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EMPLACEMENT AND DEFORMATION OF THE SITHONIA GRANITOID PLUTON (MACEDONIA, HELLAS)

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ABSTRACT

The Sithonia granitoid pluton is an Eocene I-type calc-alkaline body emplaced, concordantly with its envelope, at the boundary between the Serbomacedonian Massif and the Circum Rhodope Belt, in Central Macedonia.

Its exposed part has a rather elliptical shape with the long axis in NW-SE direction. However the internal structures and its possible connection with the neighbouring granitoids (i.e. Ouranoupolis and Gregoriou granitoids) indicate that the WSW-ENE direction has played a very important role in its emplacement.

Over most of its outcrop, the Sithonia granitoid pluton reveals a planar fabric (S-fabric), which varies in intensity, but increases toward the margins. It is a magmatic foliation in the interior and a solid-state one at the marginal parts, where the fabric is planar-linear (SL-fabric) with the development of a WSW trending stretching lineation. Both the solid-state foliation and stretching lineation of the marginal parts are in a similar orientation to the foliation and stretching lineation of the country rocks (Svoula Group, Chortiatis Magmatic Suite and Vertiskos Unit) of the envelope.

A regional deformation episode subdivided into two progressive D1 and D1' deformation stages and affected both the envelope and the Sithonia granitoid pluton, has been recognized. It is related to the emplacement of the Sithonia granitoid pluton and is responsible for the modification of the initially magmatic foliation into the solid-state one.

The D1 stage (shearing, top to ENE) is a pure ductile process and associated with the solid-state foliation and WSW trending stretching lineation observed in the envelope, contact aureole and the marginal parts of the Sithonia granitoid pluton. The D1'stage (NNW-SSE shortening) is a ductile to ductile-brittle and even brittle process, which caused the final configuration and folding of the planar fabric, as well as, the observed semi-brittle shear zones and 'early joints' of the granitoid.

The Sithonia granitoid pluton reveals the characteristics of a syn-tectonic granitoid in respect to the regional deformation episode (D1 and D1' stages). The possible emplacement mechanism could be the

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syn-tectonic ballooning due to the external tectonic forces.

The fact that the Sithonia granitoid pluton is a syn-tectonic granitoid and crystallized in Middle Eocene times (about 50 Ma) lead us to suggest a regional pre- syn- Middle Eocene deformation episode, which was imprinted in the Sithonia granitoid pluton and extended at least to Oligocene.

INTRODUCTION

The relationship between deformation, metamorphism, and magmatism in complicated orogenic belts is critical in understanding their orogenic evolution. Paterson & Tobisch (1988) pointed out that the timing of regional deformation can often be bracketed by using radiometrically dated plutons and the relative timing of their emplacement and regional deformation. Thus, the examination of the role and emplacement of the plutons within the orogen is crucial and has challenged geologists for many years.

In the Hellenic orogen, having a complex history and including many plutonic bodies, such studies might be valuable in understanding its evolution. However, significant problems arise from the strain patterns revealed in plutons. These strain patterns may be extremely complicated since they are created either by the regional stress field or by the force of the ascent and emplacement of the magma.

In this paper, we describe the particular characteristics, the internal structures and the evolution of the Sithonia granitoid pluton and outline its role and emplacement.

EMPLACEMENT MECHANISMS OF GRANITOID PLUTONS

Granitoid plutons generally appear as large bodies surrounded by metasedimentary or metavolcanic rocks developed under lesser P and T conditions than those required for granitoid genesis (Castro 1987). This situation has been interpreted as the result of intrusion of granitoid magmas into upper crustal levels from their origin zones which might be located either in lower crust or upper mantle.

To account for the rise of granitoid magma to higher levels, buoyancy can be considered the most important of the controlling physical factors of the ascent. Another important factor that controls the emplacement mechanism is the viscosity contrast between magma and wall rock, as has been suggested from the experimental studies with centrifuge models (Ramberg 1981). If the contrast is great (i.e. the magma has a low viscosity), magma will ascent along vertical zones as dike swarms. If the viscosity contrast is low, emplacement may be forceful and the result is a concordant intrusion. Generally the density of magma of granitic and granodioritic composition is lower than that of surrounding metasediments both in deep and shallow crustal levels (Ramberg 1980, Soula 1982).

In addition, natural examples suggest that external (regional) stress is also a major factor controlling the intrusion of magma (Castro 1987). Thus the intrusion process can be characterized as pre-, syn- and post-tectonic in respect to the regional deformation. Consequently, it is clear that the interaction of gravitational processes and horizontal movements (due to an anisotropic regional stress field) which is generally complex, is responsible for the emplacement of granitoid magmas at the upper crust. The principal emplacement mechanisms referred to in the literature (including natural, experimental numerical and theoretical researches) are doming, diapirism, ballooning, stoping, cauldron subsidence and dike propagation.

Doming, diapirism and ballooning are forceful emplacement mechanisms. In centrifuge experiments, doming and diapirism are considered as the initial and final stage in the evolution of a single process; diapirs are considered immature when they have domal or antiformal shapes (domes), and mature when they are mushroom-shaped (diapirs). They may predominate in a deeper level of the crust (Krohe 1991) or in the lower lithosphere and asthenosphere, as suggested by Anderson (1981), with the buoyancy stresses being the principal variable of the ascent process.

