THE GRANODIORITES WITH BIOTITE NODULES IN THE NORTHERN SEBEȘ MOUNTAINS (SOUTH CARPATHIANS)

STELEA Ion, GHENCIU Monica

In memoriam Marin Șeclăman (1938-2019)

Abstract. A large swarm of rhyodacite dykes and some granodiorite bodies outcrop along the Rășinari Shear Zone in the northern Sebeș-Cibin Massif. The rhyodacites are Cretaceous in age and the granodiorites are older (Liasic probably) since they frequently occur as lithic restites in rhyodacites. Two granodiorite bodies on the central sector of the shear zone contain spheroidal biotite nodules, a rare petrographic feature found only in granitoid rocks. The typical internal structure of the nodules is quasi-concentric, with thick shells of biotite arranged around a central core consisting of intergrowth of biotite-quartz and biotite-plagioclase. The large nodules of 3-5 cm are polycentric, with two or three secondary centers around the core. According to Van Diever (1970), the biotite nodules in the granite of Craftsbury (Vermont, US) were formed by adhering of biotite sheets around some gas bubbles to which additional gas bubbles were attached during the ascending migration through a low viscosity, volatile-rich magma. The nodules float until the collapse of the gas bubble and the nodules with uncollapsed bubbles agglomerate in the ceiling of the magmatic chamber. The pegmatitic segregations in the granodiorites with biotite nodules from the north of the Sebeș Mountains corroborated with our microscopic observations support this hypothesis.

Keywords: granodiorites, biotite nodules, Sebeș Mts., Romania.

Rezumat. Granodioritele cu noduli de biotit din nordul Munților Sebeș (Carpații Meridionali). În lungul zonei de forfecare Rășinari, în nordul Masivului Sebeș-Cibin aflorează un roi de filoane de riodacite de vârstă cretacică și mai multe corpuri de granodiorite mai vechi (probabil liasice), care apar frecvent ca restite litice în riodacite. Două corpuri de granodiorite de pe segmentul central al zonei de forfecare conțin noduli sferoidali de biotit, o particularitate petrografică rară, întâlnită doar în roci granitoide. Structura internă tipică a nodulilor este cvasi-concentrică, cu pachete groase de biotit dispuse în jurul unui nucleu central constituit din concreșteri biotit-cuarț și biotit-plagioclaz. Nodulii mari de 3-5 cm sunt policentrici, cu două sau trei centre secundare în jurul nucleului. După Van Diever (1970), nodulii biotitici din granitul de la Craftsbury (Vermont, SUA) s-au format prin aderarea foițelor de biotit în jurul unor bule de gaz de care s-au atașat și bule adiționale în timpul migrării ascensionale printr-o magmă cu vâscozitate mică, bogată în volatile. Nodulii flotează până când bula de gaz colapsează iar nodulii cu bule necolapsate se aglomerează în tavanul camerei magmatice. Segregațiile pegmatitice din granodioritele cu noduli de biotit din nordul Munților Sebeș coroborate cu observațiile noastre microscopice susțin această ipoteză.

Cuvinte cheie: granodiorite, noduli biotitici, Munții Sebeș, România.

INTRODUCTION

The granitic rocks with nodular (orbicular) concentrations of biotite are extremely rare. So far only two granite bodies with biotitic nodules are known. One is in Craftsbury (Vermont, U.S.), belonging to the New Hampshire plutonic series of Lower Devonian age (VAN DIEVER, 1970). The second is in Castanheira (Portugal), part of the Serra da Freita pluton syntectonically intruded in the area of the homonymous transcurrent shear zone of Hercynian age (REAVY, 1987). Both magmatic bodies contain agglomerations of biotite nodules accumulated in front of an obstacle which can be the ceiling of the magmatic chamber or its walls.

The orbicules in the granite of Craftsbury have spherical or flattened-spheroidal shapes, with diameter of 2-3 cm to 5 cm. They contain a granitic core (plagioclase with albite borders, quartz and finely crystallized biotite) surrounded by thick biotite packages, frequently microfolded, associated with quartzo-feldspathic material and subhedral muscovite transverse to the biotite trends. Minor amounts of calcite, sphene, rutile, apatite and zircon also appear. The presence of calcite is attributed by the author to the carbonatic nature of the country rocks of the granite. The biotitic nodules in the granite of Castanheira have similar shapes, structures and dimensions (1.5-7 cm). The granitic core also contains a muscovite transverse to the biotite and the outer zone consists of biotite-quartz intergrown with compact biotite intercalations (REAVY et al., 1993). Like in the granite of Craftsbury, the biotite show crenulations. Among the possible causes of biotite deformation formulated by VAN DIEVER (1970) we mention three: a) cooling contraction, b) crystallization pressure of large grains (quartz, plagioclase) and c) flattening of the nodules during their crowding in the ceiling of the magmatic chamber.

