of the rock. The effect of the physical properties of the rock, i.e. on strength is shown in **Fig. V.2**.

The relationships between the test results of the granites for the study area (sites1&2) are shown in **Figs. V. 2, 3** and **4**. The mean values and their standard deviation were plotted. The density, porosity and absorption are all shown to change across the strength of the rocks.

The relationship between the density and strength is shown in **Fig. V.2**. As densities decreases the strength also decreases but not linearly.

Fig. V.3 shows strength against porosity. The plot indicates the trend of decreasing strength with increasing porosity. The decrease in strength with increase in porosity is not linear. Similar trends also occurred between the absorption and strength **Fig. V.4**.

The relationships between density, porosity and absorption are also plotted and shown in **Figs. V.5, 6** and **7**. Generally, the relationships between these properties are linear. The porosity increase with absorption at (0,0) point proportionally (**Fig. V.7**). The density with porosity is also linear relationship but with inverse proportional (**Figs. V.5** and **6**). From these relationships, it can be said that an increase in porosity is normally associated with a decrease in density and strength. This result is very consistent with the alteration stage of the granites in the study area. The grey granite (mostly slightly altered) has low porosity and high strength while the red granite (highly altered and completely stained) has the highest porosity and lowest strength therefore the physical and mechanical properties of these granites are well correlated with the alteration stages of the rocks. Turk and Dearman (1986a) mentioned that the weathering grades of rocks can be best assessed by determining porosity and density of rock, while increase in weathering grade would increase the porosity it would also decrease the density and strength.

The effect of the alteration condition of the rock on strength is obvious especially in the coarse grained granite of Salma and Sihi plutons (site 1& 2). It is as the intensity of alteration, i.e. amount of staining, microcracking and secondary minerals, increases the strength decreases continuously.

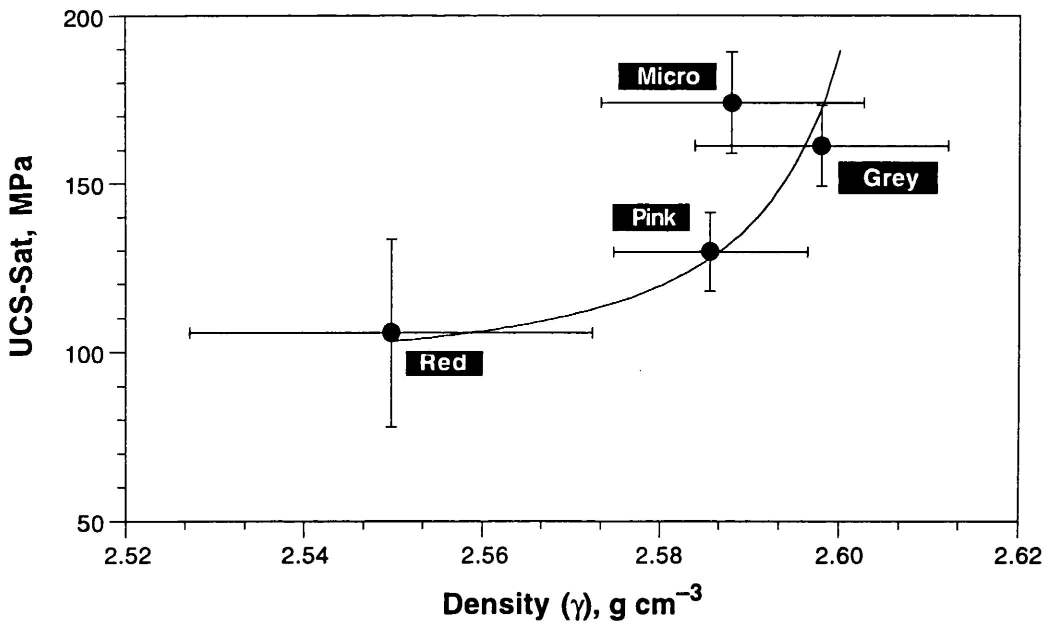


Fig. V.2: The relation between saturated uniaxial compressive strength (UCS) and the corresponding densities of granites in the study area

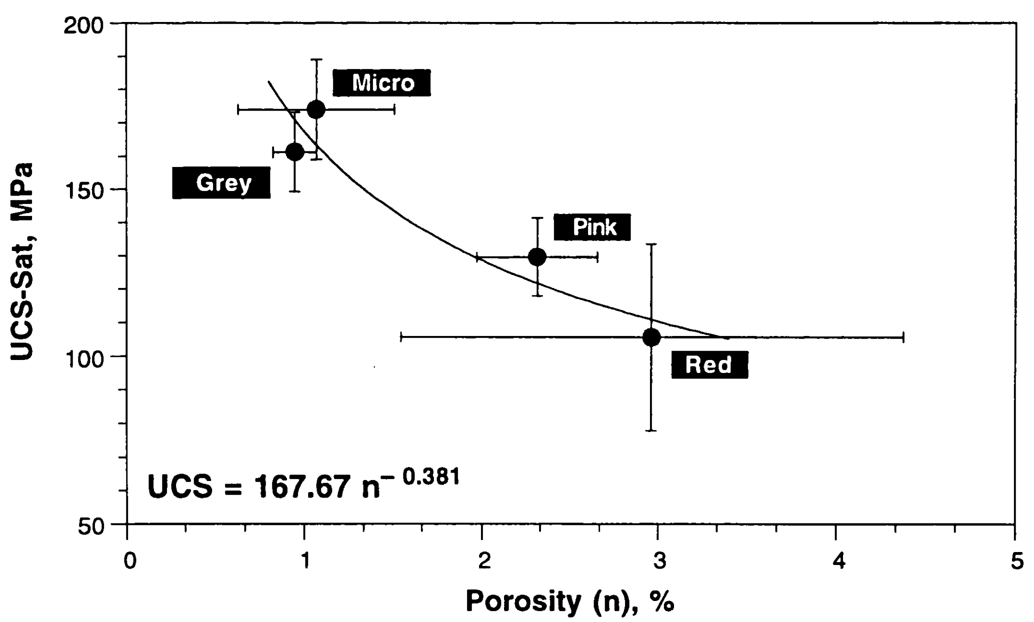


Fig. V.3: The relation between the saturated UCS and the porosity (n) of granites in the study area.

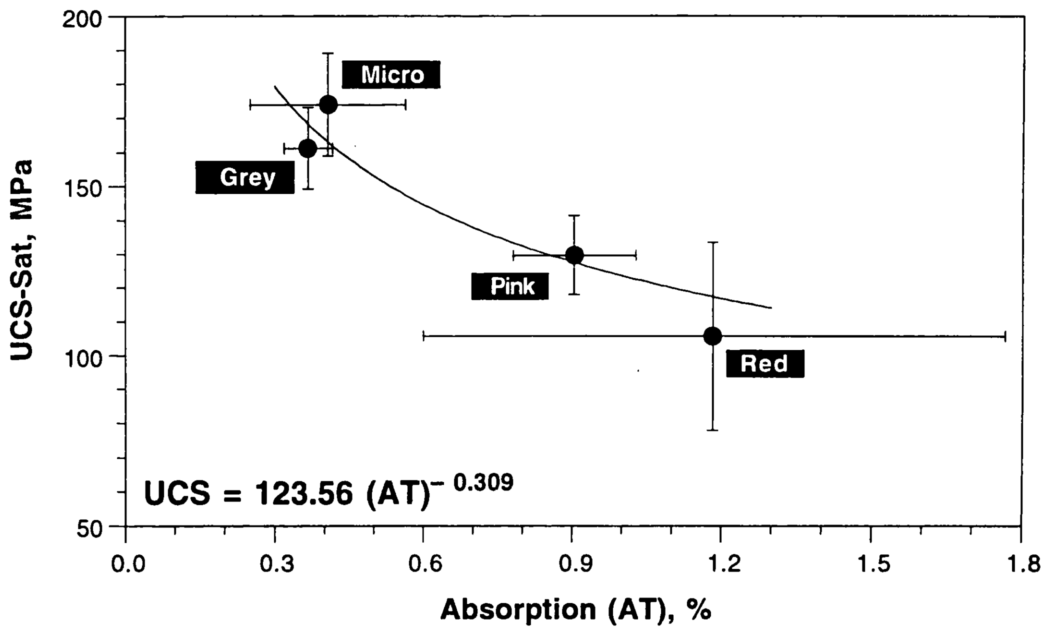


Fig. V.4: The relation between the saturated UCS and the absorption of granites in the study area.

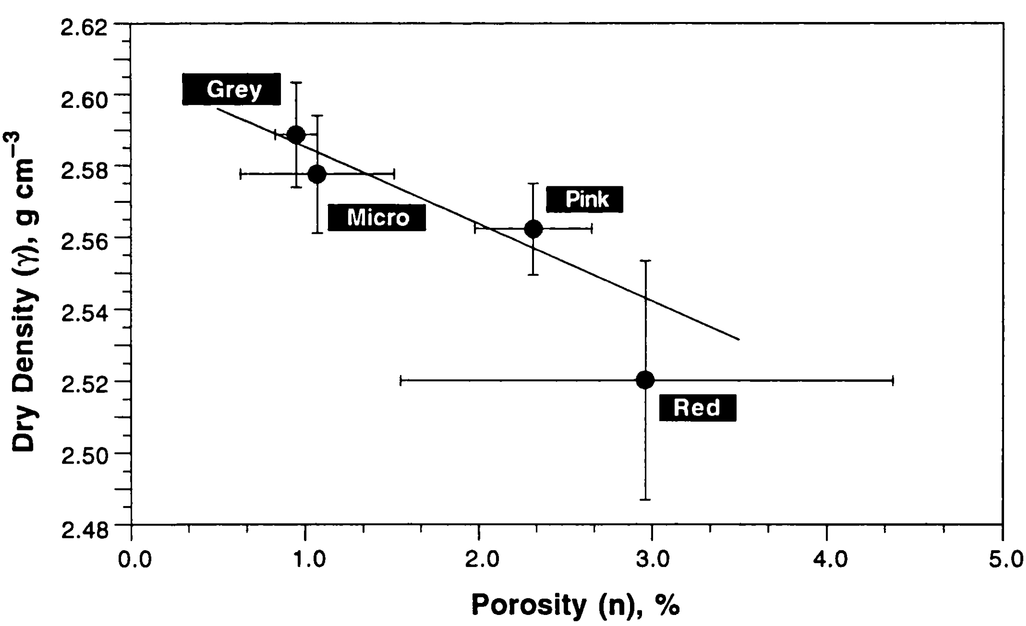


Fig. V.5: The relation between the dry porosity and density of granites in the study area.

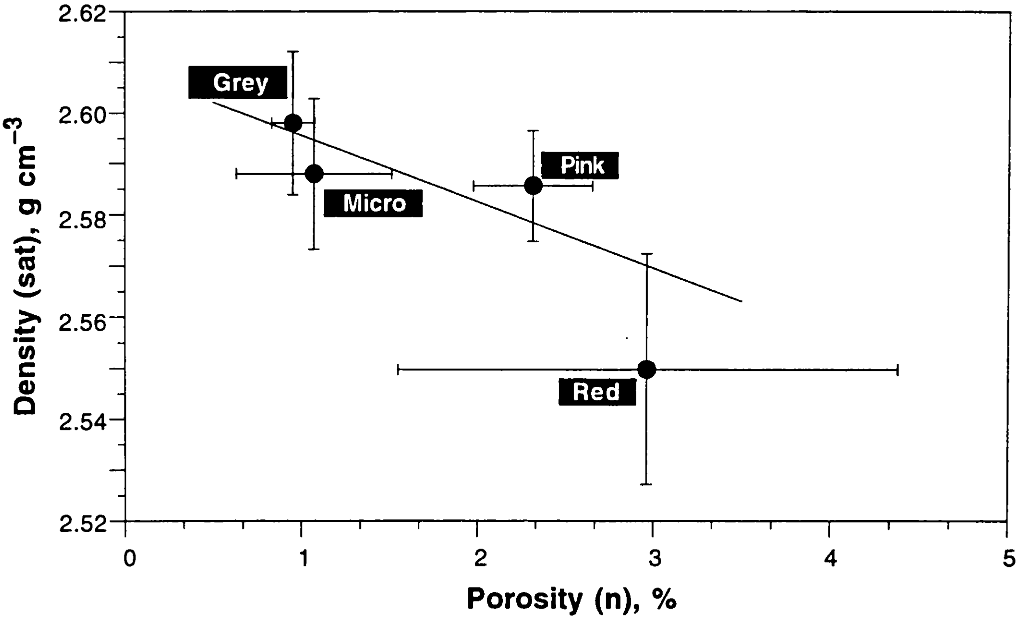


Fig. V.6: The relation between the saturated porosity and density of granites in the study area.

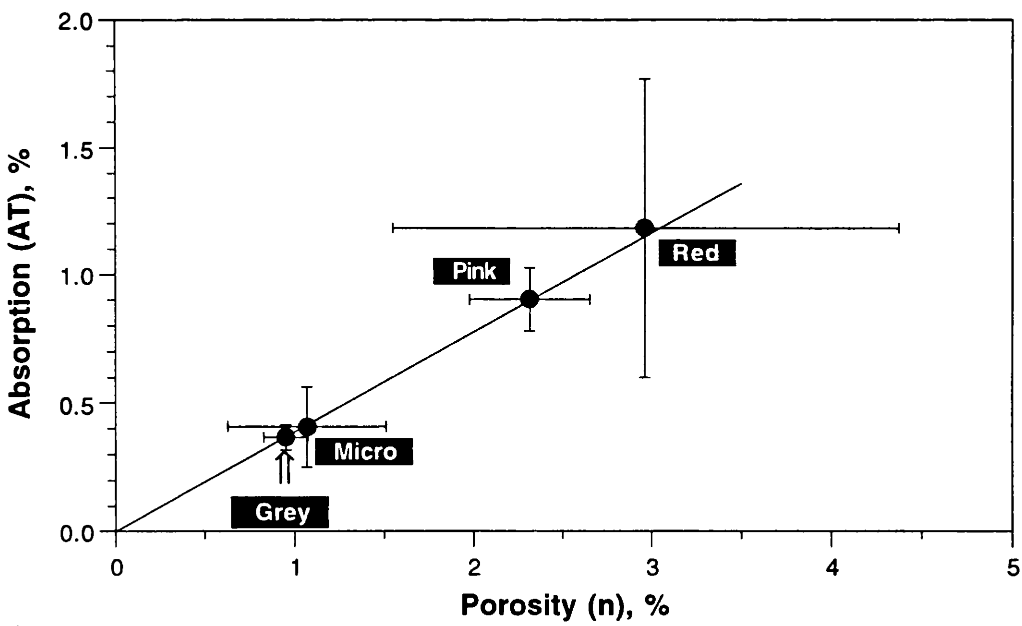


Fig. V.7: The relation between the porosity and the absorption of granites in the study area .

The granite of the studied area show different mode of failure. The high strength samples usually fail in the cataclastic mode, where the sample fail suddenly and violently and shatters into tiny pieces. The cataclastics cleavage and shear failure is the more common mode of failure among the tested samples, particularly the moderate strength granite samples i.e. pink granite. Low strength samples collapse gently without bursting i.e., red granite. Rocks containing veins, usually collapse along the vein-rock contact in a shear mode.

V.3.3 *Results of ultrasonic velocity*

The ultrasonic apparatus called PUNDIT (portable non destructive indicating digital tester) was used to measure the ultrasonic velocity of the granitic rocks used in the present study.

The velocities were measured on samples of rock cores of 100mm long by 50mm diameter with smooth flat ends at room temperature conditions. All rock units have been tested in both dry and saturated conditions. Generally the velocity of the studied material ranges between 3630 and 5108m/s (**Table V.4**) which are moderate to high (Anon 1979).

Table V.4: Ultrasonic velocity (ϑ_p) of the studied granite

Site No.	*Lithology*	***Velocity ϑ_p (mean values)***	
		ϑ_p (dry) m/s	**ϑ_p (sat) m/s**
1	Grey granite	4655	5230
	Pink granite	4924	5361
	Red granite	4188	4616
2	Grey granite	3914	5038
	Pink granite	4312	4819
	Microgranite	5108	5434
	Granophyre	4207	5173

Site1 granites (grey and pink granites) has high velocity values varying between 4188 and 4655 m/s. The red granite has the lower velocity value among them 4188 m/s (**Table V.4**).

Site 2 granites has a range of velocity varying between, 3914 to 5108 m/s. The microgranite and granophyre have velocities of 5108 and 4207m/s respectively. The grey granite have lower velocity than the pink one and they are 3914 and 4312m/s respectively. This is in fact concordant with the other physical and mechanical properties of the granites in site 2, where the grey granite generally has higher water absorption and porosity values and lower strength than the pink granite. This is because that the grey granite has more open cracks than the pink one especially on the quartz grains.

The velocity of the rocks are directly influenced by their physical properties (Duncan 1969 and Irfan & Dearman 1978a). It has been observed in this study that when the rock becomes fresher the velocity increases. This can be explained by the fact that a decrease in the amount of secondary mineral and structural defects, i.e. cracks and voids, allows the elastic waves to travel faster through the rock. The porosity and water absorption which express the amount of voids within the rock has a significant effect on the velocity. Irfan & Dearman (1978a) showed that the velocity of the granite decreases exponentially as the porosity increases. For all the studied rocks the velocity increases in saturation. This increase in velocity is significant when the porosity and absorption values are high.

In this study it has been observed that all the physical and mechanical properties correlate well with the velocity. For instance when the density is high the strength is high and the velocity is also high. On the other hand when the material is weathered or slightly weathered the porosity increases the density decreases, the strength decreases, and the velocity also decreases.

V.3.4 *Results of magnesium sulphate soundness test*

The magnesium sulphate soundness test were carried out on the rock samples of the study area. Small thin slabs of each rock unit were prepared and weighed then soaked in the Mg SO_4 solution for 17 hours, then drained for 2 hours and oven dried for 24 hours as described in (BS 812 1989). This cycle is repeated for 15 times. At the end of the test the samples were weighed again, and checked for the effect of the test on the rocks. The test conducted on the rocks in the present study is unfortunately not showing any significant deterioration of the material. Only some samples of red granite which are strongly affected by weathering and alteration have been affected by the test. The fact that the studied granite is in general of high strength is why it does not deteriorate in this crystallisation test. Rocks which generally deteriorate in this test are of low strength and unsound (Hosking & Tubbey 1969).

However, it has been observed in this test that the magnesium sulphate soundness test affects the surface texture of the tested slabs. The grey granites are the less affected, they only show some etching spots of biotite grains of about 1% of tested slab surface area (**Plate V.1**). The amount of etching has been estimated visually on the tested slab surface, using the percentage estimation chart (**Fig. V.8**). The estimations were carried out by selecting equivalent area on the tested surface, where this area is approximately equivalent to the ten times of the grain size of the tested rock. Then the amount of etching on this area have been estimated using the charts for visual estimation. The pink granite is more affected by the solution. The surface of the pink granite show to be more etched particularly along the cracks, cleavages, dark(mafic) and stained areas, the cracks and cleavages have been widened and become more visible. Potassium feldspars are also affected especially along cleavage planes. The total percentage of etching areas on the tested slab areas of the pink granite is estimated at about 10% (**Plate V.2**). The red granite is more affected and the etching is estimated to vary from 10 to 20% (**Plate V.3**). The expandable clay mineral content of the pink and red granites (as shown by XRD results in section **III.5.4**) are probably the primary factor which causes them to be more affected by the magnesium sulphate solution. The presence of this kind of clays probably causes destruction of the rock surfaces under the test condition of wetting and drying. Microgranites granophyre are slightly affected by etching and in general less affected than all types of the studied granites. It has also been observed that the colour of the Mg SO_4 solutions has changed during the tests, it has become reddish. The same results were obtained when the test is conducted on small rock cubes and cores with length to diameter 2:1. The amount of etching increases with the degree of alteration or weathering of the granitic rocks studied.

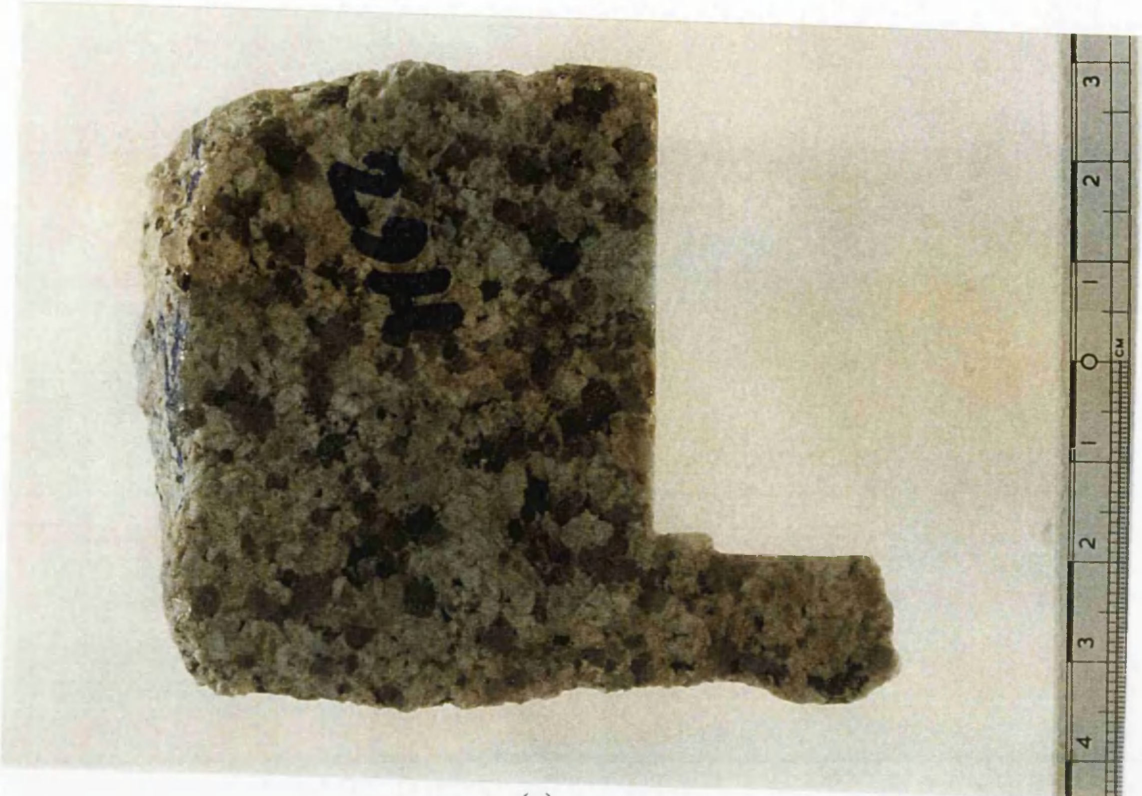
An attempt has been made to determine the strength of the rock samples which have been subjected to soundness tests. These samples were tested using the compression machine and the strength values were determined. The strength values are not showing any significant variations from the normal strength values of the rocks, thus the soundness test seem to be not the appropriate method to investigate the soundness of the granitic rocks, particularly when the granite is not affected by severe alteration and weathering (examples; sites 1 &2 pink and grey granites).

Although the soundness test does not give any clear indications concerning the strength variations, for durability and soundness of the hard and slightly to moderately altered and weathered granitic rocks, the test shows the affect on the surface appearance of the rocks, particularly the pink and hard rock samples from red granite. Thus the soundness test could be applied to investigate the stability of rock surface appearance, colour, surface textures and susceptibility to fracturing and weathering.

V.4 *CONCLUSION*

The physical and mechanical properties of the granites in sites 1& 2 are mainly controlled by texture, alteration and the presence of microfractures in the rocks.
The grey granite has generally high density, low porosity and low water absorption. It has also high value of strength as well as the ultrasonic velocity with some exceptions in site 2, due to presence of microfractures particularly in quartz crystals. The soundness of the surface texture is quite good. The pink granites in both sites have quite moderate values, while the red granite, have the poorest engineering properties

among the granites in both sites. Although, the microgranite and granophyre are completely stained as red granite but they have quite high order values of engineering properties, this could be due to their fine and interlocking texture.



(a)

(b)

Plate V.1: Grey granite surface soundness test
a) before test b) after test

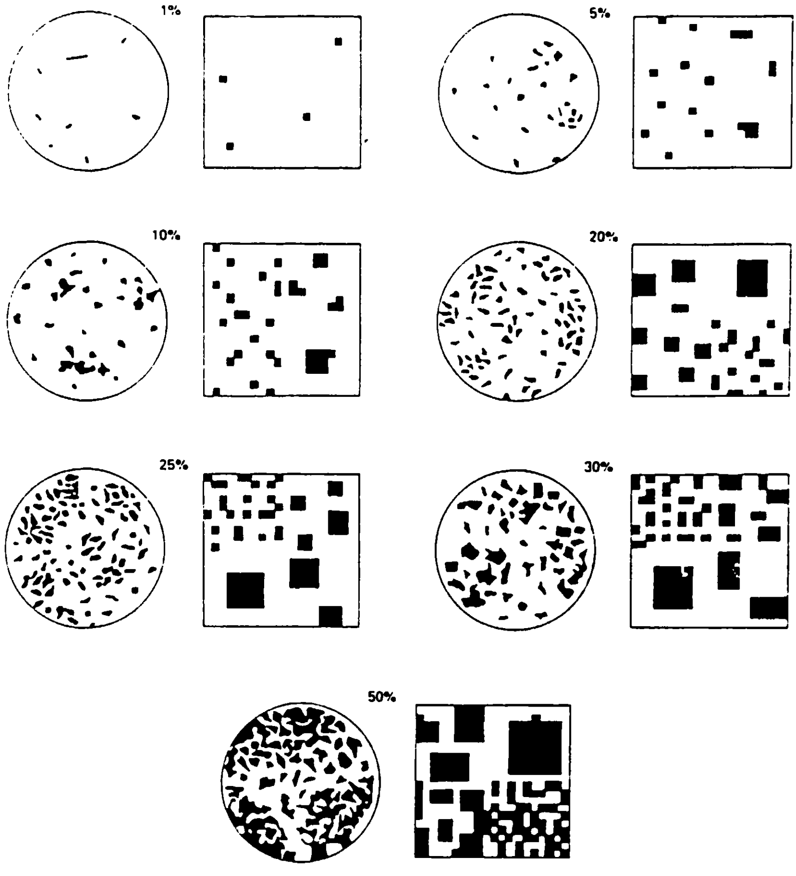
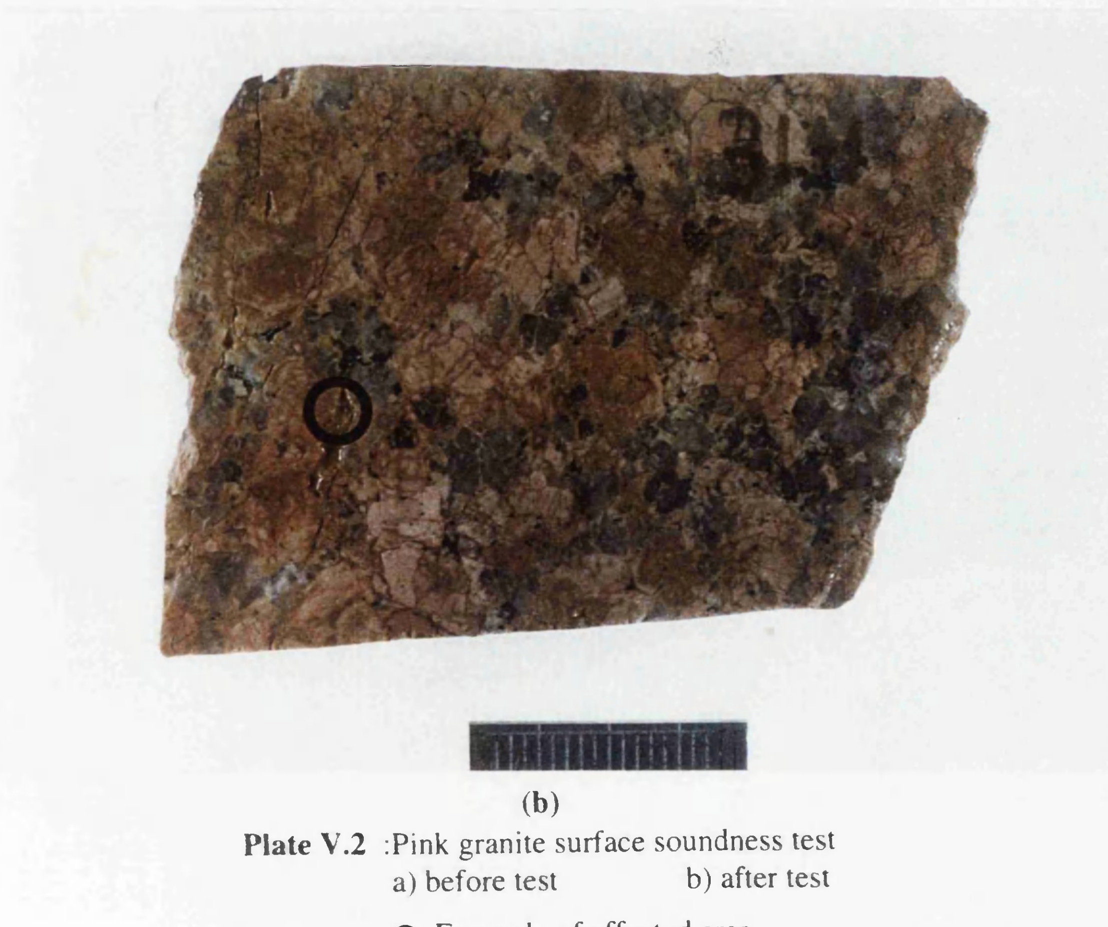


Fig.V.8: Soundness surface estimation chart

(a)



(b)

Plate V.2 :Pink granite surface soundness test
a) before test b) after test

O Example of affected area

(a)

(b)

Plate V.3 Red granite surface soundness test
a) before test b) after test

O Example of affected area

CHAPTER VI

SITE EVALUATION

VI.1 *GENERAL BACKGROUND*

The main factors controlling the suitability for exploitation of a potential dimension stone site are: quality, quantity, and whether the production is economic or not. The quality of a rock for dimension stone purposes is very important; it dictates the environment in which the stone can be used as well as the suitability of the site for production. The quality can be predicted by studying the following aspects:

① The rock type

② The uniformity of texture

③ The attractiveness of the colour

④ Absence of weathering and alteration; the depth of weathering and the overburden material should be thin. Therefore, the amount of waste material should be very limited.

⑤ Engineering (physical and mechanical) properties of the rocks

⑥ The rock mass parameters. These are very important and have a prime role in the selection of the quarry site.

Discontinuities in the rock mass may control the rock processing; well-jointed rock with orthogonal sets may provide good and easy extraction and safe quarry sites. Too many joint sets may affect the shape, the size, the quality of the material and more weathering is expected.

The quantity of a potential dimension stone resource can be estimated from a topographic map, but when the outcrops are limited the volume can be determined on the basis of subsurface work, such as geophysical methods.

The transportation of the material is one of the most important economical factors; high costs can make the operation uneconomical. The other economic factors that may effect the cost of the stone are the availability of electricity and water supply. Market demand is also an important consideration.

Laubscher (1994) listed the technical factors required in mine (quarry planning) as follows:

1. Geological investigation
2. Rock mass description and classification
3. Quality of the ore body (the stone in this case)
4. Rock mass stability
5. Homogeneity

The present chapter evaluates the granites of the study area in terms of their suitability to be extracted as dimension stone. The evaluation will be based on the properties determined in the field and on the laboratory results. There are no specific or adequate standards or specific classifications to evaluate rocks for dimension stone purposes (Jefferson 1993). However, the rock characteristics of sites 1 &2 were assessed using the generally available classifications of rocks. The rocks of the study area are also compared with the commercially-developed dimension stone of Mull Granite in Scotland, UK. Due to the unavailability both of topographical data and detaileded data on consumption of dimension stone, the evaluations were concentrated on the quality assessment of the rocks.

VI.2 *THE QUALITY OF THE STUDY ROCKS AS DIMENSION STONE*

The granites in the study area (sites 1& 2) were assessed based on the results of Chapters III, IV and V as follows:-

VI.2.1 *Petrological characteristics*

The granites of the study area are mostly grey, pink and red colours. They are mainly crystalline granular texture with medium to fine grain size. The medium granite rocks are grey, pink and red granites, while the fine grained rocks are microgranites and granophyres. The mineralogy of all granites in sites1&2 is similar. The granites of the study area are affected by alteration in different stages. The grey granite is fresh to slightly stained and altered. The pink granites in both sites have mainly the same composition as the grey granite, but they are more affected by alteration. The staining and weathering is moderate to high. The pink colour of the rocks seems to be inherited due to alteration and staining of the feldspar and biotite in these granites.

The red granite and microgranite and granophyre are highly altered and completely stained, particularly, the red granite. The mafic minerals are mostly altered. Generally, the red colour of the rock seems to be the result of alteration and staining of the feldspar and biotite. Although the microgranite and granophyre are altered and completely stained, they are fine grained and have interlocking textures. The main petrological features of the rock units of the study area are summarised in the Table VI.1.

Table VI.1: Petrological characteristics of the granites in the study area

Petrological characteristics					
Site NO.	***Colour***	***Texture & grain size***	***Main minerals***	***Alteration***	***Rock name***
1 and 2	Grey	Granular and medium to coarse grain	K-feldspar, quartz, and biotite	Partially cloudy and slightly stained	Grey granite
1 and 2	Pink	Granular and medium to coarse grain	K-feldspar, quartz, biotite	highly cloudy and to moderately highly stained	Pink granite
1	Red	Granular and medium to coarse grain	K-feldspar, quartz and altered biotite	Intensively cloudy and completely stained	Red granite
2	Red	Interlocking granular and fine grain	K-feldspar, quartz and altered biotite	Intensively cloudy and completely stained	Microgranite and granophyre

VI.2.2 *Physical and mechanical properties*

The physical and mechanical properties of the rocks may provide an indication of their durability. These properties are listed below:-

VI.2.2.1 Density, water absorption and porosity

According to the description of engineering physical properties of rock (Anon 1979) (Table VI.2), the grey granite of site1 is characterised by high density >2.60 g/cm^3 (sat) with very low porosity (0.95%) and water absorption (0.37%). The pink granite of site1 also has a high density of 2.58 g/cm^3 and a low to medium porosity (2.32%) and water absorption (0.90%). Red granite in site 1 has the lowest density values between 2.52 and 2.57 g/cm^3. The porosity and water absorption of this are quite low (n=2.97%, AT=1.2%).

Table VI.2: Description of dry density and porosity (after Anon 1979)

Class	*Dry density (Mg/m³)*	*Description*	*Porosity (%)*	*Description*
1	less than 1.80	very low	over 30	very high
2	1.80 – 2.20	low	30 – 15	high
3	2.20 – 2.55	moderate	15 – 5	medium
4	2.55 – 2.75	high	5 – 1	low
5	over 2.75	very high	less than 1	very low

The physical properties of rock units in site2 have similar characteristics as with the rocks in site1. The density of grey granite is 2.55 g/cm^3 of high class, with low porosity and low water absorption. The microgranite and granophyre have high density values of 2.58 g/cm^3 and a very low porosity (1.1%) and water absorption (0.41%). By comparing the above properties with the generalised properties of rocks as suggested by West (1996) (Table VI.3), the rocks in the study area generally show acceptable density and water absorption values--except the red granite. The grey granite and microgranite and granophyre have typical density and water absorption values after correlation with the values from West (1996).

Table VI.3: General granite properties (West 1996)

Description of granite	*UCS (MPa)*	*Saturated density (g/cm^3)*	*Water absorption (%)*
Fresh	262	2.61	0.11
Partially stained	232–163	2.62 – 2.58	0.35 – 1.09
Completely stained	105	2.56	1.52
Weak	46 – 26	2.55 – 2.44	1.97– 4.13

VI.2.2.2 Mechanical properties

The uniaxial compressive strength (UCS) and ultrasonic velocity tests have been conducted. These results were compared with values from the available classification schemes and specifically with the Engineering Group working party (Anon 1979) classification, because their classifications have more general use.

a) Uniaxial compressive strength (UCS)

The strength (UCS) has a range of values in the granites in sites1& 2. According to the grades adopted by Anon (1979) (Table VI.4), and Anon (1981), the grey granite in site1 can be describe as having a high strength value (UCS of 161 MPa, sat.) and so be a very strong rock. The pink and red granite also fit in a similar strength class, but have a wide range of strength values. This may be due to these rocks have been affected by different stages of alteration. For example, the granites in site1 have the same class of strength, but the range of strength values is quite wide. The grey granite has a strength of 161MPa (sat), the pink granite has 129 MPa, while the red granite has the lowest values of 105MPa.

The pink granites of site 2 have values of strength 136MPa (sat), This value indicates that the rock is very strong. The granophyre and microgranites exhibit very high strength values of UCS (>170MPa (sat)) and are also described as very strong rock. The latter two rocks have the highest strength values among the rocks in the study area; this may be due to these rocks having a fine interlocking texture. Based on the strength values, and the strength classes, the granites in the study area are generally classified as very strong rocks.

Table IV.4: Description of Unconfined Compressive Strength

Geological Society (Anon 1970)		*IAEG (Anon 1979)*		*ISRM (Anon 1981)*	
Strength (MPa)	**Description**	**Strength (MPa)**	**Description**	**Strength (MPa)**	**Description**
less than 1.25	very weak	1.5 – 15.0	weak	under 6	very low
1.25-5.00	weak	15.0 – 50.0	moderately strong	6 – 20	low
5.00-12.50	moderately weak	50.0 – 120.0	strong	20 – 60	moderate
12.50-50.00	moderately strong	120.0 – 230.0	very strong	60 – 200	high
50.00-100.00	strong	over 230	Extremely strong	over 200	very high
100.00- 200.00	very strong				
over 200	Extremely strong				

b) The ultrasonic velocity

According to the classes of ultrasonic velocity suggested by Anon (1979) (Table VI.5), most of the rocks in sites1&2 have high sonic velocity. However, the grey granite of site 2 has moderate velocity. Dearman *et al.* (1978) have established a range of velocities for various degrees of weathering in granite (as shown in Chapter V). By comparing the ultrasonic velocities of the granites in the study area with the velocity classes adopted by Dearman *et al.* (1978), the granites in this area could be described as fresh to slightly weathered rocks. Although the velocities were measured on intact rock samples, they give an indication about rock weathering variations of the granites in the study area. Poole (1996) indicates that the ultrasonic velocity could be used as an indication of microfractures. The grey granite of site 2 has low velocity values when compared with the others. This may be due to that this rock having a large number of intragranular cracks, particularly in the quartz grains. The red granite also has a low velocity; this may also be due to the presence of the open cracks, voids, and highly altered and weathered rocks.

However, the granites in the study area mostly have high velocities: the exception is the weathered red granite in site1. Therefore most of the granites in the area have acceptable velocity values.

Table VI.5: Description of sonic velocity (after Anon 1979)

Class	*Sonic Velocity (m/s)*	*Description*
1	Less than 2500	Very low
2	2500 – 3500	Low
3	3500 – 4000	Moderate
4	4000 – 5000	High
5	over 5000	very high

VI.2.3 *Weathering and Schmidt hardness value*

The weathering grades of the rocks in the study area have been investigated. Many grades of rock weathering occurred. These grades have variations from GI, II, III, IV and V and were classified according to Anon (1995). The zones were presented on the weathering maps (as shown in Chapter IV, Figs. IV.25 &26) for both sites. The study area generally has two zones of weathering and these are zones 1 and 2. Zone 1 mainly occurs in the grey and pink granites while zone 2 generally occurs in the red granite and microgranite and granophyre rocks. Rocks in weathering zone1 mostly are slightly to moderately weathered, while zone 2 rocks have a wide range of grades of weathering.

The Schmidt hardness test is one of the portable quickest and simplest index tests to recognise the state of weathering (Hencher & Martin 1982; Irfan & Powell 1985 and Irfan 1996). These three groups and Dearman & Irfan (1978) suggested a relationship between the weathering grade and Schmidt hammer values (*N*) of granites as shown in Chapter IV Table IV.9. The readings of *N* values and weathering grades in the study area have good correlation (Figs. IV.25 & 26). It can be seen that when the *N* values decreases the weathering grades generally increase in the area. For example, zone1 weathering area in site1 has N values generally greater than 30, while zone 2 has N values less than 30 (particularly in the red granite). Based on this, the granites in zone1 have characteristics typical of less weathered rocks than do the granites in zone 2. Therefore, the rocks in the zone1 have more potential dimension stone material than the granitic rocks in zone 2.

VI.2.4 *Soundness and durability*

The crystallisation test indicates that the granites of the study area are too hard to be affected by the test. Only the weathered red granite has been affected by the test and resulted in some degree of fragmentation. However, the test did have an effect on the surface texture of the rocks (cut surface). This effect is highly dependent on the alteration state and the presence of the cracks in the rocks. The surface textures of the red and pink granites are strongly affected by etching, pitting and enhancing the cracks and cleavages in these rocks, while the grey and microgranite and granophyre are generally slightly affected by these features. This may be due to the fact that the grey granites are less affected by alteration and the microgranite and granophyre rocks have a fine interlocking texture.

The crystallisation test gives an indication about soundness and durability of the surface texture of the granites, which is the front of the rock against weathering. It is found that the more altered the rocks the higher the susceptibility to surface weathering and then to disintegration of the rock. This is quite clear in the red granite where its surface texture is highly affected by the test. The weathered red granite contains expandable clay minerals (as confirmed by XRD in Chapter III) and it is thought that alternate wetting and drying promotes cracking of the rock due to the expansion and contraction of the clay minerals (Cawsey and Mellon 1983). This may indicate that when the rock is altered by chemical weathering, it will permit the physical disintegration to take place in very short periods of time, such as may occur in the red granite. Therefore according to this test the red granite, and also the pink one, are more susceptible to the weathering than the other rocks.

VI.2.5 *The discontinuity characteristics*

The discontinuity aspects such as orientation, frequency, spacing, block size and shape have been evaluated, in order to see if they have acceptable aspects for potential dimension stone materials.

a) Orientation

Well developed discontinuities with a small number of sets, will be very useful in extraction of the rock material, but when the frequency of discontinuities is high, the value of dimension stone will be reduced. The orientation of the discontinuities has an influence on the dimension stone extraction in terms of the size, shape and amount of waste material, and the stability of the quarry faces. The yield of the dimension stone products from the site will depend on the angle and the plunge at which sets of discontinuities intersect. The favourable angle between set strikes is 90° and the plunge of intersection of sets is preferred to be vertical (orthogonal sets). These angles will give regular block shapes (cubic blocks), hence the wastage materials during processing will be reduced (Jefferson 1996). More sets will normally reduce the block size and affect the shape as well. The rocks in sites 1&2 are well-jointed, mostly continuously with orthogonal joint sets: two vertical sets and one subhorizontal set with some minor sets.

b) Spacing

The pink and grey granites of site1 have wide, to very wide, spacing with a frequency of one joint per meter. According to the classification of Anon (1995), (Table IV.3) in Chapter IV these rocks can be evaluated as having very wide to wide spacing. The red granite has mostly medium spacing. The microgranite and granophyre of site2 has poorest rock mass mostly with close joint spacing, while the pink and grey granites of site2 have wide to very wide spacings. In terms of dimension stone the higher the class of rock mass, the more likely large blocks can be extracted (Smith 1996). Therefore, the pink and grey granites generally have a higher class in terms of suitability to be extracted as dimension stone than do the red granite and microgranite and granophyre rocks.

VI.3 *POTENTIAL DIMENSION STONE CHARACTERISTICS OF THE GRANITES IN SITE1&2*

The quality of the potential dimension stone resources of the granites from sites 1&2 a evaluated in this section. The quality assessment incorporates: petrological aspects, geotechnical properties, weathering and discontinuity characteristics.

VI.3.1 *Good quality rock type*

The grey granite in sites 1& 2 has been classified as potentially of good quality dimension stone, based on: the petrological, geotechnical, weathering and joint properties. It is a grey, medium grained granite, it is fresh to slightly altered, has a high density, is very strong, has a durable rock cut surface, and belongs to the zone 1 weathering class. It also has widely spaced horizontal joints, and orthogonal vertical joint sets, with a low lineament density. Therefore, the grey granite is considered to have high potential for dimension stone resources.

VI.3.2 *Moderate quality rock type*

The pink granite in sites 1& 2 has been classified as potentially of moderate quality. It is pink, also has a medium grain size, is partially to considerably altered and stained, generally of high density, very strong to strong, of zone 1 weathering class, and has a moderate durability rock cut surface. It has widely spaced horizontal and orthogonal vertical joint sets with low lineament density. Therefore, the pink granite is considered to have a moderate potential as a dimension stone resource.

VI.3.3 *Poor quality rock types*

The red granite in site 1 has been classified as having a poor potential quality as dimension stone. It has a red colour, and medium grain size, and is completely stained and altered; its high porosity characteristics, together with its water absorption, variable strength, zone 2 weathering class, and poor durability rock cut surface, degrade its potential. It has medium spaced horizontal and orthogonal vertical joint sets with a high lineament density. Although the microgranite and granophyre have apparently high strength and low porosity and water absorption, they are completely stained and have the poorest rock mass quality. They also have closely spaced joints with high lineament density in addition to class 2 of weathering. Therefore, the red granite, microgranite and granophyre are considered to have poor potential as a dimension stone resource.

VI.4 *EXTRACTION CONSIDERATIONS*

The stone must have acceptable properties which are required for building stone. The assessment of rocks as building stone will be done utilising specifications to categorise the rock into different groups. These groups will be defined in terms of suitability. In the exploration stage, the first parameter to be assessed is the size of rock blocks which can be extracted. This implies that a thorough investigation of the discontinuity characteristics of the rock mass should be carried out. The frequency and spacing of all the joint sets present must therefore be determined as they control the shape and size of the blocks. It is well known that the more jointed the rock mass the smaller and more irregular are the blocks that it will yield. Priest (1993) mentioned that the rock mass properties are obviously of great interest to the quarry operator as they determine the feasibility of production of large blocks. Large blocks extracted from a mass having a wide joint pattern always can be used as dimension stone materials, but small blocks which result from close spaced joints can not be used properly as dimension stone (Jefferson 1996). Although the block size parameter is important, it is not the only factor upon which acceptance or rejection of the rock depends, other factors such as strength, degree of weathering, and the appearance of the rock are also important properties (see above). Jefferson (1996) mentioned that after identifying the rock mass areas where material of suitable block size for dimension stone may be obtained, these would be again be assessed on the basis of such properties as strength, potential durability and visual appearance. Based on these properties, the suitability of the rocks as dimension stone is assessed. The quantity and the distribution of the suitable stone should be determined. The extraction and evaluation of the dimension stone could be inadequate when the rocks has variation in textures, grain size, colours, microfractures, alteration and variations in spacing.

The mineralogy of the rock can effect the durability, the appearance and strength of the dimension stone. For example, the granite has crystalline texture and primary minerals of feldspar, quartz and mafic minerals such as biotite. The major components are feldspar and quartz; these minerals exhibit high strength in the fresh state. But when the rocks, and particularly their feldspars, are affected by alteration, the strength and durability is decreased. Knill (1978) mentioned that the presence of secondary minerals such as pyrite, chlorite, iron oxides and clays can produce discoloration of dimension stone and may even cause failure through volume expansion.

The variation in discontinuities, such as number of sets, orientation, frequency and spacing are more important in the extraction. The orientation and frequency of discontinuities reflect on the size and shape of rock blocks. The amount of waste is also affected by the orientation of the discontinuities. When the rock blocks are induced by orthogonal sets, the waste material is significantly decreased in the processing of the dimension stone.

The discontinuity spacing should be greater than 1m (Fookes and Poole 1981), for suitable block and shape for extraction. Generally, the structural data have an influence on the quality of the stone, in terms of weathering, size and shape, and soon the type of product to be produced. More discontinuity sets will introduce small blocks, which are easy for extraction and are mainly used as aggregate resources, while less rock mass jointing with mainly orthogonal sets could produce regular and large block suitable for dimension stone. Normally, well jointed rocks could be extracted using manual or mechanical tools; otherwise blasting and heavy tools are needed.

Blyth and de Freitas (1974) mentioned that the important features in selecting a dimension stone are its strength, durability, spacing of joints and appearance of the stone.

The stability of the quarry face is mainly controlled by the structural features. Vertical and widely spaced sets produce safer wall faces than when the rocks have inclined sets, particularly if these sets are dipping towards outward quarry face.

Generally, the rocks are evaluated for dimension stone based on the aspects given in table Table VI.6.

Table VI.6: Geological aspects for dimension stone quality

Discontinuity characteristics	*Rock properties*
Orthogonal sets (mainly 3 sets)	Homogeneous grain and texture
wide spacing (>1m)	Homogeneous colour and good appearance
Low frequency	High density and low water absorption and porosity
Well jointed	Strong (UCS >105 MPa for granite)
Large block size(1–4 m^3)	High ultrasonic velocity
Regular block shape	Fresh and unaltered
Hard exposure and durable	Sound

The above parameters are the most important in extraction and evaluation for natural dimension stone. There are other aspects may be also relevant in the evaluation of stone: these include impact resistance, coefficient of thermal expansion and thermal shock. It is unlikely that it would be necessary to investigate such aspects at the exploration stage, since they relate more to specific products such as cladding, rather than to the general use of the rock as a building materials (Jefferson 1996).

The outcrop should be easy to access. Potential sites for dimension stone should not contain any potential for economic minerals and should not disturb the natural environmental condition of the area.

VI.4.1 *Block size and shape*

a) **Previous work**

Block size is an important indicator of rock mass behaviour (Barton 1987) and is a critical factor in determining suitability for dimension stone purposes. Blocks are created by the intersection of non-parallel discontinuities, and the spacing of individual sets controls the size of the blocks which are created (Brown 1994). The most suitable natural block size which could extracted is one to three cubic metres in volume (Smith 1996). In terms of dimension stone, the rock mass properties are obviously of great interest to the quarry operator as they determine the feasibility of the production of large blocks (Priest 1993).

The maximum size or volume of block that can be produced by a quarry, as determined by the structural geology, is an important and valuable piece of information when sourcing dimension stone. In general, the potential for dimension stone is related to the ability of the site to provide large blocks which can be handled. Usually the block size which can be processed easily is up to 10 tonnes in weight or 3 to 4 cubic metres in volume (Smith 1996). These sizes can be created naturally when the site has well developed, regular, widely-spaced patterns of joints.

Block size can also be defined as the average diameter of a typical rock block in the unit (Franklin 1994) or by the total number of joints intersecting a unit volume of the rock mass (volumetric joint count, Jv) (Barton 1978). The block size can be measured simply by observing an exposed rock face at the surface or underground; or in rock core obtained by drilling; or in a pile of broken rock, i.e. rock slope talus or muck heap after blasting (Franklin and Dusseault 1989). The volumetric joint count (Jv) is defined as the sum of the number of joints per meter for each joint set for each set present (Barton 1978). It is obtained by adding the joint intensities (number of joints per meter) measured for each individual set along lines normal to each set, using 5 to 10m sample length. For example in the case of four sets of discontinuities:

$$Jv = \frac{6}{10} + \frac{24}{10} + \frac{5}{5} + \frac{1}{10} = 0.6 + 2.4 + 1.0 + 0.1 = 4.1\,Jm^{-3} \text{(medium size block)}$$

Barton (1978) proposed the block size designation shown in **Table VI.7**.

In-situ block size distribution and shape parameters have been studied by Hudson & Priest (1979) and Wang *et al.* (1990). The latter applied a formula of the form:

$$V_i = C_i(\lambda_1\lambda_2\lambda_3)$$

where V_i is the size (volume) of a block such that i% of the rock mass is smaller than V_i, C_i are empirical coefficients and λ represents the principal mean spacing if the three sets of the discontinuities are orthogonal or

$$V_i = \frac{C_i(\lambda_1\lambda_2\lambda_3)}{\cos\theta\cos\phi\cos\alpha}$$

if they are non-orthogonal, with θ, ϕ and α being the angles between the mean of the orientations of the discontinuity sets. In this method, the block size coefficients, C_i, which are independent of the actual values of mean spacing, have been tabulated for various spacing frequency distributions (Wang *et al.* 1990).