When the mature diapir reaches its final emplacement level it starts to spread out laterally (balloon). Thus continued or pulsatory injection of magma leads to a ballooning pluton. However, Castro (1987), pointed out that in nature, ballooning plutons can be the result of a change in shape induced by a regional horizontal shortening instead of a process resulting from the continued injection of buoyant materials into the centre of the pluton.

Magmatic stoping and cauldron subsidence are passive emplacement mechanisms (i.e. low viscosity magma), which may predominate in higher levels of the crust. Cauldron subsidence is considered as a special case of magmatic stoping and both of them create annular complexes and are of local importance in magma transport.

DESCRIPTION OF THE SITHONIA GRANITOID PLUTON

General setting and petrology

The granitoid pluton of Sithonia peninsula (fig. 1) is exposed at the boundary between the Serbomacedonian Massif and the Circum Rhodope belt, covering an area of about 350 km^2.

Kockel et al. (1977) interpreted the Sithonia granitoid to be related to the Arnea granite and to be a Jurassic syn- or late-orogenic intrusion, whereas Chatzidimitriadis et al. (1983) suggested a post- Middle Jurassic to pre- Middle Cretaceous intrusion age for the Sithonia pluton. Vergely (1984) pointed out the difficulty of determining the relationship between the granitoid emplacement and the general deformation. De Wet et al. (1989) mentioned the Eocene diapirism emplacement of the Sithonia granitoid and D'Amico et al. (1991) recognized an Eocene syn-intrusive deformation and a post-intrusive one during the Oligocene (Christofides et al. 1990).

The Serbomacedonian Massif, which covers the main part of the Chalkidiki area with a NW-SE general direction, includes two tectonic units; the lower Kerdillia Unit and the upper Vertiskos Unit (Kockel et al. 1977). Both the units consist of polydeformed and polymetamorhosed Pre-Alpine crystalline rocks, biotitic gneisses, migmatitic gneisses, two-mica gneisses, amphibolites, mica schists and marbles (Kockel et al. 1977, Chatzidimitriadis et al. 1985, Papadopoulos & Kilias 1985, Patras et al. 1988, Sakelariou 1990, Dimitriadis & Godelitsas 1991).

The Circum Rhodope Belt, following the same direction with the Serbomacedonian Massif, comprises low grade metamorphic rocks of Mesozoic age, which are placed in the Deve Koran-Doubia Unit, Melissochori-Cholomontas Unit and the Aspro Vrisi-Chortiatis Unit (Kaufman et al. 1976, Kockel et al. 1977).

In the Sithonia peninsula (fig. 1) the country rocks constituting the envelope into which the Sithonia granitoid pluton has intruded belong to the Circum Rhodope Belt. Only at some places such as NE of Sikia and N of Ormos Panagias village are rocks of the Serbomacedonian Massif (Vertiskos Unit) in direct contact with the Sithonia granitoid pluton.

The northwestern and western parts of the intruded envelope consist of Lower to ?Middle Jurassic phyllites, quartzites, and some carbonate intercalations belonging to the Svoula Group of the Circum Rhodope Belt (Melissochori-Cholomonta Unit). The southwestern and southern parts comprise (except for some small outcrops of the Peonias zone in the southernmost part of the peninsula) dioritic rocks s.l, metamorphosed in the greenschist facies to greenschists and gneisses (Sapountzis 1969, Kockel et al. 1977), which constitute the Chortiatis Magmatic Suite of the Aspro Vrisi-Chortiatis Unit. Unfortunately, the other parts of the envelope are concealed by the sea and are not observable.

The Sithonia granitoid pluton is an I-type calc-alkaline metaluminous to peraluminous body, which has been divided by Christofides et al. (1990) into five main types: leucogranites, two-mica granites (to granodiorite), Bi granodiorites, Hb-Bi granodiorites, Hb-Bi granodioritic tonalites.

Recent isotopic investigations, based mainly on the Rb-Sr method, have given an Eocene age to the intrusion of the Sithonia granitoid pluton (Vergely 1984, De Wet et al. 1989, Christofides et al. 1990).

Shape of the pluton

The overall shape of the Sithonia granitoid pluton is not known, because it is half concealed by the sea. However, the exposed part of the pluton has an approximately elliptical shape with the long axis in NW-SE direction. Two almost parallel narrow strips of country rocks striking WSW-ENE subdivide the outcrop of the granitoid body into three unequal parts (fig. 1). The WSW-ENE direction is clearly very important as it results from the internal structures of the Sithonia granitoid and on the reasonable assumption that the Sithonia granitoid pluton is related to the Ouranoupolis and Gregoriou granitoid bodies which are located in the third leg of the Chalkidiki peninsula. In addition, the WSW-ENE direction seems to play an important role in the emplacement of the granitoid plutons in the Rhodope Massif as has been described for the Vrondou granite (Kolocotroni & Dixon 1991).

From the above mentioned, it is clear that to deduce the probable shape of the pluton we must recognize and define its internal structures. In our case the Sithonia granitoid pluton has been found to be concordant with its envelope (figs. 1, 2), although in some places, there are some modifications of the regional trend.

Magmatic and solid-state internal structures

Generally, the granitic rocks show a variety of structural features. Some of these were developed in ductile conditions, whereas others appear to represent late stage near-brittle deformation. The most important and critical structure, although the most ambiguous, is the foliation.

