

Hashemite Kingdom of Jordan



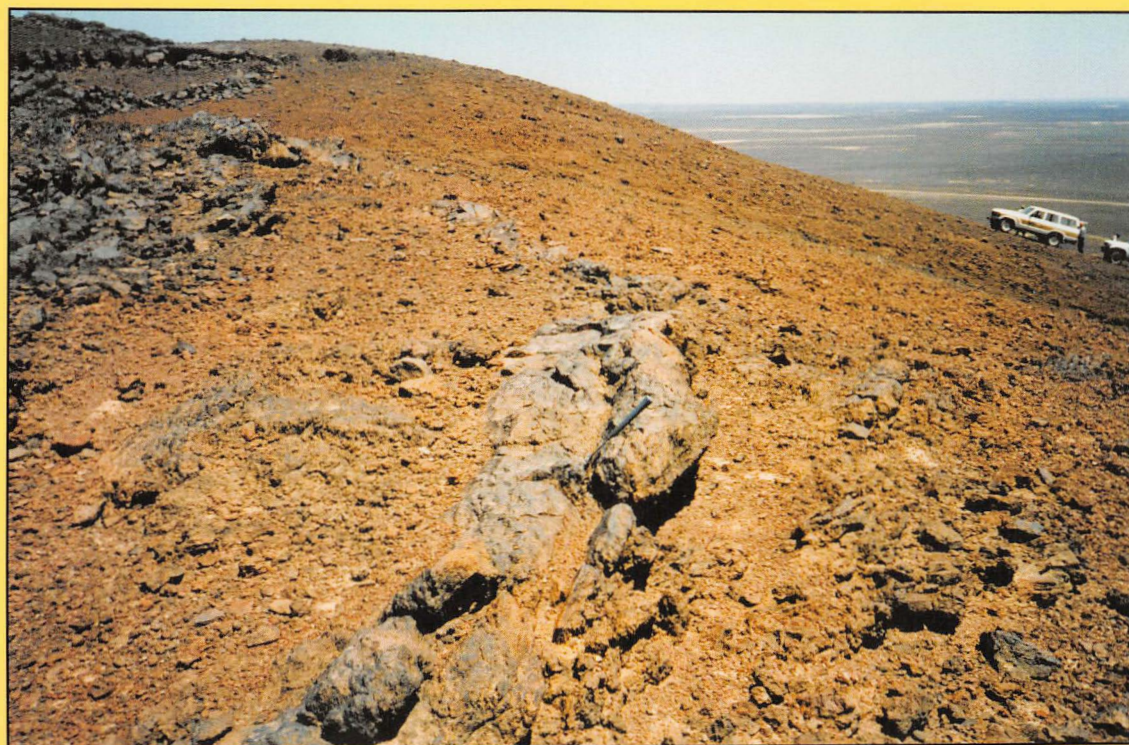
Natural Resources Authority

State of Israel



Geological Survey of Israel

Dating of the Harrat Ash Shaam Basalts
Northeast Jordan
(Phase 1)



**Khalid Tarawneh, Shimon Ilani, Ibrahim Rabba, Yehudit Harlavan,
Sergiu Peltz, Khalil Ibrahim, Ram Weinberger, and Gideon Steinitz**

March 2000

Front cover :

Tulul Al Ghasein volcanic centre
pyroclasts and basalts
(coord. N 32° 27.451' ; E 37° 45.075')

Back cover :

Structural setting and volcanic fields
of the Middle East

© 2000

Published jointly by the
Geological Survey of Israel and the
Natural Resources Authority of Jordan

Report GSI / 2 / 2000

Hashemite Kingdom of Jordan

Natural Resources Authority

Geology Directorate

Geological Mapping Division

State of Israel

Geological Survey of Israel

Dating of the Harrat Ash Shaam Basalts

Northeast Jordan

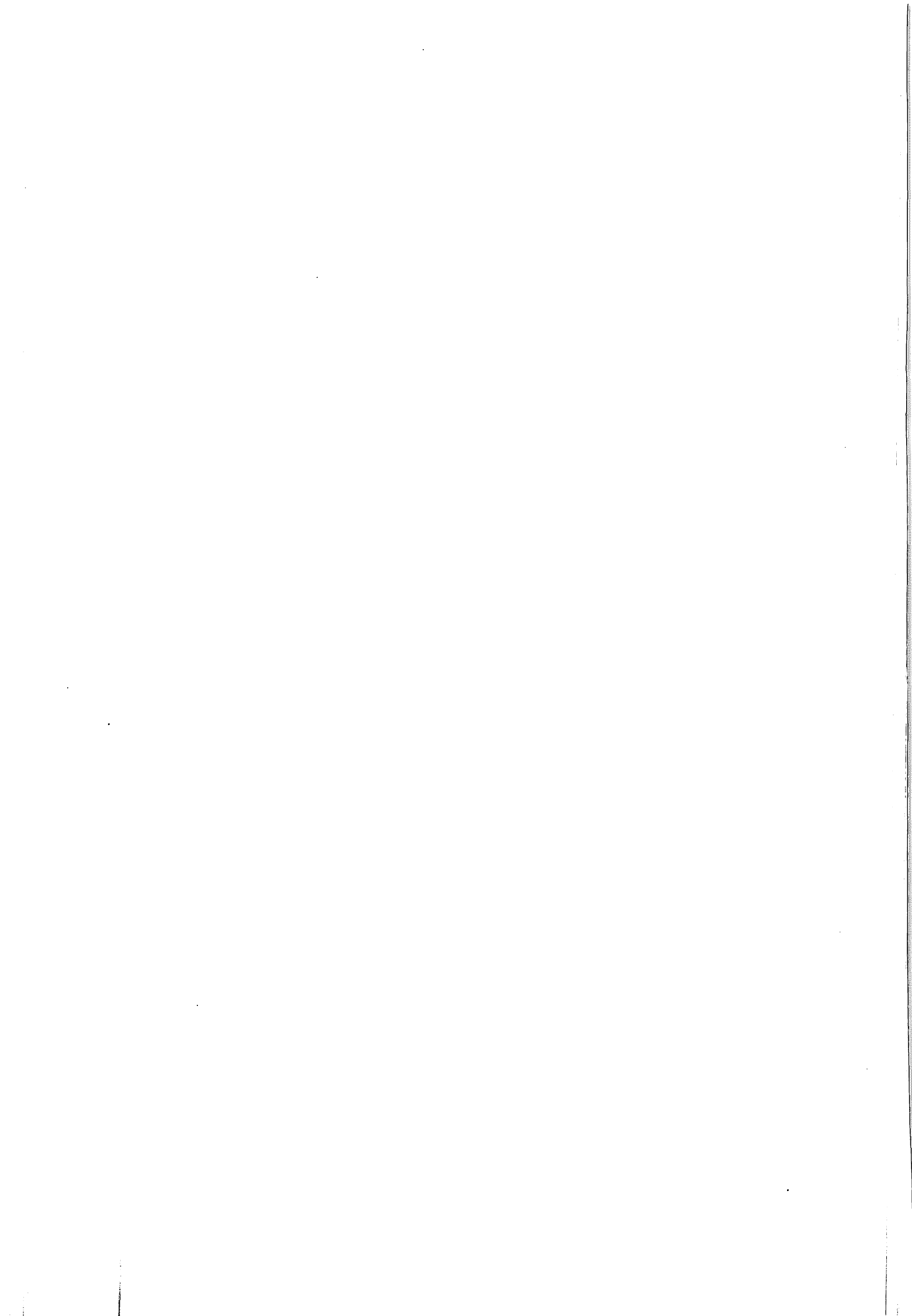
(Phase 1)

**K. Tarawneh¹, S. Ilani², I. Rabba¹, Y. Harlavan²,
S. Peltz², K. Ibrahim¹, R. Weinberger², and G. Steinitz².**

1 - Natural Resources Authority, Jordan

2 - Geological Survey of Israel

March 2000

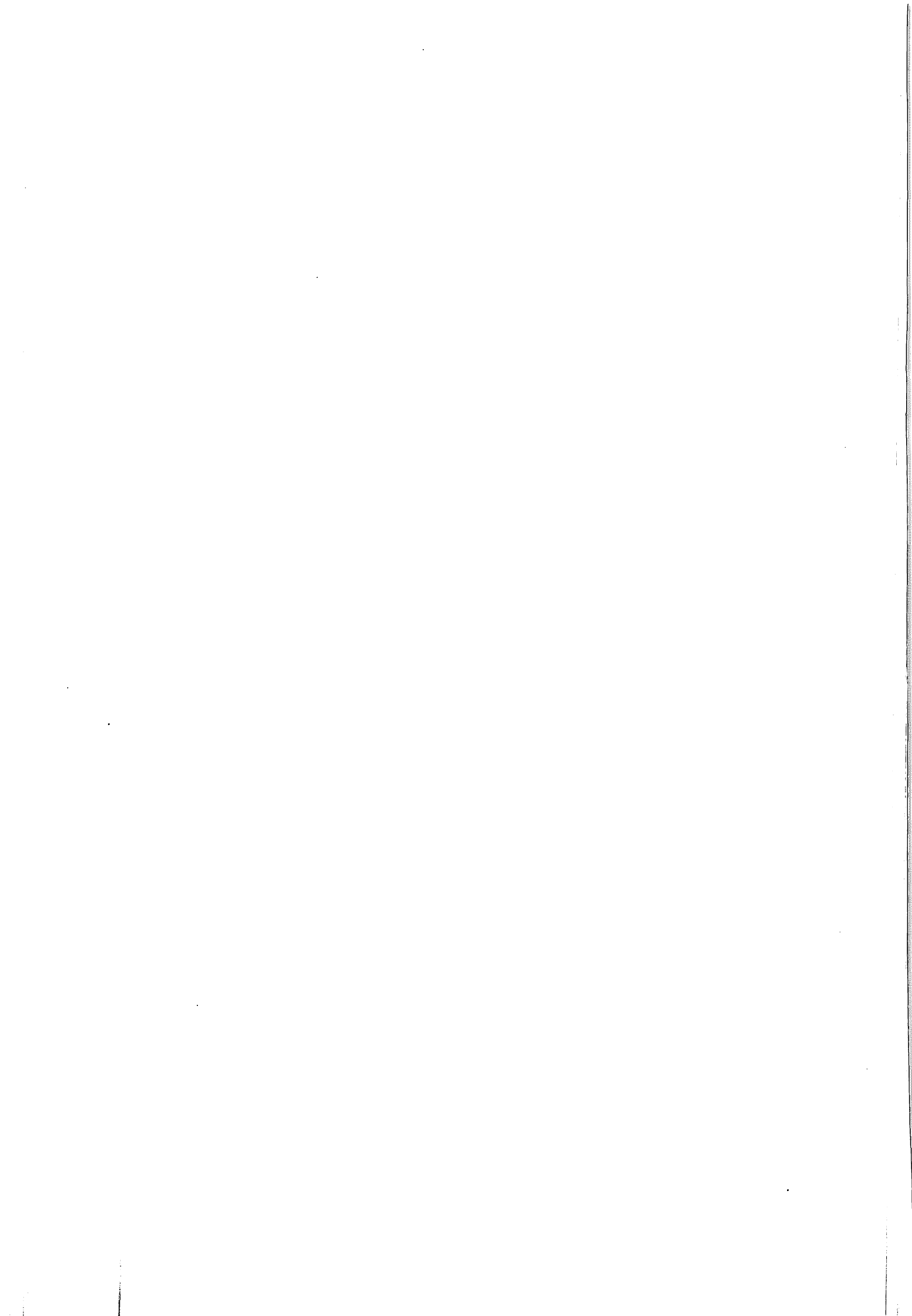


With the participation of:

Mr. Carmel Dallal, Geological Survey of Israel (K-Ar laboratory)

Mr. Peter Kotlarsky, Geological Survey of Israel (K-Ar laboratory)

Mrs. Dina Stieber, Geological Survey of Israel (Geochemical laboratory)



Abstract

New K-Ar ages of about 100 samples from the Harrat Ash Shaam basalt volcanic field in NE Jordan have been obtained. These samples, representing most of the volcanic features in the area, show a wide range of ages from 26 to 22 Ma and from 13 to less than 0.5 Ma. The K - Ar ages suggest that there were three main episodes of volcanic activity in the region: Oligocene to Early Miocene (26 to 22 Ma); Middle to Late Miocene (13 to 6 Ma); and Pliocene to Pleistocene (5 to less than 0.5 Ma). The Middle Miocene basalt flows cover the southern and eastern parts of the region, whereas the Pliocene to Pleistocene basalt flows are found mostly in the north and western parts of the region. There is no evidence for volcanic activity between 22 and 13 Ma.

One of the main observations regarding the ages obtained is that some of the formations as defined by Ibrahim (1993, 1996) have a wide range of ages. For example, samples taken from the Abed Formation yielded a range of ages, which cluster into three groups; 26-22, 13-9, and 5 to less than 0.5 Ma. The Wisad unit, which appears in association with the continental Qirma Formation, shows a narrower range of ages from 13 to ~8 Ma. The basalts above and below the calcareous sandstone of the Qirma Formation in the southern part of the area yielded an age of 12.2 and 11.9 Ma respectively, thus defining the age of the Qirma Formation at that site.

The K-Ar age results complicate the conventional mapping of the volcanics based on the previously established nomenclature. Basing on the integrated data set of basalt facies and field relations, petrology and K-Ar dating, a new stratigraphic scheme for mappable volcanic units in the Harrat Ash Shaam field is suggested.

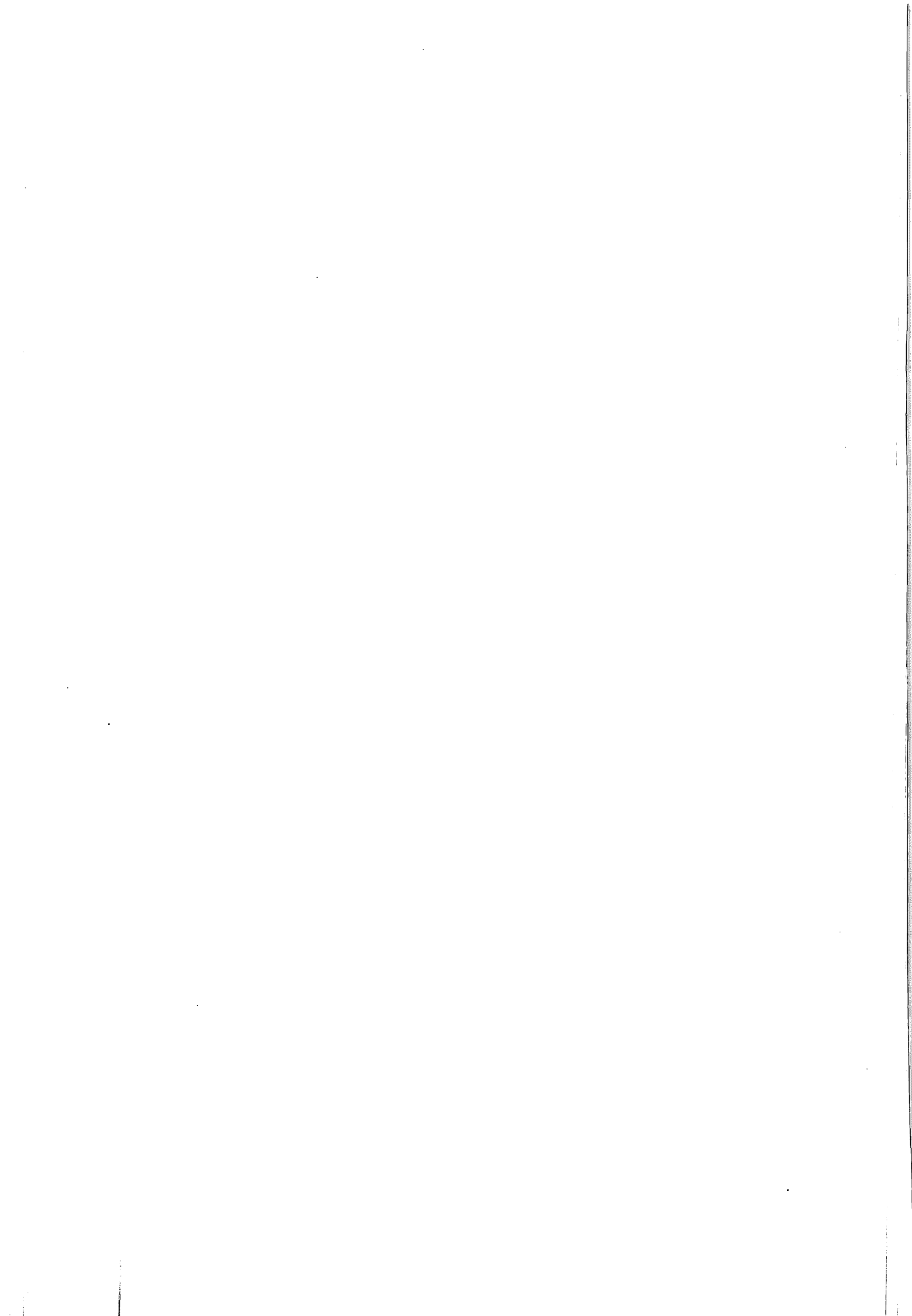
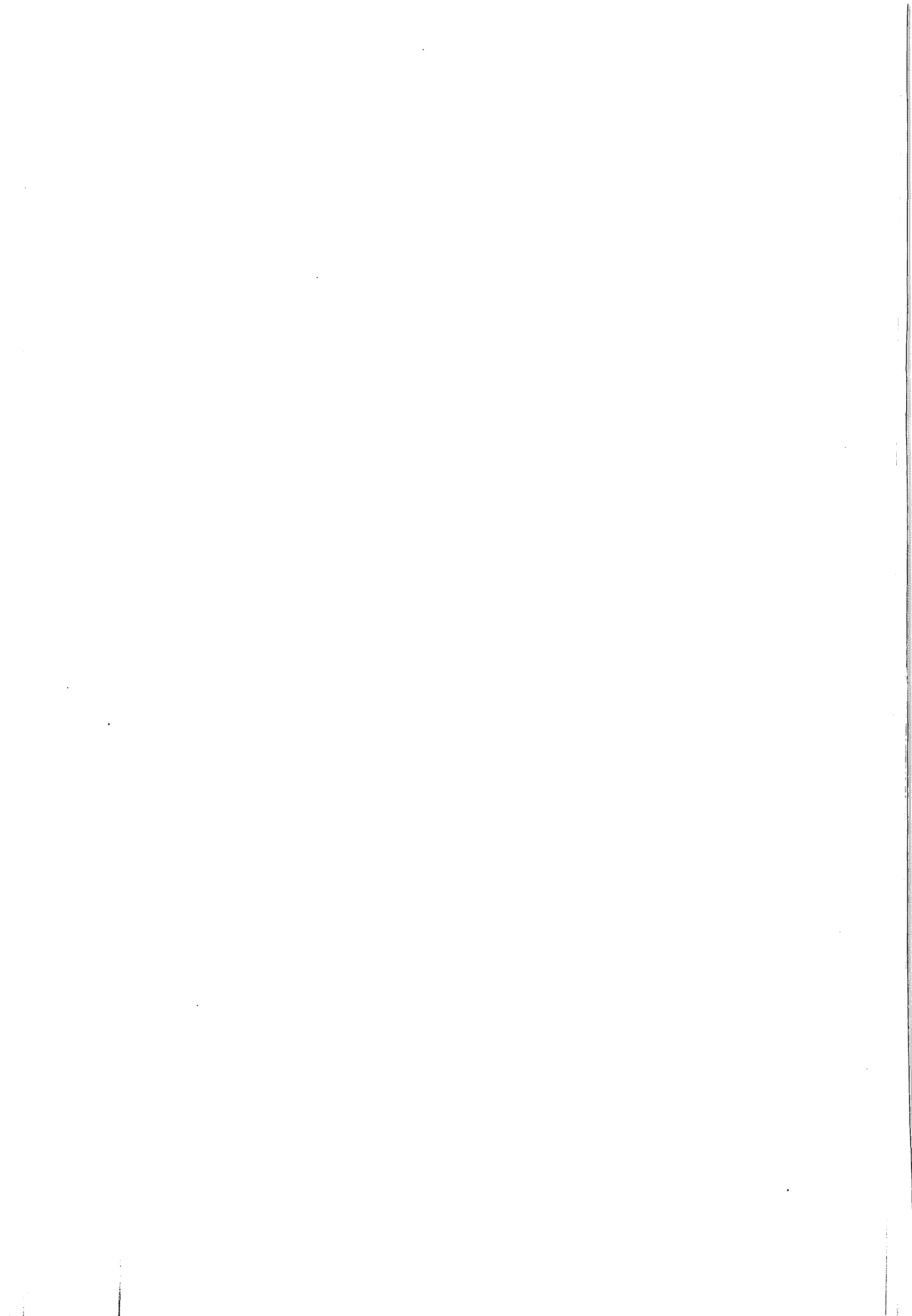


TABLE OF CONTENTS

ABSTRACT	i
CHAPTER 1: INTRODUCTION	1
1.1. BACKGROUND AND RESEARCH OBJECTIVES	1
1.2. REGIONAL SETTING	3
1.3. GEOLOGICAL BACKGROUND	6
CHAPTER 2: METHODS.....	12
2.1. FIELD WORK AND SAMPLING	12
2.2. SAMPLE PREPARATION.....	12
2.3. K-AR GEOCHRONOLOGY	12
CHAPTER 3: RESULTS.....	15
3.1. PETROGRAPHIC DESCRIPTION	15
3.2. CHEMICAL CLASSIFICATIONS AND NOMENCLATURE	20
3.3. AGE DETERMINATIONS	23
CHAPTER 4: DISCUSSION.....	26
4.1. DISTRIBUTION OF BASALTS ACCORDING TO K-AR AGES AND PETROGRAPHY	26
4.2. THE RELATIONS OF K-AR AGES AND THE BASALT PETROTYPES	28
4.3. DIKES AND VOLCANIC CENTERS	31
4.4. CHRONOSTRATIGRAPHIC EVALUATION OF THE DATED VOLCANICS.....	31
4.5. A NEW STRATIGRAPHIC SCHEME FOR THE HARRAT ASH SHAAM VOLCANICS.....	36
CHAPTER 5. CONCLUSIONS	38
5.1. CONCLUSIONS	38
5.2. RECOMMENDATIONS	40
ACKNOWLEDGMENTS.....	40
REFERENCES.....	41
PLATES	43
APPENDIX	

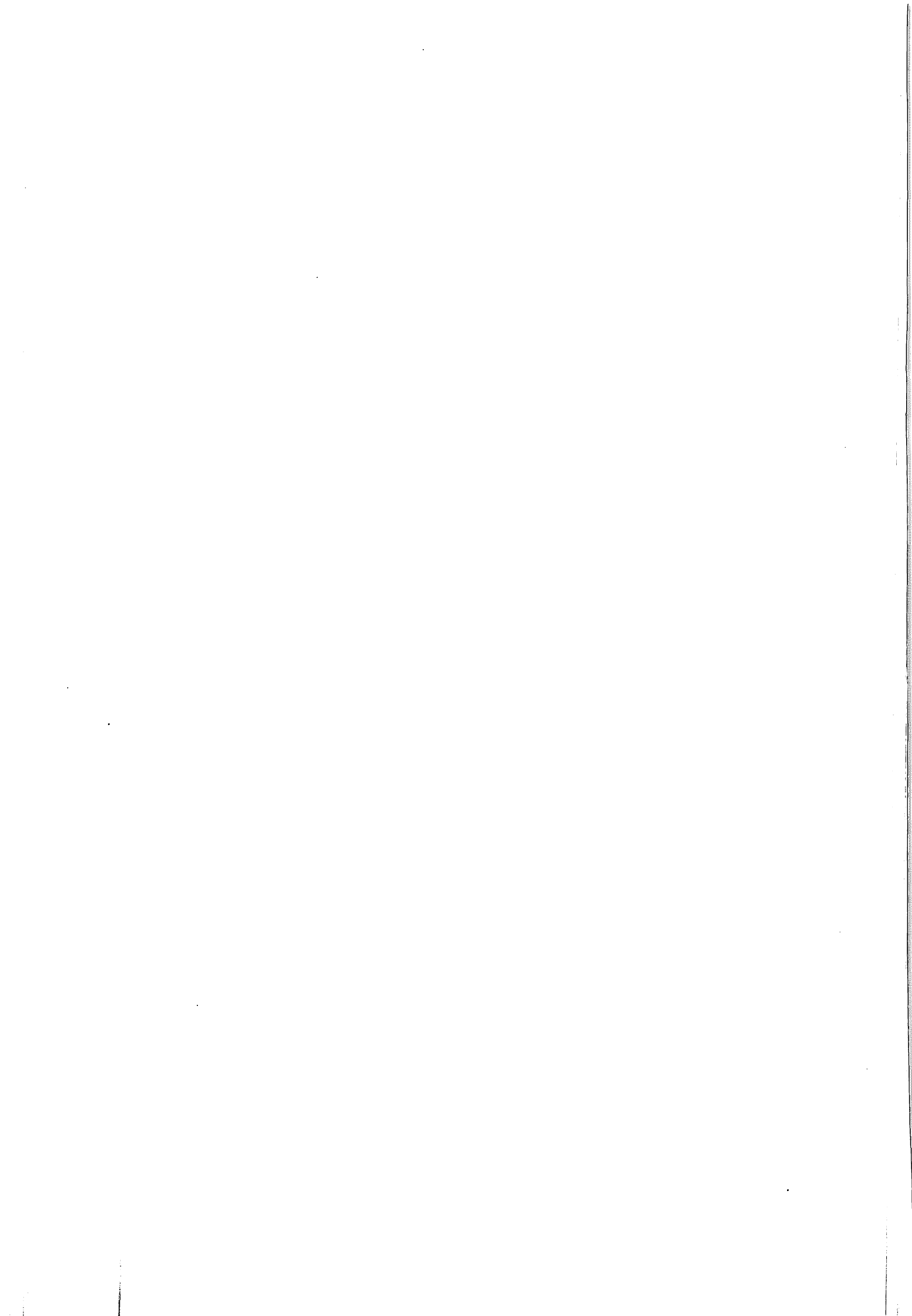


LIST OF TABLES

Table 1. Stratigraphy and previously reported K-Ar ages of the Harrat Ash Shaam basalts following Ibrahim (1996).....	6
Table 2. Distribution of the rock types within the volcanic formations of northeastern Jordan	16
Table 3. Abundance (%) of the basalt petrotypes	16
Table 4. Abundance (%) of the microtextures of the basalt petrotypes.....	19
Table 5. Major element composition of selected samples	20
Table 6. Chemical nomenclature of the volcanic rocks of northeastern Jordan	21
Table 7. New classification based on lithofacies and age, of the Harrat Ash Shaam basalts, northeast Jordan.	37

LIST OF FIGURES

Figure 1. Location of volcanic fields in the Arabian Plate (after Camp and Roobol, 1989).	2
Figure 2. Location map of the Harrat Ash Shaam showing study area, NE Jordan.....	4
Figure 3. Location map of the studied samples, Harrat Ash Shaam, NE Jordan	14
Figure 4. SiO ₂ versus Na ₂ O + K ₂ O variation diagram of 27 samples from the Harrat Ash Shaam. Rock nomenclature after Le Matire et al. (1989)	22
Figure 5. Age histograms of all samples from the different stratigraphic groups.....	24
Figure 6. Age histograms of all samples (A) Abed Formation (B) and Hashimyya Formation (C).....	25
Figure 7. Age distribution of the Harrat Ash Shaam basalts in NE Jordan.	27
Figure 8. Age distribution of the different basalt petrotypes.	29
Figure 9. Relationships between volcanic units, petrography, and chronology.....	30
Figure 10. Stratigraphic scheme of the Harrat Ash Shaam basalts. This scheme is based on the classical stratigraphy following Ibrahim (1993, 1996).	35



CHAPTER 1: INTRODUCTION

1.1. BACKGROUND AND RESEARCH OBJECTIVES

The Badia region in northeast Jordan is defined by the Jordanian government as a priority area in terms of requiring infrastructural development. The region under consideration is a desert, which covers an area of some 12,000 km². It is almost completely covered by a series of horizontal volcanic sequences termed "Plateau Basalt". This plateau basalt is part of a large volcanic field - the Harrat Ash Shaam basalt - extending from northern Israel, through southwestern Syria and northern Jordan into northwestern Saudi Arabia (Fig. 1).