Table VI.7: Block size classification and equivalent discontinuity spacing

Block size and equivalent discontinuity spacing			
Barton (1978)			*Anon (1995)*
Term	*Volumetric Joint count (Jv) (Joints m^{-3})*	*Block size m^3*	*Equivalent of discontinuity spacing in blocky rock*
Very large	< 1	Over 8.0	Very wide
Large	1 – 3	0.2 – 8.0	Wide
Medium	3 – 10	0.008 – 0.2	Medium
Small	10 – 30	0.002 – 0.008	Close
Very small	> 30	Less than 0.0002	Very close

b) Procedure used in this study

In the present study a different technique was devised. The rock mass of the granites in sites1&2 have mainly three principal (and orthogonal) joint sets. Therefore three orthogonal scanlines have been used to determine the set spacings. More than 20 spacing values for each set were determined, which gives an adequate block size determination (Wang *et al.* 1990). The spacing values of each joint set were plotted as histograms in order to see the distribution frequency of the spacing values. As an example the grey and pink granites results are shown in Figs. VI.1 and Table VI.8. Other rock types are summarised in Appendix IV. The choice of size classes varies across the range of rock type and different joint sets.

Using these spacing/frequency data, the block size distribution is found via the following procedure:-

$\boxed{1}$ Three set spacing values were obtained from three scanlines (orthogonal).

[2] Histogram distribution of actual spacing data for each set were plotted (Fig. VI.1 and Appendix IV).

[3] The spacing values and their frequencies for each set were tabulated (Tables VI.8).

Table VI.8: Joint set spacing values from orthogonal scanlines of grey and pink granites of site1

Set 1 spacing		***Set 2 spacing***		***Set 3 spacing***	
Category value (m)	***Frequency***	***Category value (m)***	***Frequency***	***Category value (m)***	***Frequency***
0.5	45	0.5	54	0.2	1
1.0	32	1.0	45	0.4	5
1.5	15	1.5	38	0.6	9
2.0	5	2.0	20	0.8	4
2.5	3	2.5	5	1.0	2
3.0	2	3.0	6	1.2	4
3.5	2	3.5	2	1.4	4
4.0	0	4.0	3	1.6	2
4.5	5	4.5	0	1.8	0
5.0	1	5.0	0	2.0	0
		5.5	1	2.2	1

[4] The block size of the volumes and their block number were obtained by multiplying:

$$\text{Block size} = SP_{1i}\, SP_{2j}\, SP_{3k} \qquad (i=1..m, j=1..n, k=1..p)$$

$$\text{Block Nos.} = FQ_{1i}\, FQ_{2j}\, FQ_{3k} \qquad (i=1..m, j=1..n, k=1..p)$$

Where:

SP_1 = Set1 spacing

SP_2 = Set2 spacing

SP_3 = Set3 spacing

FQ_1 = Frequency number of set1 spacing

FQ_2 = Frequency number of set2 spacing

FQ_3 = Frequency number of set3 spacing

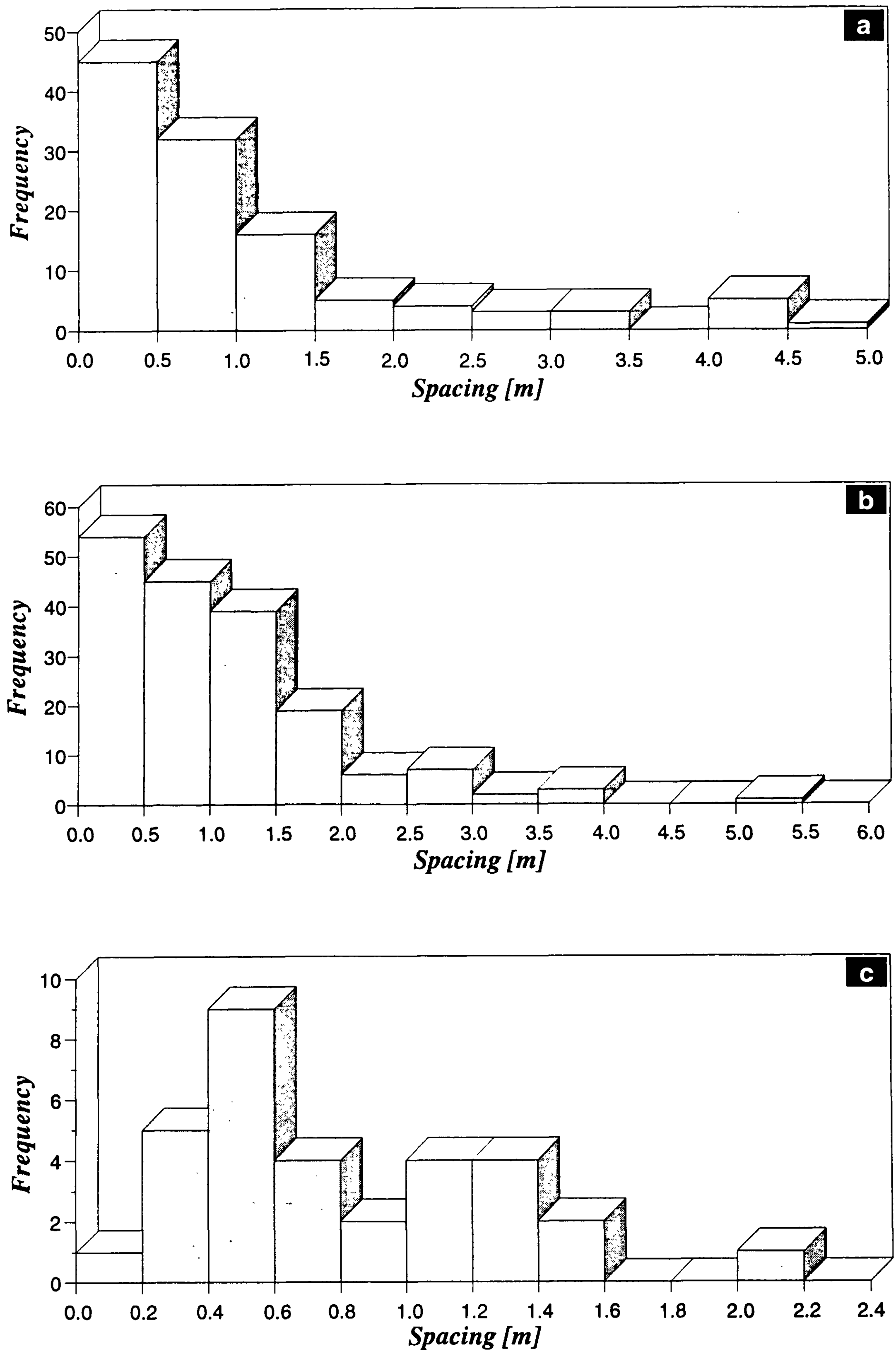


Fig. VI.1: Joint spacings in grey and pink granites from three orthogonal scanlines (a,b, and c) of site 1.

The multiplication is carried out, as shown in Fig.VI.2, by multiplying m individuals of set1 by n individuals of set 2 and each individual product is then multiplied by p individuals of set 3.

$\boxed{5}$ The results are sorted (the block size list order is sorted associated with the block number list).

$\boxed{6}$ The total block numbers were determined by summing the number of blocks of the same size.

$\boxed{7}$ Total volume for each size was determined by multiplying the frequency (block Nos.) by the volume size.

$\boxed{8}$ The cumulative of total volumes of the blocks was also calculated as well as for the block numbers.

$\boxed{9}$ Then the cumulative percentage of commutative total volumes was calculated as well as for the block numbers.

$\boxed{10}$ The block size distribution curve, by volume and by block number, was plotted.

This procedure is carried out for each rock type at both sites.

c) Results

The above established block size calculation procedures have been applied using the spacing data of site 1 and 2. The analysis has yielded into three type of results: the block size distribution; the block volume; and the numbers determinations. Two types of relationships have been obtained: block size vs. block volume; and block size vs. block numbers. The first relationship is concerned with the volume occupied by each block size; the second is concerned with the number of blocks in each block size. These are described as follows:-

1- Block size vs. volume

The block size and volumes for the granites of site 1 have been determined, plotting the grey and pink granite together (due to their similarity in discontinuity data) and the red granite by itself. The results of calculations are presented in Appendix II. The relationship between block size and volume has been plotted as shown in Fig VI.3 and the main results are presented in Table VI.9. $0.2m^3$ and $8.0m^3$ are the major class boundaries as proposed by Barton(1978).

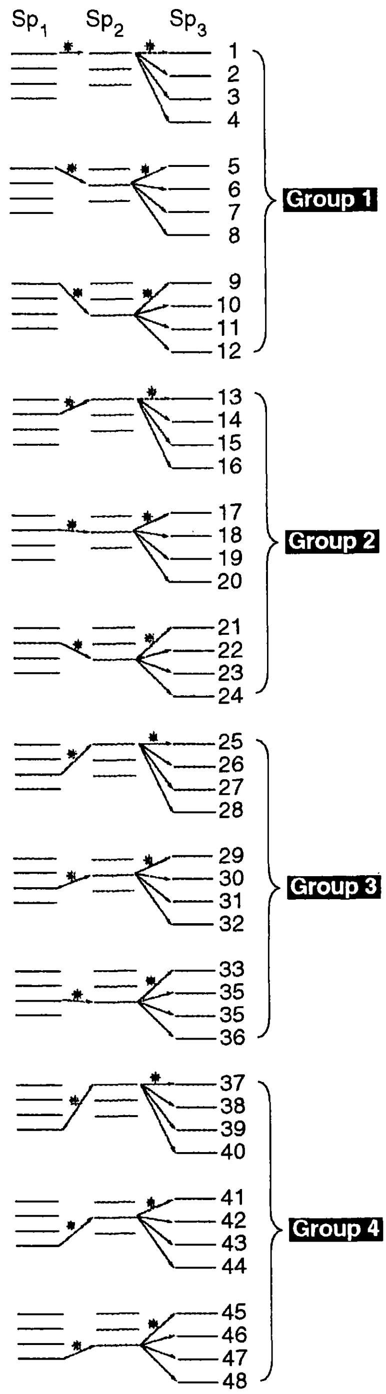


Fig. VI.2: Multiple procedure for block size calculation

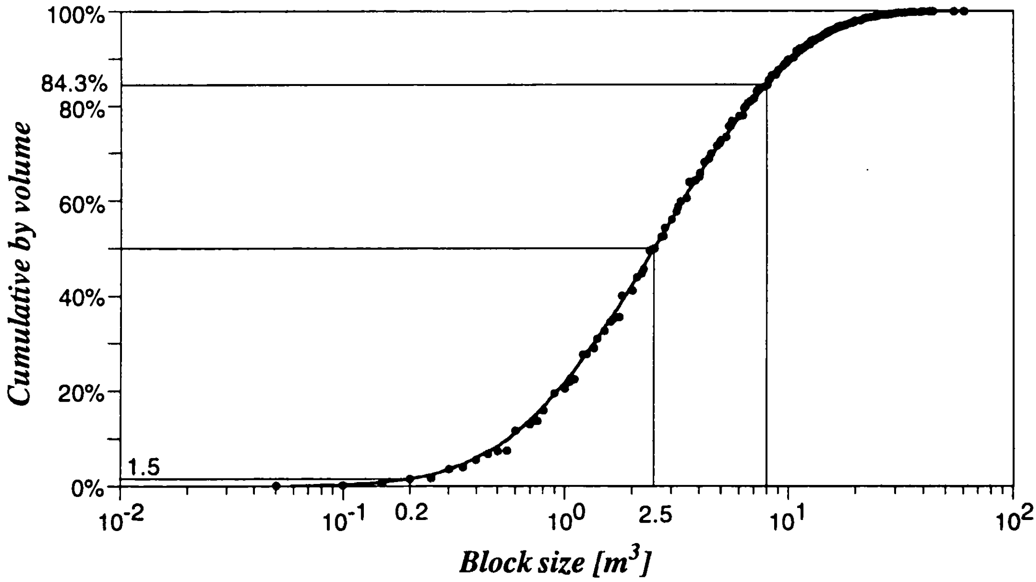


Fig VI.3: The block size vs. cumulative by volume of grey and pink granites in site 1

Table VI.9: In-situ block size distribution in sites1&2

Site No.	*Rock type*	*% of volume below size*		*% of block No. below size*		*Block size (m^3)*		
		0.2 m^3	**8 m^3**	**0.2 m^3**	**8 m^3**	**at 50% of volume**	**at 50% of block No.**	**Classification**
1	Grey and Pink granite	1.5	84.3	12	98.0	2.5000	0.740	Large
	Red granite	12.7	100	40	100	0.6000	0.250	Medium to large
2	Grey and Pink granite	≈ 0.0	71.2	≈ 2	93.6	4.4000	1.600	Large
	Microgranite & granophyre	99.7	100	100	100	0.0198	0.008	Medium to small

From Fig VI.3, we can see that in site 1 the grey and pink granite block size of 50 cumulative percentage volume is 2.5 m^3, which is in the large size class according to Barton's (1978) classification (Table VI.7). The cumulative volume percentage at 0.2 m^3 and 8 m^3 are 1.5% and 84.3%, respectively (Table VI.9). This result indicates that most of the block volumes of grey and pink granites of site 1 are concentrated between size 0.2 m^3 and 8 m^3 (large class). The block size of the red granite at 50% volume is 0.6 m^3 (Fig VI.4). The cumulative percentage volume below size 0.2 m^3 is 12.7 % (Table VI.9) and most of the block volumes of the red granite are below size 1 m^3 (Fig.VI.4).

Similarly, as in site 1, the block size and volume have been determined for the granites in site2. Here the pink and grey granites are plotted together and the microgranite and granophyre are also grouped together. For the grey and pink granites, the block size at 50% volume is 4.4 m^3 (large class) (Fig.VI.5). The majority of the volumes of the grey and pink granites are between size 0.2 m^3 and 8 m^3 of 71.2% (Table VI.9). On the other hand, the whole block volumes of the microgranite and granophyre are below size 0.2 m^3 (Fig VI.6 and Table VI.9).

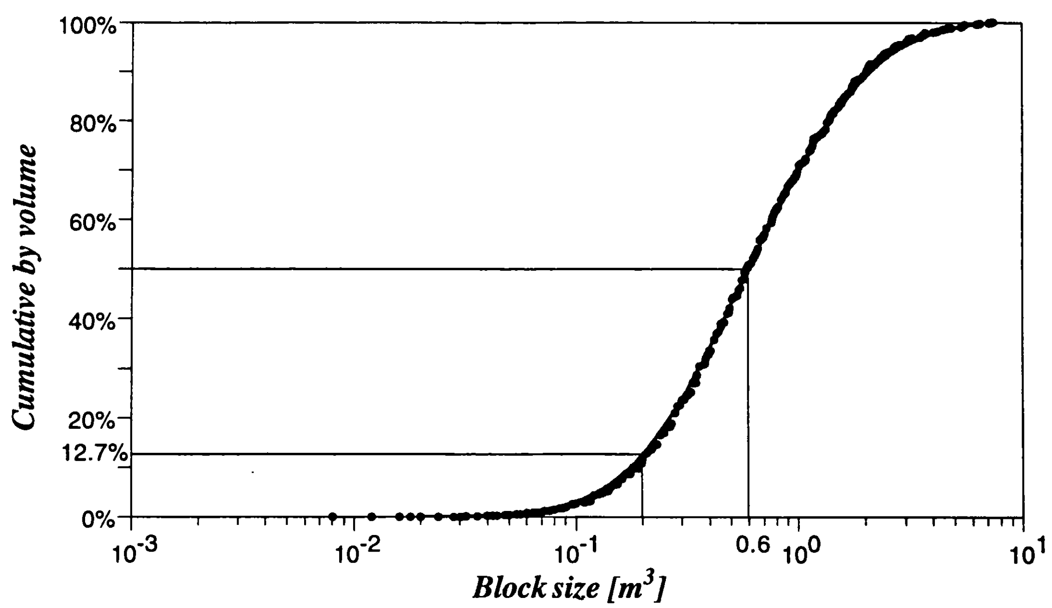


Fig VI.4: The block size vs. cumulative by volume of red granite in site 1

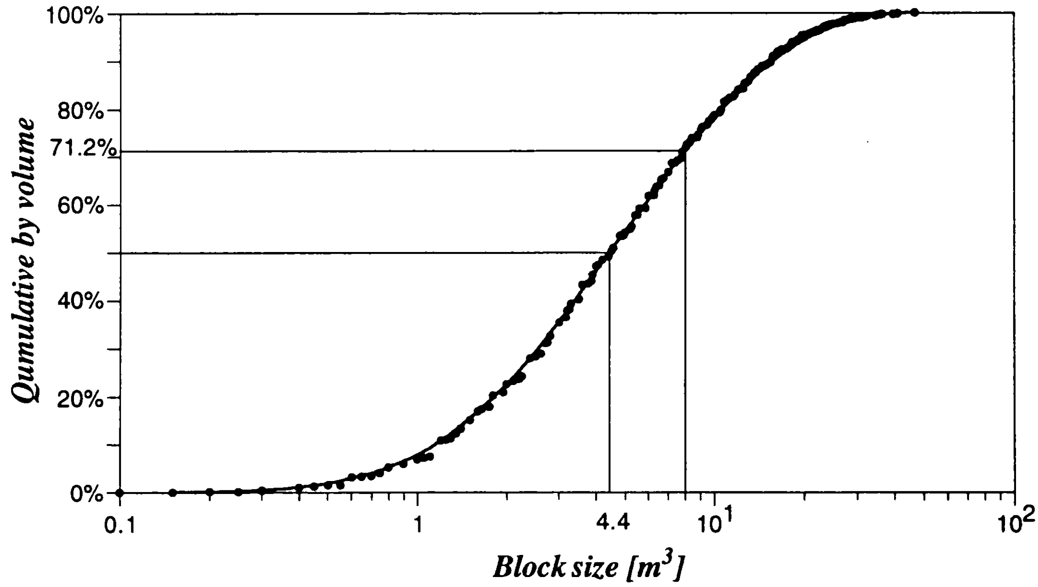


Fig VI.5: The block size vs. cumulative by volume of grey and pink granites in site 2

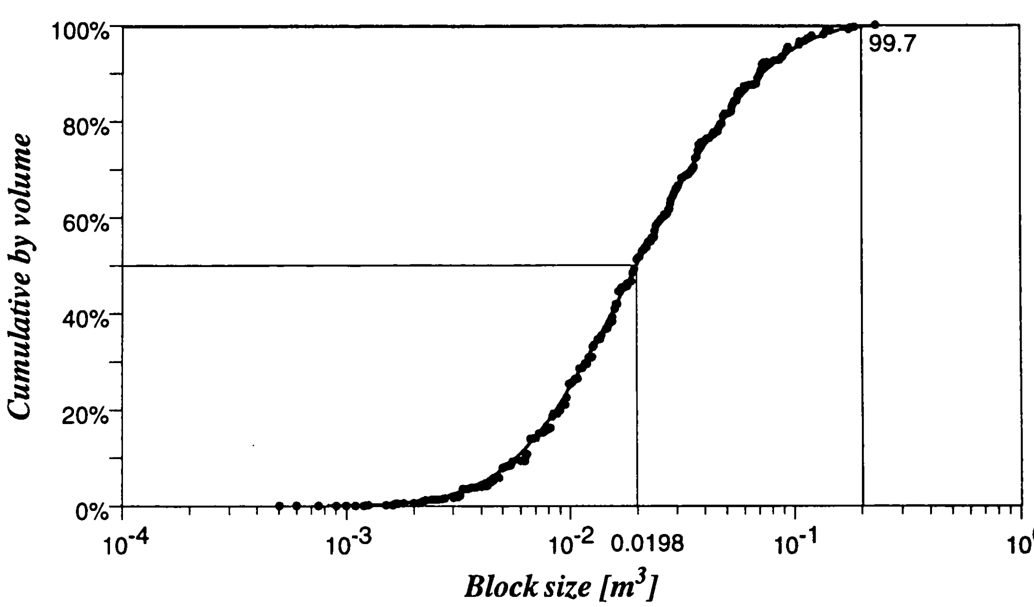


Fig VI.6: The block size vs. cumulative by volume of microgranite and granophyre in site 2

2- The block size vs. block numbers

The block numbers yield in certain block sizes are very important in finding the potential as dimension stone. The block size vs. cumulative block number percentage has been plotted and block size distribution parameters were obtained. The block size of the grey and pink granites (site 1) at 50% block numbers is 0.74 m^3 (large class). Most of the block numbers of grey and pink granites in site 1 are between size 0.2 m^3 and 8 m^3 and they have 12% and 98% respectively (Fig VI.7 and Table VI.9). The red granite has a much smaller block size of 0.25 m^3 at 50% block numbers (Fig VI.7). The cumulative percentage of block numbers of size 0.2 m^3 of red granite is 40%, while the whole block numbers in the red granite are below size 1m^3 (Fig VI.8 and Table VI.9). From these results, the red granite has block sizes ranging from medium to large.

Similarly, the block numbers vs. cumulative block numbers have been also plotted for granites in site 2. The grey and pink granites have a large block size of 1.6 m^3 at 50% of block numbers (Fig VI.9). The majority of block numbers for grey and pink granites of site 2 are within the large class of block sizes, that is between size 0.2 m^3 and 8 m^3 of more than 90% (Fig VI.9 and Table VI.9).

As in volume vs. block size distribution, the whole microgranite and granophyre block numbers are below size 0.2 m^3 (Fig VI.10), and the block size at 50% of block numbers is 0.008 m^3. These results indicate that the microgranite and granophyre rocks are within the medium to small block size classes (Fig VI.10 and Table VI.9).

The block size analysis of granites in site 1 and 2 reveals two domains. These are large blocks of grey and pink granites and medium to small sizes of red granite, microgranite and granophyre rocks.

VI.4.2 Block shape

Rock mass blocks have a characteristic shape that basically depends on the number of joints sets and their relative orientations and spacing (Franklin & Dusseault 1989 and Barton 1978, 1987). The shape is relevant in some engineering applications, for example

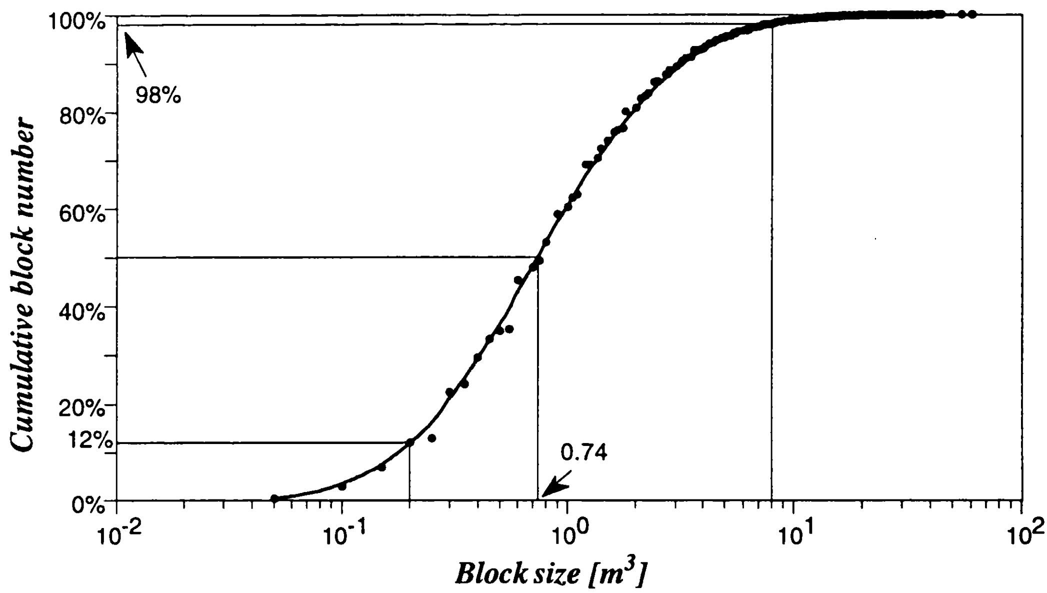


Fig VI.7: The block size vs. cumulative block number of grey and pink granites in site 1

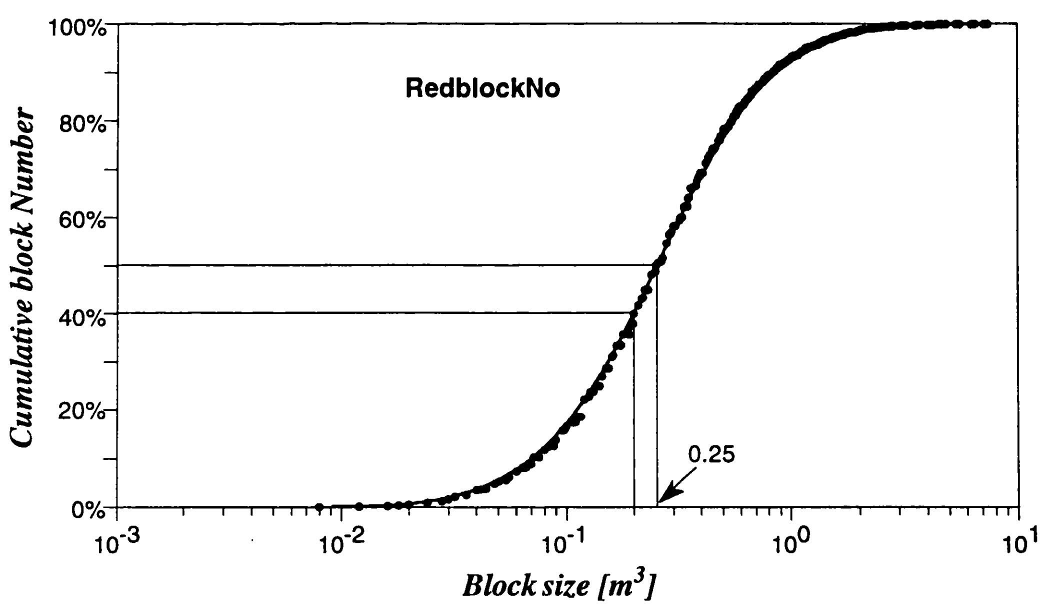


Fig VI.8: The block size vs. cumulative block number of red granite in site 1

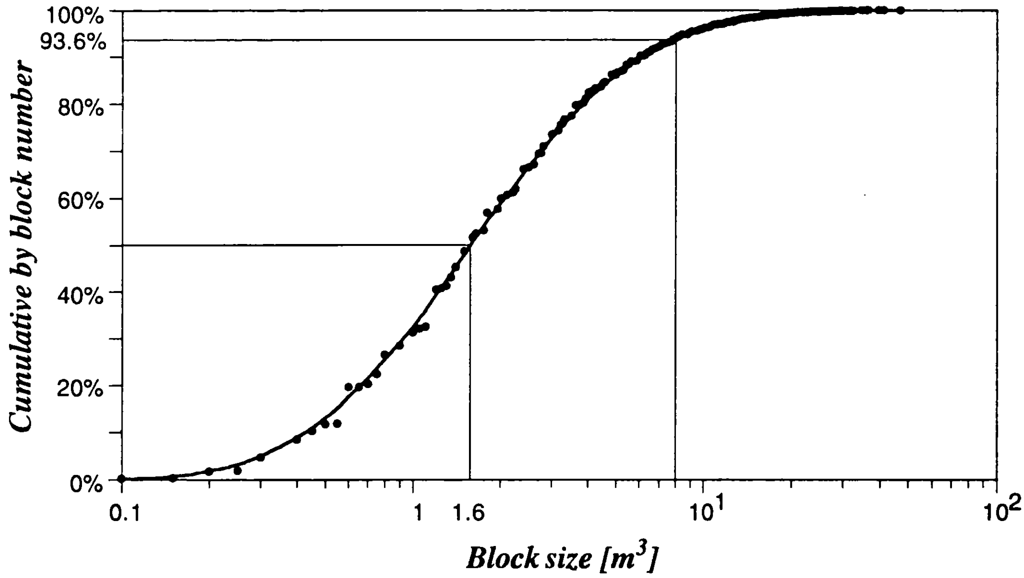


Fig VI.9: The block size vs. cumulative block number of grey and pink granites in site 2

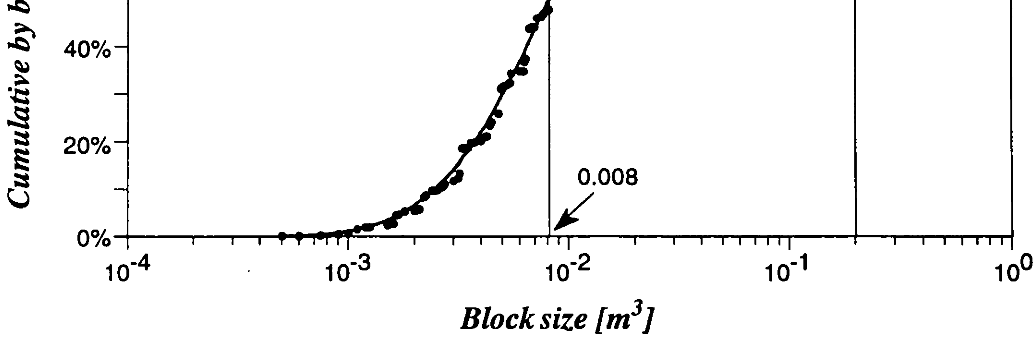


Fig VI.10: The block size vs. cumulative block number of microgranite and granophyre in site 2 if the rocks are slabs or of irregular in shape, it is not easily used as normal dimension stone (Wang *et al.* 1990). The number of joint sets, spacing and orientations are forming the shape. For example three orthogonal equally spaced joint set will produce a cubic shape, while if one of the three joints set has different spacing we will end up with prismatic, tabular or columnar blocks and irregular shapes are produced if the three joints sets have different orientations and spacings.

The block shape is determined by the ratio of the maximum length to the nominal diameter. Barton (1978) stated that the rock mass can be described by an adjective, to give an impression of block size and shape (Table VI.10).

Table VI.10: Block shape description

Barton (1978) (block shape)	
Block shape	***Description***
Blocky	Few joints or very wide spacing
Tabular	Approximately equidimensional
Columnar	One dimension considerably longer than the other two
Irregular	Wide variation of block size and shape
Crushed	Heavily jointed to 'sugar cube'

According to Barton (1978), the block shape in the study area is generally blocky to tabular. This is very obvious from set spacing values of the main three orthogonal joints. The microgranite and granophyre rocks have small blocks with some irregular shapes.

VI.4.3 *Quarry Stability*

The stability of the quarry faces is heavily dependent on the orientation of the discontinuities. When these discontinuities are vertical or horizontal, simple sliding cannot take place. On the other hand, when the rock mass contains discontinuities are dipping towards the slope face at inclined angles, sliding can occur and the stability of these slopes are significantly affected (Hoek and Bray 1981). The common modes of rock slope failure associated with surface excavation are plane, wedge, toppling and rock fall. In vertical and horizontal discontinuities, these modes of failures will not occur except for toppling and rock falling, in particular when the rock is intensively jointed.

The granites of the study area mostly have two sets of vertical joint sets and one subhorizontal set. Therefore, most of the intersections of these joints are at right angles, this will introduce cubic or tabular block shape. These forms significantly reduce the waste amount produced during the processing of the dimension stone, and promote quarry safety

General rock wall stability conditions can be expected from the orientations of the discontinuities of the rocks in the study area. The main joint sets are vertical and horizontal, therefore simple sliding will not occur in expected quarry faces in the study area according to Hoek and Bray (1981).

VI.4.4 *Engineering geological mapping*

In order to map the areas of a potential dimension stones in sites 1&2, the engineering geological mapping methods were applied. Dearman and Fookes (1974) stated that the purpose of an engineering geological map is to present the geology of the area in terms that will help in the selection of suitable sites for engineering material production ground treatment, and in the prediction of the interaction between an engineering structure and the ground. Such as map is a thematic map which has particular information. This includes the distribution of particular minerals, rock and soil, location of rock suitable for crushing and use as aggregate, and as dimension stone (Blyth and de Freitas 1984). In addition to showing the location of these reserves the maps may also record the quality of the material. These maps can be used to predict likely conditions and those that record existing condition. The methods for their preparations are given by the Anon (1972) and UNESCO (1976).

Engineering geological maps may serve a special purpose or a multipurpose UNESCO (1976). Special purpose maps provide information on one specific aspect of engineering geology such as grade of weathering or rock quality joint, spacing. Multipurpose maps cover various aspects of engineering geology. In general, the engineering geology (i.e. geotechnical) maps frequently consist of basic geological maps on which engineering geological data incorporated, concerning such facts as the physical properties of the rocks and soils, the nature of discontinuities, the degree of weathering, etc. If the engineering information is extensive, it can then take the form of notes accompanying the map. When the engineering geology map has several aspects to be displayed, the engineering geological zoning map is constructed using range values, delineating individual territorial units on a basic of uniformity of their engineering geological properties (Bell 1983b). The unit boundaries are then drawn for changes in the particular property. Frequently the boundaries of such units coincide with rock type boundaries.

In other instances, as for example, where rocks are deeply weathered, they are independent to rock type boundaries (Fookes 1969). According to Anon (1979), the engineering geological maps usually are produced on the scale of 1.10000 or smaller, Dearman *et al.* (1977) maintained that the main principles of engineering geological mapping are applicable to all maps and plans, irrespective of the scale. The variable information on the maps can be expressed by counting, either by hand or using computer. To improve the displaying quality on the map, the maps can be symbol or colour coded to show up negative and positive anomalies.

VI.4.4.1 The zoning concept in engineering geological mapping

Any map, such as geological mapping, and which includes engineering geological mapping, always involves drawing lines on the map or plan showing the areal limits of homogeneous units. Each map unit comprises in general terms a zone- an acceptable misnomer for an enclosed area. Homogeneity, is related to particular geological condition or engineering properties and the concept may be applied to all map scale (Dearman 1991). Zoning is the basic method of evaluating engineering geological conditions for engineering purposes. The process consists, simply, of the division of the country into recognised sequence of homogeneous units. In the present study, the engineering geological aspects such as joint spacing and weathering grades have been classified at each measurement locations into classes according to classification adopted by Anon (1995). The similar classes were grouped into a zone. These zones of engineering geological informations (spacing and weathering) are displayed on the engineering geological map for the study area.

VI.4.4.2 *Engineering geological map of the study area*

Engineering geological maps for both sites have been drawn. These maps were created using geotechnical information about weathering zones, and spacing distribution according to the field study. As shown in Chapter IV, the maps of spacing and maps of weathering distributions have been compiled for both sites, in order to produce the engineering geological map for each site. This was carried out by overlaying the spacing and weathering distribution maps, one on top of the other, then the engineering geological zones were constructed according to the following criteria:-

Characteristics	*Engineering Zone No (E. Zone)*
– Weathering zone1 and wide spacing	E. zone 1
– Weathering zone2 and medium to close spacings	E. zone 2

The above criteria were used to interpret the engineering geological zones (E.zones) in sites 1&2. The engineering geological map of site1 (Fig. VI.11) has two distinctive engineering geological zones. These are as follows:

1- E. zone1 which is comprised of wide to very wide spacing and weathering zone1.

2- E. zone2 which consists of wide to medium spacings and weathering zone2.

The E. zone1 is mostly underlain by grey and pink granite while E. zone2 is underlain mostly by red granite and mixed rock. Similarly, the engineering geological map of site2 (Fig. VI.12) is composed of two E. zones. These are as follows:

1- E. zone 1 which comprises of wide spacing and weathering zone1.

2- E. zone2 which consists of medium to close spacing and weathering zone2.

Engineering Geological Map

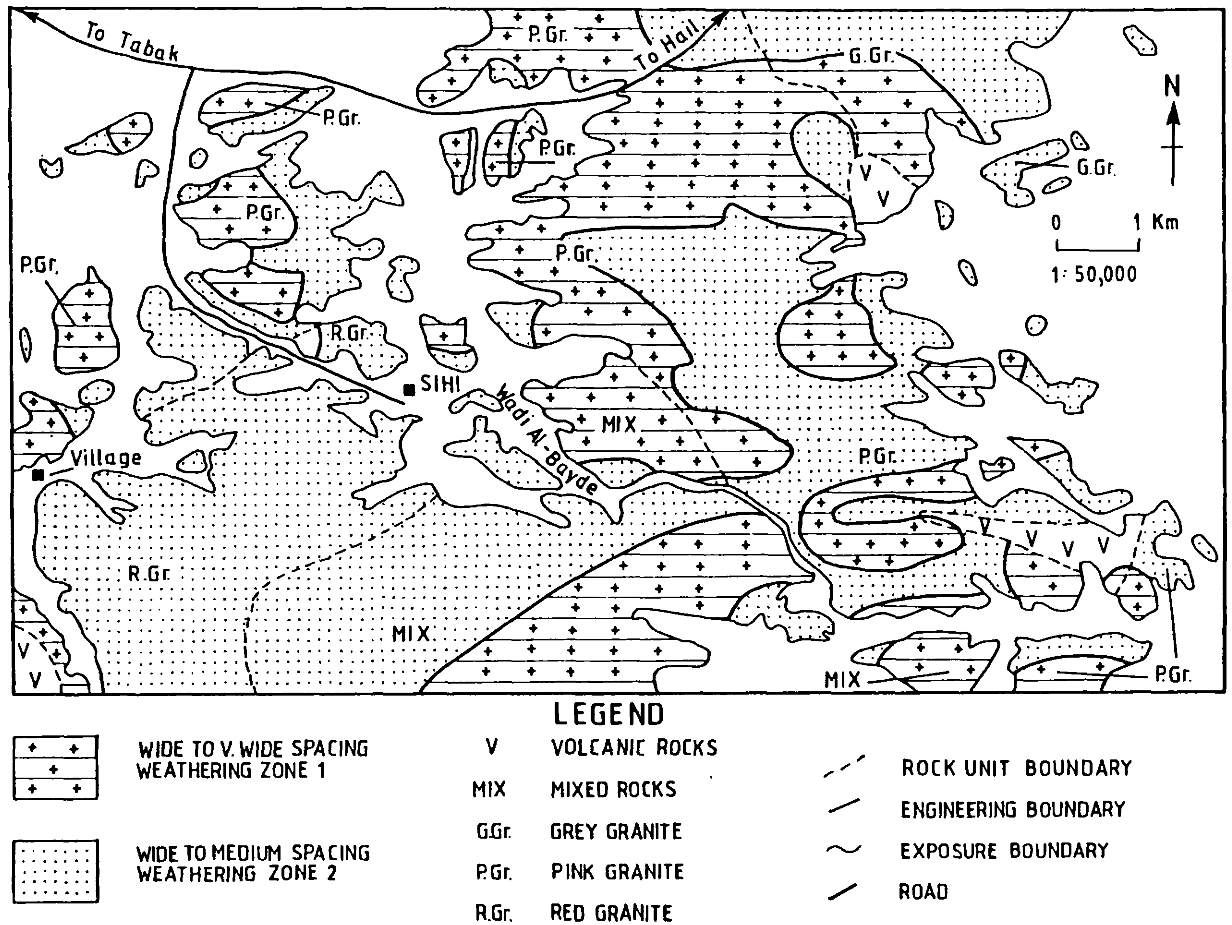


Fig. VI.11: Engineering geological map of site 1

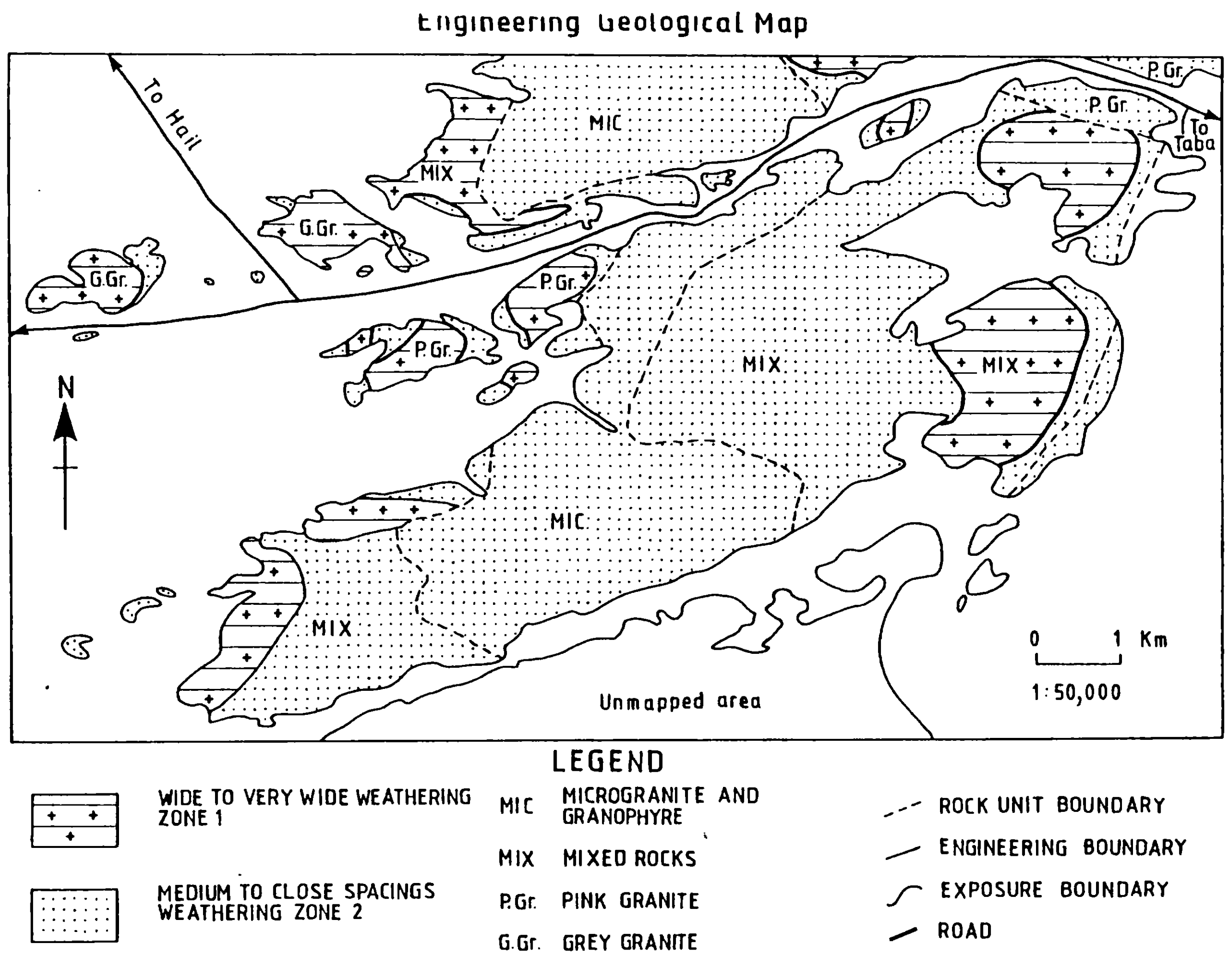


Fig. VI.12: Engineering geological map of site 2

Similarly, in site 2, the E. zone1 is underlain by in grey and pink granite (mostly) and E. zone2 is mostly underlain by microgranite and granophyre and mixed rocks. Therefore the E. zone 1 in both sites comprises high potential dimension stone grade of pink and grey granites, and E zone 2 consists the poor potential rocks.

VI.4.5 *Quantity*

After assessing the quality of rocks as dimension stone, the quantity of this stone is calculated by volume. Simply, the volume of available dimension stone can be calculated by multiplying the area of this stone by the thickness of it. The thickness of the stone can be determined from a map such as topographic maps or by measuring in the field.

Unfortunately, the topographic map of the study area is not available for the present study, because it is not permitted to go outside the country for secuirity reason. Therefore estimation of the quantity cannot be accurately determined for the present study.

VI.5 *COMPARISON BETWEEN TWO STONE PROPERTIES (THE ROSS OF MULL GRANITE (SCOTLAND) AND AJA AND SALMA GRANITE (SAUDI-ARABIA) (SITES1&2)*

The Ross of Mull granite of Scotland has a long history of use for dimension stone, with a corresponding record of in-service performance. The Ross of Mull granite appears to be fresher than the granites of the study area with less alteration, but it exhibits open cleavage and cracks quite significantly. The Ross of Mull rocks are coarser than the granites of the study area (greater than 5 mm). Generally, the Ross of Mull granites are pink to reddish in colour. The major constituent minerals are feldspars. The plagioclase seems to be more affected by alteration than other feldspars. Biotite is the second dominant mineral. There is also muscovite and some hornblende.

The Ross of Mull granite has high strength of UCS=138 (sat) MPa. The density is 2.62 gcm^{-3} (sat), water absorption is 0.35% and porosity is 0.93%. The ultrasonic velocity is 4.567×10^5 cm/s. The rock is generally sound under the soundness test. These values compare favourably with the grey granite for the study area.

Most of the jointing of the Ross of Mull granite occurs in three sets. Two of them are subvertical and almost at right angles to one another. The other set is a gently inclined joint plane with wide spacing (Plate VI.1). These structural features enable larger blocks to be obtained from the Ross of Mull granite than from any other in Britain (Bailey *et al.* 1925). In the present study, the block volume size distribution of the Ross of Mull granite was determined from scanline measurements carried out by the author, on the abandoned quarry outcrops. Large regular block shape (Plate VI.1) is a major characteristic of the Ross of Mull granite rock masses. The block size calculation and general description of the Ross of Mull granite is presented in Appendix III.

The Ross of Mull granite was largely shipped to America where it was used as dimension stone and also used for ornamental purposes, and for the frontage of shops and offices (Bailey *et al.* 1925).

A comparison of physical properties (between the Ross of Mull granite and the granites of the study area) may allow better prediction of the long-term behaviour of materials from the study area. Table VI.11 shows the comparison between the granite of the present study (sites1&2) and the Ross of Mull granite. It is quite reasonable to say, that the grey granite has closer properties to the Ross of Mull granite than the pink and red granites, microgranite and granophyre.

Plate VI.1: Blocky joints in Mull Granite (Scotland)

Table VI.11: Comparison between the properties of Mull granite and the granite of sites 1&2

Study area	*Mull (Scotland)*		*Site .1 (Sihi area)*				*Site . 2 (Salma area)*			
Rock properties	*Pink granite*	*General evaluation*	*Grey granite*	*Pink granite*	*Red granite*	*General evaluation*	*Grey granite*	*Pink granite*	*Microgr. & granoph.*	*General evaluation*
Grain size & texture	c.g. to m.g.	**Granular**	m.g. to c.g.	m.g. to c.g.	m.g. to c.g.	**Granular**	m.g. to c.g.	m.g. to c.g.	f.g.	**Granular**
Colour	Bright pink	**Bright pink homogen. colour**	Bright grey	Brigt to stained pink	Stained discolour. red	**Mostly homogen. colour**	Bright grey	Brigt to stained pink	Stained discolour. red	**Mostly homogen. colour**
Density (g/cm^3) dry / sat	2.60 2.62	**High (dry)**	2.59 2.60	2.56 2.58	2.52 2.55	**High (dry)**	2.51 2.55	2.55 2.58	—— 2.58	**High(dry)**
Absorption	0.35%	**low**	0.37%	0.90%	1.20%	**low**	——	0.9%	0.41%	**low**
Porosity	0.93%	**V.low**	0.95%	2.32%	2.97%	**low**	——	2.5%	1.1%	**low**
UCS (Mpa) dry / sat	195 138	**V.strong (dry)**	198 161	153 129	122 105	**V.strong (dry)**	131 ——	151 136	235 174	**V. Strong (dry)**
Ultrasonic velocity dry (m/s) / sat (m/s)	3.625×10^3 4.567×10^3	**Mod(dry)**	4.655×10^3 5.230×10^3	4.924×10^3 4.188×10^3	4.188×10^3 4.616×10^3	**High(dry)**	3.914×10^3 5.038×10^3	4.312×10^3 4.819×10^3	5.108×10^3 5.434×10^3	**High to V. high (dry)**
Schmidt Expos (R)	——	——	30–60	35–40	25–30	——	30-50	30–35	35–40	——
Staining and alteration	Slightly	**Slightly**	Slightly to partially	Moderate to highly	Complete	**Partially to complete**	Slightly to partially	Moderate to highly	Complete	**Partially to complete**
Weathering	Slightly	**Slightly**	Zone 1	Zones 1&2	Zone2	**Zones 1 &2**	Zone 1	Zones 1&2	Zone 2	**Zones 1& 2**
Surface texture soundness	Slightly pitting	**Satisfied**	Slightly pitting	Moderat. eatching, pitting	Higly. eatching, pitting	**Slightly to moderat. sound**	Slightly pitting	Moderat. eatching, pitting	Slightly pitting	**Slightly to moderat. sound**
Joint set Nos.	3 (orthog)	**Blocky**	3(orthog)	3(orthog)	3(orthog)	**Blocky**	3(orthog)	3(orthog)	Mainly 3(orthog)	**Blocky**
Spacing (m)	>1	**Wide**	≥0.6	≥0.6	≥0.3	**Mediume to wide**	≥0.7	≥0.7	≥0.1	**Close to wide**
Lineament (L) density (L/km^2)	——	——	20 –100	20 – 100	>120	**Low to high**	40 – 120	40 – 120	120 – 248	**Low to high**
Block size (m^3)	>1	**large**	0.74–2.50	0.74–2.50	<1	**large to medium**	1.6 – 4.4	1.6–4.4	<0.2	**large to small**
Assigned Landsat TM bands ratio	——	——	4&3	5&7	1&4	**Iron and clay bands**	4&3	5&7	1&4	**Iron and clay bands**
Dimension stone potential		**Good (suitable)**	**Good (suitable)**	**Moderate (suitable)**	**Poor**	**Good, moderate to poor**	**Good (suitable)**	**Moderate (suitable)**	**Poor**	**Good, moderate to poor**

CHAPTER VII

SATELLITE IMAGERY AS AN EXPLORATION TECHNIQUE FOR DIMENSION STONE

VII.1 *GENERAL BACKGROUND*

One of the greatest events of the twentieth century is the introduction of satellite imaging. Fourteen land sensing satellites are operating around the earth providing increasingly huge amounts of information--"remote sensing data"--about the Earth. In fact, satellite imagery is like human eyes looking down at the Earth, day and night. Satellites obtain information about the Earth regardless of any political barriers, although visual images still require clear (uncloudy) skies.

Visual remote sensing data is obtained by the reflection of sunlight from the material of the Earth's surface. The amount of sunlight reflected from an area on the Earth is recorded by a sensor, and a set of such recordings constitutes a digital satellite image. A number of studies have confirmed the benefit of using satellite data in mapping rock types, alteration conditions, and structural features; in addition, satellite data has been used to update maps and improve the quality of the information shown on them (Bell 1995).

This project seeks to evaluate the utility of remote sensing data in terms of engineering geology and the search for dimension stone. Following a review of remote sensing fundamentals, this Chapter will describe Landsat TM images of the two study sites, and evaluate the correlation between the imagery and the reality as determined in the field and confirmed in the laboratory.

VII.2 *APPLICATION OF SATELLITE IMAGERY IN ROCK ALTERATION*

In many geological areas, oxidized zones have been mapped for mineral exploration using satellite imagery; examples include Greenland (Thyrsted *et al.* 1986), the USA (Keenan 1986), and Saudi Arabia (Loughlin and Tawfiq 1985). The oxidized zones are expressed by a rusty colouration of the rocks. Oxidization is one of the weathering or degradation processes associated with hydrothermal solutions that act during mineralisation, or by ground-water reactions that end with the creation of material such as clays and iron oxides (Blyth and de Freitas 1984). Evidence of oxidization in rocks is produced by the alteration of iron-bearing minerals such as biotite, or sulphides. The oxidized zones may appear in the field as rock-surface and grain-boundary staining of a black colour, but ranging to bright red, yellow or brown. These weathering processes affect the rock's properties by decreasing the strength and durability of the rocks due to creation of weak materials such as clays and iron oxides. Therefore, the detection and mapping of alteration or oxidization areas is very important, and particularly, their distinction from areas when the rocks are fresh.

The Landsat imagery systems produce a digital image which is recorded as Digital Numbers (DN), at discrete spatial co-ordinates. The DN is also called a picture element, or pixel. Each pixel value records the amount of energy reflected from an area on the ground whose size defines the spatial resolution of the Landsat scanner system (TM data of Landsat). Each pixel is described by one byte (eight bits) of data in a grey band ranging from 0-255, where 0 corresponds to areas that are black, and 255 to white areas. A multi-band digital image consists of overlapping arrangements of pixels, with each array of pixels of representing the same scene in a different spectral band (Drury 1993).

