PRJ, Vol. 8 (January 1996); P. 13–23, 8 FIGS. 3 TABLES.

Tertiary-Quaternary Alkaline-Subalkaline Magmatism in Gharyan Area-Field Aspects and Petrography

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السمات الحقلية والبتروغرافية لصهير الحينين الثالث والرابع القلوية والتحتقلوية بمنطقة غريان

الميروك أبو سريويل و جون وودسوورث

تظهر ملامح النشاط البركاني التابع للحينين الثالث والرابع واضحة على طول الجهة الشرقية من جبل نفوسة حيث تجلت هذه الملامح بتوضع سلسلتي اللابا القديمة والحديثة والبراكين المخروطية الشكل والفونولايت ذو المظهر القبابي وصخور البيروكلاستيك. تمثل اللابا القديمة أكثر الصخور البركانية إنتشاراً حيث تشكل سلسلة مستمرة عند منتصف المنطقة بينما تظهر اللابا الحديثة جلياً في صور الأقمار الصناعية عند الحواف. كما وجدت مدفونة في مسارات بعض الوديان القديمة ، وبالرغم من أن العلاقات الحقلية والعمر المطلق يشير إلى أن اللابا تنتمي إلى أكثر من نشاط بركاني إلا أنه قد وجد أن بتروغرافية جميع هذه الصخور متشابهة مما يشير إلى أنه قد تم إشتقاق جميع اللابا من مصدر متشابه. إن إقتراح اللابا القديمة كأقدم نشاط بركاني بالمنطقة قابل للنقاش.

تتكشف صخور الفونولايت في أماكن محدودة بالمنطقة وتشير الأدلة الحقلية ومعلومات العمر المطلق إلى أن هذه الصخور أقل حداثة من صخور البراكين البيزانيتية المتكشفة حيث أن صخور هذه البراكين والصخور المتباينة منها كانت حصيلة نشاط بركاني من براكين مركزية وجذذ وأنها تمثل كميات بسيطة من نتاج النشاط البركاني داخل حقل اللابا وخارجه.

تم التعرف بالمنطقة على رواسب رديئة الفرز سوداء اللون تتكون من شظايا بركانية وكتل متماسكة بمادة لاحمة نتجت عن إنفجارات بركانية كانت قد لامست المياه السطحية وأن جزءاً من هذه الشظايا قد تعرض إلى إعادة نقل.

هذا وقد تم تقسيم هذه الصخور البيروكلاستيلية إلى سحنة الفتحات البركانية وسحنة الصخور قريبة المصدر وسحنة الصخور بعيدة المصدر.

Abstract *Tertiary – Quaternary volcanic activity is conspicuous along the eastern scarp of Jabal Nafusah and comprises an old lava series (OLS), young lava series (YLS), volcanic cones, phonolite dome – shaped intrusions and pyroclastic rocks. The OLS are the most voluminous and form a fairly continuous plateau in the central part of the region. In contrast to the older flows, the YLS is mostly restricted to the periphery of the OLS plateau, as is clearly shown on satellite images. In addition, parts of the YLS occupy an ancient buried wadi system. Both the OLS and YLS are petrographically similar, although field evidence revealed a number of separate eruptive events. The suggestion that the OLS may represent the first phase of igneous activity in the area is debatable because of suspect dating.*

The phonolites are exposed at only a few localties. Field evidence and K-Ar Age dating suggest that they are much older than the late volcanic centres (LVC). These centres, erupted from central volcanoes and dykes, are represented by very small volume of the eruptive products throughout and outside the lava field.

Black, massive, poorly-sorted deposits made of fragmented products of explosive eruptions and matrix-supported blocks are encountered in the area. These deposites are considered to have been formed initially by vent opening phreatic – phreatomagnetic explosions and part of which were later reworked. Based on field criteria they have been classified into vent facies, near – vent facies and distal facies.

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INTRODUCTION

The rocks of the Gharyan Volcanic Province (GVP) are mostly contained within a quadrilateral area of some 7000 Km^2 between the towns of Gharyan, Tarhunah, Bani Walid and Mizdah (Fig. 1). The volcanic rocks themselves cover an area of approximately 3000 Km^2 and form a generally continuous sheet in the central part of the region, with some peripheral outlier and a number of more scattered intrusions, believed to be part of the same volcanic field originally.

A summary of the work undertaken up to 1970 has been given by Busrewil (1974). The chemistry of the main groups of the GVP has been briefly established by Almond *et al.*, (1974). Later work by Busrewil and Wadsworth (1980) discussed in more detail the genesis of the basanitic suite of rocks. Geologic maps of the area at a scale 1:250.000 with explanatory booklets were published by the Industrial Research Centre (Antonovic, 1977, El Hinnawy and Cheshitev, 1975; Mann, 1975; Zivanovic, 1976).

Several K: Ar data have been previously published on the volcanic rocks from the GVP (Piccoli, 1970; Ade-Hall, *et al.*, 1975). Some determinations from the YLS are contradictory and others are inconsistent with field relations.

In this paper we present 6 K: Ar whole rock ages from rock units of the GVP. These data are considered to provide valid estimates of the ages of each of the units measured. Based on more recent field work and petrography we reiterate some of earlier conclusions (Almond *et al.*, 1970, Busrewil and Wadsworth, 1980) but incorporate the results of the subsequent investigations. A discussion of the petrogenetic relationships within the GVP will be presented elsewhere (Busrewil and Wadsworth, in Prep.).