The Natural Resources Authority of Jordan (NRA) is conducting systematic geological mapping projects, for, among others, future exploitation of natural resources such as building materials, industrial minerals (e.g., zeolites, tuff, scoria, glass sand, etc.), development of local water resources and water management systems, planning of engineering and life-line projects, etc.

One of the most important joint activities of the NRA and the GSI is the K-Ar dating of the Harrat Ash Shaam volcanics; and the first stage (phase I) of dating the volcanic rocks covering the area has been carried out. The ages yielded by 25 samples were first presented in Ibrahim et al. (1998), and already contributed to geological mapping of some areas, especially in the eastern parts of Harrat Ash Shaam, as well as to the correlation between volcanic units of basalt flow and pyroclastic units.

The objectives of the project are as follow:

1. to determine a numerical time scale for the Harrat Ash Shaam volcanics;
2. to establish the relationship between the volcanic units in the different areas;
3. to establish a geochronology-based stratigraphic framework for the region at a scale of 1:250,000;
4. to study the petrography and geochemistry of the samples in order to determine the origin of the dated units.

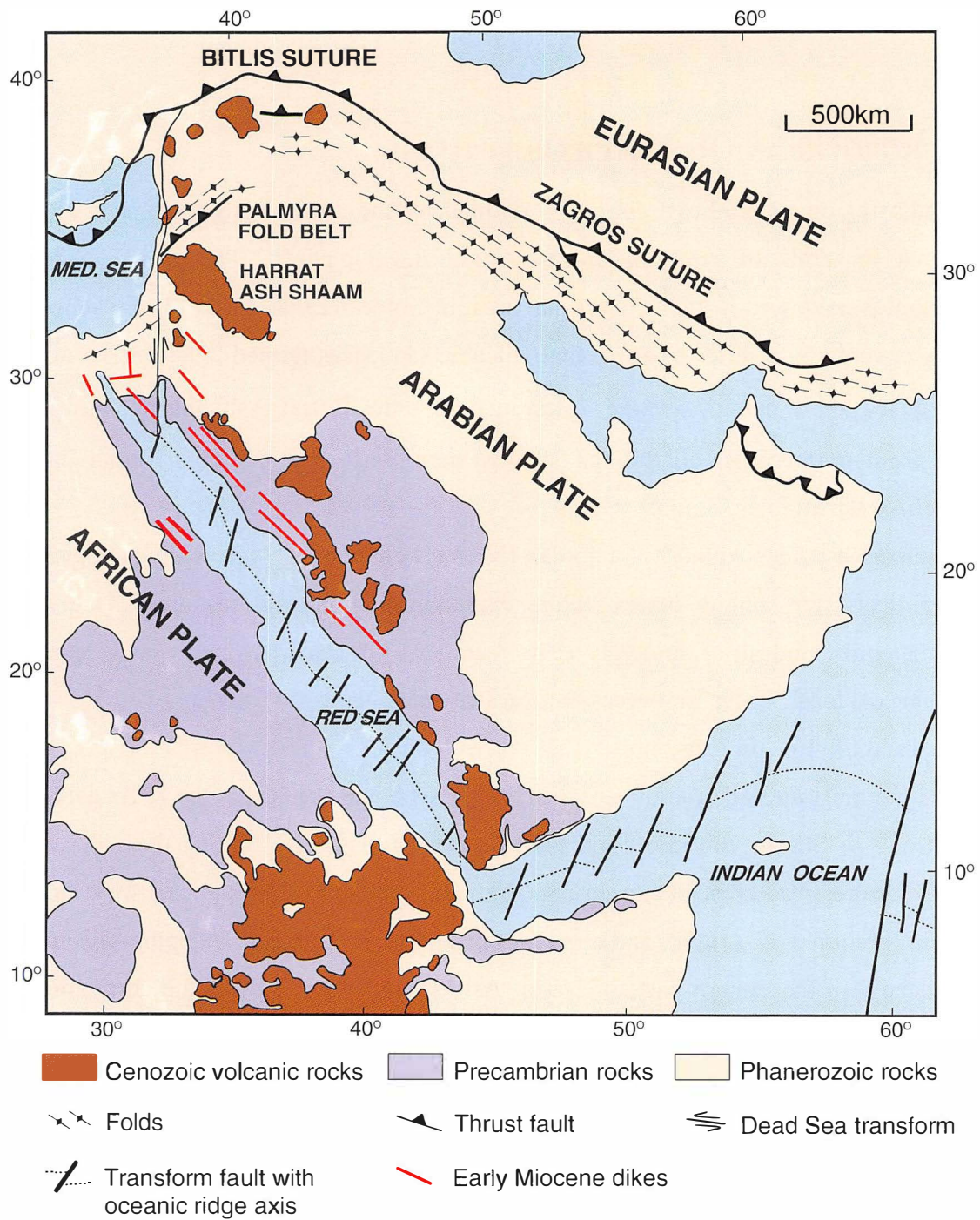


Figure 1. Location of volcanic fields in the Arabian Plate (after Camp and Roobol, 1989)

1.2. REGIONAL SETTING

The volcanic field of the Harrat Ash Shaam is one of several Cenozoic volcanic fields situated on the western Arabian Peninsula (Fig 1). These volcanic fields cover some 200,000 km² with an average thickness of up to 100 m. The volcanism is Oligocene to Holocene in age (Menzies et al., 1997) and is generally associated with the opening of the Red Sea and possibly with faulting along the Dead Sea Transform (Fig. 1). The volcanic activity within these fields can be divided into two main phases; from Oligocene to Early Miocene (~30 – 20Ma) and from Middle Miocene (12 Ma) to recent (Camp and Roobol, 1992). Limited magmatic activity has been reported for the period between 18 Ma to 12 Ma (Arno et al., 1980). The older magmatism is dominated by tholeiitic to transitional basalts and it comprises dikes parallel to the Red Sea axis, intrusive complexes, and a few small volcanic fields (Camp and Roobol, 1992; Coleman and McGuire, 1988). The younger phase consists of mildly to strongly alkaline lavas. Volcanism from this phase is exposed along the Red Sea Rift from Yemen in the south to southeastern Turkey in the north and also up to 1000 km from the Red Sea axis. Camp and Roobol (1992) suggested that the older magmatism with a NW dominant direction is associated with rifting and is mainly extension-related. The younger magmatism has N-S directions and is a result of active mantle upwelling beneath western Arabia. The N-S fissures began to develop on the Arabian plate about 15-12 Ma, in response to the collision of the Arabian and the Eurasian plates.

One of these Cenozoic fields is the Harrat Ash Shaam volcanic field, which stretches from Syria in the northwest to Saudi Arabia in the southeast (Fig. 2).

The northern part of the Harrat Ash Shaam is the Haurun-Druze Plateau in Syria, which extends 500 km in a NNE direction, and is 200 to 300 km wide. The ages of basalts there range from ~20 Ma to present (Giannerini et al., 1988; Sharkov et al., 1994). The Early Miocene basalts (~ 20 Ma) cover an area of over 200 km² in the northern part of the Haurun-Druze Plateau and are 400 m thick (Giannerini et al., 1988; Sharkov et al., 1994). These basalts unconformably overlie Cretaceous and Paleogene sediments, and are overlain by Pliocene to Quaternary basalts. Neogene to Quaternary continental and lacustrine deposits cover the Miocene basalts in the Damascus Basin. The Miocene basalts are of normal and moderate alkalinity.

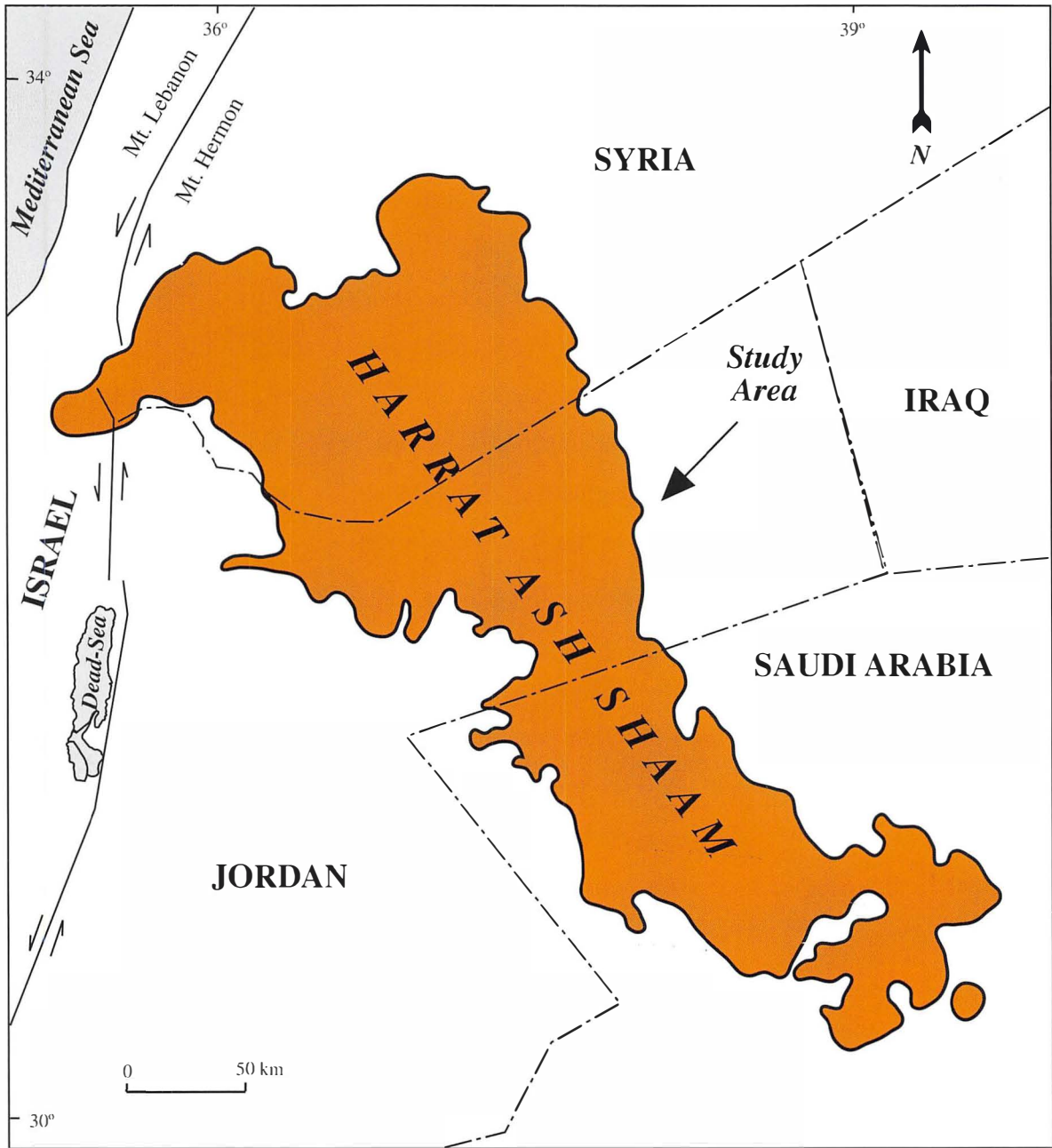


Figure 2. Location map of the Harrat Ash Shaam showing study area, NE Jordan

In the southeastern part of the plateau, Giannerini et al. (1988) reported four K-Ar ages of basalts ranging from Late Miocene to Early Pliocene (7-3Ma). In the southwestern part of the plateau Late Pliocene to Quaternary ages (2.2 ± 0.1 - 0.3 ± 0.2 Ma) were reported by Sharkov et al. (1994). In the 17th century monks witnessed eruptions in the area of the Safa volcanic center (Gushchenko, 1979). Basalt flows, which overlie cultivated soils in the Hirbet Al Ambashi Neolithic site, indicate volcanic activity younger than 7000 years.

The Harrat Ash Shaam basalt field extends to Saudi Arabia along the northeastern flank of Wadi Sirhan. It covers about 15,200 km² of Saudi Arabia, where it was studied and described by Brown et al. (1984). There the basalt flows extend southeastward 210 km in a belt averaging 75 km in width with a maximum relief of 300 m and reaching altitudes up to 1100 m. There are many flows and craters, calderas and cones. The lower flows are interbedded in calcareous lacustrine sediments, and were dated by K-Ar from 13.4 to 11.4 ± 0.4 Ma ($30^{\circ}50'N$ / $38^{\circ}10'E$). Test drilling beneath the sabkha near the sampled localities encountered as much as seven basalt flows interbedded in the lacustrine sediments, the lowermost 186 m below the dated flows on the surface (Smith, 1980). The unnamed lacustrine beds in these localities are 150 m thick and disconformably overlie the Paleocene-Eocene Hiber Formation.

A younger basalt flow of Late Pleistocene age exhibits erosion followed by accumulation of tuff and cinder cones. Eruptions from basalt cones aligned along tectonic lines parallel to the Red Sea have continued up to historic times (Bender, 1975). The southeasternmost basalt fields of the Harrat Ash Shaam in Saudi Arabia are considered Pleistocene to Holocene, with the reservation that some of the lowermost flows may be Pliocene (Brown et al., 1984).

1.3. GEOLOGICAL BACKGROUND

The stratigraphic succession of the Harrat Ash Shaam basalts in NE Jordan (Fig. 2) is described in detail in Ibrahim (1993, 1996), Tarawneh (1999a,b) and Rabb'a (in press). The description herein follows the stratigraphic scheme in use up to the present study. In places some information is added such as the upper section of the Wisad Group. The brief description below, from the base to the top, follows Table 1.

Table 1. Stratigraphy and previously reported K-Ar ages of the Harrat Ash Shaam basalts following Ibrahim (1996).

Group	K-Ar age (Ma)	Formation
Bishriyya	1.45 - 0.1	Fahda Vesicular Basalt Wadi Manasif Basalt
Rimah	2.94 - 2.01	Hassan Scoriaceous Aritayn Volcaniclastics
Asfar	3.41 - 1.96	Mahada Basalt Madhala Olivine Phyric Basalt Hashimyya Aphanitic Basalt Ushayhib Olivine Pyroxene Phyric Basalt Ufayhim Xenolithic Basalt
Safawi	9.30 - 8.45	Salaman Flood Basalt Abed Olivine Phyric Basalt Ali Doleritic Basalt
Continental / Marine Sedimentation of Qirma		
Calcareous Sandstone		
Wisad	10.53 - 9.3, 13.7	

1.3.1 Wisad Group

Wisad

The lower part comprises several flood flows, shield volcanoes, and dike systems. The unit crops out mainly in the southeastern part of the basalt province, mainly in Jabal Al Wisad and to the northeast of Abar Al Hazim, surrounding the Jabal edh Dherwa volcanic center. The flows are subaerial pahoehoe basalts related to shield volcanoes, and are highly weathered compared to other basalts. Individual dike systems are composed of intrusive centers, seen as prominent hills. Secondary fault systems are associated with these structures. Usually, the basalts have a relatively smooth landscape (Plate 1a). They are gray to light gray, fine to medium grained, massive, uniform and melanocratic with intergranular dolerite and inequigranular textures. The K-Ar ages measured by Moffat (1988) on two samples are 9.3 Ma and 10.5 Ma.

Wadi es Sibhi Formation (upper Wisad)

This formation is newly determined in the southeast part of the Harrat Ash Shaam by Rabb'a (in press). According to the newly obtained K-Ar age determinations and field relations it should be the upper part of the Wisad Group. The formation reaches up to 25 m in Wadi es Sibhi. It overlies the purple calcareous sandstone of the Qirma Formation (Plate 1b, 1c, and 1d). The morphology of the unit is characterized by a cliff composed of basalt flows with horizontal jointing, which forms basalt plates, up to 20 cm thick. The basalt is fine-grained, black to dark gray, and fresh. In the upper part of the unit it has light and dark spots. The most distinctive feature is the presence of olivine xenoliths (0.5-2 cm) highly weathered to iddingsite.

1.3.2 Safawi Group

The Safawi Group is a complex unit consisting of several doleritic flood flows and feeder dike systems while central volcanoes are absent in the group. The outcrops of the group are widespread relative to other basalt units. The most important outcrops are in the Al Azraq, As Safawi, and Wadi Al Abid areas. The surface of the Safawi basalts is rugged and includes irregular-shaped basalt boulders of up to 1 m in diameter. Vesicular pipes are common and thus indicative of the basalts of this group (Plate 2a). On the surface jointing forms prominent massive columnar polygonal blocks (Plate 2b).

K-Ar radiometric ages of 8.4 Ma and 9.3 Ma were yielded for the Safawi Group (Moffat, 1988).

Three mappable formations are defined within this group (from bottom to top).

Ali Doleritic Basalt

The individual flow units of the Ali basalts are a few meters thick (Plate 2c) exhibiting horizontal jointing. The total thickness of the unit reaches up to 25 m. The most distinctive feature is the presence of dark brown euhedral crystals of pyroxene. This is the only formation in which a trachytic texture occurs.

Abed Olivine Phyric Basalt

The Abed basalts are usually comprised of massive basalt flows up to 10 m thick and with a total thickness up to 100 m. This formation has the most extensive outcrops in the area. The Abed basalts are characterized by the presence of rounded clots, pipes, and cylindrical vesicles forms, and they are weathered light brown, dark brown and blackish gray (Plate 2d).

Salaman Flood Basalt

The Salaman basalts are composed of thin flows with a total thickness of 10-25 m. The individual flows, like those of the Ali basalts, exhibit typical horizontal jointing. The Salaman basalt is characterized by its fine surface flow and dendritic drainage pattern with darker tones.

1.3.3 Asfar Group

The Asfar Group is defined as those volcanic formations which post-date the regional Safawi flood basalts and the associated dike systems and pre-date the locally developed Bishriyya Group. The Asfar Group crops out in the area of Jabal Aritayn, Jabal Asfar and Tulul Al Ashaqif. Typically, lavas of the group flowed from shield volcanoes and stratovolcanoes. The group comprises several flood basalts and dike systems. Previous radiometric K-Ar ages for the Asfar Group are younger than 5 Ma, mostly in the range between 3.4 Ma and 1.96 Ma (Moffat, 1988). Barberi et al. (1979) reported an age of 3.5 Ma for a sample taken from the group in the As Safawi area. Five formations of basalt flood lava are recognized (from base to top).

Ufayhim Xenolithic Basalt

The Ufayhim basalts, 15-20 m thick, typically display columnar jointing and non-systematic horizontal jointing (Plate 3a). Pahoehoe structure occurs in places at the top of the flows. The ground cover is very smooth, brown to black in color, with an average boulder size of less than 10 cm in diameter. On aerial photographs the Ufayhim basalts exhibit dark color tones and have a distinctive morphological pattern. They are

characterized by the presence of very large amounts of mantle-derived olivine xenoliths, up to 60% of the rock. The xenoliths vary in size from 1 to 10 cm and are granular, orange, olive brown olivine, and have a small content of dark green tabular pyroxenes.

Ushayhib Olivine Pyroxene Phyric Basalt

The Ushayhib basalts are up to 15 m thick, generally forming a dark gray to dark brown sub-vertical cliff above the plain. Angular boulders of relatively uniform size cover its surface (Plate 3b).

Hashimyya Aphinitic Basalt

The Hashimyya basalts morphologically appear similar to the Ufayhim basalts. It comprises thin flows, mostly between 3 and 5 m, totaling less than 10 m thick, (Plate 3c). It contains in places mantle xenoliths, less than 1 cm in size, brown in color and highly weathered secondary calcite. It is mainly associated with the main volcanic centers.

Madhala Olivine Phyric Basalt

The Madhala basalts are the most widespread unit of the Asfar Group and are associated with shield volcanic centers. The latter are asymmetrical, circular to elliptical in shape and are built up by fluidal basalt lava flows, which erupted either from central vents, flank eruptions, or from both. In places the volcanic centers are composite. Upon weathering a relatively smooth ground surface is formed. The weathered basalt boulders, mainly 5-30 cm in diameter, are dark brown, black, and gray in color. Many have a light brown lime crust. Non-systematic joints and columnar jointing are present.

Mahada Basalt

The Mahada basalt differs from the other basalts of the group by its rough upper surface which comprises slightly weathered wadi-fill lava flows with poorly preserved pressure flow ridges. Morphologically the unit forms a positive feature above the planar surface developed on the older Madhala basalts. However, the shape and size of the surface-cover boulders resemble those of the rest of the group. The flow fronts are characterized by scoriaceous surfaces covered with boulders. The K-Ar ages 2.3 to 3.4 Ma were obtained for the Madhala basalts (Barberi et al., 1979).

1.3.4 Rimah Group

The Rimah Group is defined on the basis of its lithotypes only. It comprises volcano-sedimentary and scoriaceous deposits devoid of specific inference as to their magmatic source and age. This simplification is necessary at this stage as it is difficult to differentiate between volcanoclastic sediments from different magmatic sources due to lack

of detailed studies and lack of age determinations. This terminology is consistent with Bender's (1974) nomenclature. The Rimah Group comprises the two formations associated with the Asfar Group

Aritayn Volcaniclastics

The Aritayn Volcaniclastics consist of bedded, poorly cemented air-fall pyroclastics and are typified by their stratified form and typically cavernous morphology. They are characterized by a smooth ground cover surface and are weathered black, brown, red brown and gray. The boulder cover is mainly from the pyroclastic material mixed with basalt boulders. Composite stratovolcanic centers and a maar (Jabal edh Dherwa) (Plate 3d) within the formation are typically symmetrical with steeply dipping pyroclastic deposits. The formation comprises layered fine-grain ash deposits of variable colors and angular and spherical lapilli, as well as basalt bombs up to 2 m in diameter (Plate 4a). The tuff, the volcanic breccia and the agglomerate are poorly-cemented.

