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MAJOR AND TRACE ELEMENT GEOCHEMISTY OF MICAS AND AMPHIBOLES OF THE SITHONIA PLUTON (CHALKIDIKI, N. GREECE): CONSTRAINS ON ITS EVOLUTION

G. CHRISTOFIDES[1], G. ELEFTHERIADIS[1], A. M. NEIVA[2],
M. VLAHOU[1], L. PAPADOPOULOU[1]

ABSTRACT

The Sithonia pluton comprises a series of plutonic rocks ranging from tonalite to leucogranite; aplites and pegmatites are also present. The rocks are metaluminous to slightly peraluminous calc-alkaline with I-type characteristics. They display linear trends on variation diagrams except in a few cases where hornblende-biotite granodiorite deviates from the general compositional trend shown by the pluton. Such a deviation is also shown in some mineral major and trace element diagrams. Major and trace element abundances and Sr isotopic compositions exclude a single fractional crystallization process for the pluton evolution. Instead an AFC process is more plausible. An alternative hypothesis is melting of an infracrustal source formed by underplating of (meta?) magmatites.

KEY WORDS : granite, mineral trace elements, hornblende, biotite, muscovite, petrology, geochemistry, evolution.

1. INTRODUCTION - GEOLOGICAL SETTING

The mineralogical composition of granitoids is very important for their petrology. Of particular interest are the micas, the amphiboles, and the feldspars, the major and trace element variations of which provide useful information for magma chemistry, crystallization conditions and compositional trends during the evolution of the rocks.

Among the granitoids intruding the Chalkidiki Peninsula in northern Greece is the Tertiary Sithonia pluton, an elongate granitic intrusion of ca 350 km^2, which belongs to the Circum Rhodope Belt (Fig. 1). The intrusion itself has been affected by younger tectonic activity of probable Upper Eocene to Oligocene age (Sakellariou, 1989). Emplacement of the pluton is suggested to have occurred by forceful intrusion which is supported by the strongly sheared contacts of the pluton and the country rocks (De Wet et al., 1989; D' Amico et al., 1990). The country rocks are strongly sheared and flattened. Thermal metamorphism is present with the development of a contact aureole of about 100 m.

Rb-Sr geochronological data suggest an Eocene age for the Sithonia pluton (De Wet et al., 1989; Christofides et al., 1990). In the present study major and trace element abundances of minerals along with rock chemistry from the Sithonia pluton are presented for a better understanding of the pluton evolution.

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[1] Department of Mineralogy-Petrology-Economic Geology, University of Thessaloniki, 540 06 Thessaloniki, Macedonia, Greece.

[2] Department of Earth Sciences, University of Coimbra, 3000 Coimbra, Portugal.

