GEOCHEMISTRY EVOLUTION AND ORIGIN OF THE FANOS GRANITE
(N. GREECE) – MAJOR AND TRACE ELEMENT MODELLING

by

G. Christofides, T. Soldatos and A. Koroneos

Authors’ address:
Department of Mineralogy - Petrology - Economic Geology,
School of Geology, University of Thessaloniki,
540 06 Thessaloniki, Greece
ABSTRACT

The Fanos granite, a Jurassic pluton composed of high silica, fine- to coarse-grained, slightly peraluminous calc- alkaline leucogranites, is associated with and intrudes the Mesozoic Guevgueli ophiolitic complex.

Major and trace element data establish a differentiation sequence, dominantly controlled by fractional crystallization rather than by partial melting processes. A fractional crystallization process has been tested by means of major and trace element modelling.

ΣREE decreases and Eu/Eu* increases with differentiation indicating that the REE behaviour is dominantly governed by feldspars and accessories (allanite, sphene, apatite, zircon). REE fractionation has been employed to test the results of major and trace element modelling. REE results are comparable to those obtained by trace rather than by major element modelling.

Major and trace element discriminant diagrams do not distinguish on the one hand between extentional and compressional environments and on the other hand between volcanic arc and collision related environments.

An igneous source material is suggested from mineralogy, geochemistry and whole rock oxygen isotopic compositions.

Two models, involving derivation of the Fanos granite magma by partial melting of graywacke or quartz diorite have been tested by comparing the distribution of Rb, Sr, Ba and REE in Fanos granite with the calculated hypothetical abundances in li-
quids originated by partial melting. The Fanos granite pattern matches very well the patterns of partial melts derived through melting of quartz diorite.
INTRODUCTION

The ophiolite complexes in Greece and Yugoslavia form two distinct NW-SE trending belts; the western ophiolite belt forming part of the Central Dinarides and Hellenides and the eastern belt which forms part of the Inner Dinarides and Hellenides (Nicolas and Jackson, 1972; Bebien et al., 1980; Karamata et al., 1980).

Part of the eastern belt is the Guevgueli complex which is situated in the Axios (Vardar) zone and is exposed both in Greece and Yugoslavia. The Guevgueli ophiolite in Greece is associated with and intruded by the Fanos granite (Fig. 1), a large intrusion of Upper Jurassic age (Borsi et al., 1966; Spray et al., 1984).

Up until now the geochemistry and evolution of the Fanos granite have only been partially studied (Bebien, 1982; Christofides et al., 1990). This paper deals with the petrology and geochemistry of the Fanos granite and reports major, trace and rare earth element and oxygen isotopic compositions from it attempting, through petrologic modelling, to contribute to the origin and evolution of the Fanos granite and to offer some additional knowledge for the understanding of the magmatism in the broader area.
REGIONAL SETTING

The Guevgueli complex occurs both in Greece and Yugoslavia and starting from Goumenissa (Kilkis, Central Macedonia, Greece) (Fig. 1) runs for a distance of about 60 Km northwards into Yugoslavia (Bebien, 1977, 1981, 1982). In Greece it comprises a migmatitic and gneissose basement and slivers of dismembered ophiolite thrust upon a Jurassic volcano-sedimentary sequence (Bebien, 1977; Spray et al., 1984). Due to a fault the complex is separated into two petrographically distinct units: Gabbroic cumulate rocks overlain by sills and lavas comprise the western unit which is characterized by very low K₂O contents and possesses a tholeiitic affinity. The eastern unit which is more varied is made up of gabbros, sheeted dykes (of calc-alkaline affinity), lavas and magmatic breccias (of tholeiitic character) comprising dolerites in a dioritic or granitic matrix (Bebien, 1977).

The complex is associated with and intruded by a granitic intrusion. The Yugoslavian part of this intrusion is known as the Gurnicet granite (Mercier, 1968) while the Greek part is the Fanos granite (Andronopoulos, 1965; Mercier, 1968; Tsamandourides & Pergamalis, 1977; Bebien, 1982).

The Fanos granite is an elongated intrusion occupying an area of about 65 Km². It comes in contact with the Guevgueli ophiolite causing contact metamorphism phenomena.

Based on stratigraphic and radiometric evidence (Borsi et al., 1966; Mercier, 1968; Marakis, 1969; Spray et al., 1984) an Upper Jurassic age has been proposed for the Guevgueli complex.
For the Fanos granite an age of 148±3 Ma was given (K-Ar on biotite separates) by Spray et al. (1984) which is very close to the 150±2 Ma date given by Borsi et al. (1966) using K-Ar and Rb-Sr methods on a biotite separate.

PETROGRAPHY

The petrography of the Fanos granite has in general been discussed by many investigators (Andronopoulos, 1965; Mercier, 1968; Tsamantourides and Pergamalis, 1977; Bebien, 1982). In this study the treatment of the granite will be restricted to a brief summary of the most pertinent features of the intrusion regarding its mineralogy and petrography.

The Fanos granite is a leucocratic rock with ferromagnesian minerals not exceeding 2 - 3 vol%. Although it is in general a homogeneous body, differences in grain size, and to a certain extent, in biotite content, make possible the distinction of three rock-types, namely aplitic granite, granite and microgranite. The modal composition of the Fanos granite is presented in Table 1 whereas Fig. 2 shows its classification based on the Q'/ANOR diagram of Streckeisen and Le Maitre (1979).

The aplitic granite is confined to the outer part of the intrusion especially at the western margin intruding the granite. Small exposures, however, are present in the inner part e.g. on the road from Piyi to Fanos. They are normally fine-grained, pinkish to whitish rocks containing virtually no ferromagnesian
minerals (only a few yellow-brown ragged flakes of biotite < 0.5 vol%). They consist of granular interlocking aggregates of quartz, K-feldspar and sodic plagioclase. K-feldspar (Or₉₃–₈₀Ab₇–₁₀) is perthitic and mostly kaolinized. Its microcline character is obvious. Plagioclase is of albite composition (3–12 An%) and is very often sericitized. As accessories occur apatite and zircon. Rare myrmecitic intergrowths, are present.

Molybdenite and pyrite mineralization mostly in the form of veinlets following microfaults and jointings, is associated with the aplitic granite at the western margin of the Fanos granite (Andronopoulos, 1965; Tsamandourides and Pergamalis, 1977).

Granite is the main rock-type of the Fanos intrusion. They are leucocratic, reddish to whitish (when altered), medium- to coarse-grained rocks. They appear slightly porphyritic with pinkish K-feldspar phenocrysts of up to 2 cm long in a medium-grained matrix. Most of the exposure of the granite is intensively altered towards a coarse-grained granitic sand. The main mineral constituents of the granite are quartz, K-feldspar, plagioclase and biotite. K-feldspars (Or₅₄–₅₈Ab₂₆–₁₂), very often kaolinized, occur both as phenocrysts and groundmass constituents. They are strongly perthitized with patchy and flamy forms. Very often they enclose small crystals of plagioclase in a poicilitic texture. Replacement of plagioclase and quartz by K-feldspar is not uncommon. Plagioclase is slightly zoned with an oligoclase core ranging from An₂₃ to An₁₃ and a more sodic rim (An₁₅ to An₈). Zones and core are often altered to sericite. Myrmecitic and graphic intergrowths are present. Biotite is the only
femic mineral (<2 vol%). It is yellow-brown to brown and is very often discoloured or altered to chlorite. Zircon with pleochroic haloes is a common inclusion in biotite. Apatite, sphene and allanite are present as accessories.