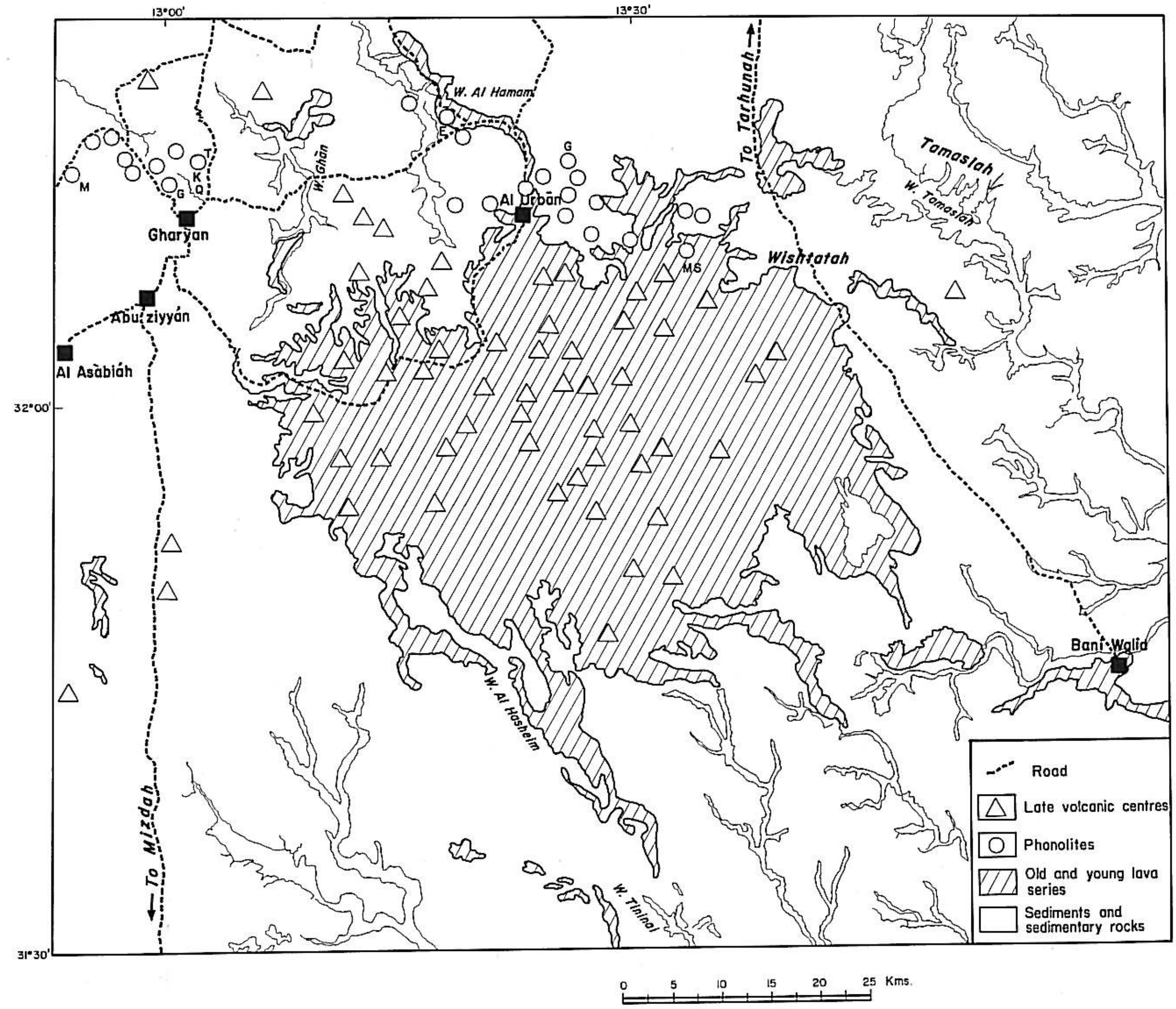

Fig. 1. Geologic map showing the distribution of the Gharyan Volcanic Province, E = Ras Umm al Ezz; G = Ras aj Jammah; K = Wadi Qurdu; M = Kaf Mantrus; Q = Wadi Qabil; RM = Ras al Massan; T = Kaf Tekut.

MODES OF OCCURRENCE

The igneous activity has four principal manifestations which can be easily recognized in the field. Firstly, there is the old lava series (OLS) with its subordinate young lava series (YLS) which cover most of the region (Fig. 1); secondly, there are the phonolitic intrusions which tend to occur as individual domes or clusters of domes just north of the Gharyan town along the northern limit of the escarpment; thirdly, there are the late volcanic centres (LVC), resting locally on top of the OLS, or represented by chemically similar minor intrusions outside the OLS area; fourthly, an episode of explosive volcanism, however, developed possibly during Quaternary time. The latter activity resulted in the emplacement of tuff cones and intrusive and reworked pyroclastics. This morphological grouping is supported by both field observation (Christie, 1955; Busrewil, 1974) and available radiometric ages (Table 1).

Table 1. K/Ar age determination of rock types in the GVP.

Locality	Age (Ma)	Classified here as
32°10′40″N 13°22′30″E*	1.3 ± 0.5	LVC
32°03′00 N 13°31′10″E*	2.9 ± 1.1	(basanitic suite)
32°12′00 N 13°13′45″E*	5.1 ± 1.5	
31°51′00 N 12°58′45″E*	7.7 ± 1.5	
32°12′30 N 12°23′00″E*	2.3 ± 0.3	YLS
32°12′30″N 13°08′30″E*	2.6 ± 0.8	(basaltic andesites)
32°05′45″N 13°19′45″E***	4.8 ± 0.4	
32°08′00″N 13°13′00″E***	5.05 ± 0.8	
32°15′05″N 13°14′31″E***	6.02 ± 1.3	
Kaf Tekut**	37.7	Phonolites
Kaf Mantrus**	39.7	
Kaf Abu Ghannush**	40.7	
Qulayb al Anz (32°23′36″N) (13°23′36″E)***	40.7 ± 1.2	
32°15′40″N 15°18′30″E***	41.4 ± 2	
Umm al Ezz***	47 ± 1.2	

* Analysed by Mobil Research Department, Dallas, Texas, 1967.
** Piccoli, 1970.
*** Carried out by the Isotope Geology Unit, British Geological Survey.

As far as the principal rock types are concerned, the OLS and YLS are composed of basaltic andesites and the LVC are generally basanitic (with related differentiates), while the domes are all phonolitic (Fig. 2).

FIELD RELATION OF THE GHARYAN VOLCANIC PROVINCE

Old Lava Series

This lava sequence rarely comprises more than four or five individual flows, reaching a maximum total thickness of approximately 40 m. In the more peripheral parts of the lava field, only one or two flows are present, but they are nevertheless surprisingly persistent and dominate wide areas of the plateau coutry. In many places the base of the lavas is not exposed but elsewhere they are seen to rest unconformably on the sedimentary rocks (Upper Cretaceous age), particularly along the wadis.

Erosion has dissected parts of the volcanic terrain into wadis and ridges with a relief in excess of 60 m. Sets of columnar joints, are sometimes exposed and accentuated vertical developmet of landslides.

