Petroleum Res. J. Vol. 19 (2006); P. 27–48, 21 Figs.

Petrography of the Pan-African Basement and Phanerozoic Within Plate Igneous Rocks, Sirt Basin

M.T. Busrewil[1], K. M. Oun[1] and M. Haman[2]

بتروغرافية الصخور القاعية التابعة للمسطح الأفريقي وصخور نارية تنتمي إلى دهر حياة ما بعد عصر الكمبري، وسط اللوحة ـ حوض سرت

المبروك أبوسريويل وخالد محمد عون ومحمد هامان

تم وباستعمال الوصف البتروغرافي فصل مجموعات الصخور القاعية التابعة للمسطح الأفريقي والصخور النارية الأحدث عمراً بوسط اللوحة إلى ثلاث مجموعات صخرية مختلفة هي الصخور المتحولة والنارية والبركانية الفتاتية.

تعتبر صخور الشيست والفيلايت أكثر الصخور المتحولة شيوعا في أعماق بعض الآبار بعقد الامتياز 32. ويشير المحتوى المعدني لهذه الصخور أنها تمثل في الأصل سحنات من الصخور الرسوبية الطينية أو شبه الطينية القديمة المترسبة في بيئة بحرية عميقة وأنها قد تحولت فيما بعد بفعل عملية التحول الإقليمي إلى سحنات الشيست الخضراء. تم إختراق صخور النايس المحزّم في أعماق بعض المناطق بعقد الامتياز 71، ويوحي تواجد رقائق من معدن البيوتايت وغياب معدن الكورديارايت ومعادن سيليكات الألومينيوم ضمن المحتوى المعدني لصخور النايس أن هذه الصخور كانت قد تحولت تحت ظروف تحول إقليمي منخفض إلى متوسط.

ومن الناحية البتروغرافية فإن نواتج النشاط الناري متنوعة وتتراوح طبيعتها من الصخور القاعدية وحتى الصخور الفلسية حيث تم التعرف على عدد أربعة عشر نوع من الصخور النارية تشمل صخور الجرانيت والجرانودايورايت والمنزونايت الغني بالمرو والدايورايت والجابرو والسيانايت والبازلت والتراكيت والأنداسيت والداسايت والرايولايت والفتات البركاني. يمكن وصف بعض الصخور البازليتية المتطورة كصخور بازلتية اندساتية وتراكي اندساتية.

تمثل الصخور الجرانيتية والجرانودايورايت والمنزونايت الغني بالمرو أكثر الصخور النارية توزيعا وتواجدا تحت السطح بينما تمثل صخور السيانايت والتراكيت والداسايت أكثر الصخور ندرة بمنطقة الدراسة.

تم وصف الصخور البركانية المتفتتة نتيجة النشاط الناري كرماد بركاني وبريشا بركانية وفتات بركاني مخلوط بالشظايا والحمم الصغيرة. ويعتقد أن معظم هذه الصخور الفتاتية البركانية متواجدة في غير مكان توضّعها الأصلي وأنها تمثل في أغلب الظن صخوراً بركانية فتاتية متعددة تم نقلها بعدة عوامل نقل مختلفة من العديد من المخاريط البركانية ومخاريط المار المبعثرة.

Abstract: *Petrographic approach is used to separate the Pan-African basement rock assemblages and younger within-plate igneous rocks into three contrasting rock groups: namely, metamorphic, igneous and volcaniclastic rocks.*

The metamorphic rocks, the mineralogy of which reflect pelitic to semi-pelitic sedimentary protolith, are dominated by phyllites and schists and subcrop mostly in the Concession 32 area. This rock association represents deep marine sedimentary facies that had been subsequently regionally metamorphosed to greenschist facies. Banded gneisses are encountered mostly in the Concession 71 area. Cordierite and aluminium

[1]. Department of Geology, University of Al-Fateh, P.O. Box 13258, Tripoli, Libya.
[2]. Waha Oil Company, P.O. Box 395, Tripoli, Libya.

silicate minerals are lacking. This, together with the presence of well- developed biotite flakes within the gneisses, suggests that these rocks were metamorphosed under low to medium grade regional metamorphism.

The igneous products are petrographically diverse ranging from mafic to felsic in character. Fourteen rock types are distinguished: granites, granodiorites, quartz monzonites, diorites, gabbros, syenites, basalts, trachyte, andesites, dacites, rhyolites as well as volcaniclastics. Some of the basaltic rocks are somewhat evolved and could be described as basaltic andesites, basaltic trachyandesites and trachyandesites. Granites, granodiorites and quartz monzonites, occupy the greatest part of the subcroped surface area while syenites, trachytes, dacites and gabbros are the least represented rocks.

The volcaniclastic rocks have been described as tuff-breccia, lapilli tuffs and pyroclatics. Most of these rocks are unlikely to be in-situ pyroclastites but more likely they represent the many reworked volcaniclastics derived from scattered highly explosive eruptive craters or maars.

INTRODUCTION

A considerable amount of exploration has been undertaken in the Sirt Basin. Numerous overviews as well as detailed accounts of specific areas have been published by the Earth Science Society of Libya (Salem *et al.*, 1996; Salem and Oun, 2003) and an account of the petroleum geology of Libya (including Sirt Basin) was reviewed by Hallett (2002). Basement and anorogenic intra-plate bimodal volcanic rocks and intrusive alkaline igneous rocks have been encountered in wells drilled primarily in search for oil and gas in Sirt Basin. The term basement rocks is used here to denote all rocks formed during the Pan-African episode (Kennedy, 1964) or older. It includes all metamorphic and magmatic rocks that form the base upon which Cambro-Ordovician and/or younger sedimentary sequences were deposited. Available work on the basement rocks of the area is limited both in number and scope and although granitic rocks produce oil and are excellent reservoir in Awjilah oil field (Williams, 1968) the petrography and chemistry of these rocks have not met the attention they merit. The spacial and temporal distribution of the various rock types are not very well known and are likely to be a continuing line of research for many years to come.

A total of 400 thin sections from 92 oil wells drilled in Concessions 32, 59, 71, NC-32 and NC-98 form the basis of this work. The nomenclature of igneous rocks follows the recommendation suggested by the IUGS (Le Maitre, 1989, Le Bas *et al*, 1992) while the nomenclature of metamorphic rocks is based on fabric and inferred P-T conditions of metamorphism.

The purpose of this work is to document, define and briefly describe the petrography of the different magmatic and metamorphic rock types generated within the study area.

METAMORPHIC ROCKS

Mica Phyllites and Mica Schists

These rocks are regionally metamorphosed rocks showing schistose texture. They are rich in platy minerals, particularly chlorite, which gives them a pale green colour and lustrous sheen, due to tiny reflecting cleavage surfaces. They are very common and similar in mineralogy to the hornfelsed type, but lack any evidence of thermal overprint. The abundance of phyllosilicate minerals and quartz in these rocks indicates a semi-pelitic sedimentary ancestor. However, the scarcity of quartz in some of them may indicate a pelitic origin.

Judging from the mineralogy, they belong to the chlorite zone of the greenschist facies in case of the phyllites and chlorite to biotite zone of the greenschist facies in case of more developed schists.

Due to the limitation imposed by grain size, it is very difficult to distinguish the phyllosilicate mineral species in the phyllites; however, it is safe to state that muscovite and chlorite are the main phases. Quartz and feldspar constitute the other main phases.

Mica schists are coarse-grained with mineralogy similar to that of the phyllites. A further increase in metamorphic grade caused the latter to grow at the expense of chlorite mainly, and muscovite to less extent.

Quartz occurs as vein forming minerals in most sections. Carbonates and scarce zeolites fill late forming fractures and Fe-oxide constitutes the main secondary mineral.

Crenulated Mica Phyllites and Mica Schists

These are phyllites and schists similar in texture

and mineralogy to the above type but record a more complex history (Fig. 1).

A graphite-mica phyllite penetrated in Concession 32 has a very well developed schistosity but the grain size is within the phyllite range. It records the following complex sequential history:

a) Tight packing and alignment of crystals to develop an extremely pronounced schistosity as shown by the intense foliation. The grains are composed of alternating layers of mica, graphite and probably quartz with graphite porphyroblasts. The mica and chlorite grains are too small to be distinguished but appear to be muscovite and chlorite.

b) The rock is then weakly folded as shown by the faint crenulation of cleavage which tends to wrap around the graphite porphyroblasts. This indicates that it was formed subsequent to the porphyroblasts.

c) Development of cracks and sealing of the cracks with silica by the conventional crack-seal mechanism. The cracks seem to have developed prior to schistosity in certain places as they run parallel to the cleavage. However, at certain other places, they obliquely cross-cut the cleavage, indicating a later development. This may indicate the presence of two generations of veins. Some thermal effect is manifested by the coarse nature of the vein quartz and its granoblastic mosaic.

d) Shearing of the rocks as shown by the offset of silica veins.

The crenulated mica schist of a well in the area south of Ad Daffah records an almost similar story. The rock shows pronounced schistosity planes that are slightly folded and intersected by planes of dislocation. The dislocation is perpendicular to slightly oblique to the schistosity.

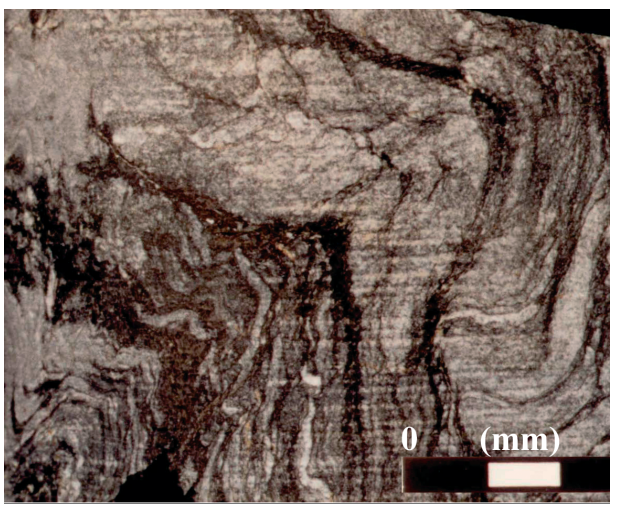


Fig. 1. Photograph of a polished core slab of a crenulate mica phyllite. (field of view is 6.5 cm.).

The main minerals are muscovite and chloritoids, Quartz is present in the form of veins composed of large crystals, forming a mosaic of interlocking crystals. However, the quartz veins must be part of the original rock as they exhibit orientations similar to the mica and are cut by the dislocation planes as well.

Hornfelsed Phyllites and Schists

These rocks show textures indicative of thermal metamorphism (hornfelsing) of originally foliated low grade metasediments. The latter are demonstrated by the distinct orientation exhibited by the phyllosilicate minerals. This is consistent with the regional geology as they form the host rocks within which large intrusives (plutons) were intruded at fairly shallow depths of 5-10 Km and have contact aureoloes, which were superimposed on regionally metamorphosed pelitic sediments. In terms of the degree of metamorphism, these rocks mostly belong to the chlorite to biotite zones of the greenschist facies.

The major minerals constituting these rocks are quartz, biotite, feldspar, chlorite and muscovite. Fe-Ti oxide minerals occur in variable amounts, normally in the vicinity, or as an alteration product, of biotites.

Quartz forms typical granoblastic textures indicative of a hornfels; mosaic of polygonal crystals. The grain size of the quartz crystals range in size from silt size to medium sand size. The larger sizes are normally present in the areas of the thin-sections that are devoid of mica clusters and vice versa. It seems that the growth of the quartz mosaic grains was hampered by the mica. Larger quartz crystals (coarse sand size) are sometimes present in the form of veins. These are interpreted to represent quartz veins within the original rock. Assuming that the hornfels are normally coarser than the original rock, these rocks must have been siltstones or fine arkose to fine greywacke.

Biotite is present in individual grains, flakes or clusters. It is a dark iron-rich variety. Preferred orientations can be detected in most of the sections especially sections cut paralel to biotite cleavage. This suggests mimicking of earlier slaty cleavage. Poikiloblastic pseudomorphs, after feldspar (no relics of original texture survived), are sometimes present. Feldspar crystals are mainly K-feldspar similar in size to quartz. It is distinguishable by its sericitic yellow weathering colour. Plagioclase is very scarce with conspicuous lamellar twinning.

Muscovite is present as pseudomorphs in schists and as a principal constituent in phyllites. Fibrous epidote was detected in a few of the wells.

Biotite Gneiss

Biotite gneiss was penetrated in a few wells south of Ad Daffah oil field. They are compositionally banded on the scale of core sample (Fig. 2) with banding gently inclined to the core axis. Under the microscope, they are composed of quartz, K-feldspar, plagioclase, biotite and chlorite. Quartz is recrystallized and highly strained and biotite is severely deformed and altered to chlorite. These rocks are hydrothermally altered with widespread sericitization, carbonate filled fractures and opaque oxides. The lack of cordierite and similar highly aluminous minerals and the conspicuous igneous texture indicates that these rocks were derived from granitic rocks.