Microgranite occurs as small exposures mostly at the northern part of the Fanos granite and north of the old molybdenum mine. They are fine- to medium-grained rocks with pinkish K-feldspar phenocrysts of up to 2 cm long. They differ from the granite in that they are finer-grained and darker in colour due the greater amount of biotite (up to 3 vol%). Their contacts with the granite are not sharp. Mineralogically they are similar with the granite but allanite, apatite, sphene and opaques are more abundant here. Besides, plagioclase is more basic (core An$_{27}$, rim An$_{15}$) and biotite more magnesian (FeO/(FeO+MgO) in biotites from granite is about 0.53 while in biotites from microgranite is about 0.49). Feldspars are altered to sericite and kaolinite. Biotite encloses apatite and needle-like minute crystals of rutile (sagenite). Remnants of few crystals of hornblende have been found. They seem to change to biotite or to be absorbed by feldspars.

**ANALYTICAL TECHNIQUES**

Rock and mineral chemical analyses were carried out at the Department of Geology, University of Manchester, England. Mineral chemical analyses were obtained with a C.A.M.E.C.A. CAMEBAX
electron microprobe analyser using a Link System Model 860-500 Energy Despersive Spectrometer and employing a ZAF correction program. Operating conditions were 15 kV accelerating potential and 3 nA beam current.

Whole rock samples were analysed by X-ray fluorescence for major and trace elements on powder pellets using a Philips model PW 1450 spectrometer. Rare earth elements were determined by ICP method in King's College, London University. FeO by wet method and ignition loss have been determined in the Department of Mineralogy, Petrology and Economic Geology, Thessaloniki University. Oxygen isotopic analyses were carried out at the Oxygen Isotopic Laboratory, Department of Geology, Case Western Reserve University, Cleveland, Ohio.

GEOCHEMISTRY

Major and trace element chemical analyses for twelve samples along with their CIPW norms, Thorton & Tuttle's (1960) differentiation index (D.I.) and other elemental ratios are listed in Table 2 while the abundances of REE for selected samples are presented in Table 3. Selected variation diagrams for major and trace elements are shown in Fig.3 and Fig. 4 respectively. Variation in REE abundances are depicted in Fig. 5 to 7.
Major elements

Variation in major element chemistry shows a continuous trend typical for magmatic differentiation. Thornton and Tuttle's (1960) index used to express the chemical variations within the plutonite ranges from 87.0 to 95.6.

With increasing D.I. the alkalies contents are almost constant although K₂O decreases slightly. This is due very probably to the early crystallization of biotite. TiO₂, Al₂O₃, FeO, MnO, MgO, CaO and P₂O₅ decrease with differentiation.

Compositional characteristics

The major element abundances of the samples analyzed show affinities of calc-alkaline magmatism. Their calc-alkaline character is obvious from their "liquid" evolution (Fig. 3) as well as from the Anderson's et al. (1980) SiO₂ vs. FeOₓ/(FeOₓ+MgO) diagram (not shown).

The Fanos granite is slightly peraluminous with molar A/CNK ratio within the range 1.00-1.08 and displays I-type characteristics after Chappell and White's (1974) and White and Chappell's (1977, 1983) criteria although some S-type characteristics (see below) also exist. On the Q-Ab-Or diagram (not shown) of White et al. (1977), however, the rocks studied plot on the I-type field.
a) High SiO₂% content with small variation (S-type)
b) Na₂O > 3.25% (I-type)
c) Low CaO% content (0.91%) (S-type)
d) Al₂O₃/(CaO+Na₂O+K₂O) < 1.1 mol. proportions (I-type)
e) Normative corundum < 1% for most specimens (I-type)
f) Linear trends in variation diagrams (I-type)
g) Muscovite low or absent, sphene present and apatite inclusions in biotite (I-type)
h) Mo mineralization (I-type)

It is concluded therefore that the origin of the Fanos granite is associated possibly with source material of igneous character although the participation of a sedimentary source material cannot be excluded.

Trace elements

The trace element contents decrease in general towards the more evolved rocks except Rb and Nb (Fig. 4). The compatible elements Ba, Sr, Zr, Zn and V decrease drastically with a depletion factor of 30, 15, 5, 7 and 7 respectively considering the mean values of the rock types. Rb is almost stable with a slightly concave pattern and Nb increases slightly with an enrichment factor of 1.6. K/Rb ratio remains rather constant around the "normal" values (K/Rb ≈ 150) of Taylor (1965).
REE

Five representative samples were analysed for REE. The results are presented in Table 3 along with ΣREE and some useful ratios. REE concentrations are plotted chondrite normalized (Nakamura, 1974) in Fig. 5. The ΣREE ranges from 91.8 to 249.3 ppm and decreases with increasing SiO₂. The LREE are enriched and more fractionated relative to the HREE with a slope (La/Lu)ch varying from 10.1 to 22.3. The REE patterns are very similar implying a common origin for all the analysed rocks. All rocks have negative Eu anomalies (Eu/Eu*=0.49-0.76) which if expressed as Eu/Sm ratios (Table 3), show that the rocks belong to the group with small to moderate Eu anomalies (Henderson, 1984).

The Eu-Sr variation (Fig. 6) shows that a very close positive correlation (correlation coefficient r=0.98) exists between these two elements.

EVOLUTION FOR THE FANOS GRANITE

1. The evolution process

Several evidence suggest that the main process which controlled the evolution of Fanos granite was the fractional crystallization of a parental magma. Field relations between rock types support such a process; the most differentiated rock type, the aplitic granite, intrudes the granite.
The study of the trace element variations can help to evaluate this suggestion. In particular Rb, Sr and Ba are very useful for the evaluation of fractional crystallization process in granitic rocks because their behavior in these rocks is strongly tied to the major minerals (feldspars, micas) in them (McCarthy, 1976; Neiva et al., 1987).

The extreme variation in compatible elements (e.g. Ba, Sr) and the small variation in incompatible ones (e.g. Rb, Nb) of the Fanos granite is consistent with fractional crystallization as the main differentiation process and excludes partial melting (Hanson, 1978; Maaløe, 1985; Cocherie, 1986; Christofides et al., 1989; Christofides et al., 1990; Soldatos et al., in preparation).

To model the hypothesis of fractional crystallization for the evolution of Fanos granite a least squares petrographic calculation program, GENMIX, designed by Le Maitre (1981) has been employed. The average major element compositions of the three rock types, A, B and C (Table 2) have been used. Rock A corresponds to the average composition of the microgranite, rock B to the average composition of the granite and rock C to the average composition of the aplitogranite. Rock A is the least differentiated type of the pluton and therefore it is considered as the parental magma.

Two methods of computation were used. Method 1 attempts to model a simplified differentiation process where rock C derives directly from rock A. In Method 2 the evolution process is considered to progress step-wise along the types of the pluton: So,
rock A is the parental magma for rock B and the latter is the parental magma for rock C.

