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GEOCHEMISTRY OF THE MAGMATIC MICROGRANULAR ENCLAVES OF WADI RAHABA AREA, SOUTHERN SINAI, EGYPT

IMBARAK SAYED HASSEN[1], RASMY ISMAIL EL-GHARBAWY[2], NABIL NASR EL-MASRY[1], GYÖRGY BUDA[3]

[1]Department of Geology, Faculty of Science, Suez Canal University, 41522 Ismailia, Egypt.

[2]Department of Geology, Faculty of Science, Ain Shams University, Cairo, Egypt.

[3]Department of Mineralogy, Eötvös Loránd University of Sciences, H-1117, Pázmány sétány 1/C, Budapest, Hungary
e-mail: buda@ludens.elte.hu

ABSTRACT

The study of the magmatic microgranular enclaves (MMEs) as relics of mafic magmas gives important information on the origin of parent magmas and their evolution. In the study area, MMEs are either concentrated at the margins of the I-type granodiorite pluton or within some parts of its interior. Most of the enclaves are either ellipsoidal or ovoid in shape and tend to have sharp contacts with the enclosing host rock. Sizeable enclaves, however, are less ellipsoidal and are characterized by curved boundaries. The contact is sometimes marked by a chilled margin with no sign of solid state deformation.

MMEs exhibit classical features of mafic melts globules trapped in granitic magma. Swarms of MMEs are either related to convection currents in magma chamber or to gravitational sorting of heterogeneous magmas.

The enclaves contain the same mineral assemblages as the host rock though their proportions are different. They contain megacrysts of plagioclase similar in composition to that of the host rock. The enclaves are composed mainly of plagioclase, K-feldspar, and hornblende in addition to minor amounts of clinopyroxene and orthopyroxene.

The MMEs are rather basic to intermediate in composition as their SiO_2 content ranges between 46% and 58%. The composition of most MMEs clusters near the granodiorite trend line. Many trace elements do not show clear linear correlation with the SiO_2 content and are scattered off the trends defined by related granodiorite.

The petrographic and geochemical characteristics of the enclaves and their hosting granodiorite indicate that granodiorite is a product of partial melting and fractional crystallization of a basic magma, and that the enclaves are trapped blobs of basic to intermediate parental magma. Both major and trace elements contents of the investigated enclaves indicate that they were formed as a result of mingling and mixing during magma evolution.

Key words: granodiorite, I-type magmatic enclaves, chilled margin, Southern Sinai.

INTRODUCTION

Saint Katherine Complex is situated in the high mountainous area of southern Sinai. The country rock includes Solaf gneisses, a volcanoclastic suite (Rutig volcanics), a calc-alkaline plutonic series represented by metagabbro-diorite complex, quartz monzonite, quartz diorite, and other granitoid rocks (Hassen 1997).

The quartz monzonite, granodiorite, and quartz syenite at Wadi Rahaba-Gebel Sheikh El-Arab area contain rounded microgranular enclaves oriented locally by the magmatic flow of the host-rocks. Large composite enclaves occur in quartz syenite, whereas very small enclaves are found in the porphyritic quartz monzonite. Granodiorite is the most prevailing magmatic phase in the study area.

The magmatic microgranular enclaves (MMEs) are common components in the I-type granitic rocks. Didier (1973), White and Chappell (1977), and Barbarin and Didier (1991) indicated that mafic enclaves provide important information about the nature of their source rocks as well as the genesis of granitic melt . The study of enclaves is of great importance because it could shed some light on the mode of emplacement of granitoid magmas, the dynamics of magma chambers, their cooling processes, and the origin and evolution of the granitoid melts.

The MMEs constitute trapped mafic fragments of fine-grained igneous products, generally with ovoid shape and sharp contacts, representing blobs of coeval magmas. Didier and Barbarin (1991) and Vernon (1983) defined and reviewed the French term "enclave". It is clearly known that xenoliths refer to foreign rock fragments, while inclusions refer to mineral grains enclosed in another. Consequently, there is a close relationship between enclaves and their host rock. Therefore, the term enclave but not xenolith is the most suitable term for the present study.

The MMEs are widespread in the granitic rocks of calc-alkaline, shoshonitic, or alkaline nature. Their characterization, geochemical affinity, genesis, and evolution have been extensively investigated by several authors. Some of them suggested that they are products of the coexistence of two contrasting magmas. Vernon (1984, 1990) and Barbarin and Didier (1992) suggested that the majority of enclaves represent the mafic end members of a more or less hybridized or mixed two magmas. The mingling, according to those authors, should be restricted to systems with mechanical interactions. The authors recognized the following three interaction processes in the coexisting magmas: thermal, mechanical, and chemical exchanges. The specific textural and compositional characteristics of an enclave will vary with the relative intensity of these three factors. For example, when the mechanical exchange predominates, megacrysts of the host magma are abundant in the enclaves. Chemical and mechanical exchanges cause the hybridization of the microgranular mafic enclaves, producing compositions closer to the host rock. These exchanges frequently precede the basic magma batch dispersion by magma flow, producing the microgranular mafic enclaves (Hibbard, 1995).

Magma mingling as a mechanism for the genesis of MMEs attracted the attention of many authors (Didier 1987, Vernon et al. 1988, Dodge and Kistler 1990, Barbarin and Didier 1991, Castro et al. 1990, 1991, Tobisch et al. 1997, Sinha et al. 2001, Dahlquist 2002). The typical igneous textures described by many researchers (Didier 1984 and Vernon 1991) stated that the fine-grained chilled margins surrounding many MMEs favor their formation from the crystallization of silicate melt.

Some authors used numerical simulations of a chaotic dynamic system involving stretching and folding processes (Perugini et al. 2002, 2003). Others have modelled the process using whole-rock compositions (Wei et al. 1997, Moyen et al. 2001). They focused their studies on the textures, trace element patterns and isotope geology of the zoned minerals, (Bussy 1990, Ginibre et al. 2002, 2004, Barbarin 2005, Gagnevin et al. 2005ab; and Słaby et al. 2007a).

In many granitic intrusions, microgranular magmatic enclaves provide strong evidence of interaction between coeval mafic and felsic magmas (Vernon 1990, 1991, Barbarin and Didier 1992, Barbarin 2005). The mechanical migration of crystals, back and forth, from one magma to another causes zonal growth (Vernon 1986, Waight et al. 2000ab, Barbarin 2005, Słaby et al. 2007ab).

Feldspars are sensitive indicators of thermal and chemical heterogeneities in their crystallization environment (Knesel et al. 1999, Ginibre et al. 2002, 2004, Troll and Schmincke 2002, Perugini et al. 2005, and Słaby et al. 2007ab). Primary melt compositions may be well reflected in the trace and major elements compositions of the growth zones if the feldspar crystals grow close to the crystal-melt equilibrium boundary. Slowly diffusing compatible trace elements, for example Ba, which is commonly chosen as an index of magma mixing, can be used to track the process step by step (Cherniak 2002) and is often used to examine growth histories of K-feldspar crystals (Long and Luth 1986, Cox et al. 1996, Ginibre et al. 2004, Gagnevin et al. 2005a and Słaby et al. 2007a).

The origin of the microgranular enclaves is interpreted as being related to one of the followings: (1) fragments of wall rock facies closely related to the host magma; (2) globules of mafic melt injected into resident felsic host melt; and (3) fragments of recrystallized refractory metamorphic rocks co-mingled with resident granitic melt (Maas et al. 1997). So the origin of the microgranular enclaves is controversial.

The enclaves of the Egyptian Precambrian granitoids have been studied by several researchers. For example, Ammar et al. (2003) studied the enclaves of El-Delihimmi-Nusla granite pluton, central Eastern Desert of Egypt, and concluded that they were formed as restite in a granite source. Several granitoid masses are also widely exposed in southern Sinai; many of them contain microgranular enclaves and granodiorite represents one of these examples. El-Metwally (1993) studied the microgranular enclaves of the granitoid rocks in southwestern Sinai and suggested a mingling model of mafic globules of different compositions. Surour and Kabesh (1998) described swarms of mafic microgranular enclaves in Wadi Risasa area southeastern Sinai. They reported that the opaque mineralogy and geochemistry of the enclaves and their host rocks are almost identical.

The main objective of this paper is to test the magmatic processes that might have been involved in the genesis of the microgranular enclaves hosted by the granodiorite of Wadi Rahaba. Therefore, the geologic setting, petrology, and geochemistry of the microgranular enclaves and their host rock are thoroughly studied to present a workable model for their petrogenetic evolution.

GEOLOGIC SETTING

Saint Katherine area is composed of late-Precambrian rocks including metagabbro-diorite complex, granodiorite, quartz-monzonite, quartz diorite, and other varieties of granitoid rocks (Fig. 1).

Granitic intrusions in southern Sinai are classified into three groups according to their geological, geochemical, and petrological characteristics (Hassen 1997). These three groups are:

(1) Calc-alkaline granitoids *(Phase I)*: (quartz diorite, quartz monzodiorite, quartz monzonite, granodiorite, and hornblende-biotite granite).

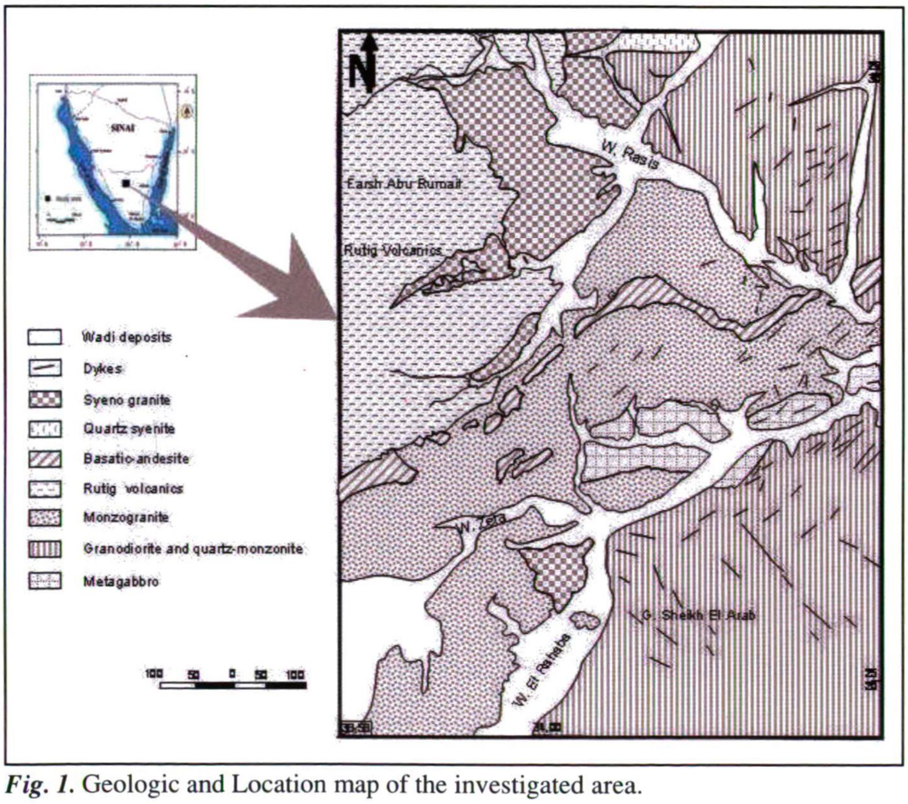

Fig. 1. Geologic and Location map of the investigated area.