The TM scanner records six bands (spectral resolution) of the reflected visible and infrared spectrum, with image element dimensions (spatial resolution) of 30 by 30 metres on the ground, and one thermal infrared band with a resolution of 120 by 120 metres on the ground (**Fig.VII. 1**). The thermal band is not used in this study. The other six bands, i.e. bands 1-5 and 7 are the ones which will be used in this study because they are spectrally and spatially significant for geological purposes.

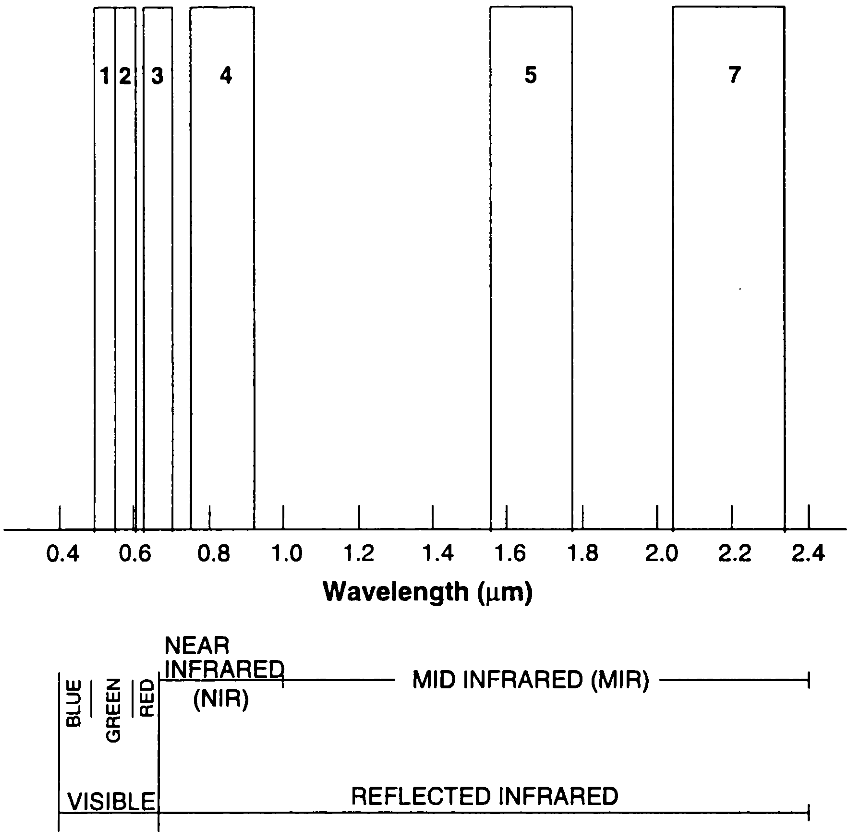


Fig. VII.1: Landsat TM bands and its spectral region. Thermal infrared band 6 is not shown (10.4-125 μm)

As an example remote sensing has been used to map oxidised zones in well exposed granites in the east of Greenland for mineral exploration purposes (Thyrsted *et al.* 1986). These authors find that the Colour Ratio Composite technique (CRC) is the most powerful method of detecting the oxidised zones in this area; a good correlation exists between the images and oxidised zones observed in the field. However there is some limitation in using Landsat data to map similar areas in the south of Greenland; this is due to vegetation cover. Therefore, Thyrsted *et al.*(1986) conclude that the methods of using remote sensing for locating oxidised zones are applicable only to unvegetated areas such as arid and semi-arid regions. In Saudi Arabia, which is arid; Landsat data have been used to map the weathered and altered areas of rock in the northern Arabian Precambrian shield of Saudi Arabia without prior knowledge of hydrothermal alteration.

The results show anomalies of oxidisation, and zones of iron oxides in areas that have good agreement with the field situation (Keenan & Raines 1986).

Other studies of relevance include those of Cloutis (1989) who used Landsat TM data in mapping weathered rocks for example in cold desert areas, and Rothery (1987a) who studied the weathered basic and ultra basic rocks in Oman. In spite of all these studies relatively little has been considered from an engineering point of view. Consequently, in the present study, an attempt has been made to establish the benefit of Landsat Thematic Mapper (TM) data in exploring the dimension stone resources which has occurred in Arabian Shield (Hail region as an example), with particular emphasis on the geological aspects (e.g. lithology, weathering and alteration) extracted from Landsat information, and their relation with the engineering properties of the dimension stone.

The Landsat wavelength sensitivity region provides the opportunity to detect iron oxides absorption features (**Fig. VII.2**). This capability is important to the present study as oxidation is the primary distinguishing factor between the rock types identified and ccharacterised in the preceding chapters.

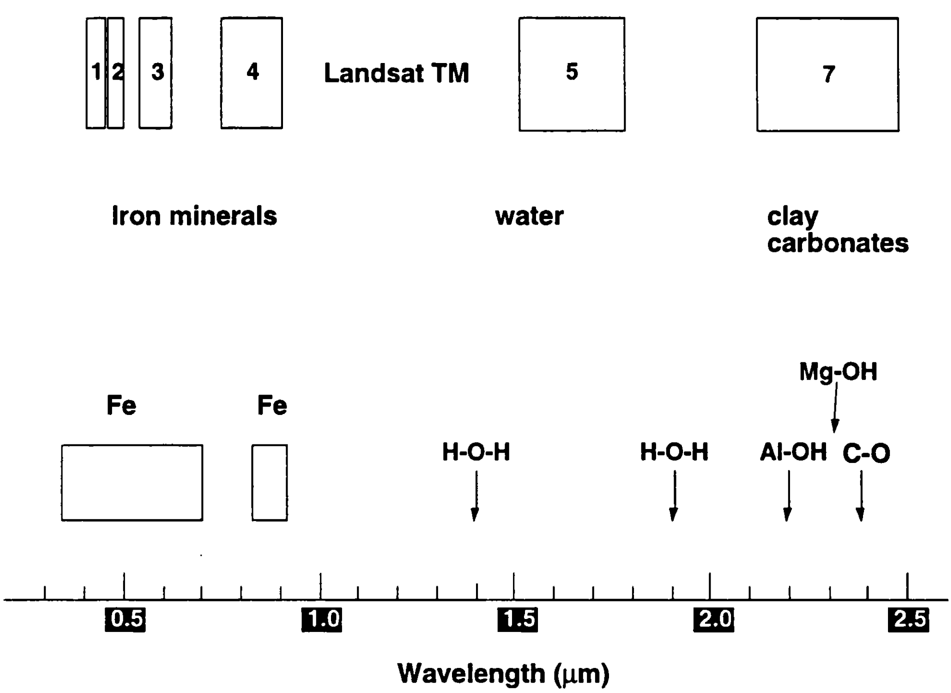


Fig.VII.2: Typical visible-near infrared reflectance spectra to show the effect of iron and clay mineralogy with six TM bands. (after Drury1993)

VII.3 *APPLICATION OF LANDSAT TM TO THE STUDY AREA SITES* 1&2

VII.3.1 *Images*

Previous remote sensing applications using Landsat TM data, in the Arabian Shield and in the Arabian Peninsula, includes the works of Bayer & Kaufmann (1986), Rothery (1987a); Al-Hinai (1988); Kaufmann & Pfeiffer (1988); Sultan *et al.* (1988); Al-Sari (1989), Pontual (1990); Qari (1991); Berlin and Tarabzouni(1983); Berlin and Sheikho (1987); Davis and Berlin (1989); and Loughlin and Tawfiq (1985). Davis and Berlin (1989) investigated the use of the Landsat TM data for rock discrimination in the Jabal Salma pluton; in particular, they were concerned with the altered basaltic rocks in the area.

The approach taken in this study is to calibrate Landsat TM interpretation at site 1, and to make predictions of rock quality at site 2. The results of the image processing are presented in this thesis as photograph prints and these were used for visual interpretation. The first area site1, is a part of Jibal Aja batholith. This area was selected to correlate the geological information on the ground with the corresponding TM image features for rock type, boundaries and alteration conditions. The only geological map of test sites1& 2 is the 1:250,000 map of Ekren *et al.* (1986), which makes broad lithological discriminations based on photo-interpretation and field checking of some localities.

Digital Landsat 5 TM scanner imagery from the Arabian winter season of 1993 was obtained for the purpose of the present remote sensing study. The sub scenes for the selected test site1 (Sihi area in the Jibal Aja batholith) and test site 2 (Jabal Salma pluton) are 500×400 and 500×330 picture elements (pixels) in size, which represents approximately 15×12 km and 15×10 km respectively.

This chapter is mainly concerned with an evaluation of the applicability of the Landsat TM sensor digital imagery to the geological resources investigations in arid regions, particularly for exploring and locating dimension stone potential site. The test sites are located in the northern Arabian Shield close to the city of Hail.

VII.3.2 *IMAGE PROCESSING SEQUENCE*

Digital image processing involves the manipulation and interpretation of digital images with the aid of a computer. The most important part of digital image processing in geological applications is image enhancement, to more effectively display the data for subsequent visual interpretation. Normally, image enhancement involves techniques for increasing the visual distinctions between features in the image (Lillesand & Kiefer 1994).

The most commonly applied digital image enhancements are: contrast manipulation for contrast stretching; spatial features manipulation for spectral filtering and edge enhancement; and the multi-image manipulation for multi spectral band ratioing.

The ratio technique is suitable in mapping geological features. This is due to the fact that it reduces the variation in illumination, and also to the fact that it provides an opportunity to usefully combine data from several bands (Lillesand & Kiefer 1994). The spectral ratios (ratio images) are enhancements resulting from DN values in one spectral band being divided by the corresponding values in another band. These ratio images can be used to generate false colour composites by combining three monochromatic ratio data sets and presenting the data in colour which is more helpful in visual interpretation.

Two main categories of technique were applied during image processing (enhancement) of the digital imagery of the two sites in this study:

❶ Contrast manipulation.

❷ Spectral enhancement for geological mapping.

In order to get good interpretation from Landsat data, one needs to concentrate only on the bands that are relevant to the study and the best enhancement techniques for the intended purpose. These essential factors can be drawn from previous considerations in which Landsat data were applied in similar conditions. For instance, to investigate alteration in an area (in which the presence of clay and iron oxides are good indicators of the alteration) the clay and iron oxides bands are chosen, then by using ratio technique, the alteration features can be enhanced further (Drury 1987).

The Landsat data is presented usually in colour image forms such as CRC images. The pattern on these images are recognised based on three main aspects (Drury 1987)

(*i*) Different kinds of surface material

(*ii*) Distinctive shape

(*iii*) Change in the area with time

The colours are produced by combining the additive primary colours (red, green, and blue). For example, white is composed of equal portions of bright red, bright green, and bright blue. Black is the absence of all primary colours. Yellow is produced by absorbing blue and reflect the red and green. Magenta it is a reddish-blue colour and it is produced by absorbing green and reflecting red and blue. The cyan is produced by absorbing red and reflecting green and blue and it appears as a greenish-blue colour. The following figure (**Fig.VII. 3**) illustrates how the three additive primary colours can be used to produce other colours. The brightness of any colour can be varied according to its brightness value which can be varied from 0 to 255 (DN value). Generally a maximum brightness value (255) gives bright and prominent colours such as bright red, bright yellow and bright cyan, while low values give dimmer, less vibrant colours (low brightness) and a minimum brightness value (0) gives black colour. **Fig.VII. 4** elaborates the effect of brightness values on the colours production. However computer image processing does allow us the ability to display subtle differences in colours that may be important in visual interpretation of images for natural resource applications, including vegetation mapping (Verbyla 1995), and geological mapping.

The interpretation of the images is based on the seeing the colour variation of the images and the context of these changes. Legg (1995) stated that the human eye is a powerful tool for detecting subtle differences in texture and recognising characteristic shapes, patterns and feature associations. He also mentioned that automated classification, of whatever type, is considerably poorer than that achievable by visual interpretation.

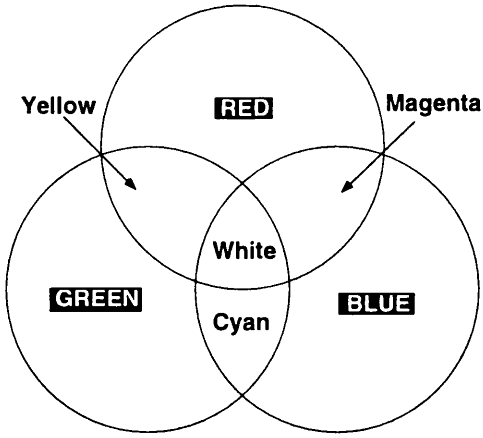


Fig. VII.3: Colours produced by combining the additive primary colours (red,green,and blue) (after Verbyla 1995)

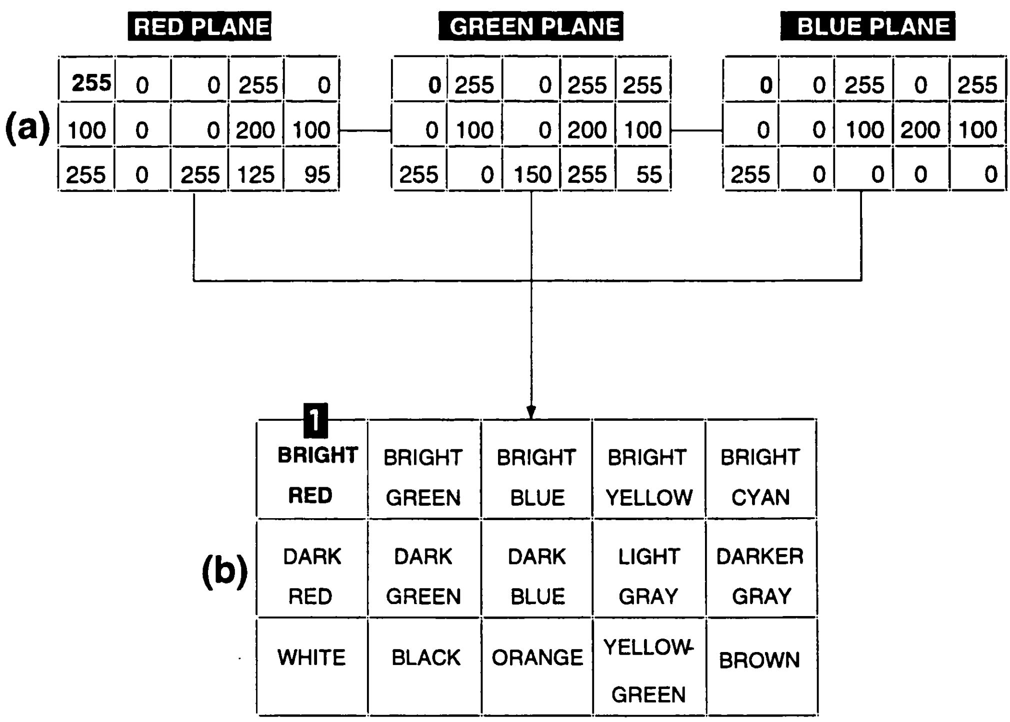


Fig. VII.4: a) Colour image produced by various digital values of red, green, and blue

b) Resulting colour display on the image (After Verbyla 1995)

1 Resulted colour.

VII.3.3 *Image preparation technique*

The method of spectral enhancement technique has been used in this study (Loughlin and Tawfiq 1985). The ratioing of TM bands was chosen in order to create a CRC image for later interpretations. Loughlin and Tawfiq (1985) found that for general geological interpretation in arid terrain, the ratioing technique CRC of combination of bands (7/5, 5/4, 4/2) in blue, green, red, respectively, is a useful method for general lithological discrimination. Similar conclusions have been reached by Davis and Berlin (1989). The above bands ratio combination has been used in the present study. A summary of this method is as follows:-

The TM bands selected were 2,4,5 and 7, where the ratio combinations which were obtained were :-

1. TM Band 7/5 was used in detecting the clay minerals (Whateley 1995). This is assigned to blue.
2. TM Band 5/4 was utilised in distinguishing the Fe bearing aluminosilicates materials (Drury 1987). This is assigned to green.
3. TM Band 4/2 was used in identifying the iron staining areas (Drury 1987). This is assigned to red.

The above selected ratio combination in the present study is called scheme 6. Other ratio combinations were also applied, these are scheme 1 of ratio combination of bands 5/7 red, 3/1 green, 5/4 blue, and scheme 4 of bands 3/1 red, 5/7 green, 3/5 blue. The bands ratio in schemes 1 and 4 were applied in detecting altered rocks by Loughlin and Tawfiq (1985); Sabins(1987) and Davis and Berlin (1989). Where the TM band 7/5 image was assigned the blue component; the TM band 5/4 image, the green component; and the TM band 4/2 image, the red component.

VII.3.4 *Description of the images*

The lithological "information" contained in three TM band ratio images has been integrated into one resultant CRC image (**Plate VII.1**). The results of the image processing are displayed in this thesis as photograph prints of Cathode-Ray Tube (CRT) monitors at the remote sensing laboratories in Ar-Riyad and Jeddah; these were used for visual interpretation. The band 7/5 ratio (with its blue component on the composite CRC) is a sign of the presence of the clay minerals in the rocks, the green (band 5/4) is a sign of Fe bearing aluminosilicates materials, and the red (band 4/2) is a sign of the presence of the iron ore or iron staining. Other, non-primary colours on the CRC images are the result of combinations of the above three colours, and are an indication of multiple contributions.

The CRC imagery of sites1&2 also show styles of colour brightness. Generally, the weathered and soil areas appear as areas of lesser brightness on the CRC images, while the bright colour areas represent the exposed fresh rock outcrops (e.g. window P1, **Plate VII.1**).

The granites of sites1&2 display in different colours on the CRC image. They appear as reddish blue (magenta), greenish-blue(cyan), blue, yellow and red (e.g. window MX1, **Plate VII.1**). The boundaries between each colour are recognisable and mappable on the CRC image. Although site1 was mapped by Ekren *et al.* (1986) as one body of massive granite, the CRC images prepared in this study display the granite in a variety of image colours.

The granite units of site 1 are similar in petrological composition, but they have been affected by different grades of alteration causing colour changes. For example, the completely stained and strongly altered granite is a reddish colour (red granite of site1) while the slightly altered granite (apparently fresh) occurs as a greyish colour (grey granite). The moderately to strongly stained and altered granite has a pink colour. These rock colour variations are reflected on the CRC image such that the variety of the granite found in the field is clearly and easily discriminated on the CRC images as well as the boundary between these units. Hence, the geology can be mapped easily and effectively. The images also display some areas of mixed colours; these area may be due to interfingering of different rock units (contact areas).

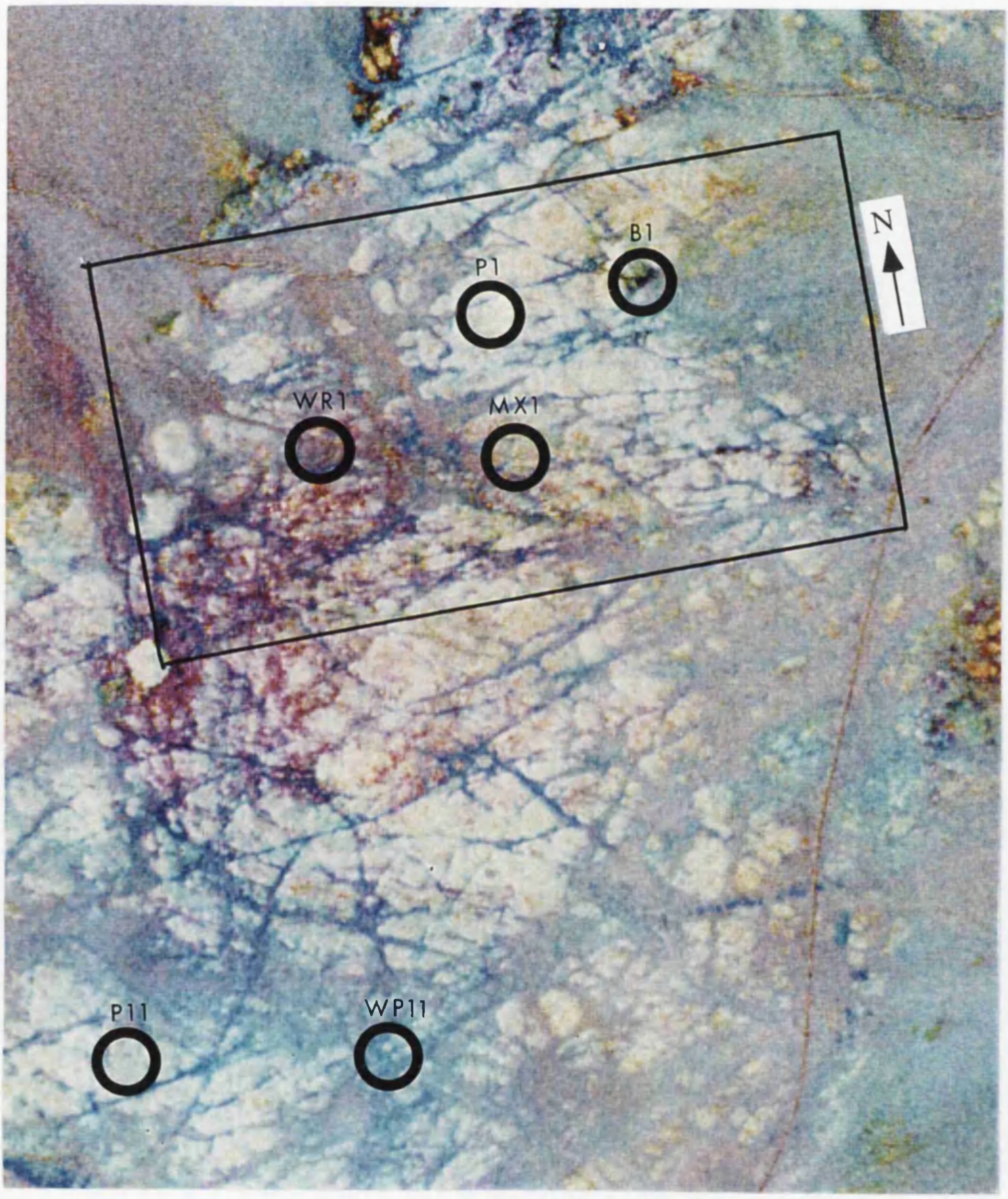


Plate VII.1: CRC image (scheme 6) for site 1:
P1 and **P11** (Pink granite); **WR1** (Weathered red granite); **MX1**(Mixed rocks); **WP11**(Weathered pink granite) and **B1**(Basaltic rocks)

VII.3.5 *site1*

The CRC images created with scheme 6 present a determination of the distribution of rock units, alteration and weathering. These characteristics have been confirmed by field mapping. Each of these factors is discussed separately below.

VII.3.5.1 Rock units

On the CRC image of site1, the granites appear in four colours: the grey granite is represented by a yellow to greenish colour on the image, the pink granite as cyan and the red granite as magenta and red (e.g. window P1, **Plate VII.1**).

The granite rocks were discriminated on the base of the CRC image and field knowledge. **Table VII.1** indicates the way of comparing the colour of these granitoid rocks on the CRC image based on mineralogy and other geological aspects such as alteration and rock colours.

Table VII.1: The comparison between geological aspects and the CRC image of site1

Geological aspects							CRC image (scheme 6)features	
Rock name	**Rock colour**	**Remarkable mineralogy**	**Alteration**	**Engineering properties**	**Rock mass**	**Weathering zone**	**colour**	**band ratio**
Grey granite	Grey	Biotite	Slightly	Good	Blocky	1	Yellow	5/4
Pink granite	Pink	Altered biotite	Partially to completely stained	moderate	Blocky	1	Cyan	7/5
Red granite	Red	Altered biotite & Iron oxide	Completely altered and stained	Poor	Fractured	2	Red and magenta	4/2

There are some very dark magenta to black and white spot areas on the CRC image of site1, these areas correspond to doleritic dykes and a circular vent (e.g. window B1, **Plate VII.1**).

VII.3.5.2 Alteration and rock colour

The alteration of the rock units in site1 is primarily the result of oxidisation processes. In the field, the alteration effect is indicated by staining of the rocks. Due to this, there is in-homogeneity in the colour pattern on the CRC image. The red granite is strongly altered and deeply stained, and the mafic minerals are mostly altered to clay minerals and iron oxides. The red granite appears on the CRC image as a bright and homogeneous distinctive red and magenta colour area (**Plate VII.1**). The pink colour granite is also affected by alteration while the grey granite is only slightly altered. They appear too distinctive on the CRC image: pink granite appears as cyan colour, and the grey granite appears as a yellow. It can be seen that these different coloured rock with their distinctive alterations have been clearly identified on the CRC image (e.g. window P1, **Plate VII.1**).

VII.3.5.3 Weathering and fracturing

From field evidence, it is clear that the grade of weathering is mostly dependent on the alteration stage of the rocks, such that the more altered rocks also show the greatest weathering. For example, the red granite (highly altered) is mostly characterised by weathering class zone 2, where high grade weathering has occurred. These weathering areas appear on the CRC image as less-bright colours with vague exposure boundaries. For example, the weathered red granite areas appear on CRC image as dark magenta and dark red colour (lower brightness); this is may be due to the low spectral reflectance of the weathered material (Gabell *et al.* 1984) with a vague (low contrast) exposure boundary (e.g. window WR1, **Plate VII.1**). The real exposure boundary cannot be easily distinguished, this is more obvious on CRC image of scheme 4; (e.g. window WR1, **Plate VII.2**). Similarly, the weathered pink granite appears as a dark cyan to bluish colour on the CRC image with vague exposure boundary. The weathered grey granite appears as a dark, yellow-greenish colour on the CRC image. A Landsat weathering map is constructed from CRC image showing the distributions of the weathering areas in addition to the rock units and rock boundaries (**Fig. VII.5**). This map is constructed by

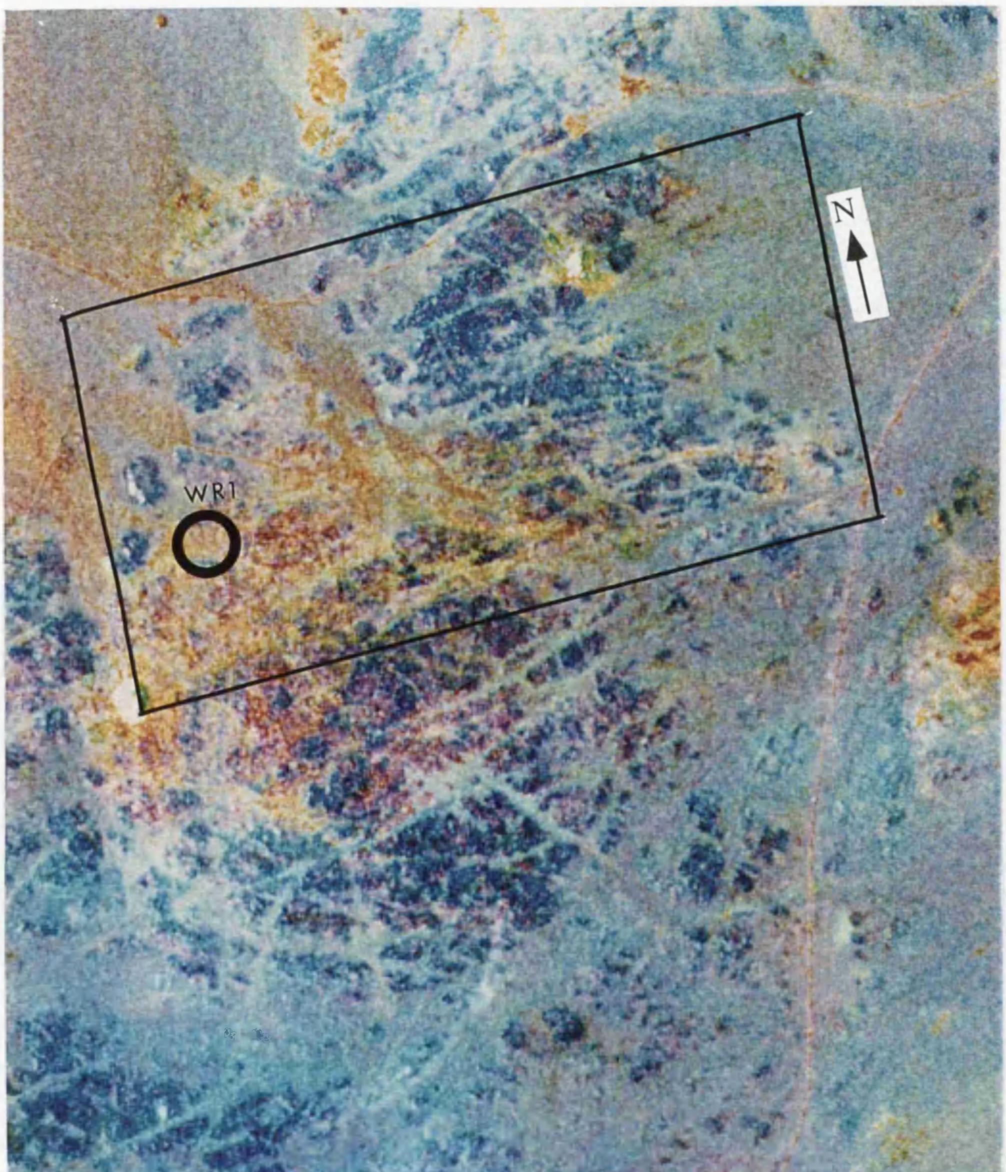


Plate VII.2: CRC image (scheme 4) for site 1: WR1(Weathered red granite)

Landsat Weathering Map

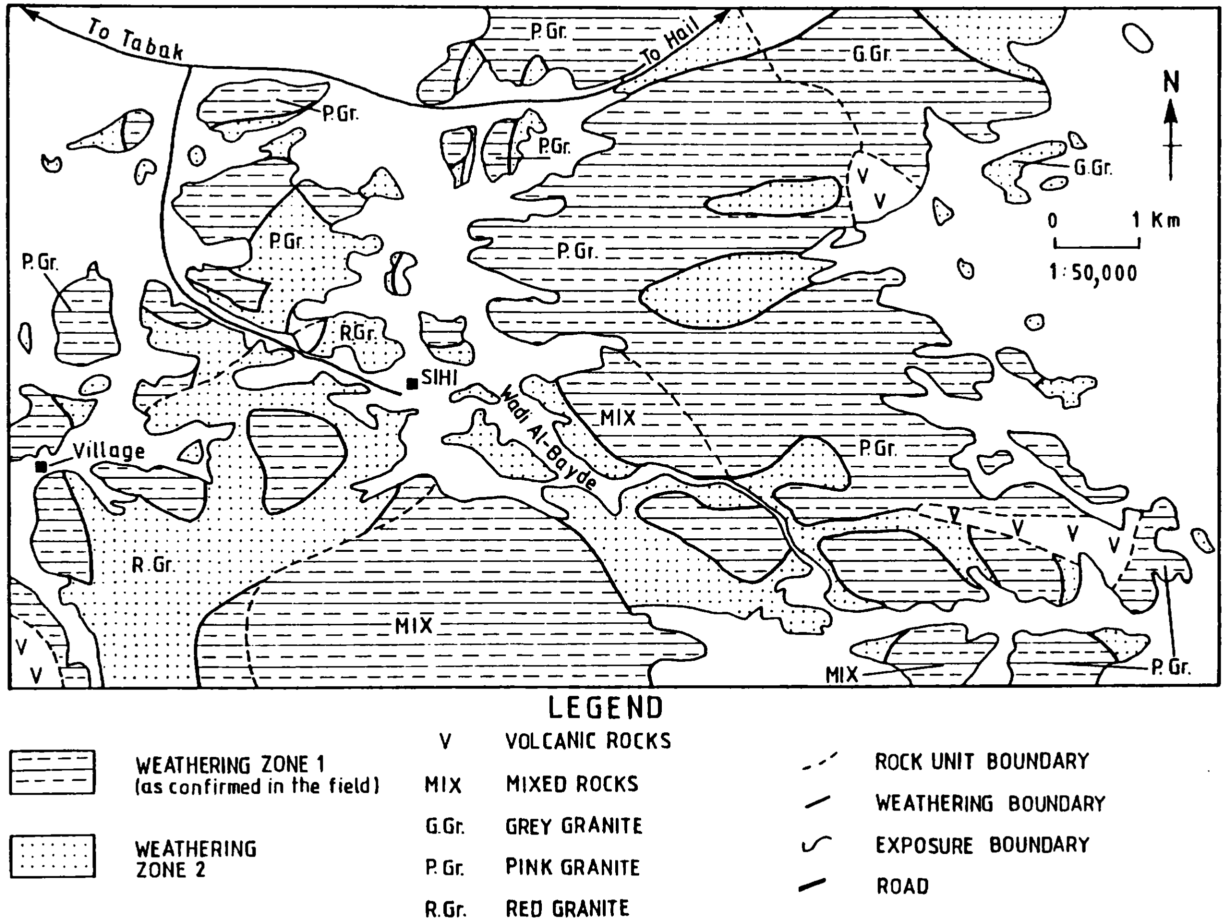


Fig. VII.5: Landsat weathering map for site 1 tracing the weathering features observed on the CRC image, and was checked with the field map. From this map we can see that the weathered areas occurr mostly in the red granite area, which can be compared to the zone of weathering. By comparing the Landsat weathering map with the field map, it is found that there is good correlation between the results of the two maps, with only slightly differences.

In the field, the sediments in the wadis consist of soil and mechanically weathered rock fragments which have been transported a short distance. The sediments are compositionally similar to the adjacent exposures, where these exposures are highly fractured and weathered. The sediments of these wadis have similar colour with that of the nearby exposures on the CRC images (e.g. window WR1, **Plate VII.1**). When the rocks are fractured and weathered, the material will be accumulated in the adjacent wadis, therefore the spectral colours will be similar between these material and the rocks.

VII.3.5.4 Rock unit boundaries

This study shows that the application of satellite imagery can be helpful in distinguishing and confirming of the lithological boundaries between rock units, as well as the rock condition, such as alteration and weathering, and the boundaries between these engineering zones. The geological boundaries have been mapped using a high-contrast image with the aid of different bands of Landsat TM. Most granite units are well distinguished on the CRC images, for example the granite units such as grey, pink and red granites are clearly distinguishable due to their bright colours.

Each of the granite units in site1 appear as a homogeneous colour pattern on the CRC image, as described above, except the mixed colour area which is related to the transitional boundaries between these units (gradational contacts). Such areas appear as in-homogeneities in colour on the CRC images. For example, the mixed rock types in the contact between the grey and pink granites appears as colours between yellow and cyan colours on the CRC image (e.g. window MX1, **Plate VII.1**). Therefore, the homogeneous rocks from non-homogeneous one (mixed area) can be easily detected using the CRC images, in addition to the type of the rock boundaries.

VII.3.5.5 Potential of dimension stone

In general the most suitable dimension stone is that which is characterised by low fracture density, fresh state, homogeneous rock type, good engineering properties and sufficient reserve.

The colours on the CRC image of the Landsat data has good correlation with the granite units and their alterations as described in the sections above. However, the alteration of the granites generally control the physical and mechanical properties of the rocks (as concluded from Chapter V). The brightness of these colours correlate with the weathering in the area; low brightness colours normally correlate with the weathered area. Therefore, the Landsat data can be used very successfully to recognise the above geological characteristics which are very relevant to the dimension stone potentials.

The remaining issue for dimension stone is fracture intensity and resultant block size. This cannot be directly observed due to spatial resolution and there do not appear to be any other Landsat characteristics which give evidence concerning this parameter. Thus Landsat data is good for exploring, but still needs data which can only be obtained using other techniques i.g. air photo and field investigation.

From field investigation and laboratory study of the granites in the area, there are three potential of granite dimension stone of different quality, based on their characteristics such as: lithology type, alteration, weathering and engineering properties. These potential granites are: Good grey granite, moderate pink granite and poor red granite, and they display as various colour on the CRC image. The grey granites present as bright yellow CRC colour, the pink granites appear as bright cyan, the poor red granite a sign as magenta and red colours, while the mixed rock area (contact area) appears as a mixture of cyan, yellow, magenta and red colours and this is not of dimension stone potential. The weathered areas are displayed as low brightness colours regions. Therefore, by using the CRC images, the target area of potential dimension stone can be identified.

VII.3.6 *Site2*

As shown in site1 the CRC image colour/brightness characteristics have good correlation with the rock properties. Therefore, they are used to predict rock types and conditions in site 2. The bright yellow of CRC image (scheme 6) is expected to indicate slightly altered and good quality rocks, the bright cyan is expected to be moderate quality and the red and magenta colours are expected to be highly altered and poor quality rocks. The mixture of these colours are expected to represent the mixed rocks. However, the dark and low brightness colours are anticipated to be the weathered rock, particularly zone 2 of weathering.

The CRC image of the Landsat data of site 2 displays similar colours and brightness as in site 1. The field check indicated that the bright yellow colour on the CRC image of site 2 (**Plate VII.3**) coincides with the grey granite of slightly altered and generally good quality. The bright cyan colour corresponds to the moderate quality of pink granite while the bright red and magenta colours correspond to the poor and completely stained microgranite and granophyre rock types. Similarly as in site 1, the dark and low brightness colours also represent the weathered rocks (zone 2) in site 2. The mixture of the colours on CRC image of site 2 represent the mixed area (contact area) between the rock types in the area. It can be said that the distribution of the CRC image colours in both sites coincides with the rock type distribution as well as with their alterations. The weathered area is also mapped on the CRC image of site 2 (**Fig. VII.6**) and it is correlated with the field weathering map. Therefore, the Landsat data seems to be a valuable exploration tool for searching for dimension stone resources.

VII.3.7 *General observations of the Landsat in the study area*

Generally, the results of the remote sensing study of sites1& 2 are very similar. The colours on the CRC images of the applied scheme 6 of both sites are similar, and there is a similarity in the geological aspects such as rock types and their weathering condition. **Table VII.2** shows the relationship between the two sites and the condition between the colours on the CRC and the ultimate suitability of the rocks for use as dimension stone

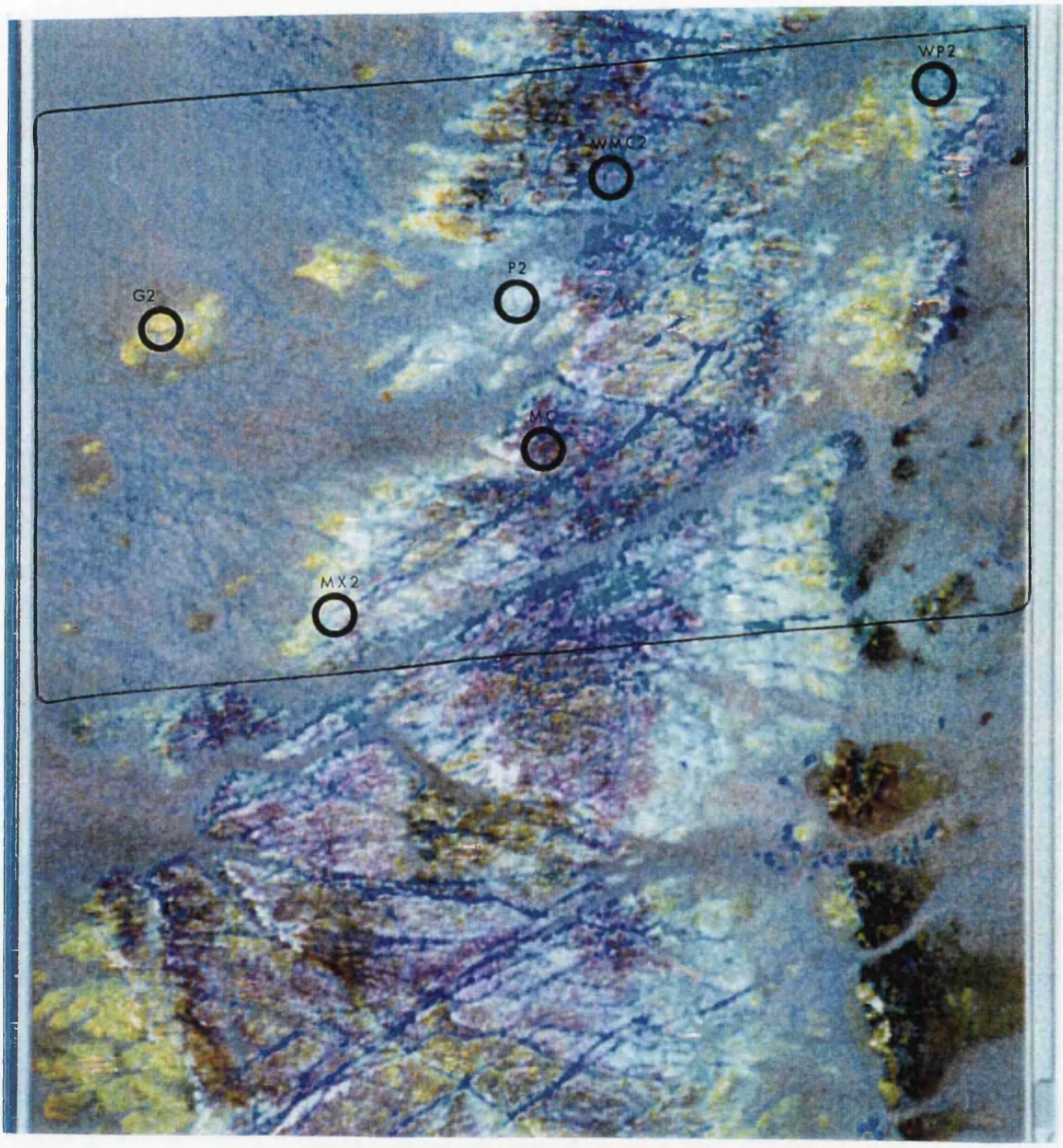


Plate VII.3: CRC image (scheme 6) for site 2:
G2 (Grey granite); **P2** (Pink granite); **WP2** (Weathered pink granite); **MC**(Microgranite); **WMC2**(Weathered microgranite) and **MX2**(Mixed rocks)

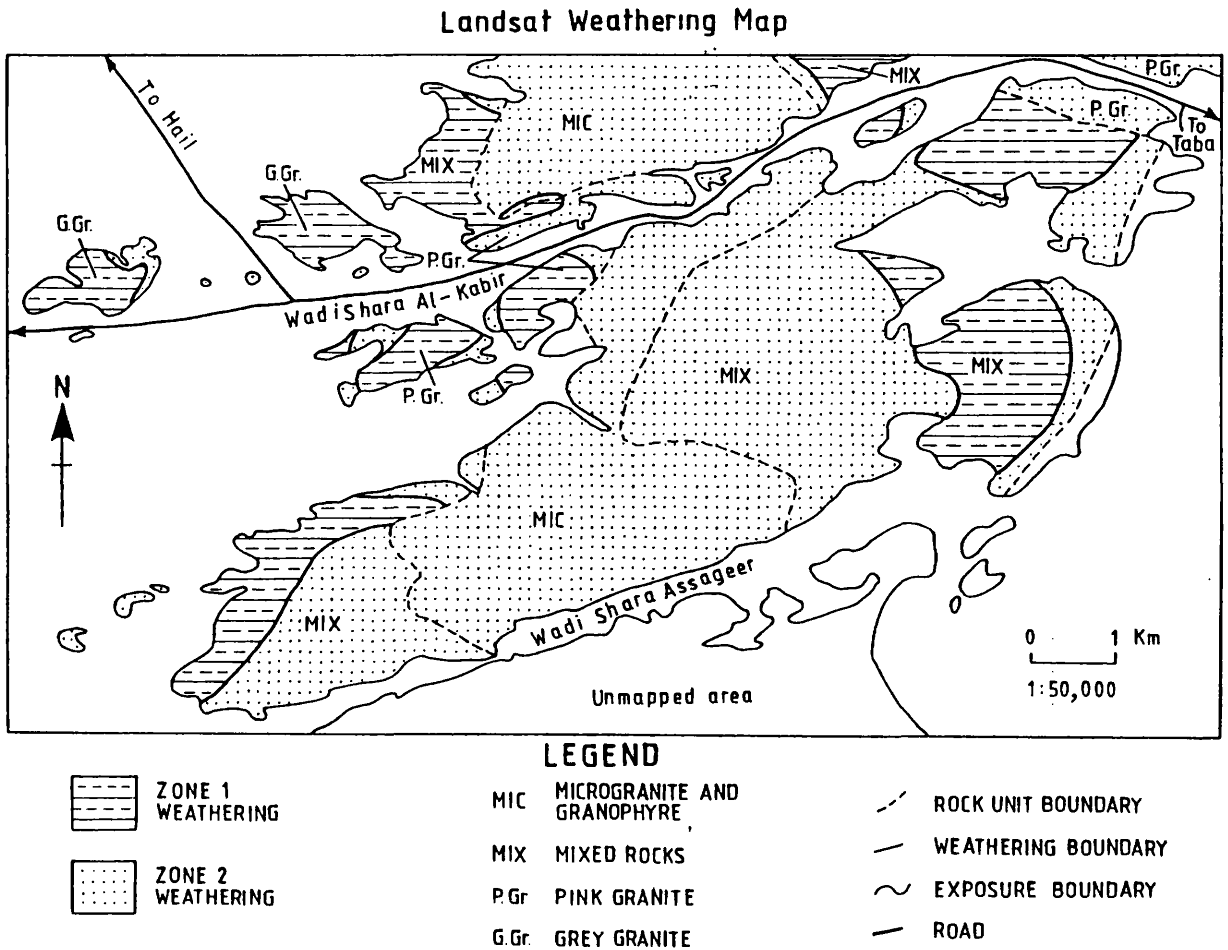


Fig. VII.6: Landsat weathering map for site 2 rocks. Other geological and engineering aspects are not directly predicted on the CRC images of the study areas.

Table VII.2: Comparison of results obtained from CRC images (scheme 6) applied on the study area

	CRC image characteristics (scheme 6)					
	Yellow		***Cyan***		***Red and magenta***	
Site No.	**Bright (ratio 4/2)**	**Dark**	**Bright (ratio 7/5)**	**Dark**	**Bright (ratio 4/2)**	**Dark**
1	Grey granite slightly altered	Weathered grey granite	Pink granite partially to completely stained	Weathered pink granite	Red granite completely altered and stained	Weathered red granite
2	Grey granite slightly altered	Weathered grey granite	Pink granite partially to completely stained	Weathered pink granite	Microgranite and granophyre completely stained	Weathered microgranite and granophyre

VII.3.8 *Additional test of the Landsat TM imagery on the study area*

The results of the application and testing of the Landsat test data at sites1&2 have been used to predict similar geological and engineering aspects in neighbouring areas, to the south of sites1&2 with area of 20 Km in length and 10 Km in wide. The colour patterns of the CRC images (scheme 6), and brightness levels show similar variations to the test sites. A brief spot check in the field has been conducted in order to see if the correlations hold. It is found that the colour areas on the images belong to the same rock units associated with these colours in sites1& 2. In general, these observations seem to suggest that the Landsat method can be applied to other granitic rocks in similar geological settings in the Arabian Shield to predict the lithologies, their boundaries, alteration stages, and weathering conditions. Such a use will determine the areas which should be focused on for ground-based studies. The prediction of these geological aspects will help also in forming a prediction of the general engineering properties such as strength and durability of the rocks.

CHAPTER VIII

DISCUSSION

VIII.1 DIMENSION STONE POTENTIAL

The potential of a site for the commercial extraction of dimension stone is very strongly related to the existing rock conditions. With adequate description of rock properties and discontinuities, it is possible to locate potential sites for dimension stone in light of the criteria mentioned in Chapter VI. Maps showing the potential for dimension stone in the study area, for both sites 1&2, have been prepared as special purpose engineering geological maps (Dearman 1991). The following criteria have been applied to both study sites in identifying potential dimension stone locations:-

① Favourable lineament densities.

② High grade engineering geological zones.

③ Large block sizes.

④ Acceptable appearance and petrography, and physical and mechanical properties.

⑤ Homogeneity and purity of the rocks.

Assessment of dimension stone potential at sites 1&2 incorporated field investigation, a Landsat TM study, interpretation of aerial photographs, and lab work, and, these elements culminated in an evaluation of engineering geological aspects.

Firstly, as a part of the field study, the types of granite present in site1 were described. Compositionaly, they are alkali feldspar granite, described in the field as grey, pink and red granite. Mixed rock types between grey, pink and red granite were found in the area, with the pink and mixed rocks dominating. Typically, the dominant rock types in both sites are less affected by the somewhat uncommon dykes, xenoliths and veining. At site 1 two basaltic cones and associated doleritic dykes are found. The rock distributions are shown in **Figs. III.5** and **6**, a geological map at scale 1:50,000.

The distribution of engineering geological characteristics were mapped in the field, using aerial photographs as a base. The weathering grade, discontinuity (mainly joint) spacing and Schmidt hardness *N* of the outcrops were studied in addition to the lineament distribution. The degree of weathering varies from slightly weathered to highly weathered and disintegrated rocks, but generally (in agreement with the N values) there are two major groups: slightly weathered with *N* values greater than 30, mostly associated in zone 1 and moderately to highly weathered with *N* values less than 30 and mostly associated with zone 2. The depth of weathering also varies from thin skin surface weathering to 15m in depth in some localities. Weathering is deeper in zone 2 and thinner in zone 1. The distribution of the above two groups has been mapped and is displayed in map view in **Figs. IV. 24** and **25**. From these maps it can be seen that zone 2 (see above) is mostly concentrated in the red granite in site 1 and in the microgranite and granophyre in site 2. Weathering zone 1 is most common in the grey and pink granites at both sites.

The distribution of joint spacing was investigated in the field. As for the weathering state, the observed joint spacing could also be divided into two major spacing zones in site1. Spacing zone1 has wide to very wide spacing and occurs in grey and pink granites and spacing zone2 has wide to medium spacing and occurs in the red granite. These two zones are displayed in **Fig. IV.22,** a map at scale of 1:500,000.

The lineament density was mapped for site1 from aerial photographs. The area has lineament density from 10 L/km^2 to 200 L/km^2. By comparing the lineament density of an area with joint spacing and frequency, it is found that the area could be divided into two lineament density areas. These are zone1, with a lineament density of less than (120 L/km^2 equivalent to the wide spacing occurring in the grey and pink granite), and of greater than 120 L/km^2 (equivalent to the medium spacing of the red granite). The lineament density was presented as a lineament contour density map (See **Sheet.3**).

The engineering geological maps created of site 1 and 2 using the above characteristics reveal two engineering geological zones (**Figs.VI.14** and **15**). High grades occur in E. zone 1 and followed by lower grades in E. zone 2. In site1 E. zone1 is mostly occupied by grey and pink granite while E. zone 2 occurs mostly in red granite and the mixed rocks. Similarly, site 2 has also two zones, E. zone1 occurring predominantly in grey and pink granites and E. zone2 in the microgranite, granophyres and mixed rocks. Most of the potential dimension stone granites are in E. zone 1 at both sites.

As mentioned earlier, block size is an important parameter in identifying the potential for dimension stone. The new devised block size calculation procedure in the present study has made the block size classification much easier than before. A block size of $1m^3$ and larger is preferred: such blocks are in the large size class (Barton 1978). This occurs most commonly in the grey and pink granites of both sites. Greater than 80% of the grey and pink granite blocks are in the large class; while most of the blocks in the red granite, the microgranite and the granophyre rocks are less than $1m^3$ in size and so fall in the medium to small block size classes (Barton 1978). Therefore, the grey and pink granites have the highest potential for dimension stone in site 1 & 2.