2. Fractionated minerals

The chemical variation of the trace elements can help to determine the mineral assemblage of the cumulates which control the fractional crystallization. In both step one (from A to B) and step two (from B to C) Sr decreases indicating mostly plagioclase separation, while the continuous decrease of Ba shows K-feldspar and/or biotite separation. Significant amount of plagioclase is also supported by the negative Eu anomalies (Table 3). The decrease of Rb from A to B reveals the participation of biotite in the cumulate. In contrast its slight increase during differentiation from B to C excludes biotite from consideration as fraction mineral at this step. The slight increase of Rb/Sr ratio at step one suggests plagioclase fractionation. The strong increase, however, of this ratio during the second step reflects very probably the absence of biotite from the cumulative minerals. The increase of K/Ba ratio at step two is the result of K-feldspar separation while the decrease of K/Rb ratio excludes biotite as a cumulative phase.

The good correlation between Eu and Sr suggests that the Eu fractionation is effectively caused by Eu²⁺ which is geochemically strongly coherent with Sr. Since the partition coefficients for Sr and Eu are >1 only for plagioclase and K-feldspar among
the major rock-forming minerals (Schnetzler & Philpots, 1970; Nagasawa & Schnetzler, 1971), the observed trend implies that feldspars are the main minerals controlling the magma differentiation in the pluton (cf. Petersen, 1980).

The ΣREE decreases with increasing SiO₂ (Fig. 7). As it is well known (cf. Gromet & Silver, 1983; Boztug et al., 1984) the REE content of granitoid rocks is essentially controlled by the accessory minerals. Thus, the decrease of ΣREE with SiO₂ in Fanos granite probably reflects the decrease of the abundances of such minerals (allanite, apatite, sphene and zircon) in the more evolved types. Actually, the weight fractions of these minerals were estimated in microgranites and aplitic granites. Zircon and apatite abundances were calculated from the average concentration in these rocks of Zr and P₂O₅ respectively (Table 2). The modal amounts of allanite and sphene were estimated by point counting of representative thin sections and were corrected for density differences to calculate the mineral weight fractions. Therefore the weight percentages of the accessory minerals in microgranites and aplitic granites were found:

<table>
<thead>
<tr>
<th></th>
<th>Allanite</th>
<th>Apatite</th>
<th>Sphene</th>
<th>Zircon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microgranite</td>
<td>0.0023</td>
<td>0.0037</td>
<td>0.0056</td>
<td>0.0006</td>
</tr>
<tr>
<td>Aplitic granite</td>
<td>-</td>
<td>0.0010</td>
<td>-</td>
<td>0.0001</td>
</tr>
</tbody>
</table>

A distinct decrease of these accessory minerals from microgranite to aplitic granite is observed.

So, allanite, apatite, sphene and zircon are responsible for
the progressive depletion of REE with fractionation. This deple-
tion is obvious for all REE but considering LREE, MREE and HREE
groups the depletion rate differs. In particular although LREE
(La-Nd) decrease they are getting enriched relative to the MREE,
the slope of (La/Sm)_c increaseing from 9.2 in FP4 to 13.4 in F5.
The largest fractionation is noted in MREE (Pm-Ho) while HREE
(Er-Lu) show only a slight depletion. It is known from the
literature (Gromet & Silver, 1983; Henderson, 1984) that allanite
controls mainly LREE, apatite and sphene MREE (with plagioclase
effecting only Eu) and zircon HREE fractionation. Having the
above considerations in mind we can propose the followings to in-
terpret the observed patterns.

i) Comparing the LREE/MREE fractionation and considering the
large Kd values of LREE for allanite and the smaller ones of MREE
for apatite and sphene we can assess that a significantly larger
amount of apatite and sphene relative to allanite is separated in
the residue. Comparable quantities of these minerals in the
residue would have resulted in a large decrease of (La/Sm)_c ratio, a fact that comes in contrast with the observed increase.
Hence only minor amount of allanite relative to apatite and
sphene in the residue could explain the observed distribution.

ii) The slight HREE fractionation indicates that zircon
crystallization was of minor importance.

The relatively larger amount of apatite and sphene in rela-
tion to allanite and zircon as crystallizing phases could be a
good explanation for the observed concave patterns. Similar pat-
terns of the Cheddar granite were explained by Wu (1984) as the
result of a volatile HREE-rich residual fluid autometasomatizing the partly crystallized granite and partially modifying an earlier magmatic signature.

MAJOR AND TRACE ELEMENT MODELLING

Major elements - Method 1

To calculate the amount and mineralogical composition of the cumulate during the differentiation from the parental magma A to the liquid C the chemical analyses of rocks A (A obs.) and C were used as input data (Table 4). As crystallizing mineral phases were used K-feldspar, biotite and sphene of sample FP1 (Table 4) and albite, anorthite and magnetite (analyses 1 and 8, Table 31 and analysis 4, Table 46 respectively after Deer et al., 1978). All analyses were used without MnO, P2O5, LOI and with total iron as FeOt.

Output data are the amounts of the residual liquid and crystallizing phases (cumulate), the computed "parent" composition (A calc.), the differences (d) between the actual and computed values of parent melt and the sum of the squared differences ($\Sigma d^2$) (Table 4). For the proposed model the d values are very small.

With this model rock C derives from rock A with 32% crystal accumulation. The mineralogical composition of the residual solid is 38.1% K-feldspar, 45.1% plagioclase (An41), 14.2% biotite,
0.6% sphene and 2.1% magnetite.

**Major elements — Method 2**

For a better estimation of the evolution process in the Fanos intrusion two steps should be considered along the series. First, liquid B derives from the parental magma A with crystal accumulation of Solid 1 (Table 5). Second, liquid B is considered as parental for liquid C by crystallization of Solid 2. The computation procedure is the same with Method 1 and has been applied twice. The minerals used in Method 2 are the same as in Method 1.

For Step 1 the percentage of crystallization is 21% with Solid 1 composed of 31.1% K-feldspar, 51.3% plagioclase (An₄₀), 15.6% biotite, 0.2% sphene and 1.8% magnetite. For Step 2 the amount of Solid 2 is 14% comprising 59.6% K-feldspar, 33.0% plagioclase (An₄₀), 3.0% sphene and 4.4% magnetite.

**Trace elements other than REE**

Major and trace element trends have indicated that fractional crystallization was the dominant evolution process. Trace element modelling substantiates this conclusion and excludes partial melting as a differentiation process.

In trace element modelling Method 2 results are used. The distribution of trace elements during fractional crystallization
is examined using the Rayleigh fractionation law and the modal composition of various crystal fractions derived from the major element mixing calculations. Using the mineralogical composition of the residual solid (Method 2, A to B and B to C) and Kd partition coefficient values for dacitic and rhyolitic rocks (Nash & Crecraft, 1985) the bulk partition coefficient D values were calculated for Rb, Sr, Ba and Nb.

To test the results of major element model (Method 2) compatible – incompatible element diagrams were made (Hanson, 1978; Robb, 1983; Maaløe, 1985). In particular Rb-Sr, Rb-Ba, Nb-Sr, Nb-Ba (not shown) as well as Rb/Sr-Sr, Rb/Ba-Ba, Nb/Sr-Sr and Nb/Ba-Ba (Fig. 8) were used. On the F.C. curve representing the fractions of hypothetical residual liquids derived from rock A by 0-21% crystallization (F=1.0-0.79) and describing Step 1 (A to B) are depicted. For Step 2 the hypothetical liquids derived from rock A by 21% fractional crystallization (F=0.79) is used as parent liquid (F=1.0) for rock-type C.