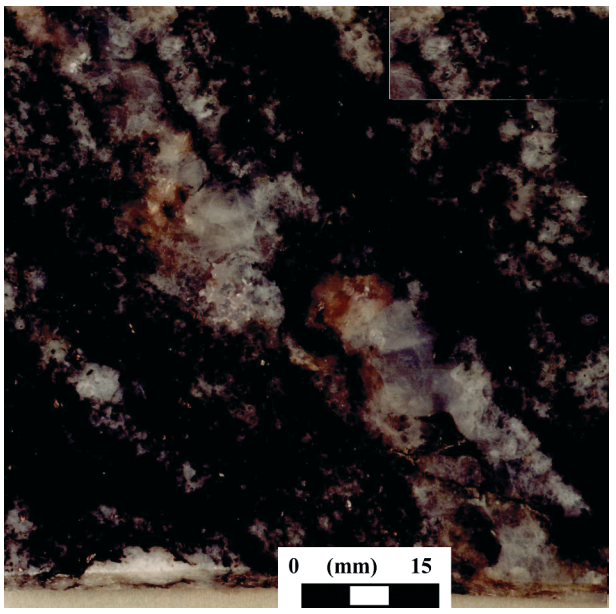


Fig. 2. Photograph of gneiss showing clearly developed gneissic banding.

CALC-ALKALINE MAGMATISM (GRANITOIDS)

Granites

The granites are medium to coarse-grained with hypidiomorphic texture. They are white, light grey to pinkish red (Figs. 3-6). Very few granites are fractured (Fig. 7). The confinement of this textural feature to the fractured areas of the core sample suggests that this phenomenon is not merely an *in-situ* mechanical effect of crushing, but most likely it represents a fracture fill made by the association of disaggregated primary crystals in the evolving residual melt (tuffisitic mix) or the crystallization of the late stage fluids and the gases. The deformed ovoidal quartz grain in the centre of the lower view (Fig. 7) may represent a residual xenocryst mineral or an early crystallizing mineral phase that was squeezed by

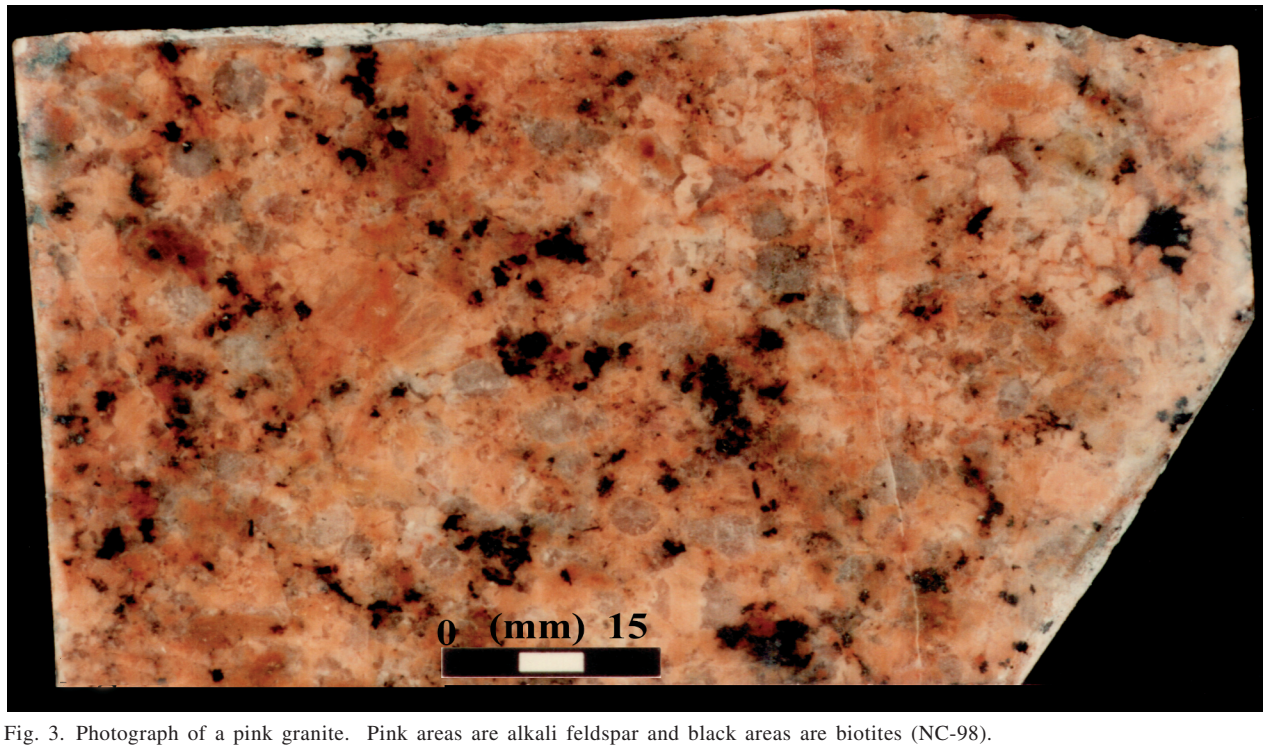


Fig. 3. Photograph of a pink granite. Pink areas are alkali feldspar and black areas are biotites (NC-98).

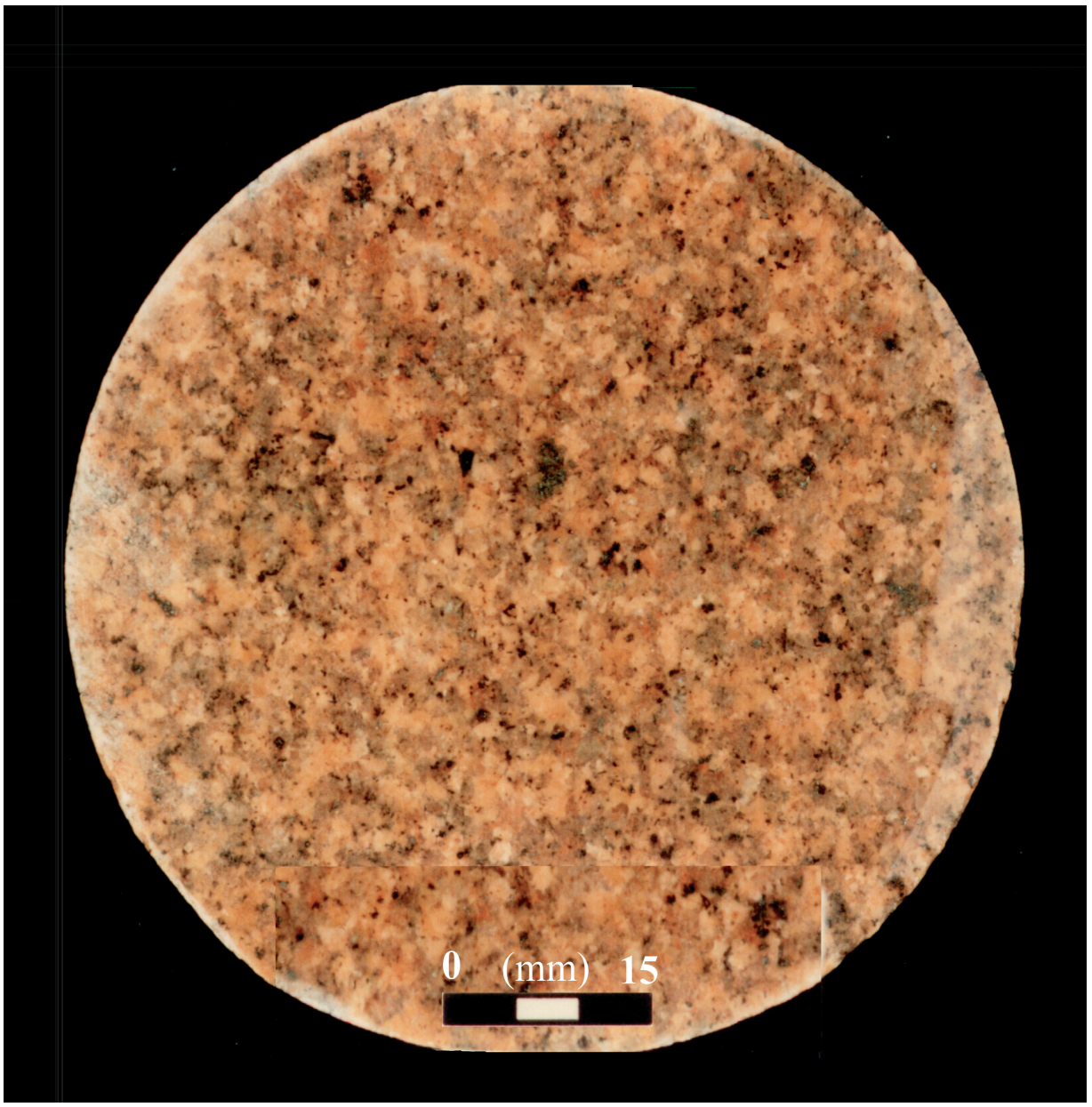


Fig. 4. Photograph of a pink granite. Although the mineralogy and texture indicate red granite, both vary from other described red granites (*e.g*. Fig. 3) in being finer in texture. It is possible that co-existing volatiles were suddenly vented into fracture system of the overlying country rocks or the cores may represent part of an enclave of a much larger pluton (east of Harash area).

pressure build up on sealed late stage liquids and gases within the crest of a high level pluton. Typical granite samples consist of K-feldspar, plagioclase, quartz ± biotite ± hornblende(Fig. 8). The accessory minerals are apatite, sphene, allanite and opaque oxide.

The alkali feldspar present is a potash-soda (microperthite) or potash variety; orthoclase or microcline. It is usually more or less anhedral. The plagioclase is made of albite that marginally grade to oligoclase. It displays zoning, albite and Carlsbad twinning, myrmekite and various degrees of sericitization. In some cases, rock deformation is manifested in plagioclase by the offset of twinning lamellae. Quartz form early individual grains as well as late interstitial phase. In some rocks, quartz grains show undulose extinction. Biotite is an iron-rich variety as shown by its dark brown colour. It shows strong pleochroism, pleochroic haloes and, sometimes, strong deformation. It occurs as individual lamellar aggregates and various degrees (partial to complete) of chloritization. Hornblende, when present, is green or brown. It occurs mainly adjacent to biotite in aggregates. The hornblende grains are, in most cases, highly resorbed and anhedral

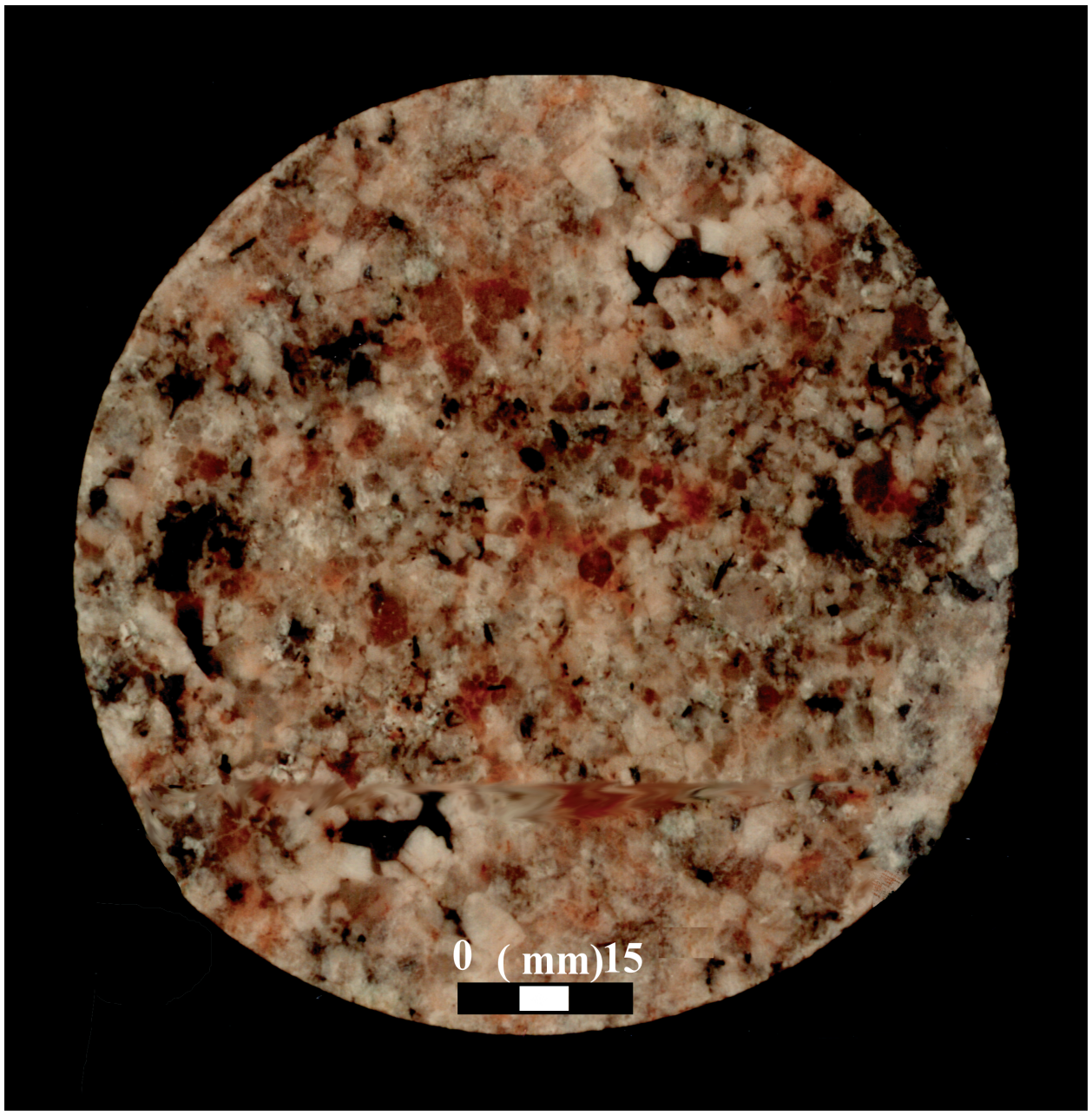


Fig. 5. Photograph of a polished surface of a core slab of a grey granite from Jalu area. The mineral assemblages of this granite are alkali feldspar (flesh colour), Na-plagioclase (whitish in colour), quartz (grey) and biotite (black).

in form rendering them difficult to recognize when they are scarce.