(2) Subcalc-alkaline granitoids *(Phase II)*: (porphyritic biotite monzogranite, coarse-grained biotite monzogranite, and pegmatitic monzogranite).

(3) Syenogranite *(Phase III)*: (Alkali feldspar granite, syenogranite, microsyenogranite, and granophyric granite).

Metagabbro is represented by small homogenous weathered outcrops (2 x 5 km) of brown to greenish-brown color, medium- to coarse-grained texture, and are massive to weakly-foliated. It also occurs as an E-W-trending belt located to the southeast of Gebel Nakhla. It is intruded by monzogranite, quartz monzonite, and the ring dyke of Saint Katherine. Some metagabbroid sheets were locally intruded by diorite and syenogranite.

The two largest occurrences of quartz diorite intrude the metagabbro-metadiorite complex at Gebel Sheikh El-Arab. They are homogeneous, weathered, greenish-grey colored rocks, and generally have medium- to coarse-grained granular to weakly-foliated texture. The fine-grained diorite, on the other hand, is recorded in the northeastern and northwestern parts of the study area. In the southeastern parts, small masses of medium- to fine-grained quartz monzodiorite are observed showing gradational contacts with quartz monzonite. There are also large elliptical monzodioritic blocks making sharp contacts with quartz monzonite.

Quartz monzodiorite is massive to weakly-foliated and heterogeneous, with subangular psammitic and gabbroic xenoliths. Foliation in the xenoliths predates the emplacement of quartz monzodiorite, which is also cut by monzogranitic dykes.

Granodiorite intrudes into mafic magmatic rocks. It has sharp contacts with the country rocks which comprise metagabbroic and dioritic rocks. The effect of contact metamorphism was observed in the surrounding country rock. Facies of contact metamorphism formed around the granodiorite porphyry dikes range from K-feldspar-cordierite-hornfels facies, and hornblende-hornfels facies down to albite-epidote-hornfels facies. Both the intrusive rock and the country rock are intruded by Katherina ring dyke. The volcanic rocks comprise andesite, latite-andesite, dacite, rhyodacite.

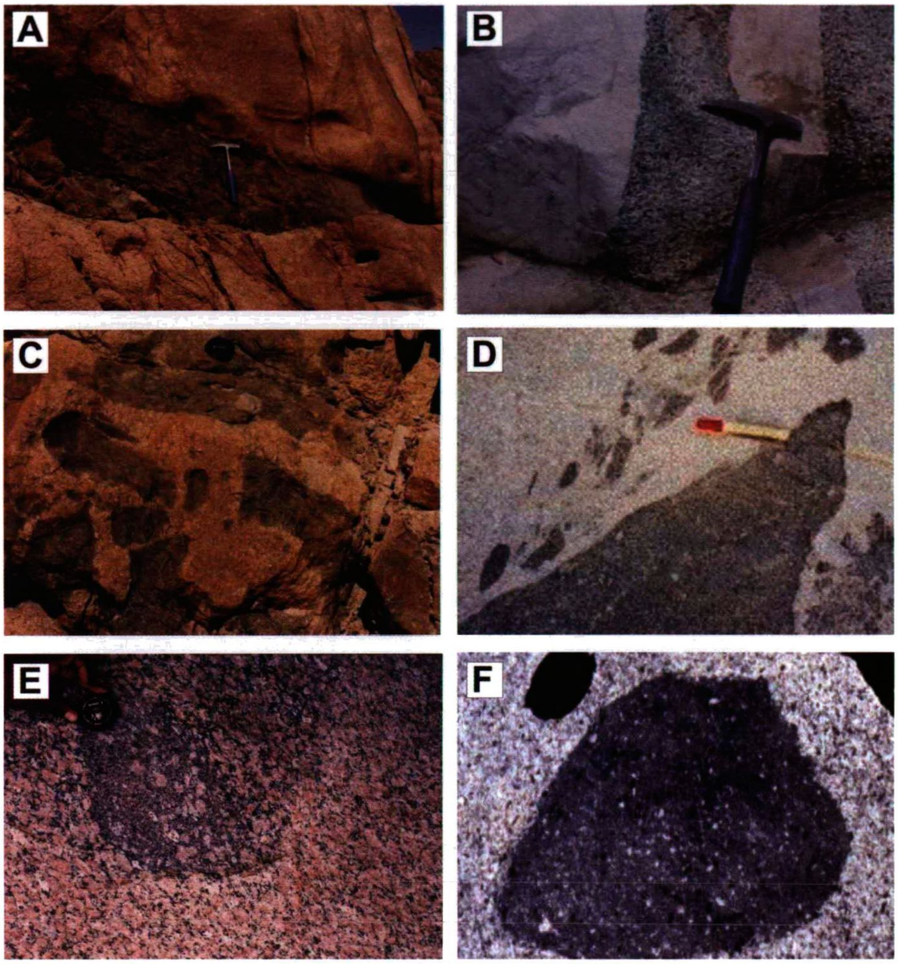

Fig. 2. Different types of microgranular enclaves (MMEs) observed in the study area. ***(A)*** Pillow-like mafic enclave formed as an offshoot of basic magma. ***(B)*** Dyke-like enclave showing curved boundary and sharp contact with the host rock. ***(C)*** Different types of microgranular enclaves. ***(D)*** A swarm of enclaves showing interaction with the host rock. Note whitish colored alkali feldspar megacrysts in the largest enclave. ***(E)*** A microgranular enclave showing gradational contacts with the host rock. Alkali feldspar crystals enclosed in the enclave are indicative of magma mingling. A hybrid zone is also observed in the upper part of the photo. ***(F)*** A microgranular mafic enclave showing a sharp contact with the host rock and enclosing prominent crystals of plagioclase feldspars.

Granodiorite has a medium- to coarse-grained hypidiomorphic granular texture. The marginal zones of the intrusion were commonly injected with aplitic veins, which have various orientations and thicknesses. Small pegmatitic as well as minor composite dikes are also observed near the margin of the intrusion. Large pegmatitic veins consisting of K-feldspar, biotite, quartz, epidote, topaz, and pyrite usually occur at the contacts between aplites and granodiorite or within the aplitic vein itself. Nodular pegmatites, which have the same mineralogical composition as the pegmatitic veins, are present around Rahaba Village.

Hornblende monzogranite pluton is either equigranular or porphyritic with a medium- to coarse-grained matrix containing K-feldspar megacrysts attaining 5 cm in length. Monzogranite intrudes granodiorite, quartz monzonite, and the metagabbroid rocks of Wadi Rahaba. Large granodiorite enclaves within monzogranite were also observed.

Pillow-like enclaves, formed as an offshoot of basic magma, are recorded near the contact between the ring complex and monzogranite (Fig. 2A). They are angular to oval in shape and locally occur as dyke-like enclaves, which become progressively thinner towards their termination with the host granitoid. They show curved boundary as well as sharp contact with the host rock (Fig. 2B).

Quartz monzonite occurs northwest of the study area at Wadi Isbaiya mainly in the central part of both the eastern and northern borders of the pluton. It is greyish-pink colored and has a massive, non-foliated, coarse- to medium-grained hypidiomorphic granular texture, in which up to 1 cm long K-feldspar megacrysts are frequently observed.

The contact between quartz monzonite and syenogranite is commonly sharp or locally grades to a fine- to medium-grained quartz syenite, which contains some dioritic enclaves and gneissose xenoliths. Other quartz monzonitic to monzodioritic masses in the investigated area have also been assigned to the quartz monzonitic intrusive suite of Wadi Isbaiya (Hassen 1997).

There are two intrusive masses which show compositional and textural affinity. The largest one is a quartz-poor, K-feldspar porphyritic hornblend-biotite monzogranite. The other monzogranitic mass has an equigranular texture and contain lesser amounts of hornblende. The contact between monzogranite and metagabbro is sharp and is interleaved with gabbro. Alignments of K-feldspar megacrysts in the central part of the mass refers to primary foliation that developed during the early stages of crystallization.

K-feldspar porphyritic hornblend-biotite monzogranite is widespread in the Rahaba area. The rock grades from porphyritic monzonite to equigranular monzogranite. The rock is pink in color, slightly weathered, massive to weakly-foliated, and ranges in texture from medium- to coarse-grained granular to strongly porphyritic. Megacrysts of K-feldspar, up to 5 cm long, account for 10 to 20% of the rock, whereas those of plagioclase feldspars are quite rare.

Syenite and quartz syenite of the ring dyke are typically massive. Most of them have a coarse- to medium-grained granular texture and a dark brown to deep purple color. They may, however, contain K-feldspar megacrysts, where K-feldspar/plagioclase ratios vary considerably. Biotite is the main mafic mineral, often associated with pyroxene and magnetite. A coarse-grained greyish variety of syenite was also observed and is characterized by well-developed laths of feldspars. Some outcrops form sheet-like bodies, up to two kilometers long, interleaved with country rocks; their margins are commonly intensively sheared.

Augite-bearing porphyritic basaltic-andesite occupies a small area of Gebel Nakhla. The rock is medium- to fine-grained, grey to black in color with some amygdales filled with epidote and K-feldspar.

Orange-pink to brick red colored syenogranite is among the most widespread rock types in Saint Katherine area. It forms roughly an oval-shaped pluton taking a NE-SW direction. The contact of syenogranite with the country rock is sharp showing no evidence of metasomatic alteration. These rocks, however, are cut by veins and pockets of pegmatite as well as microgranite dikes. Basic enclaves are occasionally observed. Miarolitic cavities are locally common and often contain orthoclase and smoky quartz crystals up to 3 cm long. In many localities, syenogranite is cut by pink to pinkish-buff colored, fine-grained aplite dikes that are mineralogically similar to granite. Aplite dikes are usually less then 5 cm wide.