The results of method 2 (Step 1:A to B, Step 2:B to C) are tested by using the same Kd values for the mineral assemblages of Solid 1 and 2. The trace element models indicate that for Step 1 and 2, 10-20% and 14-28% fractional crystallization is needed to produce the trace element concentration of rock B and C respectively instead of 21% and 14% computed from the major element models. Such discrepancies; about 10%, are observed also by Petersen (1980).

The major element chemical variations observed in the Fanos granite can also be explained by a partial melting process. To
confirm the fractional crystallization process and exclude partial melting as a possible differentiation process, some discussion on the last process, using a fusion model, is presented. In case of partial melting liquids C and B derive from a solid source having the composition of rock A by increasing amounts of melting. Steps A to C and A to B are described in Methods 1 & 2 respectively. Therefore 68% partial melting of A is needed to form rock C with a residue having a modal composition same as the residual solid of Method 1, while 79% partial melting of A is needed to give rock B leaving a residue same as Solid 1 (Method 2). Assuming bulk partition coefficient (D) and source element concentrations (Co) are the same for both processes (fractional crystallisation and partial melting) we have also constructed the partial melting trend (P.M) in figure 8. This trend represents the fractions of hypothetical residual liquids derived by partial melting of rock A. Obviously Fanos trace element abundances match better with trends and fractions of residual liquids of fractional crystallization. Moreover, the compatible elements Sr and Ba are depleted from 464 to 31 ppm and from 851 to 28 ppm respectively (Table 2). If partial melting would control the differentiation, to create such a depletion, the D values for Sr and Ba should have been 44.7 and 92.9 respectively. These values, however, are extremely high, even if we assume the highest Kds from the literature for the crystallizing phases. Consequently fractional crystallization rather than partial melting is the differentiation process.
REE

Here REE fractionation is used to test the results of major and trace element modelling with method 2 where 10% differences in F value exist. By means of the Rayleigh fractionation law and using the REE concentrations of the parental magma A as C₀ and the REE concentrations of rock C (Table 3) as C₁, the bulk partition coefficient values D for F=0.68 of each element were calculated. The patterns of hypothetical liquids for F=0.6-0.9 and the patterns of rock-types A, B and C are depicted in Fig. 9. The pattern of rock B is comparable with that of a liquid derived from liquid A by 10% fractional crystallization. This is in accordance with the result calculated from the trace element model rather than that from major elements.

Using Kd values of REE for the essential and accessory mineral constituents (Henderson, 1982, 1984) and D values as calculated above and knowing that the accessory minerals allanite, apatite, sphene and zircon are mainly responsible for the observed patterns, we have estimated their proportions in the cumulate (0.0009/0.0080/0.0270/0.0004) having solved a system of linear equations using as unknowns the quantities of the accessory minerals. The calculated proportions are consistent with the conclusion drawn from the REE distribution patterns. Actually apatite and sphene are much more than allanite and zircon.
TECTONIC SETTING

The Fanos granite is considered as a collision granite (Bebien, 1982; Pearce et al., 1984). On the trace element discrimination diagrams (Y vs. Nb and Rb vs. Y+Nb) of Pearce et al. (1984) the samples analyzed plot either in the VAG+synCOLG (volcanic arc granite+syncollision granite) field (Fig. 10a) or cluster around the VAG-synCOLG discriminant boundary (Fig 10b).

In the volcanic arc and the syn-collision fields can also plot the post-collision granites. Syn-collision and post-collision granites can be separated by the Rb/Zr ratio. The former have higher values compared to the latter. On the Rb/Zr – SiO2 diagram (Harris et al., 1986) the samples analyzed plot in the field for volcanic arc and post-collision granites (Fig. 11). Volcanic arc and post-collision granites have similar geochemical features and they cannot separate with this diagram. Other diagrams (Rb-Ta-Hf after Harris et al., 1986) can help towards this direction but unfortunately Ta and Hf are not available to us. Taking, however, into account Bebien's (1977, 1982) suggestions we can conclude that the Fanos granite is related with a post-collision plate tectonic environment.
ORIGIN AND PETROGENESIS OF THE FANOS GRANITE

Oxygen isotopic results

Two oxygen isotopic analyses on whole-rock samples (F5 and MD1) gave δ¹⁸O values 7.11 and 8.03 per mil respectively which are consistent with those of "isotopically normal" granitic rocks of Taylor (1978). Although the number of samples analyzed is insufficient to give reliable results, the δ¹⁸O values obtained show an igneous source origin (cf. O'Neil et al., 1977) which is in accordance with the results obtained from mineralogy and geochemistry.

Magma sources

Taking into account the geotectonic environment, the relation of the Fanos intrusion to the Guevgueli complex and the I- or S-type character of it we can assume that the Fanos granite originated from a) the differentiation of the basic magma from which the ophiolitic suite has been derived, b) partial melting of metasedimentary rock (graywacke) and c) partial melting of igneous rock of quartz diorite composition.

Bebien (1982) considers that although the Fanos granite is associated with the ophiolitic rocks of the Guevgueli complex, it is not related with the magmatism that gave the ophiolites. He suggests that the Fanos granite originated in a "mobilized" crust
which is intruded by the magma that gave the ophiolitic sequence.

Model of partial melting of graywacke and quartz diorite

Two models are presented here involving derivation of Fanos granite from crust using graywacke and quartz diorite as source material. These are tested by comparison of the distribution of trace elements and REE (Tables 2 and 3) in Fanos granite with the calculated hypothetical abundances of liquids originated by partial melting.

The composition of the "parental" source is assumed to be that of graywacke (average composition, column a) and quartz diorite (sample 259) referred in Tindle & Pearce (1983) for major element, Rb, Sr, Ba and REE concentrations. The partition coefficients used are those determined for minerals of dacitic and rhyolitic rocks (Henderson, 1982).

A calculation of the hypothetical composition of the residual material, expressed as a mesonorm, was done for a partial melt with the composition of the least differentiated Fanos rock-type A. The mineralogical composition of such a residuum is a) 40% quartz (Qz), 25% plagioclase (An37), 15% biotite (Bi), 10% orthopyroxene (Opx) and 10% garnet (Gr) (Qz0.40Pl0.25Bi0.15Opx0.10Gr0.10) for 20% partial melting of graywacke and b) 7% quartz (Qz), 40% plagioclase (An36), 22% biotite, (Bi) 30% hornblende (Hb) and 1% magnetite (Mt)
(Q20.07Pl0.40Bi0.22Hb0.30Mt0.01) for 20% partial melting of quartz diorite.

For trace elements the model employed involves equilibria during separation of melt fractions (Hanson, 1978, equation 10). The patterns of partial melts in equilibrium with the computed residual solids for different amounts of melting (F=0.1-0.4) of a hypothetical graywacke and quartz diorite source as well as the pattern of Fanos granite are depicted in Fig. 12.

Fig. 12A shows that the trace element and REE patterns of rock-type A of Fanos granite is not comparable to those of melts derived from melting of graywacke. The melts have lower Rb, Ba, Sr, higher LREE and MREE and lower HREE abundances. Also graywacke compositions from Haskin et al. (1966), Wedephol (1968) and Arth & Hanson (1975) have been used for modelling but the inconsistencies are even greater.

On the contrary Fanos granite pattern matches very well the patterns of the partial melts derived from melting of quartz diorite (Fig. 12B).