Foliations in granitoids could be the result of: (1) flow during ascent, (2) diapiric emplacement and ballooning, (3) emplacement during regional deformation, (4) regional deformation postdating emplacement or (5) combinations of the above.

Although a continuum is likely to exist between magmatic and solid-state processes during the development of foliations in granitoids, there is also controversy over what criteria are reliable and useful for the distinction between foliations formed in the first or the second case. Paterson et al. (1989) divided this continuum into four types: magmatic flow, submagmatic flow, high-temperature solid-state flow, and moderate- to low-temperature solid-state flow

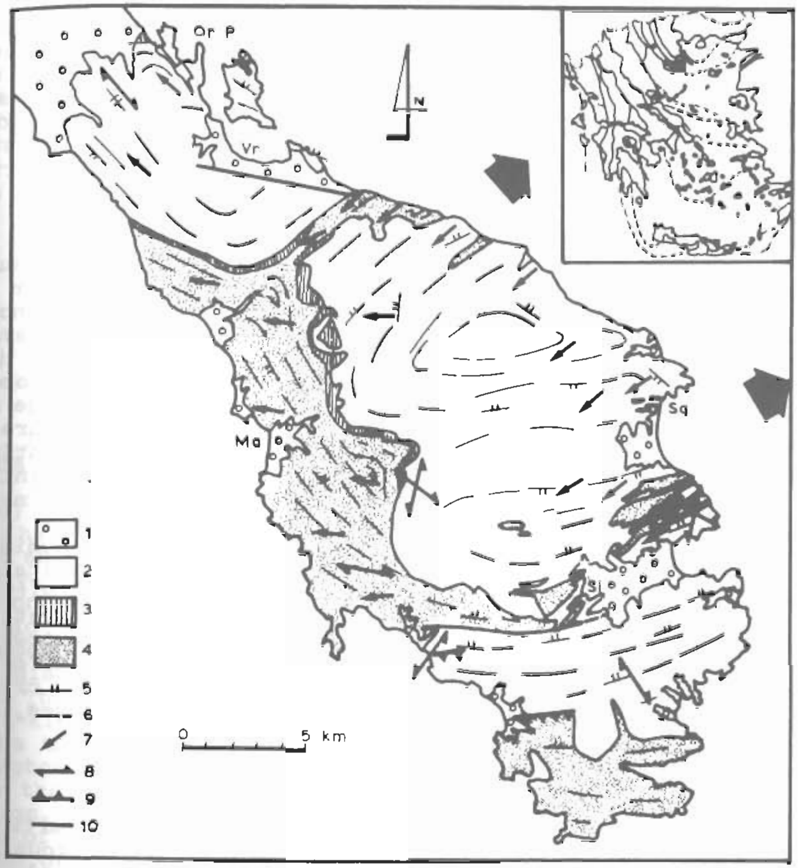

Fig. 1. Generalized geological and tectonic map of the Sithonia peninsula. 1. Neogene and Quaternary sediments, 2. Sithonia granitoid pluton (Eocene), 3. Contact aureole, 4. Country rocks including: Serbomacedonian Massif (Paleozoic), Circum Rhodobe belt (Triassic-Jurassic), Peonias zone (Mesozoic), 5. strike and dip of foliation, 6. foliation trajectories, 7. stretching lineation, 8. shear zone, 9. reverse fault, 10. fault. Thick solid arrows indicate the direction of movement. (Ma: Marmaras, OrP: Ormos Panagias, Sa: Sarti, Si: Sikia, Vr: Vourvourou).

Over most of its outcrop the Sithonia granitoid pluton reveals a planar fabric (S-fabric), which varies in intensity, but increases toward the margins. It is a S_T magmatic foliation in the interior (magmatic flow foliation according to Paterson et al. (1989); pre-full crystallization fabric (PFC) according to Hutton (1988)) and a S_{T1} solid-state one at the marginal parts with the metasediments of the Svoula group, where the fabric is planar-linear (SL-fabric, S≥L) with the development of a WSW trending stretching lineation.

The magmatic foliation is easily recognized in the Sithonia granitoid, both in the field and in thin sections, by the alignment of the primary igneous minerals such as quartz, K-feldspar, plagioclase, hornblende and biotite. In particular the alignment of the subhedral feldspars (fig. 3a) forcefully evidences the magmatic foliation, since nowhere we observe their recrystallization or plastic deformation. In addition, we have observed in thin sections imbrication or 'tiling' of K-feldspar crystals something that implies non-coaxial magmatic flow, involving rotation of the crystals in a viscous fluid (Blumenfeld 1983). However, following the idea of Hutton (1988) it could be also the result of the pre-full crystallization fabric (PFC) caused by strain of the whole body of partially crystalline magma. Anyway, the presence of the melt is of such amount that leaves no trace of strain in the crystals themselves.

Mesoscopically, the magmatic foliation is also recognized by the compositional and schlieren layering, which are the result of variations in the amounts of the different crystals species or in the crystal size of a single mineral species, although there are not very abundant features in the Sithonia granitoid pluton. Well developed structures of this type have been observed particularly in the Vourvourou area (fig. 3b). Schlieren layering has also been observed at the contact of the granitoid with the metasediments of the Svoula group to the East of Marmara village. Furthermore, the preferred alignment of elongate micrograniitoid enclaves with centimetric dimensions and sharp boundaries, but without showing any intracrystalline deformation or recrystallization, implies the magmatic foliation (Bateman et al. 1983, Vernon et al. 1988).