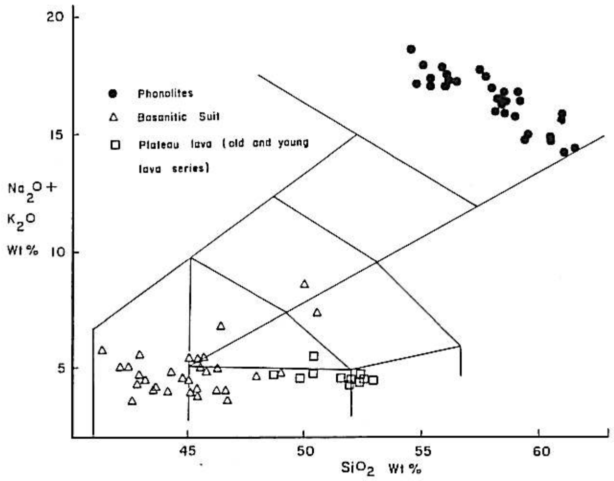

Fig. 2. Tatal alkali *vs* silica diagram for Gharyan volcanics. The style of notation is the same in the succeeding plots.

Young Lava Series

In contrast to the older flows, the younger lavas are almost barren of soil and vegetation covers. This unit produces distinctly dark colour on false colour landsat imagery. Field observation revealed that the initial invasion of the OLS was followed by a long period of erosion of unknown duration and down cutting to form new wadis which at a much later time were partly infilled by the YLS. The wadi filling lava form a thin resistant mass while the Mesozoic country rocks, on either sides, are much more rapidly removed. The original wadi segments are expressed today, either as a coherent basalt mass or as a particulate mass flow.

The existence of prominet wadi system before the eruption of the YLS is very well exhibited on satellite thematic mapper image. It is indicated by the long sinuous outcrops extending from the main volcanic region, particularly toward Beni Walid (Wadi Tininai, Wadi Ghubbeen), Wishtatah and northwards in the vicinity of the present drainage system of Wadi Ghan where Christie (1955) reported the existence of basalt on the crust of hard pan and caliche that had formed previously in the wadi bed. He believed that the basalts postdated the topographic features and must be very young, possibly of early Quaternary or late Pliocene age. Piccoli (1970) distinguished these as "valley basalts" in contrast to the OLS (flood basalts). Along Wadi al Hamam (32° 15′ 36″N, 13° 19′ 55″E), the writers have observed the existene of basalt on top of a soil-supported conglomerate. The lava flow itself shows pronounced exfoliation and attains a maximum thickness in excess of one metre. At higher levels old wadi terraces consisting of loose conglomerate, composed of rounded limestones, sandstone and basalts approximately 4–12 cm in diameter, are cemented by clay matrix. Still at higher levels, an older lava flow approximately 10 m thick is exposed along the wadi banks and pre-dates the last period of wadi incision.

North of station 520, basalt lavas were observed underlying Quaternary sediments at near-surface section of Wadi Tamasillah where the pipe line route of the Great Man-Made River Project is constructed. The basalt was found to be very fresh and shows vesicular and columnar jointing structures. Preliminary chemical data of selected samples from this locality suggest that the lavas belong to the subalkaline magma type (Busrewil and Wadsworth, in prep.). The Quaternary sediments lie unconformably on the lava and in places where the basalt is either missing or not reached, its thickness exceed the depth of the pipe line trench (7 m). The wadi deposits show a well developed fining up sequence and are characterized by interbedded sand and pebbly layers with occasional ocurrence of alluvial soils. Cobbles and boulders with a fine sand/silt matrix approximately 50 cm thick were observed in the middle level of the trench. The occurrence of such a high energy discharge in wadi section is inferred and interpreted to indicate humid phase environments. The field observations from widyan Al Hamam, Ghan and Tamasillah suggest that a Quaternary period of volcanism poured out small quantities of basalt on the surface.

PHONOLITES

General Introduction

The phonolites occur in an approximately east-west belt along the northern edge of the plateau lava field (Fig. 1) where they form prominent conical hills. Occurrences of trachytes, phonolites and alkali trachytes between Mizdah and Gharyan were reported by Lipparini (1940). Further reconnaissance of this region revealed no traces of such exposures.

The phonolites form islated dome-shaped intrusions amid the broad expanses of Mesozoic sediments. In some cases they are clearly intrusive laccoliths with the overlying sediments strongly arched over the dome-shaped intrusion, while the underlying

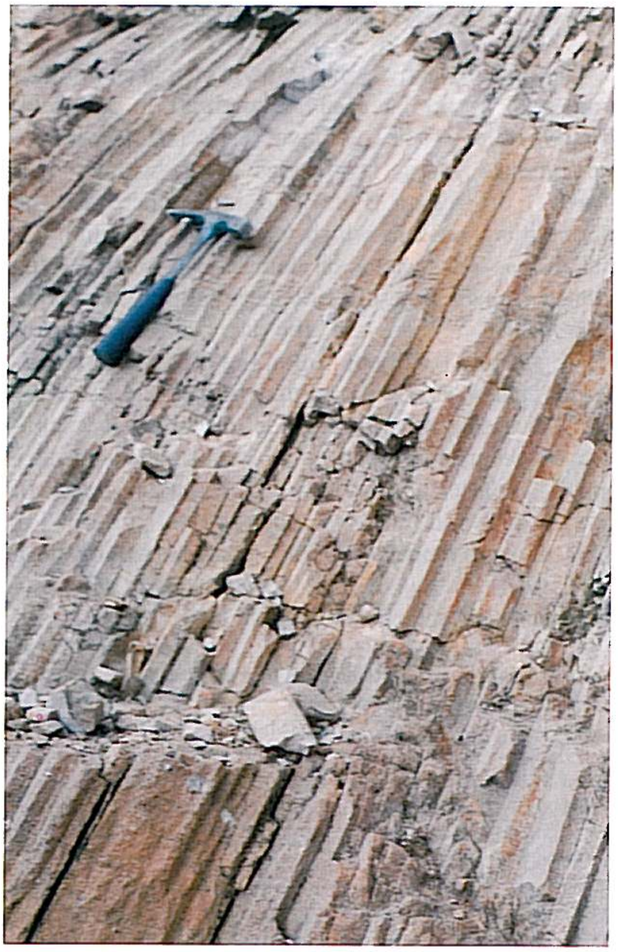

Fig. 3. Close view of columinar jointing in Abu Shaybah Formation (ss), about 1 km west of Kaf Tekut, Photo by Osama A. Joha of the Geology Department, Al Fateh University.

sediments are relatively undisturbed. In other examples, the phonolites are strikingly discordant with generally steep contacts against almost horizontal sediments, and with sill-like apophyses locally. The overall impression is of masses of viscous phonolitic magma rising diapirically through the sediments, with varying degrees of success; some appear to solidify at depth in transgressive mode, while others form domes beneath their roof of country rocks. It is believed that at few points near the top of the upheaval, the magma broke through the surface or was emplaced close to it. This is supported by the observation of vesicular phonolites at a small hill approximately 1 km NW of Kaf Abu Ghannush and horizontal jointing of the sandstone close to the contact between the Abu Shaybah Formation and the roof of an intrusive dike along the road cut about 1 km west of Kaf Tekut (Fig. 3). A brief description of few selected intrusions is summarised below:

Kaf Tekut: This is apparently the most straightforward phonolitic intrusion, as the country rock is generally domed all around it. The intrusion, now has the appearance of a crater, breached on its east side and it is not entirely regular in shape, as the phonolites bulge out beneath a skin of sediments, when it reaches lower levels on the south and south-west side. Near this bulge occur the patchy outcrops of basaltic breccia (Wadi Qurdu).