K-Ar ages of samples from the Aritayn volcaniclastics range between 2.94 and 2 Ma (Moffat, 1988)

Hassan Scoriaceous

The Hassan Scoriaceous Formation is built of scoria in and around scoria cones. The formation exhibits a smooth ground cover over these cones with weathered surface colors of brown, red brown, black and gray. The boulder cover around such cones tends to be a mixture of basalt lava flow boulders and scoriaceous material. The cones are 20-35 m high and are often circular and accompanied by ring dikes, usually steeply dipping toward the center. They are highly susceptible to weathering and erosion, which modify their morphology. The scoria cones occur as isolated cones, but also as parasitic cones on polygenetic shields and stratovolcanoes. The deposits of the cones include bombs of various shapes and coarse scoria. The formation comprises poorly bedded, very coarse-grained, red-brown scoria with meter-sized ballistic bombs and blocks. In many cases the beds do not represent air-fall layers but rather include mass flow deposits formed by scoria avalanching and sliding along the slope. Layers of agglomerate lava spatter and scoria are present (Plate 4b). Accessory lithic inclusions from the country rocks and mantle xenoliths occur in the formation.

1.3.5 Bishriyya Group

The Bishriyya Group consists of the youngest volcanics observed in the study area. It corresponds to most of the B6 basalt of Van Den Boom and Sawan (1966) and Bender

(1974). The group comprises the Wadi Manasif and the Fahda formations which are differentiated based on stratigraphy, through their lithology and morphology are similar. The characteristic features of the Bishriyya Group are: the dark color, the low degree of weathering; linear pressure ridges (Plate 4c); dark tone on aerial photographs and Landsat images; a pock-marked appearance and drainage pattern; lack of thick soil cover; absence or rarity of iddingsitization in olivine.

The occurrence of the group is associated with units of the Asfar Group. Lavas of the group comprise fresh blocky and some pahoehoe flows. The basalt flows are up to 15 m thick, dark gray, fine-grained, uniform, dense and hard, with polygonal joints (Plate 4d). According to Moffat (1988) three K-Ar radiometric ages obtained for the FHA formation are 1.45, 0.48, and younger than 0.1 Ma. Barberi et al. (1979) mentioned two ages, younger than 2 Ma and younger than 0.5 Ma.

1.3.6 Dikes

Interpretation of aerial photographs of different scales and Landsat TM images indicates that a major dike system crosses the area, trending NW-SE. However, there are also minor dikes in many parts of the study area trending NW-SE, E-W, and N-S. Field observations show that the dikes intruded all formations and have different lithological compositions, mainly the same compositions as the Abed basalts.

The major dikes have a wide distribution, and form positive features such as linear ridges or isolated hills (Plate 5a). The prominent Qitar Al Abid dike extends up to 100 km in length with a variable width of 100 to 500 m, aligned along a fissure zone (Plate 5b). Other dikes are up to 10 km long and 50 to 200 m wide (Tarawneh, 1999a,b).

The dikes within the Abed basalts are up to 100 m thick and consist of dense, hard, black to reddish basalts that impart a rough surface to the outcrop, whereas the other basalt dikes are up to 20 m thick and are associated with other groups (Plate 5c,d).

The dikes observed in the study area are quite similar in lithological characteristics but differ in mode of weathering and in the degree of olivine alteration. Megascopic studies indicate that the dikes are composed of holocrystalline basalts, medium to fine grained, porphyritic, and amygdaloidal. Olivine, plagioclase, and pyroxene are the essential mineral phases. Petrographic studies confirm that the dikes display several types of textures such as vesicular porphyritic, embayment, corona, amygdaloidal and subophitic (Tarawneh, 1999a,b).

CHAPTER 2: METHODS

2.1. FIELD WORK AND SAMPLING

In the course of five joint field trips to the study area (Fig. 3) typical and critical outcrops were visited and sampled, covering both the whole known stratigraphic sequence as well as forming a wide and representative geographic distribution. About 120 samples were collected which represent the various basalt flows, basalt dikes and cones, as well as scoriaceous and pyroclastic material from volcanic centers. Most were taken close to contacts between flows, or from sites, which are important for understanding the stratigraphy and the geological mapping of the area. The sample location and the related formation are presented in Appendix, Table A.

2.2. SAMPLE PREPARATION

Samples were broken down in the field to hand sized fragments and a representative aliquot was collected for storage and reference at the NRA.

A thin section was prepared from each sample for petrographic determinations. Some samples were prepared for detailed petrographic study with the SEM at the GSI. Each sample was crushed and sieved to an 80-100 mesh size fraction. This was followed by the separation of secondary minerals (calcite, zeolite etc.) using a Frantz magnetic separator. A representative aliquot was dissolved and analyzed for major element content using a Perkin Elmer Optima 3300 instrument (ICP-AES) at the GSI.

2.3. K-AR GEOCHRONOLOGY

Samples were dissolved using Lithium meta-borate (LiBO_2) and K concentrations were determined using ICP-AES ($1\sigma < 3\%$). The argon analysis was performed using the standard isotope dilution procedures (K-Ar) of the geochronological laboratory at the Geological Survey of Israel (Steinitz et al., 1983; Kotlarsky et al., 1992). Samples were loaded into the glass arm of a metal extraction line and heated overnight at 120°C . Argon was extracted in a molybdenum crucible using RF induction heating. The gases were scrubbed by using liquid nitrogen and ZrAl getters. Argon was concentrated on a charcoal finger and let into a MM-1200 mass spectrometer. Duplicates of argon and %K analyses (asterisk in Table C, Appendix) were performed on about 30% of the samples.

Hot blank of the extraction line was determined at the beginning of each measurement day and at the end of that day and air measurements were performed. The air value was used in determining the mass spectrometer background and was taken into consideration when calculating the age following the procedure outlined by Kotlarsky (in prep.).

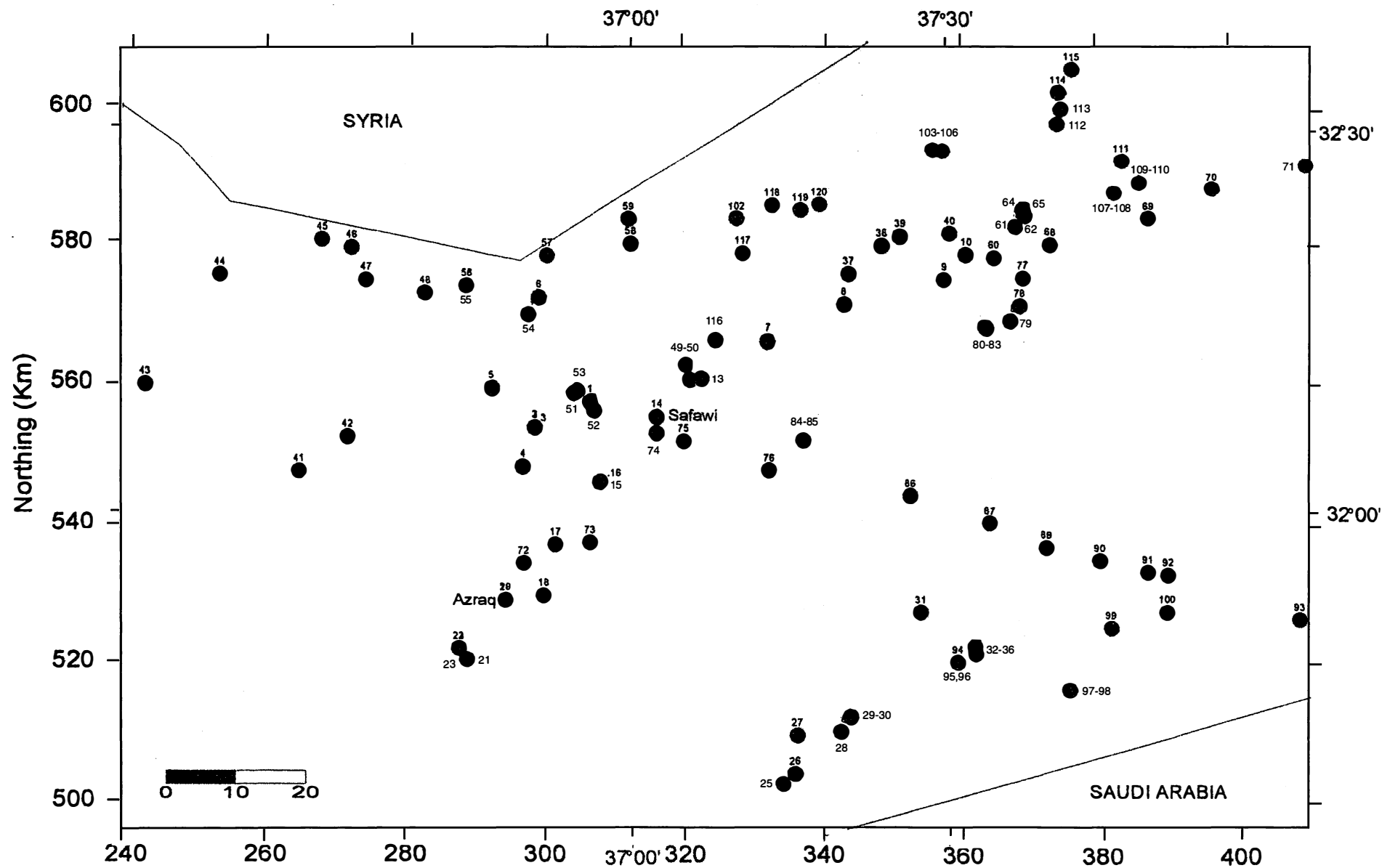


Figure 3. Location map of the samples studied, Harrat Ash Shaam, NE Jordan

CHAPTER 3: RESULTS

3.1. PETROGRAPHIC DESCRIPTION

A detailed microscopic study of the mineralogy, structure and texture of 118 samples was performed. The petrographic data for each sample are presented in Table B, Appendix. These samples represent seven rock types. The different rock types according to the volcanic units are presented in Table 2.

Olivine basalts are found in all the formations and compose 22% of all the 118 samples examined (Table 3). The basalts with olivine-pyroxene and with pyroxene-olivine are present in most of the volcanic formations (Table 3), representing 32% of the investigated samples. Olivine-iddingsite basalts and iddingsite basalts were encountered in a great number of the basalt formations (Table 2), representing 25% of the basalt types (Table 3). The pyroxene-olivine microdolerites were encountered only in the Wisad, Ali, and Abed formations (Table 2), representing 10% of the basalts of the area. The volcanoclastics are characteristic of the Aritayn Formation and represent only 4% of all the samples examined.

The results show that the olivine basalt with pyroxene is the representative rock type, the *petrofacies signature* for the sampled area.

The mineral assemblages include different combinations of labradorite, olivine and/or iddingsite, pyroxene and iron oxides. Most of the Miocene volcanics have olivine totally or partially substituted by iddingsite.

Most (65%) of the rocks examined are vesicular. Medium vesiculation is common in the basalt flows of the area, whereas strong vesiculation is representative for the scoriaceous products. The vesicles are of various sizes, commonly up to 5 mm. The small vesicles are mostly spherical in shape, whereas the big vesicles are irregular. Some of the pores and vesicles are empty, others are partially or totally filled with secondary minerals, predominantly calcite, and also zeolites, chalcedony, and opal, which characterize the alveolar structure (8% of the samples).

Table 2. Distribution of the rock types within the volcanic formations of northeastern Jordan*

Formation	Olivine Basalt	Olivine-Iddingsite Basalt	Iddingsite Basalt	Olivine-Pyroxene Basalt	Pyroxene-Olivine Basalt	Pyroxene-Iddingsite Basalt	Dolerite	Pyroxene-Olivine Micro-Dolerite	Volcanic-clastics
Fahda	+	+	-	+	+	-	-	-	-
Manasif	+	.	-	+	.	-	-	-	-
Aritayn	-	-	-	-	-	-	-	-	+
Hassan	+	.	-	-	.	-	-	-	-
Mahada	-	-	-	+	-	-	-	-	-
Madhala	+	.	+	+	+	-	-	-	-
Hashimyya	+	-	+	-	-	-	-	-	-
Ushayhib	+	.	-	+	.	-	-	-	-
Ufayhim	+	+	+	-	-	-	-	-	-
Salaman	-	+	-	+	.	-	-	-	-
Abed	+	+	+	+	+	+	+	+	-
Ali	-	.	+	+	.	-	+	-	-
Wisad	-	+	+	-	-	-	+	-	-

(*) – absent and + present

Table 3. Abundance (%) of the basalt petrotypes (n = 118)

Petrotype	Number of samples	Abundance (%)
Olivine Basalt	25	22
Olivine-Iddingsite Basalt	14	12
Iddingsite Basalt	16	13
Olivine-Pyroxene Basalt	17	14
Pyroxene-Olivine Basalt	21	18
Pyroxene-Iddingsite Basalt	8	7
Pyroxene-Olivine Microdolerite	12	10
Volcanicclastics	5	4

3.1.1. Petrographic description by volcanic formations

The following description follows the stratigraphic scheme used by Ibrahim (1993, 1996). The volcanic units are presented as formations/group.

Hand specimens of the **Wisad Group** are gray to light gray in color, fine to medium-grained and massive. Under microscope the Wisad basalts are porphyritic and inequigranular holocrystalline, intergranular, subpilotaxitic subophitic and microlitic. The rock types of the group are olivine iddingsite basalt, iddingsite basalt and pyroxene-olivine microdolerite (Appendix, Table B). The groundmass of the microdolerites includes calcite and chlorite as patches or interstitial filling.

The samples of the **Ali Formation** exhibit medium-grained phaneritic and equigranular rocks of a light gray color; they comprise iddingsite basalt, olivine-pyroxene basalt and pyroxene-olivine microdolerite (Appendix, Table B) and are porous and vesicular. In some of the microdolerites mantle xenoliths of pyroxenite were encountered. Microscopic studies revealed that the Ali Basalt is a porphyritic rock with pyroxene phenocrysts, displaying a variety of microtextures, e.g.,: intergranular, trachytic, ophitic and subophitic.

The **Abed Formation** is medium to coarse-grained porphyritic and microvesicular; light brown, dark brown and blackish gray in color. All the rock types encountered in the sampled area were identified in this formation (Table 2). Most of the rocks are intergranular; the presence of the intergranular-subophitic, pilotaxitic and trachytic microtextures is notable.

The petrography of the **Salaman Formation** is similar to that of the Abed Formation. However, it comprises only olivine-iddingsite basalt and olivine-pyroxene basalt.

The **Ufayhim Formation** is fine to very fine-grained rock that shows porphyritic and microporphyritic textures microlitic and subpilotaxitic microtextures. It consists of the following rock types: olivine basalt, olivine-iddingsite basalt, iddingsite basalt (Appendix, Table B). The iddingsite basalts are highly impregnated with opaque grains. Part of the olivine of the Ufayhim basalts is altered to serpentine and not to iddingsite, which is exceptional for basalt rocks in the area sampled where most of the olivine basalts are altered to iddingsite.

Notable is the presence of a very large amount of mantle-derived xenoliths representing up to 60% of the volume of the rock. They range in size from 1 to 10 cm, and are constituted of olivine and pyroxene.

The **Ushayhib Formation** is usually melanocratic, gray and very fine-grained, exposing mainly a glomeroporphyritic texture composed mainly of pyroxene segregations. The formation includes two rock types, namely olivine basalt and olivine-pyroxene basalt. The microtextures are microlitic, subpilotaxitic and hyalopilitic (Table 4).

Basalts of the **Hashimyya Formation** are gray to grayish, very fine-grained hypocrystalline rocks. Their texture is microporphyritic and the microtexture of the groundmass is microlitic, pilotaxitic and hyalopilitic (Table 4). They contain occasional mantle xenoliths. The representative rock types are olivine basalt and iddingsite basalt (Appendix, Table B). The presence of subphenocrysts and microlites of feldspar and melanocratic minerals is notable. The groundmass is rich in patches of opaque minerals. Hand specimens show many vugs filled with calcite. In general, the rocks show laminated white calcite.

The **Madhala Formation** is phaneritic, fine to medium-grained. The representative rock types are: olivine basalt, iddingsite basalt, olivine-pyroxene basalt, pyroxene-olivine basalt (Table 2). The basalt is porphyritic and glomeroporphyritic with a variety of microtextures: intergranular, pilotaxitic, subpilotaxitic, fluidal and trachytic (Table 4).

The **Mahada Formation**, comprises a porous-vesicular olivine-pyroxene rock exhibiting a porphyritic texture and an intergranular-trachytic microtexture.

The basalts of the **Fahda and Wadi Manasif** formations are fine-grained, phaneritic rocks, exposing glomeroporphyritic and porphyritic textures, intergranular, pilotaxitic and trachytic microtextures. The following rock types were encountered: olivine basalt, olivine-iddingsite basalt, olivine-pyroxene basalt and pyroxene-olivine basalt (Tables 2 and 4).

The basalt rocks exhibit a great variety (n=118) of groundmass microtextures (Table 4). Many of the rocks examined (30%) exhibit an intergranular microtexture, or a microlitic microtexture (15%). The subophitic-ophitic microtexture is characteristic for the granular rocks and represents only 3% of the samples.

3.1.2. Volcaniclastic rocks

The volcaniclastic rocks belong to the Aritayn and Hassan formations, and occur as layers between the flows or as volcanic cones. Pyroclastics consisting of scoria and tuffs represent the most abundant lithotype in the succession of the volcaniclastics. The scorias are porous and highly vesicular. The “cement” of pores and vesicles consists of a black or black-brownish vitric material including micronolites and microlites of feldspar and also

crystals and fragments of plagioclase, olivine and augite. Calcite, opal, and argillitic minerals are present within some vesicles. Tuffs are medium and fine-grained; their matrix is vitric, porous and highly opacified, and includes: fragments of crystals of feldspar, augite and hypersthene; fragments of phyric-vesicular basalt, spots of argillic and calcite material.

The *mixed tuff* is characterized by the presence of vitric basalt rock, carbonate rock fragments and fragments of clastic rocks.

Table 4. Abundance (%) of the microtextures of the basalt petrotypes (n = 118)

Microtexture of the groundmass	%
Fluidal	4
Pilotaxitic	4
Subpilotaxitic	9
Subpilotaxitic-fluidal	5
Microlitic	15
Microlitic-subpilotaxitic	3
Trachytic	3
Subtrachytic	3
Pilotaxitic-trachytic	3
Intergranular	30
Intergranular - pilotaxitic	5
Intergranular - trachytic	4
Intergranular - subophitic	9
Subophitic - ophitic	3

3.3.3. Dike petrography

The dikes are composed of three basalt rock types; pyroxene-iddingsite basalt, olivine-iddingsite basalt and olivine basalt.

3.2. CHEMICAL CLASSIFICATIONS AND NOMENCLATURE

Major-element analyses were carried out on 27 samples representing most of the volcanic formations, in order to establish the chemical nomenclature of the rock types. Based on a SiO₂ versus Na₂O+K₂O variation diagram (Table 5 and Fig. 4), the analyzed rocks fall in the basalt, trachybasalt, basanite, and foidite fields. Most of the rocks are alkali and subalkali basalts. For the fine-grained rocks of Hashimyya and Ushayhib, the Wisad microlitic rocks and the Aritayn scoria, the modal composition is not relevant to their denomination. This observation was confirmed by the chemical nomenclature, which indicates that the analyzed rocks are in fact more alkaline than common basalts, namely they are foidite, basanite and sodic trachybasalt (Hawaiiite) (Table 6). Notably, all the iddingsite basalts (Hashimyya and Wisad) are more alkaline basalt rocks, namely basanites.

Table 5. Major element composition of selected samples (n = 27).

Sample	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	TiO ₂	CaO	MgO	MnO	Na ₂ O	K ₂ O	P ₂ O ₅	SO ₃	L.O.I	Total
HAS-3	47.2	16.2	11.6	2.3	10.9	6.7	0.16	3.0	0.8	0.3	0.4	<0.1	99.6
HAS-5	47.9	14.8	12.3	2.1	9.5	9.2	0.17	3.0	0.8	0.3	<0.1	<0.1	100.1
HAS-6	47.4	14.5	13.3	2.2	8.7	9.3	0.17	2.9	0.7	0.3	<0.1	<0.1	99.5
HAS-7	47.0	14.6	12.7	2.2	9.5	9.7	0.1	3.2	0.9	0.4	<0.1	0.6	100.9
HAS-8	46.7	15	12.8	1.8	9.5	9.2	0.17	3.3	0.6	0.2	<0.1	0.1	99.4
HAS-9	47.5	15.6	12.4	2.5	10.7	4.0	0.17	3.1	0.8	0.4	0.1	2.2	99.5
HAS-10	46.5	14.6	12.6	2.0	9.5	9.6	0.17	3.2	0.8	0.3	0.3	<0.1	99.6
HAS-13	48.8	16.2	11.2	2.1	10.1	6.1	0.16	3.4	0.9	0.4	0.2	0.3	99.9
HAS-14	46.2	14.6	12.2	2.2	11.1	7.9	0.17	3.1	0.8	0.3	<0.1	0.7	99.3
HAS-15	46.9	15.7	12.5	2.2	10.1	8.2	0.17	3.1	0.7	0.3	<0.1	<0.1	99.9
HAS-16	47.3	16.1	11.4	2.9	9.8	5.7	0.15	3.9	1.3	1.0	<0.1	<0.1	99.6
HAS-17	45.9	14.8	12.6	2.0	9.6	9.6	0.1	3.2	0.8	0.4	<0.1	0.1	99.1
HAS-20	45.5	15.0	12.2	2.1	11.3	7.8	0.1	2.8	0.7	0.3	<0.1	1.5	99.3
HAS-26	46.9	14.9	11.7	1.7	8.5	9.7	0.1	2.7	0.6	0.3	<0.1	2.8	99.9
HAS-27	47.6	14.9	11.8	1.8	9.0	9.2	0.1	3.0	0.6	0.3	<0.1	1.0	99.3
HAS-32	44.4	13.1	13.1	2.6	9.6	9.3	0.2	3.6	1.1	0.7	<0.1	1.8	99.5
HAS-34	47.2	13.7	12.8	2.0	8.9	9.9	0.1	3.4	0.9	0.4	<0.1	0.3	99.6
HAS-40	47.2	16.1	11.5	1.8	11.6	6.1	0.1	3.2	0.6	0.3	<0.1	0.9	99.4
HAS-42	47.2	14.5	12.4	1.9	9.1	9.8	0.1	3.1	0.8	0.3	<0.1	0.2	99.4
HAS-55	47.6	16.2	12.2	2.7	9.8	5.6	0.1	3.7	1.3	0.5	<0.1	0.05	99.8
HAS-65	46.0	14.9	12.3	2.1	10.8	8.4	0.1	4.5	0.8	0.3	<0.1	0.7	100.9
HAS-79	44.5	14.3	13.3	2.5	10.4	8.4	0.1	3.8	1.3	0.6	<0.1	0.5	99.7
HAS-80	41.5	12.6	16.3	2.6	9.0	6.8	0.2	5.5	2.3	1.4	<0.1	1.7	99.9
HAS-85	50.8	13.5	12.3	1.8	9.4	7.4	0.1	3.0	0.5	0.3	0.2	1.0	100.3
HAS-87	43.4	13.5	13.9	3.2	10.2	8.5	0.1	3.9	1.4	0.7	<0.1	1.1	99.9
HAS-93	43.6	12.2	11.7	2.3	13.6	6.3	0.1	3.3	1.2	0.5	0.2	4.4	99.4
HAS-100	43.8	13.8	14.0	3.1	9.6	7.6	0.1	4.4	1.7	0.7	<0.1	1.2	100.0

Table 6. Chemical nomenclature of the volcanic rocks of northeastern Jordan

Group	Formation	Petrotype	Rock type according to chemical classification	Sample No. HAS -
	Bishriyya	Olivine - Pyroxene Basalt	Subalkali basalt	6
	Bishriyya	Olivine Basalt	Alkali basalt	42
	Bishriyya	Olivine Basalt	Subalkali basalt	5
	Bishriyya	Olivine – Pyroxene Basalt	Subalkali basalt	7
Rimah	Aritayn	Basalt scoria	Trachybasalt	55
Asfar	Hashimyya	Iddingsite Basalt	Foidite	80
	Hashimyya	Iddingsite Basalt	Basanite	87
	Hashimyya	Iddingsite Basalt	Basanite	100
	Ushayhib	Olivine Basalt	Trachybasalt	16
	Ushayhib	Olivine – Pyroxene Basalt	Basanite	72
Safawi	Salaman	Olivine – Iddingsite Basalt	Subalkali basalt	13
	Abed	Pyroxene – Olivine Basalt	Alkali basalt	8
	Abed	Olivine Basalt	Alkali basalt	10
	Abed	Pyroxene – Olivine Basalt	Alkali basalt	20
	Abed	Olivine – Pyroxene Basalt	Alkali basalt	34
	Abed	Pyroxene – Olivine Basalt	Alkali basalt	40
	Abed	Pyroxene - Iddingsite – Basalt	Subalkali basalt	85
	Abed	Pyroxene - Iddingsite Basalt	Basanite	93
	Abed	Pyroxene – Olivine Basalt	Alkali basalt	3
	Abed	Olivine - Pyroxene Basalt	Alkali basalt	15
	Ali	Pyroxene – Olivine Microdolerite	Alkali basalt	14
	Ali	Pyroxene – Olivine Microdolerite	Trachybasalt	65
Wisad		Pyroxene – Olivine Microdolerite	Subalkali basalt	9
		Olivine – Iddingsite Basalt	Subalkali basalt	26
		Pyroxene– Iddingsite Microdolerite	Subalkali basalt	27
		Iddingsite Basalt	Basanite	32
		Olivine-Pyroxene Basalt	Alkali basalt	34