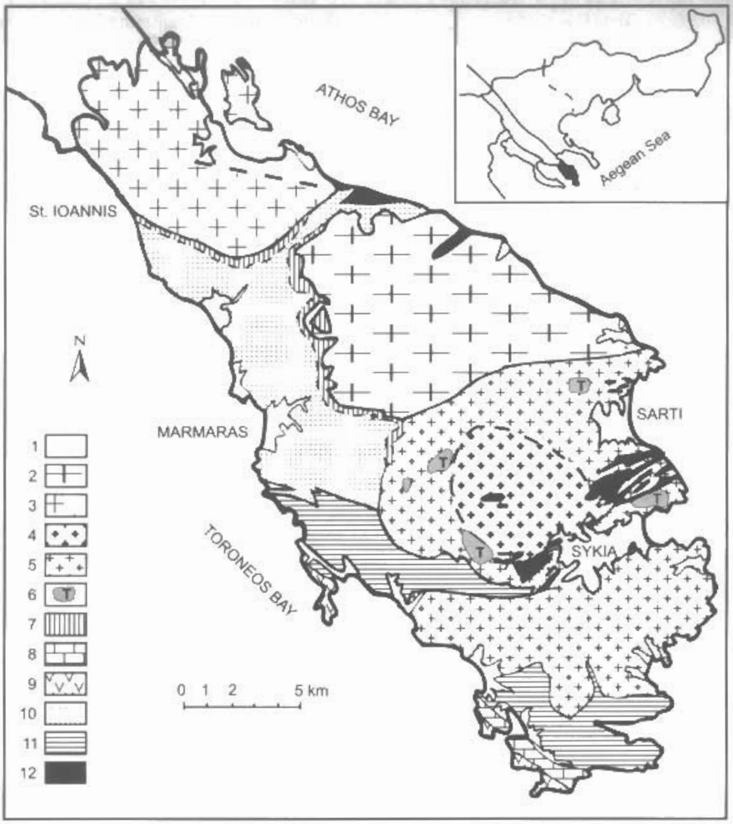

Fig. 1. Schematic map of the Sithonia plutonic complex and surrounding terraines. 1:Quaternary and Neogene sedimentary rocks; 2:leucogranite (LG); 3:two-mica granite (TMG); 4:biotite granodiotite (BGd); 5:hornblende-biotite granodiorite (HBGd); 6:hornblende-biotite tonalite (Ton); 7:contact aureole rocks; 8:Jurassic limestones; 9:ophiolites; 10:metasediments of the Svoula Group; 11:Chortiatis greenschists; 12:Paleozoic amphibolites and gneises.

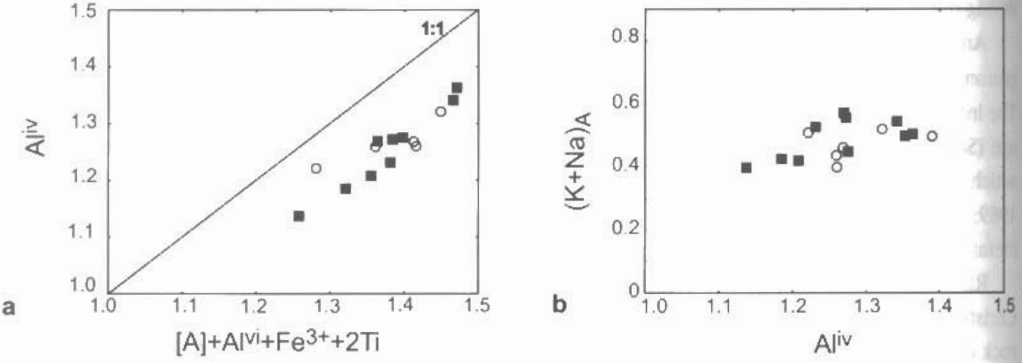

Fig. 2. Substitution mechanisms in the Sithonia amphibole. (a) Al^{iv} vs $[A]+R^{3+}$. Line represents the 1:1 ratio. (b) [A] vs Al^{iv}. The trend indicates edenitic substitution. Circles = Ton, solid squares = HBGd.

2. ANALYTICAL TECHNIQUES

The Sithonia rock samples were chemicaly analyzed for trace elements by a combination of X-ray fluorescence and atomic absorption spectrometry, at the Universities of Bologna, Pisa, and Manchester. Replicate analyses were often made in the above laboratories.

Major elements of the minerals were determined by microprobe analysis using the Modified Cambridge Geoscan with Link Systems energy-dispersive system at Manchester University, and a Jeol 740 SEM at the Thessaloniki University. Thorough interlaboratory checking showed good agreement. Pure separates of micas and amphibole were extracted by a combination of magnetic separator and heavy liquids. The purity estimated by microscopic examination of the grains is M99.8% and the contaminant is zircon. On those separates trace element analyses were carried out by X-ray fluorescence. However Li determinations as well as total Fe_2O_3 in micas were determined by atomic absorption, whereas F concentrations were achieved by selective ion electrode analysis with a precision of about 2%. Finally, FeO of separated minerals was determined by titration with a standardized potassium permanganate solution, with a precision of about 1%.

3. PETROGRAPHY - MINERALOGY

The Sithonia plutonic rocks range in composition from hornblende - biotite tonalite to leucogranite corresponding to a SiO_2 range from 63 to 77 wt% (D' Amico et al., 1990). The following main rock-types may be distinguished from north to south (Fig. 1): two - mica granite (TMG), leucogranite (LG) often porphyritic, biotite - granodiorite (BGd) and hornblende - biotite granodiorite (HBGd). Within the latter some discrete parts reach a tonalitic composition (Ton), but no clear contact has ever been found between HBGd and Ton. Microgranular enclaves of Qz-diorite composition are present within the granodiorites. Aplites and pegmatites are common, intruding the granitic bodies as well as the country rocks. LG intrude both the TMG in the north, and HBGd in the south. BGd is younger and finer - grained than HBGd and clearly domed into it (Christofides et al., 1990; D'Amico et al., 1990).