The outer part of the dome is apparently a thick skin of porphyritic phonolite (approximately 30 m. thick), showing a progressive chilling of the ground-mass towards the margin, and exhibitng a very prominent columnar jointing perpendicular to the margin. At the 'breached' entrance to the central crater of Kaf Tekut, this jointing is horizontal, while at higher levels it becomes progressively steeper as the skin turns over to form the domical roof.

Inside this jointed skin is a zone of smooth rounded outcrops of coarser (groundmass) phonolites, but equally porphyritic, and inside this is inferred to be the heavily altered zone responsible for the eroded (crater like) cores of the intrusive. It seems highly likely that the highest and most central part of the original dome-shaped plug would be the most susceptible to hydrothermal modifications, because the late stage fluids would all tend to concentrate here, beneath the viscous impervious skin. Indeed this may have helped the body rise diapirically through the sediments.

The presence of altered phonolites in the centre of the mass (G 128, Table 2) and Triassic sediments (Azizia Formation) on top of the SW part of the igneous body (Gray, 1971) suggest that the Kaf Tekut is best named as a shallow intrusive domal igneous body with an appearance of a physiographic ring structure today.

Table 2. Average of selected major chemical analyses of Charyan volcanics.

	1	2	3	4	5	G96	G127	G128
SiO_2	51.34	45.54	46.52	50.33	57.85	43.55	43.12	57.36
TiO_2	1.78	2.33	2.74	2.48	0.25	2.96	3.37	0.73
Al_2O_3	15.20	13.41	13.66	15.84	20.39	9.96	11.25	20.48
Fe_2O_3	2.25	4.02	3.72	4.41	2.32	6.43	10.34	3.17
FeO	7.88	7.05	7.52	5.09	0.91	3.87	3.52	0.55
MnO	0.15	0.18	0.18	0.21	0.20	0.22	0.22	0.11
MgO	7.07	12.23	9.36	4.94	0.20	13.99	11.85	0.94
CaO	9.28	10.40	10.29	7.92	0.70	14.98	10.55	3.49
Na_2O	3.77	3.03	3.74	5.40	9.92	2.03	2.79	2.79
K_2O	0.86	1.17	1.45	2.51	7.17	1.23	2.17	7.18
P_2O_5	O.42	0.64	0.85	0.87	0.09	0.77	0.82	0.20

1. Average of 11 YLS and OLS; 2. average of 5 alkali olivine basalts; 3. average of 7 hawaiites; 4. average of 2 mugearites; 5. average of 10 phonolites; G96 a clast of olivine basalt from the pyroclastics of Wadi Qurdu; G127 a clast of olivine basalt from the pyroclastics of Wadi Qabil; G128 phonolite from the central part of the Kaf Tekut igneous body.

Kaf Abu Ghannush: The Kaf Abu Ghannush phonolite is a discordant mass of irregular shape, displaying a variety of contact relationships. The mass itself is cut approximately in the centre by two phonolite sheets of dykes and at least one dyke-like mass at a lower level of the igneous body. The setting of the mass is best explained as a stock or laccolith with locally sill-like apophyses. Remnants of the country rock can be clearly seen in the centre. The relationship between this phonolitic mass and the country rocks is not very clear at the present level of erosion. However, the presence of a smal fault in the eastern part of the intrusion with marked dip of the sediments away from the igneous body suggests that the mass may have caused the tilting and faulting.

Kaf Mantrus: Another prominent hill with an impression of more resistant marginal facies (giving summit peaks) with steep jointing, this is also probably an intrusive dome.

It is very difficult to assess the field relationships between the phonolitic mass (Kaf Mantrus) and the country rock, as the sedimentary rocks are weathered all round, particularly north and north west of the phonolitic mass where the Jefarah lowland emerges. Piccoli (1970) interpreted the morphological setting of Kaf Mantrus as a doming protrusion or plug of highly viscous lavas similar to those known parts of the central Saharan zone of Atakor (Girod, 1964) and Tibesti (Vincent, 1970). Further reconnaissance of Kaf Mantrus and similarly formed phonolites (e.g. Ras Umm al Ezz, Ras al Jammah) suggests that they are best interpreted as shallow intrusive "phonolitic domes" rather than extrusive bodies.

LATE VOLCANIC CENTRES

These form prominent features scattered on and around the main plateau lava field. They almost always occur as distinct hills or clusters of hills rising above the general level of the plateau and usualy seen from a considerable distance in the field. Scoria cones are locally present at a few centres, suggesting that they are fairly young (Busrewil and Wadsworth, 1980). In some areas, only intrusive rocks are found, in the form of dykes, pipes, plugs and small dome-shaped masses that probably did not reach the surface in the liquid state, but have been exposed by erosion. The intrusive "centres" occur in different parts of the area, particularly north of Mizdah and the northern jabal escarpment where dykes of very limited length (a few tens of metres) indicate rather localized upwelling of magma, probably connected to a volcanic vent. Field description of the most prominent and accessible centres has already been given (Busrewil and Wadswoth, 1980) and details need not be repeated here.