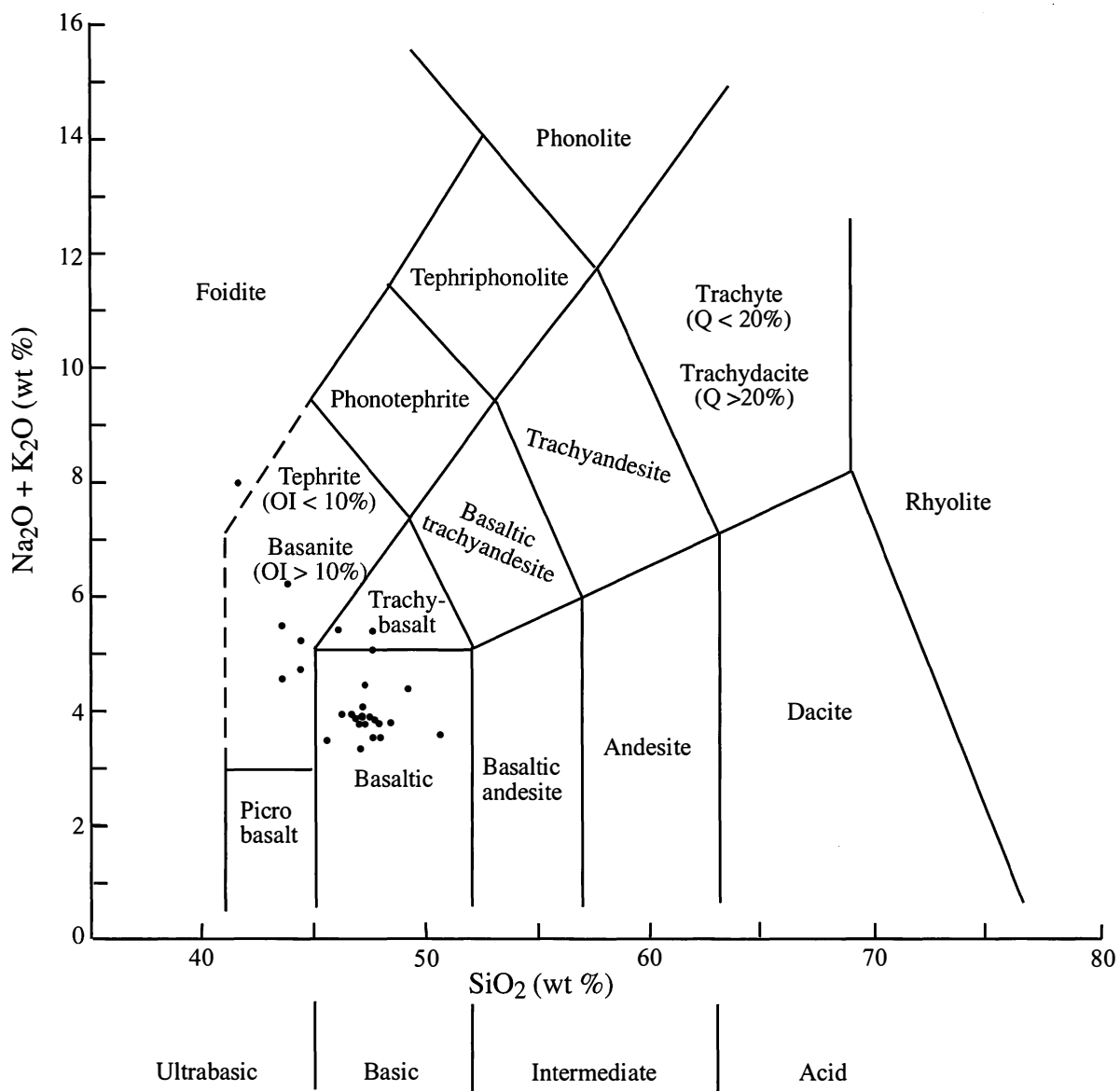


Figure 4. SiO_2 versus $\text{Na}_2\text{O} + \text{K}_2\text{O}$ variation diagram of 27 samples from the Harrat Ash Shaam. Rock nomenclature after Le Maitre et al. (1989).

3.3. AGE DETERMINATIONS

The analyzed ages are presented in the Appendix, Table C. The 100 samples analyzed yield K-Ar ages of 26 too younger than 0.5 Ma does that span the Miocene - Quaternary. The age distribution of the different stratigraphic units is presented in figures 5 and 6.

The ages of the samples from the **Wisad Group** range from 13 to 8 Ma (Figs. 5, 6). The basalts of this group overlie the Middle to Upper Eocene limestone of the Wadi Shallala Formation while the Wadi es Sibhi Formation (Wisad basalts?) overlie the continental and marine calcareous sandstone of the Qirma Formation, which is probably of Late Miocene age (11-8 Ma). Thus, the ages obtained are in agreement with the stratigraphy and field relations of these samples.

The samples from the **Safawi Group** yield ages within the range of 26 to <0.5Ma (Fig. 5). Within this group, the Abed Formation has three distinct age ranges: 26 to 22, 12.6 to 7.0, and 6.0 to 1.3 Ma. The Ali Formation ages range from 9.0 to 2.0 Ma and the Salaman Formation from 3.2 to 2.0 Ma.

The age distribution for the **Asfar Group** is bimodal, 12 to 10, and 6 to 1 Ma (Fig. 5b). Within this group the Hashimyya Formation has two distinct age ranges, one from 12 to 10 Ma, and the other from 4 to 1.3 Ma (Fig. 6).

The samples from the **Rimah Group**, which are predominantly undifferentiated pyroclastics, have two distinct phases, 9 Ma (Jabal edh Dherwa) and younger than 0.5 Ma (Plates 3 and 4, Jabal Quays).

The samples from the **Bishriyya Group** yielded ages in the range of 3.7 to younger than <0.5 Ma. The age of **dikes** range from 23 to about 1.7 Ma.

In summary, according to the former concept, the wide range of ages for each formation implies that the formations are not in the stratigraphic order as suggested by Ibrahim (1993, 1996). The ages of the Wisad Group and the Bishriyya Formation obtained in the present study agree with the previous dating carried out by Moffat (1988) and Barberi et al. (1979). However, the Abed Formation, which was considered to be within the range of 9.3 to 8.4 Ma (Table 1), was found to range from to 26 to 1.3 Ma in the present study (Fig. 6). In addition, the Hashimyya Formation, which was considered to be 3.4 to 1.96 Ma in age (Table 1), yielded ages of 12 to 1.3 Ma in the present study. For more details see Figure 6 and Table 7.

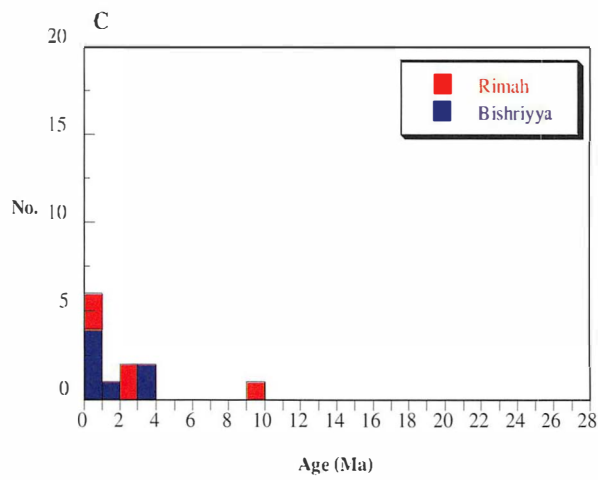
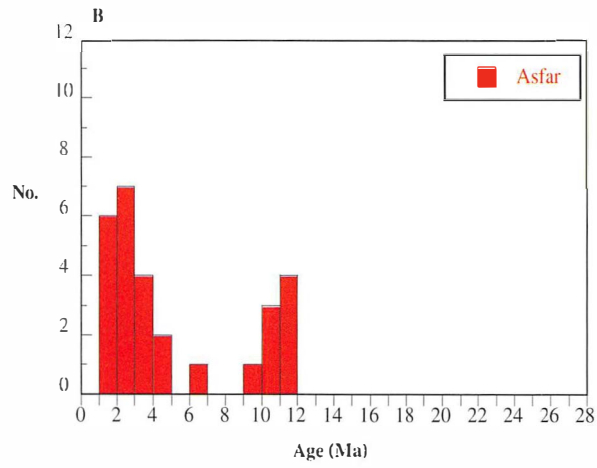
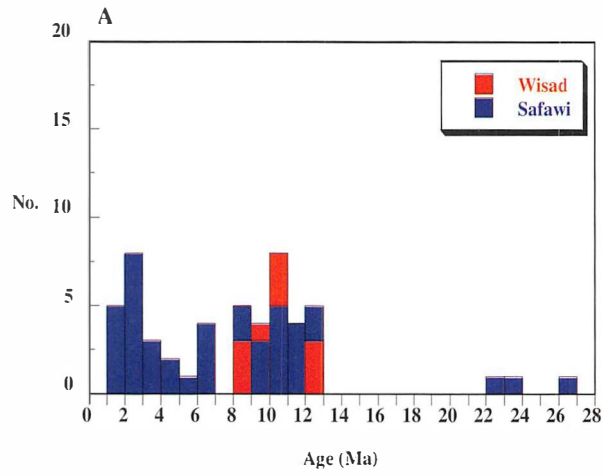


Figure 5. Age histograms of all samples from the different stratigraphic groups.

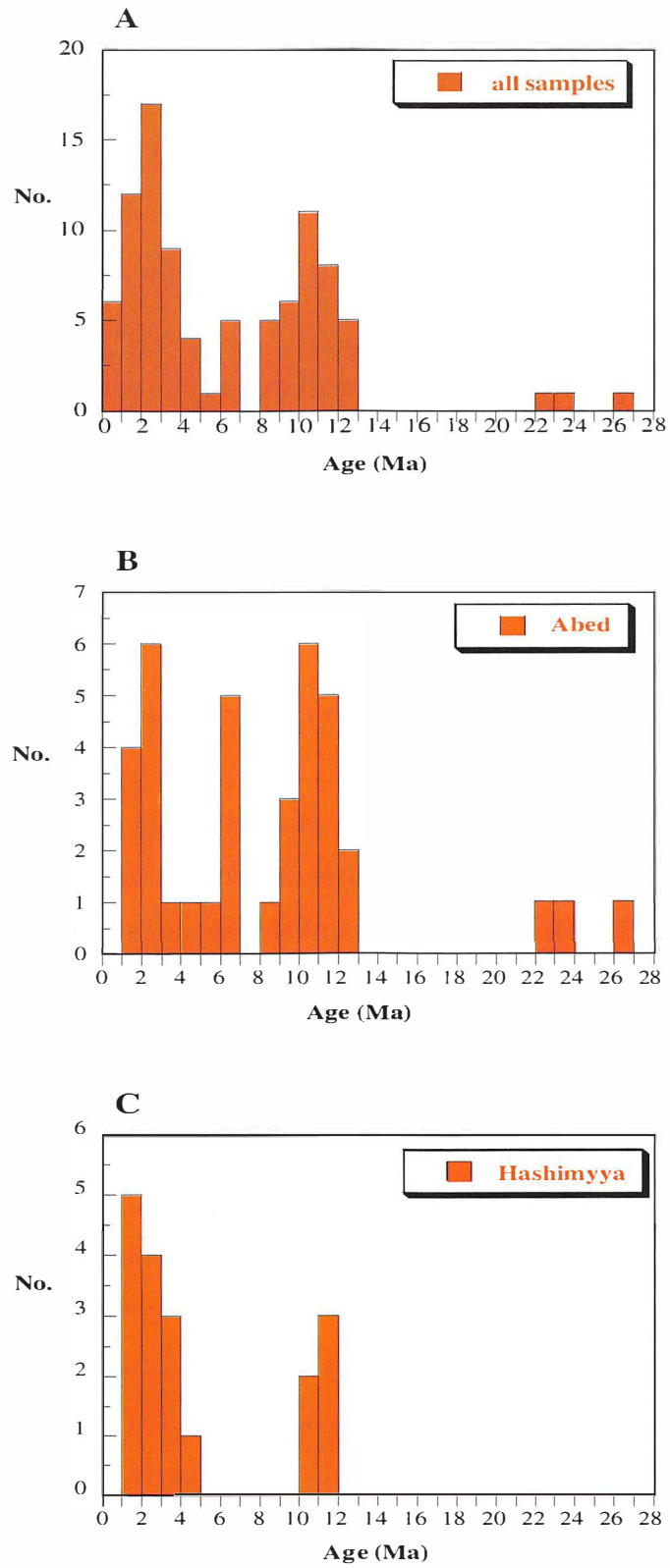


Figure 6. Age histograms of all samples (A) Abed Formation (B) and Hashimyya Formation (C).

CHAPTER 4: DISCUSSION

4.1. DISTRIBUTION OF BASALTS ACCORDING TO K-AR AGES AND PETROGRAPHY

A systematic spatial distribution of the ages in the Harrat Ash Shaam area is observed (Fig. 7). The Oligocene to Early Miocene ages (26 to 7 Ma), ascribed to the Wisad, Abed and Hashimyia basalts, are mostly from the southeastern and northeastern part of the study area. Late Miocene, Pliocene and Pleistocene volcanism is found mostly in the center and in the northwestern part of the study area. Younger ages of 1 Ma and less (close to the limit of detection) of the Bishriyya and Rimah groups are found only within the western and northwestern part of the area surveyed. The Oligocene-Miocene volcanic activity is exposed in the southern parts of the area, and the Pliocene and especially the Pleistocene volcanic activity is centered in the north and northwest parts of the area. It is feasible that the young volcanism covers older basalts.

The rock types also show a regional pattern of distribution. Basalts with olivine partially or fully altered to iddingsite are found in the southeastern section of the area where the old basalts occur (26-7 Ma). In the northern parts of the area, mainly olivine basalts are encountered, associated with olivine and pyroxene or pyroxene and olivine-bearing basalts, and microdolerite. The southern, central and the eastern parts of the area, are covered mainly by basalts with iddingsite or olivine altered to iddingsite.

According to these results, the Harrat Ash Shaam samples can be classified into three main groups (Fig. 8). The oldest group (Oligocene) consists of the Abed basalts (old phase) and is exposed in the southern part of the study area, north of Qa Hamda and Tall Al Hiber. Following the older group is a gap of 9 Ma. in volcanic activity when continental conditions prevailed. The middle group (Middle to Late Miocene) includes six different basalt units, which are exposed in the southeastern part of the Harrat Ash Shaam, e.g., in Wadi es Sibhi, Abar Al Hazim, Qatafi and Umm Nukhayla. The Qirma Formation consists of lake-deposits deposited during the Middle to Late Miocene. The youngest group (Late Miocene to Quaternary) includes eight volcanic units, which are exposed in the northwestern part of study area (e.g., Safawi, Azraq, Aritayn, ar Rifayyat, Asfar).

4.2. THE RELATIONS OF K-AR AGES AND THE BASALT PETROTYPES

Seven petrotypes were determined within the Harrat Ash Shaam basalts. In general, basalts of Oligocene age are iddingsite pyroxene basalts and those of Miocene age are mostly iddingsite, olivine-iddingsite, and microdoleritic basalts. The olivine and the olivine-pyroxene-bearing basalts are abundant within the samples of Pliocene - Quaternary age. The volcanoclastics, though defined as a separate formation are associated with most of the other formations and their ages are younger than 2.7 Ma, except for one sample which yielded 9 Ma (HAS-25, Table C).

In some of the volcanic units there is a correlation between age and the basalt petrotypes (Fig. 8). For example, two petrotypes are present in the Hashimyia Formation; olivine basalt and iddingsite basalt. The two petrotypes are correlated with the K-Ar ages where the iddingsite basalt ages range from 12 to 10 Ma and the olivine basalt ages range from 4 to 1.3 Ma (Fig. 8). However, some of the formations do not show a clear correlation with their ages; for example, all the petrotypes are present in the Abed Formation.

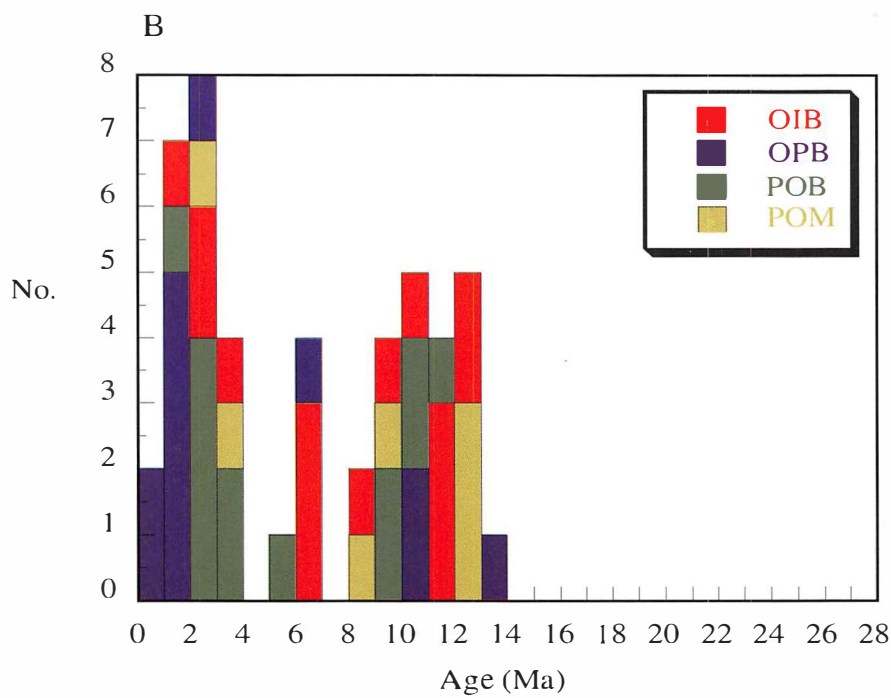
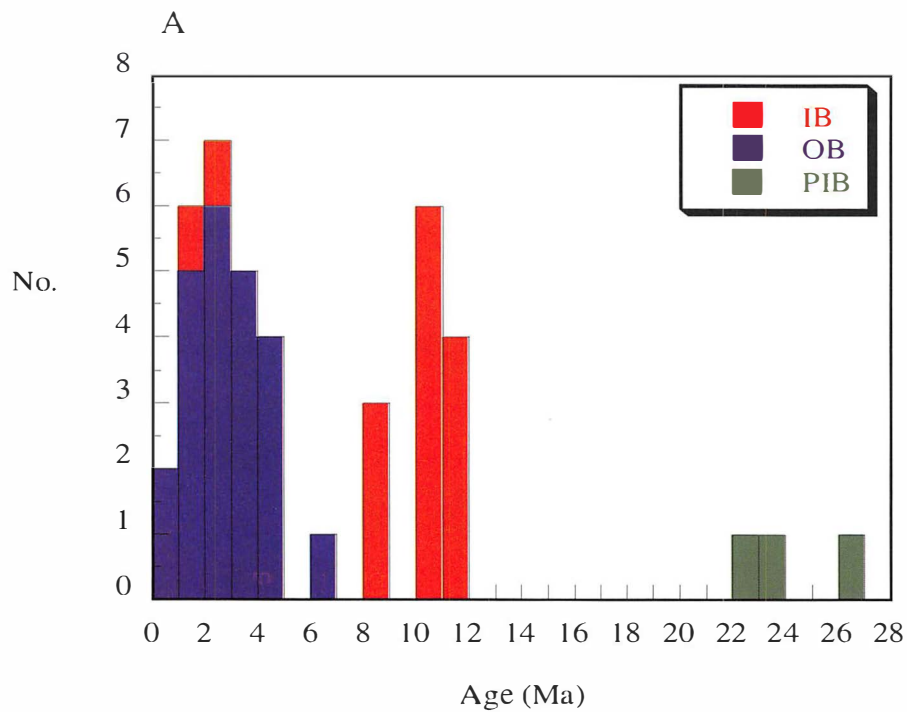


Figure 8. Age distribution of the different basalt petrotypes. IB = Iddingsite Basalt, OB = Olivine Basalt, PIB = Pyroxene Iddingsite Basalt, OIB = Olivine Iddingsite Basalt, OPB = Olivine Pyroxene Basalt, POB = Pyroxene Olivine Basalt, POM = Pyroxene Olivine Microdolerite.

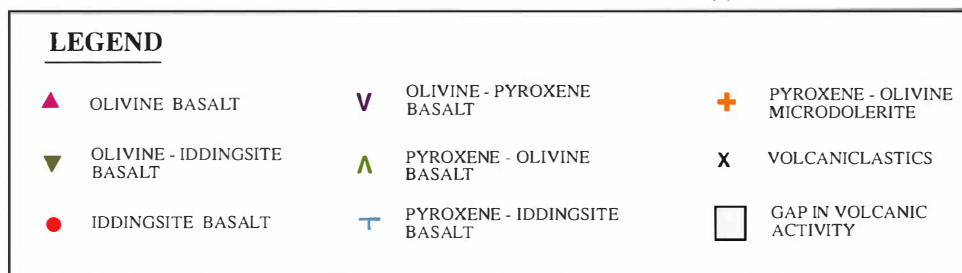
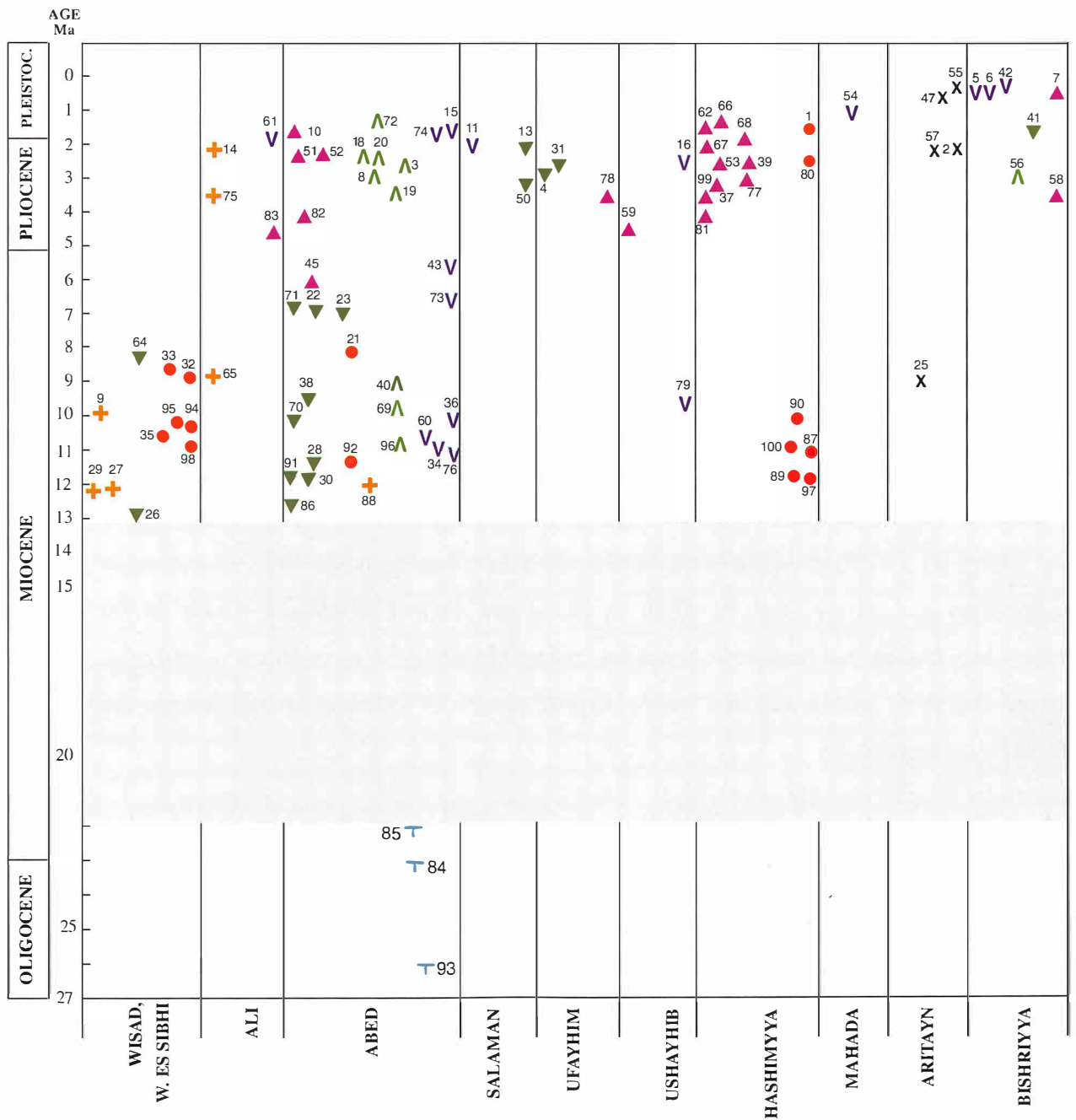


Figure 9. Relationships between volcanic units, petrography and age.