CONCLUSIONS

The Fanos granite, a leucocratic intrusion composed of aplitic granite, granite and microgranite, is associated with and intrudes the Quevguelli ophiolites.

The rocks analyzed are slightly peraluminous with Al2O3/(CaO+Na2O+K2O) molar ratio ranging between 1.00 and 1.08
and show calc-alkaline affinities and I-type characteristics.

Major and trace element behaviour suggest that fractional crystallization rather than partial melting is the differentiation process for the evolution of the Fanos granite.

The REE patterns are slightly concave and display LREE enrichment, while ΣREE decreases and Eu/Eu* progressively increases with differentiation. REE behaviour is controlled mainly by feldspars and accessories (allanite, sphene, apatite, zircon).

A fractional crystallization process has been tested by means of major and trace element modelling. A two-step major element model requires 21% and 14% fractional crystallization from microgranite (liquid A) for the derivation of granite (rock B) and aplitic granite (rock C) while the trace element model requires 10-20% and 14-28% respectively for the same rocks. To test the results of major and trace element modelling REE fractionation has been used. REE modelling requires about 10% fractional crystallization of a liquid A for the production of rock B. The F value for rock B coincides with the one calculated from the trace element model rather than that from major elements.

The δ¹⁸O values of whole rock, measured on two samples, range between 7.11 and 8.03 per mil, are consistent with those of "normal δ¹⁸O granitic rocks" and are similar to those considered to be derived from a source material of an igneous origin.

Two models involving derivation of Fanos granite magma from graywacke or quartz diorite have been tested by comparison of the distribution of Fanos Rb, Sr, Ba, and REE concentrations with the calculated abundances of these elements in hypothetical liquids
originated by partial melting. The Fanos granite pattern matches very well the patterns of partial melts derived through melting of quartz diorite.

ACKNOWLEDGEMENTS

We would like to express our thanks to Prof. J. Zussman, Head of the Dept. of Geology, Univ. of Manchester, for providing chemical facilities during the stay of two of us (G.C. and T.S.) in Manchester. We are also grateful to J. Esson and G. Elefteriadis for helpful discussions, to D. Plant, P. Lythgoe and T. Hopkins for analytical assistance and to P. Tsamandourides, Director of I.G.M.E., Thessaloniki Branch, for providing many facilities during field work. The authors thank also A. Tsiram-bides for carrying out the oxygen isotope analyses.
References


ARTH JG, HANSON GN (1972) Quartz diorites derived by partial melting of eclogite or amphibolite at mantle depths. Contrib Mineral Petrol 37: 161-174


BEBIEN J (1982) L’ association ignée de Quevgueli (Macedoine Greque), expression d’une magmatisme ophiolitique dans une dechirure continentale. These d’ Etat, Nancy (unpubl.): 470 pp


HANSON GN (1978) The application of trace elements to the petrogenesis of igneous rocks of granitic composition. Earth Planet Sci Lett 38: 26-43
IUGS (1973) Classification and nomenclature of plutonic rocks. N Jb Miner Mh 4: 149-164
(Spec Iss Tethyan Ophiolites) 1: 105-125

LE MAITRE RW (1981) GENMIX - A generalized petrological mixing model
program. Computers & Geosciences 7: 229-247

MAALØE S (1985) Principles of Igneous Petrology. Springer Verlag, Berlin,
374 pp

Ann Geol Pays Hell 21: 121-152

McCARTHY TS (1976) Chemical interrelationships in a low pressure
granulite terrain in Namaqualand, South Africa, and their bearing on
granite genesis and the composition of the lower crust. Geochim
Cosmochim Acta 40: 1057-1068

MERCIER J (1968) I-Etude geologique des zones internes des Hellenides en
Macedoine centrale (Greece). II- Contribution a l'etude du metamorphism
et de l'evolution magmatique des zones internes des Hellenides. Ann
Geol Pays Hell 20: 1-792

NAGASAWA H, SCNETZLER CC (1971) Partitioning of rare earth elements
between phenocrysts and acidic igneous magma. Geochim Cosmochim Acta
35: 953-968

NAKAMURA N (1974) Determination of REE, Ba, Fe, Mg, Na and K in
carbonaceous and ordinary chondrites. Geochim Cosmochim Acta 38: 757-
775

NASH WP, CRECRAFT HR (1985) Partition coefficients for trace elements in

NEIVA ANR, NEIVA JMC, PARRY SJ (1987) Geochemistry of the granitic rocks
and their minerals from Serra da Estrela, Central Portugal. Geochim
Cosmochim Acta 51: 439-454

NICOLAS A, JACKSON ED (1972) Repartition en deux provinces des peridotites
des chaines alpines longeant la mediterranee: implications


SOLDATOS T, KORONEOS A, CHRISTOFIDES G (in prep.) Trace and REE modeling for the origin and evolution of the Fanos granite (N. Greece). :


WHITE AJR, CHAPPELL BW (1977) Ultrametamorphism and granitoid genesis. Tectonophysics 43: 7-22


FIGURE CAPTIONS

Fig. 1. Geological map of part of the Guevgueli complex showing the Fanos granite. Simplified from Tsamandourides and Pergamalis (1977) and Bebien (1982). 1, Granite; 2, Aplitic granite; 3, Microgranite; 4, Migmatites; 5, Ophiolites; 6, Thrust; 7, Fault.

Fig. 2. Normative composition of samples analyzed. Classification scheme is after Streckeisen and Le Maitre (1979). Numbered fields correspond to the QAP fields of IUGS (1973).

Fig. 3. Major element variation diagrams for the Fanos granite. Symbols as in Figure 2.

Fig. 4. Trace element variation diagrams for the Fanos granite. Symbols as in Figure 2.

Fig. 5. Chondrite-normalized REE patterns for selected samples from Fanos granite.

Fig. 6. Eu vs. Sr variation diagram for selected samples from Fanos granite. Symbols as in Fig. 2.

Fig. 7. ΣREE vs. SiO2 variation diagram for selected samples from Fanos granite. Symbols as in Fig. 2.
Fig. 8. Incompatible/compatible element ratios vs. compatible element diagrams. Open circles, Fanos samples; filled circles, mean compositions of microgranite (A), granite (B) and aplitic granite (C); open triangles, calculated melts for F=1.0 to 0.79 (Step 1) derived from source A; inverse open triangles, calculated melts for F=1.0 to 0.8 (Step 2) derived by fractional crystallization of the most differentiated liquid of Step 1 (F=0.79).

Fig. 9. Calculated chondrite-normalized REE patterns for liquids derived by fractional crystallization (F=0.9-0.6) of microgranite (rock-type A). Mean REE composition of Fanos granite are also plotted. Symbols for the mean compositions of the Fanos granite rock-types as in Fig.5.; light lines, calculated liquids.

Fig. 10. Nb-Y (a) and Rb-(Y+Nb) (b) discriminant diagrams for the Fanos granite after Pearce et al. (1984). VAG, Volcanic arc granites; synCOLG, syn-collision granites; WPG, Within plate granites; ORG, Ocean ridge granites.