PYROCLASTIC ROCKS

Initial Statement

The occurrence of numerous localities of fragmentary volcanic rocks in the GVP raised the problem as to the primary or secondary origin of these materials (Gray, 1971). Some may have flowed down wadis (Hey, 1962). Others are associated with dykes having a NW strike (Gray, 1971). Tuff cones composed of abundant thin beds made up of fragmentary materials with accretionary lapilli, presumably resulted from large eruptive pulses, characteristic of hydrovolcanic eruption, were encountered SE of Al Urban village. In addition, numerous occurrences of diatremes with occasional presence of herzolites are partially exposed along new road cuts. Furthermore, a well bedded pyroclastic materials appear to be sandwiched between lava flows of the YLS were also observed at Wadi Mugaitilah (32° 02′10″ N, 13° 12′20″E). Based on position relative to source, these rocks are divided into vent facies, near-souce facies and distal or fluvial facies as was recognized elsewhere by many writers (R. Walker, 1984; Fisher and Schmincke, 1984; Cas and Wright, 1988). The characteristics which gave clues to the mode of deposition or environmental condition, or both, at the time of emplacement, are emphasized. These are described in descending order of frequency of occurrence and also in descending order of aggregate volume of preserved deposits as follows.

Vent Facies

Numerous occurrences are partially exposed along wadi systems or new road cuts. At Kabdet al Jamel locality, there is a distinct area of pyroclastic rocks which are separated from Kaf Tekut phonolite by Wadi Qurdu and is entirely surrounded by Abu Ghaylan Formation (Middle Jurassic). These rocks are predominantly consolidated assemblages of pyroclasts. They are black, massive, poorly sorted deposits, consisted of a mixture of volcanic fragments (>90% of lapilli tuff) and sedimentary materials (approximately 5 cm in diameter). Matrix-supported blocks (up to 80 cm in diameter) of the underlying sediments and volcanics are common.

In several other localities including Wadi Qurdu and Wadi Qabil there are breccias which are restricted to outcrops within existing wadi systems. These deposits are uniformly massive, dull grey. Subangular to subrounded fragmens 5 cm. in diameter are common. Matrix-supported blocks of basic volcanics occur locally, as do a few Mesozoic sedimentary rock fragments. Dense and unvesiculated clasts of 10–15 cm. diameter showing impressive ball – milling were found associated with the pyroclastics of Wadi Qurdu and Wadi Qabil. A whole rock chemical analysis of two clasts show their alkaline character (Table 2). Volcanic dykes, which cut through the pyroclastics, range in width from 2 m. to 15 m. and can be followed over a distance in excess of 100 m.

Abundant ultramafic xenoliths, thought to be derived from the upper mantle, were found in the vent facies and their associated dykes as well (al Urban area, 200 m east of Ras al Masid). The latter are known for their abundance of ultramafic nodules (Busrewil and Wadsworth, 1980). This may suggest that magma composition and pyroclastic eruption appear to be related. Mineralogically, they comprise variable proportion of highly magnesian olivine, orthopyroxene and clinopyroxene, commonly together with spinel (Busrewil and Wadsworth, in prep.). The presence of associated ultramafic xenoliths and accidental pieces of the underlying sediments as well as the products of ball-milling and the overall stratigraphic position demonstrate that these fragmentary materials are obviously volcanic vents. The ascending magma may have intruded through reactivated faults and the deposits may have been formed initialy by vent opening phreatomagmatic activity. Renewal of volcanism in the form of localized dykes cutting in the middle part of the vent facies deposits may be related to lack or decrease in the efficiency of water/melt interaction as all observed fractures are filled with secondary minerals (mostly calcite).

Proximal Facies

This facies represent the northern part of Wadi Ghan pyroclastic deposits. The pyroclastics itself are approximately 15 m thick and consists of small fragments cemented together in a calcareous matrix. These fragments are all subangular (up to 3 cm in diameter) and apparently 80% basic rocks and 20% sediments. The lower part of the exposed facies show trough cross-bedding while the upper part is massive. Compared with the distal facies it is darker in colour and show very little or no systematic lateral and vertical variation in clast content, size and composition. It is suggested that the near-source facies, partialy exposed at this locality, may have been formed initially by vent opening phreatic-phreatomagmatic explosion. Unlike the vent facies it appears to have been remobilized shortly after deposition within possibly an old valley or a vent flank or a cut-off channel.

Distal Facies

These pyroclastics are best displayed in the walls of Wadi Ghan area for over 1 km stretch. The deposits were first described by Hey (1962) as a "mud flow" with uncertain climatic or volcanic origin. They are unconformably underlain by the Ain Tobi Member of

Cenomanian age and overlain sharply by Qasr al Haj Formation of Pleistocene age. At its head, this facies appears as massive water-laid volcanic breccias. It is dark grey in colour, approximately 6 m thick and consists of small fragments (basalt & sediments) cemented together in a calcareous matrix. The clasts, 1–4 cm, are subangular to subrounded and poorly sorted.

The massive unit passes down-flow within some 300 m to cross-bedded subfacies. Halfway along the direction of transport, a vent facies cutting this distal facies can be observed. Both of which were intruded by a basanitic dyke. The source of the reworked pyroclastics is thought to have resulted initially from localized explosive volcanism at or near the catchmet area of Wadi Ghan. The products of which were later transported with local sediments to its present day position. The presence of few tuff cones in the area of study may reinforce this conclusion. From the previous examples, it seems clear that the three types of pyroclastic rocks have much in common in terms of lithologies, nonetheless, they are distinct in both appearance and mode of emplacement.

RADIOMETRIC DATING

Piccoli (1970) made preliminary measurements of rocks from the Gharyan Volcanic Province which has provided K-Ar results around 52, 35.5 Ma for the old lava series, 37.9, 39.7, 40.7 Ma for the isolated phonolite masses, 29.5, 5.7, 3.5 Ma for the young lava series from Wadi Ghan and Bani Walid areas. He also reported ages of 11.5 and 8.5 Ma for two isolated shield volcanoes (Rus Al Moher and Tebrah). Further age determination by Ade-Hall *et al.*, (1975) yielded a young ages of 2–6 Ma from sites in the northern part of the main lava field. From Ade-Hall *et al.*, (1975) description of the localities, these samples appear to have been collected from the YLS. They have considered that the ages of the plateau lavas (OLS) are much younger than indicated by Piccoli (1970) and attributed this discrepancy to excess argon.

The present work presented six new whole rock K-Ar age data (Table 1). This is supplemented by unpublished data by Mobil. Based on age data and field observation the following suggestions are made.