Granodiorites (BGd, HBGd) and Ton are gray, medium - uneven - grained, showing clearly a plutonic texture. In several cases, microgranular to granophyric textures are present, which may gradually pass to porphyritic ones. An oriented fabric is common.

Granites (TMG, LG) are light-gray to white in colour, with the TMG being darker, more or less heterogranular and often exhibiting schistosity. Most TMG are fine- to medium - grained, whereas LG are usually coarser - grained.

Aplites and pegmatites form whitish dykes and veins intruding all the Sithonia plutonic bodies and the surrounding metamorphic rocks. Pegmatites are generally more abundant than aplites. Both are more abundant cutting TMG and LG than cutting the other rocks.

The granitic rocks of the Sithonia pluton contain quartz, feldspars (plagioclase and K-feldspar), amphibole, biotite, muscovite, epidote, allanite, apatite, sphene, zircon, chlorite and Fe-Ti-oxides, with magnetite being more abundant in the granodiotites and ilmenite in the granites.

Both plagioclase and K-feldspar coexist in all rock-types with plagioclase predominating over K-feldspar. Plagioclase occurs as whitish or milky subhedral to anhedral and sometimes composite crystals. Their composition ranges from An_{18}-An_8 in the LG to An_{46}-An_{14} in the Ton. K-feldspar (Or_{96}-Or_{84}) is an important constituent of the pluton, its abundance decreasing towards Ton. Anorthite content is absent or very low not exceeding 1%.

Amphibole occurs as subhedral to anhedral prismatic crystals. Irregular and skeletal crystals, however, are also observed. It is pleochroic in shades of yellow-green, emerald-green and olive-green. Biotite, plagioclase, apatite and opaques are commonly included in it. The abundance of amphibole decreases with increasing silica content of the host rock and with the decrease of modal plagioclase. Major and trace element analyses of amphibo[illegible] in alumina and

Sithonia pluton. Each column represents 5 to 12 spot analyses on 2 to 5 grains.

	Hornblende analyses				Biotite analyses										Primary muscovite analyses			
	Ton		HBGD		Ton		HBGD		BGD		TMG		LG		TMG		LG	
		sdv		sdv		sdv		sdv		sdv		sdv		sdv		sdv		sdv
SiO_2	45.26	0.45	44.89	0.66	37.61	0.24	37.90	0.45	37.08	0.24	36.60	0.43	36.21	0.36	46.31	0.40	46.36	0.40
TiO_2	1.01	0.22	0.93	0.21	2.08	0.26	2.02	0.23	2.17	0.08	3.08	0.33	3.35	0.28	1.47	0.18	1.21	0.29
Al_2O_3	9.19	0.38	9.18	0.44	15.56	0.17	15.48	0.27	16.14	0.34	16.73	0.34	16.52	0.43	31.24	0.26	31.05	0.76
Fe_2O_3	5.88	0.48	6.23	0.79	4.32	0.72	3.98	0.68	5.17	0.93	3.41	0.92	4.96	0.23	2.54	0.28	2.98	0.79
FeO	12.05	0.13	11.98	0.37	14.77	0.99	14.84	0.31	15.68	0.57	18.74	0.87	17.88	0.53	1.58	0.20	1.66	0.14
MnO	0.45	0.03	0.51	0.04	0.26	0.06	0.35	0.07	0.35	0.06	0.27	0.13	0.66	0.21	-	-	-	-
MgO	11.13	0.46	10.80	0.60	12.43	0.47	12.31	0.55	10.27	0.86	7.90	0.75	6.90	0.31	0.82	0.11	0.90	0.16
CaO	11.80	0.18	11.64	0.12	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Na_2O	1.45	0.13	1.47	0.16	-	-	-	-	-	-	-	-	-	-	0.38	0.07	0.37	0.10
K_2O	0.86	0.14	0.99	0.09	9.61	0.32	9.34	0.26	9.33	0.14	9.52	0.17	9.44	0.20	10.64	0.10	10.63	0.18
Li	6	0	6	0	135	69	151	12	117	13	472	94	702	168	138	50	186	64
F	1482	154	1502	71	2439	198	2735	181	2391	181	4892	297	6948	1078	1731	159	3087	901
Nb	27	7	21	4	10	5	13	6	22	5	44	9	136	60	61	17	116	42
Zr	231	22	247	63	147	46	208	39	286	48	327	76	182	68	257	171	51	27
Y	62	8	55	18	81	51	48	2	44	5	100	65	60	9	44	4	42	3
Sr	73	14	53	9	34	9	37	4	34	7	29	3	30	7	41	6	38	8
Rb	3	1	5	1	659	127	696	66	598	39	565	313	1156	263	583	54	686	83
Zn	229	13	230	50	397	32	439	25	432	16	818	93	1127	114	103	22	156	42
Cu	24	22	11	9	28	24	25	16	20	8	3	0	3	0	6	0		
Ni	46	2	40	12	123	3	110	7	44	2	16	2	22	8	4	4	5	2
Cr	182	32	155	17	167	10	133	29	93	3	43	10	26	8	28	8	13	5
Ce	75	22	50	21	17	13	36	16	24	0	53	49	56	12	30	5	17	7
Nd	43	14	25	10	7	5	6	3	13	0	9	10	13	4	5	2	4	2
V	379	9	327	8	399	5	364	28	397	21	292	53	198	27	208	44	119	42
La	23	12	24	5	8	3	15	3	7	0	20	14	21	8	19	4	18	5
Ba	-	-	-	-	955	116	817	422	987	93	671	14	508	388	591	68	366	230
Sc	92	4	98	12	6	4	16	7	12	3	17	5	13	8	38	8	39	21