Deformation of biotite flakes, offset of plagioclase twinning lamellae and undulatory extinction of quartz crystal are taken to indicate that the granite is syn-tectonic (*i.e.* formed during the prevalence of tectonic compression). Few granites show shearing and recrystallization as evidenced by the intense granulation of the constituting minerals but geologic processes were not so intensive as to totally eradicate prior fabrics.

Granodiorites

The granodiorites are similar to the granites in colour and mineralogy (Fig. 9) but contain higher modal plagioclase. They are coarse-grained rocks and consist essentially of quartz, plagioclase, alkali feldspar and biotite ± hornblende. Quartz is almost completely anhedral and interstitial to the feldspars. The plagioclase is commonly subhedral, frequently zoned and falls within the oligoclase andesine compositional range, but most of them consist of

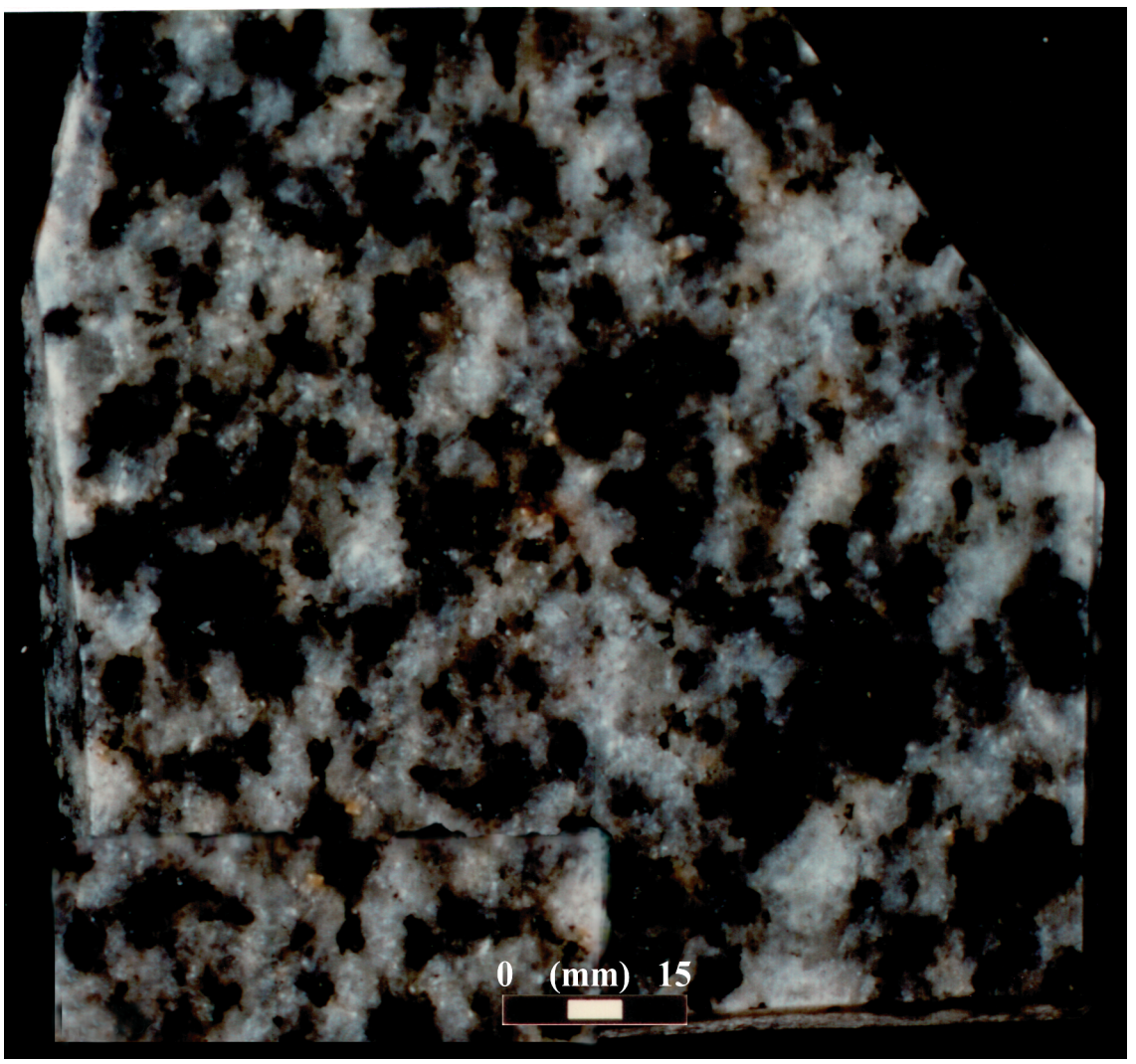


Fig. 6. Photograph of a polished surface of a coarse-grained core slab of grey granite from a well south of Ad Daffah area. The black areas are brown mica. The flesh coloured areas are mainly feldspar while the grey areas are mainly quartz.

andesine average composition. Alkali feldspar (perthite or orthoclase) is more or less anhedral. Both of these alkali feldspar types are locally altered to sericite and/or kaolinite. Biotite and hornblende are the most common mafic minerals in the studied sections. Biotite is brownish green and pleochroic. It contains inclusion of apatite, zircon (surrounded by radioactive haloes) and opaque oxides. Hornblende is dark, green and pleochroic. It contains inclusions of opaque oxides and plagioclase. Both mafic minerals are partly altered to chlorites. Muscovite is only sparingly found and apatite forms little prisms and needles while zircon forms basal sections. Deformation of biotite flakes and undulose extinction of quartz are common.

Quartz Monzodiorite

A coarse-grained rock composed of sodic plagioclase, perthite, quartz and mafites (biotite and hornblende). Feldspar make up the greater part of this rock type (Figs. 10 - 11). Quartz is found filling up the spaces between the other constituents as small aggregates of grains and many of them show undulose extinction. Biotite is partially strained and forms independent pleochroic flakes. Hornblende is green and weakly pleochroic and many sections are poikilitically enclosing plagioclase grains. In a few cases, relict clinopyroxene, associated with hornblende, contains subcalcic augite. Parts of the hornblende and biotite are altered to chlorite. Apatite in little prisms and needles is common.

Diorites

The diorites are medium to coarse-grained rocks consisting essentially of plagioclase and hornblende with subordinate biotite and scarce quartz.

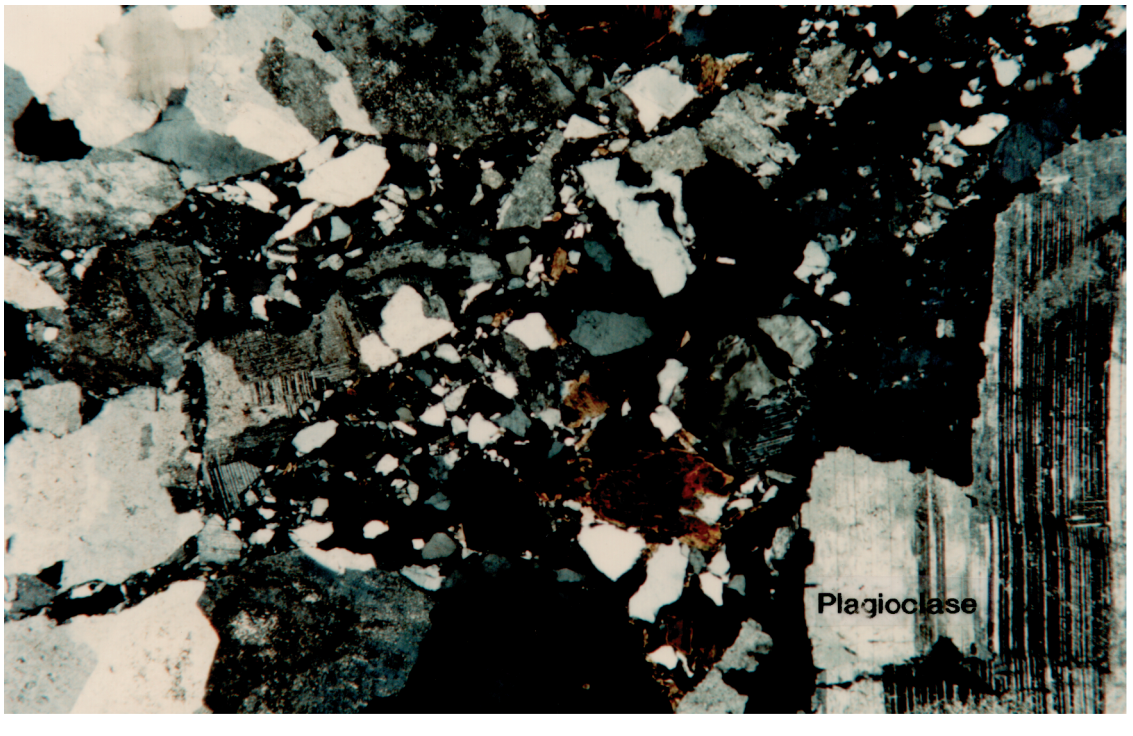


Fig. 7. Microphotographs of a highly fractured granite in Al Wahah area showing close-up views of: *a.* (upper) fractures filled by fine-grained aggregates of quartz (clear), feldspar (turbid) and biotite (black) and *b.* (lower) quartz phenocryst developing to lenticular augen surrounded by quartz and feldspar as the chief constituents (X 12.5).

Plagioclase is of oligoclase-andesine composition. It is commonly zoned with sodic rims remaining fresh while calcic cores show various degrees of sericitization. The plagioclase of many diorites contains inclusions of mafic minerals, apatite and opaque oxides. Green, but less commonly brown, hornblende forms the dominant mafic mineral. It is sometime fringed by biotite. The latter is a common constituent but less abundant than amphibole, with which it usually aggregates. In some core samples, it forms subhedral plates. In others, it is replaced by chlorite.

A medium-grained appinite (hornblende diorite)

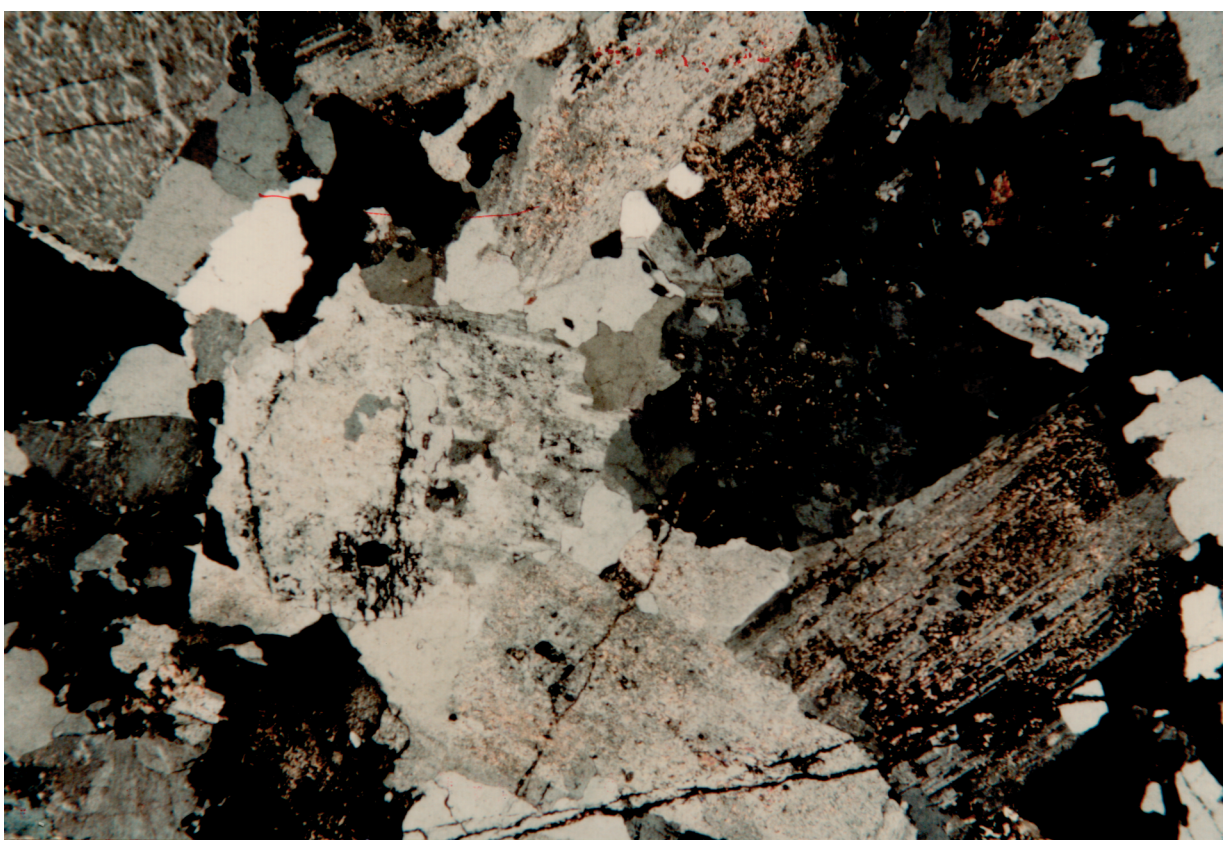


Fig. 8. Microphotograph of a granite from a well south of Ad Daffah area. Perthite, Na-plagioclase and quartz are common constituents (X 11.5, XPL view).