Fig. 11. Rb/Zr vs. SiO2 discriminant diagram after Harris et al., (1986). Upper (Group II) field corresponds to syn-collision granites; WPG, Within plate granites; ORG, Ocean ridge granites.
Fig. 12. Comparison of average composition of Fanos rock-type A to the range of composition of melts produced by 10-30% (F=0.1 to 0.3) partial melting of graywacke (A) and 10-40% (F=0.1 to 0.4) partial melting of quartz diorite (B).
Fig. 4
Fig. 5

- Microgranite
- Granite
- Apl. Granite

-rock/chondrite

La  Ce  Pr  Nd  Sm  Eu  Gd  Dy  Ho  Er  Yb  Lu
Christofides, Soldatos, Korenno

Fig. 7

\[ \Sigma \text{REE} \]

\[ \text{SiO}_2 \]
Fig. 8
Christofides, Soldatos, Koroneos

Fig. 10

(a) Diagram showing the relationship between Nb and Y, with regions labeled WPG, VAG + synCOLG, and ORG.

(b) Second diagram showing the relationship between Rb and Y + Nb, with regions labeled synCOLG, VAG, WPG, and ORG.
Christofides, Soldatos, Koroneos

Fig. 11

Graph showing the relationship between Rb/Zr and SiO2 with data points indicating Group II.
Fig. 12

*REE CHONDRITE-NORMALIZED*
Table 1. Modal composition of Fanos granite.

<table>
<thead>
<tr>
<th></th>
<th>FP1</th>
<th>FP4</th>
<th>PL1</th>
<th>MD1</th>
<th>P1</th>
<th>P3</th>
<th>F5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quartz</td>
<td>23.7</td>
<td>26.5</td>
<td>23.0</td>
<td>33.3</td>
<td>35.0</td>
<td>37.2</td>
<td>33.7</td>
</tr>
<tr>
<td>K-feldspar</td>
<td>34.6</td>
<td>35.6</td>
<td>41.7</td>
<td>44.1</td>
<td>26.7</td>
<td>33.9</td>
<td>34.1</td>
</tr>
<tr>
<td>Plagioclase</td>
<td>37.8</td>
<td>34.9</td>
<td>32.3</td>
<td>21.4</td>
<td>36.3</td>
<td>28.3</td>
<td>31.5</td>
</tr>
<tr>
<td>Biotite</td>
<td>3.0</td>
<td>2.2</td>
<td>1.7</td>
<td>1.1</td>
<td>1.6</td>
<td>0.3</td>
<td>0.4</td>
</tr>
<tr>
<td>Accessories</td>
<td>0.9</td>
<td>0.8</td>
<td>1.2</td>
<td>0.1</td>
<td>0.4</td>
<td>0.3</td>
<td>0.3</td>
</tr>
</tbody>
</table>

FP1, FP4, microgranite; PL1, MD1, P1, P3, granite; F5, aplitic granite.
Table 2. Chemical analyses, CIPW norms and selected elemental ratios of Fanos granite

<table>
<thead>
<tr>
<th></th>
<th>FP1</th>
<th>FP4</th>
<th>PL1</th>
<th>PL2</th>
<th>PL3</th>
<th>MD1</th>
<th>MD2</th>
<th>P1</th>
<th>P3</th>
<th>F5</th>
<th>F7</th>
<th>F6</th>
<th>A</th>
<th>B</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>71.16</td>
<td>69.95</td>
<td>73.51</td>
<td>73.77</td>
<td>73.24</td>
<td>76.00</td>
<td>75.84</td>
<td>74.07</td>
<td>76.10</td>
<td>76.93</td>
<td>77.55</td>
<td>76.98</td>
<td>70.56</td>
<td>74.48</td>
<td>77.15</td>
</tr>
<tr>
<td>TiO₂</td>
<td>0.24</td>
<td>0.27</td>
<td>0.17</td>
<td>0.17</td>
<td>0.20</td>
<td>0.13</td>
<td>0.10</td>
<td>0.17</td>
<td>0.08</td>
<td>0.07</td>
<td>0.07</td>
<td>0.06</td>
<td>0.26</td>
<td>0.15</td>
<td>0.07</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>1.09</td>
<td>1.38</td>
<td>1.01</td>
<td>1.00</td>
<td>1.03</td>
<td>0.78</td>
<td>0.49</td>
<td>0.77</td>
<td>0.58</td>
<td>0.52</td>
<td>0.57</td>
<td>0.52</td>
<td>1.23</td>
<td>0.61</td>
<td>0.54</td>
</tr>
<tr>
<td>FeO</td>
<td>0.69</td>
<td>0.75</td>
<td>0.48</td>
<td>0.52</td>
<td>0.59</td>
<td>0.40</td>
<td>0.43</td>
<td>0.41</td>
<td>0.18</td>
<td>0.15</td>
<td>0.14</td>
<td>0.16</td>
<td>0.72</td>
<td>0.43</td>
<td>0.15</td>
</tr>
<tr>
<td>MnO</td>
<td>0.04</td>
<td>0.04</td>
<td>0.03</td>
<td>0.04</td>
<td>0.04</td>
<td>0.02</td>
<td>0.07</td>
<td>0.04</td>
<td>0.03</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.04</td>
<td>0.04</td>
<td>0.00</td>
</tr>
<tr>
<td>MgO</td>
<td>0.71</td>
<td>0.81</td>
<td>0.57</td>
<td>0.50</td>
<td>0.80</td>
<td>0.35</td>
<td>0.32</td>
<td>0.39</td>
<td>0.13</td>
<td>0.20</td>
<td>0.20</td>
<td>0.20</td>
<td>0.76</td>
<td>0.41</td>
<td>0.20</td>
</tr>
<tr>
<td>CaO</td>
<td>1.37</td>
<td>1.59</td>
<td>1.13</td>
<td>1.07</td>
<td>1.21</td>
<td>0.79</td>
<td>0.69</td>
<td>0.77</td>
<td>0.57</td>
<td>0.54</td>
<td>0.45</td>
<td>0.51</td>
<td>1.48</td>
<td>0.92</td>
<td>0.50</td>
</tr>
<tr>
<td>Na₂O</td>
<td>3.45</td>
<td>3.54</td>
<td>3.59</td>
<td>3.43</td>
<td>3.64</td>
<td>3.49</td>
<td>3.54</td>
<td>3.43</td>
<td>3.25</td>
<td>3.45</td>
<td>3.43</td>
<td>3.71</td>
<td>3.50</td>
<td>3.48</td>
<td>3.53</td>
</tr>
<tr>
<td>K₂O</td>
<td>5.25</td>
<td>5.22</td>
<td>4.86</td>
<td>5.11</td>
<td>4.93</td>
<td>4.92</td>
<td>4.80</td>
<td>5.37</td>
<td>5.67</td>
<td>4.65</td>
<td>4.59</td>
<td>4.24</td>
<td>5.24</td>
<td>5.09</td>
<td>4.49</td>
</tr>
<tr>
<td>P₂O₅</td>
<td>0.14</td>
<td>0.16</td>
<td>0.10</td>
<td>0.09</td>
<td>0.11</td>
<td>0.07</td>
<td>0.06</td>
<td>0.07</td>
<td>0.03</td>
<td>0.03</td>
<td>0.05</td>
<td>0.04</td>
<td>0.15</td>
<td>0.08</td>
<td>0.04</td>
</tr>
<tr>
<td>LOI</td>
<td>0.77</td>
<td>1.01</td>
<td>0.38</td>
<td>0.40</td>
<td>0.46</td>
<td>0.46</td>
<td>0.45</td>
<td>0.48</td>
<td>0.58</td>
<td>0.44</td>
<td>0.36</td>
<td>0.40</td>
<td>0.89</td>
<td>0.46</td>
<td>0.35</td>
</tr>
</tbody>
</table>