Syenogranite contains 5% biotite with lesser amounts of hornblende, epidote, titanite and/or magnetite. Locally, however, it may contain up to 15% mafic minerals. It is therefore identified as biotite syenogranite that varies in texture from medium- to coarse-grained granular to fine- to medium-grained sub-porphyritic. It is composed of quartz, alkali feldspar, minor plagioclase, biotite, and minor amphibole. In the syenogranite showing sub-porphyritic texture, graphic texture is frequently recorded in the fine-grained variety and biotite is often altered to chlorite. Fluorite-bearing syenogranite was also observed in Wadi Rasis area.

Magmatic Microgranular Enclaves

Magmatic microgranular enclaves (MMEs) are fine-grained and darker in color than the host-rock (Fig. 2C). They are basic, dioritic, monzonitic, tonalitic, and granodioritic in composition. The enclaves are not only restricted to the margins of the hosting granodiorite pluton but they were also recorded in other parts as well. They may appear closely spaced but they do not commonly form swarms (Fig. 2D). Some mafic enclaves (basic in composition) may also contain smaller monzogranite enclaves indicating that mafic and felsic magmas were coeval.

The enclaves range from 1 to 70 cm in diameter. Most of the enclaves, however, may cluster around either the 2-5 cm or the 20 cm across size range. The largest enclaves are commonly observed along the margins of the granodiorite pluton. Although they vary widely in size, most of the enclaves are elliptical. They have crenulated surfaces, chilled margins, and sharp to partly diffuse contacts with their host rock. Some of these features are indicative of plastic behavior. Sharp contacts, however, are frequently observed among the smallest enclaves, which tend to show a finer grained texture and a more mafic content at their margins compared to their core. Biotite enrichment is rarely observed along the margins of the enclaves.

The enclaves have porphyritic to hypidiomorphic granular fine-grained textures (0.05-0.5 mm). Grain size varies from the chilled margin to the core of the enclave. This is largely attributed to different cooling rates, which variably affects the nucleation rates and the growth rates of the crystallizing mineral phases.

It was observed that mafic enclaves may also enclose alkali feldspar megacrysts related to the granite host rock (Fig. 2E). In this case, their margins tend to display a gradational contact with the host rock and a hybrid zone may develop. Other enclaves, enclosing host-related plagioclase crystals, have margins displaying a rather sharp contact with the granodioritic host rock (Fig. 2F). Megacrysts of amphiboles are also recorded in both the enclaves and the surrounding host rock.

These aforementioned observations suggest that two contrasting magmas were involved in the evolution of the magmatic rocks of the study area and that the MMEs represent quenched globules of a mafic magma caused by magma mixing/mingling processes (Hibbard 1991, Vernon 1991, Kim et al. 1998).

Hybrid Zone

A well-preserved outcrop of a hybrid zone shows gradational contacts with granodiorite. It is comparable, both mineralogically and texturally, to the MMEs and is composed of mesocratic to melanocratic quartz diorite and granodiorite. The dark color is attributed to the presence of microgranular enclaves where markedly higher proportions of hornblende and biotite occur. It is believed that these rocks are products of mafic-felsic magma mixing, where mafic magma is relatively more abundant.

PETROGRAPHY

The host rocks of the MMEs are as follows:

(1) Quartz Diorite:

Quartz diorite has a medium-grained granular texture and is mainly composed of oligoclase, quartz, hornblende (10%), biotite, and K-feldspar in addition to minor amounts of magnetite and epidote.

The textural characteristics of quartz diorite reflect slow cooling and the presence of volatiles, which facilitated mineral growth. Similarly, biotite and hornblende indicate the availability of water and thence high-vapor pressure during crystallization. Some of the amphibole crystals are considered as products of primary magmatic crystallization, but many others may represent late- to post-magmatic crystallization. Reactions involving water-rich fluids are also responsible for the replacement of hornblende by late-magmatic overgrowths of biotite.

(2) Granodiorite:

Granodiorite shows variation in both texture and mineral composition. It varies from medium- to coarse-grained equigranular to porphyritic in texture. Its essential mineral constituents include plagioclase, quartz, K-feldspar, hornblende, and biotite, whereas accessory mineral phases comprise zircon, apatite, titanite, allanite, and opaque minerals. Plagioclase, hornblende, and biotite tend to form euhedral to subhedral crystals, whereas quartz and K-feldspar occur as string microperthite and containing fine-grained quartz inclusions (Fig. 3A).and occurs as interstitial minerals. Zoned crystals of plagioclase may also display spongy cellular texture. Hornblende commonly displays simple twinning. Biotite is subordinate, fresh, or scarcely altered to chlorite with epidote and/or sphene. Both biotite and hornblende often have small inclusions of euhedral plagioclase, particularly near their crystal margins.

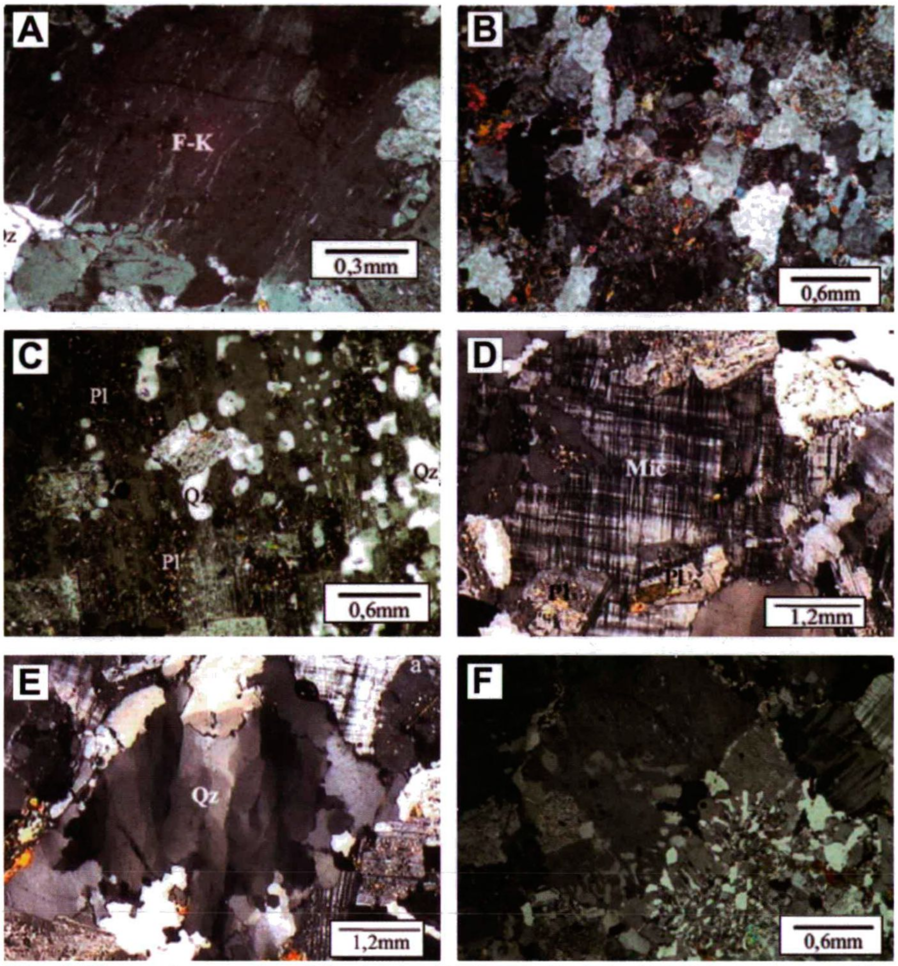

Fig. 3. Photomicrographs of the host rock (granodiorite). ***(A)*** String microperthite and fine-grained quartz inclusions in the host rock. ***(B)*** Xenomorphic plagioclase and quartz. ***(C)*** Xenomorphic aggregates of quartz grains within plagioclase phenocryst. ***(D)*** Microcline crystal showing cross-hatched twinning with plagioclase and quartz inclusions. ***(E)*** Strained quartz grain showing wavy extinction. Biotite and cross-hatched microcline are present. ***(F)*** Micrographic intergrowth in Quartz syenite.

Some samples, however, are partially replaced by secondary minerals such as sericite, clay minerals, and epidote.

Partly resorbed early-formed crystals of plagioclase are mantled with marginal overgrowths of alkali feldspar and xenomorphic plagioclase and quartz (Fig. 3B).

(3) Monzogranite:

Monzogranite consists essentially of plagioclase, quartz, and microperthitic alkali feldspar in addition to biotite and hornblende. Apatite, magnetite, zircon, allanite, and tourmaline are accessories. Sphene also is present, but the lack of idiomorphism and its disposition between biotite cleavages, indicates that it as a secondary mineral. Plagioclase predominates as an early-formed mineral phases. It appears as tabular crystals with zoning (oscillatory zoning). Monzogranite has two varieties inequigranular hornblende monzogranite and equigranular monzogranite.

(a) Plagioclse megacryst-bearing hornblende monzogranite:

This hornblende monzogranite has a light grey color and a coarse-grained porphyritic texture. It is distinguished by well-developed megacrysts of plagioclase (up to 1 cm long). Plagioclase, orthoclase microperthite, quartz, hornblende, and biotite are the essential minerals. Xenomorphic aggregates of quartz grains occur within plagioclase phenocryst (Fig. 3C). Tourmaline, allanite, and zircon are the predominant accessories in addition to smaller proportions of opaque minerals, apatite and monazite. Chlorite and opaque minerals represent the alteration products of primary mafic minerals. Alteration minerals tend to coexist with secondary biotite and tourmaline.

(b) Equigranular monzogranite:

It has a medium- to coarse-grained texture and is rich in mafic enclaves. It is composed of microperthitic K-feldspar, plagioclase, and quartz, in addition to the mafic and accessory minerals commonly observed in inequigranular monzogranite. Microcline crystal showing cross-hatched twinning with plagioclase and quartz inclusions (Fig. 3D). Strained quartz grain showing wavy extinction. Biotite and cross-hatched microcline are present (Fig. 3E). Well-developed crystals of epidote, which are ascribed to hydrothermal alteration, are accompanied by pervasive sericitization and chloritization. Some quartz grains may display weak wavy extinction.

Reaction between mafic enclaves and monzogranite is indicated by the presence of rims of biotite around the enclaves.

(4) Porphyritic quartz syenite:

Porphyritic quartz syenite has a grey color with porphyritic texture, in which phenocrysts of microperthitic alkali feldspar and partially resorbed quartz are set in a fine- to medium-grained groundmass. Essential minerals comprise alkali feldspar, quartz, biotite, and hornblende. Magnetite, ilmenite, apatite, and zircon are accessory minerals. Micrographic intergrowth is predominate at quartz syenite (Fig. 3F).