4.3. DIKES AND VOLCANIC CENTERS

Ten samples collected from feeder dikes yielded ages that range from 23 Ma to 1.7 Ma. Dikes such as the Qitar Al Abid might be the source of different basalt units such as the Abed, Hashimyya and Wisad. These dikes are controlled by a major NW - SE directed fault system, which is also the direction of the fault system of the "Red Sea" (Sebai et al.,1991). This dike system may possibly also be related to the opening of the Red Sea.

In the present study three phases related to dikes were determined; the older took place around 23 Ma, the intermediate around 9 Ma and the youngest took place around 1.7 Ma. There is good agreement between these three phases and the petrography of the dikes. During the Early Miocene there was an emplacement of dikes of a pyroxene-iddingsite basalt composition. Later, in the Middle to Late Miocene the composition of the dikes was of olivine-iddingsite basalts. The composition of the Pliocene dikes is of olivine basalts. In addition, these ages correspond with the ages of the Abed basalt flows, which extend over a large area. This strengthens the field observations that the Abed flows are related to feeder dikes such as the Qitar Al Abid. It seems that distinct lithologies, which can be easily identified in the field (and hence are mappable units) were products of different magma chambers within the area during similar phases of volcanic activity during the Oligocene to Quaternary.

4.4. CHRONOSTRATIGRAPHIC EVALUATION OF THE DATED VOLCANICS

The ages obtained so far for the Harrat Ash Shaam volcanics range from 26 Ma to younger than 0.5 Ma. Based exclusively on the K-Ar ages the volcanic sequence is divided into three major phases (Fig. 5a). The first phase is of Oligocene age (26 to 22 Ma) and its basalts are exposed in the Wadi Ausaji and Tall Al Hiber in the central and southern areas. The second phase is of Middle to Late Miocene (13 to 7 Ma) and its basalts are exposed in the Wadi es Sibhi and Wadi Qatafi in the southern part of the area. The results obtained so far indicate that there is a gap of about 9 m.y. between these two phases. No volcanic activity took place within the study area except for the edh Dherwa volcanic center where a basalt bomb yields an age of 14.5 Ma (not discussed here). The third phase is mostly of Late Miocene to Quaternary age (6 to <0.5 Ma) and basalts from this phase are exposed in the Azraq and Safawi areas.

In general, the geochronological pattern indicates that there is no correlation between the currently applied stratigraphy of the Harrat Ash Shaam volcanics as used in field

mapping (Ibrahim, 1993, 1996) and their ages determined in the present study (Figs. 5, 6). The most prominent example for this is the Abed Formation. Basalt flows and dikes that were related to the Abed unit based on field criteria have a wide range of ages starting from 26 Ma to 1.3 Ma (Fig. 6b).

4.4.1. Wisad Group

In the present study, we divide the Wisad basalts into two units. The first is the lower part that directly overlies the Eocene limestone of the Wadi Shallala Formation and is clearly covered by continental and marine calcareous sandstone of the Qirma Formation probably of Late Miocene age. The age of the lower part of the Wisad Group ranges between 13 and 8 Ma. The upper part of the Wisad basalts was recently named Wadi es Sibhi Formation (Rabba, in press) and it overlies the Qirma Formation. The age range of samples collected from this volcanic unit is 11 to 8 Ma. Thus the range of the Wisad Group is 13 to 8 Ma and is in agreement with the previous datings by Barberi et al. (1979) and Moffat (1988). Identifying the two parts of the Wisad Group can narrow the age of the Qirma Formation within the range of 12 Ma to 8 Ma. This range of ages is similar to that described in Ibrahim (1996), which is based on absolute age determinations as well as biostratigraphic data. The source of the Wisad basalt in the southern and southeastern part of the Harrat Ash Shaam area is most probably from the edh Dherwa volcanic center. The ages of volcanic tuff and basalt bombs from this volcano range between 9 and 14 Ma, respectively.

4.4.2. Safawi Group

The Abed Formation, the most prominent unit of this group makes up ~35% of all the samples collected. The Abed basalts comprise two distinct groups, young and old (Fig. 6). The source of the Oligocene to Early Miocene Abed basalts is mainly from basalt dikes which cut the area in a NW - SE direction. On the other hand, the Pliocene and Quaternary parts of the Abed basalts most probably originated from volcanic centers, vents, and ring dikes.

The young phases of the Salaman and Ali formations, which have different lithologies, yielded a similar range of ages (5 to 2 Ma). In addition, their age range is very close to the youngest phase of the Abed basalts. Thus the Salaman and Ali basalts are viewed as different lithofacies, which probably erupted at the same time in different localities, mostly in the Safawi area.

4.4.3. Asfar Group

The ages of the samples collected from the Asfar Group (Ufayhim, Ushayhib, Hashimyya, Madhala and Mahada formations; Ibrahim, 1996) present a wide range of ages, ~12 to 1 Ma. Based on the age and petrography of 16 samples collected from the Hashimyya basalt, two volcanic phases are evident. The older phase has an age range of 12 to 10 Ma and its basalts, exposed in the southeastern part of the study area, erupted from a volcanic center in the northern part of the al Qatafi area that is poorly preserved. The younger phase has an age range of 4 to 1.3 Ma; its basalts are exposed in several localities, but especially in the Hashimyya Village area. The source of the latter basalts is from volcanic centers such as Aritayn, Asfar, and Fahim, as well as from (fissure?) vents. Because of the similarity in ages, lithology and morphology of the younger phase of the Hashimyya and Ufayhim basalts, it is proposed that the Ufayhim basalts be included with the youngest phase of the Hashimyya basalts. The Ushayhib basalts has two phases, 10 Ma, and 4.5 to 1.3 Ma. They restricted to the area of Jabal Ushayhib and to south of the Tulul Al Ashaqif area. The Mahada basalts, which are also exposed in a limited area, were considered in previous studies as the youngest formation in the Asfar Group. According to its age determination (1 Ma), lithology and morphology, it is here suggested that it be included with the Bishriyya basalt.

4.4.4. Rimah Group

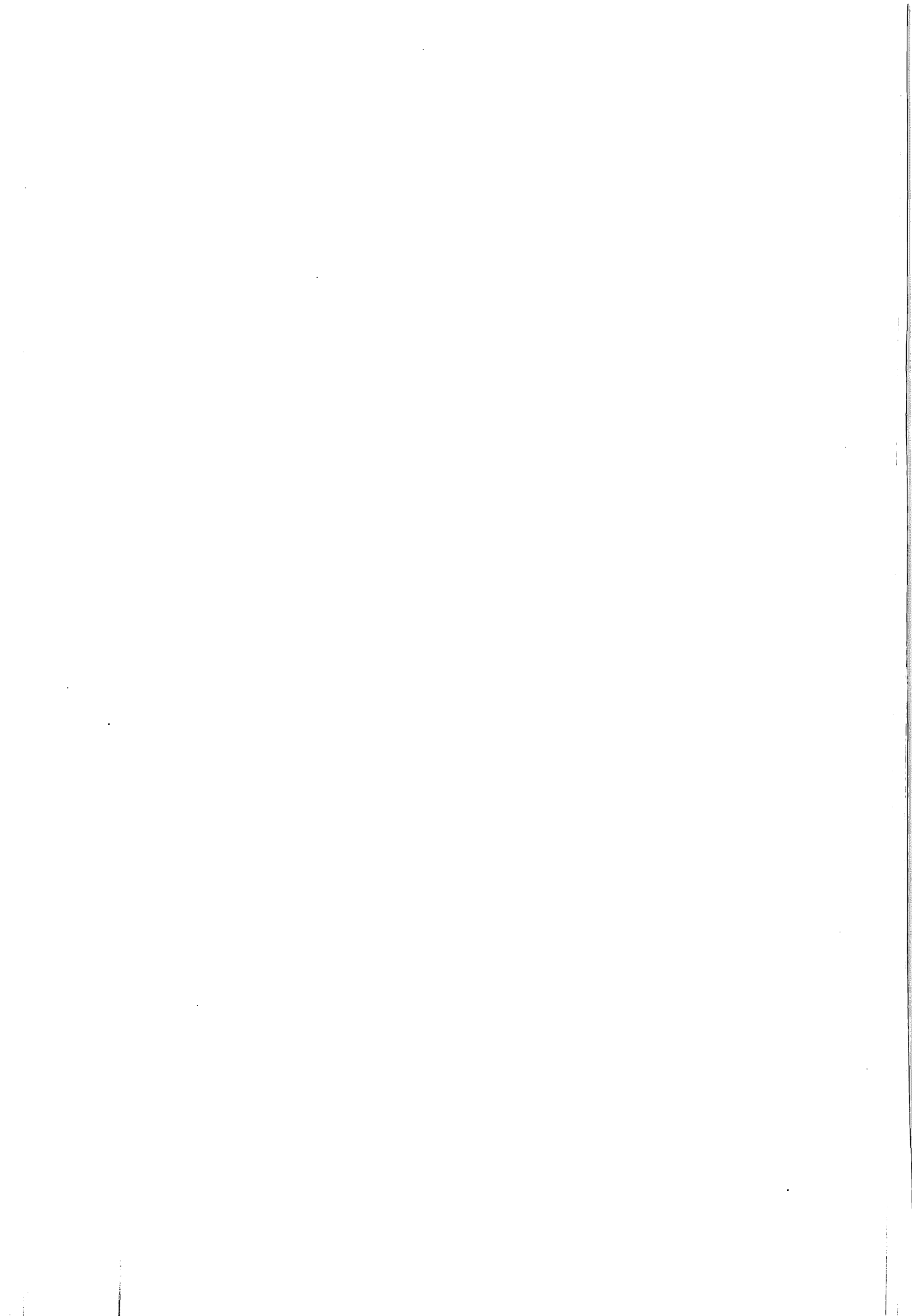
The Rimah Group, which is composed mainly of undifferentiated pyroclastics, includes the Aritayn and the Hassan formations, both of which yielded an age range of 9 Ma to younger than 0.5 Ma. The ages obtained on samples from different volcanic center show that the edh Dherwa volcanic cone in the south is the oldest, while the ar Rifayyat volcanic cones in the northwestern area are the youngest. More than 80 volcanic centers are exposed in the Harrat Ash Shaam area, and more detailed study is needed in order to get a better overview of the age distribution of the different centers, as a part of the volcanological framework of the Harrat Ash Shaam.

4.4.5. Bishriyya Group

The Wadi Manasif and Fahda formations of the Bishriyya Group (Ibrahim, 1993,1996) have a similar lithology, morphology and range of ages (3.7 Ma to <0.5 Ma). Therefore, it is herein suggested combining these two formations into a single mappable unit under the

name Bishriyya Formation. This unit is exposed mainly in the northwestern part of the Harrat Ash Shaam region, mostly in the al Hamiddyya area.

Field observations suggest that the Jawa site is the source of the Bishriyya basalt flows, which also diverted the course of Wadi Ragil eastward. However, the basalt sample from the Jawa site yielded an age of 3.5 Ma, which is considerably older than the other ages for the Bishriyya basalt elsewhere.



4.5. A NEW STRATIGRAPHIC SCHEME FOR THE HARRAT ASH SHAAM

VOLCANICS

The K-Ar ages of the Harrat Ash Shaam volcanics clearly suggest that the previous stratigraphic scheme be reevaluated and emended because the relationships between the formations as suggested by Ibrahim (1993, 1996) are not supported by their K-Ar ages. Some formations have a wide range of ages and/or the same age as other formations. The relationship between ages and formations is especially problematic in the case of the Abed Formation where the ages range from 26 to 1.3 Ma. However, the stratigraphy of the Harrat Ash Shaam basalts was previously largely based on field appearance, which allowed large-scale mapping. These field-based observations cannot be ignored and a new scheme incorporating both types of information must be established. Figure 10 summarizes the relationship between the formations as previously defined, their ages and areal distribution. The Abed Formation can be subdivided into three age groups; old (22-26 Ma), middle (13-7 Ma), and young (6-1.3 Ma). The old part of the Abed Formation appears in the central and eastern part of the Harrat Ash Shaam, the middle phase appears in the south-southeastern area and the young phase in the north-northeastern part. The age of the middle phase of the Abed Formation is coeval to other units such as the Wisad and Hashimyya. However, since the Wisad Group appears in association with the Qirma Formation while the Abed Formation does not, they are distinguishable in the field. The Hashimyya Formation itself has an older phase (12-10 Ma) and a younger (4-1.3 Ma) phase. The old phase is iddingsite basalt and the younger phase is olivine basalt, and each is exposed in different parts of the area: the older phase in the southern part; the younger phase in the northern part. The old phase of the Ali, Ushayhib, and Aritayn formations are based on a single sample from each and further work is needed on this issue.

The new chronostratigraphy is summarized in Table 7. Classification and terms are retained at this stage.

Table 7. New classification based on lithofacies and age, of the Harrat Ash Shaam basalts, northeast Jordan.

Basalt units	Age (Ma)
Hassan	<0.5
Aritayn (young phase)	2.6 – 0.6
Bishriyya	3.7 - <0.5
Salaman	3.0 - 2.0
Hashimyya (young phase)	3.0 - 4.0
Ushayhib (young phase)	4.5 - 1.3
Ali (young phase)	4.6 - 1.8
Abed (young phase)	6.0 - 1.3
Ali (old phase)	9.0
Aritayn (old phase)	9.0
Ushayhib (old phase)	10.0
Hashimyya (old phase)	12.0 - 10.0
Abed (Middle phase)	12.6 – 7.0
Wadi es Sibhi	11.0 – 8.0
Qirma Calcareous Sandstone	
Lower part of Wisad	12.8 - 7.7
Abed (old phase)	26.0 – 22.0
.	
Dikes*	23.0 - 1.7

* Dikes are found in most formations.

CHAPTER 5. CONCLUSIONS

5.1. CONCLUSIONS

Based on new K-Ar ages, petrographic analyses of approximately 100 samples from the Harrat Ash Shaam basalts and field observations, the following conclusions are drawn:

1. Three main episodes of volcanic activity are distinguished:
 - Oligocene to Early Miocene activity (26 to 22 Ma). Basalts of this period are exposed in the central and southeastern area.
 - Middle to Late Miocene activity (12 to 8 Ma). Basalts of this period are exposed mostly in the southeastern part of the area.
 - Late Miocene to Quaternary activity (6 to <0.5 Ma). Basalts of this phase are exposed mostly in the central, northern and northwestern parts of the area, between the Azraq Basin and the Syrian border.
2. In many cases the basalt units cannot be considered as “stratigraphic” units because the same lithotypes were emplaced during different events occurring between the Oligocene and the Pleistocene times.
3. The presence of basalts with olivine and pyroxene in association with basanites and foidites indicates an alkaline character of the parental basalt magma.
4. Most of the rocks are alkali basalts with olivine and pyroxene. Iddingsite basalt is the most abundant.
5. Seven petrotypes were identified and most of the volcanic formations consist of more than two petrotypes.
6. The Wisad Group should be subdivided into two: the lower part, which is covered by the calcareous sandstone Qirma Formation and the Wadi es Sibhi Formation, which overlies the Qirma Formation.
7. The Hashimyia Formation reflects two volcanic phases, one during the Middle Miocene and the other during the Plio-Pleistocene.
8. The Ufayhim and Hashimyia formations of Pliocene to Pleistocene age should be regarded as a single mapping unit.
9. All basalts belonging to the Bishriyya unit and the Mahada units are considered as a single mapping unit.

10. The basalt dikes show a wide range of ages from Oligocene to Pleistocene (23 - 1.7 Ma).
11. The ages obtained from the eruptive cone centers range between 9 Ma (edh Dherwa cone) in the south and 0.5 Ma (ar Rifayyat area) in the northwest areas. The pyroclastic phase of Aritayn contains mostly tuffs and ranges in age between 2.6 and 0.6 Ma. The age of the overlying Hassan Pyroclastic Formation, containing mostly scoria, is younger than 0.5 Ma.
12. Basalts of Quaternary age are found mostly northwest of the Azraq - Safawi road.
13. The age of basalts below and above the calcareous sandstone Qirma Formation (12.2 to 11.8 Ma, respectively) fall within the ages (12.2 - 8.5 Ma) in Ibrahim (1996).

5.2. RECOMMENDATIONS

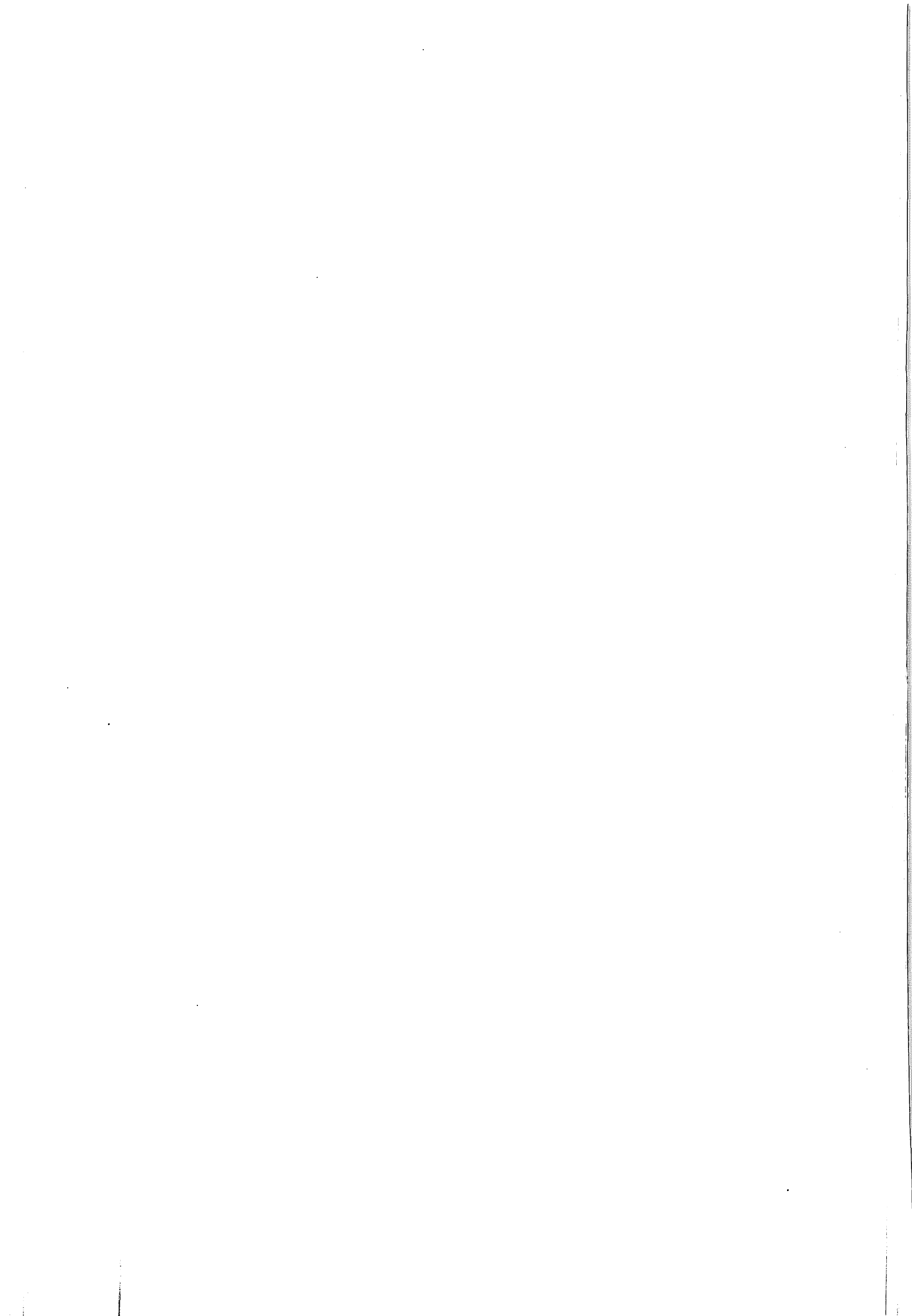
The lithology and morphology of the Madhala Formation of the Asfar Group (Ibrahim, 1996) is similar to that of the Pliocene phase of the Abed basalt, which belongs to the Safawi Group. Therefore, we suggest unifying both units and using the name Abed (Pliocene phase) as a mapping unit.

After discussing the results of the samples collected in the first stage of the study, we recommend the following:

- (a) Determining the Ar-Ar age of additional selected samples.
- (b) Sampling in detail the major volcanic centers.
- (c) Sampling in detail the major fissure dikes.
- (d) Sampling in detail the northeastern area (Jathum, Tall Mesma, Qaser Burqeh).
- (e) Studying the basalts associated with the paleosols.
- (f) Studying the xenolith occurrence in the tuff in comparison with xenolites present in the Ufayhim and Hashimyia volcanic units.
- (g) More detailed work on the geochemistry of the samples, including major and trace elements.
- (h) Correlating the volcanic units in the Harrat Ash Shaam to major volcanic units in other parts of Jordan and in the neighboring countries.

ACKNOWLEDGMENTS

We acknowledge with thanks: Dr. J. Hall and Dr. M. Shirav for their assistance in producing the location map of the sampling sites; Mr. Y. Rafael for helping with the mineral separation; the technicians Ali Hiyari, Mahmmoud Ibrahim, Yaseen Mouhamed, Husny Karabasheh and Mouhamed Mershed for their assistance in the field excursions; Eng. Main Hiyari and Eng. Darwish Jasser Director of Geology. Mrs. B. Cohen, N. Shragai and C. Netzer for technical assistance in publishing the report, and to Dr. Z. Lewy and Mrs. B. Katz for editing the manuscript.



REFERENCES

- Arno, V., Bakashwin, M.A., Bakor, A.Y., Barberi, F., Basahel, A., DiPaola, G.M., Ferrara, G., Gazzaz, M.A., Giuliani, A., Heikel, M., Marinelli, G., Nassief, A.O., Rosi, M. Santacroce, R. (1980). Recent volcanism within the Arabian plate, preliminary data from Harrats Hadan and Nawassif-al-Boqum. Geodynamic Evolution of the Afro-Arabian Rift System, Acad Naz. Lincei, **47**, 647-654.
- Barberi, F., Capaldi, G., Gasperini, P., Marinelli, G., Santacroce, R., Scandone, R., Treuil, M. and Varet, J. (1979). Recent basalt volcanism of Jordan and its implications on the geodynamic evolution of the Afro-Arabian rift system, Atti. Conv. Lincei., **47**, 667-83.
- Bender, F. (1974). Geology of Jordan. Borntraeger, Berlin. 196 p.
- Bender, F. (1975). Geology of the Arabian Peninsula; Jordan: U.S. Geological Survey Professional Paper 560-I, 36 p., map, scale 1:500,000.
- Brown, G.F., Schmidt, D.L. and Huffman, A.C. Jr. (1984). Geology of the Arabian Peninsula western shield area. Department of the Interior U.S. Geological Survey, Open-File Report 84-203, U.S. Geological Survey, Reston, VA 22092.
- Camp V. E. and Roobol M. J. (1989) The Arabian continental alkali basalt province: Part 1. Evolution of Harrat Rahat, Kingdom of Saudi Arabia, Geol. Soc. Amer. Bull. 101, 71-95
- Camp V. E. and Roobol M. J. (1992,) Upwelling asthenosphere beneath western Arabia and its regional implications, J. Geophys. Res. **97(B11)**, 15,255-15,271.
- Coleman, R.G. and McGuire, A.V. (1988). Magma systems related to the Red Sea opening, Tectonophysics. **150**, 77-100.
- Giannerini, G., Campredon, R., Feraud, G. and AbouZakhem, B. (1988). Deformations intraplaques et volcanisme associe': exempla de la border NW de la plaque Arabesque au, Bull. Soc. Geol. France, **6(8)**: 937-947.
- Gushchenko, I.I. (1979). Volcanic Eruptions of the World. Catalogue. Izverzheniya Vulkanov Mira. Katalog. Moscow: Nauka.
- Ibrahim, K. M. (1993) The geological framework for the Harrat Ash Shaam Basalt Super-group and its volcanotectonic evolution. Natural Resources Authority, Geol. Map. Div., Bull. 25, 33 p.
- Ibrahim, K. M. (1996). The regional geology of Al Azraq area. The Hashemite Kingdom of Jordan, Ministry of Energy and Mineral Resources, Natural Resources Authority, Geol. Map. Div., Bull. 36, 67 p.
- Ibrahim, K. M., Harlavan, Y., Tarawneh, K., Ilani, S., Rabba, I., Weinberger, R. and Steinitz, G. (1998). Dating the Harrat Ash Shaam basalt super-group sequence of northeast Jordan. Hashemite Kingdom of Jordan, Natural Resources Authority; Geol. Surv. Isr. Rep. GSI/21/98, 16 p.
- Le Maitre, R.W., Bateman, P., Dudek, A., Keller, J., Lameyre, J., Le Bas, M.J., Sabiue, P.A., Schmid, R., Sorensen, H., Streckeisen, A., Woolley, A.R. and Zauettin, B. (1989). A Classification of Igneous Rocks and Glossary of Terms. Blackwell Scientific Publ., London, 193 p.
- Kotlarsky, P. Kapusta, J. Lang, B. & Steinitz, G. (1992). Calculation of isotopic ratios of argon on the MM-1200 mass-spectrometer at the Geological Survey of Israel. Geol. Surv. Isr. Rep. TR-GSI/3/4/92.