On the other hand, the S_{T1} solid-state foliation is dominant in the marginal parts. It is the result of the textural modification of the S_T magmatic foliation, which although is not uniform within the body increases towards/in the marginal parts. This modification has been taken place in the solid-state, through moderate- to low-temperature, ductile process and is related to a regional deformation episode. The later using only geometrical and kinematic criteria, could be subdivided into two progressive deformation stages, the D1 and D1'.

D1 DEFORMATION STAGE

This stage is very well established in the marginal parts of the granitoid pluton with the metasediments of the Svoula group, where a contact aureole up to 100 m is also observed (Kockel et al. 1977). It is associated with the formed S_{T1} solid-state foliation and L_{T1} stretching lineation of the granitoid and the contact aureole.

Both the S_{T1} solid-state foliation and the L_{T1} stretching lineation were found everywhere in concordance with the continuous (dominant) S_c foliation and the L_c stretching lineation, observed in the country rocks (Svoula Group and Chortiatis Magmatic Suite of Circum Rhodope Belt) away from the marginal parts. The general geometrical distribution of the above structures in Sithonia peninsula is shown in figs. 1, 2.

Moreover, isolated granitoid bodies which are observed in the country rocks and in the aureole have foliation and stretching lineation which are concordant with those of the country rocks and the aureole.

Within the aureole the S_{T1} foliation appears as transposition foliation associated with the WSW trending L_{T1} stretching lineation as detected by the elongate biotite, streaking, elongate pods of biotite, actinolite, and/ or epidote). Boudinaged and rotated leuco-sheets bodies as well as σ-rigid bodies along the S_{T1} foliation indicate a WSE-over-ENE movement (fig. 4c). The same sense of shear (the top to ENE) has also been indicated by σ-porphyroclasts and asymmetric microfolds.

The majority of the leuco-sheets intruding the aureole and the country rocks beyond, appeared concordant to the S_c (S_{T1} in the aureole) and penetrated by the S_{T1} foliation. However, other leuco-sheets have been observed to crosscut the envelope discordantly without showing to be penetrated by the S_{T1} foliation. In these cases they have been folded with shortening direction normal to the S_{T1} foliation (fig. 4d). The fact that they can be easily traced from the granitoid out into the surrounding wall rocks shows that their emplacement was not at the transporting stage of intrusion (i.e. during diapiric ascent), but after it had reached its final positional. The majority of minerals formed in the aureole were of syn- to post-kinematic growth (Vergely 1984; our observations) showing that the thermal aureole has been formed by ballooning deformation (syn-tectonic, in our case), rather diapiric ascent (England 1990).

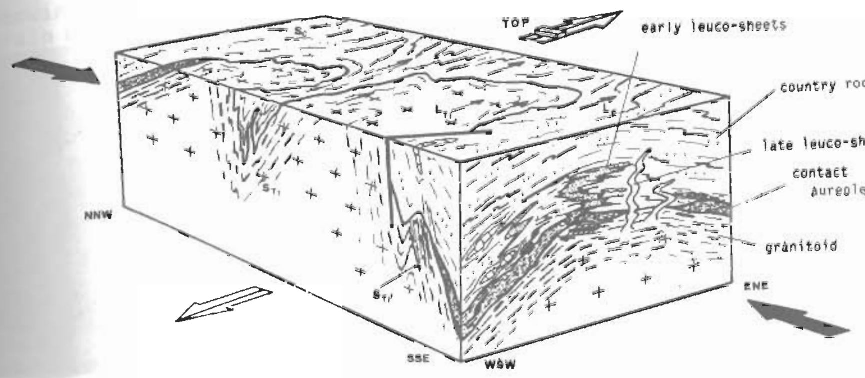

Fig. 2. Block-diagram showing the general tectonic situation of the Sithonia granitoid pluton and the country rocks of the envelope.

In the Sithonia granitoid the WSW trending L_{T1} stretching lineation (figs. 4a, 5b), which is the most characteristic and important feature of the D1 deformation stage, diminishes rapidly towards the interior of the granitoid. In contrast, the planar fabric remains observable inwards, but its modification and intensity decrease, since there is a gradual passage from the S_{T1} solid-state foliation to the S_T magmatic foliation. Despite the apparent or real scarcity of submagmatic microfractures in granitoids, due to erasure or obliteration from solid-state microstructures and the transient of the submagmatic state itshelf, we have observed from the marginal parts inwards, some microfractures such as the quartz infilled microfractures transecting single feldspar crystals (fig. 3c). These observations are indicatives of the submagmatic state and consequently the syn-tectonic intrusion of the Sithonia granitoid pluton.

Myrmekite is presented with more intensity in the well foliated parts of the granitoid showing that it is closely related to the modification processes (Simpson & Wintcsh 1989, Vernon et al. 1983). Soldatos & Sapountzis (1975) mentioned the general polygenetic character of the myrmekite formation and pointed to two main processes: such as solid-state exsolution and interaction between solid-state exsolution and metasomatic processes.