Table 1. Major (wt%) and trace element (ppm) values of amphibole and micas from the Sithonia pluton. Each column represents 5 to 12 spot analyses on 2 to 5 grains.

relatively poor in titania. The Mg/(Mg+Fe^{2+}) ratio does not show large variation (0.523-0.629).

Amphibole is magnesio-hornblende (Leak, 1978). Its crystal chemistry indicates that the main coupled substitution mechanism is pargasitic (Fig. 2). Variation diagrams using the rock SiO_2 show that Ti in the amphiboles decreases in general (except few samples) from Ton to HBGd (Fig. 3a). On the contrary Mn shows grouping of the two rock types in subparallel decreasing trends, although it seems to increase from Ton to HBGd. Al in Ton decreases and forms a linear trend which seems to be followed by the two most silica rich HBGd. The rest of the HBGd samples form also a linear trend, which however cuts the Ton trend. V, Sr/Ca (Fig. 3a), and Nd, and Sr (not shown), decrease from Ton to HBGd defining a trend but with a discontinuity in the first three diagrams. The rest of the elements are more or less scattered.

Biotite is the most abundant ferromagnesian mineral in the Sithonia pluton associated either with muscovite in the TMG and LG or with hornblende in HBGd and Ton. The biotite associated with muscovite is pleochroic in shades of brown to pale yellow, in contrast to the biotite of the other types which is brownish green to olive-green and yellow-brown. These differences in colour are composition-related (Saountzis, 1976). Common inclusions in the biotites are: apatite, zircon, sphene, epidote and opaques. In the Hb-Bi rock-types, biotite is either separate or replaces hornblende. In the Foster's (1960) R^{3+}-Mg-Fe^{2+} classification diagram (not shown) the Sithonia biotites clearly discriminate in two groups. The biotite accompanied by hornblende plots in the Mg-rich field, while that associated with muscovite in the Fe-rich field, with the biotite of the BGd plotting in between. Biotite from LG seems to be generally