- Menzies, M., Baker, J., Chazote, G., Al-Kadasi, M., (1997) Evolution of the Red Sea volcanic margin, Western Yemen. In: Mahoney, J. J. and Coffin, M. F. (eds.). Large igneous provinces; continental, oceanic, and planetary flood volcanism. American Geophysical Union Washington DC. Geophysical Monograph 100. pp. 29-43.
- Moffat, D. T. (1988). A volcanotectonic analysis of the Cenozoic continental basalts of northern Jordan; implications for hydrocarbon prospecting in the block B area. ERI Jordan EJ88-1, 73 p.
- Rabb'a, I. (in press). Wadi Qattafi Geological Map, scale 1:50,000. Natural Resources Authority, Geol. Map. Div. Amman.
- Sebai, A., Zumbo, V., Feraud, G., Bertrand, H., Hussain, A.G., Giannerini, G. and Camperdon, R. (1991). $^{40}\text{Ar}/^{39}\text{Ar}$ dating of alkaline and tholeiitic magmatism of Saudi Arabia related to the early Red Sea Rifting. Earth and Planetary Science Letters, **104**, 473-487.
- Sharkov, E.V., Chernyshev, I.V., Devyatkin, E.V., Dodonov, A.E., Ivanenko, V.V., Karpenko, M.I., Leonov, Yu.G., Novikov, V.M., Hanna, S. and Khatib, K. (1994). Geochronology of Late Cenozoic Basalts in Western Syria. Petrology. Vol. **2/4**, 385-394.
- Smith, W. J., (1980). Reconnaissance geology of the At Ta'if quadrangle, sheet 21/40 C. Kingdom of Saudi Arabia: Saudi Arabia Dep. Ministry for Min. Resource Map GM 56, scale 1:100,000 with text, 33 p.
- Steinitz, G. Lang, B. Mor, D. and Dallal, C. (1983). The K-Ar laboratory at the Geological Survey of Israel. Geol. Surv. Isr. Current Research 1982, pp. 97-98.
- Tarawneh, K. (1999a). Wadi al Abid Geological Map, scale 1:50,000. NRA Geol. Map. Div. Amman
- Tarawneh, K. (1999b). The Geology of Wadi al Abid area, NRA, Geol. Map. Div. Bull. **44**, 12-14.
- Van Den Boom, G. and Sawan, O. (1966). Report on geological and petrological studies of the plateau basalts in NE Jordan. Germ. Geol. Mission, Amman, 42 p.

PLATES

LIST OF PLATES

Plate 1. Basalt petrotypes of the Wisad and Wadi es Sibhi units	44
Plate 2. Basalt petrotypes of the Abed and Ali volcanic formations.....	46
Plate 3. Basalt petrotypes of the Ufayhim, Ushayhib, Hashimyya, and Aritayn volcaniclastic units.....	48
Plate 4. Basalt petrotypes of Aritayn and Hassan volcaniclastics, and Bishriyya basalt unit.	50
Plate 5. Basalt dikes of the Harrat Ash Shaam.....	52
Plate 6. Photomicrographs of basalts from NE Jordan. Field size 6.5 mm, crossed nicols.	54
Plate 7. Photomicrographs of basalts from NE Jordan. Field size 6.5 mm, crossed nicols.	56
Plate 8. Photomicrographs of basalts from NE Jordan. Field size 6.5 mm, crossed nicols (a) and parallel (b,c,d).....	58

Plate 1. Basalt petrotypes of the Wisad and Wadi es Sibhi units.

- a. Wisad basalts overlain by the Qirma Formation, 1 km north of Jabal edh Dherwa volcanic center.
- b. Wadi es Sibhi basalts (the upper part of the Wisad Group) overlying the Qirma Calcareous Sandstone (QCS).
- c. Wadi es Sibhi Formation overlying the Qirma Formation, Wadi es Sibhi area.
- d. Wadi es Sibhi Formation: platy forms due to the presence of horizontal joints, Wadi es Sibhi area.

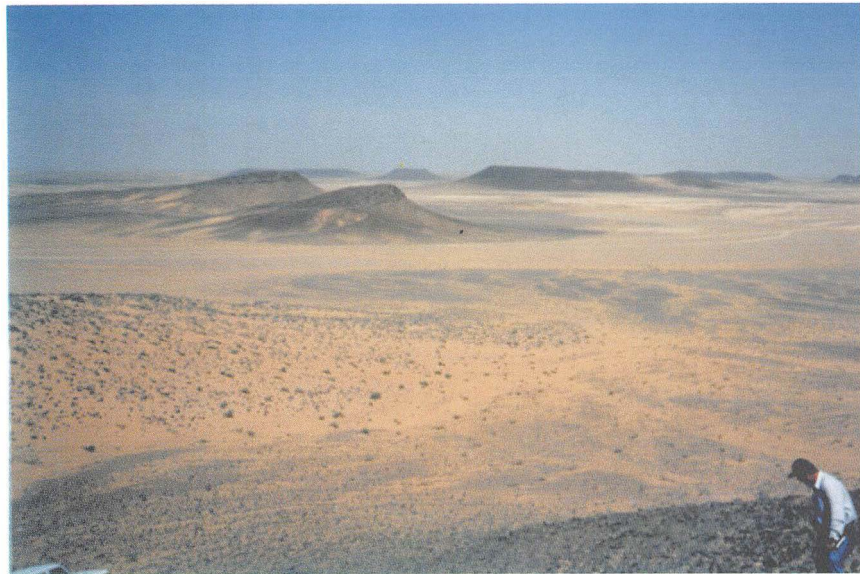


Plate 2. Basalt petrotypes of the Abed and Ali volcanic formations.

- a. Abed basalts showing pipe vesicularity, Wadi Ausaji area.
- b. Abed basalts showing polygonal blocks, Qa Hamda (Safawi sheet)
- c. Ali doleritic basalt, showing individual flow units, 2 km west of Safawi.
- d. Abed basalts, light brown in color due to weathering process, 10 km north of Jabal edh Dherwa volcanic center.



a



b



c



d

Plate 3. Basalt petrotypes of the Ufayhim, Ushayhib, Hashimyya, and Aritayn volcaniclastic units.

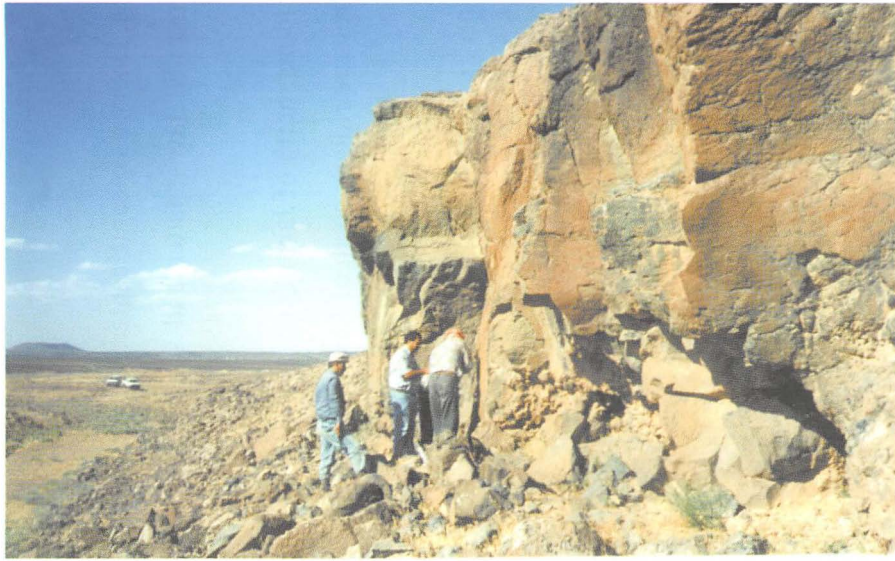
- a. Ufayhim basalts showing horizontal joints, Tulul Al Ashaqif.
- b. Ushayhib basalts showing angular boulders, quarry mine southwest of Tulul Al Ashaqif.
- c. Hashimyya basalts consist of flows reaching up to 10 m thick, Wadi Ausaji area.
- d. Jabal edh Dherwa volcanic center composed of stratified volcanic tuff.



a



b



c



d

Plate 4. Basalt petrotypes of Aritayn and Hassan volcanics, and Bishriyya basalt unit.

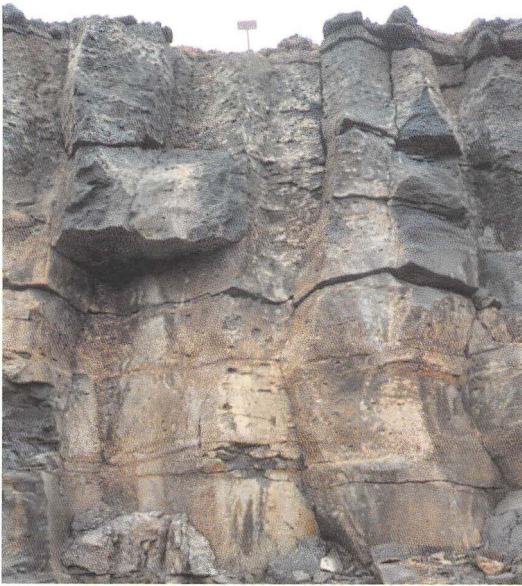
- a. Aritayn volcanics including basalt bombs, Dherwa volcanic center.
- b. Hassan Formation built of layers of agglomerated lava spatter and scoria, Jabal Quays.
- c. Bishriyya basalts showing polygonal vertical joints, north of Jabal Quays.
- d. Bishriyya basalts, showing preserved linear pressure ridges, north of Jabal Quays.



a



b



c



d

Plate 5. Basalt dikes of the Harrat Ash Shaam.

- a. Part of a fissure dike composed of Abed basalts, Wisad area.
- b. Qitar Al Abid basalt dike, showing several hills along the NW-SE directed dike, Wadi Al Abid area.
- c. Ring dike in Abed basalt, east of the Hashimyya Village.
- d. Fissure dike composed of Abed basalts, Azraq area.



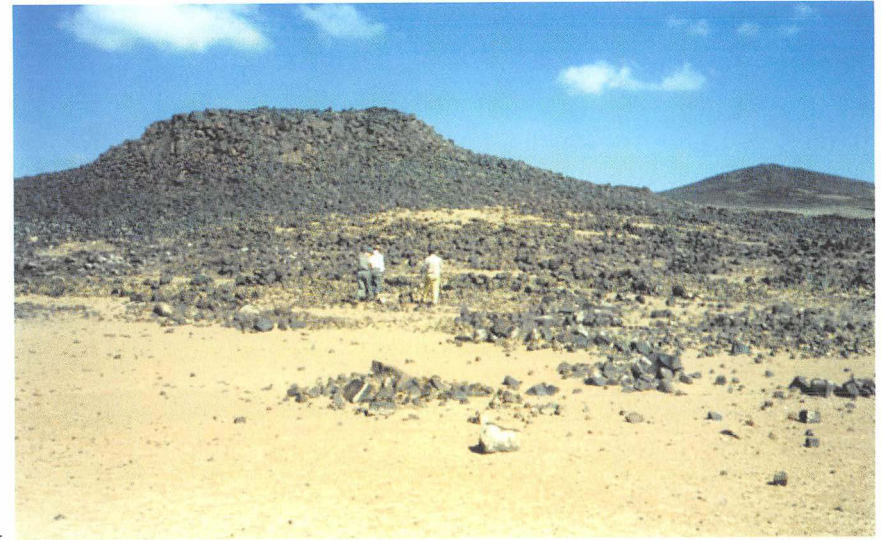
a



b



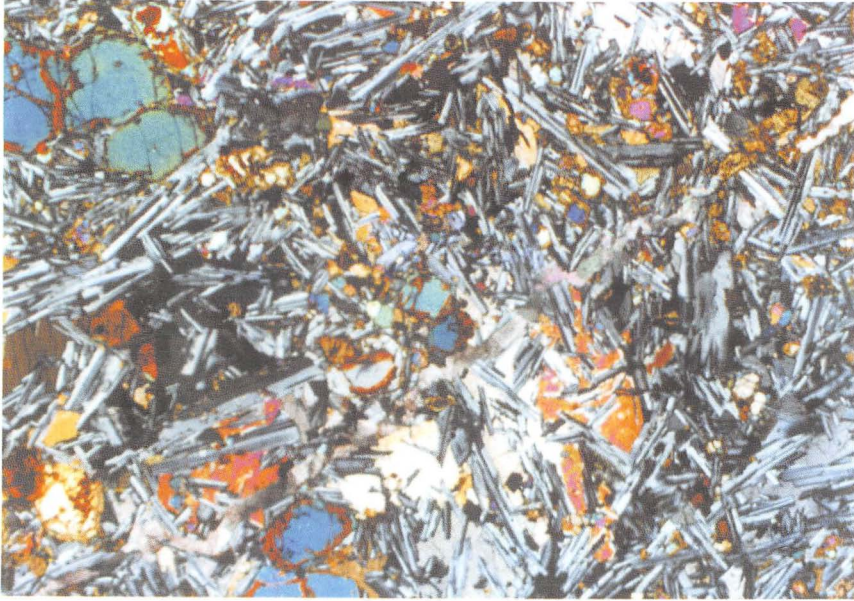
c



d

Plate 6. Photomicrographs of basalts from NE Jordan. Field size 6.5 mm, crossed nicols.

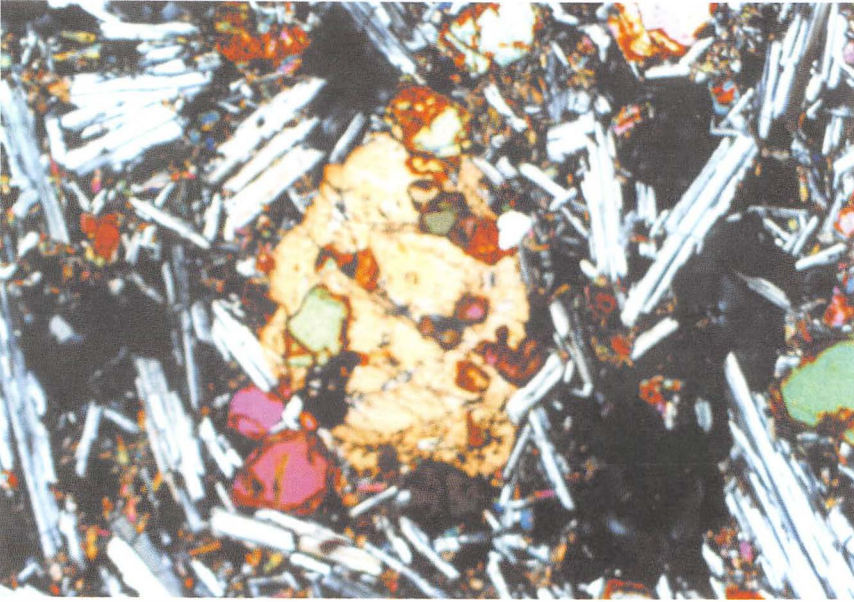
- a. Wisad Formation; microdolerite with coarse-grained, subophitic groundmass. In the upper corner of the photo, an association of phenocryst of olivine with iddingsite rim. Phenocryst of augite including subphenocryst of plagioclase, in the central part of the photo. Microphenocrysts of pyroxene and iddingsite in the upper part of the photo. Lath-shaped plagioclase, twinned (albite law).
- b. Wisad Formation; microdolerite, vesicular; coarse-grained and intergranular groundmass. Megacrysts of olivine including subphenocryst of olivine with iddingsite rim, in the center of the photo. Twinned-lathy megacrysts of labradorite. Subphenocryst of olivine with iddingsite rim and microlites of iddingsite in the spaces between plagioclase.
- c. Abed Formation; pyroxene-olivine basalt, vesicular and medium-grained; the groundmass exposes a microtexture subophitic to intergranular. Phenocryst of augite in the upper part of the photo. Phenocryst and microlites of olivine in the lower half. The black irregular spots represent vesicles.
- d. Abed Formation; pyroxene-iddingsite basalt medium-grained and intergranular groundmass. Phenocryst of olivine fully replaced by iddingsite (brownish color). Abundance of microlites of pyroxene in the interstices of the feldsparic groundmass. Empty vesicles as black spots and vesicles filled with secondary minerals (calcite), as white to pinkish spots.



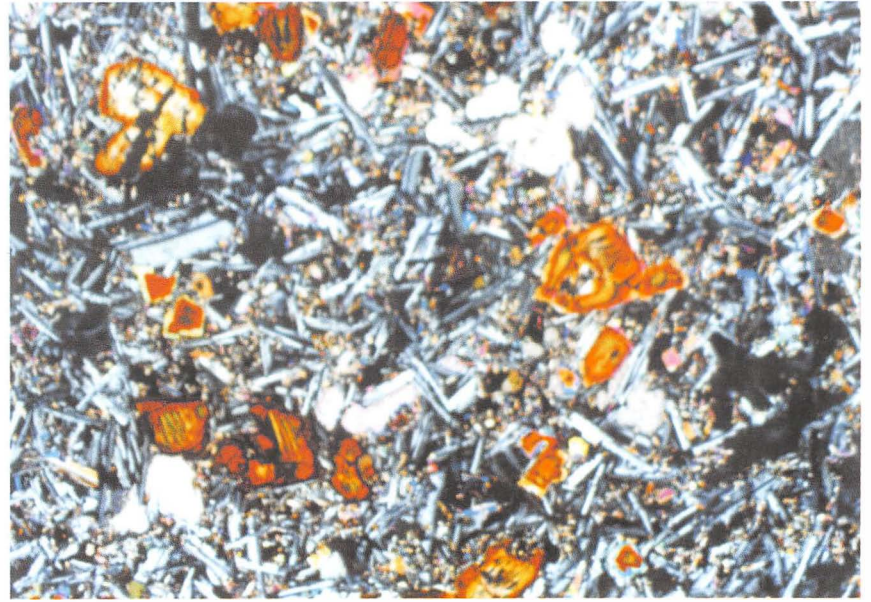
a



c



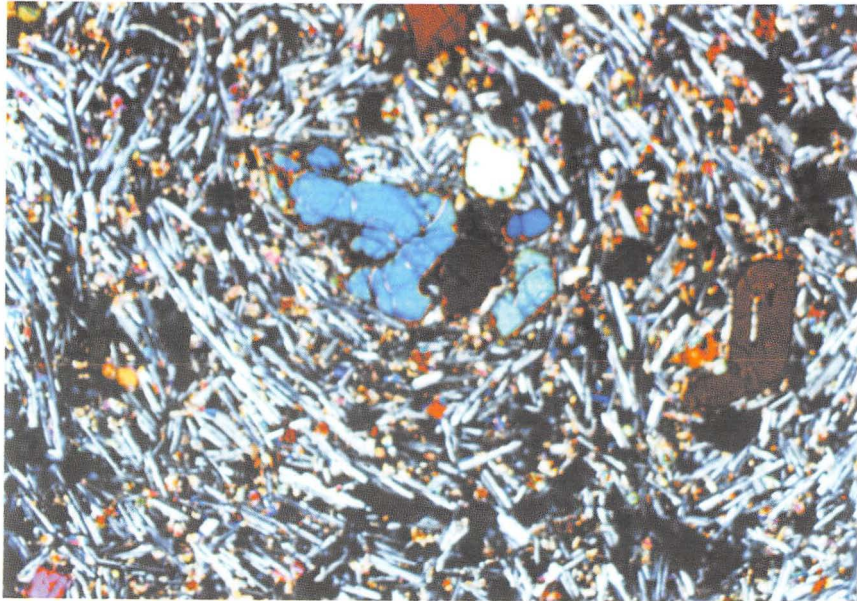
b



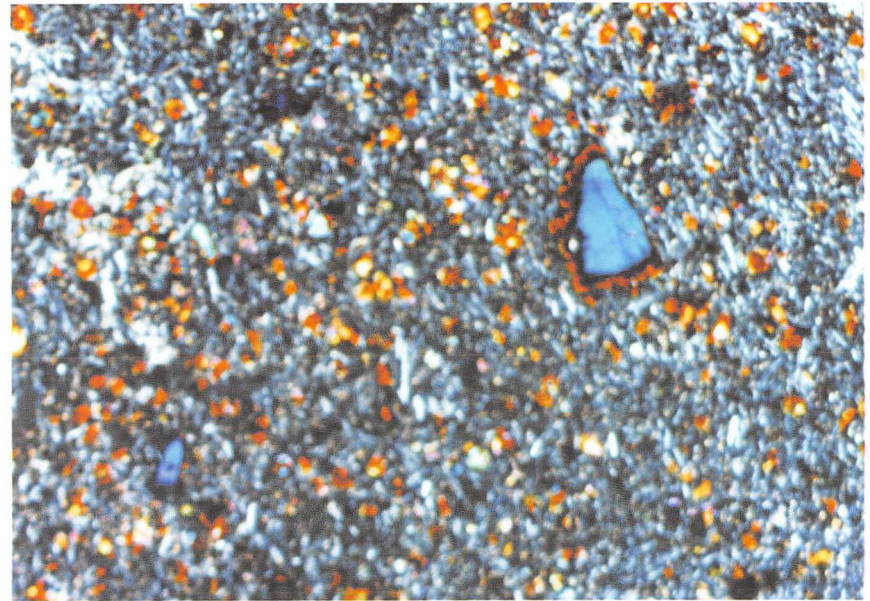
d

Plate 7. Photomicrographs of basalts from NE Jordan. Field size 6.5 mm, crossed nicols.

- a. Salaman Formation; olivine-iddingsite basalt, medium-grained; fluidal microtexture of the groundmass. Well-developed flowage of lathy labradorite crystals around a glomerule of olivine. Note the abundance of microlites of iddingsite (brownish colored spots) in the groundmass.
- b. Hashimyya Formation; olivine basalt, fine to medium-grained. Glomeroporphyritic texture and fluidal to pilotaxitic microtexture of the groundmass. Association of fresh pheno and subphenocryst of olivine in the center of the photo. In the left side of the photo, lath-shaped subphenocryst of plagioclase exposing a fluidal tendency.
- c. Hashimyya Formation; olivine-iddingsite basalt, fine-grained. Phenocryst of olivine with iddingsite rim. Microlitic groundmass consisting of plagioclase (the white microlaths), iddingsite (the brown microcrystals), and a few microcrysts of olivine (blue and pinkish).
- d. Wisad Formation; olivine basalt, fine-grained and alveolar. Phenocryst and microlites of olivine with a thin rim of iddingsite (pinkish-brownish or yellowish-brownish). Subphenocryst and microlites of plagioclase, lath-shaped, exposing a pilotaxitic microtexture. Elliptical alveolae filled with calcite are present in the central part of the photo.