Mesoscopically, the S_{T1} foliation appears usually as a gneissic to mylonitic foliation. Some small xenoliths with sharp boundaries have been found extremely elongated with aspect ratios 10:1 and penetrated without refraction by the S_{T1} foliation. This attests to their negligible viscosity contrast and reflects homogeneous strain of both components in a bulk solid state.

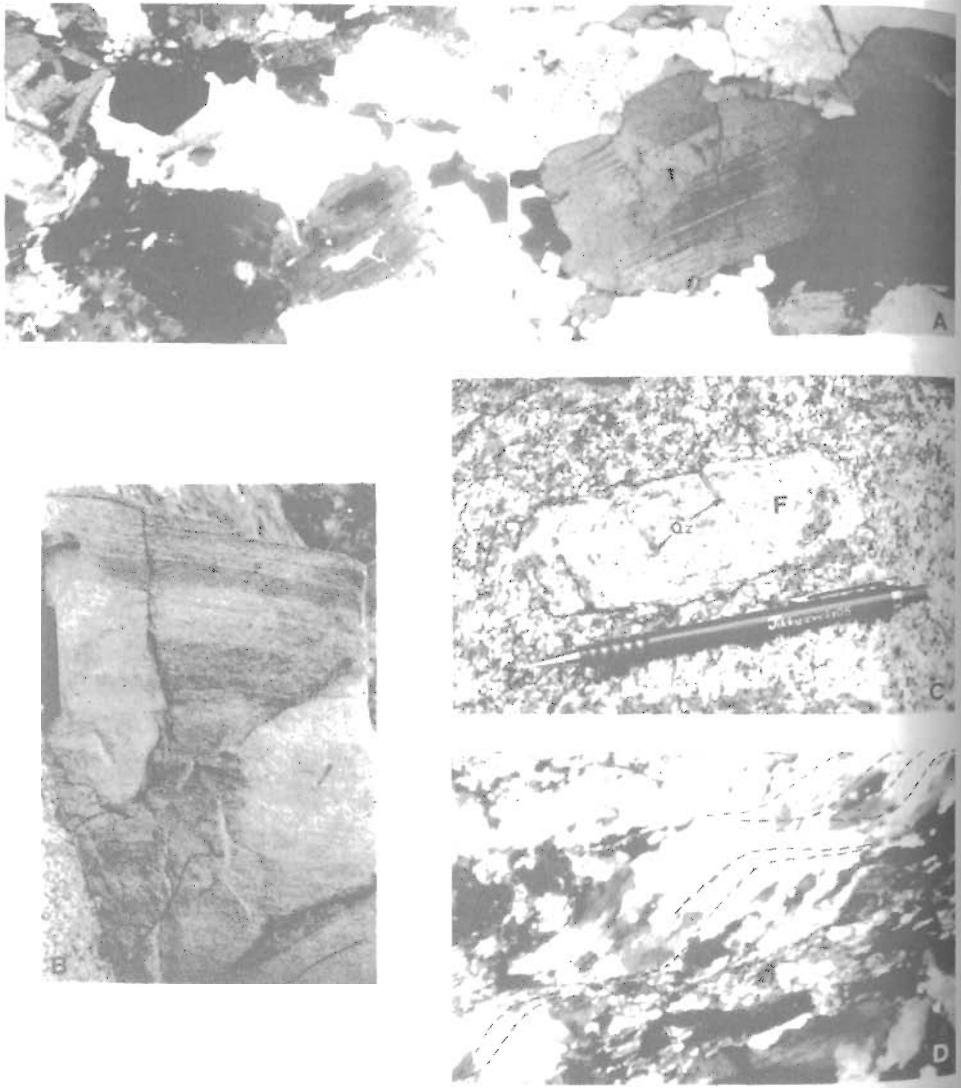

Fig. 3. (A),(D) photomicrographs of rock samples and (B),(C) field photographs from the Sithonia granitoid pluton: (A) Magmatic foliation defined by alignment of feldspars; they surrounded by no recrystallized aggregates of quartz (crossed nicols, x40), (B) Magmatic foliation as defined by schlieren layering in the Vourvourou area (hammer: 35 cm long), (C) Quartz infilled micro-fractures transecting a single feldspar crystal (submagmatic state), F: feldspar, Qz: quartz, (D) Solid-state foliation defined by elongated recrystallized aggregates of quartz. Sense of shear is top to right (crossed nicols, x40).

Under the microscope, the quartz aggregates are elongated showing undulatory extinction, polygonization, irregular and serrated grain boundaries, recrystallization giving rise to a 'ribbon' texture (fig. 3d). The biotite has altered into chlorite. The feldspars, without showing recrystallization, behave as fracturing rotate rigid crystals and the orthoclase inverts to microcline. In general, a grain size reduction took place.

Additionally, we have found S-C mylonitic foliations (type I S-C mylonites after Lister & Snoke 1984) associated with a strong stretching lineation L_{T1} (on both planes) showing that the sense of shear was top to ENE. The intersection angle of the S-C surfaces was about 20° (fig. 4b).

In the eastern part of the Sithonia peninsula, the country rocks, which belong to the Vertiskos Unit, have a S_c foliation striking WSW-ENE, but always concordant to that of the granitoid, whereas the L_c stretching lineation has a relatively constant WSW trend with the sense of shear top to ENE.