VAN DIEVER (1970) explains the formation of biotite nodules by the accumulation of biotite crystals around gas bubbles (H_2O, CO_2) and enlarging the nodules with additional bubbles during the ascending migration through a low viscosity magma. REAVY et al. (1993) adopt this hypothesis, reformulated on the basis of other mineral assemblages and of their own analytical data. The authors consider that the biotite did not crystallize directly from the magma but would be the result of chemical reactions between the gas bubbles (H_2O, Cl, $FeCl_2$) and the granitic melt.

Here we report the presence of the biotite nodules in two granodiorite bodies in the northern Sebeş Mountains outcropping inside or close to the Răşinari Shear Zone. This is a Hercynian normal fault intermittently reactivated as transcurrent sinistral fault during the Lower Jurassic-Lower Cretaceous span time (STELEA, 2000). In the paper we make an analysis of the geo-tectonic context in which these magmatic bodies outcrop, as well as a petrographic description of the biotite nodules and of the host granodiorites based on microscopic study.

THE GEO-TECTONIC CONTEXT

The Getic Crystalline. The Getic Crystalline in the Sebeş-Cibin Massif area is made up of two litho-tectonic complexes with distinct petrographic natures, separated by a cryptic pre-Hercynian tectonic plane (STELEA, 2000). The lower complex is granito-gneissic while the upper one is leptino-amphibolitic and metapelitic. Their homogeneous metamorphic history records two medium-grade metamorphic events. The first, of Cadomian age (M1), is sin-collisional, and the second, of Hercynian age (M2), is related to the post-collisional uplift when the regional tabular structure of the metamorphic pile was formed as result of the flattening during the uplift (STELEA, 2000). The Alpine low-grade metamorphism (M3) in the Getic Crystalline area of the Sebeş-Cibin Massif is practically absent, significant Alpine deformations being strictly localized along the Răşinari Shear Zone.

The Răşinari Shear Zone (RSZ). At the present level of erosion, RSZ is a lineament of mylonites and cataclasites, with a length of 150 km, which crosscut the northern part of the Sebeş-Cibin Massif from the Strei Valley to the Olt Valley. The width of the RSZ to the erosion surface varies from a few meters to 3 km, but the shear zones tend to be wider in depth under medium- to high-grade conditions of deformation (e.g. PASSCHIER et al. 1990). The exposed medium-grade mylonites were formed during the Hercynian phase of tectonic activity when the shear zone worked as normal dip-slip fault accommodating the higher uplift rates in the axial area of the orogen as against to its northern margin. The $^{40}Ar/^{39}Ar$ dating on muscovite concentrates from mylonites indicates the Upper Carboniferous age of 285.7 ± 0.5 Ma (DALLMEYER et al., 1998.

The cataclasites were formed during the Alpine reactivation of the RSZ as sinistral strike-slip fault, in the context of a transcurrent tectonic regime north of the central South Carpathians. The cataclastic deformation heterogeneously affected both the Hercynian mylonites and the Getic Crystalline adjacent to the shear zone. The $^{40}Ar/^{39}Ar$ dating on muscovite from cataclased mylonites show the Liasic age of 185.3 ± 0.5 Ma (DALLMEYER et al., 1998).

A large swarm of magmatic rocks, consisting of at least 400 dykes of rhyodacites and of 30 granodiorite bodies, outcrop along RSZ. The anatectic origin of rhyodacites and their genetic relationship with the shear zone has been demonstrated by STELEA (2000). The favourable conditions of anatexis were achieved at the base of the middle crust towards the end of the Alpine tectonic movements on RSZ. The high temperature and relatively low pressure are attested by the numerous alpha-quartz after beta-quartz paramorphoses in rhyodacites and by the presence of cordierite in several dykes. The $^{40}Ar/^{39}Ar$ dating on biotite from two dykes of rhyodacites on the Sebeş Valley (DOBRESCU & SMITH) show cooling ages of 108.4 ± 0.5 Ma and of 109.3 ± 0.5 Ma, corresponding to the Albian.