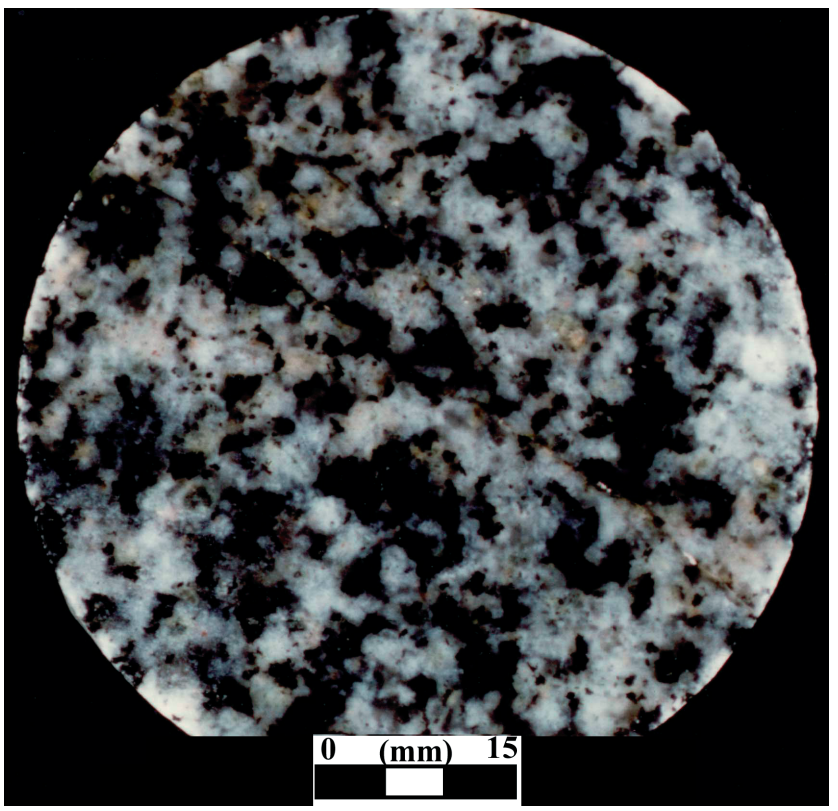


Fig. 9. Photograph of a core slab of a granodiorite from south Ad Daffah. It shows some similarities in mineralogy and texture to grey granite but it is somewhat more basic in composition.

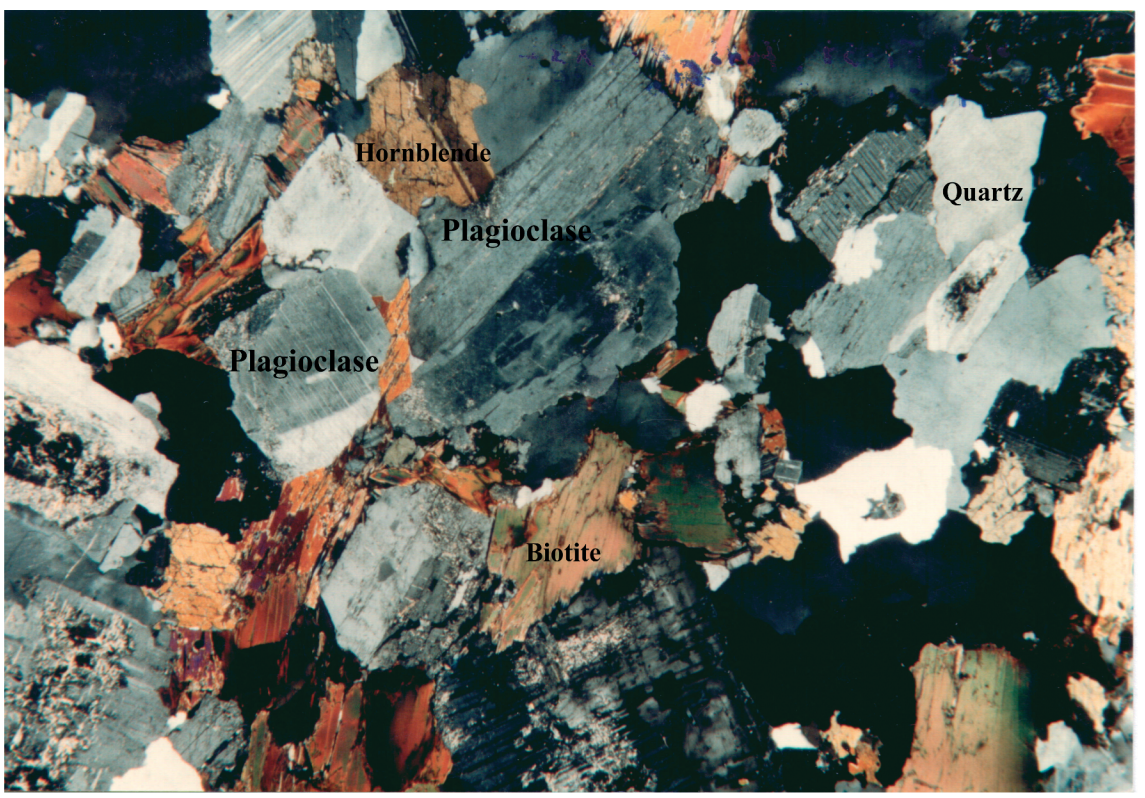


Fig. 10. Microphotographs in cross-polarized light of a quartz monzodiorites. (Khalifah area, X 8.5). Feldspar makes up the greater part of the upper microphotograph. Clear quartz is seen filling up the spaces between the other constituents as small aggregates of grains. Biotite and hornblende are common. The many mineral assemblages of the lower microphotograph consist of major albite-rich mostly zoned and altered plagioclase (sodic rims remained fresh while calcic cores are altered to sericite) and interstitial quartz. Biotite is present in large flakes.

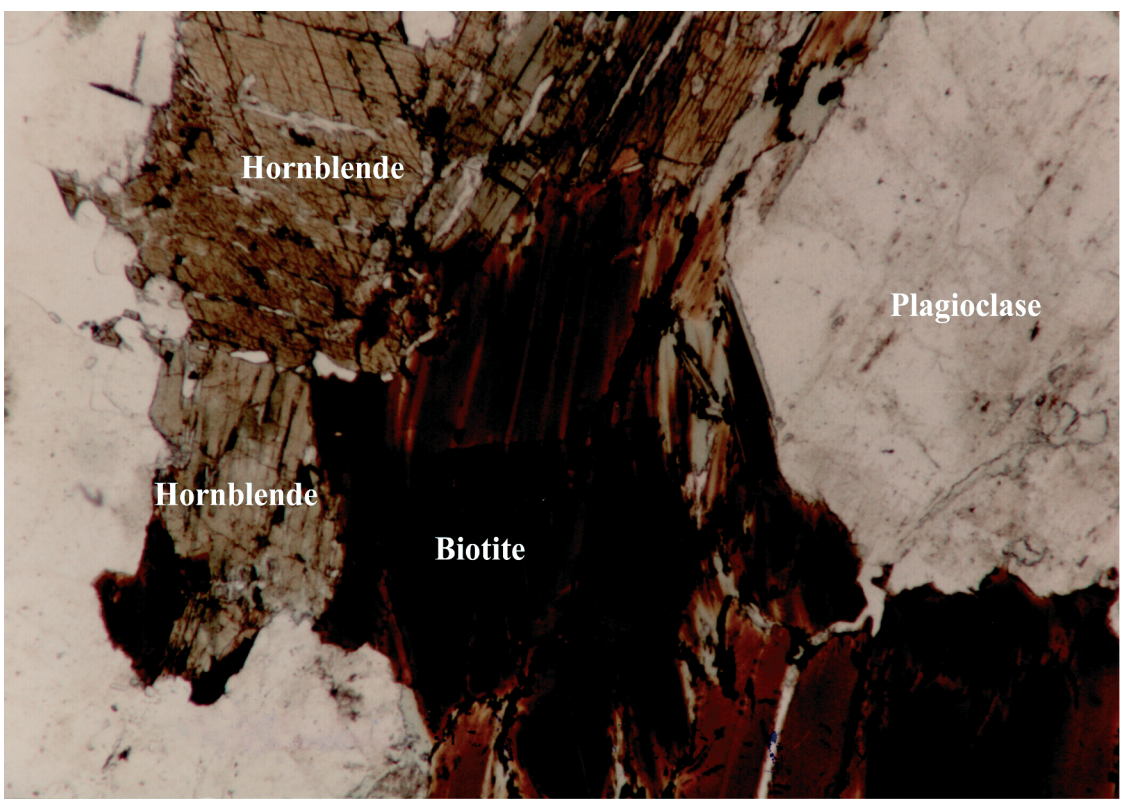


Fig. 11. Microphotograph of quartz Monzodiorite from the same locality of Fig. 10 showing the typical amphibole-shaped cleavage, kinked pleochroic biotite, multiple twinned plagioclase, K-feldspar (lower left) and interstitial quartz (X 32, PPL and XPL views).

was penetrated in Masrab field. It is composed essentially of plagioclase and hornblende (hornblende to edinite). The plagioclase (oligoclase-andensine) is zoned and altered while the hornblende occurs in irregular poikilitic plates. Common accessories are sphene, epidote and opaque oxides.

Augite Gabbro

A highly altered coarse-grained rock consisting of augites and plagioclase was penetrated in few wells. Augites ($Wo_{42.7-45}$ $En_{0.4-42}FS_{14.5-15.3}$, wt.%), when rather fresh, are pale green in section, show a fairly good cleavage and display sector zoning. Alterations of augites are accompanied by an irregular bleaching of crystals resulting in the formation of patchy areas of colourless augites. Where the amount of alteration is small, hornblende occurs as a fringe to crystals of augites. The plagioclase (An_{49}-An_{55}) is highly altered and few crystals show radiate texture. Opaque oxides and acicular apatite are common accessories. A view of a thin section of gabbro is shown in Figure 12.

Trodhjemites

This type of rock is very scarce. It consists essentially of plentiful plagioclase (albite-oligoclase) and quartz. K feldspar is only sparingly found. Biotite, zircon, sphene and opaque oxides are found as frequent accessory constituents. Decomposition process gave rise to minute flakes of mica and chlorites.

WITHIN-PLATE MAGMATISM

Alkali Felspar Syenite

This rock type is volumetrically insignificant in the study area and occurs locally in a well at Ad Daffah oil field. It is a leucocratic rock consisting of equigranular aggregates of Carlsbad twinned euhedral to subhedral perthitic K-feldspar and little interstitial quartz (Fig. 13).

The alkali feldspar shows pronounced rib structure and quartz grains are intergrown with the perthites. However, independent albite crystals are lacking.