1. Piccoli (1970) suggested that the OLS was extruded from fissure sources during Early Eocene (52 Ma). It is asssumed, until further age data are obtained, that such ages must remain conjectural, as no new data are available to substantiate such igneous activity.
2. The whole-rock ages for the phonolites, obtained from three different laboratories do cluster heavily around 40 Ma (Piccoli, 1970; Table 1). This suggests that the data are of value and supports an Eocene age for the early emplacement of the phonolites. It also suggestive of relatively long emplacement history spanning an interval of approximately 10 Ma. After long period of quiescence another phase of igneous activity led to the emplacement of the LVC and the YLS.
3. The 29 Ma age dating of a basalt sample from Wadi Ghan (Piccoli, 1970) should be considered suspect as a much younger age was obtained by Mobil from the same locality (2.6 Ma). The latter age is consistent with field observations and lies within the age range of the YLS. Two discrete episodes of the YLS are present and can best be seen in Wadi al Hamam area. The youngest of these may be of Holocene age.
4. Renewal of volcanism in the form of localized explosive volcanism is developed and resulted in the emplacement of tuff cones and intrusive as well as reworked pyroclastics. Field evidence suggests that this phase of igneous activity must be geologically very young (Pleistocene – Holocene) and could be contemporaneous with the emplacement of volcanic dykes and the extrusion of the last episode of the YLS.

PETROGRAPHY

The Lava Series (OLS and YLS)

These rocks are coarse grained compared with the basanitic suite. The phenocrysts consist exclusively of olivine and pyroxene but they are rarely abundant. Olivine phenocrysts are rounded to subhedral in shape and are partly iddingsitized, particularly in the peripheral zones. Clinopyroxene phenocrysts are usualy pale brown augite and exhibit slight zoning. The groundmass consists of plagioclase, pale brown augite, granular olivine and opaque oxides (Table 3). Plagioclase forms the dominant phase in all sections

Table 3. Microprobe analysis of selected minerals from GVP*

Rock Type	Pheonolite			Basaltic andesites		
Rock No	G66[1]	G66[2]	G66[3]	G116[4]	G19[5]	G19[6]
SiO_2	44.81	66.25	39.21	51.68	55.08	36.40
TiO_2		–	6.61	0.95	–	–
Al_2O_3	32.83	19.66	13.78	4.18	29.35	–
FeO	0.63	0.18	9.54	6.91	0.45	33.99
MgO	–	–	13.69	15.71	–	29.70
CaO	–	0.13	11.86	20.23	11.59	0.33
Na_2O	17.42	5.31	2.65	–	4.98	–
K_2O	3.96	9.43	1.18	–	0.17	–
MnO	–	–	0.09	0.15	0.07	0.50
Total	99.65	100.96	98.43	99.81	101.69	100.92

1 = Nepheline; 2 = K. Feldspar; 3 = Kaersutite; 4 = Augite; 5 = Plagioclase (An_{57}); 6 = Olivine (Fo_{61}). * = for Gharyan basanitic suite see Busrewil and Wadsworth (1980).

studied, exhibits slight normal zoning and occurs as tabular crystals. Albite twinning is common but combined carlsbad-albite twinning is often developed. The titaniferous oxides are abundant in the rocks and seem to belong to magnetite – ilmenite assemblages. Apatite needles are sparsely disseminated throughout the rocks.

Phonolites

Many of the phonolites are virtually aphyric but some of them are porphyritic. The phenocrysts include, in order of decreasing abundance, alkali feldspar, nepheline, amphibole, iron-titanium oxides and sphene. The alkali feldspar is represented by sparsely scattered phenocrysts of sanidine and to less extent of anorthoclase. Both types of alkali feldspar are locally zoned, have a patchy extinction and exhibit a small degree of late stage hydrothermal alteration in which the feldspar is altered to sericite. Small euthedral nephelines also occur as rectangular phenocrysts and are most abundant in the more sodic phonolites (Fig. 4). Phenocrysts of clinopyroxene are pale green to pale brown, weakly pleochroic sodic augite and occasionally a deep brown resorbed variety is

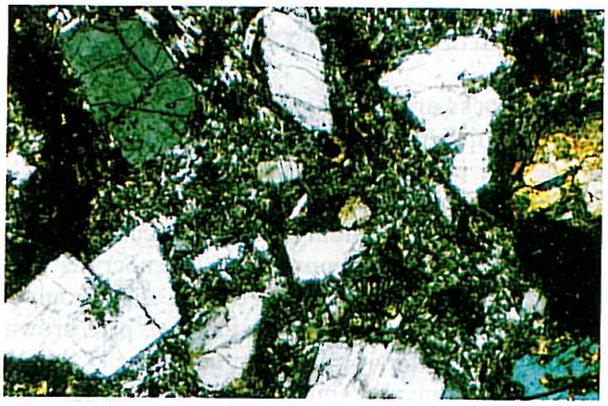

Fig. 4. Phenocrysts of anorthoclase, nepheline (top left) and augite set in a fine-grained groundness; X 35; X PL.

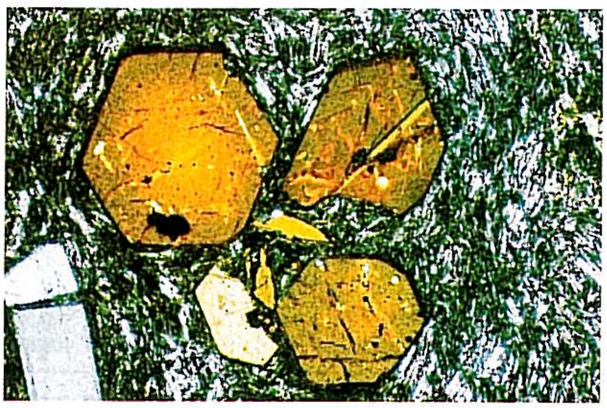

Fig. 5. Phenocrysts of sodic amphibole set in a very fine-grained groundmass; X 35; X PL.