The parent rock of rhyodacites is a granodiorite which frequently occur as lithic restites in rhyodacites, identical to the granodiorites which outcrop to the surface erosion. There are no geochronological data for granodiorites. Logically, they are older than the rhyodacites. Most likely, the age of the granodiorites can be Liasic, i.e. synchronous with the beginning of the Alpine tectonic movements along the RSZ. The genetic relationship of the granodiorites with the shear zone is still unclear. Several bodies of granodiorites were affected by the Alpine cataclastic deformation and by subsequent anatectic processes starting on the intergranular spaces.

FIELD DATA

The central sector of RSZ. The largest bodies of granodiorites, with lengths of 800-1200 m and thicknesses of 200-500 m, outcrop in the hydrographic basins of the rivers Romoşel and Sasu on the central sector of RSZ, about 20 km long between the Tisa River (a left tributary of the Sibişel River) and the Cugirul Mare River (Fig. 1). This sector has particular features compared to the eastern and western sectors, such as: I) the largest number of rhyodacites dykes (approx. 200) and granodiorite bodies (21), II) the xenoliths of mylonitic country rocks in the granodiorites on the Sasu Valley (Fig. 2a), III) the biotite nodules in the granodiorite bodies on the Sibişel Valley and the Cugirul Mare Valley (Fig. 2b-f), IV) the pegmatitic and quartz segregations in the granodiorites with biotite nodules.

On the central sector of the shear zone local phenomena of contact metamorphism in the country rocks of several granodiorites bodies were also identified, highlighted by the crystallization of high temperature-low pressure minerals such as andalusite, on the right side of the Sibişel Valley (STELEA, 2000), and cordierite, on the left side of the Sasu Valley (Fig. 3m).

One last field observation refers to the symmetry of the magmatic activity as against the shear zone lineament. The rhyodacite dykes and the granodiorite bodies on the central sector symmetrycally outcrop on both side of the shear zone (Fig. 1). Due to the Alpine sinistral displacement along the shear zone, most of the magmatic rocks west of the Cugirul Mare River are now outcropping only on the northern side of the RSZ while those east of the Sibişel River basin only on its southern side.

The field data presented above lead us to the conclusion that the central sector of the RSZ crosscut the apical zone of a granodiorite batholith whose apophyses outcrop at the present level of erosion. Arguments that support this hypothesis are the large size of the granodiorite apophyses, the mylonitic xenoliths in the granodiorites on the Sasu Valley, and the pegmatitic segregations in the granodiorites with biotite nodules.

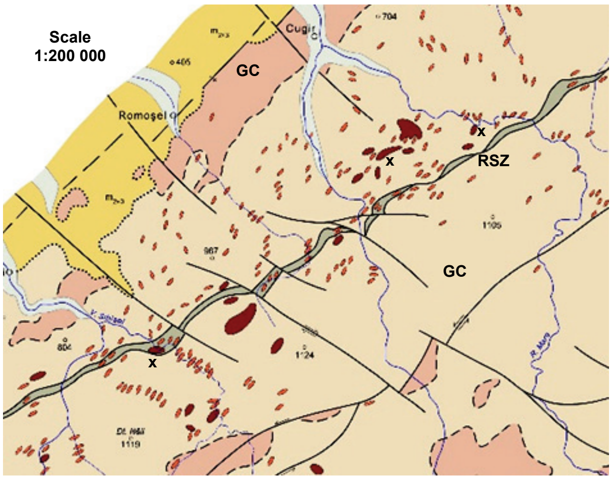

Figure 1. The central sector of the Răşinari Shear Zone (RSZ); GC-Getic Cristaline. The granodiorites are of dark red colour and the rhyodacites are of orange colour; x-granodiorites with biotite nodules on the Sibişel, Sasu and Cugirul Mare valleys.