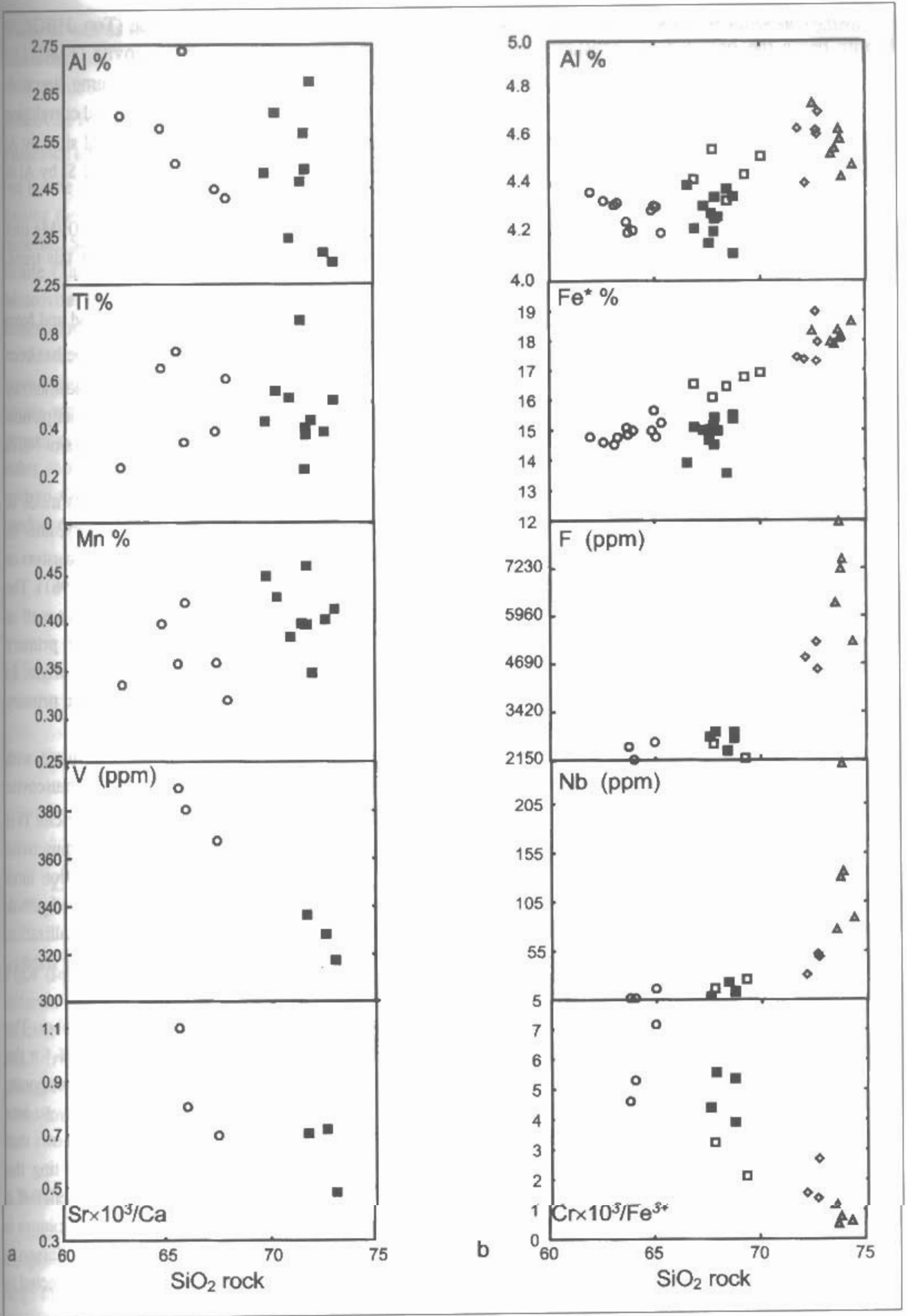

Fig. 3: Variation diagrams of selected major and trace elements of the Sithonia amphiboles (a) and biotites (b). Circles = Ton, Solid squares = HBGd [illegible]

the richest in Fe^{2+}. It is clear that on passing from biotite accompanied by hornblende (Ton, HBGd) to biotite being the only ferromagnesian mineral (BGd) to biotite associated with muscovite (TMG, LG) there is a general trend for R^{3+} to increase whereas the Y site occupancy decreases in the same direction. This indicates a variation in composition associated with replacement of R^{2+} by R^{3+}. The good correlation between Al^{iv} and Ti indicates Ti-tschermak substitution. Partial occupancy of the octahedral sites by Al and Ti is balanced by the removal of divalent ions from the octahedral site and substitution of Si by Al in the tetrahedral site (Hewitt and Abrecht, 1986).

The plots of Al, total Fe , Cr/Fe^{3+} (Fig. 3b), and Mg, Fe/(Fe+Mg), Ni, $Ni*10^3/Fe^{2+}$ and $Ni*10^3/Mg$ (not shown) of biotite versus rock SiO_2 show a trend from Ton to LG, but HBGd deviate from this trend. However, F, Nb (Fig. 3a), Li, Zn, Cr, and Rb (not shown) of HBGd biotite follow the trend.