(5) Syenogranite:

Syenogranite has a greyish-pink color and a medium- to coarse-grained equigranular to mildly porphyritic texture. Essential mineral constituents include alkali feldspar, quartz, and plagioclase. Microperthitic orthoclase and plagioclase tend to form tabular subhedral crystals. Zoning in plagioclase feldspars are not frequently observed. Individual crystals of alkali feldspar may display both pristine and brownish-colored turbid areas. The proportion of turbid areas to pristine ones is highly variable, but averages about 15–30%. Perthitic texture is common. Quartz occurs as anhedral grains. Minor brown biotite occurs as euhedral to subhedral flakes, which contains inclusions of zircon, apatite, ilmenite, and monazite. Biotite is also partly altered to chlorite. Accessory minerals, in general, include Mn-rich titanomagnetite, titanite, fluorite, zircon, and apatite.

Hybrid Rocks

The mineral assemblage of the hybrid rocks, namely mesocratic to melanocratic quartz diorite and granodiorite, includes plagioclase, quartz, K-feldspar, hornblende, and biotite with subordinate amounts of apatite, zircon, titanite, magnetite and ilmenite. Prominent textural features include rapakivi texture, where well-developed K-feldspar crystals are surrounded by rims of plagioclase, and ocellar texture, where aggregates of hornblende and biotite mantle quartz crystals.

Microgranular Enclaves

The MMEs and the host rocks show different types of textural relationship. The observed textural differences are resulted from local variations in physical conditions during crystallization. The texture of the MMEs, however, is not considered a cumulate fabric. As products of early crystallization from a parental magma, the MMEs have the same geochemical role as cumulates *sensu stricto* in basic magmatic systems, especially with regard to the development of the fractional crystallization process (Vernon 1991).

Some MMEs are equigranular, whereas others form porphyritic subhedral seriate texture and contain oligoclase-andesine phenocrysts in tonalitic enclaves, and andesine-labradorite in dioritic ones. In this case the plagioclase forms the phenocrysts and the matrix consists of fine-grained quartz, plagioclase, hornblende, and rarely biotite. The MMEs contain the same mineral phases as the granitoid host but with different proportions. They are mainly composed of Ca-plagioclase and mafic minerals, such as pyroxene, hornblende, and biotite, whereas the host granitoids tend to contain lower modal proportions of Ca-plagioclase and mafic minerals but much higher modal proportions of quartz and alkali feldspars. Plagioclase and hornblende, however, are invariably the dominant minerals in the enclaves.

The microgranular enclaves are classified modally as tonalites, granodiorites, and monzogranites. The MMEs commonly show porphyritic hypidiomorphic granular texture with phenocrysts of plagioclase, quartz, and minor biotite and alkali feldspar. The phenocrysts are thought to be petrogenetically related to the host granitic magma because they are similar to those of the surrounding granite both in size and in texture.

The groundmass is largely composed of elongated laths of zoned plagioclase feldspars, biotite, hornblende, and interstitial quartz. The grain size of the groundmass material ranges from 0.05 to 0.3 mm. Biotite and hornblende are mostly less than 0.1 mm in length. Plagioclase occurs as lath-shaped euhedral grains that may display zoning. Large desorbed plagioclase crystals with albite rims coexisting with idiomorphic plagioclase (Fig. 4A).

Phenocrysts of plagioclase occurs as euhedral to subhedral with polysynthetic twins, tabular crystals that tend to have markedly altered cores, some of which may represent isolated patches or skeletal relics of early-formed plagioclase feldspars Partial melting of enclave and its reaction with the host rock (Fig. 4B). Fine-grained plagioclase, hornblende, biotite, and accessory minerals, particularly acicular apatite may occur as inclusions in plagioclase phenocrysts. Some phenocrysts may also exhibit different types of zoning textures, such as oscillatory zoning. Others, however, do not display any chemical zoning and are plausibly derived from the host granite as they are frequently associated with primary magmatic crystals of quartz and biotite. This type of phenocrysts usually displays cellular texture. Coarse-grained zoned plagioclase with inclusions of mafic minerals (Fig. 4C) are common.. Small laths of plagioclase feldspars are clearly discernable in the groundmass material.

Alkali feldspars occur as phenocrysts and as interstitial fine-grained crystals in the groundmass. Phenocrysts comprise orthoclase and microcline microperthite. The groundmass, however, is apparently dominated by cross-hatched microcline. Many alkali feldspar phenocrysts display poikilitic textures, which are quite similar to those observed in the hosting granodiorite. Alkali feldspars may also contain minute inclusions of apatite and opaque minerals. Myrmekitic and micrographic intergrowths are frequently observed at the mutual contacts of alkali feldspars and plagioclase .

Quartz is distinguished into three main types. The first one defines markedly-developed anhedral crystals surrounded by

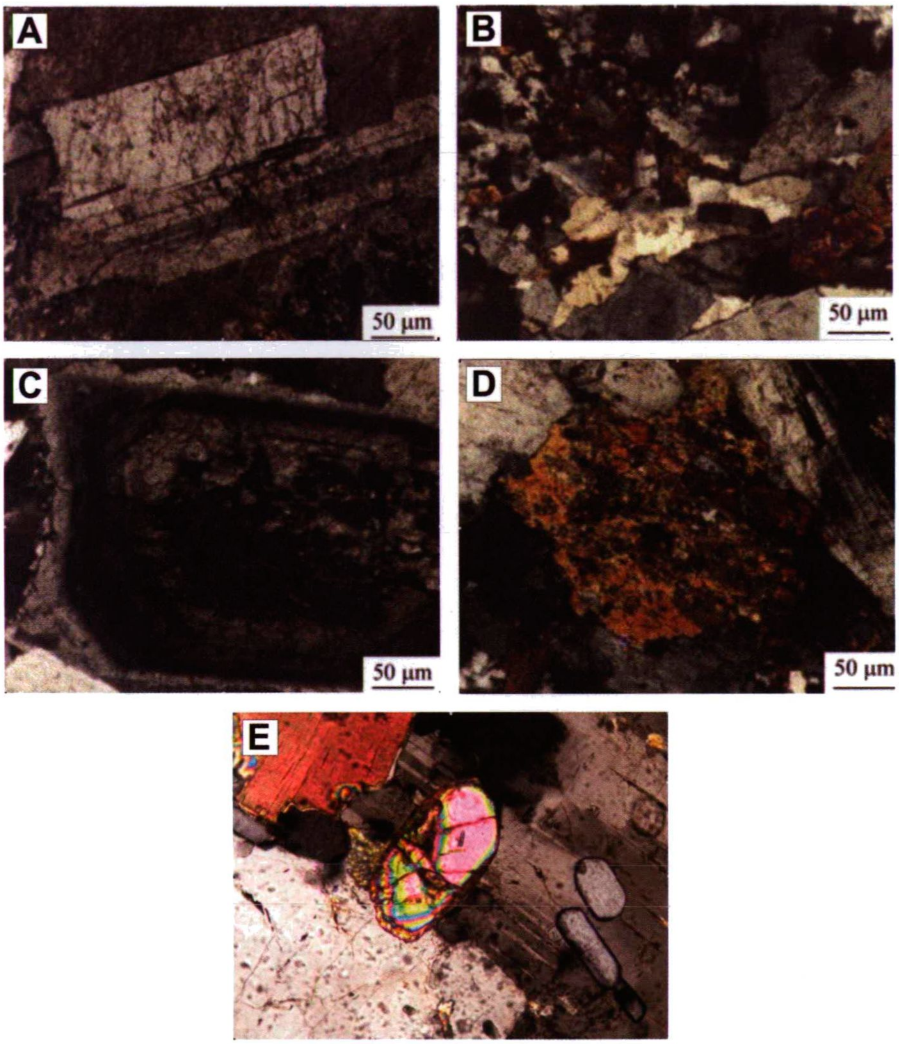

Fig. 4. Photomicrographs of the Microgranular. ***(A)*** Large resorbed plagioclase crystals with albite rims coexisting with idio-morphic plagioclase. ***(B)*** Partial melting of enclave and its reaction with the host rock. ***(C)*** Coarse-grained zoned plagioclase with inclusions of mafic minerals. ***(D)*** Amphibole rim and Fe-oxides developed along crystal cleavage. ***(E)*** Well-developed zircon, apatite, biotite and alkali feldspar in MME. Apatite shows quenched morphologies.

rims of hornblende and biotite. These large quartz ocelli, however, could be considered as xenocrysts of granitic origin. The second type is the poikilitic quartz, which is characterized by small inclusions of lath-shaped plagioclase, hornblende, biotite, Fe-Ti oxides, and acicular apatite. The third type is represented by the interstitial quartz of the groundmass material.

Biotite may attain 2 mm in length, but it is mostly less than 1 mm. It occurs either as subhedral flakes or as irregular crystals with ragged ends. Some enclaves contain blade-shaped biotite, which is usually located near the crystal margins of plagioclase. Prominent flakes of biotite may contain inclusions of plagioclase, hornblende, and zircon. Greenish-colored biotite is partly replaced with chlorite, particularly along grain boundaries and cleavage planes. Biotite, and also hornblende, may partly enclose early-formed crystals of plagioclase.

Hornblende occurs as medium-grained or fine-grained stubby prismatic crystals. It also occurs in aggregate with biotite and Fe-Ti oxides and as pseudomorphs after decomposed pyroxene. In the groundmass, hornblende evidently concentrates in the inner parts of MME. Large poikilitic crystals of hornblende enclose fine-grained biotite, plagioclase feldspars, titanite, zircon, and opaque minerals. Pyroxene crystals, which represent relics of the initial mafic magma, occur in minor amounts. They are partly or completely altered to hornblende Amphibole rim and Fe-oxides developed along crystal cleavage (Fig. 4D).

Apatite is the most common accessory mineral. It occurs mainly as acicular crystals that range from 0.1 to 1 mm in length but average less than 0.4 mm. These crystals are either arranged in radial or parallel patterns or are randomly scattered. They are enclosed in quartz, plagioclase, and K-feldspar, but they are more commonly concentrated in K-feldspar and quartz than in plagioclase. Wyllie et al. (1962) suggested that acicular apatite crystals are characteristic of rapidly cooling magmas.

Other accessory and secondary minerals include epidote, allanite, sphene, and zircon. Epidote may occur in aggregate with hornblende and biotite or as secondary alteration product that extensively replaces the Ca-rich core of the plagioclase. Allanite forms fine-grained subhedral crystals, whereas sphene occurs either as early-formed perfect wedge-shaped crystals or as interstitial crystals (<0.5 mm) in the groundmass. Zircon forms fine-grained rounded grains. Some prismatic and stubby zircon crystals, however, are enclosed alkali feldspars.