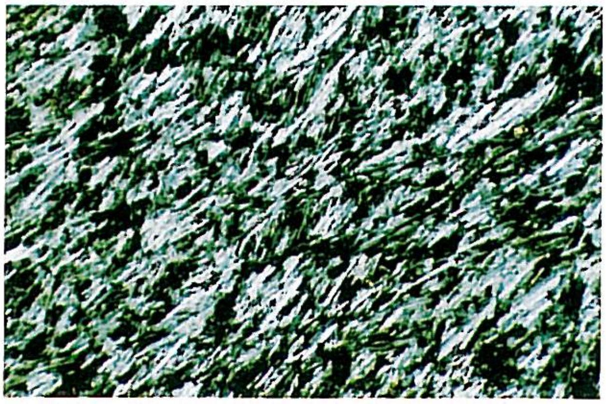

Fig. 6. Typical fine-grained phonolite. Alkali feldspar and aegirine form the bulk of the crystalline phases together with opaque oxides; X35, X PL.

locally recognised in some sections (Table 3). Phenocrysts of sodic amphiboles occur sporadically (Fig. 5). Dark brown kaersutite phenocrysts are mantled by granular clinopyroxene and opaque oxides. Similar aggregates without kaersutite cores are interpreted as completely resorbed amphibole crystals. Equant grains of iron ores are present as microphenocrysts whereas sphene occurs as euhedral grains. The groundmass is fine (trachytic texture) and consists of alkali feldspar laths (and maybe feldspathoid), laths are extremely ill-defined with marked patchy extinction (Fig. 6). The aegirine is found as minute grains which are strongly pleochroic with marked greenish colour. The iron ore is liberally scattered as interstitial patches throughout the groundmass. Apatite forms needle-shaped inclusions while the analcime makes up cloudy patches replacing the former groundmass. Deformation fabrics within the phonolites are lacking and this clearly indicates that the intrusions occurred prior to any significant crystallization of magma as this is typical of high-level forceful intrusions.

Basanitic Suite

Almost all the olivine basalts are characterised by the absence of plagioclase phenocrysts and by abundance of clinopyroxene and olivine phenocrysts. The clinopyroxene phenocrysts often occur in small clusters and individual crystals frequently display hourglass zoning. They are rarely pleochroic, though very occasionally they have mauve pleochroic rims, probably enriched in Ti. The olivine phenocrysts are often colourless, generally unzoned, unhedral or subhedral in shape and are commonly idingsitized. Large olivines (but less abundant anhedral variety) are now more magnesium-rich (Fo_{90}) and show evidence of deformation. These are interpreted as xenocrysts derived by fragmentation of the lherzolites. The compostion of resorbed olivine xenocrysts are similar to those of olivines from the ultramafic xenoliths (Busrewil and Wadsworth, 1980). Orthopyroxene grains also occur locally and probably also resulted from distintegration of ultrabasic inclusions. The groundmass of the olivine basalt is on the whole very fine grained and glassy patches are not unusual. In addition it contains a high percentage of ore minerals and randomly oriented laths of plagioclase, olivine and titanaugite. Nepheline and/or analcime, although they may be present, have not been identified under the microscope. The aphyric types are identical texturally to the groundmass of the porphyritic types.

Many hawaiites are texturally indistinguishable from the olivine basalts, although olivine and augite are almost always coexisting phases (where they are present). Their only difference being the bulk chemistry. The groundmass of typical hawaiites tends to be less mafic than the basalts. It comprises very fine grained plagioclase laths associated with iron-oxides, clinpyroxene and olivine groundmass. Apatite and iron oxides are common accessores.

The mugearites are pedominantly aphyric. The groundmass is nearly the same colour as the hawaiites except in the reduction of olivine and to lesser extent clinopyroxenes. The plagioclase consists almost entirely of very fine grained laths. Larger microphenocrysts of pale green pyroxene and colourless olivine are encountered.

CHEMISTRY

Average chemical composition of the several groups from the GVP are listed in Table 2 and pertinent features of the alkalies are plotted on TAS variation diagram (Fig. 2). Although the petrology of these rocks will be the subject of a further contribution, the variation of selected major and trace elements against S.I. is deliberately presented to support the three fold divisions of th GVP (Figs. 7–8). The phonolite analyses are conspicuous features and obviously form a discrete group with very clear separation from other groups. The plateau lava (OLS + YLS) has a narrow compositional range and attains a differentiation index (D.I.) between 35–40 (Almond *et al.*, 1974; Busrewil, 1974). This suggests that they are not primary magma, but rather fractionated melts derived from a primary magma. In

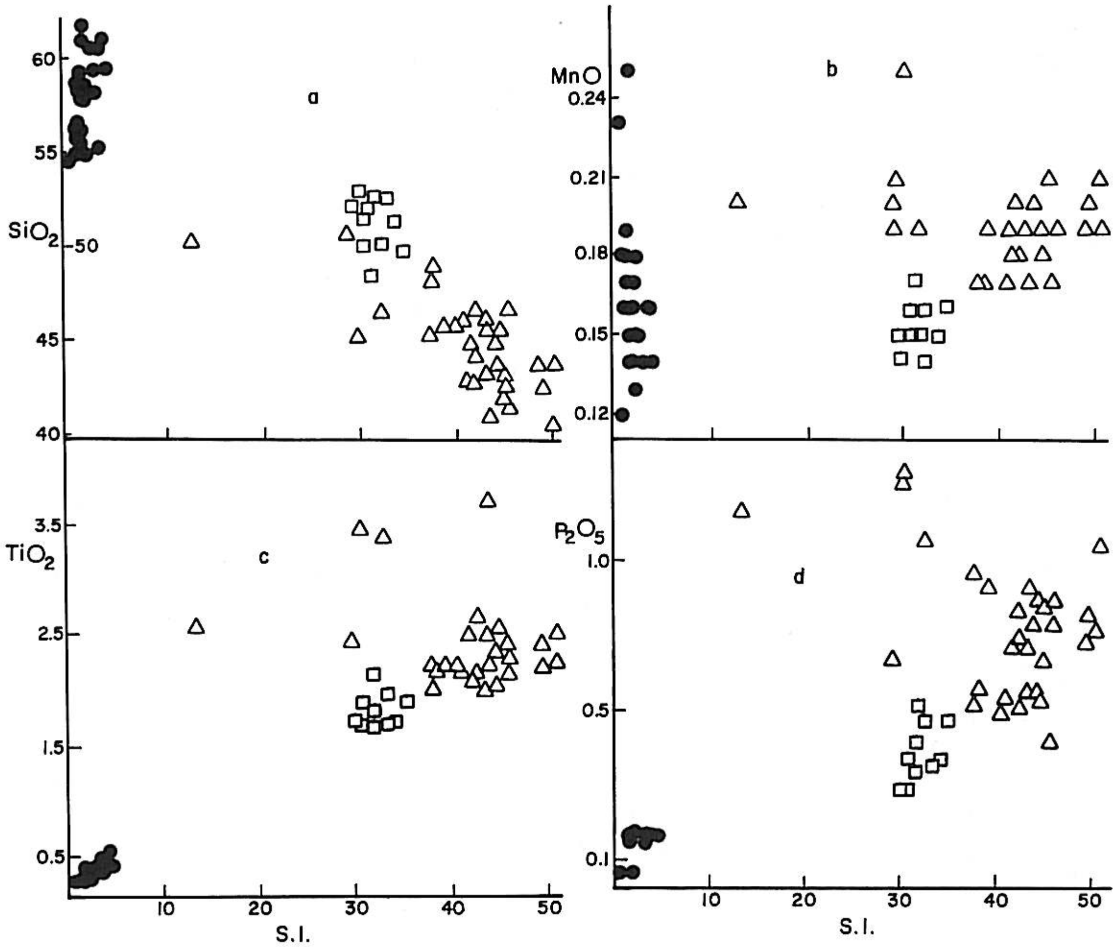

Fig. 7. SiO_2, MnO, TiO_2 and P_2O_5 *vs* Solidification Index (S.I.) for Gharyan volcanics.