The general strain patterns of the envelope and the aureole as well as the granitoid margins, are rather of flattening type caused by general shortening normal to the foliation with the addition of a shearing component in the WSW-ENE direction. It results from the observed competent particles of the quartzites and quartz-mica phyllites of the Svoula group which are boudinaged and usually form pinch-and-swell structures. The boudins have rather oblate forms. The boudinaged leuco-sheets found within the aureole also behave as competent layers. In some of these instances we observe a small amount of rotation showing the WSW-over-ENE sense of shear. Moreover, in the S-fabric dominated parts of the granitoid the maximum shortening of the finite strain ellipsoid is inferred to be normal to the S-fabric (Ramsay 1989), and the observed micr至granitoid enclaves have an oblate form.

D1' DEFORMATION STAGE

This stage is characterized by a general NNW-SSE shortening of the area. It affects the earlier structures of both the granitoid and the envelope, but also creates new ones in geometrical and/or kinematic compatibility.

It is considered as the stage responsible for the final configuration of the planar fabric (S_T or S_{T1} foliation) of the Sithonia granitoid pluton and fairly recognized, macroscopically, by its general standing, which at the most part of the granitoid shows a WSW-ENE strike coinciding with the B-axes trending (figs. 1, 5a). Mingling structures involving granitic material and country rocks are also aligned along this WSW-ENE direction (fig. 4e).

Furthermore, D1' stage has created, locally and parallel to the axial planes of the folds, a $S_{T1'}$ solid-state foliation.

The fact that the maximum shortening axis of the D1' stage is oriented orthogonally to the maximum extension axis of the D1 sta-ge, possibly, implies the progressive relationship of the D1 and D1' stages (Watkinson 1975).

Dispersed xenoliths of various dimensions, possibly derived from magmatic stoping processes, have been found everywhere in concordance with the S_T magmatic foliation. Both the xenoliths and S_T foliation have been folded during this D1' deformation stage (fig. 4f).

Additionally, the two WSW-ENE trending narrow strips mentioned earlier have to be controlled by this NNW-SSE shortening.

However, in many places the folded S_T foliation has been intruded by later, undeformed, leuco-sheets implying that the deformation was at least synchronous with intrusion (fig. 4d).