In summary, criteria shown by plagioclase indicates that crystallization took place under disequilibrium magmatic conditions and that poikilitic quartz and alkali feldspars define late stage crystallization from infiltrating granite melt. Quartz ocellars observed in the groundmass suggest mechanical transfer of quartz into the mafic microgranular enclaves during the crystallization stage of both mafic and felsic magmas. The presence of large poikilitic crystals of hornblende and blade-shaped biotite flakes indicate that they were formed during late magmatic stages. Acicular crystals of apatite are rather suggestive of a rapid growth from a mafic magma undergoing high rates of under-cooling. Pyroxene crystals, however, represent relicts of the initial mafic magma.

GEOCHEMISTRY

Method: Major-element whole-rock analyses were carried out in the laboratories of the Egyptian Geological Survey, Cairo. Most of the trace elements were determined by XRF Philips PW 1450/20. Rare earth elements were carried out in Instrumental neutron

Table 1. Whole-rock chemical analyses of the granodiorite of Wadi Rahaba, southern Sinai, Egypt.

	HR3	HR6A	HR7	HR8	HR9	HR11	HR12A	HR13	HR14A	HR15A	HR17	HR18	HR19	HR25	HR26	HR27A	HR28	HR29	HR33	HR34	HR35
SiO_2	65.5	66.25	66.8	65.5	65.5	64.82	68.71	67.67	66.85	64.11	64.95	63.94	65.36	61.26	61.86	72.94	73.47	65.76	66.96	66.15	72.81
TiO_2	0.51	0.51	0.54	0.56	0.56	0.59	0.46	0.48	0.51	0.59	0.59	0.6	0.26	0.59	0.56	0.35	0.31	0.53	0.54	0.56	0.39
Al_2O_3	15.3	14.86	14.9	14.9	14.7	15.46	14.66	14.26	15.06	15.86	15.46	15.77	15.73	16.06	15.86	13.25	12.94	15.38	14.66	15.06	13.36
$Fe_2O_3^T$	4.25	4.25	4.25	4.6	4.6	4.66	3.44	3.85	3.95	4.66	5.12	4.87	4.27	5.06	4.67	2.03	1.86	4.01	3.96	4.87	2.04
MnO	0.07	0.07	0.07	0.08	0.08	0.08	0.06	0.08	0.07	0.07	0.08	0.07	0.06	0.08	0.07	0.04	0.04	0.07	0.07	0.07	0.04
MgO	2.02	1.96	1.95	2.23	2.23	2.32	1.47	1.8	1.96	2.18	2.23	2.22	2.08	2.5	2.22	0.5	0.5	1.82	1.8	1.85	0.79
CaO	4.07	4.3	3.46	4.07	3.84	4.22	3.08	3.15	3.46	3.99	3.61	4.07	4.03	6.13	5.96	1.96	2.05	4.22	3.84	3.81	1.97
Na_2O	3.4	3.32	3.35	3.32	3.4	3.32	3.16	3.32	3.32	3.48	3.4	3.39	3.34	3.48	3.44	3.53	3.55	3.45	3.48	3.48	3.59
K_2O	3.63	3.6	3.68	3.77	3.74	3.53	3.96	3.87	3.85	3.69	3.59	3.58	4.07	3.47	3.68	4.28	4.44	3.48	3.5	3.57	4.19
LOI	0.58	0.74	0.66	0.55	0.76	0.97	0.69	0.59	0.85	0.59	0.48	0.61	0.56	0.72	0.87	0.47	0.54	0.65	0.64	0.55	0.5
Total	99.3	99.86	99.6	99.6	99.4	99.97	99.69	99.07	99.88	99.22	99.51	99.12	99.76	99.35	99.19	99.35	99.7	99.37	99.45	99.97	99.68
Ga	13.4	16.6	16.5	17.9	12.2	18.1	16.2	16.2	13.1	15.0	20.0	14.6	15.5	15.7	18.0	11.1	13.7	16.6	12.4	16.7	12.5
Rb	107.2	121.6	127.7	116.0	116.1	109.5	135.6	137.9	139.4	113.6	118.5	114.0	115.4	103.5	112.9	139.3	146.9	110.6	119.5	119.1	139.8
Sr	623.6	599.1	621.1	610.5	618.2	631.2	631.9	447.7	502.1	574.8	623.3	633.4	632.8	601.9	635.0	191.5	202.0	532.6	508.2	493.0	181.9
Y	24.9	26.6	31.0	31.6	29.3	29.7	32.7	26.0	25.8	29.0	31.3	28.2	24.0	30.6	33.0	53.6	36.1	22.7	24.0	24.3	50.8
Zr	151.0	151.0	123.7	141.8	160.6	158.1	126.6	115.5	124.6	149.6	141.1	144.7	135.1	142.7	135.9	199.4	150.9	124.4	112.4	123.3	203.1
Nb	6.0	11.7	8.4	10.9	11.2	6.7	13.9	13.8	4.7	9.9	6.0	4.0	11.3	10.5	9.4	9.5	12.3	12.1	10.7	5.5	16.0
Ba	622.5	538.6	607.1	685.1	713.1	648.0	537.7	586.3	655.4	644.9	575.2	632.1	636.0	606.4	674.6	524.5	387.3	573.1	602.3	563.9	472.2
Th	1.3	3.5	19.0	0.0	6.4	0.0	0.0	28.9	14.1	11.1	16.6	4.1	12.6	8.0	16.9	31.9	16.9	0.0	12.5	16.0	2.1
U	4.0	0.0	21.3	2.2	0.0	0.0	0.0	4.7	5.0	0.0	3.7	6.1	13.9	0.0	5.6	16.7	12.9	0.0	14.2	11.9	0.2

Table 2. Whole-rock chemical analyses of the microgranular enclaves of Wadi Rahaba, southern Sinai, Egypt.

	E1-1	E1-2	E1-3	E1-4	E1-5	E1-6	E1-7	E1-10	E1-D	E1-E	E1-F	E15-C	E16-B	E19-B	E19-D	E20-B	E40-1
SiO_2	56.14	55.02	58.46	57.46	54.58	55.82	53.23	53.30	56.45	59.15	53.10	52.47	56.80	57.76	58.46	57.25	58.44
TiO_2	0.85	0.78	0.70	0.83	0.82	0.68	0.97	1.03	0.86	0.66	1.23	1.14	0.57	0.69	0.91	0.69	0.57
Al_2O_3	17.24	14.54	17.17	17.13	16.90	17.72	14.91	18.45	17.26	15.61	15.20	18.50	15.31	14.90	17.43	16.29	14.91
$Fe_2O_3^T$	6.61	7.83	6.02	6.10	6.95	5.99	8.50	7.81	6.87	5.08	8.72	6.07	5.10	5.82	4.28	5.96	6.33
MnO	0.16	0.28	0.13	0.14	0.17	0.16	0.28	0.15	0.16	0.18	0.18	0.18	0.15	0.18	0.14	0.17	0.18
MgO	4.98	7.02	3.77	3.85	5.26	4.70	7.62	4.56	4.67	5.08	8.76	6.02	5.10	5.83	4.28	5.49	6.06
CaO	6.53	7.90	6.03	6.15	7.18	7.37	8.70	6.65	5.95	7.42	6.64	7.53	5.82	6.43	5.78	6.66	7.10
Na_2O	3.85	3.34	4.06	4.13	3.98	4.13	3.31	4.62	4.28	4.10	2.54	4.52	3.04	3.29	4.27	3.70	3.71
K_2O	3.56	3.17	3.55	4.06	3.02	3.32	2.31	3.58	3.34	2.63	3.54	3.42	7.99	4.88	4.35	3.04	2.56
Total	99.93	99.87	99.90	99.85	99.14	99.87	99.83	100.15	99.84	99.90	99.91	99.85	99.88	99.88	99.90	99.33	99.86
Ni	21.6	111.0	16.9	17.3	37.1	28.0	89.8	20.9	23.6	27.6	159.4	24.3	67.4	55.6	22.0	37.8	41.7
Cu	44.7	24.9	46.8	28.2	8.7	32.5	13.4	0.0	38.5	16.4	50.9	14.1	11.5	39.6	33.1	23.0	13.0
Zn	76.1	83.3	68.0	76.7	78.8	67.3	110.9	80.2	75.8	71.4	129.5	82.0	59.4	82.3	77.8	71.8	74.5
Ga	16.9	15.4	17.1	16.9	17.1	19.6	18.7	20.4	15.5	15.6	14.9	18.5	11.9	15.2	18.2	14.9	16.5
Rb	128.1	97.4	110.0	148.2	112.0	98.0	97.4	146.4	131.5	79.2	145.7	126.8	162.7	136.1	172.6	72.2	66.1
Sr	405.4	388.9	614.5	477.4	450.9	559.5	468.1	474.1	409.6	491.8	412.8	529.7	567.1	448.8	542.9	485.1	429.8
Y	41.6	44.3	43.4	34.6	45.2	42.4	33.7	47.9	36.7	54.3	34.1	36.2	39.4	42.2	46.2	32.1	26.1
Zr	147.7	150.4	154.8	172.6	204.7	128.5	243.5	196.2	175.0	179.8	160.4	188.1	155.2	152.6	176.3	73.5	91.7
Nb	14.2	13.6	14.1	12.3	16.8	12.3	11.8	19.4	17.8	13.6	16.1	14.7	11.7	14.3	20.8	10.9	9.0
Ba	799.0	485.0	905.1	844.8	614.5	843.5	482.4	756.4	641.6	418.9	590.2	590.6	2470.7	1522.9	696.2	694.3	601.2
Th	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	5.7	11.4	1.7	1.7	10.0	0.0	0.0	2.4	0.0
U	8.0	0.0	2.7	0.0	0.0	6.9	0.0	8.4	0.0	25.9	0.0	0.0	7.2	3.8	2.4	0.0	0.0

activation analysis (INAA) technique (Atomic Reactor of the Technical University, Budapest).

Result: Seventeen rock samples from mafic microgranular enclaves and twenty one samples from the host country rocks have been analyzed for major and minor elements (Table 1 and 2). The mafic microgranular enclaves are chemically distinct from the host granodiorite. It is observed that the chemical composition of the granodiorite is rather homogeneous.

The SiO_2 contents of the enclaves range from about 46% to 57 % and lower than the SiO_2 contents of the host rock. Al_2O_3, CaO and Na_2O of the enclaves are higher and K_2O content is generally lower than the similar components of the granodiorite host. The higher Al_2O_3 and Na_2O in the mafic microgranular enclaves are related to the higher plagioclase content and higher CaO is effect of higher plagioclase and hornblende contents.

On the diagrams of silica vs. major oxides (Fig. 5), correlations are good for apparent for all these major oxides of the enclaves and host granodiorite with the exception of Na_2O, K_2O and Al_2O_3 which show scatter plot for the sample of enclaves. Na_2O in the granodiorite shows no clear trend relative to SiO_2, but Na_2O variation fall within a narrow interval between about 3% and 3.5%. All samples of granodiorite show linear negative correlation with SiO_2 except for K_2O. The femic oxides ($Fe_2O_3^T$, MgO, CaO and MnO) show well–defined, continuous negative correlation relative to the SiO_2.