In general, the quality of rock will decrease as the degree of weathering increases (Fookes *et al.* 1988). The granites in the study area are affected by various stage of alteration. The grey granite is fresher and is less affected by staining and alteration while the pink granite is moderately stained and altered. The microgranites, the granophyres and the red granite are completely affected by alteration and staining and the physical and mechanical properties reflect this. The grey granites have the best properties and good quality, while red granite has the poorest properties. The pink granites have moderate quality properties in general. Baynes *et al.* (1978) mentioned that the greatest change in rock properties occurs between partially stained granite and completely stained granite, and that this change occurs before the boundary between acceptable and unacceptable values of density, absorption and strength has been reached (**Table VIII.1**). This

Table VIII.1: Engineering properties of granite

General properties (after Baynes et al. 1978 & West 1996)							*Study area (site 1&2)*			
Description	*Pattern*	*Rock mass weathering grade*	*Sample*	*UCS (MPa) (Saturated)*	*Saturated bulk density g/m³*	*Water absorption (%)*	*Grey granite*	*Pink granite*	*Red granite*	*Micro-gran& Granophy*
Fresh granite		I	Fresh	262	2.61	0.11				
Partially stained granite		II	Stained rim of block	232	2.62	0.35	UCS=161MPa, γ= 2.60 g/cm ^{3}, AT=0.37%			UCS=170MPa, γ= 2.58g/cm ^{3}, AT=0.41%
Partially stained granite		II	Whole sample II 90% stained	163	2.58	1.09		**UCS=129MPa, γ= 2.58 g/cm ^{3}, AT=0.90%**		
Completely stained granite		II	Completely stained II block	105	2.56	1.52			**UCS=105MPa, γ= 2.54 g/cm ^{3}, AT=1.20%**	
Weakened granite		III-IV	Rock core of III block	46	2.55	1.97				
Weakened granite		III-IV	Rock core of IV block	26	2.44	4.13				

—— practial acceptance limit for good quality granites (as aggregates and also as dimension stone)

UCS: Unconfined Compressive Strength (MPa); γ : Density (g/cm ^{3}); AT: Absorption (%)

boundary could be useful as an engineering grade boundary for quarrying purposes. According to Baynes *et al.* (1978) the practical acceptable lower limit for good quality engineering rock material is an UCS of 105, a saturated density of 2.56 g/cm^3 and water absorption 1.52%. Generally, the grey and pink granites of the study area are slightly to partially stained granites and have acceptable density, absorption and strength values, but the red granite typically has unacceptable values. The present study uses three stages of granite alteration: these are slightly; partially; and completely stained, therefore these rocks could be used to delineate the acceptable boundary for the good quality rock (that is the boundary between the poor and the good quality). The completely stained red granite has a UCS of 105 MPa, a density of less than 2.57 g/cm^3 and a water absorption of greater than 1%. It is suggested that these values be taken as the upper boundary for unacceptable values as shown in **Figs. VIII.1** and **2.**

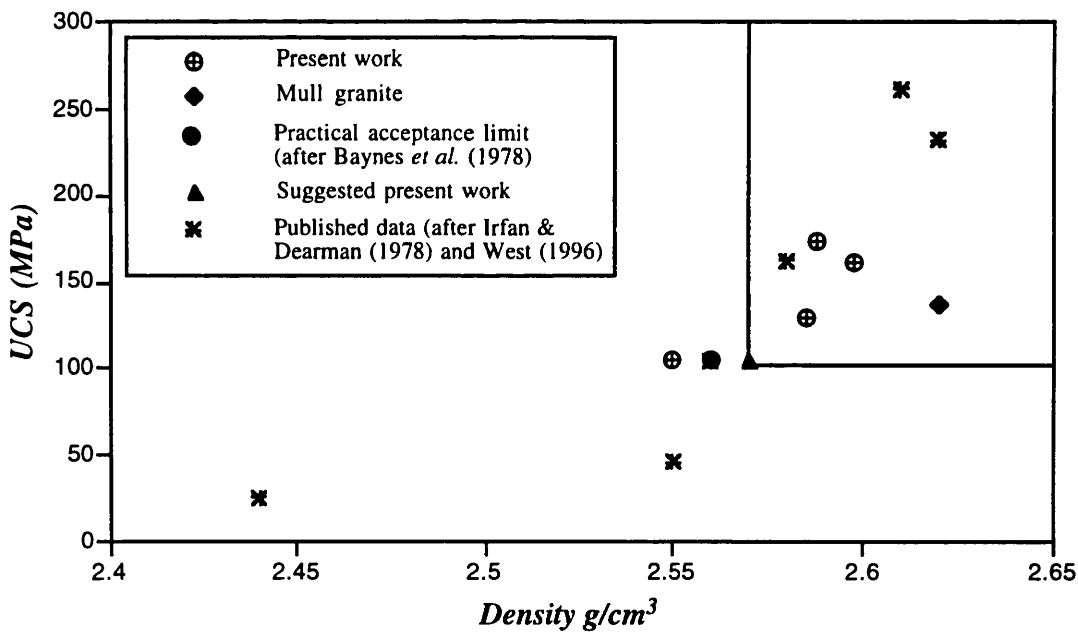


Fig. VIII.1: Suggested acceptable window for engineering limit properties of density Vs UCS for granites in sites1&2

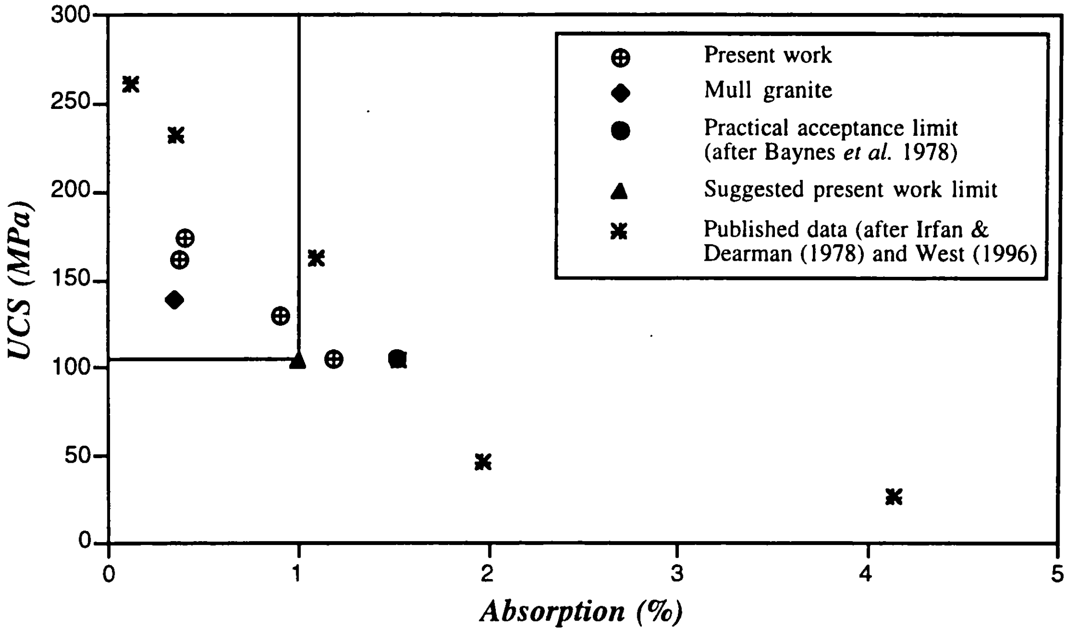


Fig. VIII.2: Suggested acceptable window for engineering limit properties of absorption Vs UCS for granites in sites 1& 2

In summary, the physical and mechanical properties and good rock mass condition of grey and pink granites support their potential as dimension stone. Although, the microgranite, the granophyre and the red granites appear to have high grade of physical and mechanical properties, their poor rock mass condition gives them a poor potential as dimension stone. According to the field and laboratory studies as compiled in Chapter VI, the granites of the study area could be graded, best to worse, as grey granite (best), pink granite (moderate) and red granite, microgranite and granophyre (poor). This arrangement is in agreement with the soundness of surface texture as presented in Chapter V.

A comparison between the Mull granite (favourable existing dimension stone) and the granites of the study area in **Chapter VI** indicates that the granites of sites1&2 could be described in term of dimension stone potential into three grades as follows:

Dimension stone potential granites of sites1&2	
Potential rocks	Evaluation
Grey granite, slightly altered, high grade engineering properties, wide spacing and blocky rocks (large blocks), good quality, high potential comparable to Mull granite	Favourable (suitable)
Pink granites, partially to highly altered, moderate grade engineering properties, wide spacing and blocky rock mass (large blocks), moderate potential	Moderate (suitable)
Completely altered red granite, microgranite and granophyre, variable engineering properties medium to close spacing and fractured rock mass (medium to small blocks), poor quality, poor potential	Poor

By applying the above criteria, the potential dimension stone areas (sites) were identified. Moreover the potential areas are seen also on the Landsat images of both sites (CRC), in order to see the compatibility between the CRC images and the identified potential area utilising the field study (engineering geological map) and the laboratory studies. It is found that there is acceptable correlation between the CRC image analysis and the above results in identifying the granite dimension stone potential areas in site 1 and 2; this will be elaborated latter in this discussion.

The identification of the dimension stone potential of the granites is presented on the potential dimension stone maps (**Figs. VIII.3** and **4)** using the engineering geological maps of the study area (**Figs. VI**. 11 and 12). The grey granites have generally good to acceptable properties for dimension stone: a uniform colour and texture (good appearance); fresh to slightly stained (slightly discoloured); strong, sound and durable (sound surface texture); and large blocky rock masses. The pink granite rates second while the red granite, microgranite and granophyre are poor dimension stone material.

At site1, the potential dimension stone map (**Fig. VIII.3)** shows the areas assigned to each of three grades: favourable grey granite, moderate pink granite; red granite and mixed poor. The description of these potential areas at site1 are as follows:

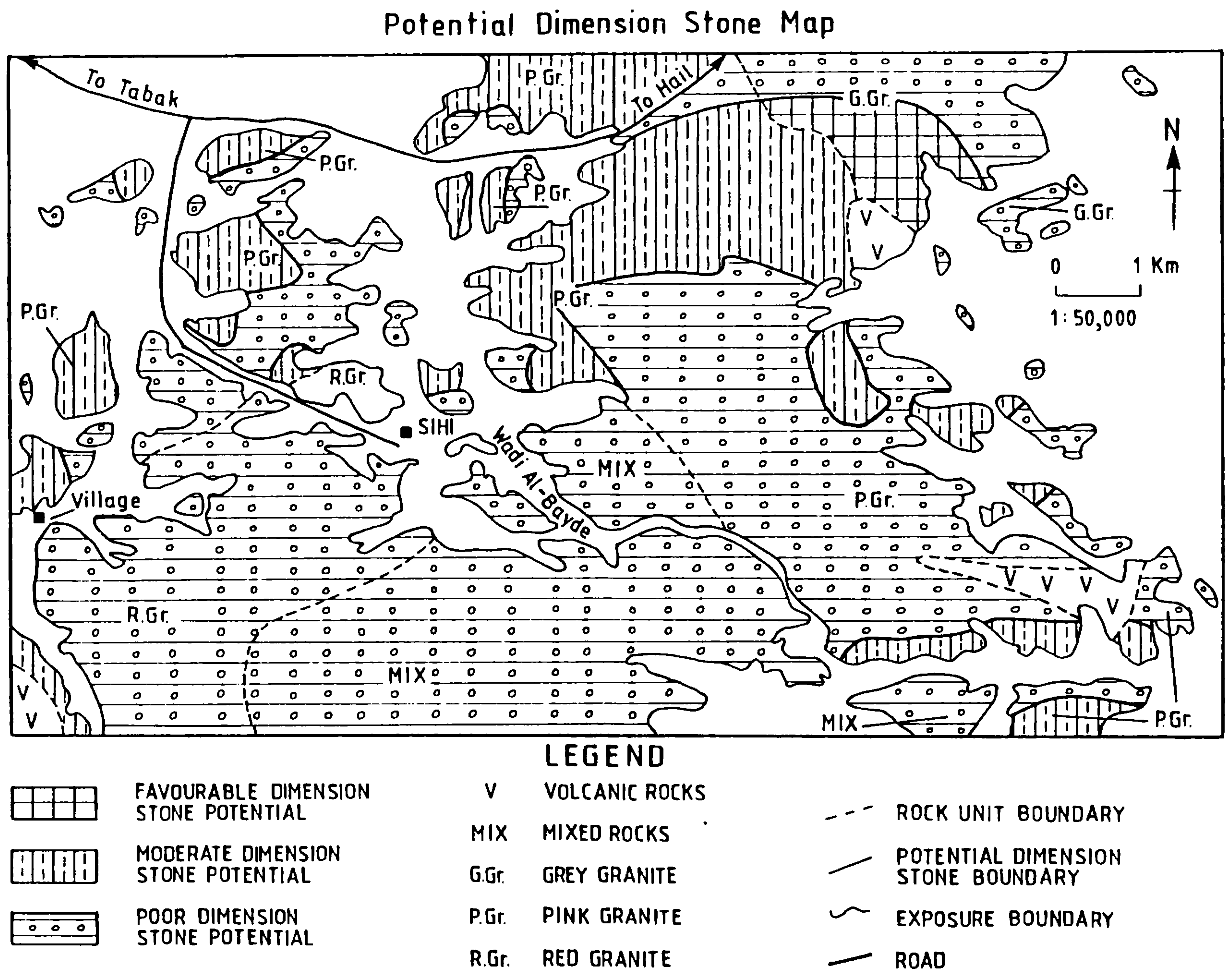


Fig. VIII.3: Potential dimension stone map of site **1**

Potential Dimension Stone Map

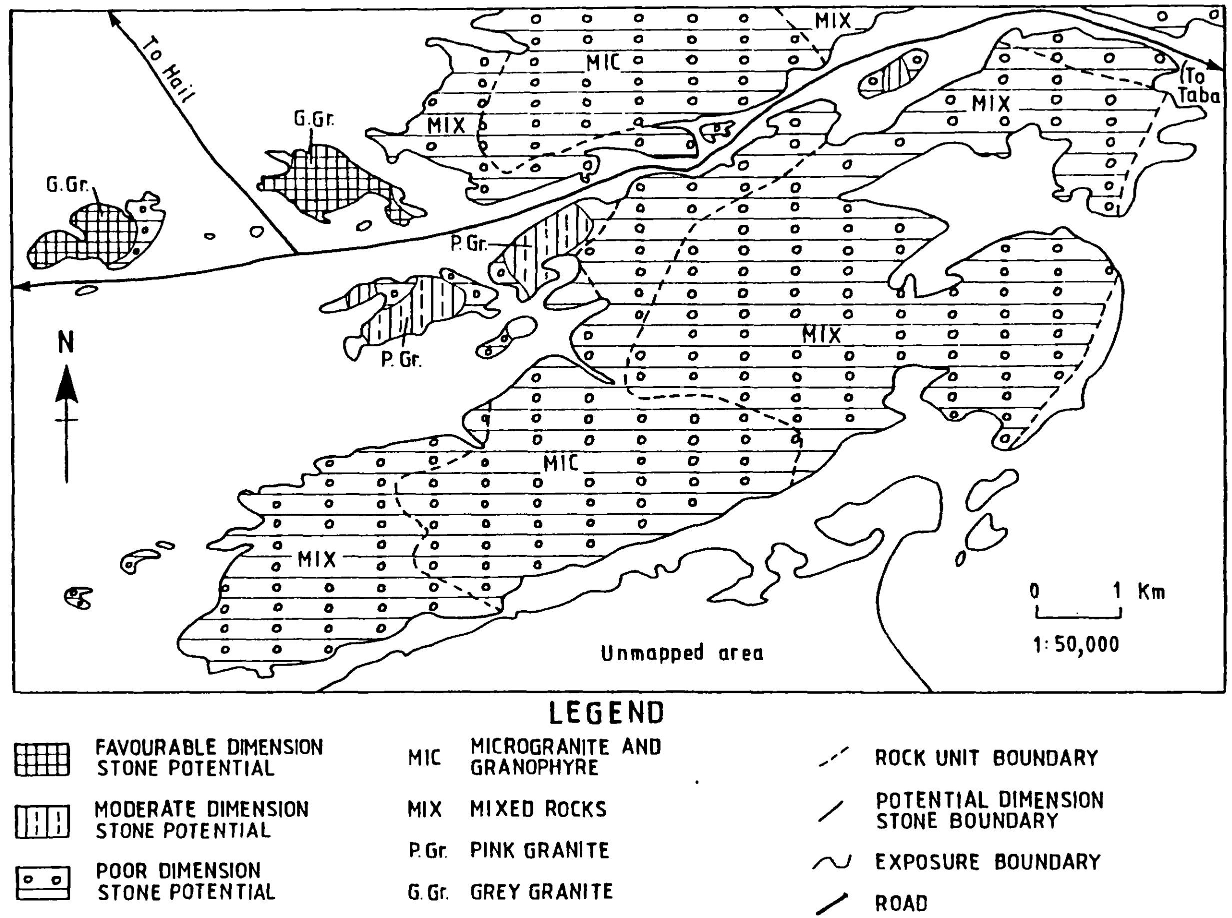


Fig. VIII.4: Potential dimension stone map of site **2**

Dimension stone potential area, site1	
Potential areas (grades)	***Description***
Favourable	Homogenous, slightly weathered altered grey granite, E. zone1, less than 120 L/km^2, acceptable engineering properties (high grade granite).
Moderate	Homogenous, partially to highly altered pink granite, E. zone1, less than 120 L/km^2, acceptable engineering properties (moderate grade granite).
Poor	Red granite, mixed rock of mostly completely altered rocks, E. zone 2, greater than 120 L/km^2, poor engineering properties.

Site2 also has 3 areas corresponding to favourable, moderate and poor dimension stone potentials **(Fig. VIII.4)**. These are summarised as follows:

Dimension stone potential area, site2	
Potential areas (grades)	***Description***
Favourable	Homogenous, grey granite, E. zone1, less than 120 L/km^2, acceptable engineering properties.
Moderate	Homogenous, pink granite, E. zone1, less than 120 L/km^2, acceptable engineering properties.
Poor	Completely altered microgranite, granophyre and mixed rocks, E. zone 2, greater than 120 L/km^2.

The sites are very similar. The suitable areas are mostly occupied by grey and pink granite while the poor potential areas are concentrated in the red granite, the microgranite and the granophyre. This may indicate a similarity in geological and engineering geological conditions.

As from dimension stone potential maps, the mass volumes have been estimated with average height of 40m in both sites. The potential grey granite in site 1 covered 3% of whole outcrops with estimated total mass of 8.45×10^6 tonne, the pink granite covered 19% of the site with total mass of 1.77×10^9 tonne. This total amount alone will supply the demand of the whole world for 50 years (based on the total amount consumption for year 1994, see Chapter 1). The poor granites of red and mixed rocks covered the rest of site1. Unfortunately the potential areas cannot be estimated for the whole batholith (not studied due to facility limitation) but they can be extrapolated for Sihi pluton by viewing the CRC images. The potential grey and pink granites in the whole Sihi pluton are also very limited as in site 1, the majority of the area is covered by poor rocks.

Site 2 has also similar areal coverage. The grey granite covered about 4% with total mass 1.71×10^7 tonne, the pink granite covered 10% area with mass of 8.95×10^7 tonne. The rest of the outcrop is composed of poor microgranites and granophyre. This distribution is also similar for the whole Salma pluton as can be seen on the CRC images.

Jefferson (1993) mentioned that 6000 tonnes per annum would be typical for quarries producing only building stone. According to this value, the potential granites in both sites have large quantity of mass as a reserve for hundreds of years. However, both pink and grey granites could be used also as good aggregate material. On the other-hand the poor rocks could not be used for aggregate because they are highly altered and contain clay materials. Based on the result of site 1, see above, the potential dimension stone area in Jibal Aja batholith was estimated of 22% approximately, which is about 132 km^2 (the total area of Jibal Aja is about 600 km^2). This vast potential area give good indication about super giant reserve of dimension stone in the area, moreover that the Arabian Shield has more than 50 batholiths of similar sizes and rock type.

VIII.2 *EVALUATION OF EXPLORATION METHODS*

VIII.2.1 *Evaluation of Landsat method*

Digital TM data covering the visible and infrared reflected spectrum were evaluated for geological aspects mapping. The analysis of processed TM data images proved invaluable in the acquisition of new geological information to this study. In the two test sites, new and detailed lithological units were observed and compared with published maps, as those maps were mostly field /photo-interpretation based, parts of them had been mapped by extrapolation of boundaries. Study of the CRC images, as presented in **Chapter VII** revealed many more complexities and allowed confident extrapolation of lithologies.

In Aja area (test-site1), and Salma area (test-site 2) previous geological maps had been prepared based on photo-interpretation and limited field checking--such as Ekren *et al.* (1986) and Williams *et al.* (1987). In this study, based on new TM imagery and field work, new maps were prepared which differ in important aspects from previously published ones.

Spectral ratio images of Landsat data were used to effectively map geological features such as rock alteration (Vincent 1997). The spectral enhancement techniques resultant of colour ratio composite image of TM bands 7/5, 5/4, 4/2 in blue, green and red. This technique was applied successfully in arid areas such as Arabian shield through studies by Davis and Berlin (1989), Qari (1991), to distinguish rock types and alteration. This technique was performed on the two studied sites to produce a colour ratio composite image as scheme 6 (**Plate VII.1**). It is found that the image produced is straight forward, easier to use and to interpret and gives a range of prominent colours. This helped in the preparation of the rock unit map and identification of other geological aspects: alteration; weathering; rock boundary; rock homogeneity and rock colour

a) Rock units and alteration

According to the field study, sites1&2 comprise many rock units. These rocks have similar compositions but various degrees of alteration. These variations in alteration have not been mapped previously and the TM data proved to have good capability in mapping these features. The fresh and slightly altered rocks (e.g. grey granite of sites1 & 2) are seen as distinct yellowish to greenish colour areas. This colour is related with the TM ratio band 5 to 4. This TM ratio is sensitive to the Fe-bearing silicate minerals (e.g. mafic minerals, hornblende and biotite) (Drury 1987). In general this feature allows discrimination of rocks having non altered or slightly altered mafic minerals. The completely altered rock areas are seen as red to magenta in colour on CRC images (e.g. red granite, site1 and microgranite and granophyre site1). This colour is associated with TM ratio band 4 to band 2, where this ratio was found to be useful in distinguishing stained rocks.

Altered rocks containing clay minerals and iron oxides due to alteration can be discriminated using the ratio of TM band 5 to 7 and ratio 4 to 2 (e.g. pink granite of sites1&2 and red granite of site1). This study indicates that the TM data, particularly band ratio methods, can be used for discriminating between fresh, altered and stained granitic rocks as confirmed by the study results from test site1&2.

The clay and iron bands of the Landsat TM data are used to distinguish hydrothermally altered rocks from unaltered ones (Drury 1987; Keenan and Raines 1986). This Landsat characteristic has been detected in both sites, particularly in the pink granite, red granite, microgranite and granophyre as mentioned above. Moreover, these rocks are affected by alteration resulting in the formation of clay minerals (XRD analysis) from feldspar, and of iron oxides after biotite. Therefore, the study area could have been affected by hydrothermal alteration.

b) Rock unit boundary

New geological maps for sites 1&2 have been constructed. The lithological boundaries between the different rock units in these maps were traced with the help of TM data. The colour differences between the different units of the granite in sites1&2 on the TM data images have made the procedure of drawing the boundary between these units easier. For example to map the boundaries between grey, pink and red granite could have been very difficult and time consuming without the help of TM data images. Moreover, the tracing of a rock unit boundary in the field can be extremely difficult, almost impossible, particularly in the non-accessible and remote areas.

c) Rock unit homogeneity

The CRC colours homogeneity indicates ground features homogeneity, such as geological rock units. For example, each rock unit in site1 has a distinguishable colour. The pink granite has cyan to light blue colour of CRC, The grey granite is yellow to green and the red granite has magenta to red CRC colours. But where these rocks are interfingering or mixed with each other (could be gradation boundary area), they appear on the CRC images as mixed colour area. Also the areas of large scale volcanic cone centres and dykes can be distinguished easily using TM data in the form of CRC images. Therefore, the homogeneity or purity of outcrop (which is useful in dimension stone exploration) can be easily detected using TM data.

d) Weathering condition

The sound exposures of the outcrop have good contrast, bright colours and sharp boundaries on the CRC images while weathered outcrops, particularly zone 2, have low contrast dark colours i.e. weathering class zone 2 in site 1 & 2 and vague exposure boundaries on the CRC images, i.e. red granite boundaries.

e) Colour of the rocks

It is found in this study that the CRC change on the image is associated with a rock colour change of the ground. Although the rock colour change in the study area is probably due to alteration and staining, it has been observed that each rock unit which has distinctive CRC colour has also a distinctive rock colour. For instance, pink granite appears as cyan and light blue the grey granite appears as yellow and greenish, and the red granites appears as magenta and red on the CRC images in both sites1& 2. This characteristic of the TM data could be taken in general as an indication of rock colour variations in the area. Despite the variation in grain size between microgranite of site 2 and red granite of site1, the CRC colour images are similar for both rock units and they are magenta and red in colour where both have similar rock colour.

In summary, most of the above geological features such as alteration and weathering have good correlation with the physical and mechanical properties of the rocks. Therefore, mapping the geological features using the Landsat TM data can be predict the geotechnical properties as indicated by the thesis.

f) Characteristics of TM data

The TM data provides a low cost method of geological data collection. The computer compatibility of satellite remote sensing saves time and manpower required to produce geological survey information; to recognize target areas; to get general view; to cover large area; less cost; to prepare map easily without climate control and to map remote areas.

VIII.2.2 *Field method*

The field study of geological characteristics of rocks can be used for the assessment of potential sites for dimension stone. Studies include rock type, alteration and weathering conditions, discontinuity characteristics, and exposure conditions. The field work is necessary in order to assess basic rock types, delineate major geological structures, e.g., faults, dykes, geological contacts and areas of heavy fracturing and weathering.

In this study all the geological characteristics of the rock are gathered as follows: rock type, colour and appearance, grain size, hardness of the rock, size and shape of the blocks. Grade and depth of weathering can also be assessed. The discontinuity characteristics in terms of number of sets, orientation, type, dip and dip direction, aperture and other characteristics could also be evaluated directly. Scanline measurement is also conducted to determine discontinuity spacing and frequency.

The overburden thickness can be determined by geophysical means, and shallow overburden by trenching, particularly when the outcrop is not well exposed, but in the study area most of the rocks are well exposed. Geomorphological features such as cliffs, slopes, wadis and terrain features can also be described in the field. The study of the landforms in the area give some indication of the durability of the rock as building stone. For example the absence of exposures, often coupled with a subdued topography, could signify a low resistance to weathering of this rock.

Infrastructures such as highways and roads are also necessary in developing quarries for building stone. Such infrastructures assure easy transport of the material and movement of people and work force.

VIII.2.3 *Combination and correlation*

Both methods of investigation have their own advantages and disadvantages. Generally field investigation is expensive, requires more effort, and takes more time, but it can never be overstepped. Exploring large remote areas for dimension stone, using conventional mapping methods, could be extremely difficult or mostly impractical. In this circumstances, it becomes necessary to locate some target areas which are likely to host important potential rocks, and this can be done effectively by satellite, particularly by TM imagery systems. Different rocks have different spectral characteristics and if these are known the possible composition of the surface can be inferred from the satellite data. Landsat data can be used as an aid in exploration by highlighting target areas for detailed field investigation. The satellite also produce a very consistent data source world-wide, so interpretation of data in one area can be generalised and applied, not only in adjacent areas but even from continent to continent (Press 1993). Moreover the data is relatively cheap, individual pre-1988 scenes covering 34000 km^2 cost about $200 (Lamb and Lawrence, 1993). The TM data with resolution of 30 meters can result in map scale down to 1: 50000. The TM has also spectral bands specially optimised for geological observations of different types of clay minerals, hydrothermal alteration effects and iron-rich zones, all often important in mineral exploration. The resolution of the present satellite data is in-fact too low for detail ground study. With progressive advance in technology of satellite systems, the resolution can be improved to adequate value of better than one meter, then the satellite data could have more and wide advantages to map the ground surface and will improve the field mapping effectively (Drury 1993). The satellite imagery and TM data is proven in arid and semi-arid terrain where rock outcrops are exposed at the surface.

The present study shows that both Landsat and field investigation methods can be used to detect some similar geological aspects, while other aspects can only be detected by one of them. Rock type can be directly mapped in the field including grain size, texture, colour, alteration, outcrop weathering, outcrop exposure, outcrop extent, boundaries and contacts, rock type homogeneity and mixed areas and rock hardness.

The TM data can help in detecting and recognizing the above rock type aspects indirectly, and on larger scale (covers larger areas). Rock characteristics which can not be detected by TM data includes grain size, texture, appearance, veining and direct estimation of rock hardness. For example the red granite (site1) and microgranite (site2) display similar colours on TM images and appears as red and magenta. Both of them have similar granitic composition, outcrop colour, and weathering and alteration features. But the microgranite is fine grained and relatively of high strength compared to the medium to coarse grained red granite.

Overall view of outcrop homogeneity and mixed outcrop areas, either due to dyking or volcanic cones, all these aspects can be viewed at wide angle by the satellite TM data, where in the field one is restricted to the locality covered by the investigation. It is also tedious work to delineate the boundaries between different lithologies in the mixed rock areas, while it is quite easy and more precise on the CRC images to delineate this area. For example the mixed area, which is composed of interfingering of pink, grey and sometimes red granite in site1 is clearly shown on CRC images as interfingering of CRC colours such as cyan, yellow and red. The boundary between these colours is spotty and curvy. So this area is identified as a zone of mixed rocks between the above mentioned rock units and can be best detected by the TM data. This mixed area is not going to be a favourable site for dimension stone, due to the colour and properties heterogeneity and limited outcrop, unless there is a special demand for this type of rock.

The colour of the rock can be described exactly in the field, the data shows ability in helping to distinguish the rock colour zone, for example the grey granite appears as yellow and green on the CRC images. It is also clear in the mixed area, when grey granite and pink or red granite are interfingered, the CRC images display the patches of grey granite as yellow and the patches of red granite as red and magenta. This gives opportunity to distinguish the colour of the rocks, particularly when the colour of the rock is affected by alteration.

Generally alteration conditions of the rock can be detected by TM data for large area, where in the field method it needs number of location in order to describe the overall alteration of the rock, particularly when the rock has distinctive features of alteration and /or weathering, i.e. staining. For example the rock in the study area is affected by different grades of alteration, this feature is not quite obvious in the field, but the CRC images obtained with band ratio 3/4 or 4/2 (Drury 1987) can show clearly the occurrence of staining features. When the product of alteration is mainly clay with little or no iron staining the band ratio 7/5 is the most appropriate to appear on the CRC image (Whateley 1995).

Prediction of subsurface geology of wadi areas (50-100 m large) can be made by extrapolation, i.e. if both sides of the wadi are red granite the wadi area which is usually covered by detrital material is mapped as red granite. This is done in both field and CRC images.

The exposure weathering conditions can be described clearly in the field, while the TM data can help to distinguish weathered exposures. In this study it has been observed that when the exposure is highly weathered and fractured, its boundaries especially in the nearby wadis are not clear (not sharp or low contrast). The detrital wadi material has almost similar spectral characteristics to that of the exposure boundaries. For example on the CRC images the boundaries of red granite are not as clear as they appear on the field. The vagueness of the exposure boundaries comes from the fact that this latter, in addition to staining, it is generally disintegrated and contain more clay minerals than the rest of the exposure. Therefore in the context of large areas, the TM data is quite helpful in distinguishing the weathering of the exposure.

Discontinuity characteristics such as spacing, type, orientation, block size and shape could only be determined from the field. Remote sensing methods due to its resolution can be used effectively to study lineaments and major structure. Detailed structural information, i.e. for dimension stone purpose, can only be done in the field, nevertheless remote sensing method can be useful in locating target and representative areas.

Generalisation (general view recognition), extension and distribution of rock properties over the exposure can be precisely and easily done on TM data images. This is in fact due to the special consistency of the TM data. On the other hand, this work on the field can also be precise but needs numerous locations which result in a huge effort, and the boundaries between areas of different properties can never be drawn correctly. Therefore, rock properties distribution in order to be precisely shown on the map field and TM data methods should be used together.

The construction of the map from field study, needs compilation of the data from all the studied locations, while the TM data using CRC methods could have ready computer processed colour map for the study area and also ready for visual interpretation. Satellite data are complementary to the field investigation and the ground check. The correlation between the TM data observations and the field study in the study area has confirmed that TM data can detect and distinguish numerous geological information particularly alteration and weathering as clear as in the field study. Therefore it could be said that the TM data using CRC images is a good exploration tool in searching for earth resources such as dimension stone...etc. **Table VIII.2** shows most of the geological aspects studied in the field and can be detected using TM data.

Fig. VIII.5 outlines the exploration and assessment of the granitic rocks for dimension stone investigation based on the present study have been suggested as follows:

The highlighted area is the suggested systematic procedure of the exploration for the potential dimension stone particularly in the granitic rocks in the Arabian Shield.

Table VIII.2: Comparison between field and Landsat data (TM) methods in exploration for dimension stone characteristics

Characteristics	*Field*	*Landsat (TM)*
Rock type (recognition)	✓	✓
Rock colour (recognition)	✓	✓
Grain size (recognition)	✓	
Texture & appearance (recognition)	✓	
Alteration & staining (recognition)	✓	✓
Rock boundary type (recognition)	✓	✓
Lineament (detection)		✓
Discontinuity orientation (determination)	✓	
Discontinuity spacing (determination)	✓	
Block size (determination)	✓	
Block shape (description)	✓	
Exposure homogeneity (recognition)	✓	✓
Strength (determination)	✓	
Surface weathering (recognition)	✓	✓
Sampling location (recognition)	✓	✓
Target area (recognition)	✓	✓
Rock spectral properties (detection)		✓
General view (recognition)		✓
Large area mapping (efficiency)		✓
Cost & time (efficiency)		✓
Availability and easy access to data		✓
Ready computer processing		✓
Easy map preparation	✓	✓
Remote and hazardous areas mapping	✓	✓
Climate controless		✓
Human view sensitivity	✓	

✓ Subsidiary method (small ticks)

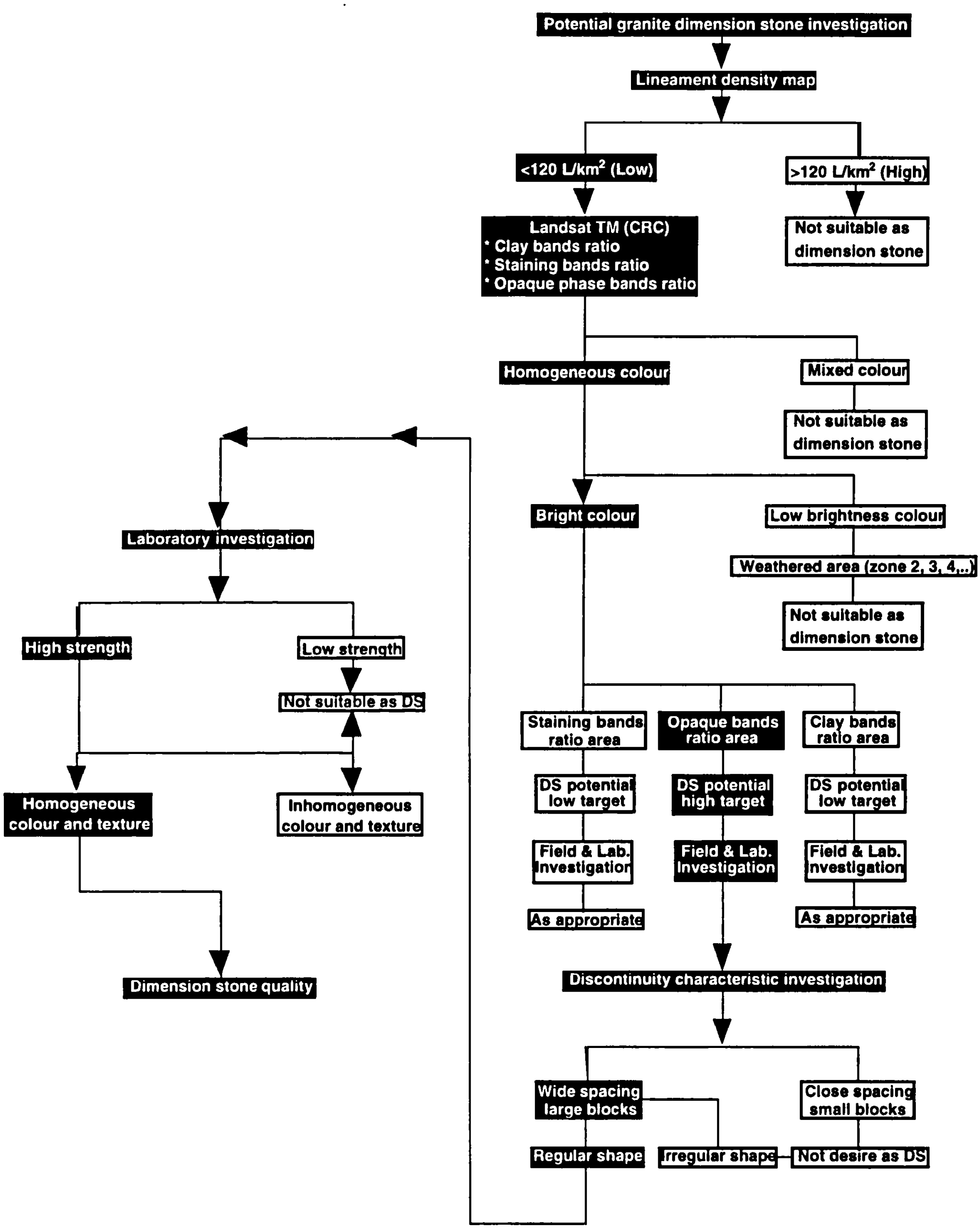


Fig. VIII.5: Flow chart for suggested exploration procedure of dimension stone potential

VIII.3 *RECOMMENDATIONS FOR FUTURE WORK*

Several ideas for future work can be recommended based on the present study. These are as follows:

1. The present study procedure can be applied on the new interesting granites sites within Arabian Shield and as well as other igneous and sedimentary rocks, particularly plutonic, sandstone and limestone rocks.
2. Particular study on the effect of microfractures on geotechincal properties of the rocks and durability as dimension stone.
3. Particular study on the relationship between the alteration stages (staining in different type rocks) with weathering, geotechincal properties and rock mass condition is recommended in the other part of the Arabian Shield.
4. The study of the relationship between the areal distribution of alteration, weathering and rock mass condition with subsurface condition will give complete view of dimension stone potential and help to identify and prediction the distribution of geotechincal properties, quality and the reserve of the material.
5. The present study shows quite good correlation between the CRC image features, alteration and geotechincal properties of the granites in site1&2. Similar features may be observed in the other areas. Application of the exploration and assessment of potential dimension stone methodology outlined in this thesis will test the procedure explained in Chapter VI and IX in this thesis.
6. The suggested acceptable engineering windows could be tested on the other granites in the Arabian Shield and other types of rocks in order to establish this method.
7. The new development in this thesis of in-situ block size calculation method. can be tested on other granites and other types of rocks in the Arabian Shield.
8. In-situ spectral measurement should be conducted to investigate the geological and geotechincal aspects in the granites of the Arabian Shield, which produce effective mapping within appropriate time and cost.
9. The Landsat (TM) data should be used in mapping of geological and geotechnical

aspects of the rocks in the Arabian Shield particularly using hybrid remote sensing classification and manipulated using Geographical Information System (GIS) method.

10 The geotechnical and geometrical data can be extracted and analysed (resource investigation and urban planning) using coming more advanced Landsat observation system with high spectral and spatial resolutions (15 -1m) particularly in mapping arid areas such as well exposed Arabian Shield.

11 The geotechnical properties of the mixed area should studied.

12 According to the existing classification, the range of the large class of block size are too wide so it is necessary to re-categorise the range of this class into two or more classes such as 0.2-1.0m^3, 1.0-3m^3, 3-8.0m^3 and $\geq$ 8.0 m^3, because the most of the block sizes of the potential dimension stone granites in the sites 1& 2 are within the large class (0.2-8.0m^3), and the best potential dimension stone natural block sizes are between 1.0-3m^3. This can be achieved using the new block size calculation method developed in this thesis for dimension stone prospect.

13 By applying the procedure used in the thesis it is possible to locate and quantify the dimension stone potential resource in the Arabian Shield, particularly by utilizing the Landsat data.

14 The two sites have large quantity of potential dimension stone, particularly grey and pink granites in very accessible areas, therefore it is highly recommended to be exploited commercially inside and outside the country.

CHAPTER IX

CONCLUSIONS

The main aims of this thesis are: (1) to assess the dimension stone potential of sites 1& 2; and (2) to propose an efficient method to explore for, and predict the performance, of granites as sources of dimension stone. The thesis indicates that the freshness, texture and the block size are the main geological factors which control the quality and durability of the rocks in these sites, and consequently, their potential as a dimension stone.

This research reveals that there are several petrologically distinct granitic rock types in the study area: granites, microgranite and granophyre. Alteration and the associated staining, produce three granites: grey, pink and red. These lithologies have been mapped, both via field observation and by Landsat data.

Geotechnical differences between rocks are associated primarily with the degree of alteration, and secondly with the lithology. Two acceptable engineering limits have been suggested for the granites in the study area; these relates to plots of: (1) strength vs. density, and (2) absorption vs. strength. The suggested limits are: density (sat) >2.57 g/cm^3; absorption $\leq$ 1% and strength (sat) >105 MPa. The grey and pink granites in site 1& 2 have properties higher than these limits, as does the Ross of Mull Granite. The red granite's properties are generally below the limits. Although, the microgranite and granophyre have values within the limits, they have poor rock mass parameters and are completely stained, making them unsuitable as dimension stone.

There is a good correlation between the texture, alteration and staining stages, weathering grades, joint spacing, block size and lineament density, and the physical and mechanical properties of the granites, in sites 1& 2. The highly altered rocks (red granites) have a poor grade and are highly weathered (zone 2), while less altered rocks such as grey granite are highly resistant to weathering (zone1). Surface soundness tests show that the completely stained and altered granites, such as red granites, are highly susceptible to weathering and disintegration, indicating their low performance and poor durability, while the fresh to slightly altered grey granite has a high resistance to disintegration and therefore it is highly durable, and would perform well as dimension stone.

High lineament densities ($\geq$120 L/Km^2) observed on aerial photos correspond to high joint intensities and close joint spacing (the red granite, microgranite and granophyre). These rock-mass characteristics also correspond with completely stained and weathered rocks, possibly because highly jointed areas are more susceptible to weathering. Areas with a low lineament density ($\leq$120 L/Km^2) and wide joint spacings have a low level of alteration and low weathering grades, as typified by the grey granites.

A new technique has been devised for block size calculations using the in-situ joint spacings. This method provides quantitative results for block volume and block numbers, rather than the semi qualitative values produced by existing methods. This new method could be introduced into rock mass classifications: (see Barton *et al.* 1974; Bieniawski 1989). In the study area, areas of high dimension stone potential generally are in the large block size class (0.2–8.0m^3). These areas are mostly underlain by grey and pink granites. In contrast the poor potential dimension stone granites (red granite, microgranite, granophyre) are generally in the medium to small block class (smaller than 0.2 m^3).

The best dimension stone potentials, with high geotechnical grade and good quality, occur in grey granite. There is an estimated total mass of 1.02×10^8 tonne. Most of this mass has large block sizes and sound geotechnical properties. The pink granite is of moderate grade and large block size. It has an estimated total mass of 1.87×10^9 tonne, but only moderate geotechnical properties. The areas of poor potential occur in red granite, microgranite and granophyre. These are highly altered and highly fractured masses.

For the first time in the Arabian shield, alteration conditions of granitic rocks have been mapped using Landsat TM digital data. This mapping technique permitted a clear distinction between grades of alteration and staining of the granitic rocks.

The geological mapping of site1 was carried out almost entirely in the field and lasted nearly two months. The lithological, structural and geotechnical informations gathered from this field work were checked and correlated with the CRC image of the area. Based on this experience, site 2 was mapped directly from the CRC images with limited checking in the field. This method proved to be successful. Although the type of granite is not quite detectable by the remote sensing method, this study suggests that the granite types can very probably be recognised utilising the Landsat (TM) data, particularly when the granites are affected by alteration. The distribution of rock homogeneity as well as the conditions of the rock unit boundaries can be detected using the Landsat (TM) data. The traditional procedure of field investigation only can be improved using the Landsat method, particularly in the exploration stage, so as to exclude large poor rock-quality areas.

The thesis has suggested an outline for the systematic exploration for dimension stone potential in the granitic rocks in the Arabian Shield. The procedure is presented in Chapter VIII.

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Appendix I

Location: 1/14

Scanline 1 attitude (Azimuth/plunge): 130/5

No.	*Type*	*Intercept (cm)*	*Dip direction*	*Dip*
1	joint	0	92	86
2	joint	60	100	90
3	joint	170	90	90
4	joint	320	92	90
5	joint	450	85	85
6	joint	460	110	90
7	joint	470	90	88
8	joint	480	94	86
9	joint	570	80	80
10	joint	610	75	80
11	joint	630	110	90
12	joint	740	100	85
13	joint	800	90	78
14	joint	830	94	90
15	joint	970	115	90
16	joint	1000	90	76
17	joint	1040	85	68
18	joint	1130	75	70
19	joint	1220	86	90
20	joint	1370	110	86
21	joint	1500	80	75

Scanline 2 attitude (Azimuth/plunge): 285/ 10

No.	*Type*	*Intercept (cm)*	*Dip direction*	*Dip*
1	joint	0	96	86
2	joint	70	90	85
3	joint	180	95	80
4	joint	190	90	86
5	joint	260	360	90
6	joint	270	360	90
7	joint	330	60	90
8	joint	370	280	90
9	joint	450	294	70
10	joint	460	290	68
11	joint	540	286	75
12	joint	520	332	90
13	joint	670	284	90
14	joint	625	330	90
15	joint	670	330	90

Scanline 3 attitude (Azimuth/plunge): 0/90

No.	*Type*	*Intercept (cm)*	*Dip direction*	*Dip*
1	joint	40	270	20
2	joint	70	0	0
3	joint	80	265	25
4	joint	140	260	20
5	joint	170	270	15
6	joint	200	275	22
7	joint	240	270	20
8	joint	320	265	20

Location: 1/17

Scanline 1 attitude (Azimuth/plunge): 200/5

No.	*Type*	*Intercept (cm)*	*Dip direction*	*Dip*
1	joint	0	200	90
2	joint	30	205	88
3	joint	210	30	86
4	joint	230	30	85
5	joint	270	30	88
6	joint	550	360	85
7	joint	650	210	90
8	joint	750	230	86
9	joint	1020	235	80
10	joint	1320	200	90

Scanline 2 attitude (Azimuth/plunge):340/5

No.	*Type*	*Intercept (cm)*	*Dip direction*	*Dip*
1	joint	0	336	90
2	joint	70	335	90
3	joint	130	335	90
4	joint	170	340	87
5	joint	200	30	90
6	joint	270	65	90
7	joint	272	90	80
8	joint	275	325	90
9	joint	400	20	90
10	joint	460	5	90
11	joint	540	325	90
12	joint	600	10	90

Scanline 3 attitude (Azimuth/plunge): 0/90

No.	*Type*	*Intercept (cm)*	*Dip direction*	*Dip*
1	joint	40	270	20
2	joint	70	0	0
3	joint	80	265	25
4	joint	140	260	20
5	joint	170	270	15
6	joint	200	275	22
7	joint	240	270	20
8	joint	320	265	20

Location: 1/20

Scanline 1 attitude (Azimuth/plunge): 285/10

No.	*Type*	*Intercept (cm)*	*Dip direction*	*Dip*
1	joint	0	285	90
2	joint	5	285	90
3	joint	10	280	88
4	joint	110	285	90
5	joint	230	280	86
6	joint	300	280	90
7	joint	420	260	90
8	joint	530	260	87
9	joint	630	265	90
10	joint	770	280	87
11	joint	780	315	90
12	joint	880	270	90
13	joint	930	270	90
14	joint	975	270	86
15	joint	1050	60	90
16	joint	1140	305	90
17	joint	1210	10	90
18	joint	1290	86	75
19	joint	1370	266	90
20	joint	1440	266	90

Scanline 2 attitude (Azimuth/plunge):360/5

No.	*Type*	*Intercept (cm)*	*Dip direction*	*Dip*
1	joint	0	360	90
2	joint	70	10	90
3	joint	100	360	90
4	joint	130	10	88
5	joint	180	12	85
6	joint	230	12	90
7	joint	270	12	86
8	joint	300	10	90
9	joint	320	10	90
10	joint	340	360	90
11	joint	450	12	87
12	joint	485	40	80

Scanline 3 attitude (Azimuth/plunge): 0/90

No.	*Type*	*Intercept (cm)*	*Dip direction*	*Dip*
1	joint	40	270	20
2	joint	70	0	0
3	joint	80	265	25
4	joint	140	260	20
5	joint	170	270	15
6	joint	200	275	22
7	joint	240	270	20
8	joint	320	265	20

Location: 1/20

Scanline 1 attitude (Azimuth/plunge): 170/5

No.	*Type*	*Intercept (cm)*	*Dip direction*	*Dip*
1	joint	0	87	90
2	joint	60	87	88
3	joint	100	80	90
4	joint	140	76	86
5	joint	270	70	85
6	joint	280	80	87
7	joint	340	85	86
8	joint	390	85	90
9	joint	430	90	87
10	joint	500	90	89
11	joint	530	62	70
12	joint	585	65	74
13	joint	614	58	77
14	joint	640	105	84
15	joint	770	100	86
16	joint	840	104	85
17	joint	880	110	88
18	joint	900	60	60
19	joint	940	65	75
20	joint	970	60	68
21	joint	1120	87	86
22	joint	1070	240	90
23	joint	1065	64	87
24	joint	1230	90	76
25	joint	1285	86	82

Scanline 2 attitude (Azimuth/plunge): 90/2

No.	*Type*	*Intercept (cm)*	*Dip direction*	*Dip*
1	joint	0	80	90
2	joint	100	85	90
3	joint	200	86	90
4	joint	250	85	88
5	joint	300	235	80
6	joint	325	132	86
7	joint	375	125	90
8	joint	525	85	90
9	joint	560	82	86

Scanline 3 attitude (Azimuth/plunge): 0 / 90

No.	*Type*	*Intercept (cm)*	*Dip direction*	*Dip*
1	joint	0	280	15
2	joint	100	300	10
3	joint	350	0	0
4	joint	550	70	20
5	joint	600	80	15
6	joint	650	310	15

Location: 1/22

Scanline 1 attitude (Azimuth/plunge): 145/5

No.	*Type*	*Intercept (cm)*	*Dip direction*	*Dip*
1	joint	0	290	80
2	joint	100	10	90
3	joint	125	250	84
4	joint	126	5	85
5	joint	225	250	84
6	joint	250	10	90
7	joint	350	330	86
8	joint	450	170	86
9	joint	575	173	90

Scanline 2 attitude (Azimuth/plunge): 284/5

No.	*Type*	*Intercept (cm)*	*Dip direction*	*Dip*
1	joint	0	280	86
2	joint	64	100	62
3	joint	66	282	85
4	joint	150	280	86
5	joint	240	40	85
6	joint	440	50	75
7	joint	384	282	85
8	joint	610	295	86
9	joint	625	300	85
10	joint	610	305	60
11	joint	730	80	86

Scanline 3 attitude (Azimuth/plunge): 0 / 90

No.	*Type*	*Intercept (cm)*	*Dip direction*	*Dip*
1	joint	0	280	15
2	joint	100	300	10
3	joint	350	0	0
4	joint	550	70	20
5	joint	600	80	15
6	joint	650	310	15

Location:2/2

Scanline 1 attitude (Azimuth/plunge): 245/5

No.	*Type*	*Intercept (cm)*	*Dip direction*	*Dip*
1	joint	0	26	90
2	joint	20	25	90
3	joint	50	20	90
4	joint	66	20	88
5	joint	80	25	90
6	joint	100	24	90
7	joint	110	74	85
8	joint	220	350	70
9	joint	230	350	80
10	joint	270	355	86
11	joint	275	360	90
12	joint	280	360	90
13	joint	290	360	90
14	joint	340	350	90
15	joint	350	10	90
16	joint	347	85	80
17	joint	354	197	86

Scanline 2 attitude (Azimuth/plunge): 50/2

No.	*Type*	*Intercept (cm)*	*Dip direction*	*Dip*
1	joint	0	95	75
2	joint	10	95	78
3	joint	10	215	87
4	joint	20	216	88
5	joint	40	215	90
6	joint	60	210	90
7	joint	76	217	88
8	joint	80	210	90
9	joint	90	215	86
10	joint	100	214	85
11	joint	110	213	87
12	joint	115	215	90
13	joint	130	214	88
14	joint	140	215	87
15	joint	160	78	82
16	joint	170	215	82
17	joint	180	215	80
18	joint	200	76	80
19	joint	210	75	80
20	joint	230	75	84
21	joint	240	76	80
22	joint	250	78	86
23	joint	265	80	85
24	joint	270	75	82
25	joint	280	75	80
26	joint	295	78	84
27	joint	310	76	80

Scanline 3 attitude (Azimuth/plunge): 0 / 90

No.	*Type*	*Intercept (cm)*	*Dip direction*	*Dip*
1	joint	0	260	10
2	joint	30	80	10
3	joint	56	200	30
4	joint	85	210	15
5	joint	110	270	10
6	joint	120	0	0
7	joint	140	70	5
8	joint	160	0	0
9	joint	170	80	15
10	joint	265	120	50
11	joint	315	120	45