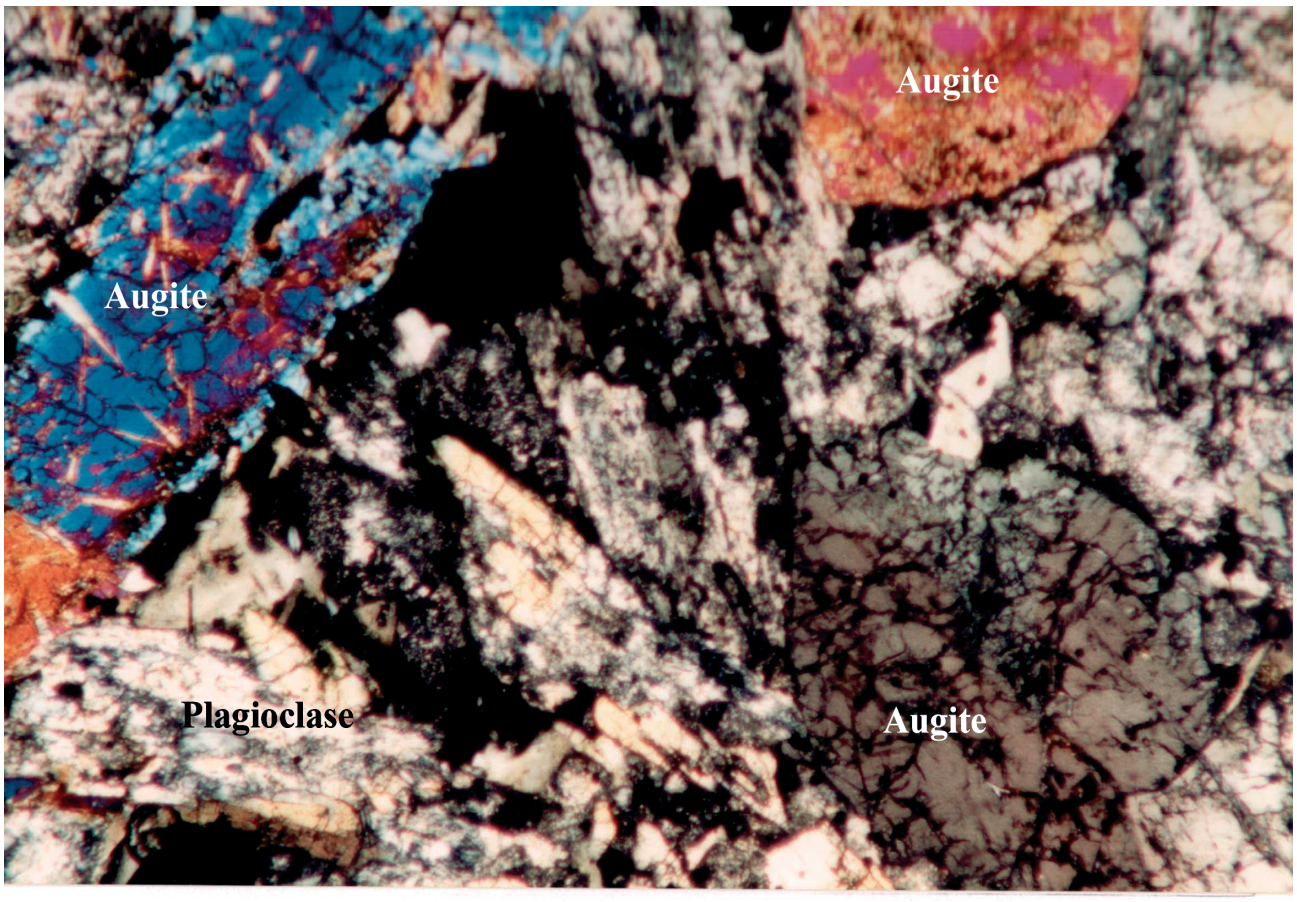
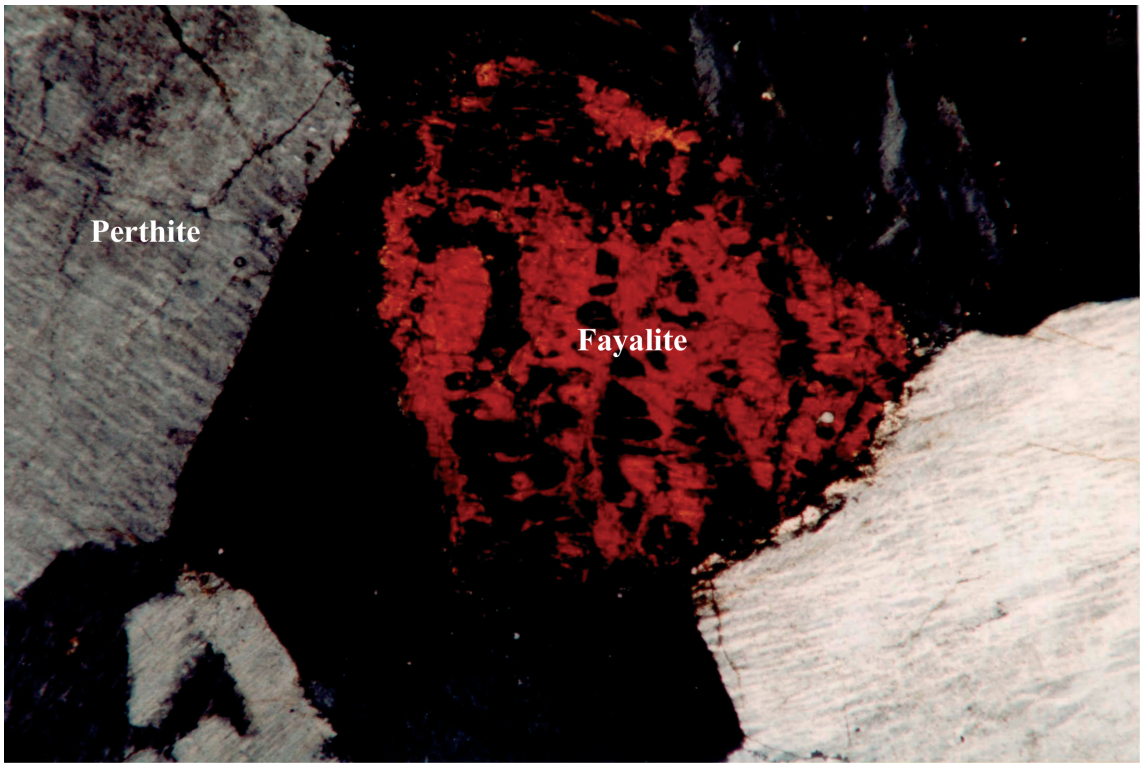


Fig. 12. Microphotograph of gabbro in a well south of Ad Daffah area. Here augite is the only essential ferromagnesian constituent. The feldspar occurs as crudely radiating clusters of tabular calcic plagioclase.



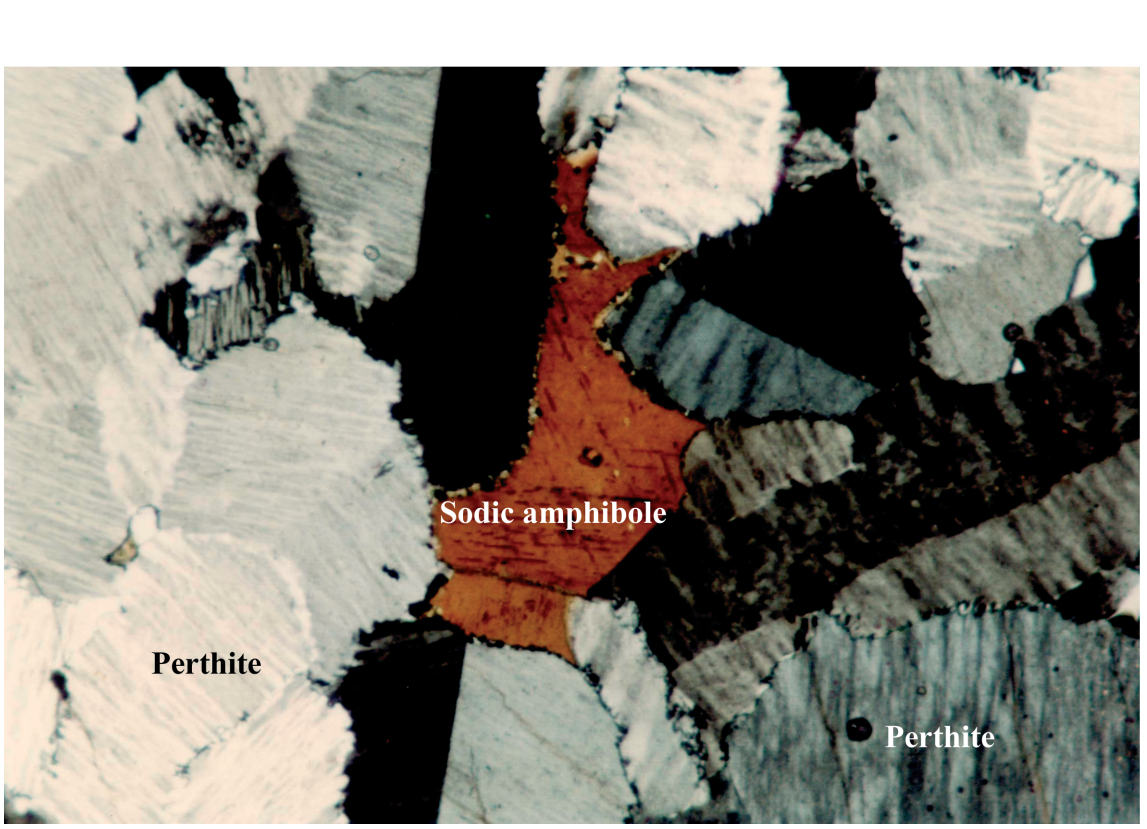


Fig. 13. The upper microphotograph is a close-up XPL view of granular-textured alkali feldspar syenite from Ad Daffah area. It exhibits almost pure fayalite (showing red interference colour) and perthite (X32). A thin section cut from the same core, illustrated in XPL view, shows that in addition to perthite, sodic amphibole with its typical cleavage (X9) can be seen. All areas which appear black in the two microphotographs are perthites at extinction.

Few grains of green pleochroic sodic amphibole, ferrohedenbergite and fayalite ($Fa_{99.15-99.65}$) were encountered. The accessories are opaque oxides, allanite and apatite.

Basalts

The basalts are, megascopically, dark grey to black coloured volcanic rocks of generally very fine-grained texture. Many core samples contain extensive micro and macro fractures filled by secondary minerals, such as zeolites, silica, epidote, unhydrite and calcite. Vesicles and amygdales are encountered in some of these rocks (Fig. 14). The latter is usually filled with zeolites, calcite and chlorite or less commonly with epidote and chalcedony. This may suggest the subaerial emplacement of these rocks. Microscopically, the basaltic rocks are essentially fine-grained rocks composed of calcic-plagioclase and augite. Despite their comparatively simple gross mineralogy, the basalts vary considerably in grain size and texture; however, some granular and porphyritic basalt also exist. Varieties of basalts rich in phenocrysts of either olivine, plagioclase or, less commonly, augites, are also common. Examples of the first were encountered in Al Farigh area. In this core sample, serpentine almost completely replaced the olivines. Characteristically it pseudomorphically preserves the crystal outlines of the olivine crystals it replaces. These are cut by irregular curving fractures that are typical of olivine (Fig. 15).

Plagioclase, usually confined to the groundmass, occurs, to some extent, as phenocrysts in a number of core samples. These are usually elongated in shape, however, more or less equidimensional crystals were also found. Plagioclase phenocrysts have undergone varying degrees of alteration to sericite/illite. It ranges from fresh zoned albite twinned crystals to entirely altered crystals in which very little of the original plagioclase remained.

Augite is faint brown in colour. It is a rare constituent in fresh, unaltered basalt and when it does occur, it is decomposed to form aggregates of fine-grained chlorites and opaque oxides.

The groundmass of the porphyritic basalt is almost identical to the aphyric types. It is composed of calcic plagioclases and augites. The plagioclase is lath shaped and exhibits zoning and twinning. Augites are generally pale brown in colour. In many examined thin sections, it had undergone almost total replacement by chlorite.

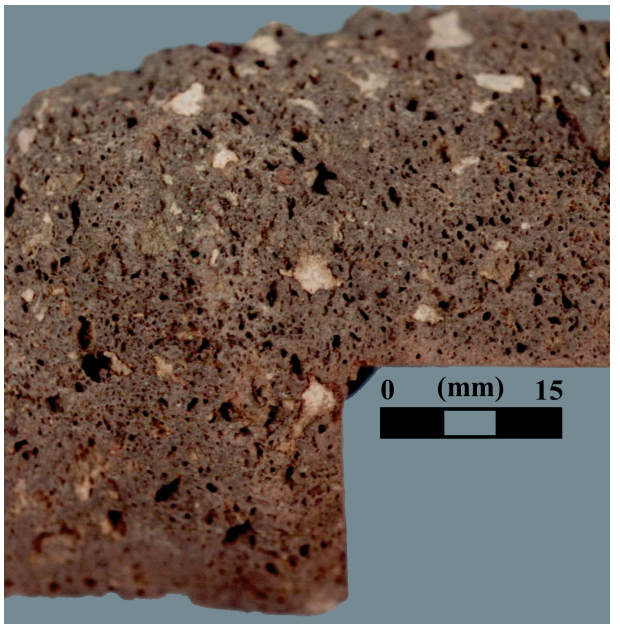


Fig. 14. Polished surface of a vesicular basalt from a well south of Ad Daffah area. The vesicles are partly filled by secondary products and become amygdales. The presence of this structure may suggest subaerial emplacement for this basalt (field of view is 8 cm.).

Olivine is either absent or may appear in the groundmass as accessory subhedral pseudomorphs. Accessory grains of alkali feldspar, belonging to the low sanidine-high albite series with bulk composition ranging from Or_{32} to Or_{57}, are present in few rock samples. Incipient alteration to serpentine or total breakdown to dark aggregates of opaque oxides is common. Opaque oxides are not uncommon in accessory amounts in these rocks. Apatite is less frequently encountered. The rareness of olivine and the concentration of opaque oxides in the groundmass of these basalts, is typical of most subalkalline basalts.

Many basaltic core samples show various degrees of alteration to spilitic mineral assemblages. Here, the plagioclase is albite instead of normal labradorite and chlorite, partially or completely, takes the place of normal Fe-Mg minerals. In such rocks, loss on ignition (LO1) is obviously higher than normal basalts (Table 1, analysis 6).