The distribution coefficient $K_D=(X_{Mg}/X_{Fe})_{Bi}/(X_{Mg}/X_{Fe})_{Hb}$ ranges from 0.8 to 1.15 in HBGd and from 0.7 to 1.12 in Ton. In pairs in which FeO and Fe_2O_3 have not been determined the above value has been determined graficaly and it is mostly greater or equal to 1. This may reflect amphibole's replacement by biotite in magmatic state (Speer, 1987). Zr, Sc, Y, La, Ce, Nd, Nb and Sr are concentrated in amphibole while Li, Ni, Zn, Ba, Rb, V and F prefer biotite, which agrees for most of these elements with data of Neiva et al. (1996).

Muscovite is usually more abundant than biotite in LG and subordinate to it in TMG. Its mode of occurrence as well as its relationship with the rest minerals enables the recognition of primary, late- or post-magmatic and secondary muscovite. Large flakes and lath-shaped crystals, are isolated, in clusters or intergrown with biotite, and have characteristics favoring a primary origin (cf. Miller et al., 1981). The secondary muscovite is fine-grained (sericite) replacing mainly plagioclase. Small clear laths as well as large laths and flakes in LG are late- or post-magmatic. Large flakes, resembling those of primary muscovite in all respects except for being slightly coloured are suggested to be of secondary origin. In some deformed rock samples, lath-like muscovite is a matrix constituent. The distinction between primary and secondary origin is difficult in this case.

Compositionally the primary muscovite is richer in Ti, Na, and Al, which is in agreement with variations found by Miller et al. (1981) and Mulja et al. (1995). The TiO_2 content of the primary muscovite ranges from 0.88 to 2.22 wt%, whereas in the late muscovite ranges from 0.23 to 0.72 wt%; in sericite Ti is either absent or is present in amounts less than 0.3. The distinction between these three types of muscovite is shown in figure 4. According to Guidotti et al. (1977) and Puziewicz (1995) the Ti saturation limit increases with temperature, which is in favor of a primary origin of the large flakes, since the Ti-tschermak substitution mechanism is temperature dependent. Monier and Robert (1986) proposed a crystallization temperature range for primary muscovites with TiO_2 content 2.2-0.87% from 700 °C (their upper stability limit) to 650 °C (the granitic solidus temperature).

The Sithonia muscovites have chemical compositions close to the pure muscovite end member. The celadonitic component ranges between 10 and 16.5 mol% for the primary and 10.5 to 23.2 mol% for the late-magmatic, while the paragonitic component only in one case exceeds 7 mol%. The paragonite component is controlled by Na substitution (Neiva, 1992). Celadonite increases from primary to late muscovite indicating decrease of the crystallization temperature (Monier et al., 1984). Figure 5 shows that the muscovites (especially the late ones) do not deviate significantly from the line representing the phengitic substitution. The small deviation of the primary muscovite indicates probably the presence of a ferrimuscovite component (Harrison, 1990). Therefore the primary white mica of the Sithonia pluton is Ti-rich ferriceladonitic, which is common in all two-mica granitoids that lack aluminosilicates (Anderson & Roley, 1981). The substitution that connects dioctahedral to trioctahedral micas has not been detected in the muscovite of the Sithonia pluton.

On major and trace element variation diagrams of the primary muscovite versus the rock SiO_2 content (not shown), a continuous trend from the TMG to the LG is obvious for Ti, total Fe, Nb, Zr, Zn, Cr, Ce, V, and Sc as well as the ratios $Cr*10^3/Fe^{3+}$, and $V*10^3/Fe^{3+}$. The rest of the elements plotted show significant scattering.

Regarding the biotite-muscovite pair, the titanium partition coefficient K_D Bi/Mu between biotite and muscovite is found to be high (1.74-3.81), while the TiO_2 content in the host rocks is low. According to Puziewicz and Koepke (1991), the K_D Bi/Mu for titanium is not affected by the bulk rock titanium content but by the presence of a titanium saturating phase. In the TMG and LG ilmenite was formed probably causing the saturation of primary muscovite in titanium. As for the element distribution between the two minerals, Sc, Sr, Nb, and Cu tend to concentrate in muscovite, while Y, Ni, Nd, Zr, Li, and Zn prefer biotite (Table 1), a tendency similar with that found by Mulja et al. (1995), and Neiva et al. (1996). Muscovite does not seem to result from replacement of biotite since dioctahedral-trioctahedral substitution in muscovite has not been detected.