Location: M1/10

Scanline 1 attitude (Azimuth/plunge): 260/5

No.	*Type*	*Intercept (cm)*	*Dip direction*	*Dip*
1	joint	70	240	60
2	joint	140	245	65
3	joint	270	240	85
4	joint	360	242	67
5	joint	410	238	70
6	joint	440	230	75
7	joint	510	240	68
8	joint	780	240	78
9	joint	880	240	80
10	joint	900	245	70
11	joint	940	245	85
12	joint	1000	232	86
13	joint	1020	236	88
14	joint	1050	230	80
15	joint	1230	248	80
16	joint	1310	250	86
17	joint	1350	255	87
18	joint	1570	260	70
19	joint	1590	252	75
20	joint	1592	260	88
21	joint	1600	250	72
22	joint	1610	262	86
23	joint	1620	270	86
24	joint	1720	268	90
25	joint	1800	270	90
26	joint	1930	248	82
27	joint	1950	278	87
28	joint	2000	252	90
29	joint	2050	255	73

Scanline 2 attitude (Azimuth/plunge): 170/20

No.	*Type*	*Intercept (cm)*	*Dip direction*	*Dip*
1	joint	0	355	70
2	joint	140	360	75
3	joint	150	350	80
4	joint	280	344	90
5	joint	360	340	90
6	joint	500	350	90
7	joint	540	340	86
8	joint	640	338	85
9	joint	670	360	86
10	joint	700	345	80
11	joint	740	340	90
12	joint	750	342	88
13	joint	800	346	52
14	joint	900	350	60
15	joint	1000	340	50
16	joint	1080	345	56
17	joint	1165	350	60

Scanline 3 attitude (Azimuth/plunge): 0/90

No.	*Type*	*Intercept (cm)*	*Dip direction*	*Dip*
1	joint	40	270	20
2	joint	70	0	0
3	joint	80	265	25
4	joint	140	260	20
5	joint	170	270	15
6	joint	200	275	22
7	joint	240	270	20
8	joint	320	265	20

Location: M12

Scanline 1 attitude (Azimuth/plunge): 350/5

No.	*Type*	*Intercept (cm)*	*Dip direction*	*Dip*
1	joint	0	75	90
2	joint	60	80	80
3	joint	85	85	90
4	joint	120	80	86
5	joint	200	86	90
6	joint	310	90	80
7	joint	350	75	80
8	joint	380	72	85
9	joint	460	80	85
10	joint	530	90	86
11	joint	600	85	90

Scanline 2 attitude (Azimuth/plunge): 340/10

No.	*Type*	*Intercept (cm)*	*Dip direction*	*Dip*
1	joint	0	345	90
2	joint	20	340	90
3	joint	130	350	80
4	joint	195	350	85
5	joint	240	350	80
6	joint	300	360	80

Scanline 3 attitude (Azimuth/plunge): 0/90

No.	*Type*	*Intercept (cm)*	*Dip direction*	*Dip*
1	joint	0	325	15
2	joint	50	0	0
3	joint	150	250	10
4	joint	200	0	0
5	joint	260	320	10
6	joint	300	255	26
7	joint	330	320	12
8	joint	374	186	50

Location: M9

Scanline 1 attitude (Azimuth/plunge): 350/15

No.	*Type*	*Intercept (cm)*	*Dip direction*	*Dip*
1	joint	0	330	80
2	joint	20	320	85
3	joint	300	80	30
4	joint	480	80	30
5	joint	570	330	90
6	joint	770	85	25
7	joint	1180	340	70
8	joint	1230	330	70
9	joint	1630	340	70
10	joint	1750	330	65
11	joint	2020	340	70

Scanline 2 attitude (Azimuth/plunge): 250/10

No.	*Type*	*Intercept (cm)*	*Dip direction*	*Dip*
1	joint	0	250	80
2	joint	80	250	80
3	joint	340	260	80
4	joint	440	270	80
5	joint	940	270	86

Scanline 3 attitude (Azimuth/plunge): 0/90

No.	*Type*	*Intercept (cm)*	*Dip direction*	*Dip*
1	joint	40	270	20
2	joint	70	0	0
3	joint	80	265	25
4	joint	140	260	20
5	joint	170	270	15
6	joint	200	275	22
7	joint	240	270	20
8	joint	320	265	20

Location: Mull4

Scanline 1 attitude (Azimuth/plunge): 347/5

No.	*Type*	*Intercept (cm)*	*Dip direction*	*Dip*
1	joint	0	100	60
2	joint	140	135	72
3	joint	254	0	0
4	joint	321	140	75
5	joint	541	130	80
6	joint	561	135	76
7	joint	621	145	78
8	joint	681	100	65
9	joint	706	136	70

Scanline 2 attitude (Azimuth/plunge): 225/5

No.	*Type*	*Intercept (cm)*	*Dip direction*	*Dip*
1	joint	0	245	86
2	joint	94	245	88
3	joint	210	240	90
4	joint	326	230	90
5	joint	518	240	90
6	joint	586	246	88
7	joint	632	245	87
8	joint	706	245	85
9	joint	783	240	90
10	joint	861	250	86
11	joint	963	240	85
12	joint	1081	245	90
13	joint	1278	242	90

Scanline 3 attitude (Azimuth/plunge): 0/90

No.	*Type*	*Intercept (cm)*	*Dip direction*	*Dip*
1	joint	0	0	0
2	joint	100	25	15
3	joint	214	0	0
4	joint	327	20	15
5	joint	407	25	12
6	joint	477	0	0
7	joint	599	22	10
8	joint	709	0	0

Location: S1R

Scanline 1 attitude (Azimuth/plunge): 310/10

No.	*Type*	*Intercept (cm)*	*Dip direction*	*Dip*
1	joint	0	315	85
2	joint	80	310	80
3	joint	340	315	80
4	joint	500	320	82
5	joint	720	315	80
6	joint	1100	315	82
7	joint	1730	320	80
8	joint	1920	315	80
9	joint	2100	320	80
10	joint	2380	315	80
11	joint	2880	315	80

Scanline 2 attitude (Azimuth/plunge):170/20

No.	*Type*	*Intercept (cm)*	*Dip direction*	*Dip*
1	joint	0	60	80
2	joint	220	65	80
3	joint	350	70	80
4	joint	500	75	80
5	joint	600	55	90
6	joint	640	60	90
7	joint	680	62	90
8	joint	720	70	90
9	joint	890	65	90
10	joint	950	65	90
11	joint	1020	65	90
12	joint	1075	60	90
13	joint	1180	255	90
14	joint	1390	270	90
15	joint	1460	265	90
16	joint	1900	270	90

Scanline 3 attitude (Azimuth/plunge): 0/90

No.	*Type*	*Intercept (cm)*	*Dip direction*	*Dip*
1	joint	40	270	20
2	joint	66	85	5
3	joint	80	265	25
4	joint	138	260	20
5	joint	170	90	15
6	joint	188	110	20
7	joint	240	270	20
8	joint	322	85	20

Location:S4

Scanline 1 attitude (Azimuth/plunge): 180/10

No.	*Type*	*Intercept (cm)*	*Dip direction*	*Dip*
1	joint	0	175	75
2	joint	400	170	70
3	joint	540	180	90
4	joint	960	170	90
5	joint	1020	180	80
6	joint	1470	170	80
7	joint	1590	170	80
8	joint	1740	180	90
9	joint	1930	170	80

Scanline 2 attitude (Azimuth/plunge): 265/10

No.	*Type*	*Intercept (cm)*	*Dip direction*	*Dip*
1	joint	0	265	85
2	joint	280	270	80
3	joint	600	265	80
4	joint	620	260	80
5	joint	640	265	80
6	joint	690	270	80
7	joint	720	270	80
8	joint	880	260	80
9	joint	970	255	80
10	joint	1060	270	80
11	joint	1190	260	70
12	joint	1200	260	80
13	joint	1280	265	80
14	joint	1290	270	80
15	joint	1520	270	80
16	joint	1720	265	80
17	joint	1840	260	70
18	joint	1870	270	80
19	joint	1880	260	80
20	joint	1900	265	80
21	joint	1910	260	70
22	joint	1970	270	80
23	joint	1990	260	70
24	joint	2080	265	70
25	joint	2000	270	80
26	joint	2020	270	80
27	joint	2040	260	90
28	joint	2035	265	80
29	joint	2070	265	84

Scanline 3 attitude (Azimuth/plunge): 0/90

No.	*Type*	*Intercept (cm)*	*Dip direction*	*Dip*
1	joint	40	270	20
2	joint	66	85	5
3	joint	80	265	25
4	joint	138	260	20
5	joint	170	90	15
6	joint	188	110	20
7	joint	240	270	20
8	joint	322	80	20
9	joint	340	86	20
10	joint	400	270	10
11	joint	465	90	20
12	joint	500	260	20
13	joint	540	270	10
14	joint	610	110	20
15	joint	685	275	25
16	joint	710	85	20

Appendix II

BLOCK SIZE CALCULATION DATA ANALYSIS

Table AII.1: Block size calculation data analysis of Pink granite in site1

1 SORTED BLOCK SIZE (m^3)
2 SORTED BLOCK NUMBERS
3 CORRECTED BLOCK SIZE (m^3)
4 CORRECTED BLOCK NUMBERS
5 SORTED AND CORRECTED BLOCK SIZE (m^3)
6 SORTED AND CORRECTED BLOCKNUMBERS FOR EACH SIZE
7 TOTAL VOLUME FOR EACH BLOCK SIZE (m^3)
8 CUMULATIVE BLOCK NUMBERS
9 CUMULATIVE BLOCK VOLUMES
10 CUMULATIVE BLOCK NUMBERS PRECTENTAGE
11 CUMULATIVE BLOCK VOLUME PRECTENTAGE

1	2	3	4	5	6	7	8	9	10	11
0.05	2430	0.05	2430	0.05	2430	121.50	2430	121.50	0.40	0.01
0.10	12150			0.10	15903	1590.30	18333	1711.80	2.99	0.20
0.10	2025			0.15	24390	3658.50	42723	5370.30	6.98	0.62
0.10	1728	0.10	15903	0.20	31095	6219.00	73818	11589.30	12.05	1.34
0.15	21870			0.25	5247	1311.75	79065	12901.05	12.91	1.49
0.15	1710			0.30	58366	17509.80	137431	30410.85	22.44	3.52
0.15	810	0.15	24390	0.35	9918	3471.30	147349	33882.15	24.06	3.92
0.20	9720			0.40	33922	13568.80	181271	47450.95	29.60	5.49
0.20	10125			0.45	23520	10584.00	204791	58034.95	33.44	6.71
0.20	900			0.50	9790	4895.00	214581	62929.95	35.03	7.27
0.20	8640			0.55	2475	1361.25	217056	64291.20	35.44	7.43
0.20	1440			0.60	60699	36419.40	277755	100710.60	45.35	11.64
0.20	270	0.20	31095	0.70	16156	11309.20	293911	112019.80	47.99	12.95
0.25	4860			0.75	8712	6534.00	302623	118553.80	49.41	13.70
0.25	225			0.80	23142	18513.60	325765	137067.40	53.19	15.84
0.25	162	0.25	5247	0.90	35092	31582.80	360857	168650.20	58.92	19.50
0.30	9720			1.00	8643	8643.00	369500	177293.20	60.33	20.49
0.30	18225			1.05	11968	12566.40	381468	189859.60	62.28	21.95
0.30	8550			1.10	4010	4411.00	385478	194270.60	62.94	22.46
0.30	270			1.20	37531	45037.20	423009	239307.80	69.06	27.66
0.30	15552			1.25	789	986.25	423798	240294.05	69.19	27.78
0.30	1216			1.35	7750	10462.50	431548	250756.55	70.46	28.99
0.30	4050			1.40	12052	16872.80	443600	267629.35	72.42	30.94
0.30	675			1.50	10238	15357.00	453838	282986.35	74.10	32.71
0.30	108	0.30	58366	1.60	10215	16344.00	464053	299330.35	75.76	34.60
0.35	9720			1.65	2940	4851.00	466993	304181.35	76.24	35.16
0.35	90			1.75	1960	3430.00	468953	307611.35	76.56	35.56
0.35	108	0.35	9918	1.80	21451	38611.80	490404	346223.15	80.07	40.02
0.40	4860			2.00	4849	9698.00	495253	355921.15	80.86	41.14
0.40	8100			2.10	11800	24780.00	507053	380701.15	82.78	44.01
0.40	4500			2.20	2955	6501.00	510008	387202.15	83.27	44.76
0.40	135			2.25	3406	7663.50	513414	394865.65	83.82	45.64
0.40	6912			2.40	13971	33530.40	527385	428396.05	86.10	49.52
0.40	7200			2.45	796	1950.20	528181	430346.25	86.23	49.75
0.40	640			2.50	778	1945.00	528959	432291.25	86.36	49.97
0.40	1350			2.70	7859	21219.30	536818	453510.55	87.64	52.42
0.40	225	0.40	33922	2.75	480	1320.00	537298	454830.55	87.72	52.58
0.45	15390			2.80	5268	14750.40	542566	469580.95	88.58	54.28
0.45	7290			3.00	5202	15606.00	547768	485186.95	89.43	56.09
0.45	570			3.15	4324	13620.60	552092	498807.55	90.14	57.66
0.45	270	0.45	23520	3.20	2859	9148.80	554951	507956.35	90.60	58.72
0.50	4050			3.30	2814	9286.20	557765	517242.55	91.06	59.79
0.50	1125			3.50	1786	6251.00	559551	523493.55	91.36	60.51
0.50	3456			3.60	7942	28591.20	567493	552084.75	92.65	63.82
0.50	160			3.75	513	1923.75	568006	554008.50	92.74	64.04
0.50	810			3.85	380	1463.00	568386	555471.50	92.80	64.21
0.50	135			4.00	1758	7032.00	570144	562503.50	93.08	65.02
0.50	54	0.50	9790	4.05	1710	6925.50	571854	569429.00	93.36	65.82
0.55	2430			4.20	4658	19563.60	576512	588992.60	94.12	68.09
0.55	45	0.55	2475	4.40	1243	5469.20	577755	594461.80	94.33	68.72
0.60	8100			4.50	2257	10156.50	580012	604618.30	94.70	69.89

0.60	6840			4.80	2953	14174.40	582965	618792.70	95.18	71.53
0.60	8100			4.90	636	3116.40	583601	621909.10	95.28	71.89
0.60	1350			4.95	980	4851.00	584581	626760.10	95.44	72.45
0.60	6912			5.00	345	1725.00	584926	628485.10	95.50	72.65
0.60	12960			5.25	1112	5838.00	586038	634323.10	95.68	73.33
0.60	6080			5.40	3482	18802.80	589520	653125.90	96.25	75.50
0.60	192			5.50	429	2359.50	589949	655485.40	96.32	75.77
0.60	3240			5.60	1322	7403.20	591271	662888.60	96.53	76.63
0.60	3375			6.00	1683	10098.00	592954	672986.60	96.81	77.79
0.60	300			6.05	45	272.25	592999	673258.85	96.82	77.83
0.60	2430			6.25	30	187.50	593029	673446.35	96.82	77.85
0.60	190			6.30	2182	13746.60	595211	687192.95	97.18	79.44
0.60	540			6.40	452	2892.80	595663	690085.75	97.25	79.77
0.60	90	0.60	60699	6.60	1015	6699.00	596678	696784.75	97.42	80.55
0.70	8100			6.75	605	4083.75	597283	700868.50	97.52	81.02
0.70	450			7.00	694	4858.00	597977	705726.50	97.63	81.58
0.70	6912			7.20	1819	13096.80	599796	718823.30	97.93	83.09
0.70	64			7.35	460	3381.00	600256	722204.30	98.00	83.48
0.70	540			7.50	237	1777.50	600493	723981.80	98.04	83.69
0.70	90	0.70	16156	7.70	292	2248.40	600785	726230.20	98.09	83.95
0.75	3420			8.00	421	3368.00	601206	729598.20	98.16	84.34
0.75	2025			8.10	1030	8343.00	602236	737941.20	98.32	85.30
0.75	1620			8.25	246	2029.50	602482	739970.70	98.36	85.54
0.75	75			8.40	990	8316.00	603472	748286.70	98.53	86.50
0.75	1458			8.75	92	805.00	603564	749091.70	98.54	86.59
0.75	114	0.75	8712	8.80	280	2464.00	603844	751555.70	98.59	86.88
0.80	4050			9.00	642	5778.00	604486	757333.70	98.69	87.54
0.80	3600			9.45	850	8032.50	605336	765366.20	98.83	88.47
0.80	675			9.60	314	3014.40	605650	768380.60	98.88	88.82
0.80	3456			9.80	216	2116.80	605866	770497.40	98.92	89.07
0.80	5760			9.90	494	4890.60	606360	775388.00	99.00	89.63
0.80	3200			10.00	108	1080.00	606468	776468.00	99.02	89.76
0.80	96			10.50	378	3969.00	606846	780437.00	99.08	90.22
0.80	1080			10.80	1083	11696.40	607929	792133.40	99.25	91.57
0.80	1125			11.00	177	1947.00	608106	794080.40	99.28	91.79
0.80	100	0.80	23142	11.20	184	2060.80	608290	796141.20	99.31	92.03
0.90	6840			11.25	50	562.50	608340	796703.70	99.32	92.10
0.90	2430			11.55	184	2125.20	608524	798828.90	99.35	92.34
0.90	10944			12.00	311	3732.00	608835	802560.90	99.40	92.77
0.90	3240			12.10	32	387.20	608867	802948.10	99.41	92.82
0.90	6075			12.25	72	882.00	608939	803830.10	99.42	92.92
0.90	2850			12.50	10	125.00	608949	803955.10	99.42	92.93
0.90	90			12.60	552	6955.20	609501	810910.30	99.51	93.74
0.90	972			12.80	30	384.00	609531	811294.30	99.52	93.78
0.90	76			13.20	173	2283.60	609704	813577.90	99.54	94.05
0.90	1350			13.50	160	2160.00	609864	815737.90	99.57	94.30
0.90	225	0.90	35092	13.75	21	288.75	609885	816026.65	99.57	94.33
1.00	1800			14.00	168	2352.00	610053	818378.65	99.60	94.60
1.00	900			14.40	308	4435.20	610361	822813.85	99.65	95.11
1.00	2880			14.70	80	1176.00	610441	823989.85	99.66	95.25
1.00	800			14.85	235	3489.75	610676	827479.60	99.70	95.65
1.00	540			15.00	32	480.00	610708	827959.60	99.71	95.71
1.00	25			15.40	78	1201.20	610786	829160.80	99.72	95.85
1.00	648			15.75	120	1890.00	610906	831050.80	99.74	96.07
1.00	675			16.00	70	1120.00	610976	832170.80	99.75	96.20
1.00	60			16.20	120	1944.00	611096	834114.80	99.77	96.42
1.00	270			16.50	91	1501.50	611187	835616.30	99.79	96.59
1.00	45	1.00	8643	16.80	80	1344.00	611267	836960.30	99.80	96.75
1.05	6840			17.15	16	274.40	611283	837234.70	99.80	96.78
1.05	810			17.50	24	420.00	611307	837654.70	99.81	96.83
1.05	3240			17.60	25	440.00	611332	838094.70	99.81	96.88
1.05	30			18.00	104	1872.00	611436	839966.70	99.83	97.10
1.05	972			18.15	15	272.25	611451	840238.95	99.83	97.13
1.05	76	1.05	11968	18.90	160	3024.00	611611	843262.95	99.85	97.48
1.10	2025			19.20	12	230.40	611623	843493.35	99.86	97.50
1.10	225			19.25	32	616.00	611655	844109.35	99.86	97.58
1.10	1728			19.60	32	627.20	611687	844736.55	99.87	97.65
1.10	32	1.10	4010	19.80	140	2772.00	611827	847508.55	99.89	97.97
1.20	3420			20.00	16	320.00	611843	847828.55	99.89	98.01
1.20	3600			21.00	32	672.00	611875	848500.55	99.90	98.08
1.20	1080			21.60	120	2592.00	611995	851092.55	99.92	98.38
1.20	1215			22.00	39	858.00	612034	851950.55	99.92	98.48
1.20	5760			22.05	40	882.00	612074	852832.55	99.93	98.58
1.20	4864			22.40	12	268.80	612086	853101.35	99.93	98.61
1.20	5760			23.10	32	739.20	612118	853840.55	99.94	98.70
1.20	960			24.00	24	576.00	612142	854416.55	99.94	98.77
1.20	1620			24.20	5	121.00	612147	854537.55	99.94	98.78
1.20	2700			24.50	8	196.00	612155	854733.55	99.94	98.80
1.20	1500			24.75	35	866.25	612190	855599.80	99.95	98.90
1.20	45			25.20	80	2016.00	612270	857615.80	99.96	99.14
1.20	1080			26.40	10	264.00	612280	857879.80	99.96	99.17
1.20	2025			26.95	12	323.40	612292	858203.20	99.97	99.20
1.20	950			27.50	7	192.50	612299	858395.70	99.97	99.23
1.20	30			28.00	16	448.00	612315	858843.70	99.97	99.28
1.20	432			28.80	30	864.00	612345	859707.70	99.97	99.38
1.20	450			29.70	50	1485.00	612395	861192.70	99.98	99.55
1.20	40	1.20	37531	30.25	3	90.75	612398	861283.45	99.98	99.56
1.25	450			30.80	10	308.00	612408	861591.45	99.98	99.60
1.25	324			32.00	6	192.00	612414	861783.45	99.99	99.62
1.25	15	1.25	789	33.00	10	330.00	612424	862113.45	99.99	99.66
1.35	5130			34.65	30	1039.50	612454	863152.95	99.99	99.78
1.35	2430			36.30	2	72.60	612456	863225.55	99.99	99.79
1.35	190	1.35	7750	38.50	6	231.00	612462	863456.55	99.99	99.81
1.40	3600			39.60	25	990.00	612487	864446.55	100.00	99.93
1.40	360			42.35	2	84.70	612489	864531.25	100.00	99.94

1.40	5760			44.00	5	220.00	612494	864751.25	100.00	99.96
1.40	320			54.45	5	272.25	612499	865023.50	100.00	99.99
1.40	1080			60.50	1	60.50	612500	865084.00	100.00	100.00
1.40	10									
1.40	432									
1.40	450									
1.40	40	1.40	12052							
1.50	900									
1.50	540									
1.50	2432									
1.50	1440									
1.50	1350									
1.50	375									
1.50	648									
1.50	1215									
1.50	570									
1.50	18									
1.50	216									
1.50	10									
1.50	486									
1.50	38	1.50	10238							
1.60	1800									
1.60	540									
1.60	2880									
1.60	2560									
1.60	480									
1.60	540									
1.60	900									
1.60	500									
1.60	15	1.60	10215							
1.65	1710									
1.65	405									
1.65	810									
1.65	15	1.65	2940							
1.75	900									
1.75	180									
1.75	648									
1.75	6									
1.75	216									
1.75	10	1.75	1960							
1.80	1080									
1.80	4864									
1.80	1728									
1.80	2700									
1.80	2280									
1.80	2700									
1.80	450									
1.80	1710									
1.80	432									
1.80	810									
1.80	380									
1.80	12									
1.80	1080									
1.80	1125									
1.80	100	1.80	21451							
2.00	450									
2.00	270									
2.00	1280									
2.00	640									
2.00	450									
2.00	125									
2.00	324									
2.00	540									
2.00	300									
2.00	9									
2.00	216									
2.00	225									
2.00	20	2.00	4849							
2.10	1080									
2.10	360									
2.10	4864									
2.10	576									
2.10	2700									
2.10	150									
2.10	432									
2.10	4									
2.10	432									
2.10	810									
2.10	380									
2.10	12	2.10	11800							
2.20	900									
2.20	180									
2.20	1440									
2.20	160									
2.20	270									
2.20	5	2.20	2955							
2.25	1140									
2.25	675									
2.25	1026									
2.25	540									
2.25	25	2.25	3406							
2.40	540									
2.40	540									
2.40	2432									
2.40	2560									

2.40	768		
2.40	864		
2.40	1350		
2.40	1200		
2.40	225		
2.40	900		
2.40	760		
2.40	900		
2.40	150		
2.40	216		
2.40	360		
2.40	200		
2.40	6	2.40	13971
2.45	360		
2.45	432		
2.45	4	2.45	796
2.50	320		
2.50	270		
2.50	75		
2.50	108		
2.50	5	2.50	778
2.70	2280		
2.70	810		
2.70	684		
2.70	1080		
2.70	2025		
2.70	950		
2.70	30	2.70	7859
2.75	225		
2.75	90		
2.75	162		
2.75	3	2.75	480
2.80	180		
2.80	540		
2.80	2560		
2.80	256		
2.80	900		
2.80	50		
2.80	216		
2.80	360		
2.80	200		
2.80	6	2.80	5268
3.00	640		
3.00	384		
3.00	600		
3.00	300		
3.00	380		
3.00	225		
3.00	540		
3.00	456		
3.00	540		
3.00	90		
3.00	180		
3.00	50		
3.00	216		
3.00	405		
3.00	190		
3.00	6	3.00	5202
3.15	2280		
3.15	270		
3.15	684		
3.15	1080		
3.15	10	3.15	4324
3.20	270		
3.20	1280		
3.20	384		
3.20	450		
3.20	400		
3.20	75	3.20	2859
3.30	270		
3.30	180		
3.30	1216		
3.30	288		
3.30	675		
3.30	75		
3.30	108		
3.30	2	3.30	2814
3.50	640		
3.50	128		
3.50	540		
3.50	30		
3.50	180		
3.50	50		
3.50	216		
3.50	2	3.50	1786
3.60	768		
3.60	1140		
3.60	1200		
3.60	360		
3.60	405		
3.60	760		
3.60	270		
3.60	360		
3.60	304		
3.60	360		

3.60	60		
3.60	540		
3.60	900		
3.60	500		
3.60	15	3.60	7942
3.75	150		
3.75	228		
3.75	135	3.75	513
3.85	90		
3.85	180		
3.85	108		
3.85	2	3.85	380
4.00	320		
4.00	192		
4.00	200		
4.00	100		
4.00	270		
4.00	240		
4.00	45		
4.00	108		
4.00	180		
4.00	100		
4.00	3	4.00	1758
4.05	1710	4.05	1710
4.20	768		
4.20	256		
4.20	1200		
4.20	120		
4.20	760		
4.20	90		
4.20	360		
4.20	20		
4.20	360		
4.20	304		
4.20	360		
4.20	60	4.20	4658
4.40	135		
4.40	90		
4.40	640		
4.40	128		
4.40	225		
4.40	25	4.40	1243
4.50	300		
4.50	180		
4.50	456		
4.50	162		
4.50	152		
4.50	90		
4.50	450		
4.50	125		
4.50	342	4.50	2257
4.80	384		
4.80	384		
4.80	600		
4.80	180		
4.80	380		
4.80	400		
4.80	120		
4.80	135		
4.80	180		
4.80	160		
4.80	30	4.80	2953
4.90	256		
4.90	360		
4.90	20	4.90	636
4.95	570		
4.95	135		
4.95	270		
4.95	5	4.95	980
5.00	50		
5.00	120		
5.00	60		
5.00	90		
5.00	25	5.00	345
5.25	300		
5.25	60		
5.25	456		
5.25	54		
5.25	152		
5.25	90	5.25	1112
5.40	360		
5.40	304		
5.40	108		
5.40	900		
5.40	760		
5.40	900		
5.40	150	5.40	3482
5.50	160		
5.50	64		
5.50	135		
5.50	15		
5.50	54		
5.50	1	5.50	429
5.60	128		
5.60	384		

5.60	400		
5.60	40		
5.60	180		
5.60	160		
5.60	30	5.60	1322
6.00	150		
6.00	90		
6.00	100		
6.00	60		
6.00	228		
6.00	240		
6.00	72		
6.00	81		
6.00	80		
6.00	40		
6.00	180		
6.00	152		
6.00	180		
6.00	30	6.00	1683
6.05	45	6.05	45
6.25	30	6.25	30
6.30	360		
6.30	120		
6.30	304		
6.30	36		
6.30	304		
6.30	108		
6.30	900		
6.30	50	6.30	2182
6.40	192		
6.40	200		
6.40	60	6.40	452
6.60	192		
6.60	128		
6.60	300		
6.60	60		
6.60	190		
6.60	45		
6.60	90		
6.60	10	6.60	1015
6.75	380		
6.75	225	6.75	605
7.00	100		
7.00	20		
7.00	240		
7.00	24		
7.00	80		
7.00	40		
7.00	180		
7.00	10	7.00	694
7.20	180		
7.20	180		
7.20	120		
7.20	152		
7.20	160		
7.20	48		
7.20	54		
7.20	450		
7.20	400		
7.20	75	7.20	1819
7.35	120		
7.35	304		
7.35	36	7.35	460
7.50	60		
7.50	36		
7.50	20		
7.50	76		
7.50	45	7.50	237
7.70	64		
7.70	128		
7.70	90		
7.70	10	7.70	292
8.00	50		
8.00	30		
8.00	120		
8.00	36		
8.00	90		
8.00	80		
8.00	15	8.00	421
8.10	760		
8.10	270	8.10	1030
8.25	75		
8.25	30		
8.25	114		
8.25	27	8.25	246
8.40	60		
8.40	180		
8.40	120		
8.40	40		
8.40	160		
8.40	16		
8.40	152		
8.40	160		
8.40	48		
8.40	54	8.40	990

8.75	60		
8.75	12		
8.75	20	8.75	92
8.80	96		
8.80	64		
8.80	100		
8.80	20	8.80	280
9.00	72		
9.00	40		
9.00	24		
9.00	200		
9.00	100		
9.00	152		
9.00	54	9.00	642
9.45	760		
9.45	90	9.45	850
9.60	90		
9.60	60		
9.60	60		
9.60	80		
9.60	24	9.60	314
9.80	40		
9.80	160		
9.80	16	9.80	216
9.90	90		
9.90	60		
9.90	76		
9.90	18		
9.90	225		
9.90	25	9.90	494
10.00	30		
10.00	18		
10.00	40		
10.00	20	10.00	108
10.50	72		
10.50	24		
10.50	40		
10.50	8		
10.50	40		
10.50	24		
10.50	152		
10.50	18	10.50	378
10.80	48		
10.80	380		
10.80	400		
10.80	120		
10.80	135	10.80	1083
11.00	25		
11.00	10		
11.00	60		
11.00	12		
11.00	45		
11.00	5	11.00	177
11.20	20		
11.20	60		
11.20	80		
11.20	24	11.20	184
11.25	50	11.25	50
11.55	30		
11.55	60		
11.55	76		
11.55	18	11.55	184
12.00	36		
12.00	36		
12.00	20		
12.00	12		
12.00	76		
12.00	80		
12.00	24		
12.00	27	12.00	311
12.10	32	12.10	32
12.25	24		
12.25	40		
12.25	8	12.25	72
12.50	10	12.50	10
12.60	48		
12.60	16		
12.60	48		
12.60	400		
12.60	40	12.60	552
12.80	30	12.80	30
13.20	45		
13.20	30		
13.20	30		
13.20	20		
13.20	40		
13.20	8	13.20	173
13.50	100		
13.50	60	13.50	160
13.75	15		
13.75	6	13.75	21
14.00	12		
14.00	36		
14.00	20		
14.00	12		

14.00	80		
14.00	8	14.00	168
14.40	24		
14.40	24		
14.40	200		
14.40	60	14.40	308
14.70	16		
14.70	48		
14.70	16	14.70	80
14.85	190		
14.85	45	14.85	235
15.00	20		
15.00	12	15.00	32
15.40	10		
15.40	20		
15.40	40		
15.40	8	15.40	78
15.75	100		
15.75	20	15.75	120
16.00	18		
16.00	40		
16.00	12	16.00	70
16.20	120	16.20	120
16.50	18		
16.50	12		
16.50	10		
16.50	4		
16.50	38		
16.50	9	16.50	91
16.80	8		
16.80	24		
16.80	24		
16.80	24	16.80	80
17.15	16	17.15	16
17.50	20		
17.50	4	17.50	24
17.60	15		
17.60	10	17.60	25
18.00	50		
18.00	30		
18.00	24	18.00	104
18.15	15	18.15	15
18.90	120		
18.90	40	18.90	160
19.20	12	19.20	12
19.25	6		
19.25	12		
19.25	10		
19.25	4	19.25	32
19.60	8		
19.60	24	19.60	32
19.80	12		
19.80	8		
19.80	100		
19.80	20	19.80	140
20.00	10		
20.00	6	20.00	16
21.00	24		
21.00	8	21.00	32
21.60	60		
21.60	60	21.60	120
22.00	9		
22.00	6		
22.00	20		
22.00	4	22.00	39
22.05	40	22.05	40
22.40	12	22.40	12
23.10	4		
23.10	8		
23.10	12		
23.10	8	23.10	32
24.00	12		
24.00	12	24.00	24
24.20	5	24.20	5
24.50	8	24.50	8
24.75	25		
24.75	10	24.75	35
25.20	20		
25.20	60	25.20	80
26.40	6		
26.40	4	26.40	10
26.95	4		
26.95	8	26.95	12
27.50	5		
27.50	2	27.50	7
28.00	4		
28.00	12	28.00	16
28.80	30	28.80	30
29.70	30		
29.70	20	29.70	50
30.25	3	30.25	3
30.80	6		
30.80	4	30.80	10
32.00	6	32.00	6
33.00	6		

33.00	4	33.00	10
34.65	10		
34.65	20	34.65	30
36.30	2	36.30	2
38.50	2	38.50	6
38.50	4		
39.60	15		
39.60	10	39.60	25
42.35	2	42.35	2
44.00	3		
44.00	2	44.00	5
54.45	5	54.45	5
60.50	1	60.50	1

End of Table AII.1

Table AII.2: Block size calculation data analysis of Red granite in site1

1 SORTED BLOCK SIZE (m^3)
2 SORTED BLOCK NUMBERS
3 CORRECTED BLOCK SIZE (m^3)
4 CORRECTED BLOCK NUMBERS
5 SORTED AND CORRECTED BLOCK SIZE (m^3)
6 SORTED AND CORRECTED BLOCKNUMBERS FOR EACH SIZE
7 TOTAL VOLUME FOR EACH BLOCK SIZE (m^3)
8 CUMULATIVE BLOCK NUMBERS
9 CUMULATIVE BLOCK VOLUMES
10 CUMULATIVE BLOCK NUMBERS PRECTENTAGE
11 CUMULATIVE BLOCK VOLUME PRECTENTAGE

1	2	3	4	5	6	7	8	9	10	11
0.008	6	0.008	6	0.008	6	0.048	6	0.048	0.0138	0.0003
0.012	6			0.012	42	0.504	48	0.552	0.1102	0.0032
0.012	36	0.012	42	0.016	60	0.960	108	1.512	0.2480	0.0088
0.016	18			0.018	36	0.648	144	2.160	0.3307	0.0126
0.016	36			0.020	66	1.320	210	3.480	0.4823	0.0203
0.016	6	0.016	60	0.024	218	5.232	428	8.712	0.9830	0.0508
0.018	36	0.018	36	0.028	54	1.512	482	10.224	1.1070	0.0596
0.020	36			0.030	246	7.380	728	17.604	1.6719	0.1026
0.020	30	0.020	66	0.032	192	6.144	920	23.748	2.1129	0.1384
0.024	12			0.036	200	7.200	1120	30.948	2.5722	0.1804
0.024	108			0.040	383	15.320	1503	46.268	3.4518	0.2697
0.024	36			0.042	114	4.788	1617	51.056	3.7137	0.2976
0.024	12			0.044	12	0.528	1629	51.584	3.7412	0.3006
0.024	6			0.048	472	22.656	2101	74.240	4.8252	0.4327
0.024	36			0.050	180	9.000	2281	83.240	5.2386	0.4851
0.024	8	0.024	218	0.054	132	7.128	2413	90.368	5.5418	0.5267
0.028	12			0.056	268	15.008	2681	105.376	6.1573	0.6141
0.028	42	0.028	54	0.060	543	32.580	3224	137.956	7.4043	0.8040
0.030	216			0.064	296	18.944	3520	156.900	8.0841	0.9144
0.030	30	0.030	246	0.066	12	0.792	3532	157.692	8.1117	0.9191
0.032	108			0.070	312	21.840	3844	179.532	8.8283	1.0463
0.032	18			0.072	618	44.496	4462	224.028	10.2476	1.3057
0.032	18			0.076	6	0.456	4468	224.484	10.2614	1.3083
0.032	36			0.080	645	51.600	5113	276.084	11.7427	1.6091
0.032	12	0.032	192	0.084	334	28.056	5447	304.140	12.5098	1.7726
0.036	12			0.088	48	4.224	5495	308.364	12.6200	1.7972
0.036	72			0.090	526	47.340	6021	355.704	13.8280	2.0731
0.036	12			0.096	854	81.984	6875	437.688	15.7894	2.5509
0.036	12			0.098	84	8.232	6959	445.920	15.9823	2.5989
0.036	36			0.100	301	30.100	7260	476.020	16.6736	2.7743
0.036	8			0.108	336	36.288	7596	512.308	17.4452	2.9858
0.036	48	0.036	200	0.110	72	7.920	7668	520.228	17.6106	3.0320
0.040	216			0.112	432	48.384	8100	568.612	18.6027	3.3140
0.040	90			0.114	6	0.684	8106	569.296	18.6165	3.3179
0.040	36			0.116	6	0.696	8112	569.992	18.6303	3.3220
0.040	30			0.120	1522	182.640	9634	752.632	22.1258	4.3865
0.040	11	0.040	383	0.126	284	35.784	9918	788.416	22.7780	4.5950
0.042	72			0.128	366	46.848	10284	835.264	23.6186	4.8680
0.042	42	0.042	114	0.132	52	6.864	10336	842.128	23.7380	4.9081
0.044	12	0.044	12	0.140	527	73.780	10863	915.908	24.9483	5.3381
0.048	72			0.144	896	129.024	11759	1044.932	27.0061	6.0900
0.048	36			0.150	691	103.650	12450	1148.582	28.5931	6.6941
0.048	18			0.152	24	3.648	12474	1152.230	28.6482	6.7154
0.048	12			0.154	24	3.696	12498	1155.926	28.7033	6.7369
0.048	12			0.160	1003	160.480	13501	1316.406	31.0068	7.6722
0.048	108			0.162	136	22.032	13637	1338.438	31.3192	7.8006
0.048	36			0.168	884	148.512	14521	1486.950	33.3494	8.6662
0.048	12			0.174	6	1.044	14527	1487.994	33.3632	8.6723
0.048	24			0.176	60	10.560	14587	1498.554	33.5010	8.7338
0.048	48			0.180	916	164.880	15503	1663.434	35.6047	9.6947
0.048	12			0.190	36	6.840	15539	1670.274	35.6874	9.7346
0.048	72			0.192	742	142.464	16281	1812.738	37.3915	10.5649
0.048	10	0.048	472	0.196	144	28.224	16425	1840.962	37.7222	10.7294
0.050	180	0.050	180	0.198	40	7.920	16465	1848.882	37.8141	10.7756
0.054	72			0.200	921	184.200	17386	2033.082	39.9293	11.8491
0.054	12			0.210	789	165.690	18175	2198.772	41.7413	12.8148
0.054	48	0.054	132	0.216	612	132.192	18787	2330.964	43.1468	13.5852
0.056	72			0.220	94	20.680	18881	2351.644	43.3627	13.7057
0.056	126			0.224	660	147.840	19541	2499.484	44.8785	14.5674
0.056	12			0.228	26	5.928	19567	2505.412	44.9382	14.6019
0.056	12			0.232	24	5.568	19591	2510.980	44.9933	14.6344
0.056	42			0.240	1325	318.000	20916	2828.980	48.0364	16.4877
0.056	4	0.056	268	0.250	330	82.500	21246	2911.480	48.7943	16.9686
0.060	60			0.252	554	139.608	21800	3051.088	50.0666	17.7822
0.060	72			0.256	216	55.296	22016	3106.384	50.5627	18.1045
0.060	216			0.264	116	30.624	22132	3137.008	50.8291	18.2830
0.060	30			0.266	12	3.192	22144	3140.200	50.8566	18.3016
0.060	48			0.270	330	89.100	22474	3229.300	51.6145	18.8209
0.060	40			0.280	1321	369.880	23795	3599.180	54.6484	20.9766
0.060	11			0.288	770	221.760	24565	3820.940	56.4168	22.2690

0.060	66	0.060	543	0.290	36	10.440	24601	3831.380	56.4995	22.3299
0.064	6			0.294	188	55.272	24789	3886.652	56.9312	22.6520
0.064	54			0.300	542	162.600	25331	4049.252	58.1760	23.5997
0.064	108			0.304	30	9.120	25361	4058.372	58.2449	23.6528
0.064	18			0.308	32	9.856	25393	4068.228	58.3184	23.7103
0.064	36			0.320	458	146.560	25851	4214.788	59.3703	24.5644
0.064	72			0.324	228	73.872	26079	4288.660	59.8939	24.9950
0.064	2	0.064	296	0.330	118	38.940	26197	4327.600	60.1649	25.2219
0.066	12	0.066	12	0.336	890	299.040	27087	4626.640	62.2089	26.9648
0.070	60			0.342	20	6.840	27107	4633.480	62.2548	27.0046
0.070	252	0.070	312	0.348	26	9.048	27133	4642.528	62.3145	27.0574
0.072	72			0.350	692	242.200	27825	4884.728	63.9038	28.4689
0.072	24			0.352	88	30.976	27913	4915.704	64.1059	28.6495
0.072	36			0.360	844	303.840	28757	5219.544	66.0443	30.4203
0.072	12			0.378	200	75.600	28957	5295.144	66.5036	30.8609
0.072	12			0.380	47	17.860	29004	5313.004	66.6115	30.9650
0.072	72			0.384	434	166.656	29438	5479.660	67.6083	31.9363
0.072	12			0.392	344	134.848	29782	5614.508	68.3983	32.7222
0.072	12			0.396	76	30.096	29858	5644.604	68.5729	32.8976
0.072	16			0.400	258	103.200	30116	5747.804	69.1654	33.4991
0.072	144			0.406	12	4.872	30128	5752.676	69.1930	33.5275
0.072	48			0.420	924	388.080	31052	6140.756	71.3151	35.7893
0.072	16			0.432	468	202.176	31520	6342.932	72.3899	36.9676
0.072	72			0.440	210	92.400	31730	6435.332	72.8722	37.5061
0.072	10			0.448	338	151.424	32068	6586.756	73.6484	38.3886
0.072	60	0.072	618	0.450	242	108.900	32310	6695.656	74.2042	39.0233
0.076	6	0.076	6	0.456	58	26.448	32368	6722.104	74.3374	39.1775
0.080	108			0.462	40	18.480	32408	6740.584	74.4293	39.2852
0.080	216			0.464	30	13.920	32438	6754.504	74.4982	39.3663
0.080	90			0.480	606	290.880	33044	7045.384	75.8899	41.0616
0.080	72			0.486	32	15.552	33076	7060.936	75.9634	41.1522
0.080	60			0.490	362	177.380	33438	7238.316	76.7948	42.1860
0.080	33			0.504	620	312.480	34058	7550.796	78.2187	44.0072
0.080	66	0.080	645	0.512	110	56.320	34168	7607.116	78.4714	44.3354
0.084	24			0.522	20	10.440	34188	7617.556	78.5173	44.3963
0.084	84			0.528	112	59.136	34300	7676.692	78.7745	44.7409
0.084	12			0.532	16	8.512	34316	7685.204	78.8113	44.7906
0.084	72			0.540	308	166.320	34624	7851.524	79.5186	45.7599
0.084	42			0.550	132	72.600	34756	7924.124	79.8218	46.1830
0.084	16			0.560	499	279.440	35255	8203.564	80.9678	47.8116
0.084	56			0.570	59	33.630	35314	8237.194	81.1033	48.0076
0.084	4			0.576	376	216.576	35690	8453.770	81.9668	49.2699
0.084	24	0.084	334	0.580	47	27.260	35737	8481.030	82.0748	49.4287
0.088	36			0.588	252	148.176	35989	8629.206	82.6535	50.2923
0.088	12	0.088	48	0.594	32	19.008	36021	8648.214	82.7270	50.4031
0.090	60			0.600	132	79.200	36153	8727.414	83.0302	50.8647
0.090	72			0.608	44	26.752	36197	8754.166	83.1312	51.0206
0.090	288			0.616	72	44.352	36269	8798.518	83.2966	51.2791
0.090	40			0.630	286	180.180	36555	8978.698	83.9534	52.3292
0.090	66	0.090	526	0.640	162	103.680	36717	9082.378	84.3255	52.9335
0.096	36			0.648	160	103.680	36877	9186.058	84.6929	53.5378
0.096	36			0.660	164	108.240	37041	9294.298	85.0696	54.1686
0.096	36			0.672	442	297.024	37483	9591.322	86.0847	55.8997
0.096	72			0.684	38	25.992	37521	9617.314	86.1720	56.0512
0.096	36			0.686	56	38.416	37577	9655.730	86.3006	56.2751
0.096	18			0.696	58	40.368	37635	9696.098	86.4338	56.5104
0.096	12			0.700	132	92.400	37767	9788.498	86.7369	57.0489
0.096	144			0.704	24	16.896	37791	9805.394	86.7921	57.1473
0.096	24			0.720	274	197.280	38065	10002.674	87.4213	58.2971
0.096	24			0.756	244	184.464	38309	10187.138	87.9817	59.3722
0.096	216			0.760	105	79.800	38414	10266.938	88.2229	59.8373
0.096	72			0.768	156	119.808	38570	10386.746	88.5811	60.5356
0.096	24			0.770	92	70.840	38662	10457.586	88.7924	60.9484
0.096	30			0.784	140	109.760	38802	10567.346	89.1140	61.5881
0.096	60			0.792	88	69.696	38890	10637.042	89.3161	61.9943
0.096	2			0.798	20	15.960	38910	10653.002	89.3620	62.0873
0.096	12	0.096	854	0.800	55	44.000	38965	10697.002	89.4883	62.3438
0.098	84	0.098	84	0.810	44	35.640	39009	10732.642	89.5894	62.5515
0.100	180			0.812	16	12.992	39025	10745.634	89.6261	62.6272
0.100	66	0.100	301	0.840	315	264.600	39340	11010.234	90.3495	64.1693
0.100	55			0.864	180	155.520	39520	11165.754	90.7629	65.0757
0.108	24			0.870	59	51.330	39579	11217.084	90.8984	65.3749
0.108	24			0.880	24	21.120	39603	11238.204	90.9536	65.4980
0.108	72			0.882	72	63.504	39675	11301.708	91.1189	65.8681
0.108	12			0.896	188	168.448	39863	11470.156	91.5507	66.8498
0.108	16			0.912	56	51.072	39919	11521.228	91.6793	67.1475
0.108	96			0.924	56	51.744	39975	11572.972	91.8079	67.4491
0.108	16			0.928	44	40.832	40019	11613.804	91.9090	67.6870
0.108	16			0.950	66	62.700	40085	11676.504	92.0605	68.0525
0.108	60	0.108	336	0.960	96	92.160	40181	11768.664	92.2810	68.5896
0.110	72	0.110	72	0.972	40	38.880	40221	11807.544	92.3729	68.8162
0.112	36			0.980	92	90.160	40313	11897.704	92.5842	69.3416
0.112	36			0.990	44	43.560	40357	11941.264	92.6852	69.5955
0.112	6			1.008	242	243.936	40599	12185.200	93.2410	71.0172
0.112	72			1.024	48	49.152	40647	12234.352	93.3512	71.3037
0.112	126			1.026	16	16.416	40663	12250.768	93.3880	71.3994
0.112	12			1.044	38	39.672	40701	12290.440	93.4753	71.6306
0.112	24			1.056	24	25.344	40725	12315.784	93.5304	71.7783
0.112	84			1.064	36	38.304	40761	12354.088	93.6131	72.0015
0.112	12			1.078	16	17.248	40777	12371.336	93.6498	72.1020
0.112	24	0.112	432	1.080	44	47.520	40821	12418.856	93.7509	72.3790
0.114	6	0.114	6	1.120	226	253.120	41047	12671.976	94.2699	73.8542
0.116	6	0.116	6	1.134	16	18.144	41063	12690.120	94.3066	73.9600
0.120	72			1.140	82	93.480	41145	12783.600	94.4950	74.5048
0.120	60			1.152	80	92.160	41225	12875.760	94.6787	75.0419

0.120	72			1.160	105	121.800	41330	12997.560	94.9198	75.7518
0.120	288			1.176	92	108.192	41422	13105.752	95.1311	76.3823
0.120	120			1.188	40	47.520	41462	13153.272	95.2230	76.6593
0.120	432			1.216	12	14.592	41474	13167.864	95.2506	76.7443
0.120	60			1.218	20	24.360	41494	13192.224	95.2965	76.8863
0.120	22			1.232	8	9.856	41502	13202.080	95.3149	76.9438
0.120	198			1.260	44	55.440	41546	13257.520	95.4159	77.2669
0.120	66			1.280	43	55.040	41589	13312.560	95.5147	77.5876
0.120	22			1.296	48	62.208	41637	13374.768	95.6249	77.9502
0.120	60			1.330	46	61.180	41683	13435.948	95.7306	78.3068
0.120	50	0.120	1522	1.344	166	223.104	41849	13659.052	96.1118	79.6071
0.126	84			1.368	44	60.192	41893	13719.244	96.2129	79.9579
0.126	24			1.372	16	21.952	41909	13741.196	96.2496	80.0858
0.126	96			1.386	16	22.176	41925	13763.372	96.2863	80.2150
0.126	56			1.392	56	77.952	41981	13841.324	96.4150	80.6694
0.126	24	0.126	284	1.400	66	92.400	42047	13933.724	96.5665	81.2079
0.128	36			1.408	24	33.792	42071	13967.516	96.6217	81.4048
0.128	6			1.440	22	31.680	42093	13999.196	96.6722	81.5895
0.128	54			1.450	66	95.700	42159	14094.896	96.8238	82.1472
0.128	216			1.512	72	108.864	42231	14203.760	96.9891	82.7817
0.128	36			1.520	12	18.240	42243	14222.000	97.0167	82.8880
0.128	6			1.536	58	89.088	42301	14311.088	97.1499	83.4072
0.128	12	0.128	366	1.566	16	25.056	42317	14336.144	97.1866	83.5533
0.132	24			1.568	72	112.896	42389	14449.040	97.3520	84.2112
0.132	12			1.584	8	12.672	42397	14461.712	97.3704	84.2851
0.132	16	0.132	52	1.596	28	44.688	42425	14506.400	97.4347	84.5455
0.140	72			1.624	36	58.464	42461	14564.864	97.5173	84.8863
0.140	60			1.680	82	137.760	42543	14702.624	97.7057	85.6892
0.140	252			1.710	22	37.620	42565	14740.244	97.7562	85.9084
0.140	22			1.728	28	48.384	42593	14788.628	97.8205	86.1904
0.140	77			1.740	82	142.680	42675	14931.308	98.0088	87.0220
0.140	24			1.760	22	38.720	42697	14970.028	98.0593	87.2476
0.140	20	0.140	527	1.764	16	28.224	42713	14998.252	98.0961	87.4121
0.144	36			1.792	62	111.104	42775	15109.356	98.2385	88.0597
0.144	24			1.824	12	21.888	42787	15131.244	98.2660	88.1872
0.144	72			1.856	12	22.272	42799	15153.516	98.2936	88.3170
0.144	24			1.862	8	14.896	42807	15168.412	98.3120	88.4038
0.144	36			1.920	22	42.240	42829	15210.652	98.3625	88.6500
0.144	12			1.960	46	90.160	42875	15300.812	98.4681	89.1755
0.144	96			2.016	60	120.960	42935	15421.772	98.6059	89.8805
0.144	48			2.030	46	93.380	42981	15515.152	98.7116	90.4247
0.144	24			2.048	6	12.288	42987	15527.440	98.7254	90.4963
0.144	16			2.052	20	41.040	43007	15568.480	98.7713	90.7355
0.144	24			2.088	44	91.872	43051	15660.352	98.8724	91.2709
0.144	144			2.112	20	42.240	43071	15702.592	98.9183	91.5171
0.144	24			2.128	4	8.512	43075	15711.104	98.9275	91.5667
0.144	24			2.240	34	76.160	43109	15787.264	99.0056	92.0106
0.144	20			2.304	24	55.296	43133	15842.560	99.0607	92.3329
0.144	180			2.320	12	27.840	43145	15870.400	99.0882	92.4951
0.144	60			2.352	28	65.856	43173	15936.256	99.1525	92.8790
0.144	20			2.394	8	19.152	43181	15955.408	99.1709	92.9906
0.144	12	0.144	896	2.432	12	29.184	43193	15984.592	99.1985	93.1607
0.150	240			2.436	28	68.208	43221	16052.800	99.2628	93.5582
0.150	396			2.464	8	19.712	43229	16072.512	99.2812	93.6731
0.150	55	0.150	691	2.520	22	55.440	43251	16127.952	99.3317	93.9962
0.152	18			2.610	22	57.420	43273	16185.372	99.3822	94.3308
0.152	6	0.152	24	2.688	40	107.520	43313	16292.892	99.4741	94.9575
0.154	24	0.154	24	2.736	4	10.944	43317	16303.836	99.4833	95.0213
0.160	30			2.744	8	21.952	43325	16325.788	99.5016	95.1492
0.160	108			2.784	12	33.408	43337	16359.196	99.5292	95.3439
0.160	432			2.816	4	11.264	43341	16370.460	99.5384	95.4096
0.160	180			2.842	8	22.736	43349	16393.196	99.5567	95.5421
0.160	198			3.024	20	60.480	43369	16453.676	99.6027	95.8946
0.160	33			3.040	11	33.440	43380	16487.116	99.6279	96.0894
0.160	12			3.072	4	12.288	43384	16499.404	99.6371	96.1611
0.160	10	0.160	1003	3.132	20	62.640	43404	16562.044	99.6831	96.5261
0.162	24			3.136	12	37.632	43416	16599.676	99.7106	96.7455
0.162	96			3.248	4	12.992	43420	16612.668	99.7198	96.8212
0.162	16	0.162	136	3.528	8	28.224	43428	16640.892	99.7382	96.9857
0.168	24			3.584	16	57.344	43444	16698.236	99.7749	97.3199
0.168	24			3.648	10	36.480	43454	16734.716	99.7979	97.5325
0.168	6			3.654	8	29.232	43462	16763.948	99.8163	97.7029
0.168	24			3.712	12	44.544	43474	16808.492	99.8438	97.9625
0.168	84			4.032	4	16.128	43478	16824.620	99.8530	98.0565
0.168	12			4.176	4	16.704	43482	16841.324	99.8622	98.1538
0.168	96			4.256	4	17.024	43486	16858.348	99.8714	98.2530
0.168	168			4.480	11	49.280	43497	16907.628	99.8967	98.5403
0.168	16			4.640	11	51.040	43508	16958.668	99.9219	98.8377
0.168	144			4.864	2	9.728	43510	16968.396	99.9265	98.8944
0.168	84			5.376	10	53.760	43520	17022.156	99.9495	99.2077
0.168	20			5.568	10	55.680	43530	17077.836	99.9724	99.5323
0.168	70			6.272	4	25.088	43534	17102.924	99.9816	99.6785
0.168	8			6.496	4	25.984	43538	17128.908	99.9908	99.8299
0.168	72			7.168	2	14.336	43540	17143.244	99.9954	99.9135
0.168	24			7.424	2	14.848	43542	17158.092	100.0000	100.0000
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0.176	36									
0.176	24	0.176	60							
0.180	60									
0.180	72									
0.180	80									
0.180	96									
0.180	22									
0.180	132									