Many trace elements do not show clear correlation with SiO_2 (Fig. 6). They are scattered off the trends defined by related granodiorite. The Rb plot displays notable scatter. Although a vague trend of increasing Rb with increasing SiO_2 is apparent for the granodiorite, while Rb abundances in the enclaves, show notable scatter plot. Nb abundances roughly increase relative to decreasing SiO_2, though in view of the scatter, the trend probably has little significance. Ga abundances in both enclaves and granodiorite are characterized by their scatter plot. Usually Th and U abundances of the enclaves are lower than the host granodiorite. The Y and Zr abundances vary widely in the enclave samples. It is observed that the Y and Zr abundances increase relative to decreasing SiO_2 although the scatter of values has little linear trend. The Sr plot is marked by curved pattern, and shows the maximum Sr amount at 60% SiO_2.

It is observed that the behavior of some major and trace elements relative to silica contents (Fig. 5 and 6), especially Al, Na, and K, confirms that chemical variations among micro-granular enclaves are not explained by magmatic differentiation processes. These chemical variations related mostly to hybridization resulting from a mingling process as suggested petrographically.

The Zr/SiO_2, Y/SiO_2, Nb/SiO_2 diagrams of Collins *et al.* (1982), shown in Fig. 6 indicates also

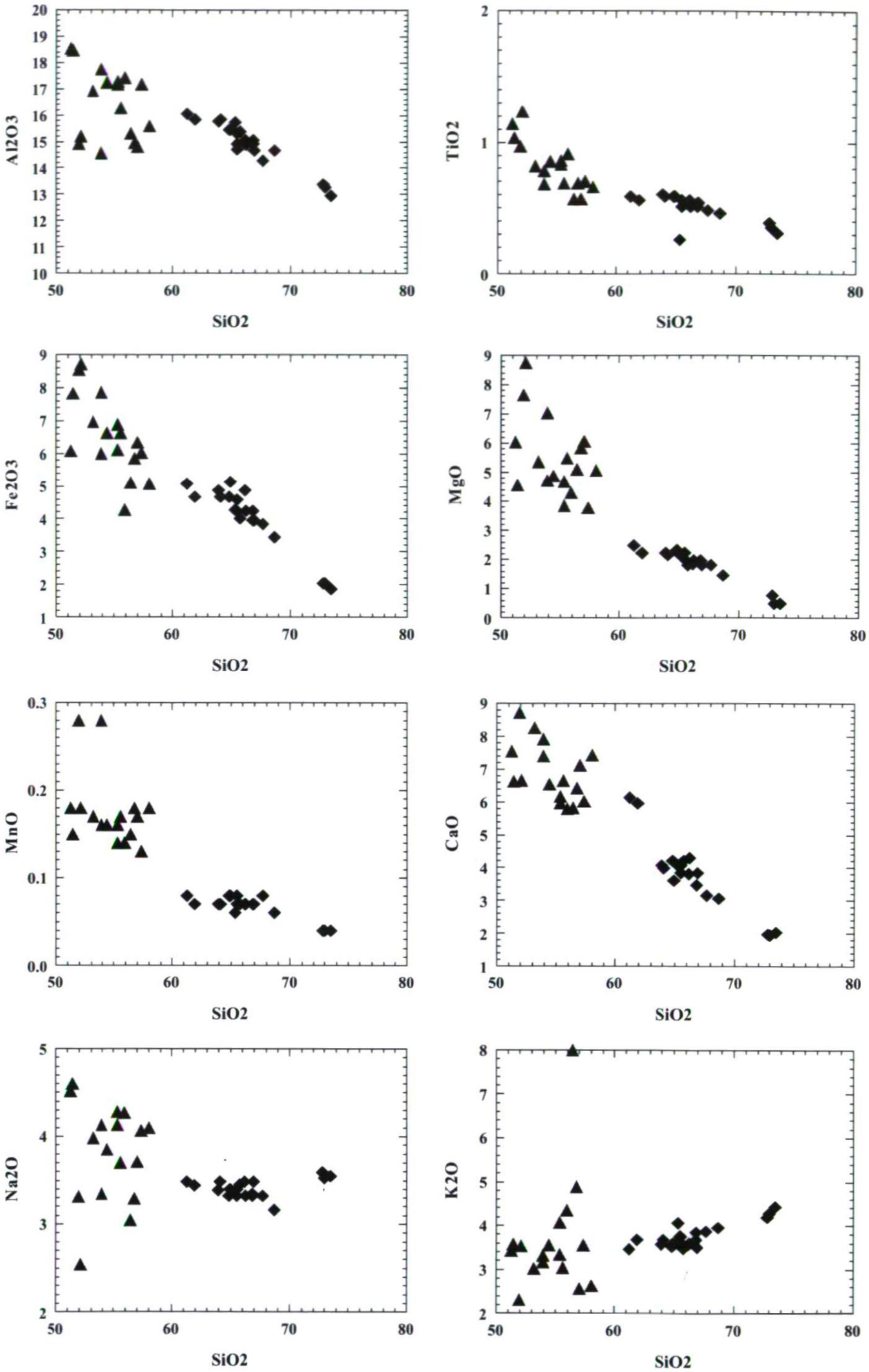

Fig. 5. Silica vs. major oxides variation diagram of the studied MMEs and host rock granodiorite samples. Symbols: (▲ Enclaves) and (♦ Host rock).

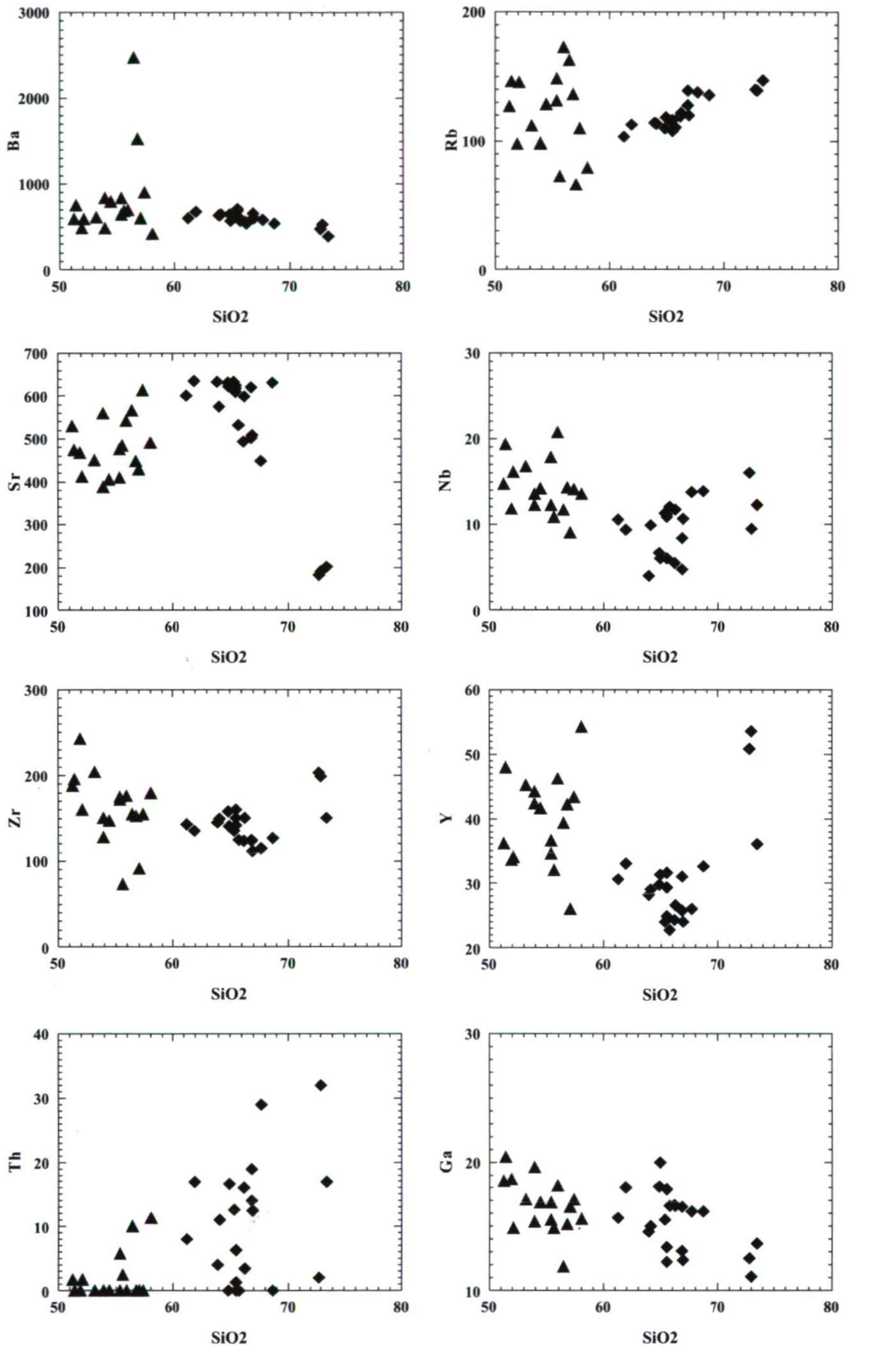

Fig. 6. Silica vs. trace elements variation diagram of both MMEs and host rock granodiorite samples.

that all the analyzed calc–alkaline granodiorite samples fall within the I-type granite field (Nb values are less than 21 ppm, Zr values are less than 250 ppm and Y contents are less than 55 ppm).

By using Shand index diagram (Fig. 7), it is evident that the host rock has meta-aluminous characteristics

Applying the diagram of Pearce et al. (1984) shown in Fig. 8 and 9, it is evident that the analyzed microgranular enclave samples occupy the subduction-related volcanic arc granite field (VAG) near the separating line of the (WPG) field.

By applying the diagram of Pearce et al. (1984) shown in Fig. 6, the analyzed granodiorite samples fall in the volcanic arc or syncollision granite field and occupy the same site of the enclave samples and still near the separating line of the (WPG) field.

On the diagram R1 vs. R2 (Fig. 10), it is evident that the host rock granodiorite and enclaves occupy the field of the pre-plate collision and post-collision uplift area.

Chemically (Debon and Le Fort 1982), the granitoid rocks are granodiorite , adamellite , and quartz monzodiorite . The majority of the analyzed samples lie within the granodiorite field.. According to Debon and Le Fort (1982) this cafemic association indicates a mantle–derived source.

White and Chappell (1977) suggested that linear trends on variation diagrams have been interpreted as evidence either of magma mixing or of restite unmixing.