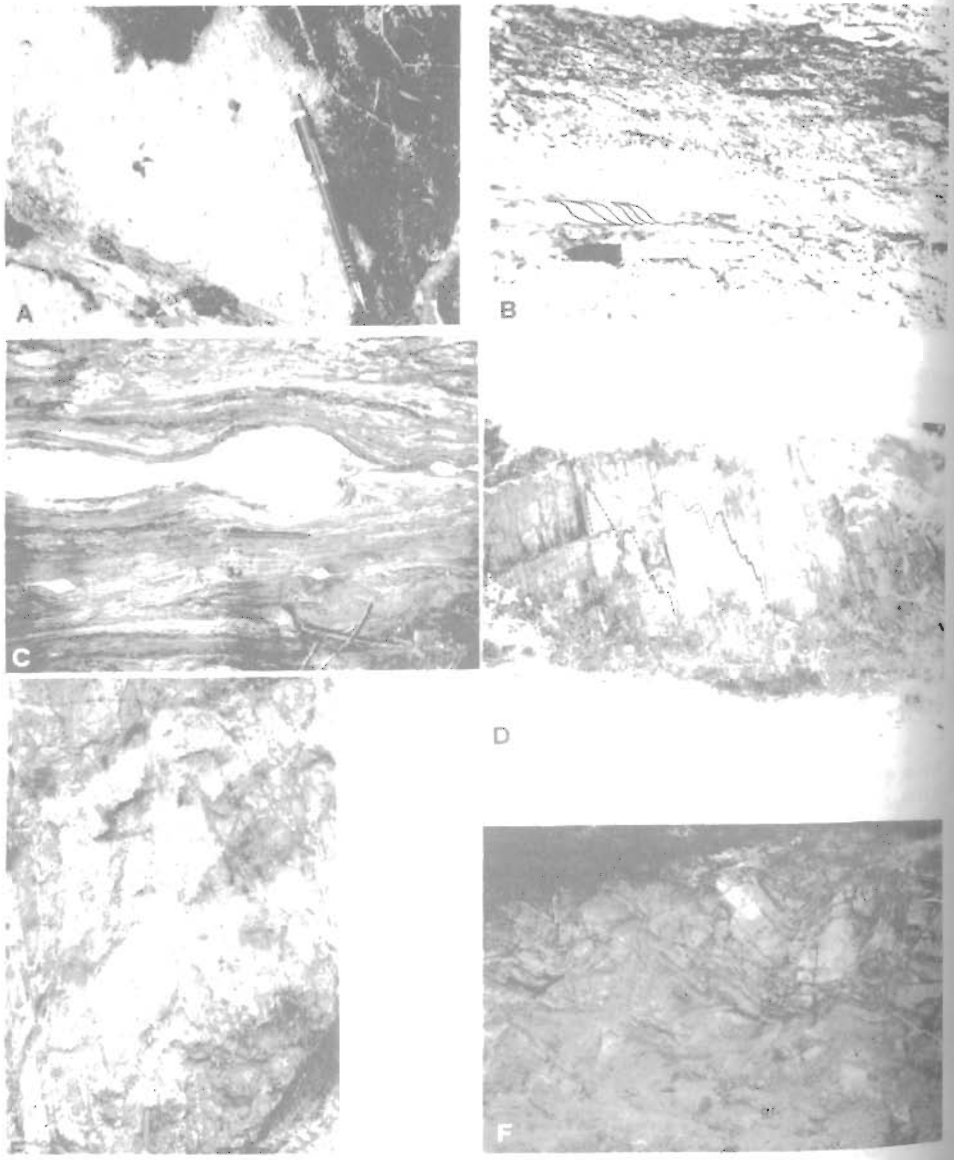

Fig. 4. Field photographs of mesoscopic structures observed in the Sithonia granitoid pluton and the country rocks of the envelope (hammer: 35 cm long): (A) Stretching lineation L and (B) S-C mylonitic fabric, sense of shear top to left, in the granitoid [illegible] to Parthenonas village, (C) Rotated early leuco-sheet boudins and asymmetric σ-rigid bodies within the aureole east of Marmaras,

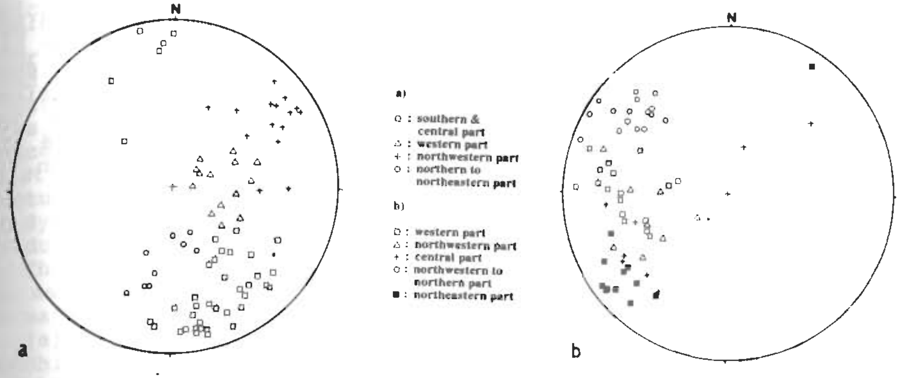

Fig. 5. Equal area, lower-hemisphere projections of (a) poles to foliation of the Sithonia granitoid pluton (squares; n = 82), (b) poles to stretching lineation of the Sithonia granitoid pluton and the country rocks (circles; n = 64).

The most important conclusion of the structural analysis is that the D1' deformation stage, although is a pure ductile process as clearly implied by the folding of S_T or S_{T1} foliation, continuous up to ductile-brittle and even brittle processes related to the late cooling stage of the granitoid emplacement. The following observations support this conclusion.

Within the granitoid we observe planar semi-brittle shear zones, which are vertical or steeply inclined and have generally a NW-SE and/or NNE-SSW direction (fig. 1). They occur in parallel sets with similar sense of displacement or in crossing sets with two directions making a conjugate arrangement of broadly synchronous aspect. Within the conjugate sets, the NW-SE striking set always shows a dextral sub-horizontal sense of displacement and the other NNE-SSW striking set shows a sinistral, also sub-horizontal, sense of displacement. The overall displacement of the shear zones, either conjugate or not, is such as to imply shortening in a NNW-SSE direction. The width of these shear zones is a few centimetres and the pre-existing foliation is deflected into these zones. Along the shear zones biotite has altered to chlorite.

Analogous vertical or steeply inclined shear zones, but with greater width, have been found in the country rocks (Svoula Group and Chortiatis Magmatic Suite) around the granitoid. They show a well developed S-C fabric giving the same NNW-SSE shortening observed in granitoid.

We have also observed some reverse faults affecting both the country rocks and the granitoid pluton. These reverse faults strike generally E-W and have been observed to modify the southern contacts between the granitoid and the Chortiatis Magmatic Suite.

Furthermore, the 'early joints', which are post-crystallization

Fig. 4. (continued): sense of shear is top to left, (D) Folded early leuco-sheets with axial planes parallel to S_c, south of Sarti, (E) Marginal part of the Sithonia granitoid pluton, south of Sarti. Mingling of the granitic material with the country rocks of the envelope-forming S-fabric (S_T) parallel to S_c, (F) Asymmetric folds, due to D1' deformation stage, affected both the Sithonia granitoid (gr) and the country rocks (c.r).

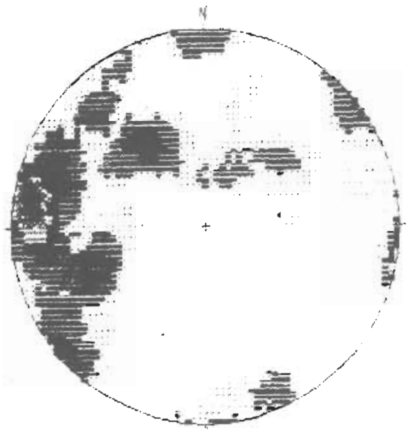

Fig. 6. Pole-density diagram (Equal area, lower hemisphere projection) showing the preferred orientation of the 'early joints' (n = 999) of the Sithonia granitoid pluton.

features and related to late cooling stage of emplacement, are aligned along a NNW to NNE direction of shortening, which the later could be incorporated into the D1' deformation stage (fig. 6).