Among the accessories of great petrological importance is epidote which occurs in all petrographic types except LG. It is usually pleochroic yellow-green to nearly colourless. In the BGd, HBGd and Ton it occurs occasionaly in perfectly euhedral crystals which, along with some textural relationships with other mineral constituents, favor a primary origin for it (Christofides and Eleftheriadis, 1992). Allanite occurs either as individual stout prismatic or elongated, euhedral or rounded crystals or as a core, rimmed by epidote. Opaques are mostly magnetite, ilmenomagnetite and secondary ilmenite. Chlorite is an alteration product of biotite and hornblende.

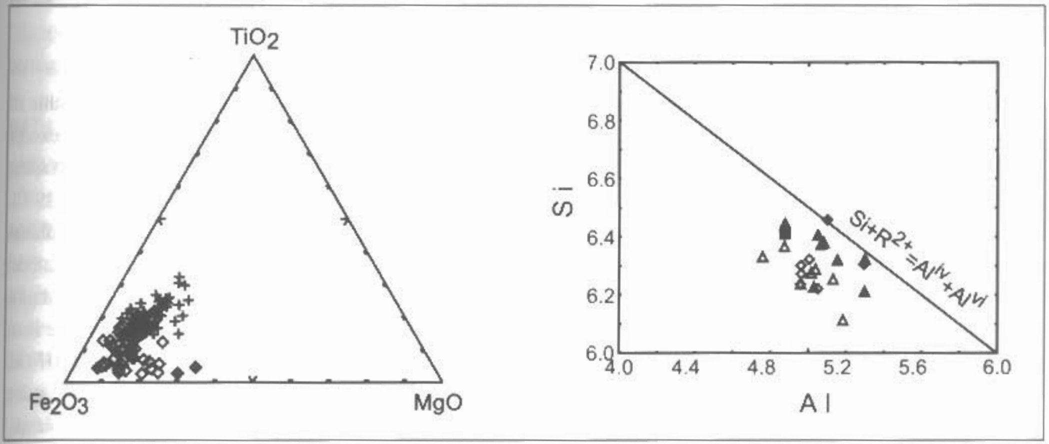

Fig.4 (left): Ternary diagram after Monier et al. (1984) where the three types of white micas plot in different areas. Crosses = primary muscovite, diamonds = late-magmatic muscovite, solid diamonds = sericite.

Fig.5 (right): Si in muscovite versus their total Al pfu content. Line represents theoretically perfect phengitic substitution. Diamonds = muscovite from TMG; Triangles = muscovite from LG; solid symbols = late-magmatic muscovite.

4. ROCK GEOCHEMISTRY

The rocks analyzed are metaluminous to slightly peraluminous with I-type characteristics and compositions similar to calc-alkaline suites with generally $Na_2O>K_2O$. As a whole, the Sithonia pluton range more or less continuously from Ton to LG. Most major element oxides display linear trends on SiO_2 variation diagrams; Al_2O_3, TiO_2, MgO and CaO display strong negative correlation with SiO_2, although some scattering is observed. Among the trace elements Sr and Ba display also strong negative correlation with SiO_2 whereas Rb is positively correlated. Sr is also negatively correlated with Rb, whereas Rb/Sr, a useful fractionation index, increases with differentiation. K/Rb remains rather constant, whereas Ba/Rb decreases and Ba/Sr increases with rock silica. The granodiorites (HBGd and BGd) show similar compositional variations, except in a few cases e.g. TiO_2, K_2O, Zr where HBGd has lower, higher and lower abundances respectively. The leucogranite shows a widely scattered distribution for some elements e.g. Sr, indicating heterogeneity. Rock analyses from all rock types from the Sithonia pluton and variation diagrams are given by D'Amico et al. (1990).

5. CRYSTALLISATION CONDITIONS

The hornblende geobarometer of Schmidt (1992), used for the Sithonia amphiboles, gives crystallization pressures between 3.6 and 6.1 kb. Slightly lower values concerning the maximum ones (3.6-5.1) have been obtained using the geobarometer of Anderson and Smith (1995) for temperature of 729°C (see below). Temperatures from 677-765°C (average=729°C) for Ton and 695-780°C (average=727°C) for HBGd have been calculated using the pressures obtained above, and Blundy & Holland's (1990) amphibole-plagioclase geothermometer. Oxygen fugacity was defined from the triangle Fe^{3+}-Fe^{2+}-Mg of Wones & Eugster (1965) based on the composition of biotites. Biotites plot between the Ni-NiO and Fe_3O_4-Fe_2O_3 buffer curves and give an average value of $\log f_{O_2} = -12$. The presence of magmatic epidote along with the compositions of Mg-biotite and amphibole suggest crystallization under relatively oxidizing conditions.