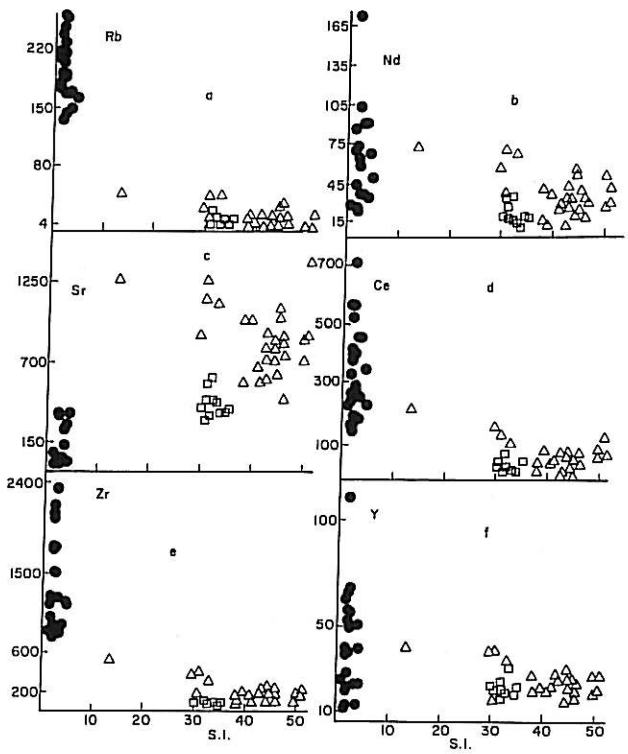

Fig. 8. Rb, Nd, Sr, Ce, Zr and Y *vs* Solidification Index (S.I.) for Gharyan volcanics.

addition most of the analysed rocks contain normative hypersthene and were thus named transitional hawaiites by Busrewil, (1974). Utilizing the parameters Total Alkali-Silica diagram for the chemical classification of volcanic rocks (Le Bas *et al.*, 1986, 92) they lie in the basalt andesite field (Fig. 2). The basanitic suit as a whole is strongly sodic with Na_2O/K_2O ratio exceeding 2:1 (Table 2). Compared with the OLS and YLS, they cover a much wider range (Basalt-hawaiite-mugearite) of composition. They also contain less SiO_2, Al_2O_3 and exhibit a more pronounced enrichment of the minor elements (TiO_2, P_2O_5, MnO, K_2O, Na_2O) and most of the trace elements (Figs. 7–8) compared with the lava series of similar S.I. values. This difference emphasises the individuality of the basanitic rocks when compared with the old and young lavas series and may be related to higher pressure fractionation or lower degrees of partial melting of upper mantle materials (Busrewil and Wadsworth, 1980).

The volcanic materials of the vent facies, although, altered, are mafic, very poor in silica and high in MgO (Table 2) suggesting little or no fractionation since equilibration of magma with mantle materials.

DISCUSSION

In Tertiary time the Gharyan area has been the site of extensive alkaline volcanism that has continued (but with interruption) to recent times and resulted in the emplacement of three suites of alkalic rocks. The products of the OLS and YLS were mildly basaltic andesites. These subalkaline rocks are by far the dominant rock type exposed on east Jabal Nafusah. They show no evidence of wide spread differentiation and form the lava plateau field. Similar subalkaline rocks were described from central Libya (Busrewil and Suwesi, 1993) and Ethiopia (Mohr and Zanettin, 1988). The phonolites form prominent isolated dome-shaped intrusions and display a variety of contact relationships with the associated Mesozoic sediments. In a few places the phonolites were intruded by the basanitic dykes (e.g. Kabdat al Jamal area) but nowhere show contact with the plateau lava. They are much older than the associated basanitic rocks and were thus interpreted as an ultimate residue of fractionation from an undersaturated basic parental melt at depth (Almond *et al.*, 1974). Similar suggestion was envisaged for the evolution of Harrat Kishb phonolites of Saudi Arabia (Camp *et al.*, 1992).

The LVC are, for the most part, extrusive (volcanic cones, shield volcanoes). However, there is a possibility that in some instances the dykes had an intact roof, and the magma never reached to the surface. The rocks themselves display a particularly rather wide variety of rock types (olivine basalt – hawaiite – mugearite). The more evolved varieties are exposed at only few localites and appear to constitute a very small volume of eruptive products (less than 2% in areal extent). The parental melts are thought to have been moved rapidly from depth to higher levels, where most of the chemical variation is produced by low pressure crystal fractionation (Busrewil and Wadsworth, 1980).

The pyroclastic rocks are predominantly consolidated assemblages of volcanic fragments. Based on field criteria, these rocks are divided into source or vent facis, near-source facies and distal facies. The source facies are thought to be related to pyroclastic dykes and tuff cones and their origin seems to be due to interaction between magma and subsurface water. The abundance of ultramafic nodules in this facies is a clear testimony to their rapid flow rate through the crust. The souce of the reworked pyroclastic rocks (near-source and distal facies) is probably related to these localised explosive volcanism. The products of which were later transported by wadi system to their present localities.

Radiometric dating of the GVP has been confined to limited number of K-Ar whole rock. Despite their inherent flaws (inherited Ar and/or Ar loss) existing K-Ar ages for the GVP do cluster heavily in two discrete episodes (around 40 Ma for the phonolites and 10-1 Ma for the LVC and YLS. There is thus an agreement that the two periods witnessed the emplacement of phonolites, the extrusion of volcanic cones and pyroclastic rocks as well as the outpouring of the YLS. The age of the OLS has been much debated (Ade-Hall *et al.*, 1975) and the existing data emphasize the need for better understanding of relative age distribution within the GVP.

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