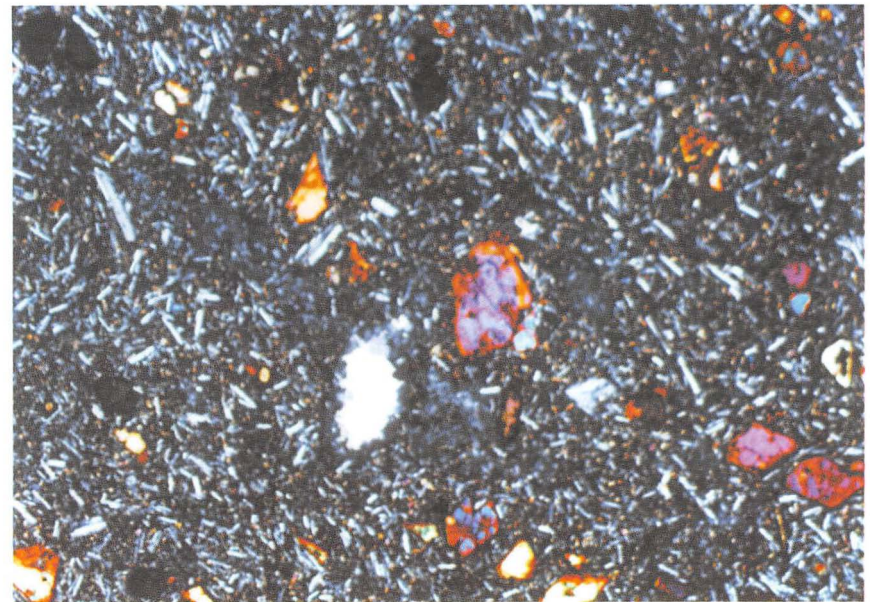
a



c



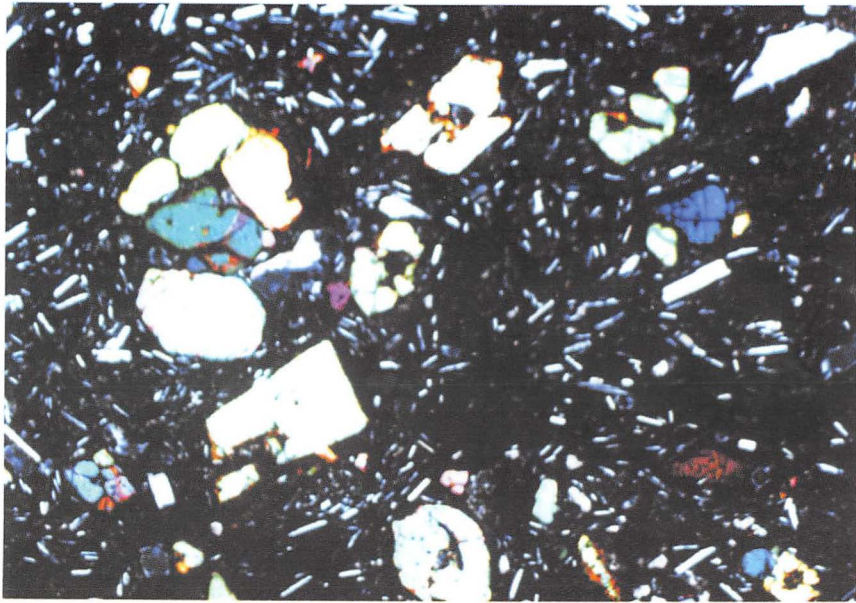
b



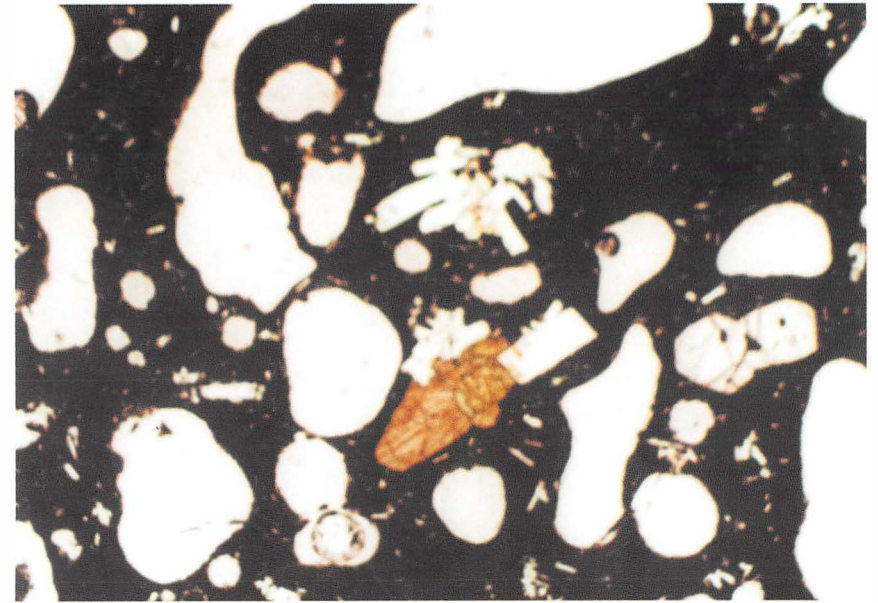
d

Plate 8. Photomicrographs of basalts from NE Jordan. Field size 6.5 mm, crossed nicols (a) and parallel (b,c,d).

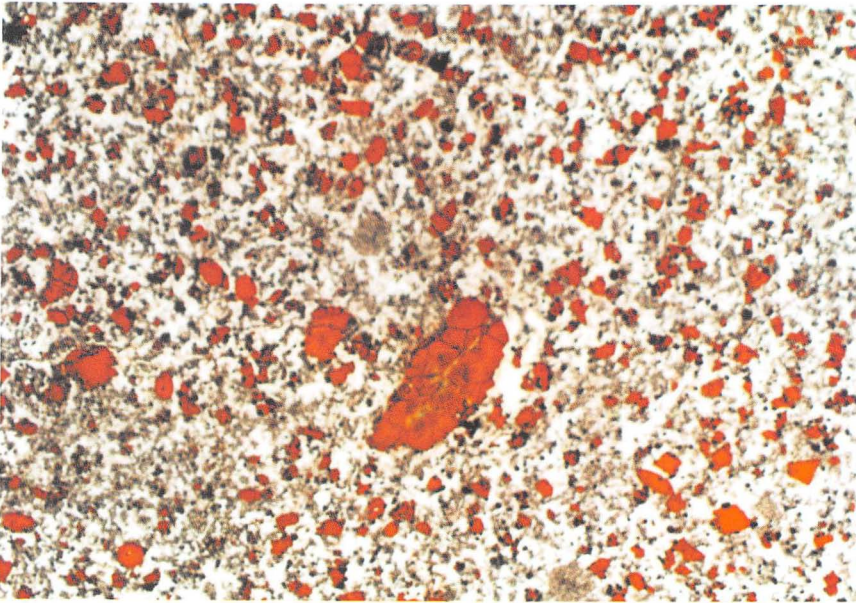
- a. Hashimyya Formation; olivine basalt, fine-grained. Porphyritic texture revealed by abundant phenocrysts of olivine, part of them replaced by iddingsite along rims and microfractures. The groundmass consists of lath microcryst of plagioclase and glassy material (black).
- b. Wisad Formation; Iddingsite Basalt, medium-grained. Porphyritic texture devoted to a few phenocrysts of olivine fully replaced by iddingsite. The microlitic groundmass consist of lath and anhedral feldspar (white and yellowish), iddingsite (brown) and magnetite (black).
- c. Aritayn Formation; basalt scoria. Irregular, elliptical and spherical vesicles and the glassy opacified (black color) matrix with a few crystals of plagioclase (white) and an augite phenocryst (yellowish).
- d. Aritayn Formation; welded basalt scoria. The left segment of the photo shows a fragment of a highly porous scoria rich in vesicles of different sizes and shapes. The right one shows a more compact scoria consisting of elongated, stretched vesicles. The glassy matrix shows a high limonitic alteration (brownish).



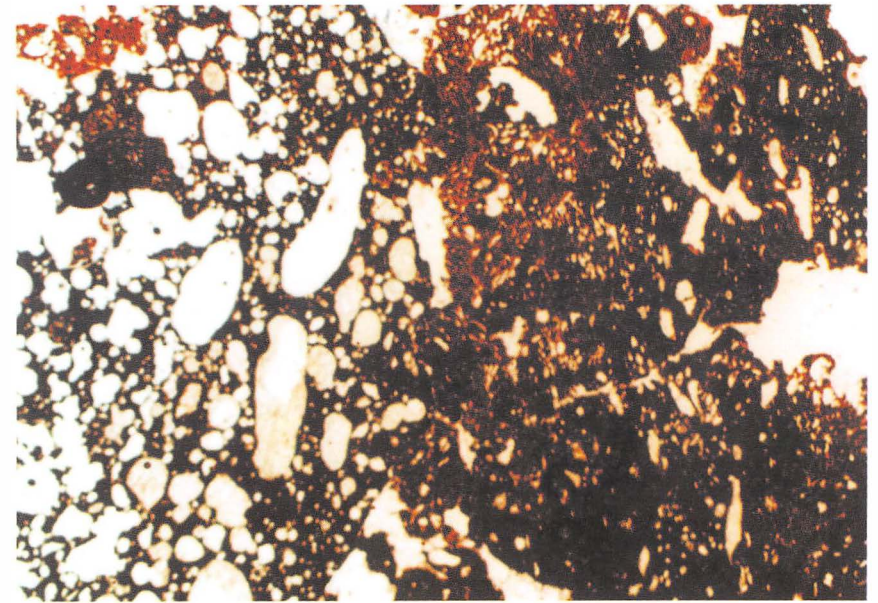
a



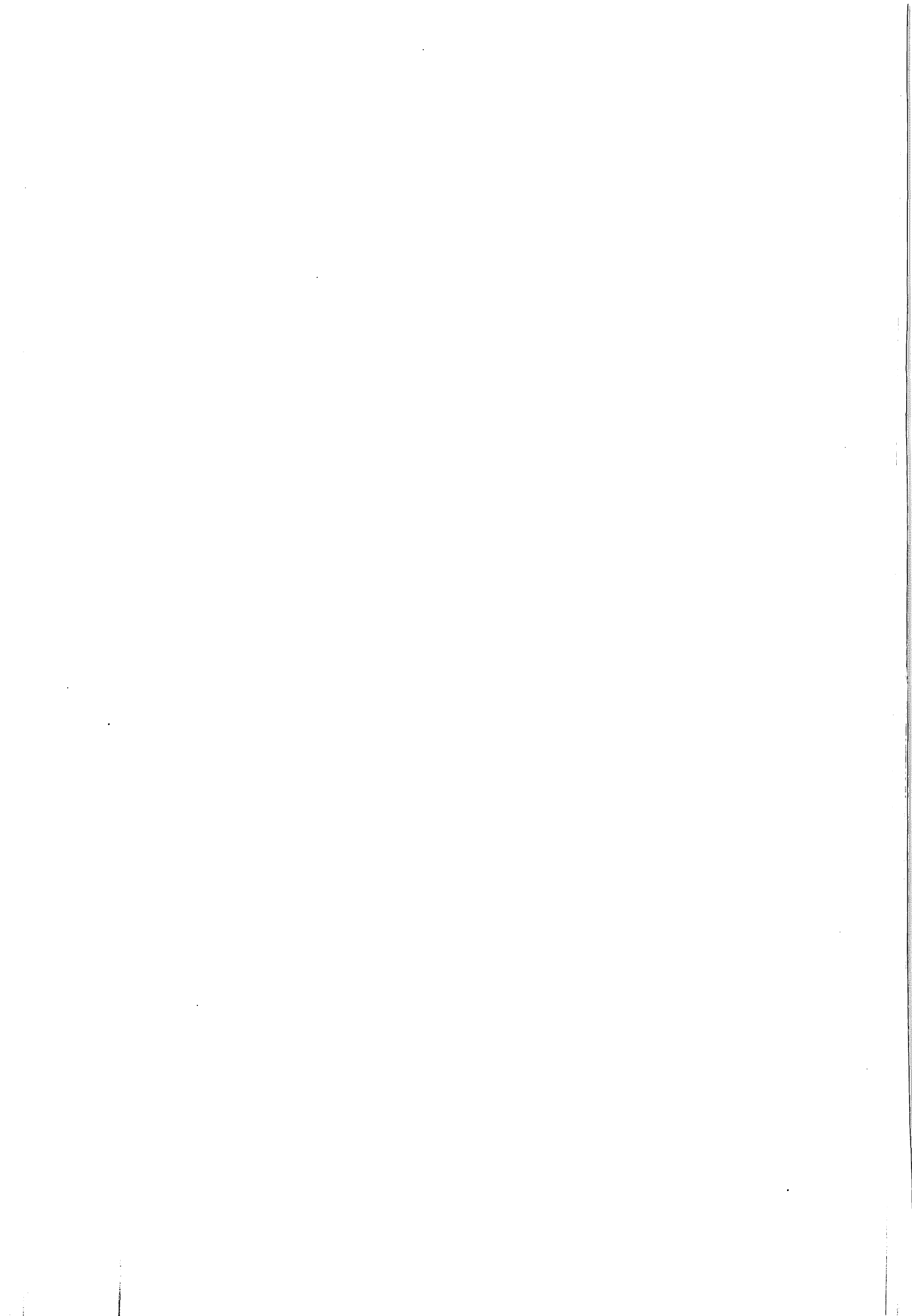
c



b



d



APPENDIX

Table A. Location of the Harrat Ash Shaam samples, northeast Jordan.

Table B. Type of rock, minerals, and relative abundance, and texture of studied samples.

Table C. K-Ar ages of samples from the Harrat Ash Shaam basalts, northeast Jordan.

Table A. Location of the Harrat Ash Shaam samples, northeast Jordan.

Sample	Formation	Location	Coordinates	Remarks
HAS-1	Hashimyya	Hashimyya Village	32°08.125'N / 36°57.003'E	
HAS-2	Aritayn	Wadi Aritayn	32°06.058'N / 36°52.008'E	
HAS-3	Abed	Wadi Aritayn	32°06.058'N / 36°52.008'E	
HAS-4	Ufayhim	Wadi Ufayhim	32°03.025'N / 36°51.005'E	
HAS-5	Bishriyya	Bishriyya Village	32°09.015'N / 36°48.000'E	
HAS-6	Bishriyya	Deir Al Kahf	32°16.010'N / 36°52.125'E	
HAS-7	Bishriyya	9 km east of as Safawi	32°13.450'N / 37°13.350'E	Type locality
HAS-8	Abed	22 km east of as Safawi	32°16.250'N / 37°20.050'E	Quarry
HAS-9	Wisad	Tulul Al Shahba	32°18.360'N / 37°29.420'E	
HAS-10	Abed	Qitar Al Abid	32°20.320'N / 37°31.490'E	Dike
HAS-11	Salaman	South of as Safawi	32°10.530'N / 37°07.260'E	
HAS-12	Paleosol	South of as Safawi (5km)	32°10.530'N / 37°07.260'E	Overlain by HAS-11
HAS-13	Salaman	As Safawi – Al Azraq road	32°10.200'N / 37°06.060'E	
HAS-14	Ali	Wadi Ali	32°07.300'N / 37°03.200'E	
HAS-15	Abed	West of Jabal Ushayhib	32°02.120'N / 37°58.250'E	
HAS-16	Ushayhib	West of Jabal Ushayhib	32°02.120'N / 37°58.250'E	
HAS-17		Tall Hassan Quarry	31°57.160'N / 36°54.400'E	Dike intruding Hassan
HAS-18	Abed	East of Al Azraq	31°53.050'N / 36°53.540'E	
HAS-19	Abed	Between N and S Al Azraq	31°51.930'N / 36°49.372'E	Lower flow, weathered
HAS-20	Abed	As HAS-19	31°51.930'N / 36°49.372'E	Upper flow, fresh, blocky
HAS-21	Abed	Ash Shuwmaryi area	31°47.479'N / 36°45.730'E	Blocky
HAS-22	Abed	Jabal Uaynid	31°47.991'N / 36°44.869'E	Overlying Qirma and Shallala fms
HAS-23	Abed	Jabal Uaynid	31°47.991'N / 36°44.869'E	Overlying Qirma and Shallala fms
HAS-24	Aritayn	Edh Dherwa Volcanic Center	31°37.966'N / 37°15.049'E	Basalt xenolite
HAS-25	Aritayn	Edh Dherwa Volcanic Center	31°37.966'N / 37°15.049'E	Layered tuff
HAS-26	Wisad	East of Edh Dherwa Volc. Center	31°38.836'N / 37°15.715'E	Weathered basalt flow
HAS-27	Wisad	Mafrash Al Ghamar	31°42.243'N / 37°15.793'E	Weathered fluidal basalt
HAS-28	Abed	Abar Al Hazim	31°42.473'N / 37°19.781'E	Blocky

Table A. (continued)

Sample	Formation	Location	Coordinates (Lon Lat.)	Notes
HAS-29	Wisad	Umm Nukhayla	31°43.581'N / 37°21.093'E	Overlying the Shallala Fm
HAS-30	Abed	Umm Nukhayla	31°43.581'N / 37°21.093'E	Overlying the Qirma Fm
HAS-31	Ufayhim	Jibal Al Qatafi	31°52.128'N / 37° 26.810'E	Flow sheet weathered
HAS-32	Wadi es Sibhi	Wadi es Sibhi	31°48.962'N / 37°31.823'E	From foothill
HAS-33	Wadi es Sibhi	Wadi es Sibhi	31°48.962'N / 37°31.823'E	20 m below HAS-34
HAS-34	Abed	Wadi es Sibhi	31°48.962'N / 37°31.823'E	Blocky massive flow
HAS-35	Wisad	Wadi es Sibhi	31°48.962'N / 37°31.823'E	
HAS-36	Abed	Wadi es Sibhi	31°48.962'N / 37°31.823'E	Blocky and massive
HAS-37	Hashimyya	West of Hulayhil and Al Adid	32°18.256'N / 37°19.839'E	
HAS-38	Abed	Kaf Al Kalb	32°19.983'N / 37°22.806'E	Dike NW-SE
HAS-39	Hashimyya	South of Qa Jabiriyya	32°20.837'N / 37°24.591'E	Overlying Abed Fm
HAS-40	Abed	Qitar Al Abid	32°21.384'N / 37°29.299'E	Dike, fresh
HAS-41	Bishriyya	Qa Khanna – quarry	32°01.764'N / 36°30.408'E	Rock wool quarry
HAS-42	Bishriyya	East of Abu-Setteh farms	32°04.610'N / 36°34.633'E	
HAS-43	Abed	Wadi Dulayl	32°05.822'N / 36°14.636'E	Flow from east
HAS-44	Abed?	Rawdat Basma	32°17.116'N / 36°23.062'E	Madhala Fm?
HAS-45	Hashimyya	East of Sabha and Subhiya	32°20.082'N / 36°32.215'E	
HAS-46	Bishriyya	Kshaa Slaytin east of Sabha	32°19.331'N / 36°35.033'E	From flow ridge
HAS-47	Aritayn	Jabal Quays volcanic cone	32°17.046'N / 36°35.847'E	Black scoria
HAS-48	Bishriyya	Tall Abu Al Fart	32°10.960'N / 37°05.558'E	Nari on basalt flow
HAS-49	Ali	2 Km west of as Safawi	32°10.667'N / 37°05.366'E	Flow sheet
HAS-50	Salaman	As HAS-49	As HAS-49	Blocky flow
HAS-51	Abed	West of as Safawi, south of bridge	As HAS-50	Massive blocky flow
HAS-52	Abed	As HAS-51	As HAS-50	Massive blocky flow
HAS-53	Hashimyya	East of Hashimyya Village	32°08.448'N / 36°54.898'E	Rim dike within pyroclasts of volcanic cone
HAS-54	Mahadda	Deir Al Kahf	32°14.405'N / 36°50.733'E	Blocky
HAS-55	Aritayn	Al Jbaya Village, Jibal ar Rifayyat	32°16.503'N / 36°45.314'E	Black scoria, quarry, volcanic cone
HAS-56	Bishriyya	As HAS-55	As HAS-55	Basalt
HAS-57	Aritayn	Tall ar Rimah volcanic cone	32°18.776'N / 36°52.472'E	Basalt within pyroclasts
HAS-58	Wadi Manasif	Jawa Village	32°20.226'N / 37°00.253'E	Massive, blocky
HAS-59	Ushayhib	Mithnat Rajil	32°21.789'N / 37 00.095'E	

Table A. (continued)

Sample	Formation	Location	Coordinates (Lon Lat.)	Notes
HAS-60	Abed	Qa ash Shahba	32°19.487'N / 37°32.975'E	Dike NW-SE
HAS-61	Ali	Tulul ash Shabha sheet	32°22.184'N / 37°35.329'E	Covered by HAS-63
HAS-62	Hashimyya	Tulul ash Shabha sheet	As HAS-61	Overlaying HAS-63
HAS-63	Aritayn	Tulul ash Shabha sheet	As HAS-61	Tuff includes obsidian
HAS-64	Wisad	Wadi Sa'ada	32°23.095'N / 37°35.846'E	Layered flow sheet
HAS-65	Ali	As HAS-64	32°23.553'N / 37°37.171'E	Blocky
HAS-66	Hashimyya	As HAS-64	As HAS-65	Overlying tuff
HAS-67	Hashimyya	As HAS-64	As HAS-64	Overlying tuff
HAS-68	Hashimyya	Biyar Al Ghasein	32°20.557'N / 37°38.477'E	
HAS-69	Abed	Biyar Al Ghasein	32°23.067'N / 37°47.400'E	Blocky
HAS-70	Abed	Wadi Al Ghasein	32°24.937'N / 37°52.937'E	Blocky
HAS-71	Abed	East end of Badia sheet	32°26.957'N / 38°02.750'E	Blocky, covers Shallala Fm
HAS-72	Abed	Between Al Azraq N and Tall Hassan	31°54.895'N / 36°50.729'E	Blocky
HAS-73	Abed	Tall Usaykhim	31°56.753'N / 36°57.129'E	Blocky, covers Shallala Fm
HAS-74	Madhala	As Safawi sheet	32°05.482'N / 37°02.625'E	
HAS-75	Ali	Qabr Rath'an	32°04.741'N / 37°05.316'E	Blocky, as Safawi sheet
HAS-76	Abed (Qastalya Mb)	Qa Buqaya' awiyya	32°03.074'N / 37°13.258'E	Blocky
HAS-77	Hashimyya	Tulul Al Ashaqif	32°17.773'N / 37°35.785'E	Dike NW-SE
HAS-78	Ufayhim	Tulul Al Ashaqif	32°15.649'N / 37°36.037'E	Basalt within pyroclasts of volcanic cone.
HAS-79	Ushayhib	Quarry SW of Tulul Al Ashaqif	32°14.541'N / 37°35.119'E	Covers tuff
HAS-80	Hashimyya	Wadi Al Ausajy Sheet	32° 14.190'N / 37° 32.622'E	Massive, blocky, cover pleo-soil
HAS-81	Hashimyya	As HAS-80	as HAS-80	Massive
HAS-82	Abed	As HAS-80	32°14.245'N / 37°32.532'E	Blocky
HAS-83	Ali?	As HAS-80	As HAS-80	
HAS-84	Abed	North of Qa Hamda	32°04.885'N / 37°16.340'E	Dike NW-SE, blocky polygons
HAS-85	Abed	As HAS-84	As HAS-84	As HAS-84
HAS-86	Abed	Along the TAP-line	32°01.227'N / 37°25.775'E	Blocky, west of Ausajy Sheet
HAS-87	Hashimyya	Along the TAP-line	31°58.834'N / 37°32.916'E	Overlying Abed Fm
HAS-88	Abed	Along the TAP-line	31°57.310'N / 37°38.465'E	Blocky, west of es Subhi Sheet,
HAS-89	Hashimyya	As HAS-88	as HAS-88	Flow from north
HAS-90	Hashimyya	Along the TAP-line	31°56.324'N / 37°42.961'E	Flow from north

Table A. (continued)

Sample	Formation	Location	Coordinates (Lon Lat.)	Notes
HAS-91	Abed	Along the TAP-line	31°55.428'N / 37°47.576'E	Dike NW-SE, Wisad Sheet
HAS-92	Abed	Along the TAP-line	31°55.322'N / 37°49.466'E	Flow from north
HAS-93	Abed	TAP-line – Al Hiber	31° 51.681'N / 38° 01.587'E	overlying Shallala Fm
HAS-94	Wadi es Sibhi	Wadi es Sibhi	31°47.822'N / 37°30.479'E	Overlying Qirma Fm
HAS-95	Wadi es Sibhi	Wadi es Sibhi	31°49.033'N / 37°31.878'E	Flow sheet overlying Qirma Fm.
HAS-96	Abed	As HAS-95	As HAS-95	Massive, blocky
HAS-97	Hashimyya	Jibal Ash Shumeisanat	31°45.816'N / 37°40.629'E	
HAS-98	Wisad	As HAS-97	As HAS-97	Weathered
HAS-99	Hashimyya	Qa Al Wuteidat	31°51.143'N / 37°44.424'E	
HAS-100	Hashimyya	Um Rujoom Track –	31°52.344'N / 37°49.443'E	Wisad Sheet
HAS-101	Abed	Near Hashimyya Village	32°07.467'N / 36°57.350'E	Zarqa Sheet
HAS-102	Salaman	NE of as Safawi sheet	32°21.914'N / 37°09.614'E	
HAS-103	Wisad?	On QA-1 Oil Well track	32°27.809'N / 37°28.433'E	West of Abid Sheet
HAS-104	Abed	As HAS-103	As HAS-103	Overlying HAS-103
HAS-105	Wisad?	SE of QA-1 Oil Well	32°27.850'N / 37°27.505'E	Fresh
HAS-106	Abed?	As HAS-103	As HAS-105	Overlying HAS-105
HAS-107	Hashimyya	West of Sa'ada – Biyar Al Ghasein	32°25.064'N / 37°44.215'E	Massive flow covered by pyroclasts
HAS-108	Abed	Covers HAS-107	As HAS-107	Covers pyroclasts
HAS-109	Abed	Biyar Al Ghasein	32°25.594'N / 37°46.484'E	Massive flow, polygons
HAS-110	Wadi es Sibhi	As HAS-109	as HAS-109	Overlying soil (Qirma Fm?)
HAS-111	Hashimyya	Tulul Al Ghasein Volcano	32°27.451'N / 37°45.075'E	Basalt within pyroclasts
HAS-112	Abed	NW of Biyar Al Ghasein	32°30.393'N / 37°38.747'E	Blocky, Misma Sheet
HAS-113	Ali	West of Tall Khudayry	32°31.508'N / 37°39.334'E	Flow sheet, Misma Sheet
HAS-114	Abed	Wadi NW of Tall Khudayry	32°32.680'N / 37°38.787'E	Massive, blocky
HAS-115	Wadi es Sibhi	South of Tall Misma	32° 34.588'N / 37°39.891'E	Misma Sheet
HAS-116	Salaman	Qa Shubeika Road	32°12.626'N / 37°08.184'E	Thin flow
HAS-117	Bishriyya	Qa Shubeika Road	32°19.507'N / 37°10.401'E	Flow ridge
HAS-118	Bishriyya	Qa Shubeika Well	32°22.994'N / 37°13.177'E	Fahda? Shubayka Sheet
HAS-119	Salaman ? Madhala?	East of Qa Shubeika	32°23.180'N / 37°15.522'E	Blocky, west of Al Abid Sheet
HAS-120	Abed	West of Qitar Al Abid	32°23.473'N / 37°16.945'E	West of Qatar Al Abid dike

Table B. Type of rock, minerals, and relative abundance, and texture of studied samples.