**DI**

<p>| | | | | | | | | | | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Rb</td>
<td>264</td>
<td>282</td>
<td>255</td>
<td>91.11</td>
<td>91.47</td>
<td>90.72</td>
<td>92.31</td>
<td>93.35</td>
<td>95.33</td>
<td>95.29</td>
<td>95.44</td>
<td>95.61</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sr</td>
<td>453</td>
<td>474</td>
<td>293</td>
<td>302</td>
<td>284</td>
<td>166</td>
<td>141</td>
<td>248</td>
<td>30</td>
<td>31</td>
<td>464</td>
<td>223</td>
<td>31</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ba</td>
<td>876</td>
<td>825</td>
<td>521</td>
<td>547</td>
<td>500</td>
<td>291</td>
<td>266</td>
<td>419</td>
<td>27</td>
<td>32</td>
<td>25</td>
<td>551</td>
<td>394</td>
<td>28</td>
<td></td>
</tr>
<tr>
<td>Zr</td>
<td>260</td>
<td>290</td>
<td>131</td>
<td>134</td>
<td>152</td>
<td>117</td>
<td>91</td>
<td>143</td>
<td>69</td>
<td>57</td>
<td>58</td>
<td>275</td>
<td>120</td>
<td>60</td>
<td></td>
</tr>
<tr>
<td>Nb</td>
<td>38</td>
<td>33</td>
<td>36</td>
<td>34</td>
<td>40</td>
<td>46</td>
<td>37</td>
<td>33</td>
<td>29</td>
<td>44</td>
<td>66</td>
<td>38</td>
<td>36</td>
<td>59</td>
<td></td>
</tr>
<tr>
<td>Zn</td>
<td>15</td>
<td>19</td>
<td>9</td>
<td>10</td>
<td>17</td>
<td>10</td>
<td>3</td>
<td>8</td>
<td>5</td>
<td>3</td>
<td>3</td>
<td>17</td>
<td>7</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>Y</td>
<td>16</td>
<td>13</td>
<td>7</td>
<td>6</td>
<td>8</td>
<td>5</td>
<td>3</td>
<td>12</td>
<td>7</td>
<td>3</td>
<td>3</td>
<td>15</td>
<td>7</td>
<td>3</td>
<td></td>
</tr>
</tbody>
</table>

K/Rb  165  154  158  161  156  151  149  192  181  134  135  139  159.31 164.13 136.03
Rb/Sr 0.58 0.59 0.87 0.87 0.92 1.63 1.89 0.94 2.00 9.60 9.10 8.16 0.59 1.30 8.95
Nb/Sr 0.08 0.07 0.12 0.11 0.14 0.28 0.26 0.23 0.13 0.22 1.47 2.13 2.19 0.08 0.18 1.93
Rb/Ba 0.30 0.34 0.49 0.48 0.52 0.93 1.00 0.55 1.20 10.29 8.81 10.12 0.32 0.74 9.74
Nb/Ba 0.04 0.04 0.07 0.08 0.08 0.16 0.14 0.08 0.13 1.57 2.06 2.72 0.04 0.10 2.12
Ba/Sr 1.93 1.74 1.78 1.81 1.76 1.75 1.89 1.69 1.67 0.93 1.03 0.81 1.84 1.76 0.92

FP1, FP4, microgranite (A); PL1 to P3, granite (B); F5 to F6, aplitegranite (C)
<table>
<thead>
<tr>
<th></th>
<th>FP4</th>
<th>PL1</th>
<th>MD1</th>
<th>P1</th>
<th>F5</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>La</td>
<td>71.31</td>
<td>61.30</td>
<td>61.30</td>
<td>48.13</td>
<td>30.40</td>
<td>71.31</td>
</tr>
<tr>
<td>Ce</td>
<td>110.82</td>
<td>94.50</td>
<td>75.90</td>
<td>81.86</td>
<td>41.20</td>
<td>110.82</td>
</tr>
<tr>
<td>Pr</td>
<td>12.86</td>
<td>9.00</td>
<td>8.60</td>
<td>8.63</td>
<td>3.50</td>
<td>12.86</td>
</tr>
<tr>
<td>Nd</td>
<td>38.15</td>
<td>29.00</td>
<td>27.00</td>
<td>24.14</td>
<td>10.20</td>
<td>38.15</td>
</tr>
<tr>
<td>Sm</td>
<td>4.79</td>
<td>4.00</td>
<td>3.70</td>
<td>3.13</td>
<td>1.40</td>
<td>4.79</td>
</tr>
<tr>
<td>Eu</td>
<td>1.03</td>
<td>0.75</td>
<td>0.56</td>
<td>0.57</td>
<td>0.19</td>
<td>1.03</td>
</tr>
<tr>
<td>Gd</td>
<td>3.11</td>
<td>2.70</td>
<td>2.30</td>
<td>2.09</td>
<td>0.90</td>
<td>3.11</td>
</tr>
<tr>
<td>Dy</td>
<td>2.58</td>
<td>2.24</td>
<td>1.88</td>
<td>1.91</td>
<td>0.86</td>
<td>2.58</td>
</tr>
<tr>
<td>Ho</td>
<td>0.61</td>
<td>0.50</td>
<td>0.41</td>
<td>0.49</td>
<td>0.22</td>
<td>0.61</td>
</tr>
<tr>
<td>Er</td>
<td>1.91</td>
<td>1.88</td>
<td>1.62</td>
<td>1.60</td>
<td>1.02</td>
<td>1.91</td>
</tr>
<tr>
<td>Yb</td>
<td>1.79</td>
<td>2.12</td>
<td>2.00</td>
<td>1.85</td>
<td>1.63</td>
<td>1.79</td>
</tr>
<tr>
<td>Lu</td>
<td>0.33</td>
<td>0.36</td>
<td>0.35</td>
<td>0.35</td>
<td>0.31</td>
<td>0.33</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>ΣREE</td>
<td>249.29</td>
</tr>
<tr>
<td>(La/Lu)_CN</td>
<td>22.27</td>
</tr>
<tr>
<td>(La/Sm)_CN</td>
<td>9.19</td>
</tr>
<tr>
<td>(Gd/Lu)_CN</td>
<td>1.16</td>
</tr>
<tr>
<td>Eu/Sm</td>
<td>0.22</td>
</tr>
<tr>
<td>Eu/Eu*</td>
<td>0.76</td>
</tr>
</tbody>
</table>
### Table 4. Sample input and output data for computer calculations in Method 1.