6. DISCUSSION

The Sithonia pluton consists of metaluminous to slightly peraluminous rocks ranging from tonalite to leucogranite. It is calc-alkaline with Na>K and continuous compositional trends from Ton to LG except HBGd which deviates from the linear trend in some variation diagrams. This deviation is also seen in some hornblende and biotite major and trace element variation diagrams (Fig. 3). Christofides et al. (1990), based mostly on Sr, Rb, and Ba abundances and variations, interpreted the evolution of the Sithonia pluton as due to fractional crystallization during which radiogenic crustal material was incorporated. To model the hypothesis of fractional crystallization for the evolution of the Sithonia pluton the average major element compositions of the rock-types have been used. The average composition of the Ton, the least differentiated rock-type, was taken as the parental magma, while the average compositions of HBGd, BGd, TMG, and LG were selected as liquids. The least-squares regression method was employed using compositions of the rock constituents. From Ton to HBGd 26% crystallization (plagioclase, hornblende, biotite) is needed, while from HBGd to BGd 6% (plagioclase, biotite, K-feldspar), from BGd to TMG 18% (plagioclase, biotite) and from TMG to LG 5% (plagioclase, biotite) crystallization is required.

To test the results of major element model, Ba, Rb, and Sr as well as ratios of them were used since these elements are strongly tied to the major minerals (feldspars, micas) of the granite. The distribution of trace elements during fractional crystallization is examined using the Rayleigh fractionation law. To calculate the bulk partition coefficient D values for Ba, Rb, and Sr, the average contents of Ba, Rb, and Sr of Ton, the modal composition of the residual solids (cumulate) and the weight fractions of melt remaining (F) based on major element mixing calculations, and partition coefficient Kd values for dacites and rhyolites (Arth, 1976; Nash and Crecraft, 1985) were used.

The calculated Rb, Sr, and Ba values along with the observed ones are shown in Table 2. Calculated *Rb, Sr, and Ba abundances and Ba/Rb and Sr/Rb ratios are fairly close to the observed for the LG and TMG* although Sr is lower and Ba is higher in LG than the observed. Calculated Rb, and Ba values are close to the analytical data for the BGd while Sr and Sr/Rb is lower in the same rock-type.

In the HBGd calculated and observed values for Ba, Rb, and Ba/Rb are similar while calculated Sr and Sr/Rb are lower in the same rocks. The differences between observed and calculated values may be due either to the Kds used or/and to deformation of the rocks (Christofides et al., 1990).

Available Sr isotopic data, however, show an increase of the initial $^{87}Sr/^{86}Sr$ ratio from 0.7055 in HBGd to 0.7072 in TMG with the least differentiated Ton having 0.7060 (Christofides et al., 1990; Table 4). Hence, a single fractional crystallization process cannot be considered for the Sithonia pluton evolution. Rather an AFC process must be responsible. On the other hand the slightly higher initial $^{87}Sr/^{86}Sr$ ratio of Ton, in respect to the more acidic HBGd, is difficult to be explained if we consider either FC or AFC process. One or more rock types may represent different magma pulses, and additional isotopic data may help to resolve the problem.

Table 2. Observed and calculated abundaces of Sr, Rb, and Ba in solids and liquids.

	SiO_2	Rb(obs)	Rb(cal)	Sr(obs)	Sr(cal)	Ba(obs)	Ba(cal)
C0(Ton)	64.29	75	75	935	935	792	792
Cl(HBGd)	68.30	91	91	755	539	820	829
Cl(BGd)	69.13	83	91	674	469	664	703
Cl(TMG)	72.90	109	116	383	319	529	585
Cl(LG)	74.40	125	121	416	287	507	603

An alternative hypothesis for the evolution of the Sithonia pluton is the one suggested by D'Amico et al. (1990) who interpreted the Sithonia pluton as an I-type granite with cogenetic characteristics generated by melting of an infracrustal source formed by underplating of (meta?)magmatites, in accordance with Chappell and Stephens' (1988) model. The underplated (meta?)magmatites probably had calc-alkaline comagmatic character which has been inherited by the present Sithonia rocks.

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