However Wall et al. (1987) have shown that under certain conditions fractional crystallization can also generate linear trends. Dorais et al. (1990) reported that, if the compositional spectrum of enclave samples ranges from 46 to 57 wt% SiO_2, this will be related to fractional crystallization.

Discussion and Conclusions

It is worthy to mention that the present study revealed that the mafic microgranular enclaves, (MMEs) in the Egyptian granitoids needs more investigations in order to reach a new plateau in the understanding of their genesis and also to formulate a basic hypothetical model for their evolution.

The existence of MMEs within the granitoid rocks represents an important characteristic feature of the granitic magma and the petrogenesis of these enclaves is controversial. Various hypotheses have been advanced by several authors to explain the petrogenesis of these enclaves and their host granitic magma.

The enclaves are fragments of earlier mafic parental magma. The trapping or these basic fragments by acidic magma has been called magma mingling. The trapped basic magma was generally considered of mantle origin, (Clarke 1992), whereas the acidic magma may represent either products of crustal melting or residues from the differentiation of basic magma. Bailey (1984) suggested also that mafic microgranular enclaves and their host granites are hybrid rocks resulting from incomplete mixing and mingling of acidic and basic components. Clarke (1992) indicated also that continental arc metaluminous

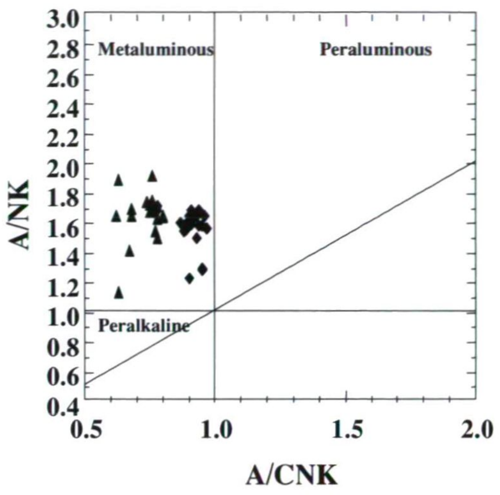

Fig. 7. Shand Index diagram for the studied MMEs and host rock granodiorite samples, (Maniar and Piccoli 1989). Symbols are the same than in the previous figures.

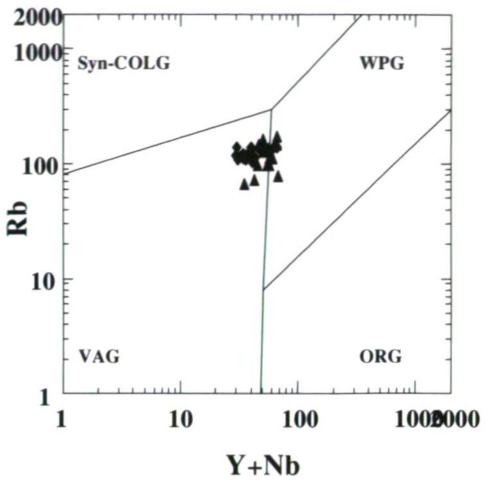

Fig. 8. Rb vs. Y+Nb tectonic diagram for the investigated host rock granodiorite, (Pearce *et al.* 1984).

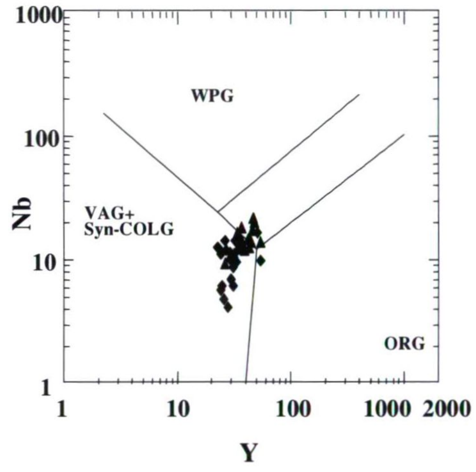

Fig. 9. Nb vs. Y tectonic diagram for the investigated host rock granodiorite, (Pearce *et al*, 1984).

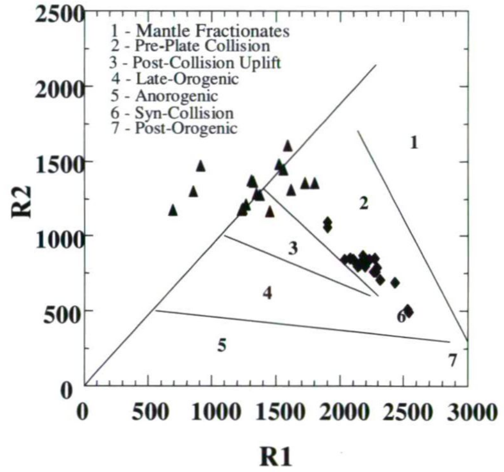

Fig. 10. R1 vs R2 diagram of the host rock granodiorite.

granitoids created by the partial melts of basaltic rocks that were previously derived from the partial melts of the mantle. Orsini et al. (1991) suggested that mixing involves thermal equilibration and various types of interactions between the two coeval magmas, such as material exchanges between the two components through either mechanical transfers of crystals or chemical transfers. During chemical transfer, the migration of alkali elements from the acid towards the basic components is recognized by chemical analyses.

Field relations revealed that the contact between enclaves and their host rocks is often marked by a chilled margin with no sign of solid state deformation.

Hybrid quartz diorite-granodiorite rocks are mesocratic to melanocratic in composition. They represent zones of mafic-felsic magma mixing. Hybrid quartz diorite-monzodiorite-granodiorite is exclusive to the granodiorite at the southwest of Wadi Rahaba. Their texture is porphyritic to equigranular showing growth textures compatible with magma mixing.

The hybrid zone is surrounded by granodioritic rocks. An important feature of the hybrid zone is that the mineral constituents of the granodiorite and the monzogranite show a good linear relationship, suggesting dynamics of a mafic magma batch. The hybrid zone is another type of mafic microgranular enclave, formed by magma mixing/mingling process where mafic magma is more abundant than granitic magma.

The interaction between magma and country rocks (assimilation) is also present. Although there could have been assimilation, there was little chance for chemical interaction. These are mostly unmodified rocks that show only scarce hornfels structure.

Bussy and Ayrton (1990) indicated that the quartz ocelli are result of the mechanical transfer of the quartz xenocrysts from the acid system into the more basic environment. The mingling process followed by mixing process. During the incomplete mixing process some igneous textures are developed in the enclaves, Hibbard (1995).

The microgranular enclaves neither contain andalusite, sillimanite, cordierite, garnet nor residual minerals formed from mica dehydration. There is no continuous variation in the meta-aluminosity from enclaves to granodiorite; so they do not represent restites.

Some of the MMEs contain quartz and plagioclase megacrysts of similar size and composition to those of the host rock, suggesting that these megacrysts have been mechanically transferred from the host granitic magma to the enclave.

There is no regular decrease in anorthite content of plagioclase from the granodioritic enclave to the host granite. This observation does not support fractional crystallization model, suggesting that the microgranular enclaves do not represent autoliths. The fine grain size of the studied enclaves than the host rock, the existence of double enclaves, the rounded and ovoid shapes of them, the complex oscillatory zoning of plagioclase phenocrysts in the granodioritic enclaves and the acicular apatite crystals found in the majority of enclaves, suggest that a mixing process between both mafic and felsic magma can be operated and the enclaves have been incorporated by the host granitic melt as magma globules.

The studied MMEs are enriched in biotite, the mafic magma had a higher water content, which enable it to remain liquid inside the granite magma and favored chemical mixing (Grasset and Albarede 1994). Biotite crystallized early during the fast cooling stage and was chemically re-equilibrated after the thermal equilibration, during the slow cooling stage of the basic magma inside the granite magma. Biotites from the cores and rims of the small granodioritic enclaves show some chemical differences suggesting that the rims have more fully equilibrated with the host rock

The textural features in the MMEs such as poikilitic K–feldspars and plagioclase, irregular poikilitic quartz patches, quartz ocelli rimmed by mafic minerals, skeletal relic plagioclase crystals, are all consistent with magma mixing process between felsic (host) and mafic (enclave) magma. The relic pyroxenes in the enclaves represent residual crystals of initial basic magma.

The important textural variations described for the granitoids at the outcrop scale reflect slow cooling and the presence of a volatile, which facilitates mineral growth. In the same way, biotite and amphibole indicate the availability of water and elevated pressure during crystallization. However, it is possible that not all crystals of amphibole are products of magmatic crystallization. In some crystals, commonly preserved relic patches of clinopyroxene, indicate late magmatic or post-magmatic crystallization replacement. Reactions involving water-rich fluids also include late magmatic overgrowth processes responsible for the replacement of pyroxene by green hornblende especially at the contact with the gabbroid rocks.

During magma mingling/mixing process, mechanical and chemical transfers developed from acidic to basic magma. A mafic magma intruded and mingled with the granite magma, which were partially crystallized, because phenocrysts of host granite were transferred to microgranular enclaves as xenocrysts. Quick crystallization took place due to the thermal contrast and mechanical mixing, which was important in the petrogenesis of granodioritic enclaves.

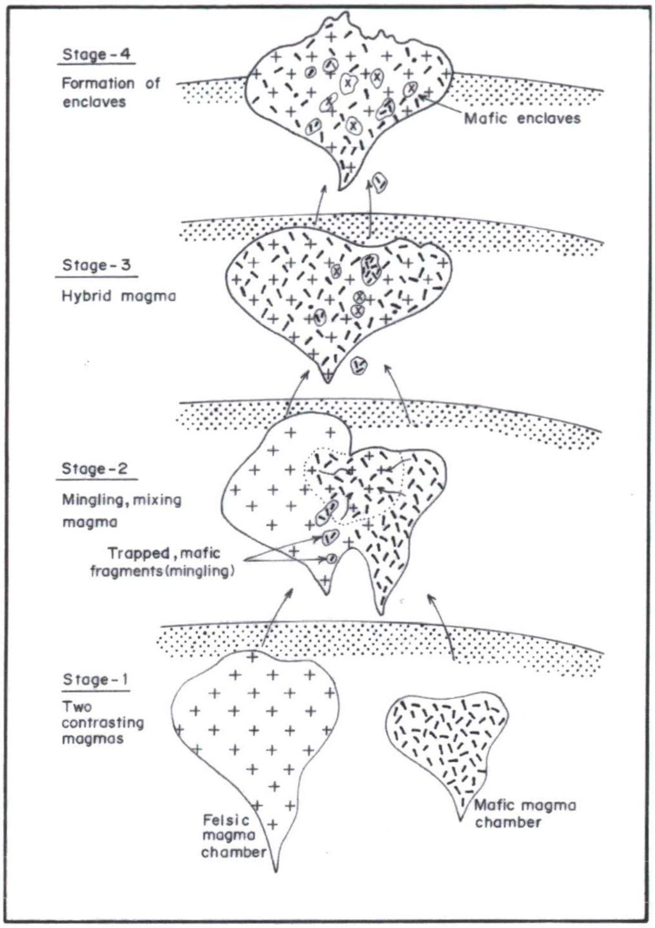

Fig. 11. Hypothetical diagram shows the evolution of the MMEs and their granodiorite host rock.