0.180	22		
0.180	22		
0.180	360		
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0.192	12		
0.192	36		
0.192	36		
0.192	36		
0.192	8		
0.192	72		
0.192	144		
0.192	72		
0.192	36		
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0.192	36		
0.192	12		
0.192	4	0.192	742
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0.196	84		
0.196	8		
0.196	28	0.196	144
0.198	24		
0.198	16	0.198	40
0.200	360		
0.200	396		
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0.210	336		
0.210	132		
0.210	77		
0.210	144		
0.210	20	0.210	789
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0.216	24		
0.216	24		
0.216	96		
0.216	32		
0.216	48		
0.216	16		
0.216	144		
0.216	24		
0.216	20		
0.216	120		
0.216	20		
0.216	20	0.216	612
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0.224	18		
0.224	36		
0.224	36		
0.224	6		
0.224	144		
0.224	252		
0.224	24		
0.224	72		
0.224	12		
0.224	4		
0.224	14	0.224	660
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0.228	8	0.228	26
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0.232	6	0.232	24
0.240	72		
0.240	144		
0.240	120		
0.240	144		
0.240	132		
0.240	66		
0.240	33		
0.240	22		
0.240	360		
0.240	150		
0.240	72		
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0.252	84		
0.252	24		
0.252	32		
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0.252	120		
0.252	70		
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0.252	48		
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0.256	36		

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0.256	108		
0.256	36		
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0.264	24		
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0.324	32		
0.324	120		
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0.336	24		
0.336	24		
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0.336	48		
0.336	48		
0.336	8		
0.336	48		
0.336	168		
0.336	24		
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0.336	210		
0.336	20		
0.336	48		
0.336	24		
0.336	12		
0.336	8		
0.336	24		
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0.360	96		

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0.384	72		
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0.384	6		
0.384	4	0.384	434
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0.432	48		
0.432	120		
0.432	40		
0.432	60		
0.432	20		
0.432	24		
0.432	4	0.432	468
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0.440	66	0.440	210
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0.480	180		
0.480	20	0.480	606
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0.490	154		
0.490	40		
0.490	168	0.490	362
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0.504	32		

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0.504	48		
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0.504	24		
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0.540	100		
0.540	120	0.540	308
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0.560	66		
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0.560	72		
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0.576	72		
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0.576	60		
0.576	60		
0.576	60		
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0.588	56		
0.588	8	0.588	252
0.594	32	0.594	32
0.600	132	0.600	132
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0.608	36		
0.608	2	0.608	44
0.616	48		
0.616	24	0.616	72
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0.630	44		
0.630	40		
0.630	48	0.630	286
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0.640	66		
0.640	36	0.640	162
0.648	32		
0.648	48		
0.648	40		
0.648	40	0.648	160
0.660	44		
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0.672	56		
0.672	24		
0.672	48		
0.672	48		
0.672	12		
0.672	60		
0.672	60		
0.672	10		
0.672	24		
0.672	24		
0.672	24		
0.672	8		
0.672	28		
0.672	4	0.672	442
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0.684	16		
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0.686	56	0.686	56
0.696	12		

0.696	24		
0.696	12		
0.696	10	0.696	58
0.700	132	0.700	132
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0.704	12	0.704	24
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0.720	44		
0.720	120		
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0.720	24	0.720	274
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0.756	140		
0.756	40		
0.756	16		
0.756	16	0.756	244
0.760	72		
0.760	33	0.760	105
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0.768	24		
0.768	24		
0.768	60		
0.768	12		
0.768	12		
0.768	12	0.768	156
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0.770	48	0.770	92
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0.784	48		
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0.784	24		
0.784	4		
0.784	28	0.784	140
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0.798	4	0.798	20
0.800	55	0.800	55
0.810	44	0.810	44
0.812	12		
0.812	4	0.812	16
0.840	48		
0.840	44		
0.840	44		
0.840	11		
0.840	120		
0.840	48	0.840	315
0.864	16		
0.864	48		
0.864	60		
0.864	40		
0.864	8		
0.864	8	0.864	180
0.870	48		
0.870	11	0.870	59
0.880	24	0.880	24
0.882	56		
0.882	16	0.882	72
0.896	6		
0.896	12		
0.896	84		
0.896	36		
0.896	24		
0.896	12		
0.896	12		
0.896	2	0.896	188
0.912	24		
0.912	30		
0.912	2	0.912	56
0.924	40		
0.924	16	0.924	56
0.928	6		
0.928	36		
0.928	2	0.928	44
0.950	66	0.950	66
0.960	22		
0.960	50		
0.960	24	0.960	96
0.972	40	0.972	40
0.980	44		
0.980	48	0.980	92
0.990	44	0.990	44
1.008	12		
1.008	16		
1.008	48		
1.008	40		
1.008	40		
1.008	10		
1.008	24		
1.008	16		
1.008	28		
1.008	8	1.008	242
1.024	36		
1.024	12	1.024	48
1.026	16	1.026	16

1.044	12		
1.044	16		
1.044	10	1.044	38
1.056	16		
1.056	8	1.056	24
1.064	24		
1.064	12	1.064	36
1.078	16	1.078	16
1.080	44	1.080	44
1.120	72		
1.120	77		
1.120	33		
1.120	20		
1.120	24	1.120	226
1.134	16	1.134	16
1.140	22		
1.140	60	1.140	82
1.152	16		
1.152	24		
1.152	20		
1.152	12		
1.152	8	1.152	80
1.160	72		
1.160	33	1.160	105
1.176	16		
1.176	40		
1.176	16		
1.176	16		
1.176	4	1.176	92
1.188	40	1.188	40
1.216	6		
1.216	6	1.216	12
1.218	16		
1.218	4	1.218	20
1.232	8	1.232	8
1.260	44	1.260	44
1.280	33		
1.280	10	1.280	43
1.296	40		
1.296	8	1.296	48
1.330	22		
1.330	24	1.330	46
1.344	16		
1.344	24		
1.344	70		
1.344	30		
1.344	8		
1.344	8		
1.344	8		
1.344	2	1.344	166
1.368	24		
1.368	20	1.368	44
1.372	16	1.372	16
1.386	16	1.386	16
1.392	24		
1.392	30		
1.392	2	1.392	56
1.400	66	1.400	66
1.408	24	1.408	24
1.440	22	1.440	22
1.450	66	1.450	66
1.512	16		
1.512	40		
1.512	16	1.512	72
1.520	12	1.520	12
1.536	24		
1.536	30		
1.536	4	1.536	58
1.566	16	1.566	16
1.568	24		
1.568	28		
1.568	12		
1.568	8	1.568	72
1.584	8	1.584	8
1.596	20		
1.596	8	1.596	28
1.624	24		
1.624	12	1.624	36
1.680	22		
1.680	60	1.680	82
1.710	22	1.710	22
1.728	20		
1.728	8	1.728	28
1.740	22		
1.740	60	1.740	82
1.760	22	1.760	22
1.764	16	1.764	16
1.792	6		
1.792	24		
1.792	12		
1.792	14		
1.792	6	1.792	62
1.824	8		
1.824	4	1.824	12
1.856	6		

1.856	6	1.856	12
1.862	8	1.862	8
1.920	22	1.920	22
1.960	22		
1.960	24	1.960	46
2.016	24		
2.016	20		
2.016	8		
2.016	8	2.016	60
2.030	22		
2.030	24	2.030	46
2.048	6	2.048	6
2.052	20	2.052	20
2.088	24		
2.088	20	2.088	44
2.112	20	2.112	20
2.128	4	2.128	4
2.240	22		
2.240	12	2.240	34
2.304	20		
2.304	4	2.304	24
2.320	12	2.320	12
2.352	20		
2.352	8	2.352	28
2.394	8	2.394	8
2.432	12	2.432	12
2.436	20		
2.436	8	2.436	28
2.464	8	2.464	8
2.520	22	2.520	22
2.610	22	2.610	22
2.688	8		
2.688	20		
2.688	8		
2.688	4	2.688	40
2.736	4	2.736	4
2.744	8	2.744	8
2.784	8		
2.784	4	2.784	12
2.816	4	2.816	4
2.842	8	2.842	8
3.024	20	3.024	20
3.040	11	3.040	11
3.072	4	3.072	4
3.132	20	3.132	20
3.136	8		
3.136	4	3.136	12
3.248	4	3.248	4
3.528	8	3.528	8
3.584	12		
3.584	4	3.584	16
3.648	10	3.648	10
3.654	8	3.654	8
3.712	12	3.712	12
4.032	4	4.032	4
4.176	4	4.176	4
4.256	4	4.256	4
4.480	11	4.480	11
4.640	11	4.640	11
4.864	2	4.864	2
5.376	10	5.376	10
5.568	10	5.568	10
6.272	4	6.272	4
6.496	4	6.496	4
7.168	2	7.168	2
7.424	2	7.424	2

End of Table AII.2

Table AII.3: Block size calculation data analysis of Pink granite in site2

[1] SORTED BLOCK SIZE (m^3)
[2] SORTED BLOCK NUMBERS
[3] CORRECTED BLOCK SIZE (m^3)
[4] CORRECTED BLOCK NUMBERS
[5] SORTED AND CORRECTED BLOCK SIZE (m^3)
[6] SORTED AND CORRECTED BLOCKNUMBERS FOR EACH SIZE
[7] TOTAL VOLUME FOR EACH BLOCK SIZE (m^3)
[8] CUMULATIVE BLOCK NUMBERS
[9] CUMULATIVE BLOCK VOLUMES
[10] CUMULATIVE BLOCK NUMBERS PRECTENTAGE
[11] CUMULATIVE BLOCK VOLUME PRECTENTAGE

1	2	3	4	5	6	7	8	9	10	11
0.10	90	0.10	90	0.10	90	9.00	90	9.00	0.184	0.007
0.15	90	0.15	90	0.15	90	13.50	180	22.50	0.368	0.017
0.20	450			0.20	711	142.20	891	164.70	1.820	0.124
0.20	225			0.25	90	22.50	981	187.20	2.004	0.141
0.20	36	0.20	711	0.30	1351	405.30	2332	592.50	4.764	0.446
0.25	90	0.25	90	0.40	1818	727.20	4150	1319.70	8.478	0.994
0.30	810			0.45	910	409.50	5060	1729.20	10.337	1.303
0.30	450			0.50	717	358.50	5777	2087.70	11.802	1.573
0.30	45			0.55	45	24.75	5822	2112.45	11.894	1.592
0.30	36			0.60	3769	2261.40	9591	4373.85	19.593	3.296
0.30	10	0.30	1351	0.65	45	29.25	9636	4403.10	19.685	3.318
0.40	360			0.70	362	253.40	9998	4656.50	20.425	3.509
0.40	1125			0.75	1006	754.50	11004	5411.00	22.480	4.077
0.40	45			0.80	2052	1641.60	13056	7052.60	26.672	5.314
0.40	180			0.90	961	864.90	14017	7917.50	28.635	5.966
0.40	90			1.00	1368	1368.00	15385	9285.50	31.429	6.997
0.40	18	0.40	1818	1.05	362	380.10	15747	9665.60	32.169	7.283
0.45	810			1.10	243	267.30	15990	9932.90	32.665	7.485
0.45	90			1.20	3836	4603.20	19826	14536.10	40.502	10.954
0.45	10	0.45	910	1.25	186	232.50	20012	14768.60	40.882	11.129
0.50	180			1.30	243	315.90	20255	15084.50	41.378	11.367
0.50	450			1.35	912	1231.20	21167	16315.70	43.241	12.295
0.50	45			1.40	1059	1482.60	22226	17798.30	45.405	13.412
0.50	36			1.50	1597	2395.50	23823	20193.80	48.667	15.217
0.50	6	0.50	717	1.60	1458	2332.80	25281	22526.60	51.646	16.975
0.55	45	0.55	45	1.65	410	676.50	25691	23203.10	52.483	17.485
0.60	540			1.75	362	633.50	26053	23836.60	53.223	17.962
0.60	360			1.80	1791	3223.80	27844	27060.40	56.881	20.391
0.60	2025			1.95	410	799.50	28254	27859.90	57.719	20.994
0.60	225			2.00	1101	2202.00	29355	30061.90	59.968	22.653
0.60	324			2.10	393	825.30	29748	30887.20	60.771	23.275
0.60	180			2.20	279	613.80	30027	31501.00	61.341	23.737
0.60	18			2.25	352	792.00	30379	32293.00	62.060	24.334
0.60	50			2.40	2049	4917.60	32428	37210.60	66.246	28.040
0.60	25			2.50	207	517.50	32635	37728.10	66.669	28.430
0.60	18			2.60	279	725.40	32914	38453.50	67.239	28.976
0.60	4	0.60	3769	2.70	1088	2937.60	34002	41391.10	69.461	31.190
0.65	45	0.65	45	2.75	93	255.75	34095	41646.85	69.651	31.383
0.70	360			2.80	646	1808.80	34741	43455.65	70.971	32.746
0.70	2	0.70	362	3.00	1237	3711.00	35978	47166.65	73.498	35.542
0.75	180			3.15	420	1323.00	36398	48489.65	74.356	36.539
0.75	810			3.20	603	1929.60	37001	50419.25	75.588	37.993
0.75	10			3.25	93	302.25	37094	50721.50	75.778	38.221
0.75	6	0.75	1006	3.30	459	1514.70	37553	52236.20	76.715	39.362
0.80	180			3.50	363	1270.50	37916	53506.70	77.457	40.320
0.80	900			3.60	1120	4032.00	39036	57538.70	79.745	43.358
0.80	225			3.75	86	322.50	39122	57861.20	79.921	43.601
0.80	144			3.85	181	696.85	39303	58558.05	80.290	44.126
0.80	450			3.90	459	1790.10	39762	60348.15	81.228	45.475
0.80	18			4.00	564	2256.00	40326	62604.15	82.380	47.175
0.80	90			4.05	110	445.50	40436	63049.65	82.605	47.511
0.80	45	0.80	2052	4.20	330	1386.00	40766	64435.65	83.279	48.555
0.90	540			4.40	207	910.80	40973	65346.45	83.702	49.241
0.90	405			4.50	339	1525.50	41312	66871.95	84.395	50.391
0.90	450			4.55	181	823.55	41493	67695.50	84.764	51.012
0.90	324			4.80	695	3336.00	42188	71031.50	86.184	53.525
0.90	36			4.90	8	39.20	42196	71070.70	86.200	53.555
0.90	90			4.95	46	227.70	42242	71298.40	86.294	53.726
0.90	50			5.00	141	705.00	42383	72003.40	86.583	54.258
0.90	5			5.20	207	1076.40	42590	73079.80	87.005	55.069
0.90	4			5.25	86	451.50	42676	73531.30	87.181	55.409
0.90	2	0.90	961	5.40	580	3132.00	43256	76663.30	88.366	57.769
1.00	450			5.50	51	280.50	43307	76943.80	88.470	57.981
1.00	360			5.60	281	1573.60	43588	78517.40	89.044	59.166
1.00	225			5.85	46	269.10	43634	78786.50	89.138	59.369
1.00	72			6.00	552	3312.00	44186	82098.50	90.266	61.865
1.00	180			6.25	12	75.00	44198	82173.50	90.290	61.921
1.00	18			6.30	219	1379.70	44417	83553.20	90.738	62.961
1.00	18			6.40	162	1036.80	44579	84590.00	91.069	63.742
1.00	30			6.50	51	331.50	44630	84921.50	91.173	63.992

1.00	15	1.00	1368	6.60	219	1445.40	44849	86366.90	91.620	65.081
1.05	360			6.75	96	648.00	44945	87014.90	91.816	65.570
1.05	2	1.05	362	7.00	227	1589.00	45172	88603.90	92.280	66.767
1.10	225			7.20	361	2599.20	45533	91203.10	93.018	68.726
1.10	18	1.10	243	7.35	8	58.80	45541	91261.90	93.034	68.770
1.20	180			7.50	87	652.50	45628	91914.40	93.212	69.262
1.20	1350			7.70	77	592.90	45705	92507.30	93.369	69.708
1.20	180			7.80	219	1708.20	45924	94215.50	93.816	70.995
1.20	405			8.00	168	1344.00	46092	95559.50	94.159	72.008
1.20	216			8.10	127	1028.70	46219	96588.20	94.419	72.783
1.20	144			8.25	37	305.25	46256	96893.45	94.494	73.013
1.20	810			8.40	143	1201.20	46399	98094.65	94.787	73.919
1.20	90			8.75	28	245.00	46427	98339.65	94.844	74.103
1.20	40			8.80	72	633.60	46499	98973.25	94.991	74.581
1.20	125			9.00	177	1593.00	46676	100566.25	95.352	75.781
1.20	5			9.10	77	700.70	46753	101266.95	95.510	76.309
1.20	162			9.45	66	623.70	46819	101890.65	95.645	76.779
1.20	90			9.60	110	1056.00	46929	102946.65	95.869	77.575
1.20	9			9.75	37	360.75	46966	103307.40	95.945	77.847
1.20	20			9.80	20	196.00	46986	103503.40	95.986	77.994
1.20	10	1.20	3836	9.90	53	524.70	47039	104028.10	96.094	78.390
1.25	180			10.00	48	480.00	47087	104508.10	96.192	78.751
1.25	6	1.25	186	10.40	72	748.80	47159	105256.90	96.339	79.316
1.30	225			10.50	71	745.50	47230	106002.40	96.484	79.877
1.30	18	1.30	243	10.80	203	2192.40	47433	108194.80	96.899	81.530
1.35	810			11.00	30	330.00	47463	108524.80	96.960	81.778
1.35	90			11.20	50	560.00	47513	109084.80	97.062	82.200
1.35	10			11.25	16	180.00	47529	109264.80	97.095	82.336
1.35	2	1.35	912	11.55	29	334.95	47558	109599.75	97.154	82.588
1.40	900			11.70	53	620.10	47611	110219.85	97.263	83.055
1.40	144			12.00	108	1296.00	47719	111515.85	97.483	84.032
1.40	10			12.15	18	218.70	47737	111734.55	97.520	84.197
1.40	5	1.40	1059	12.25	8	98.00	47745	111832.55	97.536	84.271
1.50	540			12.50	6	75.00	47751	111907.55	97.549	84.327
1.50	90			12.60	114	1436.40	47865	113343.95	97.781	85.410
1.50	405			12.80	18	230.40	47883	113574.35	97.818	85.583
1.50	72			13.00	30	390.00	47913	113964.35	97.880	85.877
1.50	324			13.20	72	950.40	47985	114914.75	98.027	86.593
1.50	20			13.50	67	904.50	48052	115819.25	98.163	87.275
1.50	50			13.65	29	395.85	48081	116215.10	98.223	87.573
1.50	5			13.75	6	82.50	48087	116297.60	98.235	87.635
1.50	54			14.00	58	812.00	48145	117109.60	98.353	88.247
1.50	30			14.40	66	950.40	48211	118060.00	98.488	88.963
1.50	3			14.70	4	58.80	48215	118118.80	98.496	89.008
1.50	4	1.50	1597	14.85	9	133.65	48224	118252.45	98.515	89.108
1.60	450			15.00	22	330.00	48246	118582.45	98.560	89.357
1.60	180			15.40	40	616.00	48286	119198.45	98.641	89.821
1.60	72			15.60	72	1123.20	48358	120321.65	98.789	90.668
1.60	360			15.75	36	567.00	48394	120888.65	98.862	91.095
1.60	90			16.00	24	384.00	48418	121272.65	98.911	91.384
1.60	72			16.20	38	615.60	48456	121888.25	98.989	91.848
1.60	225			16.25	6	97.50	48462	121985.75	99.001	91.922
1.60	9	1.60	1458	16.50	22	363.00	48484	122348.75	99.046	92.195
1.65	405			16.80	16	268.80	48500	122617.55	99.079	92.398
1.65	5	1.65	410	17.50	14	245.00	48514	122862.55	99.107	92.582
1.75	360			17.55	9	157.95	48523	123020.50	99.126	92.701
1.75	2	1.75	362	17.60	18	316.80	48541	123337.30	99.162	92.940
1.80	270			18.00	34	612.00	48575	123949.30	99.232	93.401
1.80	360			18.20	40	728.00	48615	124677.30	99.314	93.950
1.80	216			18.90	32	604.80	48647	125282.10	99.379	94.406
1.80	162			19.20	4	76.80	48651	125358.90	99.387	94.463
1.80	180			19.25	14	269.50	48665	125628.40	99.416	94.666
1.80	60			19.50	22	429.00	48687	126057.40	99.461	94.990
1.80	40			19.60	4	78.40	48691	126135.80	99.469	95.049
1.80	225			19.60	16	313.60	48707	126449.40	99.502	95.285
1.80	25			20.00	6	120.00	48713	126569.40	99.514	95.376
1.80	162			20.25	4	81.00	48717	126650.40	99.522	95.437
1.80	18			20.80	18	374.40	48735	127024.80	99.559	95.719
1.80	36			21.00	14	294.00	48749	127318.80	99.587	95.940
1.80	20			21.60	16	345.60	48765	127664.40	99.620	96.201
1.80	2			22.00	6	132.00	48771	127796.40	99.632	96.300
1.80	10			22.05	8	176.40	48779	127972.80	99.649	96.433
1.80	5	1.80	1791	22.40	2	44.80	48781	128017.60	99.653	96.467
1.95	405			22.50	2	45.00	48783	128062.60	99.657	96.501
1.95	5	1.95	410	22.75	14	318.50	48797	128381.10	99.685	96.741
2.00	180			23.10	14	323.40	48811	128704.50	99.714	96.984
2.00	90			23.40	16	374.40	48827	129078.90	99.747	97.267
2.00	180			24.00	4	96.00	48831	129174.90	99.755	97.339
2.00	180			24.30	12	291.60	48843	129466.50	99.779	97.559
2.00	144			24.50	4	98.00	48847	129564.50	99.788	97.633
2.00	90			24.75	2	49.50	48849	129614.00	99.792	97.670
2.00	36			25.20	8	201.60	48857	129815.60	99.808	97.822
2.00	90			26.00	6	156.00	48863	129971.60	99.820	97.939
2.00	9			26.40	4	105.60	48867	130077.20	99.828	98.019
2.00	24			26.95	4	107.80	48871	130185.00	99.837	98.100
2.00	75			27.00	6	162.00	48877	130347.00	99.849	98.222
2.00	3	2.00	1101	27.30	14	382.20	48891	130729.20	99.877	98.510
2.10	180			28.00	2	56.00	48893	130785.20	99.882	98.552
2.10	144			28.35	8	226.80	48901	131012.00	99.898	98.723
2.10	40			28.80	2	57.60	48903	131069.60	99.902	98.767
2.10	18			29.25	2	58.50	48905	131128.10	99.906	98.811
2.10	10			29.70	6	178.20	48911	131306.30	99.918	98.945
2.10	1	2.10	393	30.80	2	61.60	48913	131367.90	99.922	98.991
2.20	180			31.20	4	124.80	48917	131492.70	99.931	99.085
2.20	90			31.50	4	126.00	48921	131618.70	99.939	99.180

2.20	9	2.20	279	31.85	4	127.40	48925	131746.10	99.947	99.276
2.25	180			32.40	4	129.60	48929	131875.70	99.955	99.374
2.25	20			34.65	4	138.60	48933	132014.30	99.963	99.479
2.25	90			35.10	6	210.60	48939	132224.90	99.975	99.637
2.25	54			36.00	2	72.00	48941	132296.90	99.980	99.691
2.25	6			36.40	2	72.80	48943	132369.70	99.984	99.746
2.25	2	2.25	352	39.60	2	79.20	48945	132448.90	99.988	99.806
2.40	90			40.95	4	163.80	48949	132612.70	99.996	99.929
2.40	270			46.80	2	93.60	48951	132706.30	100.000	100.000
2.40	72									
2.40	540									
2.40	72									
2.40	162									
2.40	20									
2.40	100									
2.40	25									
2.40	108									
2.40	72									
2.40	405									
2.40	45									
2.40	16									
2.40	50									
2.40	2	2.40	2049							
2.50	90									
2.50	72									
2.50	12									
2.50	30									
2.50	3	2.50	207							
2.60	180									
2.60	90									
2.60	9	2.60	279							
2.70	540									
2.70	324									
2.70	60									
2.70	45									
2.70	50									
2.70	36									
2.70	4									
2.70	18									
2.70	10									
2.70	1	2.70	1088							
2.75	90									
2.75	3	2.75	93							
2.80	180									
2.80	360									
2.80	72									
2.80	8									
2.80	25									
2.80	1	2.80	646							
3.00	270									
3.00	216									
3.00	36									
3.00	162									
3.00	50									
3.00	40									
3.00	25									
3.00	36									
3.00	162									
3.00	36									
3.00	24									
3.00	135									
3.00	15									
3.00	8									
3.00	20									
3.00	2	3.00	1237							
3.15	360									
3.15	40									
3.15	18									
3.15	2	3.15	420							
3.20	90									
3.20	180									
3.20	72									
3.20	36									
3.20	180									
3.20	45	3.20	603							
3.25	90									
3.25	3	3.25	93							
3.30	270									
3.30	162									
3.30	25									
3.30	2	3.30	459							
3.50	180									
3.50	144									
3.50	24									
3.50	4									
3.50	10									
3.50	1	3.50	363							
3.60	180									
3.60	108									
3.60	144									
3.60	20									
3.60	150									
3.60	20									
3.60	45									
3.60	108									

3.60	81		
3.60	90		
3.60	24		
3.60	16		
3.60	90		
3.60	10		
3.60	8		
3.60	25		
3.60	1	3.60	1120
3.75	20		
3.75	12		
3.75	54	3.75	86
3.85	180		
3.85	1	3.85	181
3.90	270		
3.90	162		
3.90	25		
3.90	2	3.90	459
4.00	90		
4.00	72		
4.00	36		
4.00	72		
4.00	90		
4.00	72		
4.00	45		
4.00	12		
4.00	60		
4.00	15	4.00	564
4.05	90		
4.05	18		
4.05	2	4.05	110
4.20	72		
4.20	100		
4.20	72		
4.20	16		
4.20	12		
4.20	8		
4.20	45		
4.20	5	4.20	330
4.40	90		
4.40	72		
4.40	45	4.40	207
4.50	72		
4.50	60		
4.50	10		
4.50	45		
4.50	36		
4.50	27		
4.50	30		
4.50	8		
4.50	36		
4.50	4		
4.50	10		
4.50	1	4.50	339
4.55	180		
4.55	1	4.55	181
4.80	36		
4.80	108		
4.80	50		
4.80	20		
4.80	36		
4.80	270		
4.80	36		
4.80	81		
4.80	8		
4.80	40		
4.80	10	4.80	695
4.90	8	4.90	8
4.95	45		
4.95	1	4.95	46
5.00	36		
5.00	36		
5.00	30		
5.00	24		
5.00	15	5.00	141
5.20	90		
5.20	72		
5.20	45	5.20	207
5.25	40		
5.25	24		
5.25	4		
5.25	18	5.25	86
5.40	216		
5.40	30		
5.40	40		
5.40	162		
5.40	24		
5.40	18		
5.40	20		
5.40	12		
5.40	8		
5.40	45		
5.40	5	5.40	580
5.50	36		
5.50	15	5.50	51

5.60	72		
5.60	180		
5.60	4		
5.60	20		
5.60	5	5.60	281
5.85	45		
5.85	1	5.85	46
6.00	108		
6.00	20		
6.00	10		
6.00	20		
6.00	108		
6.00	18		
6.00	81		
6.00	12		
6.00	90		
6.00	12		
6.00	27		
6.00	20		
6.00	16		
6.00	10	6.00	552
6.25	12	6.25	12
6.30	144		
6.30	20		
6.30	16		
6.30	12		
6.30	9		
6.30	10		
6.30	8	6.30	219
6.40	36		
6.40	90		
6.40	36	6.40	162
6.50	36		
6.50	15	6.50	51
6.60	108		
6.60	20		
6.60	81		
6.60	10	6.60	219
6.75	20		
6.75	54		
6.75	4		
6.75	18	6.75	96
7.00	72		
7.00	72		
7.00	60		
7.00	10		
7.00	8		
7.00	5	7.00	227
7.20	72		
7.20	10		
7.20	30		
7.20	54		
7.20	72		
7.20	8		
7.20	60		
7.20	8		
7.20	18		
7.20	4		
7.20	20		
7.20	5	7.20	361
7.35	8	7.35	8
7.50	10		
7.50	36		
7.50	6		
7.50	27		
7.50	8	7.50	87
7.70	72		
7.70	5	7.70	77
7.80	108		
7.80	20		
7.80	81		
7.80	10	7.80	219
8.00	36		
8.00	36		
8.00	18		
8.00	36		
8.00	30		
8.00	12	8.00	168
8.10	60		
8.10	36		
8.10	12		
8.10	9		
8.10	10	8.10	127
8.25	10		
8.25	27	8.25	37
8.40	20		
8.40	36		
8.40	40		
8.40	4		
8.40	30		
8.40	4		
8.40	9	8.40	143
8.75	24		
8.75	4	8.75	28
8.80	36		

8.80	36	8.80	72
9.00	30		
9.00	36		
9.00	18		
9.00	24		
9.00	24		
9.00	4		
9.00	18		
9.00	10		
9.00	8		
9.00	5	9.00	177
9.10	72		
9.10	5	9.10	77
9.45	40		
9.45	18		
9.45	8	9.45	66
9.60	10		
9.60	18		
9.60	54		
9.60	20		
9.60	8	9.60	110
9.75	10		
9.75	27	9.75	37
9.80	20	9.80	20
9.90	30		
9.90	18		
9.90	5	9.90	53
10.00	18		
10.00	12		
10.00	6		
10.00	12	10.00	48
10.40	36		
10.40	36	10.40	72
10.50	20		
10.50	12		
10.50	16		
10.50	12		
10.50	2		
10.50	9	10.50	71
10.80	20		
10.80	108		
10.80	12		
10.80	16		
10.80	4		
10.80	30		
10.80	4		
10.80	9	10.80	203
11.00	18		
11.00	12	11.00	30
11.20	36		
11.20	10		
11.20	4	11.20	50
11.25	12		
11.25	4	11.25	16
11.55	20		
11.55	9	11.55	29
11.70	30		
11.70	18		
11.70	5	11.70	53
12.00	10		
12.00	54		
12.00	6		
12.00	18		
12.00	8		
12.00	4		
12.00	8	12.00	108
12.15	18	12.15	18
12.25	8	12.25	8
12.50	6	12.50	6
12.60	72		
12.60	8		
12.60	6		
12.60	8		
12.60	20	12.60	114
12.80	18	12.80	18
13.00	18		
13.00	12	13.00	30
13.20	10		
13.20	54		
13.20	8	13.20	72
13.50	36		
13.50	8		
13.50	12		
13.50	2		
13.50	9	13.50	67
13.65	20		
13.65	9	13.65	29
13.75	6	13.75	6
14.00	36		
14.00	12		
14.00	4		
14.00	2		
14.00	4	14.00	58
14.40	36		
14.40	4		

14.40	12		
14.40	10		
14.40	4	14.40	66
14.70	4	14.70	4
14.85	9	14.85	9
15.00	18		
15.00	4	15.00	22
15.40	36		
15.40	4	15.40	40
15.60	10		
15.60	54		
15.60	8	15.60	72
15.75	24		
15.75	4		
15.75	8	15.75	36
16.00	18		
16.00	6	16.00	24
16.20	24		
16.20	6		
16.20	8	16.20	38
16.25	6	16.25	6
16.50	18		
16.50	4	16.50	22
16.80	8		
16.80	2		
16.80	6	16.80	16
17.50	12		
17.50	2	17.50	14
17.55	9	17.55	9
17.60	18	17.60	18
18.00	12		
18.00	12		
18.00	4		
18.00	2		
18.00	4	18.00	34
18.20	36		
18.20	4	18.20	40
18.90	16		
18.90	12		
18.90	4	18.90	32
19.20	4	19.20	4
19.25	12		
19.25	2	19.25	14
19.50	18		
19.50	4	19.50	22
19.60	4	19.60	4
19.80	12		
19.80	4	19.60	16
20.00	6	20.00	6
20.25	4	20.25	4
20.80	18	20.80	18
21.00	8		
21.00	6	21.00	14
21.60	8		
21.60	2		
21.60	6	21.60	16
22.00	6	22.00	6
22.05	8	22.05	8
22.40	2	22.40	2
22.50	2	22.50	2
22.75	12		
22.75	2	22.75	14
23.10	8		
23.10	6	23.10	14
23.40	12		
23.40	4	23.40	16
24.00	4	24.00	4
24.30	12	24.30	12
24.50	4	24.50	4
24.75	2	24.75	2
25.20	4		
25.20	4	25.20	8
26.00	6	26.00	6
26.40	4	26.40	4
26.95	4	26.95	4
27.00	6	27.00	6
27.30	8		
27.30	6	27.30	14
28.00	2	28.00	2
28.35	8	28.35	8
28.80	2	28.80	2
29.25	2	29.25	2
29.70	6	29.70	6
30.80	2	30.80	2
31.20	4	31.20	4
31.50	4	31.50	4
31.85	4	31.85	4
32.40	4	32.40	4
34.65	4	34.65	4
35.10	6	35.10	6
36.00	2	36.00	2
36.40	2	36.40	2
39.60	2	39.60	2
40.95	4	40.95	4
46.80	2	46.80	2

Table AII.4: Block size calculation data analysis of Microgranite in site2

1 SORTED BLOCK SIZE (m^3)
2 SORTED BLOCK NUMBERS
3 CORRECTED BLOCK SIZE (m^3)
4 CORRECTED BLOCK NUMBERS
5 SORTED AND CORRECTED BLOCK SIZE (m^3)
6 SORTED AND CORRECTED BLOCKNUMBERS FOR EACH SIZE
7 TOTAL VOLUME FOR EACH BLOCK SIZE (m^3)
8 CUMULATIVE BLOCK NUMBERS
9 CUMULATIVE BLOCK VOLUMES
10 CUMULATIVE BLOCK NUMBERS PRECTENTAGE
11 CUMULATIVE BLOCK VOLUME PRECTENTAGE

1	2	3	4	5	6	7	8	9	10	11
0.0005	12	0.00050	12	0.00050	12	0.00600	12	0.00600	0.0537	0.0021
0.0006	24	0.00060	24	0.00060	24	0.01440	36	0.02040	0.1612	0.0070
0.0007	28	0.00075	28	0.00075	28	0.02100	64	0.04140	0.2866	0.0143
0.0009	56	0.00090	56	0.00090	56	0.05040	120	0.09180	0.5374	0.0316
0.0010	24			0.00100	39	0.03900	159	0.13080	0.7120	0.0450
0.0010	15	0.00100	39	0.00110	180	0.19800	339	0.32880	1.5181	0.1132
0.0011	180	0.00110	180	0.00120	78	0.09360	417	0.42240	1.8674	0.1454
0.0012	48			0.00125	8	0.01000	425	0.43240	1.9033	0.1489
0.0012	30	0.00120	78	0.00150	96	0.14400	521	0.57640	2.3332	0.1985
0.0012	8	0.00125	8	0.00160	60	0.09600	581	0.67240	2.6019	0.2315
0.0015	12			0.00165	420	0.69300	1001	1.36540	4.4828	0.4701
0.0015	16			0.00170	12	0.02040	1013	1.38580	4.5365	0.4772
0.0015	35			0.00180	160	0.28800	1173	1.67380	5.2530	0.5763
0.0015	33	0.00150	96	0.00200	33	0.06600	1206	1.73980	5.4008	0.5991
0.0016	60	0.00160	60	0.00210	60	0.12600	1266	1.86580	5.6695	0.6425
0.0016	420	0.00165	420	0.00220	585	1.28700	1851	3.15280	8.2893	1.0856
0.0017	12	0.00170	12	0.00225	77	0.17325	1928	3.32605	8.6341	1.1453
0.0018	24			0.00240	206	0.49440	2134	3.82045	9.5567	1.3155
0.0018	70			0.00250	29	0.07250	2163	3.89295	9.6865	1.3405
0.0018	66	0.00180	160	0.00255	28	0.07140	2191	3.96435	9.8119	1.3650
0.0020	30			0.00270	154	0.41580	2345	4.38015	10.5016	1.5082
0.0020	3	0.00200	33	0.00275	120	0.33000	2465	4.71015	11.0390	1.6219
0.0021	60	0.00210	60	0.00300	152	0.45600	2617	5.16615	11.7197	1.7789
0.0022	360			0.00315	140	0.44100	2757	5.60715	12.3466	1.9307
0.0022	225	0.00220	585	0.00320	195	0.62400	2952	6.23115	13.2199	2.1456
0.0023	77	0.00225	77	0.00330	1200	3.96000	4152	10.19115	18.5938	3.5091
0.0024	140			0.00340	39	0.13260	4191	10.32375	18.7685	3.5548
0.0024	60			0.00350	6	0.02100	4197	10.34475	18.7953	3.5620
0.0024	6	0.00240	206	0.00360	188	0.67680	4385	11.02155	19.6373	3.7951
0.0025	4			0.00375	57	0.21375	4442	11.23530	19.8925	3.8687
0.0025	10			0.00400	46	0.18400	4488	11.41930	20.0985	3.9320
0.0025	15	0.00250	29	0.00420	207	0.86940	4695	12.28870	21.0255	4.2314
0.0026	28	0.00255	28	0.00425	8	0.03400	4703	12.32270	21.0614	4.2431
0.0027	154	0.00270	154	0.00440	495	2.17800	5198	14.50070	23.2781	4.9930
0.0028	120	0.00275	120	0.00450	167	0.75150	5365	15.25220	24.0260	5.2518
0.0030	8			0.00480	412	1.97760	5777	17.22980	25.8710	5.9328
0.0030	15			0.00495	1160	5.74200	6937	22.97180	31.0658	7.9099
0.0030	20			0.00500	37	0.18500	6974	23.15680	31.2315	7.9736
0.0030	66			0.00510	80	0.40800	7054	23.56480	31.5898	8.1141
0.0030	7			0.00525	54	0.28350	7108	23.84830	31.8316	8.2117
0.0030	30			0.00540	106	0.57240	7214	24.42070	32.3063	8.4088
0.0030	6	0.00300	152	0.00550	438	2.40900	7652	26.82970	34.2678	9.2383
0.0031	140	0.00315	140	0.00600	89	0.53400	7741	27.36370	34.6664	9.4222
0.0032	120			0.00625	10	0.06250	7751	27.42620	34.7112	9.4437
0.0032	75	0.00320	195	0.00630	428	2.69640	8179	30.12260	36.6279	10.3722
0.0033	180			0.00640	165	1.05600	8344	31.17860	37.3668	10.7358
0.0033	525			0.00660	1416	9.34560	9760	40.52420	43.7080	13.9537
0.0033	495	0.00330	1200	0.00675	14	0.09450	9774	40.61870	43.7707	13.9863
0.0034	24			0.00680	33	0.22440	9807	40.84310	43.9185	14.0636
0.0034	15	0.00340	39	0.00700	12	0.08400	9819	40.92710	43.9722	14.0925
0.0035	6	0.00350	6	0.00720	415	2.98800	10234	43.91510	45.8307	15.1213
0.0036	30			0.00750	50	0.37500	10284	44.29010	46.0546	15.2505
0.0036	132			0.00765	77	0.58905	10361	44.87915	46.3995	15.4533
0.0036	14			0.00770	90	0.69300	10451	45.57215	46.8025	15.6919
0.0036	12	0.00360	188	0.00800	145	1.16000	10596	46.73215	47.4519	16.0913
0.0037	22			0.00810	28	0.22680	10624	46.95895	47.5773	16.1694
0.0037	35	0.00375	57	0.00825	862	7.11150	11486	54.07045	51.4375	18.6181
0.0040	40			0.00840	189	1.58760	11675	55.65805	52.2839	19.1648
0.0040	6	0.00400	46	0.00850	32	0.27200	11707	55.93005	52.4272	19.2585
0.0042	120			0.00875	4	0.03500	11711	55.96505	52.4451	19.2705
0.0042	75			0.00880	90	0.79200	11801	56.75705	52.8482	19.5432
0.0042	12	0.00420	207	0.00900	78	0.70200	11879	57.45905	53.1975	19.7849
0.0042	8	0.00425	8	0.00945	385	3.63825	12264	61.09730	54.9216	21.0377
0.0044	450			0.00960	470	4.51200	12734	65.60930	57.0264	22.5913
0.0044	45	0.00440	495	0.00990	809	8.00910	13543	73.61840	60.6494	25.3491
0.0045	33			0.01000	1	0.01000	13544	73.62840	60.6538	25.3526
0.0045	44			0.01020	100	1.02000	13644	74.64840	61.1017	25.7038
0.0045	70			0.01050	159	1.66950	13803	76.31790	61.8137	26.2786

0.0045	14			0.01080	36	0.38880	13839	76.70670	61.9749	26.4125
0.0045	6	0.00450	167	0.01100	564	6.20400	14403	82.91070	64.5007	28.5487
0.0048	60			0.01120	30	0.33600	14433	83.24670	64.6350	28.6644
0.0048	175			0.01130	4	0.04520	14437	83.29190	64.6529	28.6800
0.0048	165			0.01160	210	2.43600	14647	85.72790	65.5934	29.5188
0.0048	12	0.00480	412	0.01190	6	0.07140	14653	85.79930	65.6202	29.5434
0.0050	1160	0.00495	1160	0.01200	287	3.44400	14940	89.24330	66.9055	30.7293
0.0050	5			0.01210	45	0.54450	14985	89.78780	67.1070	30.9167
0.0050	2			0.01250	5	0.06250	14990	89.85030	67.1294	30.9383
0.0050	30	0.00500	37	0.01260	482	6.07320	15472	95.92350	69.2880	33.0295
0.0051	12			0.01280	94	1.20320	15566	97.12670	69.7089	33.4438
0.0051	35			0.01320	243	3.20760	15809	100.33430	70.7971	34.5482
0.0051	33	0.00510	80	0.01350	14	0.18900	15823	100.52330	70.8598	34.6133
0.0053	40			0.01360	6	0.08160	15829	100.60490	70.8867	34.6414
0.0053	14	0.00525	54	0.01380	152	2.09760	15981	102.70250	71.5674	35.3637
0.0054	66			0.01440	265	3.81600	16246	106.51850	72.7541	36.6777
0.0054	28			0.01470	30	0.44100	16276	106.95950	72.8885	36.8295
0.0054	12	0.00540	106	0.01490	210	3.12900	16486	110.08850	73.8289	37.9069
0.0055	60			0.01500	12	0.18000	16498	110.26850	73.8827	37.9689
0.0055	150			0.01530	67	1.02510	16565	111.29360	74.1827	38.3219
0.0055	225			0.01540	180	2.77200	16745	114.06560	74.9888	39.2764
0.0055	3	0.00550	438	0.01580	285	4.50300	17030	118.56860	76.2651	40.8269
0.0060	10			0.01600	185	2.96000	17215	121.52860	77.0936	41.8461
0.0060	3			0.01620	12	0.19440	17227	121.72300	77.1473	41.9130
0.0060	4			0.01650	464	7.65600	17691	129.37900	79.2253	44.5492
0.0060	60			0.01680	100	1.68000	17791	131.05900	79.6731	45.1277
0.0060	12	0.00600	89	0.01700	43	0.73100	17834	131.79000	79.8657	45.3794
0.0063	10	0.00625	10	0.01750	2	0.03500	17836	131.82500	79.8746	45.3915
0.0063	60			0.01760	15	0.26400	17851	132.08900	79.9418	45.4824
0.0063	175			0.01790	14	0.25060	17865	132.33960	80.0045	45.5687
0.0063	165			0.01800	4	0.07200	17869	132.41160	80.0224	45.5935
0.0063	28	0.00630	428	0.01800	105	1.89000	17974	134.30160	80.4926	46.2442
0.0064	150			0.01870	48	0.89760	18022	135.19920	80.7076	46.5533
0.0064	15	0.00640	165	0.01890	265	5.00850	18287	140.20770	81.8943	48.2779
0.0066	225			0.01920	75	1.44000	18362	141.64770	82.2302	48.7737
0.0066	990			0.01930	60	1.15800	18422	142.80570	82.4989	49.1725
0.0066	105			0.01980	290	5.74200	18712	148.54770	83.7976	51.1496
0.0066	90			0.02000	50	1.00000	18762	149.54770	84.0215	51.4940
0.0066	6	0.00660	1416	0.02040	27	0.55080	18789	150.09850	84.1424	51.6836
0.0067	14	0.00675	14	0.02100	189	3.96900	18978	154.06750	84.9888	53.0503
0.0068	30			0.02130	12	0.25560	18990	154.32310	85.0425	53.1383
0.0068	3	0.00680	33	0.02160	70	1.51200	19060	155.83510	85.3560	53.6589
0.0070	12	0.00700	12	0.02200	22	0.48400	19082	156.31910	85.4545	53.8256
0.0072	385			0.02210	70	1.54700	19152	157.86610	85.7680	54.3582
0.0072	6			0.02240	60	1.34400	19212	159.21010	86.0367	54.8210
0.0072	24	0.00720	415	0.02250	2	0.04500	19214	159.25510	86.0457	54.8365
0.0075	11			0.02300	14	0.32200	19228	159.57710	86.1084	54.9474
0.0075	15			0.02310	105	2.42550	19333	162.00260	86.5786	55.7826
0.0075	20			0.02380	12	0.28560	19345	162.28820	86.6323	55.8809
0.0075	4	0.00750	50	0.02400	150	3.60000	19495	165.88820	87.3041	57.1205
0.0076	77	0.00765	77	0.02420	135	3.26700	19630	169.15520	87.9086	58.2454
0.0077	90	0.00770	90	0.02480	60	1.48800	19690	170.64320	88.1773	58.7578
0.0080	20			0.02520	75	1.89000	19765	172.53320	88.5132	59.4086
0.0080	50			0.02550	37	0.94350	19802	173.47670	88.6789	59.7335
0.0080	75	0.00800	145	0.02640	50	1.32000	19852	174.79670	88.9028	60.1880
0.0081	28	0.00810	28	0.02640	47	1.24080	19899	176.03750	89.1133	60.6152
0.0082	330			0.02700	4	0.10800	19903	176.14550	89.1312	60.6524
0.0082	525			0.02720	15	0.40800	19918	176.55350	89.1984	60.7929
0.0082	7	0.00825	862	0.02750	78	2.14500	19996	178.69850	89.5477	61.5315
0.0084	150			0.02800	20	0.56000	20016	179.25850	89.6373	61.7243
0.0084	15			0.02810	112	3.14720	20128	182.40570	90.1388	62.8080
0.0084	24	0.00840	189	0.02840	70	1.98800	20198	184.39370	90.4523	63.4925
0.0085	4			0.02880	90	2.59200	20288	186.98570	90.8554	64.3850
0.0085	10			0.02890	3	0.08670	20291	187.07240	90.8688	64.4149
0.0085	15			0.02940	60	1.76400	20351	188.83640	91.1375	65.0223
0.0085	3	0.00850	32	0.02970	90	2.67300	20441	191.50940	91.5405	65.9427
0.0088	4	0.00875	4	0.02980	4	0.11920	20445	191.62860	91.5584	65.9837
0.0088	90	0.00880	90	0.03030	30	0.90900	20475	192.53760	91.6928	66.2967
0.0090	22			0.03060	24	0.73440	20499	193.27200	91.8003	66.5496
0.0090	30			0.03150	150	4.72500	20649	197.99700	92.4720	68.1766
0.0090	6			0.03200	5	0.16000	20654	198.15700	92.4944	68.2317
0.0090	8			0.03300	39	1.28700	20693	199.44400	92.6691	68.6748
0.0090	12	0.00900	78	0.03360	30	1.00800	20723	200.45200	92.8034	69.0219
0.0094	385	0.00945	385	0.03400	1	0.03400	20724	200.48600	92.8079	69.0336
0.0096	75			0.03470	35	1.21450	20759	201.70050	92.9646	69.4518
0.0096	330			0.03520	45	1.58400	20804	203.28450	93.1661	69.9972
0.0096	35			0.03570	15	0.53550	20819	203.82000	93.2333	70.1816
0.0096	30	0.00960	470	0.03600	20	0.72000	20839	204.54000	93.3229	70.4295
0.0099	495			0.03630	150	5.44500	20989	209.98500	93.9946	72.3044
0.0099	210			0.03680	20	0.73600	21009	210.72100	94.0842	72.5578
0.0099	90			0.03740	99	3.70260	21108	214.42360	94.5275	73.8328
0.0099	14	0.00990	809	0.03780	90	3.40200	21198	217.82560	94.9306	75.0042
0.0100	1	0.01000	1	0.03830	4	0.15320	21202	217.97880	94.9485	75.0569
0.0102	15			0.03850	30	1.15500	21232	219.13380	95.0828	75.4546
0.0102	66			0.03960	6	0.23760	21238	219.37140	95.1097	75.5364
0.0102	7			0.04000	25	1.00000	21263	220.37140	95.2217	75.8808
0.0102	6			0.04080	35	1.42800	21298	221.79940	95.3784	76.3725
0.0102	6	0.01020	100	0.04200	5	0.21000	21303	222.00940	95.4008	76.4448
0.0105	20			0.04250	6	0.25500	21309	222.26440	95.4277	76.5326
0.0105	50			0.04320	30	1.29600	21339	223.56040	95.5620	76.9788
0.0105	75			0.04340	7	0.30380	21346	223.86420	95.5934	77.0834
0.0105	6			0.04400	10	0.44000	21356	224.30420	95.6382	77.2350
0.0105	8	0.01050	159	0.04410	30	1.32300	21386	225.62720	95.7725	77.6905
0.0108	12			0.04590	6	0.27540	21392	225.90260	95.7994	77.7853
0.0108	24	0.01080	36	0.04620	45	2.07900	21437	227.98160	96.0009	78.5012