Trachybasalt and Basaltic Trachyandesites

These basaltic rocks are megascopically similar to true basalts and their root names were deduced from chemical analysis. They are fine-grained, consisting of calcic plagioclase and augites. The plagioclase is usually lath-shaped and twinned. Albite twinning is rather narrow lamellae. The augites are generally pale in colour as groundmass and

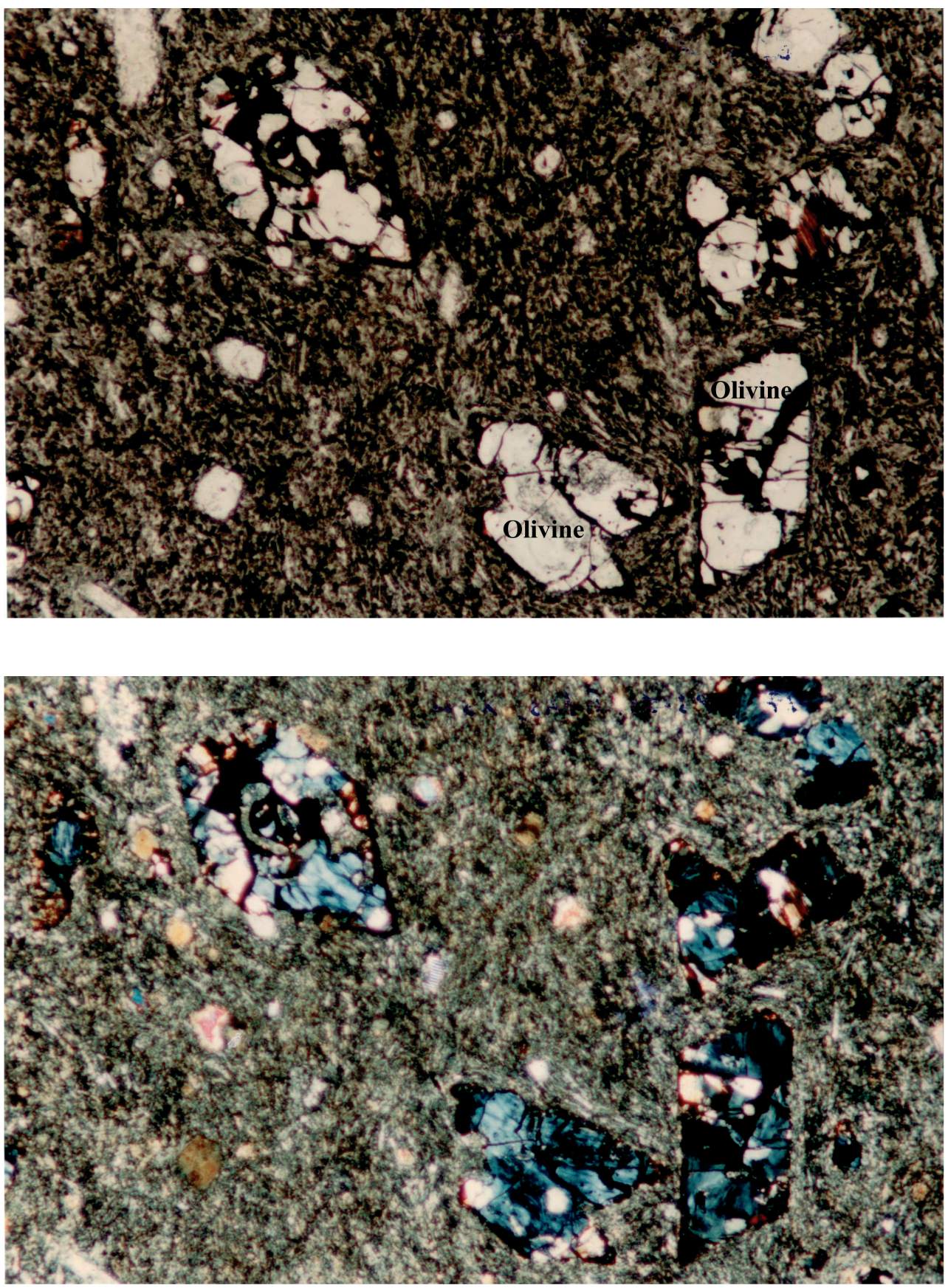


Fig. 15. Microphotographs of basalt from a well in Al Farigh. Serpentine, occurring as phenocrysts and microphenocrysts, is ubiquitous. It characteristically preserves pseudomorphically the form of olivine it replaced. It is cut by irregularly curving fractures typical of olivine. The matrix is cryptocrystalline and consists of plagioclase and chlorite (X32, PPL and XPL views).

microphenocrysts and many of them are chloritized. In addition, olivine microphenocrysts are present and opaque oxides are found in many thin sections. Many basaltic rocks are cryptocrystalline in texture with plagioclase phenocrysts. The latter show alteration, twinning and zoning.

Trachyte

In a well east of As Sarir field, a fine-grained trachytic mass was penetrated (Table 1). It is made up largely of little laths of alkali feldspar with relatively abundant aegirine as acicular needles and short prisms. A little interstitial quartz is present in the groundmass. Subordinate sodic amphibole (riebeckite) is also encountered as subhedral microphenocrystal constituent. Small euhedral crystals of opaque oxides are found in the groundmass of the rock.

The feldspar laths have a more or less parallel arrangement as a result of magmatic flow giving a typical trachytic texture (Fig. 16).

Basaltic Andesites

This rock type was penetrated in one of Al Wahah field wells. The core sample itself is dark and texturally resembles normal basalts. Fractures, less than one centimeter in width, which cut the core axis perpendicularly, are filled mostly by quartz and calcite.

Plagioclase feldspars are the most abundant mineral phase (Fig. 17). They are responsible for the development of the porphyritic texture in the core samples. Consequently, these rocks are notably A1-rich, containing some 18% Al_2O_3 (Table 1). The plagioclose phenocrysts are zoned showing a change from labradorite, in the centre, to andesine, in the margin. Occasionally, some phenocrysts in some cores are formed of calcic bytownite.

The groundmass is fine-grained and is essentially composed of zoned plagioclase laths, minute tabular green pleochroic hornblende (Magnesiohastingsite) and brown biotite. Alteration of Fe-Mg minerals to chlorite aggregates is common. Secondary pyrite (cubes), a few grains of apatite needles and clots of opaque and interstitial quartz form its accessory minerals.

Andesite

This core sample shows a chemical affinity of andesite proper (Table 1). It is made largely of sodic plagioclase laths together with sparse mafic constituents. The plagioclase is zoned and altered in varying degrees to sericite and chlorite, while the mafic minerals are totally replaced by chlorite. Sphene and opaque oxides are common accessories. Voids filled by secondary minerals, suggestive of an amygdaloidal structure, are prevalent.

Table 1. Chemical composition (wt.%) of selected rocks from Sirt Basin.

Rock Type	Granite		Grdr	Q. Mdr	Diorite	Gabbro	Syenite	Basalt	Basalt	B.A	Andesite	Dacite	Rhyolite	Trachyte
Area	1*	2	3	4	1	3	5		6	1	6	7	8	9
SiO_2	79.22	76.57	69.02	57.53	50.66	46.9	64.71	49.47	51.35	54.88	56.28	63.91	75.85	63.73
Al_2O_3	11.76	11.62	15.04	16.55	16.42	18.28	16.02	12.62	16.41	18.1	12.93	16.54	11.5	16.07
Fe_2O_3	0.44	0.77	3.89	7.67	13.54	7.96	5.19	9.35	11.45	8.51	8	4.56	2.04	5.43
MgO	0.08	0.15	1.53	4.22	4.47	11.25	0.05	14.1	4.57	2.33	8.56	2	0.21	0.06
CaO	0.56	0.51	3.13	5.8	8.41	8.42	1.12	5.8	7.62	7.61	4.91	4.17	0.01	1.18
Na_2O	5.20	3.80	3.83	3.76	2.87	2.02	6.29	1.94	3.07	3.39	3.1	3.31	2.34	7.18
K_2O	0.938	4.706	1.835	1.723	0.701	0.551	5.617	0.632	1.622	1.579	2.182	2.432	6.15	4.919
TiO_2	0.108	0.137	0.399	0.896	1.119	0.546	0.273	0.628	1.531	1.288	0.603	0.52	0.25	0.248
MnO	0.007	0.01	0.06	0.122	0.195	0.118	0.133	0.116	0.18	0.124	0.112	0.14	0	0.226
P_2O_5	0.017	0.018	0.073	0.229	0.296	0.06	0.024	0.104	0.412	0.363	0.117	0.151	0.01	0.045
LOI	1.28	0.46	0.92	1.2	1.2	3.82	0.43	4.86	1.63	1.55	2.92	1.84	0.98	0.47
Total	99.61	99.75	99.72	99.7	99.87	99.94	99.86	99.62	99.84	99.71	99.7	99.57	99.34	99.57

* plagiogranite; Grdr = granodiorite; Q. Mdr = quartzmonzodiorite; B.A. = basaltic andesite 1 = Al Wahah; 2 = N. Ad Daffah; 3 = S. Ad Daffah; 4 = Masrab; 5 = Ad Daffah; 6 = Al Farigh; 7 = NE Al Wahah; 8 = Zaqqut; 9 = E. As Sarir

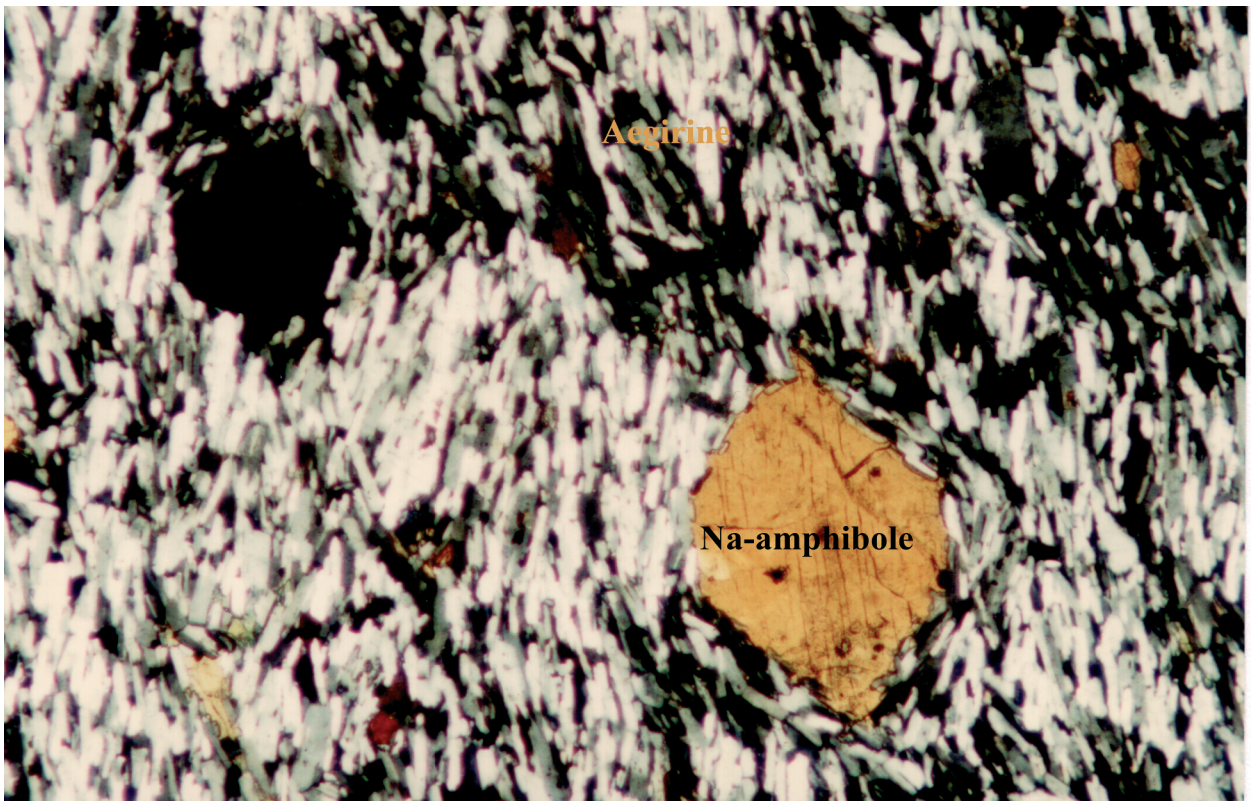


Fig 16. Microphotographs of trachyte in a well east of As Sarir area showing a Na-amphibole phenocryst set in a matrix of aligned (flow texture) lath-shaped K-feldspar and aegirine microlites (X32, XPL view).



Fig. 17. Microphotograph of porphyritic basaltic andesite (Al Wahah area). The plagioclase occurs in two generations as phenocrysts often of relatively large size and commonly zoned, and as microlites of somewhat more sodic composition in the groundmass. Chlorites (after ferromagnesian minerals) and opaque oxides are common (X32, XPL view).

Dacite

This rock type was penetrated in NE Al Wahah area (Table 1) and is composed of plagioclase phenocrysts imbedded in a very fine-grained groundmass. Weathering rendered plagioclase phenocrysts turbid and, in some extreme cases, the whole plagioclase phenocrysts (Andesine) are replaced and only the shapes of the original phenocrysts survive as "ghost pseudomorphs". In other cases, plagioclase phenocrysts are replaced by secondary albite.

The groundmass is obscured by iron-ore and alteration products, but it seems to consist of densely-packed small grains of quartz and minute feldspar microlites. Both mineral types are so mixed with each other that they are distinguished with difficulty. Coloured minerals are totally altered to/or replaced by chlorite.

Rhyolites

A light-coloured silicic rhyolite, composed of tabular feldspar and unhedral quartz embedded in cryptocrystalline or microcrystalline groundmass, was penetrated in the Zaqqut area. The microphenocrysts illustrate abundant K-feldspar and quartz (Fig. 18). The latter is often corroded with inlets of the groundmass. Sparce microphenocrysts of sodic plagioclase in tabular crystals with the usual twin lamellation and pale brown augites are encountered. The matrix is composed of silica minerals (tridymite and/or quartz) and alkali feldspar. The latter, being in microlite form, cannot be subjected to optical tests to determine their nature. Microscopic quartz-alkali feldspar intergrowth are widespread (granophyric texture occurring in the groundmass as microphenocrysts).