<table>
<thead>
<tr>
<th></th>
<th>Rock A (obs)</th>
<th>Rock A (calc)</th>
<th>d</th>
<th>Rock C</th>
<th>Kf</th>
<th>Plagioclase</th>
<th>Bi</th>
<th>Sp</th>
<th>Mt</th>
</tr>
</thead>
<tbody>
<tr>
<td>iO₂</td>
<td>70.56</td>
<td>70.57</td>
<td>-0.01</td>
<td>77.15</td>
<td>64.83</td>
<td>67.84</td>
<td>43.88</td>
<td>38.78</td>
<td>28.82</td>
</tr>
<tr>
<td>iO₂</td>
<td>0.26</td>
<td>0.23</td>
<td>0.03</td>
<td>0.07</td>
<td>0.03</td>
<td>0.00</td>
<td>0.00</td>
<td>2.63</td>
<td>33.75</td>
</tr>
<tr>
<td>i²O₃</td>
<td>15.16</td>
<td>15.14</td>
<td>0.02</td>
<td>12.42</td>
<td>18.91</td>
<td>19.65</td>
<td>36.18</td>
<td>12.89</td>
<td>1.75</td>
</tr>
<tr>
<td>eO₂</td>
<td>1.83</td>
<td>1.84</td>
<td>-0.01</td>
<td>0.64</td>
<td>0.00</td>
<td>0.05</td>
<td>0.07</td>
<td>16.22</td>
<td>2.22</td>
</tr>
<tr>
<td>nO</td>
<td>0.04</td>
<td>0.05</td>
<td>-0.01</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>1.05</td>
<td>0.09</td>
</tr>
<tr>
<td>gO</td>
<td>0.76</td>
<td>0.79</td>
<td>-0.03</td>
<td>0.20</td>
<td>0.00</td>
<td>0.04</td>
<td>0.00</td>
<td>14.41</td>
<td>0.09</td>
</tr>
<tr>
<td>aO</td>
<td>1.48</td>
<td>1.55</td>
<td>-0.07</td>
<td>0.50</td>
<td>0.17</td>
<td>0.00</td>
<td>19.37</td>
<td>0.02</td>
<td>25.94</td>
</tr>
<tr>
<td>a²O</td>
<td>3.50</td>
<td>3.57</td>
<td>-0.07</td>
<td>3.53</td>
<td>0.63</td>
<td>11.07</td>
<td>0.22</td>
<td>0.29</td>
<td>0.25</td>
</tr>
<tr>
<td>tO</td>
<td>5.24</td>
<td>5.29</td>
<td>-0.05</td>
<td>4.49</td>
<td>14.59</td>
<td>0.29</td>
<td>0.00</td>
<td>9.55</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Σd² = 0.0143

**Partial A = 0.6814 Rock C + 0.1214 Kf + 0.1437 Pl (An₄0) + 0.0451 Bi + 0.0018 Sp + 0.0066 Mt**

**Solid = 38.10% Kf + 45.10% Pl + 14.16% Bi + 0.56% Sp + 2.07% Mt**
Table 5. Sample input and output data for computer calculations in Method 2.

<table>
<thead>
<tr>
<th></th>
<th>Rock A (obs)</th>
<th>Rock A (calc)</th>
<th>d1</th>
<th>Rock B (obs)</th>
<th>Rock B (calc)</th>
<th>d2</th>
<th>Rock C</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>70.56</td>
<td>70.58</td>
<td>-0.02</td>
<td>74.48</td>
<td>74.51</td>
<td>-0.03</td>
<td>77.15</td>
</tr>
<tr>
<td>TiO₂</td>
<td>0.26</td>
<td>0.22</td>
<td>0.04</td>
<td>0.15</td>
<td>0.21</td>
<td>-0.06</td>
<td>0.07</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>15.16</td>
<td>15.14</td>
<td>0.02</td>
<td>13.46</td>
<td>13.50</td>
<td>-0.04</td>
<td>12.42</td>
</tr>
<tr>
<td>FeO₄</td>
<td>1.83</td>
<td>1.85</td>
<td>-0.02</td>
<td>1.16</td>
<td>1.19</td>
<td>-0.03</td>
<td>0.64</td>
</tr>
<tr>
<td>MnO</td>
<td>0.04</td>
<td>0.07</td>
<td>-0.03</td>
<td>0.04</td>
<td>0.00</td>
<td>0.04</td>
<td>0.00</td>
</tr>
<tr>
<td>MgO</td>
<td>0.76</td>
<td>0.80</td>
<td>-0.04</td>
<td>0.41</td>
<td>0.17</td>
<td>0.24</td>
<td>0.20</td>
</tr>
<tr>
<td>CaO</td>
<td>1.48</td>
<td>1.58</td>
<td>-0.10</td>
<td>0.92</td>
<td>0.92</td>
<td>0.00</td>
<td>0.50</td>
</tr>
<tr>
<td>Na₂O</td>
<td>3.50</td>
<td>3.60</td>
<td>-0.10</td>
<td>3.48</td>
<td>3.48</td>
<td>0.00</td>
<td>3.53</td>
</tr>
<tr>
<td>K₂O</td>
<td>5.24</td>
<td>5.31</td>
<td>-0.07</td>
<td>5.09</td>
<td>5.01</td>
<td>-0.01</td>
<td>4.49</td>
</tr>
</tbody>
</table>

\[ \Sigma d^2 = 0.0305 \quad \Sigma d^2 = 0.0651 \]

Step 1: Rock A = 0.7867Rock B + 0.0663Kf* + 0.1095Pl(An₄₀) + 0.0332Bi + 0.0004Sp + 0.0039Mt
Step 2: Rock B = 0.8571Rock C + 0.0852Kf + 0.0471Pl(An₄₁) + 0.0043Sp + 0.0063Mt

Solid 1 = 31.08%Kf + 51.34%Pl + 15.56%Bi + 0.19%Sp + 1.83%Mt
Solid 2 = 59.62%Kf + 32.96%Pl + 3.01%Sp + 4.41%Mt

* The crystallizing minerals used are the same as in Method 1
ΚΛΕΙΣΤΗΡΙΟ ΚΑΙ ΧΙΩΤΙΖΩΤΟΥ
ΜΝΗΜΕΑΩΤΙΚΕ ΡΟΛΑΔΟΥ ΕΘΝΙΚΟ ΕΛΔΥΟΥ ΕΝΕΡΓΗΚΟΤΩΤΟΥ
ΑΝΕΝΕΝΙΑ ΑΓΙΑ ΤΑΞΙΑ ΕΝ Η ΝΑΝΘΡΩΠΗ

"Ν. ΓΡΕΒΕΝΗ - ΜΑΥΡΟ ΑΝΔ ΤΡΑΙΣ ΕΛΕΓΚΤΗ έντειν ΑΛΕΓΚΤΗ "
ΓΕΩΕΧΗΜΙΣΤΡΙΑ, ΕΒΟΧΟΝΙΑ ΝΙΩΜΑΤΟΣ ΑΓΙΟΝ ΕΝ ΝΕΒΟΛΑΙΑΝ ΧΡΙΣΤΟΥΛΗ
ΟΛΕ ΤΗΝ ΟΠΩΙΤΟΛΙΑ ΕΓΩΣ ΤΙΝΗΝ ΔΕΞΙΣ ΑΝΕΡΕΥΝΤΕΣ

ΠΡΟΒΕΔΕΟ ΖΑΙΛΙΑ
ΤΟ ΤΟΥ ΚΩΣΤΑΝΤΙΝΟΥ ΚΤΕΣΙΑ ΑΝΤΩΛ
ΑΝΤΙΒΙΩΤΙΚΟΝ ΚΩΠΑΝΩΝ
ΤΡΑΝΣΓΙΩΝ ΠΟΛΑ ΤΕΛΩΤΙΩΝ ΧΡΙΣΤΟΠΟΛΑΩΝ

ΕΔΩΣΕ ΘΗ ΑΚΑΘΜΙΑ ΑΘΩΝΗ
ΤΥΧΗ ΑΛΑΘΗ

ΑΚΑΘΜΙΑ ΑΘΩΝΗ