0.0110	75		
0.0110	30		
0.0110	450		
0.0110	6		
0.0110	3	0.01100	564
0.0112	30	0.01120	30
0.0113	4	0.01130	4
0.0116	210	0.01160	210
0.0119	6	0.01190	6
0.0120	110		
0.0120	2		
0.0120	175	0.01200	287
0.0121	45	0.01210	45
0.0125	5	0.01250	5
0.0126	75		
0.0126	330		
0.0126	35		
0.0126	30		
0.0126	12	0.01260	482
0.0128	22		
0.0128	30		
0.0128	35		
0.0128	7	0.01280	94
0.0132	45		
0.0132	180		
0.0132	12		
0.0132	6	0.01320	243
0.0135	6		
0.0135	8	0.01350	14
0.0136	6	0.01360	6
0.0138	150		
0.0138	2	0.01380	152
0.0144	165		
0.0144	70		
0.0144	30	0.01440	265
0.0147	30	0.01470	30
0.0149	210	0.01490	210
0.0150	10		
0.0150	2	0.01500	12
0.0153	33		
0.0153	14		
0.0153	6		
0.0153	14	0.01530	67
0.0154	180	0.01540	180
0.0158	110		
0.0158	175	0.01580	285
0.0160	25		
0.0160	10		
0.0160	150	0.01600	185
0.0162	12	0.01620	12
0.0165	165		
0.0165	225		
0.0165	60		
0.0165	3		
0.0165	4		
0.0165	7	0.01650	464
0.0168	30		
0.0168	70	0.01680	100
0.0170	5		
0.0170	2		
0.0170	30		
0.0170	6	0.01700	43
0.0175	2	0.01750	2
0.0176	15	0.01760	15
0.0179	14	0.01790	14
0.0180	4	0.01800	4
0.0182	105	0.01800	105
0.0187	3		
0.0187	45	0.01870	48
0.0189	165		
0.0189	70		
0.0189	30	0.01890	265
0.0192	15		
0.0192	60	0.01920	75
0.0193	60	0.01930	60
0.0198	90		
0.0198	180		
0.0198	6		
0.0198	14	0.01980	290
0.0200	50	0.02000	50
0.0204	3		
0.0204	12		
0.0204	12	0.02040	27
0.0210	25		
0.0210	10		
0.0210	150		
0.0210	4	0.02100	189
0.0213	10		
0.0213	2	0.02130	12
0.0216	70	0.02160	70
0.0220	15		
0.0220	6	0.02200	22
0.0221	70	0.02210	70
0.0224	60	0.02240	60
0.0225	2	0.02250	2

0.04680	32	1.49760	21469	229.47920	96.1442	79.0169
0.04730	20	0.94600	21489	230.42520	96.2338	79.3426
0.04800	10	0.48000	21499	230.90520	96.2785	79.5079
0.04840	90	4.35600	21589	235.26120	96.6816	81.0078
0.04950	30	1.48500	21619	236.74620	96.8159	81.5191
0.05100	4	0.20400	21623	236.95020	96.8339	81.5894
0.05250	25	1.31250	21648	238.26270	96.9458	82.0413
0.05280	50	2.64000	21698	240.90270	97.1697	82.9503
0.05360	35	1.87600	21733	242.77870	97.3265	83.5963
0.05440	30	1.63200	21763	244.41070	97.4608	84.1582
0.05500	1	0.05500	21764	244.46570	97.4653	84.1772
0.05600	10	0.56000	21774	245.02570	97.5101	84.3700
0.05610	55	3.08550	21829	248.11120	97.7564	85.4324
0.05670	30	1.70100	21859	249.81220	97.8907	86.0182
0.05780	16	0.92480	21875	250.73700	97.9624	86.3366
0.05950	2	0.11900	21877	250.85600	97.9713	86.3776
0.06050	45	2.72250	21922	253.57850	98.1729	87.3150
0.06300	10	0.63000	21932	254.20850	98.2176	87.5319
0.06600	2	0.13200	21934	254.34050	98.2266	87.5774
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0.06930	50	3.46500	21994	258.48550	98.4953	89.0046
0.07040	30	2.11200	22024	260.59750	98.6296	89.7319
0.07140	30	2.14200	22054	262.73950	98.7640	90.4694
0.07200	10	0.72000	22064	263.45950	98.8088	90.7173
0.07230	2	0.14460	22066	263.60410	98.8177	90.7671
0.07260	45	3.26700	22111	266.87110	99.0193	91.8921
0.07350	10	0.73500	22121	267.60610	99.0640	92.1451
0.07480	6	0.44880	22127	268.05490	99.0909	92.2997
0.07650	2	0.15300	22129	268.20790	99.0999	92.3524
0.08160	15	1.22400	22144	269.43190	99.1670	92.7738
0.08670	3	0.26010	22147	269.69200	99.1805	92.8634
0.08800	15	1.32000	22162	271.01200	99.2476	93.3179
0.08930	10	0.89300	22172	271.90500	99.2924	93.6254
0.09240	30	2.77200	22202	274.67700	99.4268	94.5799
0.09350	18	1.68300	22220	276.36000	99.5074	95.1594
0.09450	10	0.94500	22230	277.30500	99.5522	95.4848
0.10600	15	1.59000	22245	278.89500	99.6193	96.0323
0.10700	15	1.60500	22260	280.50000	99.6865	96.5849
0.11200	3	0.33600	22263	280.83600	99.7000	96.7006
0.11600	15	1.74000	22278	282.57600	99.7671	97.2998
0.12100	15	1.81500	22293	284.39100	99.8343	97.9247
0.13600	5	0.68000	22298	285.07100	99.8567	98.1589
0.13900	15	2.08500	22313	287.15600	99.9239	98.8768
0.14500	1	0.14500	22314	287.30100	99.9283	98.9267
0.17600	5	0.88000	22319	288.18100	99.9507	99.2297
0.17900	5	0.89500	22324	289.07600	99.9731	99.5379
0.18700	1	0.18700	22325	289.26300	99.9776	99.6023
0.23100	5	1.15500	22330	290.41800	100.0000	100.0000

0.0230	14	0.02300	14
0.0231	90		
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0.0238	12	0.02380	12
0.0240	55		
0.0240	75		
0.0240	20	0.02400	150
0.0242	90		
0.0242	45	0.02420	135
0.0248	60	0.02480	60
0.0252	15		
0.0252	60	0.02520	75
0.0255	11		
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0.0255	4		
0.0255	3		
0.0255	4	0.02550	37
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0.0264	35		
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0.0270	4	0.02700	4
0.0272	15	0.02720	15
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0.0275	1		
0.0275	2	0.02750	78
0.0280	20	0.02800	20
0.0281	7		
0.0281	105	0.02810	112
0.0284	70	0.02840	70
0.0288	30		
0.0288	60	0.02880	90
0.0289	3	0.02890	3
0.0294	60	0.02940	60
0.0297	90	0.02970	90
0.0298	4	0.02980	4
0.0303	30	0.03030	30
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0.0306	12		
0.0306	6	0.03060	24
0.0315	55		
0.0315	75		
0.0315	20	0.03150	150
0.0320	5	0.03200	5
0.0330	30		
0.0330	2		
0.0330	3		
0.0330	4	0.03300	39
0.0336	30	0.03360	30
0.0340	1	0.03400	1
0.0347	35	0.03470	35
0.0352	30		
0.0352	15	0.03520	45
0.0357	6		
0.0357	15	0.03570	15
0.0360	20	0.03600	20
0.0363	45		
0.0363	105	0.03630	150
0.0368	20	0.03680	20
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0.0374	90		
0.0374	3	0.03740	99
0.0378	30		
0.0378	60	0.03780	90
0.0383	4	0.03830	4
0.0385	30	0.03850	30
0.0396	6	0.03960	6
0.0400	25	0.04000	25
0.0408	35	0.04080	35
0.0420	5	0.04200	5
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0.0432	30	0.04320	30
0.0434	7	0.04340	7
0.0440	10	0.04400	10
0.0441	30	0.04410	30
0.0459	6	0.04590	6
0.0462	30		
0.0462	15	0.04620	45
0.0468	2		
0.0468	30	0.04680	32
0.0473	20	0.04730	20
0.0480	10	0.04800	10
0.0484	90	0.04840	90
0.0495	30	0.04950	30
0.0510	2		
0.0510	2	0.05100	4
0.0525	25	0.05250	25
0.0528	15		
0.0528	35	0.05280	50
0.0536	35	0.05360	35
0.0544	30	0.05440	30
0.0550	1	0.05500	1
0.0560	10	0.05600	10
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0.0561	45		

0.0561	7	0.05610	55
0.0567	30	0.05670	30
0.0578	10		
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0.0595	2	0.05950	2
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0.0605	30	0.06050	45
0.0630	10	0.06300	10
0.0660	2	0.06600	2
0.0680	10	0.06800	10
0.0693	15		
0.0693	35	0.06930	50
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0.0714	30	0.07140	30
0.0720	10	0.07200	10
0.0723	2	0.07230	2
0.0726	45	0.07260	45
0.0735	10	0.07350	10
0.0748	6	0.07480	6
0.0765	2	0.07650	2
0.0816	15	0.08160	15
0.0867	3	0.08670	3
0.0880	5		
0.0880	10	0.08800	15
0.0893	10	0.08930	10
0.0924	30	0.09240	30
0.0935	1		
0.0935	15		
0.0935	2	0.09350	18
0.0945	10	0.09450	10
0.1060	15	0.10600	15
0.1070	15	0.10700	15
0.1120	3	0.11200	3
0.1160	5		
0.1160	10	0.11600	15
0.1210	15	0.12100	15
0.1360	5	0.13600	5
0.1390	15	0.13900	15
0.1450	1	0.14500	1
0.1760	5	0.17600	5
0.1790	5	0.17900	5
0.1870	1	0.18700	1
0.2310	5	0.23100	5

End of Table AII.4

Appendix III

MULL GRANITE PROPERTIES

AIII.1 *Geological characteristics*

Mull Granite was chosen as standard dimension stone rocks, because it has been quarried and used in UK from long time ago until the present time. The rock is occurred as small hills with slightly weathered surface. The exposed part of the granites appeared to be fresh particularly by the sea. The rocks are generally pink in colour and coarse grained.

Petrographycally, the rock is holocrystalline, phaneritic, coarse crystalline 10-15 mm. in size, subhedral to anhedral shape.

The rocks composed of major minerals of alkalifeldspar, quartz, plagioclase, biotite and hornblende. The alkalifeldspar comprise of 50% of the rock of large crystal up to 10 mm. in size, two set of cleavage recognised. Generally they are cloudy and slightly stained, which are more intense along cracks and some cleavage. Some feldspars are altered to sericite typically along the cracks and cleavages, the altered areas are mostly cloudy and combined with the staining features. The grain boundary is mostly clear and tight, but some is stained. The feldspars are of perthite composition and containing both orthoclase and microcline. Plagioclase is present as large lathes and composed of about 8% of the rock, mostly cloudy and appeared to be altered into sericite more densely than the alkalifeldspar.

The quartz's are the second dominant minerals in the rocks of about 30%. they are mostly subhedral, the grain size is about 10 to 15mm. in size. The quartz grains are mostly clear and exhibit microcracks and wavy extension. Mafic minerals consist of biotite and amphibole of about 5% of the rock, with brownish in colour , they have good cleavage and high pleochroism. The mafic minerals are largely unaltered but some grains affected by partial alteration and along cleavage planes into opaque iron oxides.

Generally, Mull Granite is affected by staining and alteration, with the alteration products are mostly of chlorite and iron oxides after biotite and amphibole and sericite after feldspar. The alteration minerals occur as replacement of the primary minerals; or as partially replacement along the cracks and cleavage directions. The cleavage and cracks are mostly open. The Mull Granite appears as pink colour which may be due to the cloudiness and staining resulted of feldspar alterations in the rocks.

AIII.2 *Physical and Mechanical Properties*

The physical properties of Mull Granite were determined in order to compare them with the physical properties of rocks in the study area. The density is ranging between 2.60 gm^{-3} and 2.62 gm^{-3} and absorption from 0.30% to 0.36% with porosity values ranging from 0.79% to 0.93%. **Table VI.11** shows list of the physical properties in the study area.

The Mull Granite is characterised by high strength of 195 MPa and high density of 2.62 with a low absorption.

The velocity of Mull Granite in average is 3625 m/s, lower than all the granite of sites 1&2 (Sihi and Sihi pluton). Mull Granite has relatively lower values of velocity. This can be due to the presence of open cleavage and microcracks particularly in the quartz grains and may also due to the amount of the high quartz content in the rock.

The magnesium sulphate soundness test were carried out on the rock samples of the study area and Mull Granite. Mull Granite is less affected by the magnesium sulphate solution than the granites in site 1&2. It is very slightly affected along cleavage planes of feldspars and cracks (**Plate VI.**).

AIII.3 Geometrical Characteristics

❶ *Joint orientation*

The joint orientations of the Mull Granite have been measured in the field. it is plotted using the steriographic projection method. The contour, scatter plot and great circles of joints in Mull Granite were shown in **Fig. A.III.1**. From this plot, it can be seen that Mull Granite has mainly three orthogonal joint sets, Two sub-vertical (NE-SW and NW-SE) and sub-horizontal set. Mostly these joints form the cubic blocks of the Mull Granite.

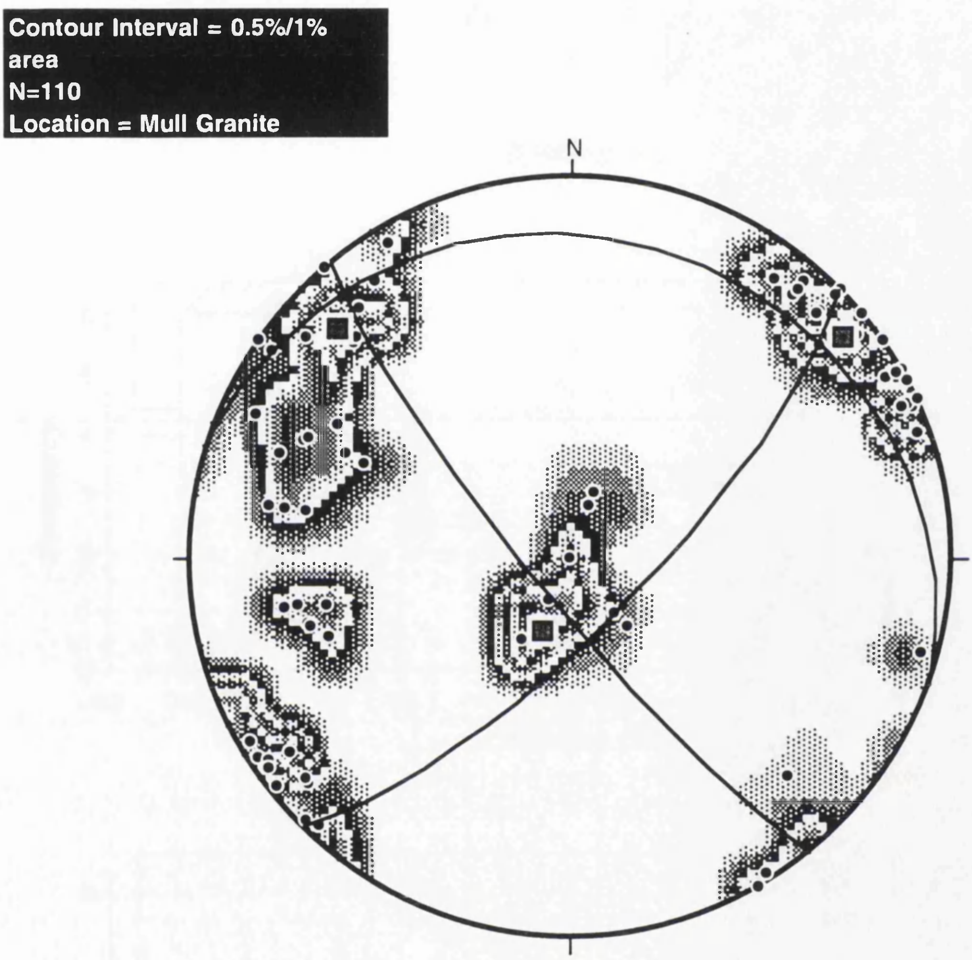


Fig. AIII.1: Contour, scatter plot (equal area) and great circles of joints in Mull Granite

❷ *Joint spacing*

The joint spacings have been measured using three orthogonal scanlines. The spacings were plotted as histograms as shown in **Fig AIII.2**. From these histograms we can see that the spacings are mostly wide class (0.4 - 3.0m).

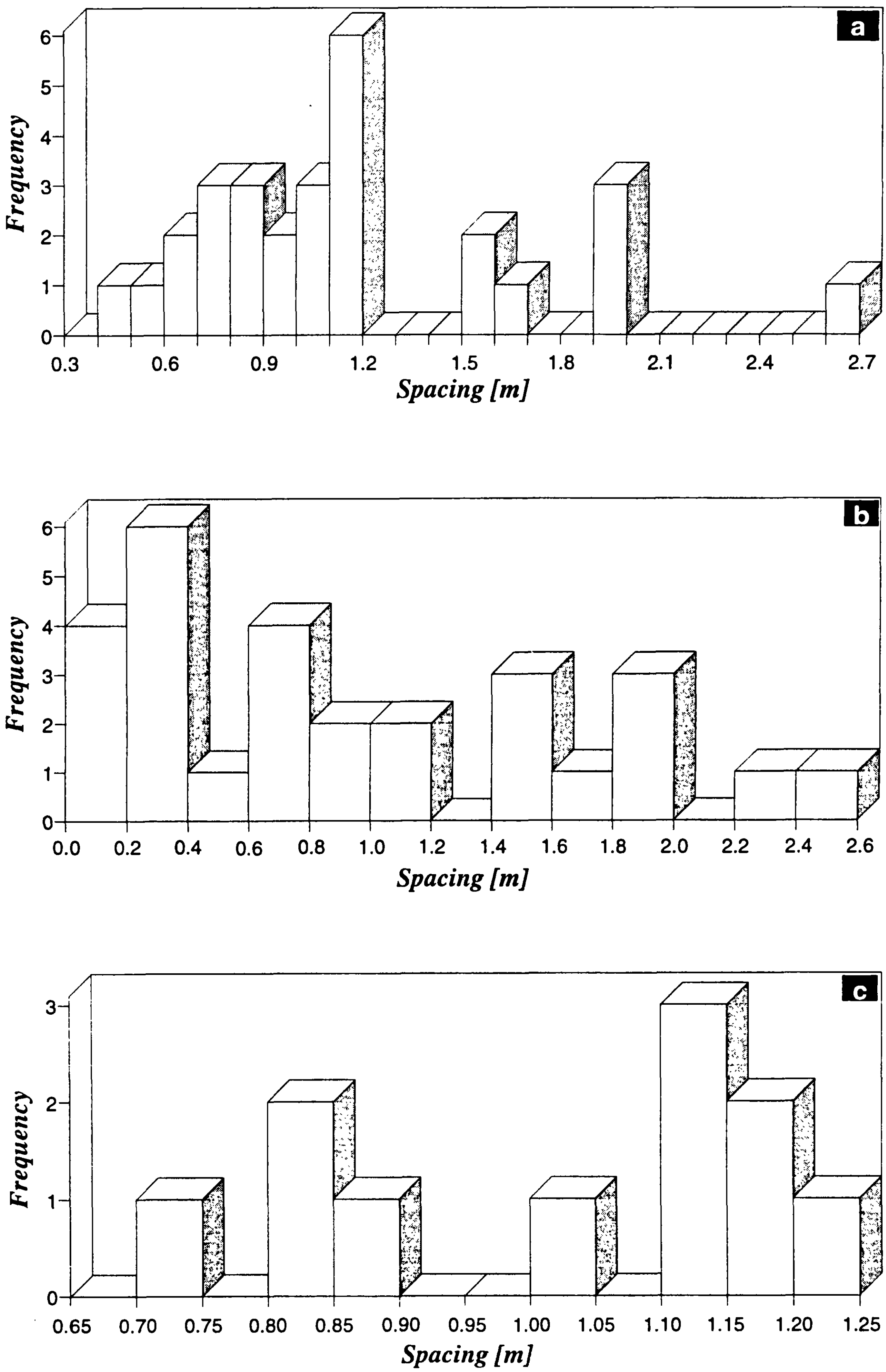


Fig. AIII.2: Joint spacings of Mull granite from three orthogonal scanlines (a, b, and c)

❸ *Block size Vs volume*

The block size and volumes for Mull Granite have been determined using the new method. The results of calculations are presented in **Table AIII.1**. The relationship between block size Vs volume has been plotted as shown in **Fig. AIII.3**.

From **Fig.AIII.3**, it is obvious that the block size of 50 cumulative percentage volume is 2.0 m^3, which is large size class according to Barton (1978) classification. The cumulative volume percentage at 0.2m^3 and 8 m^3 is 100%. This results indicate that most of the block volumes in Mull Granite is concentrated between size 0.2 m^3 and 8.0 m^3 (large class).

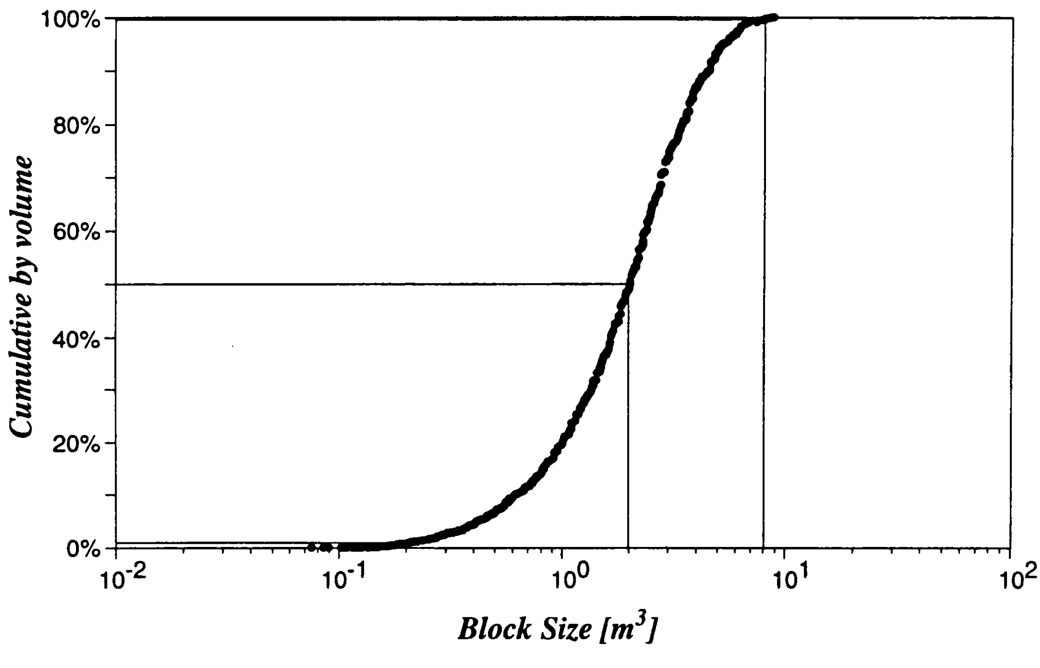


Fig. AIII.3: The Cumulative by volume Vs block size of Mull Granite

❹ *Block size Vs block numbers*

The block numbers yield in certain block size are very important in the potential of dimension stone. The block size Vs cumulative block number percentage has been plotted and block size distribution parameters were obtained. The block size of Mull Granite of 50% block numbers is 0.93 m^3 (large class). Most of the block numbers of Mull Granite is between size 0.2 m^3 and 8 m^3 and the have 12% and they have 93% (**Fig. AIII.4**). From this results, Mull Granite has block sizes of large class.

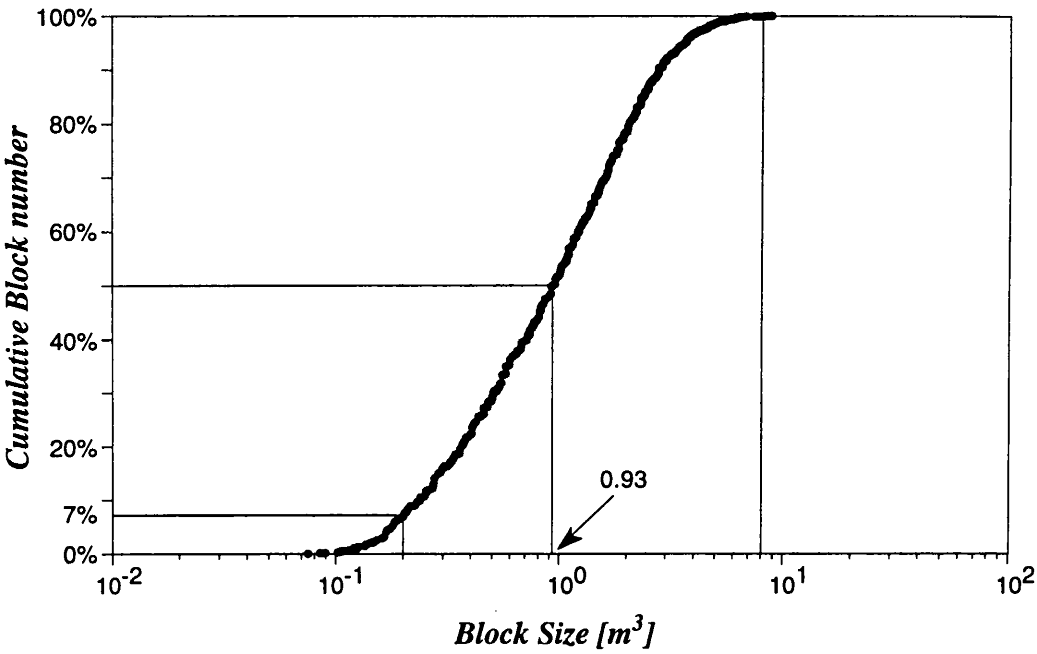


Fig. AIII.4: The Cumulative block number Vs block size of Mull Granite

Table AIII.1: Block size calculation data analysis of Mull Granite

1 BLOCK SIZE (m^3)
2 BLOCK NUMBERS
3 SORTED BLOCK SIZE (m^3)
4 SORTED BLOCK NUMBERS
5 CORRECTED BLOCK SIZE (m^3)
6 CORRECTED BLOCK NUMBERS
7 SORTED AND CORRECTED BLOCK SIZE (m^3)
8 SORTED AND CORRECTED BLOCK NUMBERS FOR EACH SIZE
9 TOTAL VOLUME FOR EACH BLOCK SIZE (m^3)
10 CUMULATIVE BLOCK NUMBERS PERCENTAGE
11 CUMULATIVE BLOCK VOLUME PERCENTAGE

1	2	3	4	5	6	7	8	9	10	11
0.075	4	0.075	4	0.075	4	0.075	4	0.300	0.046	0.00267
0.085	8	0.085	8	0.085	8	0.085	8	0.680	0.138	0.00872
0.090	4	0.090	4			0.090	8	0.720	0.230	0.01513
0.105	4	0.090	4	0.090	8	0.102	8	0.816	0.321	0.02240
0.115	12	0.102	8	0.102	8	0.105	12	1.260	0.459	0.03361
0.120	8	0.105	4			0.108	4	0.432	0.505	0.03746
0.125	4	0.105	8	0.105	12	0.115	12	1.380	0.643	0.04974
0.150	6	0.108	4	0.108	4	0.119	16	1.904	0.826	0.06669
0.170	12	0.115	12	0.115	12	0.120	20	2.400	1.056	0.08806
0.180	6	0.119	16	0.119	16	0.125	4	0.500	1.102	0.09251
0.210	6	0.120	8			0.126	12	1.512	1.240	0.10597
0.230	18	0.120	12	0.120	20	0.135	12	1.620	1.377	0.12039
0.240	12	0.125	4	0.125	4	0.136	24	3.264	1.653	0.14945
0.250	6	0.126	4			0.138	12	1.656	1.791	0.16419
0.225	1	0.126	8	0.126	12	0.144	20	2.880	2.020	0.18983
0.255	2	0.135	12	0.135	12	0.147	8	1.176	2.112	0.20029
0.270	1	0.136	24	0.136	24	0.150	18	2.700	2.319	0.22433
0.315	1	0.138	12	0.138	12	0.153	24	3.672	2.594	0.25702
0.345	3	0.144	8			0.161	24	3.864	2.870	0.29141
0.360	2	0.144	12	0.144	20	0.162	12	1.944	3.007	0.30872
0.375	1	0.147	8	0.147	8	0.165	12	1.980	3.145	0.32635
0.300	4	0.150	6			0.168	82	13.776	4.086	0.44898
0.340	8	0.150	4			0.170	28	4.760	4.408	0.49135
0.360	4	0.150	8	0.150	18	0.175	24	4.200	4.683	0.52874
0.420	4	0.153	24	0.153	24	0.180	44	7.920	5.188	0.59924
0.460	12	0.161	24	0.161	24	0.184	60	11.040	5.877	0.69752
0.480	8	0.162	12	0.162	12	0.187	24	4.488	6.152	0.73747
0.500	4	0.165	12	0.165	12	0.189	12	2.268	6.290	0.75766
0.375	2	0.168	16			0.192	24	4.608	6.566	0.79868
0.425	4	0.168	12	0.168	82	0.198	12	2.376	6.703	0.81983
0.450	2	0.170	12			0.200	12	2.400	6.841	0.84120
0.525	2	0.170	16	0.170	28	0.204	60	12.240	7.530	0.95016
0.575	6	0.175	8	0.175	24	0.207	36	7.452	7.943	1.01650
0.600	4	0.180	6			0.210	26	5.460	8.242	1.06510
0.625	2	0.180	6			0.216	55	11.880	8.873	1.17086
0.450	2	0.180	8	0.180	44	0.225	13	2.925	9.022	1.19689
0.510	4	0.180	24			0.230	42	9.660	9.504	1.28289
0.540	2	0.184	36	0.184	60	0.231	12	2.772	9.642	1.30756
0.630	2	0.187	24	0.187	24	0.238	24	5.712	9.917	1.35841
0.690	6	0.189	12	0.189	12	0.240	54	12.960	10.537	1.47378
0.720	4	0.192	24	0.192	24	0.250	14	3.500	10.698	1.50494
0.750	2	0.198	12	0.198	12	0.252	42	10.584	11.180	1.59916
0.600	3	0.200	12	0.200	12	0.253	36	9.108	11.593	1.68023
0.680	6	0.204	12			0.255	6	1.530	11.662	1.69385
0.720	3	0.204	48	0.204	60	0.264	24	6.336	11.938	1.75026
0.840	3	0.207	36	0.207	36	0.270	20	5.400	12.167	1.79833
0.920	9	0.210	6			0.272	54	14.688	12.787	1.92908
0.960	6	0.210	12			0.275	12	3.300	12.925	1.95846
1.000	3	0.210	8	0.210	26	0.276	90	24.840	13.958	2.17958
0.675	1	0.216	6			0.288	86	24.768	14.945	2.40006
0.765	2	0.216	24			0.289	8	2.312	15.037	2.42065
0.810	1	0.216	24	0.216	55	0.294	12	3.528	15.174	2.45205
0.945	1	0.225	1			0.300	58	17.400	15.840	2.60695
1.035	3	0.225	12	0.225	13	0.306	42	12.852	16.322	2.72135
1.080	2	0.230	18			0.315	3	0.945	16.357	2.72977
1.125	1	0.230	24	0.230	42	0.322	36	11.592	16.770	2.83296
0.750	3	0.231	12	0.231	12	0.324	19	6.156	16.988	2.88776
0.850	6	0.238	24	0.238	24	0.330	18	5.940	17.195	2.94063
0.900	3	0.240	12			0.336	50	16.800	17.769	3.09019
1.050	3	0.240	18			0.340	56	19.040	18.411	3.25968
1.150	9	0.240	16			0.345	3	1.035	18.446	3.26889
1.200	6	0.240	8	0.240	54	0.350	12	4.200	18.584	3.30628
1.250	3	0.250	6			0.357	8	2.856	18.675	3.33171
0.900	1	0.250	8	0.250	14	0.360	73	26.280	19.513	3.56565
1.020	2	0.252	6			0.368	54	19.872	20.133	3.74255
1.080	1	0.252	12			0.368	24	8.832	20.409	3.82117
1.260	1	0.252	24	0.252	42	0.374	36	13.464	20.822	3.94103
1.380	3	0.253	36	0.253	36	0.375	3	1.125	20.856	3.95104
1.440	2	0.255	2			0.378	21	7.938	21.097	4.02171
1.500	1	0.255	4	0.255	6	0.384	52	19.968	21.694	4.19946

0.975	1	0.264	24	0.264	24	0.391	12	4.692	21.832	4.24123
1.105	2	0.270	1			0.396	18	7.128	22.039	4.30468
1.170	1	0.270	1			0.400	26	10.400	22.337	4.39726
1.365	1	0.270	18	0.270	20	0.405	7	2.835	22.417	4.42250
1.495	3	0.272	36			0.408	94	38.352	23.496	4.76391
1.560	2	0.272	16	0.272	54	0.414	57	23.598	24.151	4.97397
1.625	1	0.275	12	0.275	12	0.420	36	15.120	24.564	5.10857
0.090	4	0.276	18			0.425	8	3.400	24.656	5.13884
0.102	8	0.276	72	0.276	90	0.432	81	34.992	25.585	5.45033
0.108	4	0.288	12			0.441	2	0.882	25.608	5.45819
0.126	4	0.288	18			0.450	27	12.150	25.918	5.56635
0.138	12	0.288	48			0.459	14	6.426	26.079	5.62355
0.144	8	0.288	8	0.288	86	0.460	84	38.640	27.043	5.96752
0.150	4	0.289	8	0.289	8	0.462	18	8.316	27.250	6.04155
0.180	6	0.294	12	0.294	12	0.476	16	7.616	27.433	6.10935
0.204	12	0.300	4			0.480	80	38.400	28.352	6.45118
0.216	6	0.300	6			0.483	6	2.898	28.421	6.47698
0.252	6	0.300	12			0.486	7	3.402	28.501	6.50726
0.276	18	0.300	24			0.495	3	1.485	28.535	6.52048
0.288	12	0.300	12	0.300	58	0.500	28	14.000	28.857	6.64511
0.300	6	0.306	2			0.504	55	27.720	29.488	6.89187
0.270	1	0.306	36			0.506	54	27.324	30.108	7.13511
0.306	2	0.306	4	0.306	42	0.510	18	9.180	30.315	7.21683
0.324	1	0.315	1			0.525	8	4.200	30.406	7.25422
0.378	1	0.315	2	0.315	3	0.528	36	19.008	30.820	7.42343
0.414	3	0.322	36	0.322	36	0.540	26	14.040	31.118	7.54841
0.432	2	0.324	1			0.544	48	26.112	31.669	7.78086
0.450	1	0.324	18	0.324	19	0.550	18	9.900	31.876	7.86899
0.360	4	0.330	18	0.330	18	0.552	129	71.208	33.356	8.50288
0.408	8	0.336	24			0.561	6	3.366	33.425	8.53284
0.432	4	0.336	18			0.567	7	3.969	33.506	8.56817
0.504	4	0.336	8	0.336	50	0.575	6	3.450	33.574	8.59888
0.552	12	0.340	8			0.576	110	63.360	34.837	9.16291
0.576	8	0.340	24			0.578	12	6.936	34.975	9.22466
0.600	4	0.340	24	0.340	56	0.588	8	4.704	35.067	9.26653
0.450	2	0.345	3	0.345	3	0.594	3	1.782	35.101	9.28239
0.510	4	0.350	12	0.350	12	0.595	8	4.760	35.193	9.32477
0.540	2	0.357	4			0.600	82	49.200	36.134	9.76274
0.630	2	0.357	4	0.357	8	0.612	46	28.152	36.662	10.01335
0.690	6	0.360	2			0.621	21	13.041	36.903	10.12944
0.720	4	0.360	4			0.625	2	1.250	36.926	10.14057
0.750	2	0.360	4			0.630	14	8.820	37.087	10.21908
0.540	2	0.360	3			0.644	24	15.456	37.362	10.35667
0.612	4	0.360	12			0.648	34	22.032	37.753	10.55280
0.648	2	0.360	36			0.660	12	7.920	37.890	10.62330
0.756	2	0.360	12	0.360	73	0.672	40	26.880	38.349	10.86259
0.828	6	0.368	54	0.368	54	0.675	14	9.450	38.510	10.94671
0.864	4	0.368	24	0.368	24	0.680	70	47.600	39.314	11.37044
0.900	2	0.374	36	0.374	36	0.690	18	12.420	39.520	11.48101
0.720	3	0.375	1			0.693	3	2.079	39.555	11.49951
0.816	6	0.375	2	0.375	3	0.700	8	5.600	39.646	11.54936
0.864	3	0.378	1			0.714	14	9.996	39.807	11.63835
1.008	3	0.378	2			0.720	82	59.040	40.748	12.16392
1.104	9	0.378	18	0.378	21	0.735	4	2.940	40.794	12.19009
1.152	6	0.384	36			0.736	72	52.992	41.621	12.66182
1.200	3	0.384	16	0.384	52	0.748	24	17.952	41.896	12.82163
0.810	1	0.391	12	0.391	12	0.750	13	9.750	42.045	12.90842
0.918	2	0.396	18	0.396	18	0.756	24	18.144	42.321	13.06994
0.972	1	0.400	18			0.759	9	6.831	42.424	13.13075
1.134	1	0.400	8	0.400	26	0.765	15	11.475	42.596	13.23290
1.242	3	0.405	3			0.768	48	36.864	43.147	13.56106
1.296	2	0.405	4	0.405	7	0.782	18	14.076	43.354	13.68637
1.350	1	0.408	8			0.792	18	14.256	43.561	13.81327
0.900	3	0.408	6			0.800	24	19.200	43.836	13.98419
1.020	6	0.408	72			0.805	12	9.660	43.974	14.07018
1.080	3	0.408	8	0.408	94	0.810	20	16.200	44.203	14.21439
1.260	3	0.414	3	0.414	57	0.816	82	66.912	45.145	14.81004
1.380	9	0.414	54			0.825	9	7.425	45.248	14.87614
1.440	6	0.420	4			0.828	60	49.680	45.937	15.31839
1.500	3	0.420	8			0.840	49	41.160	46.499	15.68479
1.080	1	0.420	12			0.850	14	11.900	46.660	15.79073
1.224	2	0.420	12	0.420	36	0.864	75	64.800	47.521	16.36757
1.296	1	0.425	4			0.867	2	1.734	47.544	16.38301
1.512	1	0.425	4	0.425	8	0.875	4	3.500	47.590	16.41416
1.656	3	0.432	2			0.882	4	3.528	47.635	16.44557
1.728	2	0.432	4			0.900	50	45.000	48.209	16.84616
1.800	1	0.432	3			0.918	27	24.786	48.519	17.06680
1.170	1	0.432	36			0.920	105	96.600	49.725	17.92673
1.326	2	0.432	36	0.432	81	0.924	12	11.088	49.862	18.02544
1.404	1	0.441	2	0.441	2	0.935	12	11.220	50.000	18.12532
1.638	1	0.450	2			0.945	9	8.505	50.103	18.20103
1.794	3	0.450	2			0.952	12	11.424	50.241	18.30272
1.872	2	0.450	1			0.960	87	83.520	51.240	19.04621
1.950	1	0.450	2			0.966	12	11.592	51.377	19.14940
0.105	8	0.450	18			0.972	13	12.636	51.527	19.26189
0.119	16	0.450	2	0.450	27	0.975	1	0.975	51.538	19.27057
0.126	8	0.459	6			0.990	12	11.880	51.676	19.37632
0.147	8	0.459	8	0.459	14	1.000	35	35.000	52.078	19.68789
0.161	24	0.460	12			1.008	49	49.392	52.640	20.12758
0.168	16	0.460	36			1.012	36	36.432	53.053	20.45189
0.175	8	0.460	36	0.460	84	1.020	50	51.000	53.627	20.90589
0.210	12	0.462	18	0.462	18	1.035	21	21.735	53.868	21.09938
0.238	24	0.476	16	0.476	16	1.050	17	17.850	54.063	21.25828
0.252	12	0.480	8			1.056	24	25.344	54.339	21.48389
0.294	12	0.480	12			1.071	5	5.355	54.396	21.53156

0.322	36	0.480	24			1.080	62	66.960	55.108	22.12763
0.336	24	0.480	12			1.088	34	36.992	55.498	22.45693
0.350	12	0.480	24	0.480	80	1.100	12	13.200	55.636	22.57444
0.315	2	0.483	6	0.483	6	1.104	105	115.920	56.841	23.60635
0.357	4	0.486	3			1.105	2	2.210	56.864	23.62603
0.378	2	0.486	4	0.486	7	1.122	12	13.464	57.002	23.74588
0.441	2	0.495	3	0.495	3	1.125	7	7.875	57.082	23.81598
0.483	6	0.500	4			1.134	15	17.010	57.254	23.96741
0.504	4	0.500	12			1.150	21	24.150	57.495	24.18239
0.525	2	0.500	12	0.500	28	1.152	87	100.224	58.494	25.07458
0.420	8	0.504	4			1.155	6	6.930	58.563	25.13627
0.476	16	0.504	4			1.156	8	9.248	58.655	25.21859
0.504	8	0.504	8			1.170	2	2.340	58.678	25.23942
0.588	8	0.504	3			1.173	3	3.519	58.712	25.27075
0.644	24	0.504	36	0.504	55	1.176	6	7.056	58.781	25.33356
0.672	16	0.506	54	0.506	54	1.188	6	7.128	58.850	25.39702
0.700	8	0.510	4			1.190	12	14.280	58.988	25.52414
0.525	4	0.510	4			1.200	80	96.000	59.906	26.37872
0.595	8	0.510	4			1.215	4	4.860	59.952	26.42199
0.630	4	0.510	6	0.510	18	1.224	56	68.544	60.595	27.03216
0.735	4	0.525	2			1.242	39	48.438	61.042	27.46335
0.805	12	0.525	2	0.525	8	1.250	7	8.750	61.123	27.54125
0.840	8	0.525	4			1.260	31	39.060	61.478	27.88896
0.875	4	0.528	36	0.528	36	1.265	18	22.770	61.685	28.09165
0.630	4	0.540	2			1.275	3	3.825	61.719	28.12570
0.714	8	0.540	2			1.288	18	23.184	61.926	28.33209
0.756	4	0.540	2			1.296	51	66.096	62.511	28.92047
0.882	4	0.540	12			1.320	21	27.720	62.753	29.16723
0.966	12	0.540	2			1.323	2	2.646	62.775	29.19079
1.008	8	0.540	6	0.540	26	1.326	2	2.652	62.798	29.21439
1.050	4	0.544	24			1.344	29	38.976	63.131	29.56136
0.840	6	0.544	24	0.544	48	1.350	24	32.400	63.407	29.84978
0.952	12	0.550	18	0.550	18	1.360	62	84.320	64.118	30.60039
1.008	6	0.552	12			1.365	3	4.095	64.153	30.63685
1.176	6	0.552	9			1.375	6	8.250	64.222	30.71029
1.288	18	0.552	108	0.552	129	1.377	8	11.016	64.314	30.80835
1.344	12	0.561	6	0.561	6	1.380	69	95.220	65.106	31.65600
1.400	6	0.567	3			1.386	6	8.316	65.174	31.73002
0.945	2	0.567	4	0.567	7	1.400	6	8.400	65.243	31.80480
1.071	4	0.575	6	0.575	6	1.404	1	1.404	65.255	31.81730
1.134	2	0.576	8			1.428	8	11.424	65.347	31.91899
1.323	2	0.576	6			1.440	102	146.880	66.517	33.22651
1.449	6	0.576	12			1.445	4	5.780	66.563	33.27797
1.512	4	0.576	72			1.449	6	8.694	66.632	33.35536
1.575	2	0.576	12	0.576	110	1.458	4	5.832	66.678	33.40728
1.050	6	0.578	12	0.578	12	1.470	6	8.820	66.747	33.48579
1.190	12	0.588	8	0.588	8	1.472	51	75.072	67.332	34.15408
1.260	6	0.594	3	0.594	3	1.485	3	4.455	67.367	34.19374
1.470	6	0.595	8	0.595	8	1.495	3	4.485	67.401	34.23366
1.610	18	0.600	4			1.496	18	26.928	67.608	34.47337
1.680	12	0.600	3			1.500	35	52.500	68.010	34.94073
1.750	6	0.600	4			1.512	31	46.872	68.365	35.35798
1.260	2	0.600	3			1.518	18	27.324	68.572	35.60122
1.428	4	0.600	6			1.530	26	39.780	68.871	35.95533
1.512	2	0.600	8			1.536	34	52.224	69.261	36.42023
1.764	2	0.600	36			1.547	4	6.188	69.307	36.47532
1.932	6	0.600	18	0.600	82	1.560	5	7.800	69.364	36.54475
2.016	4	0.612	4			1.564	12	18.768	69.502	36.71182
2.100	2	0.612	24			1.575	2	3.150	69.525	36.73986
1.365	2	0.612	12			1.584	21	33.264	69.766	37.03598
1.547	4	0.612	6	0.612	46	1.600	17	27.200	69.961	37.27811
1.638	2	0.621	9			1.610	18	28.980	70.168	37.53609
1.911	2	0.621	12	0.621	21	1.620	24	38.880	70.443	37.88220
2.093	6	0.625	2	0.625	2	1.625	1	1.625	70.455	37.89666
2.184	4	0.630	2			1.632	58	94.656	71.120	38.73929
2.275	2	0.630	2			1.638	3	4.914	71.155	38.78303
0.120	12	0.630	4			1.650	15	24.750	71.327	39.00335
0.136	24	0.630	4			1.656	75	124.200	72.188	40.10898
0.144	12	0.630	2	0.630	14	1.680	43	72.240	72.681	40.75205
0.168	12	0.644	24	0.644	24	1.683	6	10.098	72.750	40.84194
0.184	36	0.648	2			1.700	28	47.600	73.072	41.26568
0.192	24	0.648	6			1.701	4	6.804	73.118	41.32625
0.200	12	0.648	12			1.728	75	129.600	73.978	42.47994
0.240	18	0.648	6			1.734	4	6.936	74.024	42.54168
0.272	36	0.648	8	0.648	34	1.750	6	10.500	74.093	42.63515
0.288	18	0.660	12	0.660	12	1.755	3	5.265	74.128	42.68202
0.336	18	0.672	16			1.764	2	3.528	74.151	42.71343
0.368	54	0.672	12			1.768	6	10.608	74.219	42.80786
0.384	36	0.672	12	0.672	40	1.782	3	5.346	74.254	42.85545
0.400	18	0.675	1			1.785	2	3.570	74.277	42.88723
0.360	3	0.675	3			1.794	3	5.382	74.311	42.93514
0.408	6	0.675	6			1.800	63	113.400	75.034	43.94462
0.432	3	0.675	4	0.675	14	1.836	28	51.408	75.356	44.40225
0.504	3	0.680	6			1.840	93	171.120	76.423	45.92555
0.552	9	0.680	12			1.848	9	16.632	76.527	46.07361
0.576	6	0.680	16			1.863	12	22.356	76.664	46.27262
0.600	3	0.680	36	0.680	70	1.870	18	33.660	76.871	46.57226
0.480	12	0.690	6			1.872	5	9.360	76.928	46.65559
0.544	24	0.690	6			1.890	11	20.790	77.055	46.84066
0.576	12	0.690	6	0.690	18	1.911	2	3.822	77.078	46.87468
0.672	12	0.693	3	0.693	3	1.920	68	130.560	77.858	48.03692
0.736	36	0.700	8	0.700	8	1.932	6	11.592	77.927	48.14011
0.768	24	0.714	8			1.944	21	40.824	78.168	48.50352
0.800	12	0.714	6	0.714	14	1.950	3	5.850	78.202	48.55560
0.600	6	0.720	4			1.955	6	11.730	78.271	48.66002

0.680	12	0.720	3			1.980	12	23.760	78.409	48.87153
0.720	6	0.720	4			1.989	6	11.934	78.478	48.97777
0.840	6	0.720	3			2.000	31	62.000	78.834	49.52969
0.920	18	0.720	6			2.016	29	58.464	79.167	50.05013
0.960	12	0.720	6			2.024	27	54.648	79.477	50.53661
1.000	6	0.720	4			2.025	6	12.150	79.545	50.64476
0.720	6	0.720	8			2.040	59	120.360	80.223	51.71620
0.816	12	0.720	24			2.070	33	68.310	80.601	52.32429
0.864	6	0.720	2			2.079	3	6.237	80.636	52.37982
1.008	6	0.720	18	0.720	82	2.093	6	12.558	80.705	52.49161
1.104	18	0.735	4	0.735	4	2.100	14	29.400	80.865	52.75332
1.152	12	0.736	36			2.106	3	6.318	80.900	52.80957
1.200	6	0.736	36	0.736	72	2.112	18	38.016	81.107	53.14798
0.960	9	0.748	24	0.748	24	2.125	2	4.250	81.129	53.18582
1.088	18	0.750	2			2.142	2	4.284	81.152	53.22395
1.152	9	0.750	3			2.145	3	6.435	81.187	53.28124
1.344	9	0.750	2			2.160	56	120.960	81.830	54.35802
1.472	27	0.750	2			2.176	12	26.112	81.967	54.59046
1.536	18	0.750	4	0.750	13	2.184	7	15.288	82.048	54.72656
1.600	9	0.756	2			2.200	9	19.800	82.151	54.90282
1.080	3	0.756	4			2.208	75	165.600	83.012	56.37698
1.224	6	0.756	12			2.210	4	8.840	83.058	56.45567
1.296	3	0.756	6	0.756	24	2.244	6	13.464	83.127	56.57553
1.512	3	0.759	9	0.759	9	2.250	11	24.750	83.253	56.79585
1.656	9	0.765	2			2.275	13	29.575	83.402	57.05913
1.728	6	0.765	12			2.275	2	4.550	83.425	57.09963
1.800	3	0.765	1	0.765	15	2.277	9	20.493	83.528	57.28206
1.200	9	0.768	24			2.295	5	11.475	83.586	57.38421
1.360	18	0.768	24	0.768	48	2.300	36	82.800	83.999	58.12129
1.440	9	0.782	18	0.782	18	2.304	56	129.024	84.642	59.26985
1.680	9	0.792	6			2.310	9	20.790	84.745	59.45493
1.840	27	0.792	12	0.792	18	2.312	6	13.872	84.814	59.57841
1.920	18	0.800	12			2.340	8	18.720	84.906	59.74506
2.000	9	0.800	12	0.800	24	2.346	6	14.076	84.975	59.87036
1.440	3	0.805	12	0.805	12	2.376	9	21.384	85.078	60.06072
1.632	6	0.810	1			2.392	9	21.528	85.181	60.25236
1.728	3	0.810	1	0.810	20	2.400	64	153.600	85.916	61.61970
2.016	3	0.810	6			2.430	4	9.720	85.962	61.70623
2.208	9	0.810	6			2.431	6	14.586	86.031	61.83607
2.304	6	0.810	6			2.448	23	56.304	86.295	62.33729
2.400	3	0.816	6			2.457	3	7.371	86.329	62.40291
1.560	3	0.816	12			2.475	3	7.425	86.364	62.46900
1.768	6	0.816	48			2.484	39	96.876	86.811	63.33139
1.872	3	0.816	4			2.496	6	14.976	86.880	63.46470
2.184	3	0.816	12	0.816	82	2.500	12	30.000	87.018	63.73176
2.392	9	0.825	3			2.520	26	65.520	87.316	64.31502
2.496	6	0.825	6	0.825	9	2.530	27	68.310	87.626	64.92311
2.600	3	0.828	6			2.550	5	12.750	87.684	65.03661
0.135	12	0.828	36			2.574	3	7.722	87.718	65.10535
0.153	24	0.828	18	0.828	60	2.592	34	88.128	88.108	65.88986
0.162	12	0.840	3			2.600	3	7.800	88.143	65.95930
0.189	12	0.840	8			2.601	2	5.202	88.166	66.00560
0.207	36	0.840	6			2.640	18	47.520	88.372	66.42863
0.216	24	0.840	6			2.652	12	31.824	88.510	66.71192
0.225	12	0.840	8			2.688	6	16.128	88.579	66.85549
0.270	18	0.840	18	0.840	49	2.691	9	24.219	88.682	67.07109
0.306	36	0.850	6			2.700	16	43.200	88.866	67.45565
0.324	18	0.850	8			2.720	30	81.600	89.210	68.18205
0.378	18	0.850	6	0.850	14	2.730	2	5.460	89.233	68.23066
0.414	54	0.864	4			2.750	9	24.750	89.337	68.45098
0.432	36	0.864	3			2.754	5	13.770	89.394	68.57356
0.450	18	0.864	6			2.760	78	215.280	90.289	70.48997
0.405	3	0.864	24			2.772	3	8.316	90.324	70.56400
0.459	6	0.864	12			2.808	12	33.696	90.461	70.86396
0.486	3	0.864	24			2.835	2	5.670	90.484	70.91443
0.567	3	0.864	2	0.864	75	2.856	3	8.568	90.519	70.99071
0.621	9	0.867	2	0.867	2	2.880	69	198.720	91.311	72.75970
0.648	6	0.875	4	0.875	4	2.890	6	17.340	91.380	72.91406
0.675	3	0.882	4	0.882	4	2.916	2	5.832	91.403	72.96598
0.540	12	0.900	3			2.925	3	8.775	91.437	73.04409
0.612	24	0.900	1			2.944	18	52.992	91.644	73.51582
0.648	12	0.900	2			2.990	6	17.940	91.713	73.67553
0.756	12	0.900	3			3.000	35	105.000	92.114	74.61023
0.828	36	0.900	12			3.003	3	9.009	92.149	74.69043
0.864	24	0.900	4			3.024	8	24.192	92.241	74.90578
0.900	12	0.900	4			3.036	9	27.324	92.344	75.14902
0.675	6	0.900	6			3.060	10	30.600	92.459	75.42142
0.765	12	0.900	12			3.072	12	36.864	92.596	75.74958
0.810	6	0.900	3	0.900	50	3.105	6	18.630	92.665	75.91543
0.945	6	0.918	2			3.120	6	18.720	92.734	76.08207
1.035	18	0.918	12			3.128	9	28.152	92.837	76.33268
1.080	12	0.918	1			3.168	6	19.008	92.906	76.50189
1.125	6	0.918	12	0.918	27	3.200	6	19.200	92.975	76.67280
0.810	6	0.920	9			3.213	1	3.213	92.987	76.70141
0.918	12	0.920	18			3.240	10	32.400	93.101	76.98983
0.972	6	0.920	24			3.250	2	6.500	93.124	77.04769
1.134	6	0.920	54	0.920	105	3.264	10	32.640	93.239	77.33825
1.242	18	0.924	12	0.924	12	3.276	6	19.656	93.308	77.51323
1.296	12	0.935	12	0.935	12	3.289	9	29.601	93.411	77.77673
1.350	6	0.945	1			3.300	3	9.900	93.446	77.86486
1.080	9	0.945	2			3.312	24	79.488	93.721	78.57246
1.224	18	0.945	6	0.945	9	3.315	1	3.315	93.733	78.60197
1.296	9	0.952	12	0.952	12	3.360	15	50.400	93.905	79.05063
1.512	9	0.960	6			3.375	2	6.750	93.928	79.11072
1.656	27	0.960	12			3.400	21	71.400	94.169	79.74632