Rhyolite porphyry of quartz keratophyre composition was penetrated in a well within Al Wahah oil field. It is characterized by the presence of plagioclase and quartz phenocrysts set in microcrystalline groundmass of feldspar and silica minerals. Equally remarkable is the occurrence of rhyolite (potassium keratophyre) with high contents of potash and little soda.

Traces of spherulitic texture, giving rise, possibly to the so-called nodular rhyolite, can be seen under the microscope from a few rhyolite core samples. Original ferromagnesian minerals are represented by scattered chlorite and epidote. Radiate aggregates of feldspar fibers, resulting from the intergrowth of feldspar and quartz, are a common feature (Fig. 18).

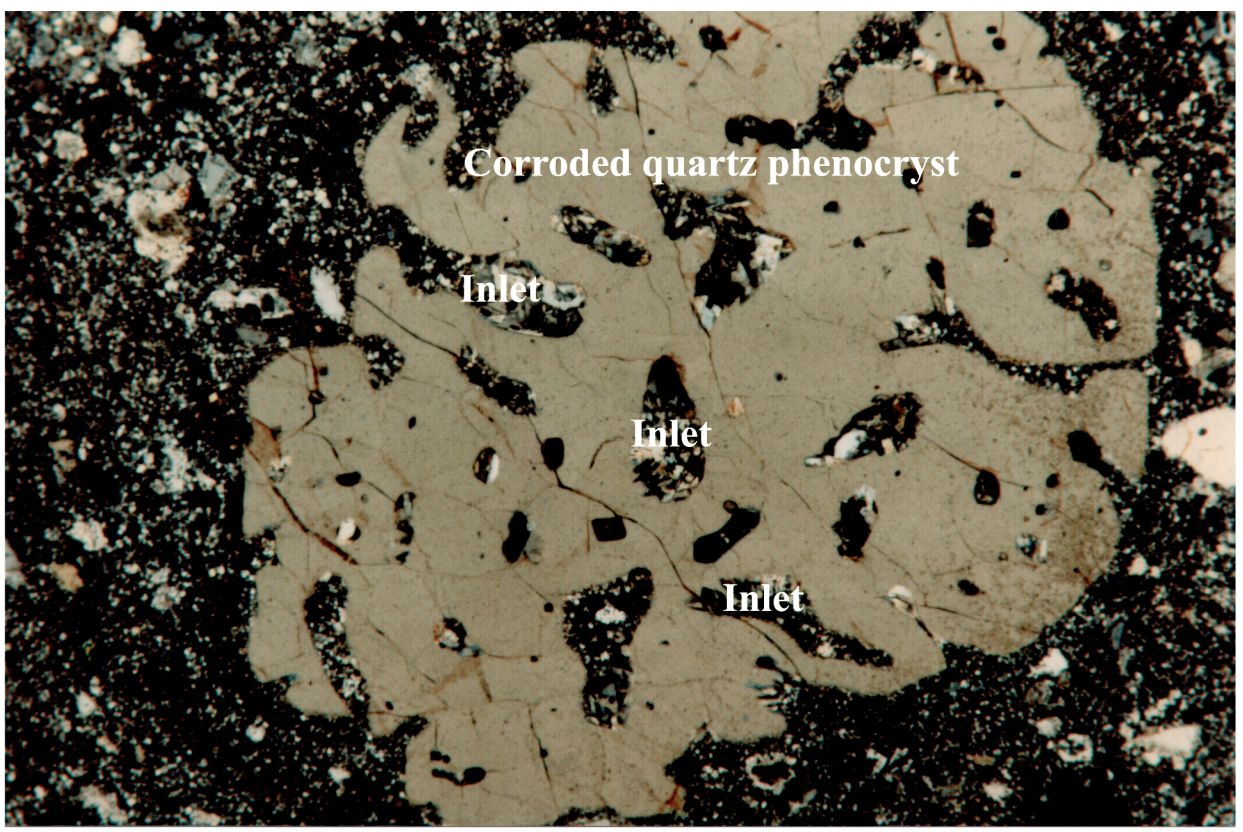
CHEMISTRY

Chemical analyses of representative rocks are presented (Table 1) as a practical tool used in connection with the petrographic description of magmatic rocks of this study and to reinforce their suggested nomenclature following the divisions used by Le Bas *et al* (1992) and Wilson (1989). It is obvious that the magmatic rocks have a wide, yet definable, range of chemical composition matched, of course, by mineralogical variation. The large percentage of silica and alkalies of the granites explain the predominance of feldspar and quartz in these rocks. The larger amount of lime in the granodiorites-diorites and gabbros is related to the increase in the modal percentage and type of plagioclase and clinophyroxene. Furthermore, the increase of iron and magnesian in these rocks indicate larger amounts of mafic minerals. Trondhjemite is distinguished from granites by lower content of K_2O and higher content of Na_2O which accounts for the sodic plagioclase nature of the feldspar. Similarly, syenite is distinguished from granite by the smaller content of silica and the higher content of alkalies and iron, which reflects the scarcity of quartz and the predominance of perthite feldspar and the presence of fayalite.

The volcanic rocks (basalt - rhyolite) cover a wide range of SiO_2, MgO, total iron and CaO contents, reflecting the spread from extremely silica saturated mafic poor (rhyolite) to silica-deficient rocks. Trachyte composition is characterized by rather high to moderate contents of silica and alumina, but is rich in alkalies, reflecting the abundance of alkali minerals (alkali feldspar, aegirine and soda amphibole) and the alkaline affinity of this rock. Discussion of the petrochemistry of these rocks is beyond the scope of this work.

VOLCANICLASTIC ROCKS

Effusive rocks and their associated fragmental debris of volcanic parentage were penetrated in a few wells of Concessions 98 and 100. The volcanic rocks themselves are mostly composed of cryptocrystalline basalts with traces of plagioclase microlites and subordinate microphenocrysts of olivine psuedomorphs.



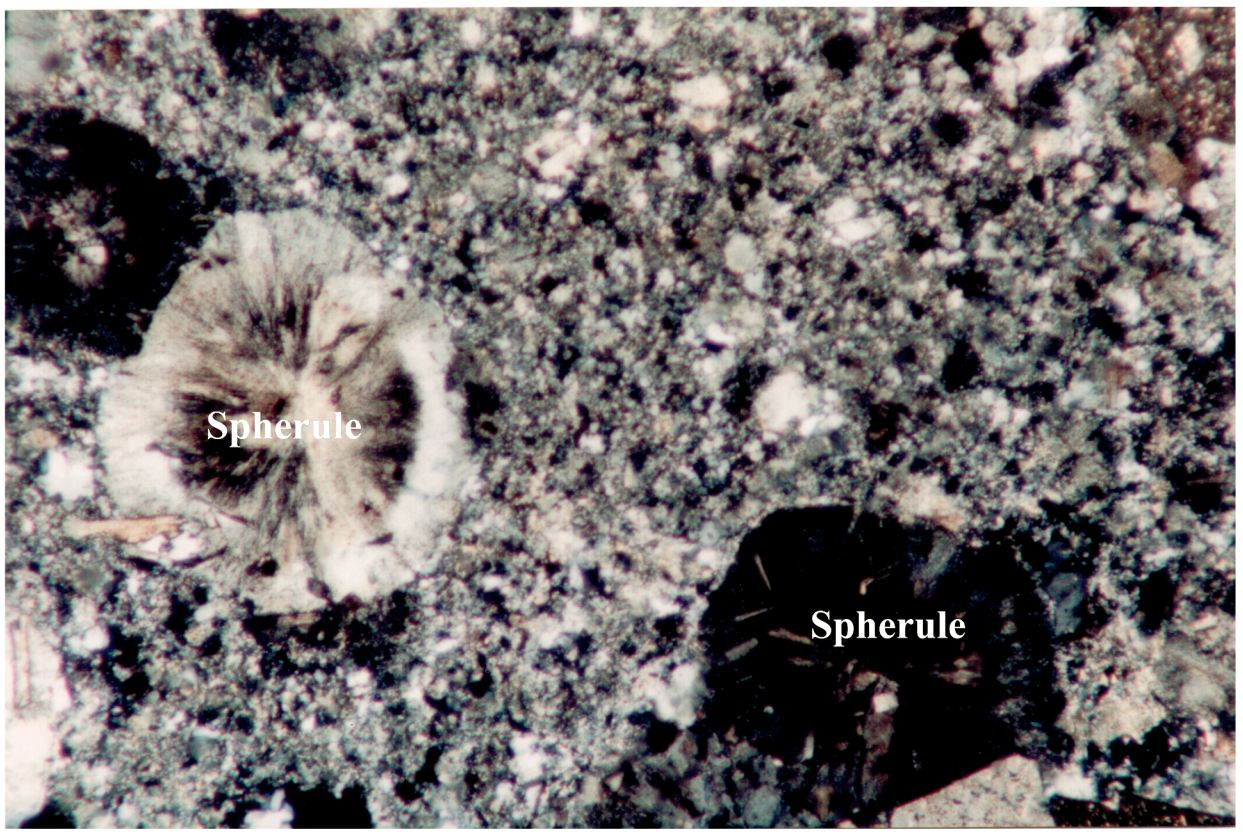


Fig. 18. The upper microphotograph from Zaqqut area shows corroded quartz phenocrysts with inlets of cryptocrystalline groundmass (X14, XPL view). The field of view of the lower microphotograph, taken from a well south of Harash area has been chosen so as to show the spheriolites surrounded by a cryptocrystalline groundmass (X32, XPL view).

The general term 'volcaniclastic', introduced by Fisher (1961), is applied as a collective non-genetic term to both the pyroclastic and the epiclastic deposits of this study. Using few currently accepted schemes (Cas and Wright, 1987; Fisher and Schmincke, 1984; Walker, 1984), petrographic approach based on core characteristics and thin section observations, is used to separate volcaniclastic rocks into broad, purely descriptive, individual levels.

The fragmental debris are blocky and nearly equant. They are composed of basaltic rock fragments cemented together by a matrix made up mostly of clays. Intermixing of epiclastic, volcaniclastic and sedimentary materials resulting from erosion and re-deposition is common. A petrographic approach is used to separate volcaniclastic rocks into broad, individual, depositional units. Thus, at certain levels, these rock fragments are very abundant and make up at least 90% by volume of the volcaniclastic rocks (Fig. 19). These assemblages are interpreted to be the primary products of highly explosive eruption (diatreme breccia) or a direct consequence of its erosion and deposition. Here, shallow groundwater or surface water is thought to have had access to the ascending magma which fueled hydromagmatic eruption. This is a common feature in areas of basaltic volcanism e.g. Gharyan area; (Busrewil and Wadsworth, 1996) and without the interaction with water, the basaltic magma would have been erupted in the form of scoria cones and lava flows.

In other levels or wells, the fragmentary rocks are less abundant and comprised of heterolithological basalt clasts of already consolidated volcaniclastics and supported mostly by quartz matrix (15-30 % by volume) (Fig. 20). Calcite cement is common and can be observed in almost all thin sections (Fig. 21).

Under the microscope, the basalt rock fragments vary from glassy to granular texture. Some of them are composed of fine-grained plagioclase laths set in a birefringent matrix, probably of clay minerals. Other volcaniclastics consist of plagioclase crystals set in a glassy groundmass or in altered groundmass which is too fine-grained for its constituents to be identified by the polarizing microscope.

These rocks are poorly sorted and have moderately high matrix which supports the clasts. In addition, they show preferred orientation and this may suggest horizontal transport of the constituents. Mixed materials formed in this way are classed as lappilli-tuff. They are interpreted to be pyroclastically fragmented detritus that were deposited by epiclastic debris-flow processes.