Sample	Type of rock	Minerals and relative abundance	Texture	Remarks
HAS-1	Iddingsite Basalt	plg > idd > op > ol > cc	fine-grained porphyritic – microlitic + subpilotaxitic	opaques-rich; vesicular
HAS-2	Basaltic Scoria	ol, cc	scoriaceous	welded scoria; Fe/Mn impregnation
HAS-3	Pyroxene-Olivine Basalt	plg > px > ol > op	porphyritic - intergranular and microsubophitic	vesicular-rich
HAS-4	Olivine -Iddingsite Basalt	ol > idd > plg > op	fine-grained; porphyritic – microlitic	vesicular -rich xenolith - poor
HAS-5	Olivine-Pyroxene Basalt	plg > ol > px > op	porphyritic - intergranular	porous+vesicular very rich
HAS-6	Olivine- Pyroxene -Basalt	plg > ol > idd > px > op	porphyritic - intergranular to trachytic	vesicular - rich
HAS-7	Olivine Basalt	plg > ol > op	porphyritic-glomeroporphyritic - trachytic	porous - vesicular
HAS-8	Pyroxene-Olivine Basalt	plg > px > ol > idd > op	porphyritic - intergranular and microophitic	vesicular - rich
HAS-9	Pyroxene-Olivine Microdolerite	plg > px > ol+idd > op > cc	porphyritic - intergranular	olivine with idd. rim; vesicular
HAS-10	Olivine Basalt	plg > ol > op > cc	porphyritic - to glomeroporphyritic; intergranular - trachytic	porous + vesicular
HAS-11	Olivine-Pyroxene Basalt	plg > ol > idd > px > op > cc	porphyritic - intergranular - pilotaxitic	porous + vesicular
HAS-13	Olivine-Iddingsite Basalt	plg > ol > idd > op	porphyritic - pilotaxitic to trachytic	porous + vesicular
HAS-14	Pyroxene-Olivine Microdolerite	plg > idd > px > op > cc	porphyritic - intergranular	pyroxenite xenoliths
HAS-15	Olivine-Pyroxene Basalt	plg > ol > px > op	porphyritic - pilotaxitic	porous + vesicular
HAS-16	Olivine-Pyroxene Basalt	plg > ol > px > op	fine – grained; porphyritic - microlitic	xenolith and vesicular opaques-rich
HAS-17	Olivine Basalt	ol > plg > op	fine-grained; porphyritic – subpilotaxitic to fluidal	porous + vesicular
HAS-18	Pyroxene-Olivine Basalt	plg > px > ol > op > cc	porphyritic - intergranular + pilotaxitic	porous + vesicular
HAS-19	Pyroxene-Olivine Basalt	plg > px > ol > op > cc	porphyritic-intergranular and subophitic	microporous + vesicular
HAS-20	Pyroxene-Olivine Basalt	plg > px > ol > op	porphyritic-intergranular	porous + vesicular; cc. in groundmass
HAS-21	Iddingsite Basalt	plg > idd > ol > op > cc	porphyritic-intergranular + pilotaxitic	ol. with idd-rim; cc. in interstices and around vesicles
HAS-22	Olivine-Iddingsite Basalt	plg > ol > idd > cc > op	porphyritic-pilotaxitic + trachytic	porous + vesicular; op. rich; cc. in groundmass-rich
HAS-23	Olivine-Iddingsite Basalt	plg > ol > idd > op	porphyritic-intergranular	chlorite in groundmass
HAS-24	Olivine- Pyroxene Basalt	plg > ol > px > chl > op > cc	porphyritic-intergranular to trachytic	chlorite-rich; propilitic facies
HAS-25	Scoriaceous Tuff, mixed	Feldspars	vitric-lithic-crystalloclastic	vitric basalt and carbonate rock
HAS-26	Olivine-Iddingsite Basalt	plg > cl > ol > idd > op	porphyritic – intergranular + pilotaxitic	high chloritization
HAS-27	Pyroxene-Olivine Microdolerite	plg > px > ol+idd > op > cc > cl	porphyritic – intergranular +subophitic;	olivine with idd. rim
HAS-28	Olivine-Iddingsite Basalt	plg > ol+idd > px > cc > op	porphyritic-intergranular	high alteration calcite vesicular-rich

Table B. (continued)

Sample	Type of rock	Minerals and relative abundance	Texture	Remarks
HAS-30	Olivine-Iddingsite Basalt	plg > ol > idd > px > cc > op	porphyritic-intergranular transitional to microdolerite	porous – rich; calcite-rich
HAS-31	Olivine-Iddingsite Basalt	idd > plg > ol > op > cc	porphyritic-microlitic	calcite filling microcracks
HAS-32	Iddingsite Basalt	idd > op > plg	aphyric- microlitic	vitric groundmass; opaque-rich
HAS-33	Iddingsite Basalt	idd > plg > op > cc	aphyric- microlitic	microcracks filled with calcite
HAS-34	Olivine-Pyroxene Basalt	plg > ol > px > op > cc	porphyritic-intergranular	porous + vesicular-rich
HAS-35	Iddingsite Basalt	plg > idd > op > cc	fine-grained; porphyritic-subpilotaxitic	vesicular-rich;
HAS-36	Olivine-Pyroxene Basalt	plg > ol > px > op > cc	porphyritic-intergranular	porous+vesicular-rich
HAS-37	Olivine Basalt	plg > ol > op > cc	fine grained; porphyritic-subpilotaxitic	porous+vesicular
HAS-38	Olivine-Iddingsite Basalt	plg > ol > idd > px > op > cc	porphyritic-intergranular	porous+vesicular
HAS-39	Olivine Basalt	plg > ol > op > cc	fine-grained, microlitic	porous+vesicular
HAS-40	Pyroxene-Olivine Basalt	plg > px > ol > idd > cc > op	porphyritic-intergranular	vesicular
HAS-41	Olivine-Iddingsite Basalt	plg > ol > idd > op	porphyritic-intergranular	porous+vesicular
HAS-42	Olivine-Pyroxene Basalt	plg > ol > px > op	porphyritic to glomeroporphyritic and intergranular	vesicular
HAS-43	Pyroxene-Olivine Basalt	plg > px > idd > op > cc	porphyritic-intergranular	vesicular-rich
HAS-44	Olivine-Pyroxene Basalt	plg > ol > px > op	porphyritic-intergranular	porous+vesicular
HAS-45	Olivine Basalt	plg > ol > op	porphyritic to glomeroporphyritic and intergranular	microlitic-rich, a few xenoliths
HAS-46	Pyroxene-Olivine Basalt	plg > px > ol	porphyritic-intergranular to pilotaxitic	vesicular-rich
HAS-47	Basaltic Scoria	ol, plg	scoriaceous	
HAS-48	Olivine Basalt	plg > op > ol > cc	porphyritic+glomeroporphyritic, fluidal+ pilotaxitic	fine and rich impregnation with op
HAS-49	Pyroxene-Olivine Basalt	plg > px > ol > idd > op	porphyritic intergranular	vesicular-rich
HAS-50	Olivine-Iddingsite Basalt	plg > ol > idd > px > op	porphyritic trachytic	vesicular-rich
HAS-51	Olivine Basalt	plg > ol > op	porphyritic-intergranular	porous+vesicular-rich
HAS-52	Olivine Basalt	plg > ol > op > cc	fine-grained; glomeroporphyritic -pilotaxitic	
HAS-53	Olivine Basalt	plg > ol > op	porphyritic-fluidal	opacitization of grm
HAS-54	Olivine-Pyroxene Basalt	plg > ol > idd > px > op > cc	porphyritic-intergranular to trachytic	porous+vesicular-rich
HAS-55	Basaltic Scoria	plg, ol, px	scoriaceous	glomerules of pyroxene
HAS-56	Pyroxene-Olivine Basalt	plg > px > idd > ol > op > cc	porphyritic-intergranular	porous+vesicular- very rich
HAS-57	Basaltic Tuff	plg, px	vitro-crystallo-lithoclastic	vitric matrix complete opacified
HAS-58	Olivine Basalt	plg > ol > op > cc	fine-grained; porphyritic to glomeroporphyritic; subpilotaxitic	
HAS-59	Olivine Basalt	plg > ol > op	fine-grained; porphyritic to glomeroporphyritic; hyalopilitic	
HAS-60	Pyroxene-Olivine Basalt	plg > px > ol > idd > op	porphyritic intergranular+subophitic	vesicular-rich

Table B. (continued)

Sample	Type of rock	Minerals and relative abundance	Texture	Remarks
HAS-61	Olivine-Pyroxene Basalt	plg > ol > px > op	porphyritic glomeroporphyritic - intergranular	
HAS-62	Olivine Basalt	plg > ol > op > cc	fine-grained; microlitic	
HAS-64	Olivine-Iddingsite Basalt	plg > ol > idd > op > cc	porphyritic-subpilotaxitic	vesicular+olveolar- poor
HAS-65	Pyroxene-Olivine Microdolerite	plg > px > ol > idd > op	porphyritic-subophitic	olivine with iddingsite rim
HAS-66	Olivine Basalt	ol > op	fine-grained; vitric groundmass +microlites	no of plg; opacified groundmass
HAS-67	Olivine Basalt	ol > op > plg > chrisotile+antigorite > cc	fine-grained; porphyritic-glassy groundmass	serpentinization alveolar+cc
HAS-68	Olivine Basalt	plg > ol > op	fine-grained; microlitic+subpilotaxitic	vesicular; opacitization of the groundmass
HAS-69	Pyroxene-Olivine Basalt	plg > px > ol > idd > op	porphyritic-intergranular	vesicular-rich
HAS-70	Olivine-Iddingsite Basalt	plg > px > idd > op	porphyritic-intergranular + subophitic	porous+vesicular
HAS-71	Olivine-Iddingsite Basalt	plg > px > idd > op > cc	porphyritic-intergranular + subophitic	porous+vesicular
HAS-72	Pyroxene-Olivine Basalt	plg > px > ol > op	porphyritic+pilotaxitic	vesicular-rich
HAS-73	Olivine-Pyroxene Basalt	plg > ol > idd > op > px	fine-grained porphyritic-pilotaxitic + fluidal	vesicular-rich
HAS-75	Pyroxene-Olivine Microdolerite	plg > px > ol > idd > op > cc	porphyritic-intergranular	ol with idd. rim; porous+vesicular
HAS-76	Pyroxene-Olivine Basalt	plg > px > ol > idd > op > cc	porphyritic-intergranular + subophitic	vesicular-rich
HAS-77	Olivine Basalt	plg > ol > op	fine-grained; microlitic+subpilotaxitic	opacitization of the groundmass
HAS-78	Olivine Basalt	ol > idd > op	fine-grained; porphyritic-glassy groundmass	absence of plg; a few xenoliths
HAS-79	Pyroxene-Iddingsite Basalt	plg > ol+idd > px > op > cc	porphyritic subpilotaxitic	opaque-rich
HAS-80	Iddingsite Basalt	plg > idd > op	fine-grained, microlitic	
HAS-81	Olivine Basalt	plg > ol > op	porphyritic to glomeroporphyritic, intergranular-trachytic	
HAS-82	Olivine Basalt	plg > ol > op > cc	porphyritic-intergranular	porous+vesicular
HAS-83	Olivine Basalt	plg > ol > op	porphyritic-glomeroporphyritic; pilotaxitic-fluidal	microgabbro xenoliths
HAS-84	Pyroxene-Iddingsite Basalt	plg > px > idd > op > cc	porphyritic-intergranular	alveolar
HAS-85	Pyroxene-Iddingsite Basalt	plg > px > idd > cc > > op	porphyritic-intergranular + subpilotaxitic	porous+vesicular
HAS-86	Olivine Iddingsite Basalt	plg > ol > idd > px > cc > op	porphyritic-intergranular	porous+vesicular-rich
HAS-87	Iddingsite Basalt	plg > idd > ol > op > cc	micropilotaxitic	opaque-rich
HAS-88	Pyroxene Olivine Microdolerite	plg > px > idd > op	porphyritic-ophitic	vesicular
HAS-74	Olivine-Pyroxene Basalt	plg > ol > px > op	glomeroporphyritic-subpilotaxitic	vesicular
HAS-89	Iddingsite Basalt	plg > idd > ol > op > cc	micropilotaxitic	opaque-rich
HAS-90	Iddingsite Basalt	plg > idd > op > ol	fine-grained, microlitic	abundance of microlites

Table B. (continued).

Sample	Type of rock	Minerals and relative abundance	Texture	Remarks
HAS-92	Iddingsite Basalt	plg > idd > px > op > cc	porphyritic-pilotaxitic to fluidal	vesicular
HAS-93	Pyroxene-Iddingsite Basalt	plg > px > idd > cc > op	porphyritic-subtrachytic	porous+vesicular; cc- very rich
HAS-94	Iddingsite Basalt	plg > idd > op	porphyritic-microlitic	
HAS-95	Iddingsite Basalt	idd > plg > op > cc	aphytic- microlitic	fine-grained alveolar, porous
HAS-96	Pyroxene-Olivine Basalt	plg > px > ol > idd > op	porphyritic-intergranular to holocrystalline microgranular	porous
HAS-97	Iddingsite Basalt	plg > idd > ol > op > cc	fine-grained, porphyritic-subpilotaxitic	alveolar
HAS-98	Iddingsite Basalt	plg > idd > op > ol	porphyritic-subpilotaxitic	porous; opaque-rich
HAS-99	Olivine Basalt	plg > ol > op > cc	fine-grained, microlitic-fluidal	opacified groundmass
HAS-100	Iddingsite Basalt	plg > idd > op > ol > cc	porphyritic-microlitic	opaque-rich
HAS-101	Pyroxene-Iddingsite Basalt	plg > px > idd > op	porphyritic-intergranular subophitic	vesicular-rich
HAS-102	Olivine-Pyroxene Basalt	plg > ol > px > op	porphyritic-intergranular	vesicular and porous
HAS-103	Pyroxene-Iddingsite Microdolerite	plg > px > idd > ol > op	medium-grained; porphyritic-intergranular	
HAS-104	Pyroxene-Iddingsite Microdolerite	plg > px > idd > sphene	coarse-grained; subophitic	vesicular-rich
HAS-105	Pyroxene-Iddingsite Microdolerite	plg > px > idd > op > cc	porphyritic-intergranular	
HAS-106	Pyroxene-Iddingsite Microdolerite	plg > px > idd > ol > op > cc	medium-grained; porphyritic-intergranular	vesicular, sphene-rich
HAS-107	Iddingsite Basalt	idd > plg > cc > op	fine-grained; vitric-microlitic	
HAS-108	Olivine Basalt	plg > ol > op	porphyritic-subpilotaxitic	
HAS-109	Pyroxene-Iddingsite Basalt	plg > px > idd > cc > op	porphyritic-intergranular	vesicular-rich
HAS-110	Olivine- Iddingsite Basalt	ol > idd > op > plg	porphyritic-microlitic	opaque -rich; vitric grm
HAS-111	Olivine Basalt	ol > plg > op	porphyritic-fluidal	porous-rich
HAS-112	Olivine-Pyroxene Basalt	plg > ol > px > idd > op	porphyritic-intergranular	vesicular-rich sphene-sagenite
HAS-113	Pyroxene-Olivine Microdolerite	plg > px > ol > idd > op	porphyritic- subophitic	vesicular-rich
HAS-114	Pyroxene-Olivine Basalt	plg > px > ol > idd > op	porphyritic-subpilotaxitic+trachitic	
HAS-115	Iddingsite-Pyroxene Basalt	idd > px > ol > op > cc	fine-grained; microlitic	opaque -rich
HAS-116	Pyroxene-Olivine Basalt	plg > px > ol > op > cc	porphyritic-intergranular	vesicular-rich
HAS-117	Pyroxene-Olivine Basalt	plg > px > ol > op	porphyritic-trachytic	vesicular-rich

Table B. (continued).

Sample	Type of rock	Minerals and relative abundance	Texture	Remarks
HAS-118	Olivine-Pyroxene Basalt	plg > ol > px > op	porphyritic-intergranular	vesicular-rich; sagenite
HAS-119	Pyroxene-Olivine Basalt	plg > px > ol > idd > op	porphyritic-intergranular+ subpiloxitic-fluidal	vesicular+ porous-rich
HAS-120	Pyroxene-Olivine Basalt	plg > px > ol > idd > op > cc	porphyritic-intergranular	vesicular+ porous opaque-rich

Symbols:

- plg = plagioclase
- ol = olivine
- px = pyroxene
- idd = iddingsite
- op = opaques (Fe-Ti oxides)
- cc = calcite
- chl = chlorite
- gm = groundmass

Table C. K-Ar ages of samples from the Harrat Ash Shaam basalts, northeast Jordan.

SAMPLE	AGE (Ma)	Error (± Ma)	⁴⁰ Arrad (ccSTP/g)	%K	⁴⁰ Arrad %	MEASID
HAS-1*	1.54	0.33	7.50E-08	1.26	22.65	
HAS-2*	2.14	0.25	7.71E-08	0.93	20.22	
HAS-3*	2.68	0.03	6.11E-08	0.88	28.17	
HAS-4*	2.93	0.11	8.64E-08	0.76	22.29	
HAS-5*	0.42	0.01	1.30E-08	0.80	6.78	
HAS-6*	0.42	0.09	1.32E-08	0.81	10.73	
HAS-7*	0.46	0.01	1.58E-08	0.90	7.96	
HAS-8*	2.88	0.18	4.92E-08	0.44	9.32	
HAS-9*	9.93	0.02	1.68E-07	0.59	32.32	
HAS-10	1.64	0.08	4.97E-08	0.78	13.84	
HAS-11*	1.96	0.01	7.36E-08	0.97	29.72	
HAS-13*	2.13	0.14	8.10E-08	0.98	12.56	
HAS-14*	2.06	0.06	6.87E-08	0.86	15.21	
HAS-15	1.50	0.10	4.43E-08	0.76	16.03	11417
HAS-16*	2.55	0.02	7.77E-08	0.54	23.41	
HAS-17*	1.73	0.03	6.96E-08	0.75	20.16	
HAS-18	2.32	0.13	6.57E-08	0.73	21.40	11408
HAS-19*	3.49	0.03	7.84E-08	0.76	17.17	
HAS-20*	2.38	0.06	7.23E-08	0.66	15.27	
HAS-21*	8.13	0.10	1.32E-07	0.61	24.36	
HAS-22*	6.95	0.02	1.70E-07	0.63	33.98	
HAS-23*	6.97	0.26	1.55E-07	0.86	33.37	
HAS-24*	13.97	0.86	4.30E-07	0.79	45.36	
HAS-25*	9.05	0.46	3.34E-07	0.95	27.04	
HAS-26*	12.79	0.20	3.04E-07	0.61	38.31	
HAS-27	12.09	0.27	3.10E-07	0.66	39.09	11604
HAS-28	11.40	0.28	4.66E-07	1.05	47.13	11602
HAS-29	12.19	0.47	2.61E-07	0.55	10.45	11557
HAS-30	11.89	0.25	4.30E-07	0.93	51.69	11596
HAS-31	2.59	0.10	8.44E-08	0.84	13.22	11601
HAS-32	8.85	0.21	3.61E-07	1.05	51.08	11578
HAS-33*	8.94	0.19	2.89E-07	0.83	64.33	
HAS-34	10.88	0.24	3.47E-07	0.82	53.45	11599
HAS-35	10.62	0.23	5.70E-07	1.38	45.91	11582
HAS-36*	10.13	0.16	2.95E-07	0.75	23.69	
HAS-37	3.19	0.09	1.44E-07	1.16	47.22	11567
HAS-38	9.50	0.20	5.25E-07	1.42	70.62	11584

Table C. (continued).

SAMPLE	AGE (Ma)	Error (± Ma)	⁴⁰ Arrad (ccSTP/g)	%K	⁴⁰ Arrad %	MEASID
HAS-39	2.47	0.19	1.15E-07	1.20	5.30	11556
HAS-40	9.06	0.22	1.73E-07	0.49	25.14	11610
HAS-41	1.59	0.12	4.50E-08	0.73	11.16	11606
HAS-42	0.15	0.09	4.54E-09	0.77	1.89	11612
HAS-43	5.63	0.13	1.51E-07	0.69	28.19	11611
HAS-44	1.37	0.14	4.21E-08	0.79	14.44	12316
HAS-45	6.00	0.62	2.79E-08	0.12	9.61	11609
HAS-46	1.80	0.08	4.96E-08	0.71	12.59	12318
HAS-47	0.60	0.05	2.80E-08	1.21	5.75	11678
HAS-48	1.16	0.12	4.10E-08	0.91	5.19	12317
HAS-49	2.94	0.12	6.62E-08	0.58	27.00	12319
HAS-50	3.16	0.23	9.19E-08	0.75	9.90	11674
HAS-51	2.31	0.07	6.56E-08	0.73	22.24	11673
HAS-52	2.25	0.09	5.58E-08	0.64	17.18	11677
HAS-53	2.61	0.12	1.01E-07	1.00	13.26	11676
HAS-54	1.00	0.05	3.07E-08	0.79	9.68	11675
HAS-55	0.26	0.03	1.15E-08	1.15	3.25	11684
HAS-56*	3.00	1.02	6.76E-08	0.58	4.25	
HAS-57	2.19	0.06	1.30E-07	1.53	43.63	11683
HAS-58*	3.47	0.04	1.19E-07	0.74	34.30	
HAS-59	4.52	0.15	9.48E-08	0.54	13.03	11695
HAS-60	10.66	0.68	2.82E-07	0.68	23.47	11696
HAS-61	1.82	0.07	6.83E-08	0.97	18.24	11692
HAS-62	1.51	0.09	4.21E-08	0.72	8.31	11688
HAS-63	40.05	0.83	7.07E-07	0.45	68.55	11685
HAS-64*	8.25	0.44	3.69E-07	1.15	56.16	
HAS-65*	8.81	0.01	3.56E-07	1.04	28.63	
HAS-66	1.29	0.06	4.05E-08	0.81	12.90	11691
HAS-67	2.10	0.12	5.12E-08	0.63	8.00	11589
HAS-68	1.79	0.11	6.61E-08	0.95	7.49	11687
HAS-69	9.79	0.22	2.89E-07	0.76	47.12	11694
HAS-70	10.07	0.29	2.11E-07	0.54	26.82	12083
HAS-71	6.78	0.18	1.69E-07	0.64	22.48	12081
HAS-72	1.27	0.07	2.80E-08	0.57	9.12	12217
HAS-73	6.63	0.19	1.67E-07	0.65	14.27	12085
HAS-74	1.61	0.16	4.69E-08	0.75	11.48	12084
HAS-75	3.43	0.08	1.07E-07	0.80	20.47	11583

Table C. (continued).

SAMPLE	AGE (Ma)	Error (\pm Ma)	⁴⁰ Arrad (ccSTP/g)	%K	⁴⁰ Arrad %	MEASID
HAS-76	11.09	0.25	3.62E-07	0.84	42.52	12055
HAS-77	3.09	0.07	1.55E-07	1.29	56.45	11585
HAS-78	3.60	0.14	1.93E-07	1.38	10.18	11591
HAS-79	9.74	0.21	4.43E-07	1.17	67.50	11590
HAS-80	2.54	0.07	1.88E-07	1.91	58.38	11526
HAS-81	4.07	0.21	1.33E-07	0.84	27.52	11527
HAS-82	4.22	0.26	1.20E-07	0.73	24.99	11528
HAS-83	4.59	0.11	1.55E-07	0.87	60.46	11529
HAS-84*	23.17	0.41	3.50E-07	0.58	33.27	
HAS-85*	22.17	0.01	6.49E-07	0.75	33.29	
HAS-86	12.59	0.29	2.74E-07	0.56	56.24	11533
HAS-87	11.13	0.25	5.45E-07	1.26	73.18	11535
HAS-88	12.02	0.25	3.04E-07	0.65	50.94	11534
HAS-89	11.78	0.25	6.09E-07	1.33	60.07	11525
HAS-90	10.08	0.21	6.78E-07	1.73	72.67	11516
HAS-91	11.78	0.27	3.48E-07	0.76	53.54	11524
HAS-92	11.28	0.25	3.73E-07	0.85	52.06	11521
HAS-93*	26.23	1.77	1.09E-06	1.06	58.64	
HAS-94	10.31	0.24	4.17E-07	1.04	51.95	11519
HAS-95*	10.23	0.01	5.73E-07	1.44	74.40	
HAS-96	10.93	0.26	3.87E-07	0.91	39.08	11513
HAS-97	11.85	0.25	4.06E-07	0.88	65.97	11517
HAS-98	10.79	0.23	2.56E-07	0.61	49.85	11520
HAS-99	3.59	0.11	1.90E-07	1.36	41.98	11514
HAS-100	10.91	0.23	6.24E-07	1.47	74.72	11515

* = duplicates., error = 1σ