However, the differences in viscosity of the contrasting magmas, decrease the rate of the chemical mixing between them.

Evidence of disequilibrium are manifested in feldspars by oscillatory zoning, resorbed rims, mantling and punctuated growth, together with overgrowth of clinopyroxene/amphibole on quartz crystals, as well as the development of Fe–Ti oxides along clinopyroxene cleavages. According to Hibbard (1995) spongy cellular texture is formed as a result of dissolution or direct melting caused by reheating of a Ca-plagioclase component in more a felsic plagioclase composition. These observations suggest that the MMEs are derived from a hybrid-magma formed as a result of the intrusion of a mafic magma into the base of a felsic magma chamber, (Fig. 11.).

The higher contents of some major oxides (except SiO_2 and K_2O) and Nb, Y ratios in the enclaves related to the chemical transfer of trace and major elements.

Granodiorite is metaluminous, I–type, calc-alkaline in character. The enclaves have intermediate composition. They are classified as mafic microgranular enclaves on the basis of their dark color, grain size and textural properties. Petrographic and geochemical studies of the MMEs and their granodioritic host rock indicate that the latter is a product of partial melting and fractional crystallization of basic magma and that the MMEs are trapped blobs of basic magma in acidic magma. The mineralogical compositions of mafic microgranular enclaves are more or less similar to the granodioritic host rock but have different proportions of the mineral constituents.

The Y and Nb contents of the enclaves are generally higher than those of the host rock; these high contents are similarly explained by a chemical transfer of trace and major elements out of the acid component.

REFERENCES

AMMAR, S.E., ABDELWAHED, A.A., EL-HUSSEINY, M.O. (2003): Enclaves in the El-Delihimmi-Nusla granitic pluton, central Eastern Desert, Egypt; petrography, geochemistry and origin, Egypt. J. Geol., **47/2**, 583–596

BAILEY, J.C. (1984): Geochemistry and origin of hornblende–bearing xenoliths in the I–type Petford Granite, north–eastern Queensland. Aust. J. Earth Sci., **31**, 7–23.

BARBARIN B. (2005): Mafic magmatic enclaves and mafic rocks associated with some granitoids of the central Sierra Nevada batholith, California: nature, origin, and relations with the hosts. Lithos, **80**, 155–177

BARBARIN, B. (1986): Comparison of mineralogy of mafic magmatic enclaves and host granitoids, central Sierra Nevada, California, Abstracts with Programs-Geological Society of America 18 (1986), 83.

BARBARIN, B. (1988) Field evidence for successive mixing and mingling between the Piolard Diorite and the Saint Julien-la-Vêtre Monzogranite (Nord Forez, Massif Central, France). Canadian Journal of Earth Sciences, **25**, 49–59.

BARBARIN, B. DIDIER, J. (1991): Conclusions: enclaves and granite petrology. In: Didier, J., Barbarin, B. (Eds.): Enclaves and granite petrology, Elsevier, Amsterdam, 545–549.

BARBARIN, B. DIDIER, J. (1992): Genesis and evolution of mafic microgranular enclaves through various types of interaction between coexisting felsic and mafic magmas. Trans. R. Soc. Edinburgh Sci., **83**, 145–153.

BUSSY, F. AYRTON, S. (1990): Quartz textures in dioritic rocks of hybrid origin. Schweiz. Mineral. Petrog. Mitt., **70**, 223–235.

CASTRO, A., MERENO-VENTAS, I., DE LA ROSA, J. D. (1990): Microgranular enclaves as indicators of hybridization processes in granitoid rocks. Hercynian Belt, Spain. Wally Pitcher Conference, University of Liverpool, January 1990. Geological Journal, **25**, 391–404.

CASTRO, A., MORENO-VENTAS, I., DE LA ROSA, J.D. (1991): H-type (hybrid) granitoids: a proposed revision of the granite-type classification and nomenclature. Earth Sciences, **31**, 237–253.

CHAPPELL B. W. (1996): Magma mixing and the production of compositional variation within granite suites: Evidence from the granites of Southeastern Australia". J. Petrol, l449–470.

CLARKE, D.B. (1992): Granitoid Rocks. Chapman and Hall Publications, Hong Kong, 283.

COLLINS, W.J., BEAMS, S.D., WHITE, A.J.R., CHAPPELL, B.M. (1982): Nature and origin of A–type granites with particular reference to Southeastern Australia. Contrib. Mineral. Petrol., **80**, 189–200.

DAHLQUIST, J.A. (2002): Mafic microgranular enclaves: early segregation from metaluminous magma (Sierra de Chepes), Pampean Ranges, NW Argentina. Journal of South America Earth Sciences, **15**, 643–655.

DEBON, F. LE FORT, P. (1982): A chemical–mineralogical classification of common plutonic rocks and associations. Royal Soc. of Edinburg Transaction, **73**, 135–149.

DIDIER, J. (1973): Granites and their Enclaves, Elsevier, Amsterdam, 393.

DIDIER, J. (1973): Granite and Their Enclaves: The Bearing of Enclave on the Origin of Granites, Development in Petrology, 3, Elsevier, Amsterdam, 393.

DIDIER, J. (1984): The problem of enclaves in granitic rocks, a review of recent ideas on their origin. In: Xu, K.Q. and Tu, G.C. (eds.): Geology of Granites and their Metallogenetic Relations, Proceeding of International Symposium, Nanjing, October 1982, Science Press, Beijing, 137–144.

DIDIER, J. (1987): Contribution of enclave studies to the understanding of origin and evolution of granitic magmas. Geologische Rundschau, **79**, 41–50.

DIDIER, J. BARBARIN, B. (1991): The different types of enclaves in granites-Nomenclature. In: Didier, J. and Barbarin, B. (eds.): Developments in Petrology 13: Enclaves and granite petrology. Elsevier, Amsterdam, 19–24.

DODGE, F.C.W. KISTLER, R.W. (1990): Some additional observations on inclusions in the granitic rocks of the Sierra Nevada. Journal of Geophysical Research, **95**, 17841–17848.

DORAIS, M.J., WHITNEY, J.A., RODEN, M.F. (1990): Origin of mafic enclaves in the Dinkey Creek Pluton, Central Sierra Nevada batholith, California. J. Petrol., **31**, 853–881.

EL-METWALLY, A. A. (1993): Microgranular enclaves in the Pan African granites from the Sinai massif; petrography, mineralogy and geochemistry. J. Afri. Sci., **14**, 111–119.

EYAL, M. BARTOV, Y. SHIMRON, A. E., BENTOR, Y. K. (1980): Sinai geological map (1:500,000); Geological Survey of Israel.

GRASSET, O. ALBAREDE, F. (1994): Hybridization of mingling magmas with different denisties. Earth Planet. Sci. Lett., **121**, 327–332.

HASSEN, I. S. (1997): Mineralogy, petrology and geochemistry of granitiod rocks of St. Katherine area, South Sinai, Egypt. Ph.D. Thesis (Unpublished), Eötvös Lorand University, Budapest, Hungary, 83.

HIBBARD, M.J. (1995): Petrography to Petrogenesis. Prentice Hall, 587.

MAAS, R., NICHOLLS, I. A. LEGG, C. (1997): Igneous and metamorphic enclaves in the S-type Deddick Granodiorite, Lachlan Fold Belt, SE Australia: petrographic, geochemical and Nd-Sr isotopic evidence for crustal melting and magma mixing. J. Petrol., **38**, 815–841.

MANIAR, P. D. PICCOLI, P. M. (1989): Tectonic discrimination of granitoids. Geol. Soc. Am. Bull., **101**, 635–643.

ORSINI, J.B., CORCIRTA, C., ZORPI, M. J. (1991): Genesis of mafic microgranular enclaves through differentiation of basic magmas, mingling and chemical exchanges with their host granitoid magmas. In: Didier, J., Barbarin, B. (eds.): Developments in Petrology 13: Enclaves and Granite Petrology. Elsevier, Amsterdam, 445–464.

PEARCE, J.A., HARRIS, N.B.W., TINDLE, A.G.W. (1984): Trace element discrimination diagrams for the tectonic interpretation of granitic rocks. J. Petrol., **25**, 56–983.

SINHA, K. K., NAUTIYAL-KULDEEP, SHARMA, P.K., GUPTA, R.K. (2001): Petrochemical evidences of magma mingling and mixing in Bundelkhand Massif, Rajghat, Uttar Pradesh, Gondwana. Geological Magazine, **13**, 1–11.

SUROUR, A.A. KABESH, M.L. (1998): Calc-alkaline magmatism and associated mafic microgranular enclaves of Wadi Risasa area, southeastern Sinai, Egypt, Annals Geol. Surv. Egypt, V.XXI; 35-54.

TOBISCH, O.T., MCNULTY, B.A., VERNON, R.H. (1997): Microgranitoid enclave swarms in granitic plutons, Central Sierra Nevada, California. Lithos, **40**, 321–339.

VERNON, R.H. (1983): Restite, xenoliths and microgranitoid enclaves in granites. J. Proc. R. Soc. N. S. W., **116**, 77–103.

VERNON, R.H. (1984): Microgranitoid enclaves: Globules of hybrid magma quenched in a plutonic environment. Nature, **304**, 438–439.

VERNON, R.H. (1990): K-feldspar megacrysts in granites: Phenocrysts not Porphyroblasts. Earth Sci. Rev., **23**, 1–36.

VERNON, R.H. (1991): Interpretation of microstructures of microgranitoid enclaves. In: Didier, J., Barbarin, B. (Eds.): Enclaves and Granite Petrology, Elsevier, Amsterdam, 277–292.

VERNON, R.H., ETHERIDGE, M.A., WALL, V. J. (1988): Shape and microstructure of microgranitoid enclaves: indicators of magmatic mingling and flow. Lithos, **22**, 1–12.

WHITE, A.R. CHAPPELL, B.W. (1977): Ultrametamorphism and granitoid genesis. Tectonophysics, **43**, 7–22.

WINCHESTER, J. A. FLOYD, P. A. (1977): Geochemical discrimination products using immobile elements. Chem. Geol., **20**, 325-343.

WYLLIE, P.J., COX, K.G., BIGGAR, G.M. (1962): The habit of apatite in synthetic systems and igneous rocks. J. Petrol., **3**, 238–243.

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