Still, in other levels, the proportion of the volcanic rock fragments to the total of the associated clastic sediments is volumetrically insignificant (4-10% by

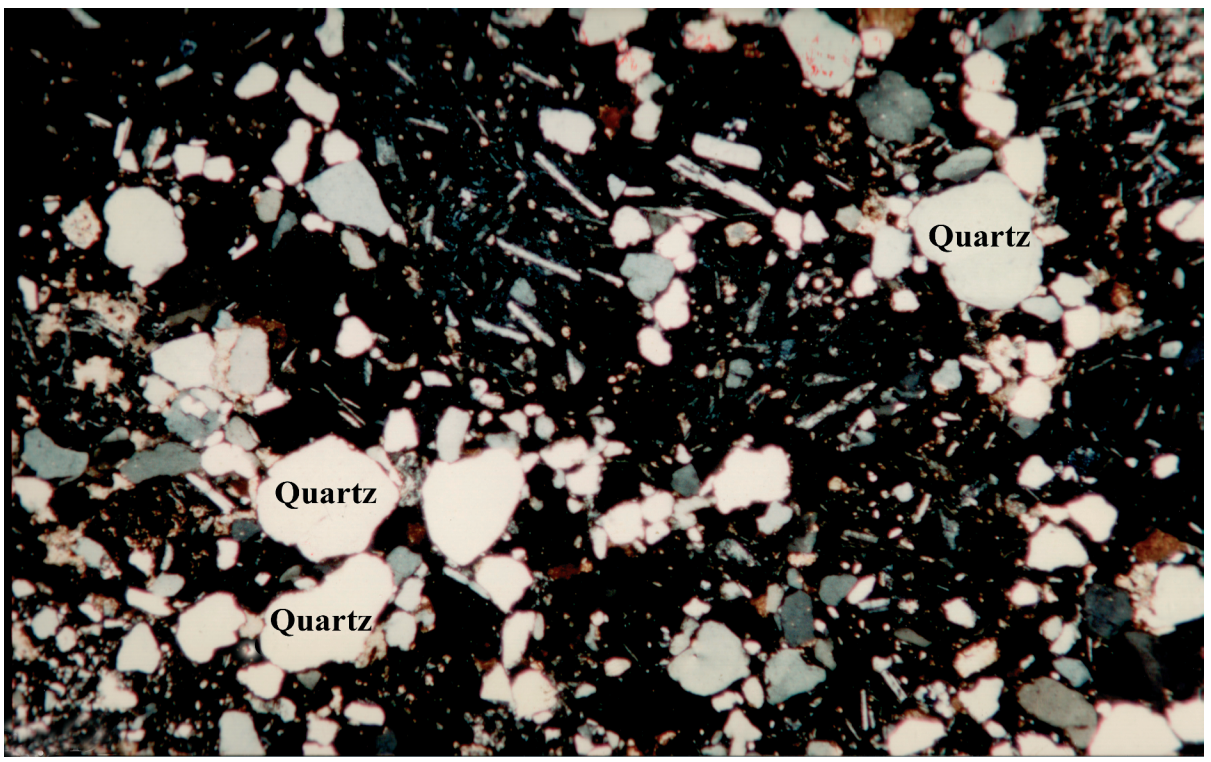


Fig. 19. Microphotograph of lapilli tuff from NC-98 area showing the predominance of quartz grains filling the interspaces between basalt rock fragments (XPL view, X32).

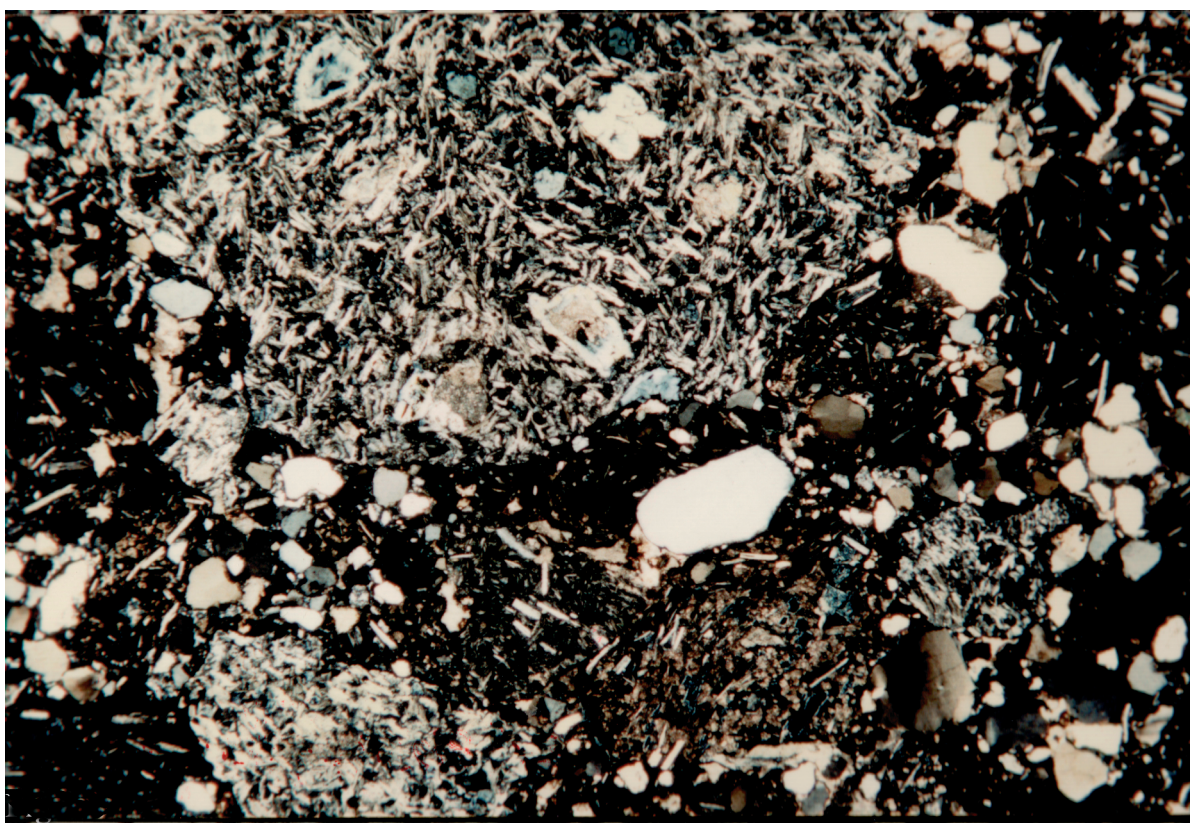


Fig. 20. Close up view of a volcaniclastic microphotograph from the same locality (NC-98) exhibiting the heterolithologic nature of basaltic debris (XPL, X32).

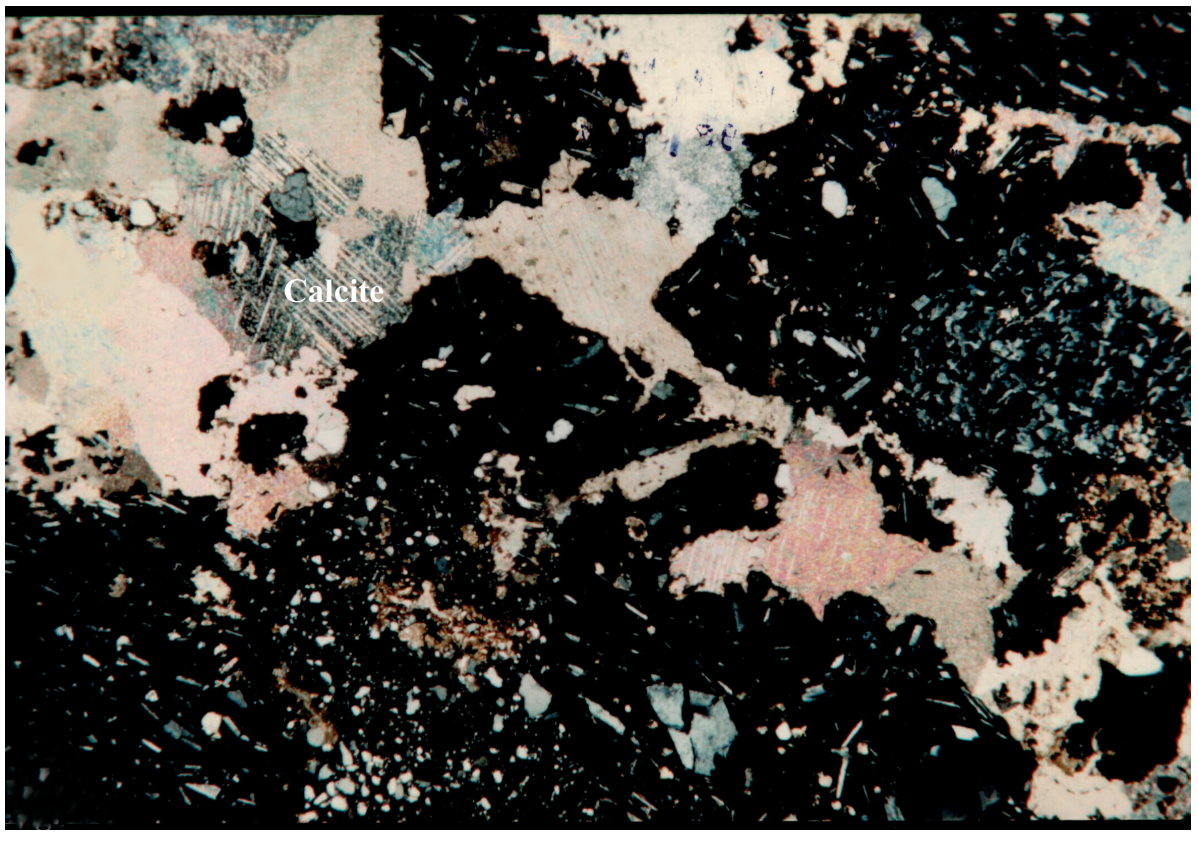


Fig. 21. Microphotograph taken under crossed polars of lapilli tuff showing a lithified volcaniclastic rock penetrated in a well from the NC-98 area. Here the interspaces are filled by calcite (X32).

volume) and quartz grains are the dominant constituents while, medium-grained granitoid chips are subordinate (less than 2% by volume). They are poorly sorted and a large proportion of the quartz grains exhibit moderate rounding and undulose extinction. Clays, calcite and dolomite form the cementing materials. Materials of this sort are inferred to be volcanic arenites and/or lithic arenites.

The sequence of events has possibly started with explosive phase or phases of areally limited (in extent) vents, (maar-type volcanoes, tuff rings, tuff cones and explosive pits) in which it was then graded to the next phase where basaltic rocks were interbedded with (or intruded into) the pyroclastic bodies. Here water has no access to the ascending magma or lavas. Reworked land derived pyroclastics and epiclastic volcanic materials took place, then, and resulted in the deposition of lapilli-tuff. The volcanic arenite is thought to have had its source materials from basement and subordinate subaerial volcanics. The presence of minor percentage of volcaniclastics within the sandstone may suggest the penecontemporaneity of volcanic arenites with volcanism.

CONCLUSIONS

1. The penetrated lithologies within the study area bracket a considerable period of time, spanning from Pan-African metamorphic rocks to Late Pan-African granitoids, through Phanerozoic basin fill and its associated within-plate magmatism.

2. The metamorphic rocks represent a low pressure metamorphic terrain within which the magmatic intrusions were emplaced. These rocks, like the rest of parts of Libya, represent parts of an older oceanic crust in the present day Sirt Basin. Information obtained from wells drilled to basement revealed that these metamorphic rocks, although once widespread, are preserved only locally. It is thought that they have been largely removed by erosion as a result of updoming, magmatic intrusions, deformation and subsequent weathering.

3. The igneous rocks are divided into two broad categories: granitoids and within-plate magmatic rocks. Under each of these headings, various rock types are grouped. Each rock type is described on the basis of mineral proportions or major elements. Many other individual characteristics, ranging from differences in mineral association, mineral species and texture are used.

4. Wilhin-plate anorogenic igneous activity is represented by felsic, intermediate and mafic rocks. It is important to point out that detailed systematic studies and available geochronological investigation of these rocks are, as yet, insufficient.

5. The volcaniclastics are fragmental rocks in which the grains are of volcanic origin. They are, as yet known, restricted to the eastern portion of Sirt Basin, where they most likely form concealed maars, cinder cones and/or sheets. Regardless of their origin, they represent a period of hydromagmatic activity during the deposition of the associated Nubian Formation.

REFERENCES

Busrewil, M. T. and Wadsworth, W. J., 1996. Tertiary-Quaternary alkaline-subalkaline magmatism in Gharyan area-field aspects and petrography. *Petrol. Res. J.,* **8**, 13-23.

Cas, R.A.F and Wright, J.V., 1987. *Volcanic Successions Modern and Ancient*. Chapman and Hall, London, 528 p.

Fisher, R.V., 1961. Proposed classification of volcaniclastic sediments and rocks. *Geol. Soc. Am. Bull.*, **72**, 1409-14.

Fisher, R.V. and Schmincke, H.U., 1984. *Pyroclastic Rocks*. Springer-Verlag, Berlin, 472 p.

Hallet, Don, 2002. *Petroleum Geology of Libya*. Elsevier, Amsterdam, 503 p.

Kennedy, W.Q., 1964. *The Structural Differentiation of Africa in the Pan-African (+500 m,y) Tectonic Episode*. Research Institute of African Geology, University of Leeds 8th Annual Report, 48-49.

Le Bas, M. J., Le Maitre, R.W. and Woolly, A.R., 1992. The construction of the total alkali-silica chemical classification of volcanic rocks. *Mineral. Petrology*, **46**, 1-22.

Le Maitre, R.W. (ed). 1989. *A classification of Igneous Rocks and Glossary of Terms: Recommendation of the International Union of Geological Sciences Subcommission on the Systematic of Igneous Rocks,* Blackwell, Oxford, 193 p.

Salem, M.J. *et al* (eds.), 1996. *The Geology of Sirt Basin*, I-III volumes, Elsevier, Amsterdam.

Salem , M.J. and Oun, K.M., 2003. *The Geology of Northwest Libya*, **I-III** volumes, Earth Science Society, Tripoli, Libya.

Schmid, R., 1981. Descriptive nomenclature and classification of pyroclastic deposits and fragments: Recommendations of the IUGS Subcommission on the Systematics of Igneous Rocks. *Geology*, **9**, 41-43.

Walker, R.G. (*ed*). 1984. *Facies Models* 2nd Ed. Geol. Assoc. Can., Geosci. Repr. Ser 1.

Williams, J.J., 1971. Igneous and sedimentary reservoir rocks, Augila Field, Libyan Arab Republic. In: C. Gray (ed.) *Symposium on the Geology of Libya*, Faculty of Science, University of Libya, Libyan Arab Republic, 501-512.

Wilson, M., 1989. *Igneous Petrogensis*. Unwin Hydman, London.