1.728	18	0.960	9		
1.800	9	0.960	16		
1.215	3	0.960	8		
1.377	6	0.960	36	0.960	87
1.458	3	0.966	12	0.966	12
1.701	3	0.972	1		
1.863	9	0.972	6		
1.944	6	0.972	6	0.972	13
2.025	3	0.975	1	0.975	1
1.350	9	0.990	6		
1.530	18	0.990	6	0.990	12
1.620	9	1.000	3		
1.890	9	1.000	6		
2.070	27	1.000	8		
2.160	18	1.000	18	1.000	35
2.250	9	1.008	3		
1.620	3	1.008	8		
1.836	6	1.008	6		
1.944	3	1.008	6		
2.268	3	1.008	24		
2.484	9	1.008	2	1.008	49
2.592	6	1.012	36	1.012	36
2.700	3	1.020	2		
1.755	3	1.020	6		
1.989	6	1.020	8		
2.106	3	1.020	24		
2.457	3	1.020	4		
2.691	9	1.020	6	1.020	50
2.808	6	1.035	3		
2.925	3	1.035	18	1.035	21
0.150	8	1.050	3		
0.170	16	1.050	4		
0.180	8	1.050	6		
0.210	8	1.050	4	1.050	17
0.230	24	1.056	24	1.056	24
0.240	16	1.071	4		
0.250	8	1.071	1	1.071	5
0.300	12	1.080	2		
0.340	24	1.080	1		
0.360	12	1.080	3		
0.420	12	1.080	1		
0.460	36	1.080	3		
0.480	24	1.080	12		
0.500	12	1.080	9		
0.450	2	1.080	4		
0.510	4	1.080	12		
0.540	2	1.080	12		
0.630	2	1.080	3	1.080	62
0.690	6	1.088	18		
0.720	4	1.088	16	1.088	34
0.750	2	1.100	12	1.100	12
0.600	8	1.104	9		
0.680	16	1.104	18		
0.720	8	1.104	72		
0.840	8	1.104	6	1.104	105
0.920	24	1.105	2	1.105	2
0.960	16	1.122	12	1.122	12
1.000	8	1.125	1		
0.750	4	1.125	6	1.125	7
0.850	8	1.134	1		
0.900	4	1.134	2		
1.050	4	1.134	6		
1.150	12	1.134	6	1.134	15
1.200	8	1.150	9		
1.250	4	1.150	12	1.150	21
0.900	4	1.152	6		
1.020	8	1.152	12		
1.080	4	1.152	9		
1.260	4	1.152	48		
1.380	12	1.152	4		
1.440	8	1.152	8	1.152	87
1.500	4	1.155	6	1.155	6
1.200	6	1.156	8	1.156	8
1.360	12	1.170	1		
1.440	6	1.170	1	1.170	2
1.680	6	1.173	3	1.173	3
1.840	18	1.176	6	1.176	6
1.920	12	1.188	6	1.188	6
2.000	6	1.190	12	1.190	12
1.350	2	1.200	6		
1.530	4	1.200	3		
1.620	2	1.200	6		
1.890	2	1.200	9		
2.070	6	1.200	8		
2.160	4	1.200	6		
2.250	2	1.200	24		
1.500	6	1.200	2		
1.700	12	1.200	4		
1.800	6	1.200	12	1.200	80
2.100	6	1.215	3		
2.300	18	1.215	1	1.215	4
2.400	12	1.224	2		
2.500	6	1.224	6		
1.800	2	1.224	18		
2.040	4	1.224	24		

3.402	2	6.804	94.192	79.80689
3.432	6	20.592	94.261	79.99020
3.456	18	62.208	94.467	80.54397
3.468	2	6.936	94.490	80.60571
3.519	3	10.557	94.525	80.69969
3.536	4	14.144	94.571	80.82560
3.570	3	10.710	94.605	80.92094
3.575	3	10.725	94.640	81.01641
3.588	18	64.584	94.846	81.59134
3.600	20	72.000	95.076	82.23228
3.645	1	3.645	95.087	82.26472
3.672	9	33.048	95.191	82.55892
3.680	45	165.600	95.707	84.03308
3.726	6	22.356	95.776	84.23209
3.744	14	52.416	95.937	84.69870
3.757	2	7.514	95.960	84.76558
3.780	3	11.340	95.994	84.86653
3.825	1	3.825	96.006	84.90058
3.840	30	115.200	96.350	85.92609
3.888	7	27.216	96.430	86.16836
3.900	9	35.100	96.534	86.48082
3.910	9	35.190	96.637	86.79408
3.978	1	3.978	96.648	86.82949
4.000	15	60.000	96.820	87.36361
4.032	2	8.064	96.843	87.43540
4.050	5	20.250	96.901	87.61566
4.080	12	48.960	97.039	88.05150
4.131	2	8.262	97.062	88.12505
4.140	9	37.260	97.165	88.45673
4.200	9	37.800	97.268	88.79323
4.250	3	12.750	97.303	88.90673
4.284	1	4.284	97.314	88.94486
4.320	9	38.880	97.417	89.29097
4.368	2	8.736	97.440	89.36874
4.374	1	4.374	97.452	89.40768
4.416	6	26.496	97.521	89.64354
4.420	6	26.520	97.590	89.87962
4.500	3	13.500	97.624	89.99980
4.536	3	13.608	97.658	90.12094
4.590	6	27.540	97.727	90.36610
4.600	27	124.200	98.037	91.47172
4.608	4	18.432	98.083	91.63580
4.641	1	4.641	98.095	91.67711
4.680	3	14.040	98.129	91.80210
4.692	3	14.076	98.163	91.92740
4.784	6	28.704	98.232	92.18292
4.800	20	96.000	98.462	93.03751
4.860	4	19.440	98.508	93.21056
4.896	2	9.792	98.531	93.29773
4.968	9	44.712	98.634	93.69575
4.992	4	19.968	98.680	93.87351
5.000	9	45.000	98.783	94.27410
5.040	3	15.120	98.818	94.40869
5.083	3	15.249	98.852	94.54444
5.100	1	5.100	98.864	94.58984
5.103	1	5.103	98.875	94.63527
5.184	6	31.104	98.944	94.91215
5.200	2	10.400	98.967	95.00473
5.265	1	5.265	98.978	95.05160
5.304	2	10.608	99.001	95.14603
5.400	3	16.200	99.036	95.29024
5.460	3	16.380	99.070	95.43606
5.508	2	11.016	99.093	95.53412
5.520	9	49.680	99.197	95.97637
5.525	1	5.525	99.208	96.02556
5.589	3	16.767	99.242	96.17481
5.670	3	17.010	99.277	96.32624
5.760	6	34.560	99.346	96.63389
5.832	0	0.000	99.346	96.63389
5.967	2	11.934	99.369	96.74012
5.980	9	53.820	99.472	97.21923
6.000	3	18.000	99.506	97.37946
6.075	1	6.075	99.518	97.43354
6.210	9	55.890	99.621	97.93107
6.240	6	37.440	99.690	98.26436
6.318	1	6.318	99.702	98.32060
6.480	6	38.880	99.770	98.66671
6.500	3	19.500	99.805	98.84030
6.750	3	20.250	99.839	99.02056
6.804	1	6.804	99.851	99.08113
7.371	1	7.371	99.862	99.14675
7.452	3	22.356	99.897	99.34576
7.776	2	15.552	99.920	99.48420
8.073	3	24.219	99.954	99.69980
8.100	1	8.100	99.966	99.77191
8.424	2	16.848	99.989	99.92189
8.775	1	8.775	100.000	100.00000

2.160	2	1.224	2		
2.520	2	1.224	4	1.224	56
2.760	6	1.242	3		
2.880	4	1.242	18		
3.000	2	1.242	18	1.242	39
1.950	2	1.250	3		
2.210	4	1.250	4	1.250	7
2.340	2	1.260	1		
2.730	2	1.260	3		
2.990	6	1.260	6		
3.120	4	1.260	2		
3.250	2	1.260	4		
0.165	12	1.260	12		
0.187	24	1.260	3	1.260	31
0.198	12	1.265	18	1.265	18
0.231	12	1.275	1		
0.253	36	1.275	2	1.275	3
0.264	24	1.288	18	1.288	18
0.275	12	1.296	2		
0.330	18	1.296	1		
0.374	36	1.296	3		
0.396	18	1.296	12		
0.462	18	1.296	9		
0.506	54	1.296	12		
0.528	36	1.296	12	1.296	51
0.550	18	1.320	12		
0.495	3	1.320	9	1.320	21
0.561	6	1.323	2	1.323	2
0.594	3	1.326	2	1.326	2
0.693	3	1.344	12		
0.759	9	1.344	9		
0.792	6	1.344	8	1.344	29
0.825	3	1.350	1		
0.660	12	1.350	6		
0.748	24	1.350	9		
0.792	12	1.350	2		
0.924	12	1.350	6	1.350	24
1.012	36	1.360	18		
1.056	24	1.360	12		
1.100	12	1.360	8		
0.825	6	1.360	24	1.360	62
0.935	12	1.365	1		
0.990	6	1.365	2	1.365	3
1.155	6	1.375	6	1.375	6
1.265	18	1.377	6		
1.320	12	1.377	2	1.377	8
1.375	6	1.380	3		
0.990	6	1.380	9		
1.122	12	1.380	12		
1.188	6	1.380	36		
1.386	6	1.380	9	1.380	69
1.518	18	1.386	6	1.386	6
1.584	12	1.400	6	1.400	6
1.650	6	1.404	1	1.404	1
1.320	9	1.428	4		
1.496	18	1.428	4	1.428	8
1.584	9	1.440	2		
1.848	9	1.440	6		
2.024	27	1.440	9		
2.112	18	1.440	3		
2.200	9	1.440	8		
1.485	3	1.440	6		
1.683	6	1.440	24		
1.782	3	1.440	18		
2.079	3	1.440	4		
2.277	9	1.440	4		
2.376	6	1.440	6		
2.475	3	1.440	12	1.440	102
1.650	9	1.445	4	1.445	4
1.870	18	1.449	6	1.449	6
1.980	9	1.458	3		
2.310	9	1.458	1	1.458	4
2.530	27	1.470	6	1.470	6
2.640	18	1.472	27		
2.750	9	1.472	24	1.472	51
1.980	3	1.485	3	1.485	3
2.244	6	1.495	3	1.495	3
2.376	3	1.496	18	1.496	18
2.772	3	1.500	1		
3.036	9	1.500	3		
3.168	6	1.500	4		
3.300	3	1.500	6		
2.145	3	1.500	12		
2.431	6	1.500	3		
2.574	3	1.500	6	1.500	35
3.003	3	1.512	1		
3.289	9	1.512	4		
3.432	6	1.512	2		
3.575	3	1.512	3		
0.180	24	1.512	9		
0.204	48	1.512	12	1.512	31
0.216	24	1.518	18	1.518	18
0.252	24	1.530	18		
0.276	72	1.530	4		
0.288	48	1.530	2		

0.300	24	1.530	2	1.530	26
0.360	36	1.536	18		
0.408	72	1.536	16	1.536	34
0.432	36	1.547	4	1.547	4
0.504	36	1.560	2		
0.552	108	1.560	3	1.560	5
0.576	72	1.564	12	1.564	12
0.600	36	1.575	2	1.575	2
0.540	6	1.584	12		
0.612	12	1.584	9	1.584	21
0.648	6	1.600	9		
0.756	6	1.600	8	1.600	17
0.828	18	1.610	18	1.610	18
0.864	12	1.620	9		
0.900	6	1.620	3		
0.720	24	1.620	2		
0.816	48	1.620	6		
0.864	24	1.620	4	1.620	24
1.008	24	1.625	1	1.625	1
1.104	72	1.632	6		
1.152	48	1.632	36		
1.200	24	1.632	8		
0.900	12	1.632	8	1.632	58
1.020	24	1.638	1		
1.080	12	1.638	2	1.638	3
1.260	12	1.650	6		
1.380	36	1.650	9	1.650	15
1.440	24	1.656	3		
1.500	12	1.656	9		
1.080	12	1.656	27		
1.224	24	1.656	36	1.656	75
1.296	12	1.680	12		
1.512	12	1.680	9		
1.656	36	1.680	6		
1.728	24	1.680	4		
1.800	12	1.680	12	1.680	43
1.440	18	1.683	6	1.683	6
1.632	36	1.700	12		
1.728	18	1.700	4		
2.016	18	1.700	12	1.700	28
2.208	54	1.701	3		
2.304	36	1.701	1	1.701	4
2.400	18	1.728	2		
1.620	6	1.728	6		
1.836	12	1.728	3		
1.944	6	1.728	18		
2.268	6	1.728	24		
2.484	18	1.728	18		
2.592	12	1.728	4	1.728	75
2.700	6	1.734	4	1.734	4
1.800	18	1.750	6	1.750	6
2.040	36	1.755	3	1.755	3
2.160	18	1.764	2	1.764	2
2.520	18	1.768	6	1.768	6
2.760	54	1.782	3	1.782	3
2.880	36	1.785	2	1.785	2
3.000	18	1.794	3	1.794	3
2.160	6	1.800	1		
2.448	12	1.800	3		
2.592	6	1.800	9		
3.024	6	1.800	6		
3.312	18	1.800	2		
3.456	12	1.800	12		
3.600	6	1.800	18		
2.340	6	1.800	6		
2.652	12	1.800	6	1.800	63
2.808	6	1.836	6		
3.276	6	1.836	12		
3.588	18	1.836	2		
3.744	12	1.836	8	1.836	28
3.900	6	1.840	27		
0.240	8	1.840	18		
0.272	16	1.840	12		
0.288	8	1.840	36	1.840	93
0.336	8	1.848	9	1.848	9
0.368	24	1.863	9	1.863	12
0.384	16	1.863	3		
0.400	8	1.870	18	1.870	18
0.480	12	1.872	2		
0.544	24	1.872	3	1.872	5
0.576	12	1.890	9		
0.672	12	1.890	2	1.890	11
0.736	36	1.911	2	1.911	2
0.768	24	1.920	18		
0.800	12	1.920	12		
0.720	2	1.920	8		
0.816	4	1.920	6		
0.864	2	1.920	24	1.920	68
1.008	2	1.932	6	1.932	6
1.104	6	1.944	6		
1.152	4	1.944	3		
1.200	2	1.944	6		
0.960	8	1.944	2		
1.088	16	1.944	4	1.944	21
1.152	8	1.950	1		

1.344	8	1.950	2	1.950	3
1.472	24	1.955	6	1.955	6
1.536	16	1.980	9		
1.600	8	1.980	3	1.980	12
1.200	4	1.989	6	1.989	6
1.360	8	2.000	9		
1.440	4	2.000	6		
1.680	4	2.000	4		
1.840	12	2.000	12	2.000	31
1.920	8	2.016	4		
2.000	4	2.016	3		
1.440	4	2.016	18		
1.632	8	2.016	4	2.016	29
1.728	4	2.024	27	2.024	27
2.016	4	2.025	3		
2.208	12	2.025	1		
2.304	8	2.025	2	2.025	6
2.400	4	2.040	4		
1.920	6	2.040	36		
2.176	12	2.040	4		
2.304	6	2.040	3		
2.688	6	2.040	12	2.040	59
2.944	18	2.070	27		
3.072	12	2.070	6	2.070	33
3.200	6	2.079	3	2.079	3
2.160	2	2.093	6	2.093	6
2.448	4	2.100	2		
2.592	2	2.100	6		
3.024	2	2.100	6	2.100	14
3.312	6	2.106	3	2.106	3
3.456	4	2.112	18	2.112	18
3.600	2	2.125	2	2.125	2
2.400	6	2.142	2	2.142	2
2.720	12	2.145	3	2.145	3
2.880	6	2.160	18		
3.360	6	2.160	4		
3.680	18	2.160	2		
3.840	12	2.160	18		
4.000	6	2.160	6		
2.880	2	2.160	2		
3.264	4	2.160	6	2.160	56
3.456	2	2.176	12	2.176	12
4.032	2	2.184	4		
4.416	6	2.184	3	2.184	7
4.608	4	2.200	9	2.200	9
4.800	2	2.208	9		
3.120	2	2.208	54		
3.536	4	2.208	12	2.208	75
3.744	2	2.210	4	2.210	4
4.368	2	2.244	6	2.244	6
4.784	6	2.250	9		
4.992	4	2.250	2	2.250	11
5.200	2	2.268	3		
0.255	4	2.268	6		
0.289	8	2.268	4	2.275	13
0.306	4	2.275	2	2.275	2
0.357	4	2.277	9	2.277	9
0.391	12	2.295	1		
0.408	8	2.295	4	2.295	5
0.425	4	2.300	18		
0.510	6	2.300	18	2.300	36
0.578	12	2.304	6		
0.612	6	2.304	36		
0.714	6	2.304	8		
0.782	18	2.304	6	2.304	56
0.816	12	2.310	9	2.310	9
0.850	6	2.312	6	2.312	6
0.765	1	2.340	2		
0.867	2	2.340	6	2.340	8
0.918	1	2.346	6	2.346	6
1.071	1	2.376	6		
1.173	3	2.376	3	2.376	9
1.224	2	2.392	9	2.392	9
1.275	1	2.400	3		
1.020	4	2.400	12		
1.156	8	2.400	18		
1.224	4	2.400	4		
1.428	4	2.400	6		
1.564	12	2.400	12		
1.632	8	2.400	9	2.400	64
1.700	4	2.430	2		
1.275	2	2.430	2	2.430	4
1.445	4	2.431	6	2.431	6
1.530	2	2.448	12		
1.785	2	2.448	4		
1.955	6	2.448	4		
2.040	4	2.448	3	2.448	23
2.125	2	2.457	3	2.457	3
1.530	2	2.475	3	2.475	3
1.734	4	2.484	9		
1.836	2	2.484	18		
2.142	2	2.484	12	2.484	39
2.346	6	2.496	6	2.496	6
2.448	4	2.500	6		
2.550	2	2.500	6	2.500	12

2.040	3	2.520	2		
2.312	6	2.520	18		
2.448	3	2.520	6	2.520	26
2.856	3	2.530	27	2.530	27
3.128	9	2.550	2		
3.264	6	2.550	3	2.550	5
3.400	3	2.574	3	2.574	3
2.295	1	2.592	6		
2.601	2	2.592	12		
2.754	1	2.592	6		
3.213	1	2.592	2		
3.519	3	2.592	8	2.592	34
3.672	2	2.600	3	2.600	3
3.825	1	2.601	2	2.601	2
2.550	3	2.640	18	2.640	18
2.890	6	2.652	12	2.652	12
3.060	3	2.688	6	2.688	6
3.570	3	2.691	9	2.691	9
3.910	9	2.700	3		
4.080	6	2.700	6		
4.250	3	2.700	3		
3.060	1	2.700	4	2.700	16
3.468	2	2.720	12		
3.672	1	2.720	18	2.720	30
4.284	1	2.730	2	2.730	2
4.692	3	2.750	9	2.750	9
4.896	2	2.754	1		
5.100	1	2.754	4	2.754	5
3.315	1	2.760	6		
3.757	2	2.760	54		
3.978	1	2.760	18	2.760	78
4.641	1	2.772	3	2.772	3
5.083	3	2.808	6		
5.304	2	2.808	6	2.808	12
5.525	1	2.835	2	2.835	2
0.300	12	2.856	3	2.856	3
0.340	24	2.880	4		
0.360	12	2.880	36		
0.420	12	2.880	6		
0.460	36	2.880	2		
0.480	24	2.880	12		
0.500	12	2.880	9	2.880	69
0.600	18	2.890	6	2.890	6
0.680	36	2.916	2	2.916	2
0.720	18	2.925	3	2.925	3
0.840	18	2.944	18	2.944	18
0.920	54	2.990	6	2.990	6
0.960	36	3.000	2		
1.000	18	3.000	18		
0.900	3	3.000	6		
1.020	6	3.000	9	3.000	35
1.080	3	3.003	3	3.003	3
1.260	3	3.024	6		
1.380	9	3.024	2	3.024	8
1.440	6	3.036	9	3.036	9
1.500	3	3.060	3		
1.200	12	3.060	1		
1.360	24	3.060	6	3.060	10
1.440	12	3.072	12	3.072	12
1.680	12	3.105	6	3.105	6
1.840	36	3.120	4		
1.920	24	3.120	2	3.120	6
2.000	12	3.128	9	3.128	9
1.500	6	3.168	6	3.168	6
1.700	12	3.200	6	3.200	6
1.800	6	3.213	1	3.213	1
2.100	6	3.240	3		
2.300	18	3.240	4		
2.400	12	3.240	3	3.240	10
2.500	6	3.250	2	3.250	2
1.800	6	3.264	4		
2.040	12	3.264	6	3.264	10
2.160	6	3.276	6	3.276	6
2.520	6	3.289	9	3.289	9
2.760	18	3.300	3	3.300	3
2.880	12	3.312	18		
3.000	6	3.312	6	3.312	24
2.400	9	3.315	1	3.315	1
2.720	18	3.360	6		
2.880	9	3.360	9	3.360	15
3.360	9	3.375	2	3.375	2
3.680	27	3.400	3		
3.840	18	3.400	18	3.400	21
4.000	9	3.402	2	3.402	2
2.700	3	3.432	6	3.432	6
3.060	6	3.456	12		
3.240	3	3.456	4		
3.780	3	3.456	2	3.456	18
4.140	9	3.468	2	3.468	2
4.320	6	3.519	3	3.519	3
4.500	3	3.536	4	3.536	4
3.000	9	3.570	3	3.570	3
3.400	18	3.575	3	3.575	3
3.600	9	3.588	18	3.588	18
4.200	9	3.600	6		

4.600	27	3.600	2		
4.800	18	3.600	9		
5.000	9	3.600	3	3.600	20
3.600	3	3.645	1	3.645	1
4.080	6	3.672	2		
4.320	3	3.672	1		
5.040	3	3.672	6	3.672	9
5.520	9	3.680	18		
5.760	6	3.680	27	3.680	45
6.000	3	3.726	6	3.726	6
3.900	3	3.744	12		
4.420	6	3.744	2	3.744	14
4.680	3	3.757	2	3.757	2
5.460	3	3.780	3	3.780	3
5.980	9	3.825	1	3.825	1
6.240	6	3.840	12		
6.500	3	3.840	18	3.840	30
0.405	4	3.888	4		
0.459	8	3.888	3	3.888	7
0.486	4	3.900	6		
0.567	4	3.900	3	3.900	9
0.621	12	3.910	9	3.910	9
0.648	8	3.978	1	3.978	1
0.675	4	4.000	6		
0.810	6	4.000	9	4.000	15
0.918	12	4.032	2	4.032	2
0.972	6	4.050	2		
1.134	6	4.050	3	4.050	5
1.242	18	4.080	6		
1.296	12	4.080	6	4.080	12
1.350	6	4.131	2	4.131	2
1.215	1	4.140	9	4.140	9
1.377	2	4.200	9	4.200	9
1.458	1	4.250	3	4.250	3
1.701	1	4.284	1	4.284	1
1.863	3	4.320	6		
1.944	2	4.320	3	4.320	9
2.025	1	4.368	2	4.368	2
1.620	4	4.374	1	4.374	1
1.836	8	4.416	6	4.416	6
1.944	4	4.420	6	4.420	6
2.268	4	4.500	3	4.500	3
2.484	12	4.536	3	4.536	3
2.592	8	4.590	6	4.590	6
2.700	4	4.600	27	4.600	27
2.025	2	4.608	4	4.608	4
2.295	4	4.641	1	4.641	1
2.430	2	4.680	3	4.680	3
2.835	2	4.692	3	4.692	3
3.105	6	4.784	6	4.784	6
3.240	4	4.800	2		
3.375	2	4.800	18	4.800	20
2.430	2	4.860	3		
2.754	4	4.860	1	4.860	4
2.916	2	4.896	2	4.896	2
3.402	2	4.968	9	4.968	9
3.726	6	4.992	4	4.992	4
3.888	4	5.000	9	5.000	9
4.050	2	5.040	3	5.040	3
3.240	3	5.083	3	5.083	3
3.672	6	5.100	1	5.100	1
3.888	3	5.103	1	5.103	1
4.536	3	5.184	6	5.184	6
4.968	9	5.200	2	5.200	2
5.184	6	5.265	1	5.265	1
5.400	3	5.304	2	5.304	2
3.645	1	5.400	3	5.400	3
4.131	2	5.460	3	5.460	3
4.374	1	5.508	2	5.508	2
5.103	1	5.520	9	5.520	9
5.589	3	5.525	1	5.525	1
5.832	2	5.589	3	5.589	3
6.075	1	5.670	3	5.670	3
4.050	3	5.760	6	5.760	6
4.590	6	5.832	2		
4.860	3	5.832	1	5.832	0
5.670	3	5.967	2	5.967	2
6.210	9	5.980	9	5.980	9
6.480	6	6.000	3	6.000	3
6.750	3	6.075	1	6.075	1
4.860	1	6.210	9	6.210	9
5.508	2	6.240	6	6.240	6
5.832	1	6.318	1	6.318	1
6.804	1	6.480	6	6.480	6
7.452	3	6.500	3	6.500	3
7.776	2	6.750	3	6.750	3
8.100	1	6.804	1	6.804	1
5.265	1	7.371	1	7.371	1
5.967	2	7.452	3	7.452	3
6.318	1	7.776	2	7.776	2
7.371	1	8.073	3	8.073	3
8.073	3	8.100	1	8.100	1
8.424	2	8.424	2	8.424	2
8.775	1	8.775	1	8.775	1

Appendix IV

Scanline Spacing Histograms

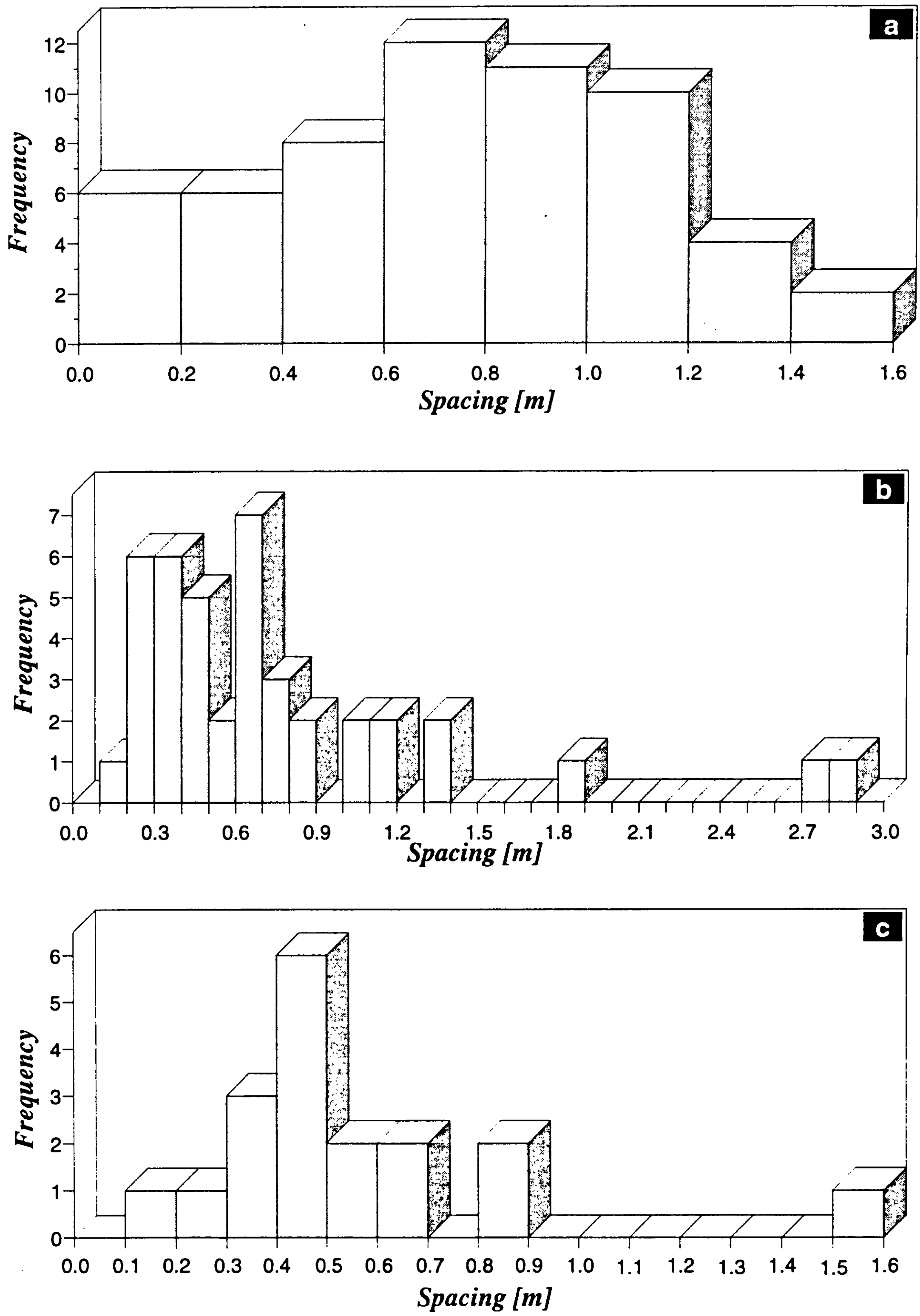


Fig. AVI.1: Joint spacings in red granite from three orthogonal scanlines (a,b, and c) of site1.

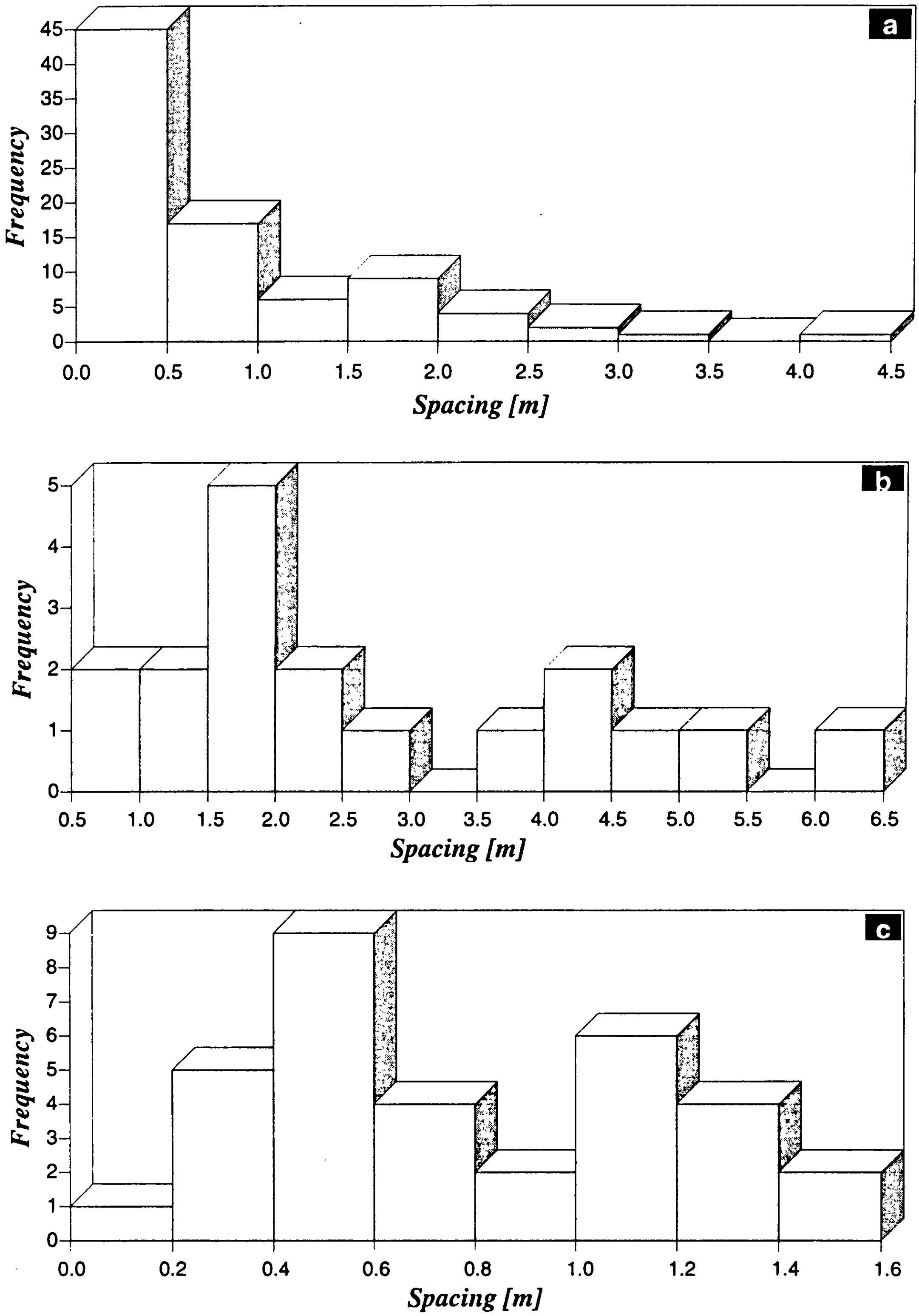


Fig. AIV.2: Joint spacings in grey and pink granites from three orthogonal scanlines (a,b, and c) of site 2.

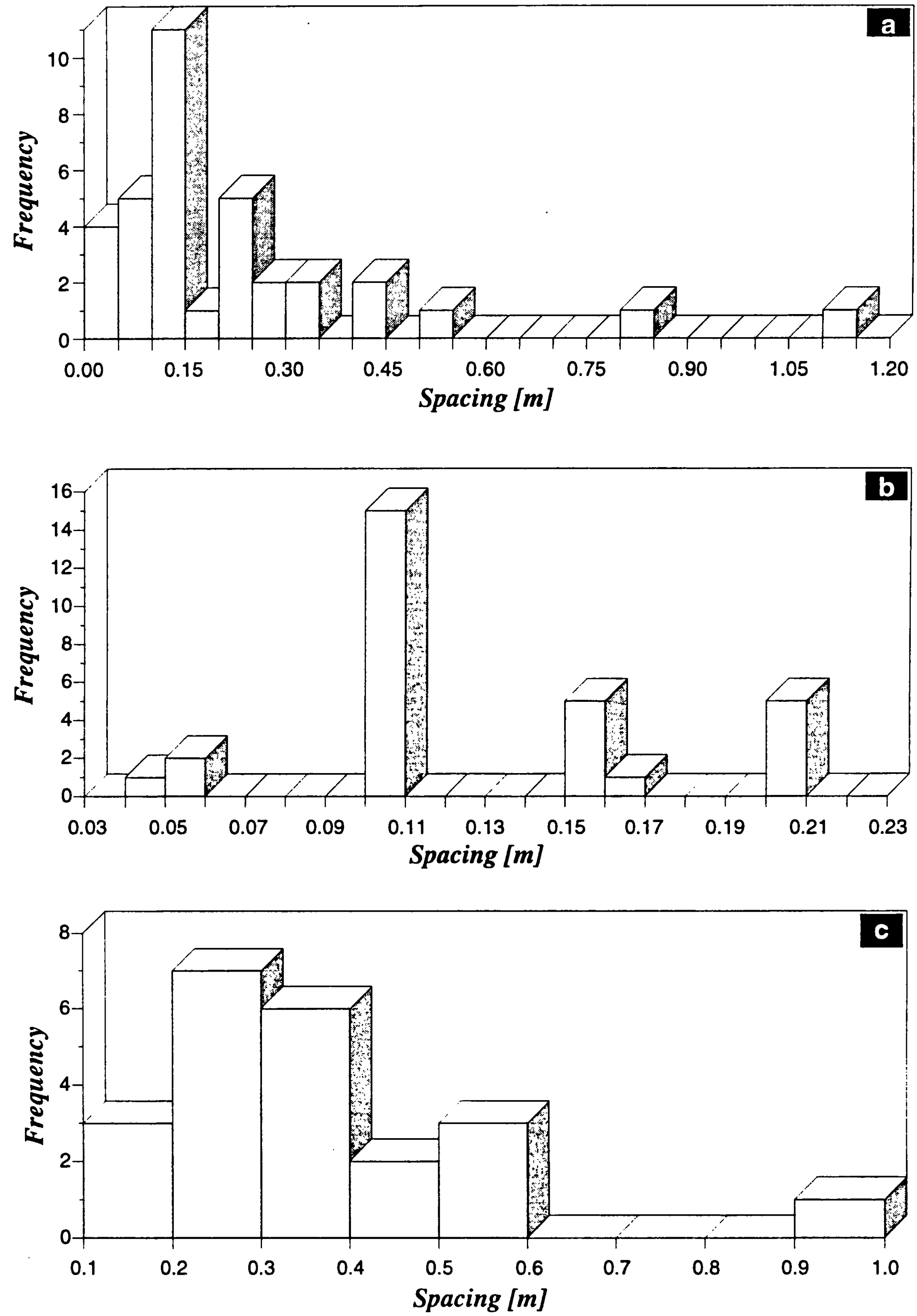
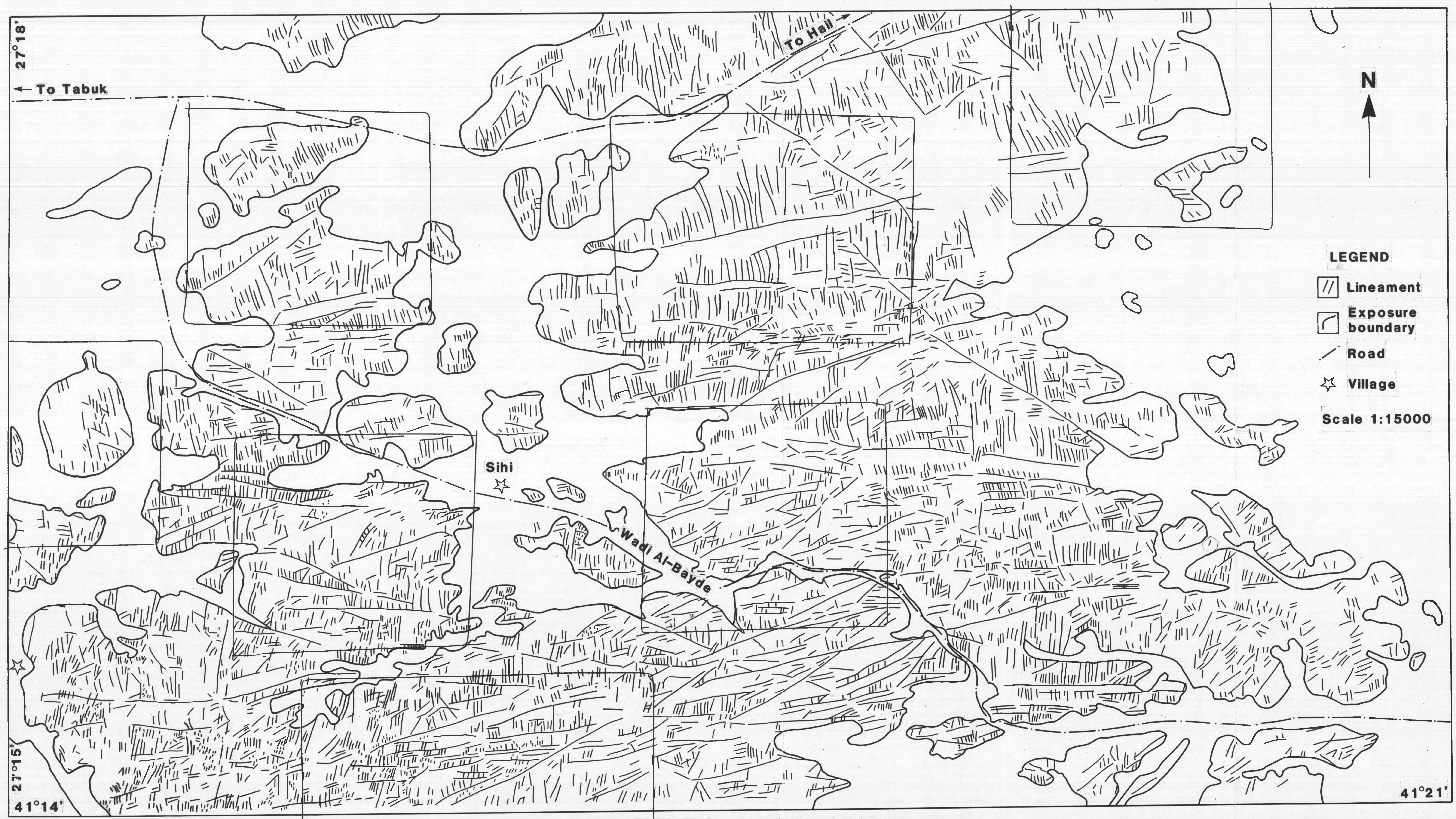


Fig. AIV.3: Joint spacings in microgranite from three orthogonal scanlines (a,b, and c) of site 2.



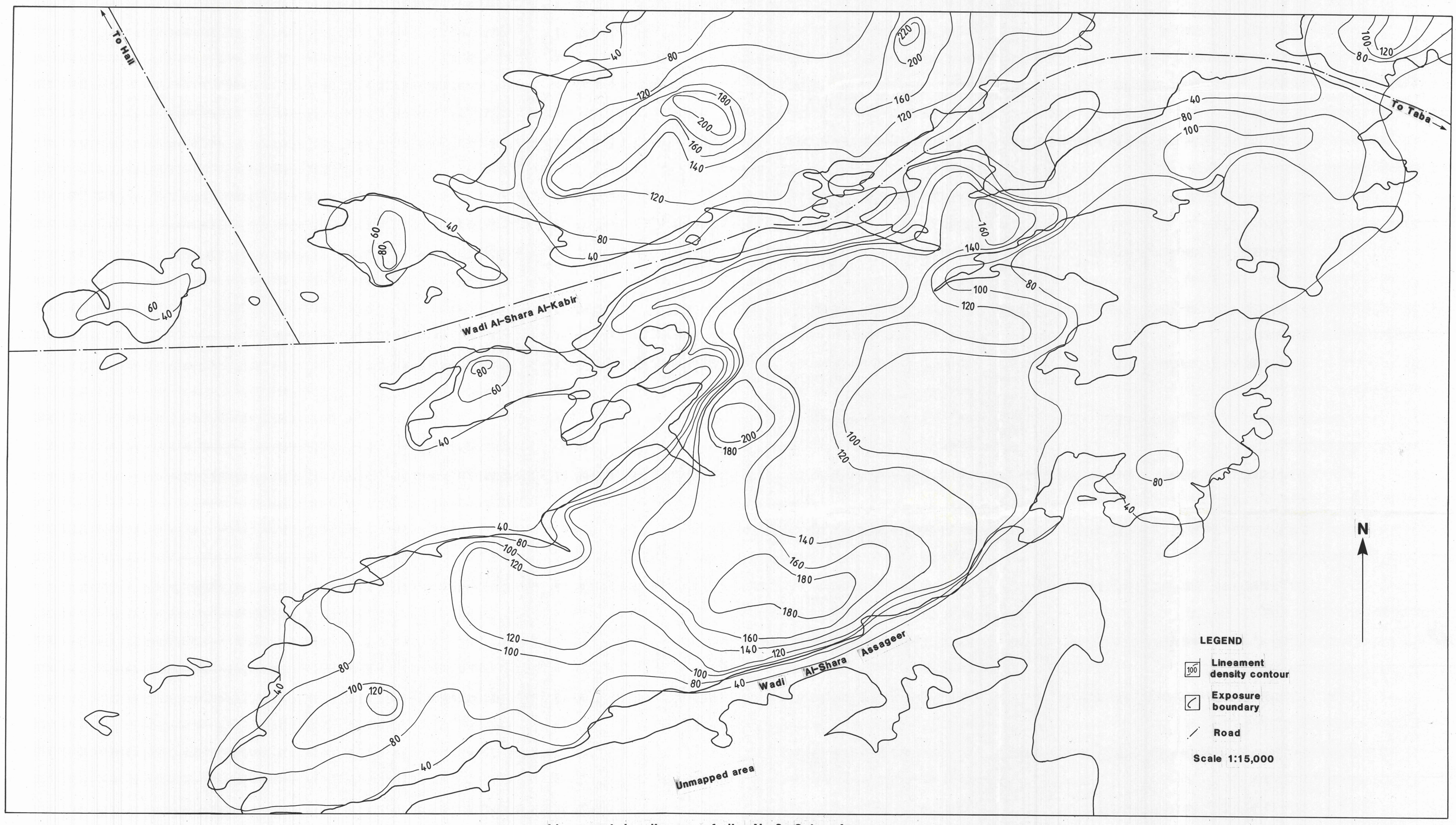
Lineament map of site No.1, Sihi Area at Jabal Aja

Hail Region

Kingdom of Saudi Arabia

by Abdullah R.A. Ghouth-Ali 1996

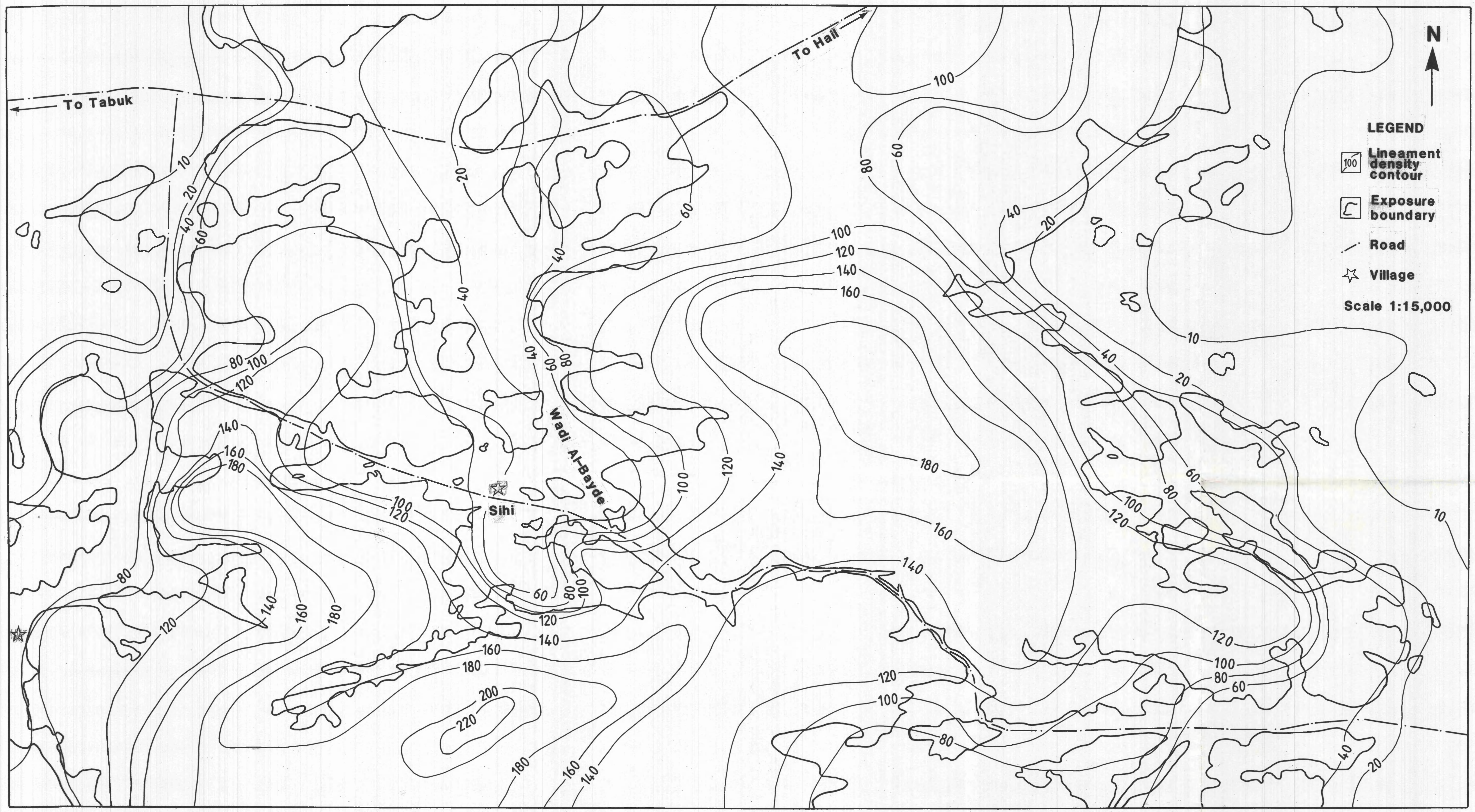
SHEET 1



Lineament density map of site No.2, Salma Area
Hail Region
Kingdom of Saudi Arabia
by Abdullah R.A. Ghouth-Ali 1996

SHEET 4

Lineament map of site No.2, Salma Area
Hail Region
Kingdom of Saudi Arabia
by Abdullah R.A. Ghouth-Ali 1996
SHEET 2



Lineament density map of site No.1, Sihi Area at Jaba Aja

Hail Region

Kingdom of Saudi Arabia

by Abdullah R.A. Ghouth-Ali 1996

SHEET 3