An important problem concerning the internal structure of the Sithonia granitoid pluton in its northern part is the remarkable change in the trend of the L_{T1} stretching lineation. Specifically, the stretching lineation in the country rocks, the aureole and the granitoid has a NW-SE (N300°-320°) trend, which is quite different from the constant WSW-ENE trend of the L_{T1} in all the other areas of the Sithonia peninsula (fig. 5b). The sense of shear is top to SE, as indicated by K-feldspar σ-porphyroclasts and the S-C fabric which is the dominant feature of the granitoid in that part. It is very difficult to attribute this change in the D1 or D1' stage. It could be the result of the D1 stage which has been affected latter by the D1' stage or is the result of the D1' stage. In our opinion, it is a progressive result of the D1 to the D1' stage, since this deflection in the trend is not abrupt from that of the southern parts, but gradual. Moreover, the same is also inferred, in more regional scale, from the similar bending of the general trending of the geotectonic zones in this area.

DISCUSSION

As we mentioned in previous section the discrimination of the processes of the emplacement mechanism is a very complicate problem, since the criteria which commonly used to distinguish the structures related to each or the other are not generally admitted (Paterson & Tobisch 1988). The problem is enlarged when the emplacement mechanism involves both magmatic and solid-state processes, as commonly has been demonstrated in syn-tectonic granitoids. Thus, Berger & Pitcher (1970) drew attention to the difficulty involved in distinguishing fabrics developed in pluton that consolidated during a phase of regional compression, from those developed as a consequence of forceful emplacement of magma. In that case the problem relates to the discrimination between magmatic and solid-state structures. Paterson et al. (1989) pointed out that within the syn-tectonic plutons evidence of high-temperature subsolidus deformation or deformation of magmas by 'submagmatic flow' should occur. On the contrary, Brun et al. (1990) stated that within syn-tectonic plutons the transition between intrusion-induced fabrics and purely tectonic

fabrics has no basic reason to coincide with the magmatic - solid-state transition as Paterson et al. (1989) have pointed out. The latter is obviously directly controlled, in space and time, by the thermal evolution within the pluton, whereas the former, which reflects the relative ratio between internal forces and tectonic forces, is clearly linked to bulk crystal mechanics operating during emplacement. Finally, Castro (1987) mentioned that in most cases such a distinction is irrelevant and unrealistic because deformation structures (foliations, shear zones etc.) can be caused by emplacement dynamics, and flow structures can be the result of an externally-induced deformation processes.

The Sithonia granitoid pluton reveals characteristics (fig. 2) such as of a syn-tectonic granitoid in respect to the regional deformation state (D1 & D1' stages). These characteristics are:

(a) The similar orientation of both the S_{T1} foliation and L_{T1} stretching lineation of the granitoid with the S_c foliation and L_c stretching lineation of the country rocks.

(b) The presence within the granitoid of xenoliths which have been deformed by the regional deformation (D1 & D1' stages).

(c) The syn-kinematic-to-D1 stage growth of minerals of the contact aureole.

(d) The simultaneous folding of both the granitoid and the country rocks, due to D1' stage.

(e) The fact that there are both leuco-sheets which have been affected by the D1 stage and others which crosscut the S_c foliation without having any internal deformation.

(f) The superposed development of the S_{T1} solid-state foliation onto the S_T magmatic one through the submagmatic state.

The fact that the Sithonia granitoid pluton, presents a pronounced planar fabric (S-fabric), which although controlled by the regional stress state, is parallel to the contacts and more intensive toward them, indicates that, although the internal forces are less intense in comparison with the external ones, have played a quite significant role in the emplacement mechanism. Besides, the above feature and the syn-kinematic growth of metamorphic minerals in the contact aureole have been used as evidence of a ballooning emplacement. This emplacement mechanism can be caused either by buoyancy forces (Ramsay 1981, Bateman 1985) or tectonic shortening (Castro 1987). In addition, D'Amico et al. (1990) stated that in rather the central part of the Sithonia granitoid pluton there was a dome-like relatively younger intrusion of Bi granodiorites into Hb-Bi granodiorites to Hb-Bi granodioritic tonalites.

Consequently, we are in favour of a syn-tectonic ballooning emplacement mechanism for the Sithonia granitoid pluton due to the tectonic forces rather than to the buoyancy ones.

Referring to the regional geology we could compare the D1 stage (shearing, top to ENE) of the Sithonia area with the D1 stage (shearing, top to SW) which took place in Eocene-Oligocene times in the Rhodope Massif, as suggested by Kilias & Mountrakis (1990) and Kolocotroni & Dixon (1991), although the sense of shear is opposite. The fact that the Sithonia granitoid pluton was a syn-tectonic one crystallized in Middle Eocene times (about 50 Ma) lead us to suggest a regional deformation episode in pre- syn- Middle Eocene times, which was imprinted in the Sithonia granitoid pluton and extended at least to Oligocene. Likewise, the D1' stage of the Sithonia peninsula could be analogous to the D1' compressive stage of the Rhodope Massif, which after Kilias & Mountrakis (1990), took place in the Eocene-Oligocene times. The similarity in the geometrical and kinematic features in both areas support this comparison.

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