The granodiorites with biotite nodules. The granodiorite body with biotite nodules on the Sibişel Valley (500 x 240 m) outcrop on the southern margin of the RSZ. On its northern margin the magmatic body comes in contact with the shear zone mylonites over a distance of 24 m in which no less than six rhyodacite dykes outcrop, concordant with the mylonitic foliation. The granodiorite is coarse grained on the northern margin and fine grained on its southern margin. The northern part of the granodiorite has a more biotitic composition and contains pegmatitic segregations with graphic structures and fibro-radial clusters of muscovite of 1-6 cm. Biotite nodules are rare, single or in clusters of three to five nodules (Fig. 2b). They have globular-ellipsoidal shapes, slightly flattened, with long axis of 2-5 cm and short axis of 1.5-4 cm. The wrinkled surface and their black colour make the nodules look like smoked plums (Fig. 2f).

A smaller body (30 m thick exposed) of coarse granodiorite with quartz segregations outcrop on the Cugirul Mare Valley, 1 km north of the shear zone. The biotite nodules are small, of 1-2 cm in diameter (Fig. 2d), and some of them are strongly flattened. Small nodules agglomerations of ten to twenty centimetres also appear (Fig. 2e). Very rarely, biotitic nodules of similar size were observed in the granodiorite body (1100 x 200 m) outcropping in the thalweg of the Sasu River, a left tributary of the Cugirul Mare River.

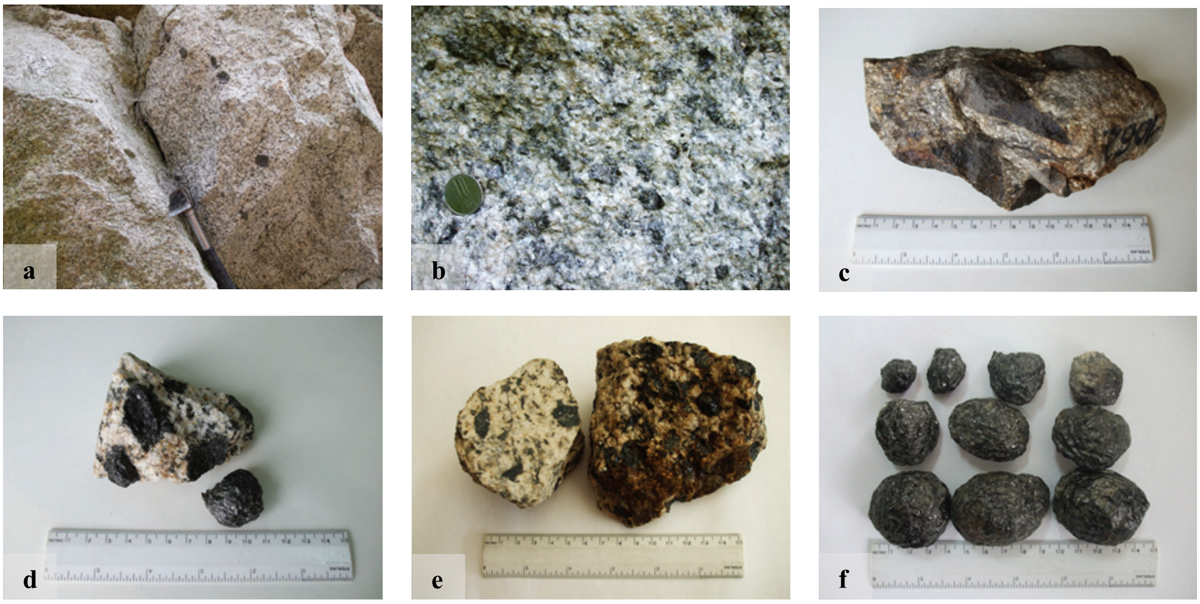

Figure 2. **a**) Outcrop of granodiorite with biotite nodules on the Sibişel Valley. **b**) Detail in the granodiorite outcrop on the Cugirul Mare Valley. **c**) Granodiorite sample with mylonitic xenolits from the Sasu Valley. **d**) Sample of granodiorite with two flattened biotite nodules from the Sibişel Valley; the detached nodule is from the granodiorite on the Cugirul Mare Valley. **e**) Samples of granodiorite with biotite nodules from the Cugirul Mare Valley; on the polished surface in the left sample can be seen a strongly flattened nodule. **f**) Biotite nodules detached from the host rocks; the small nodules on the top row come from the granodiorite on the Cugirul Mare Valley and the large nodules on the next two rows come from the granodiorite on the Sibişel Valley.

PETROGRAPHIC STUDY

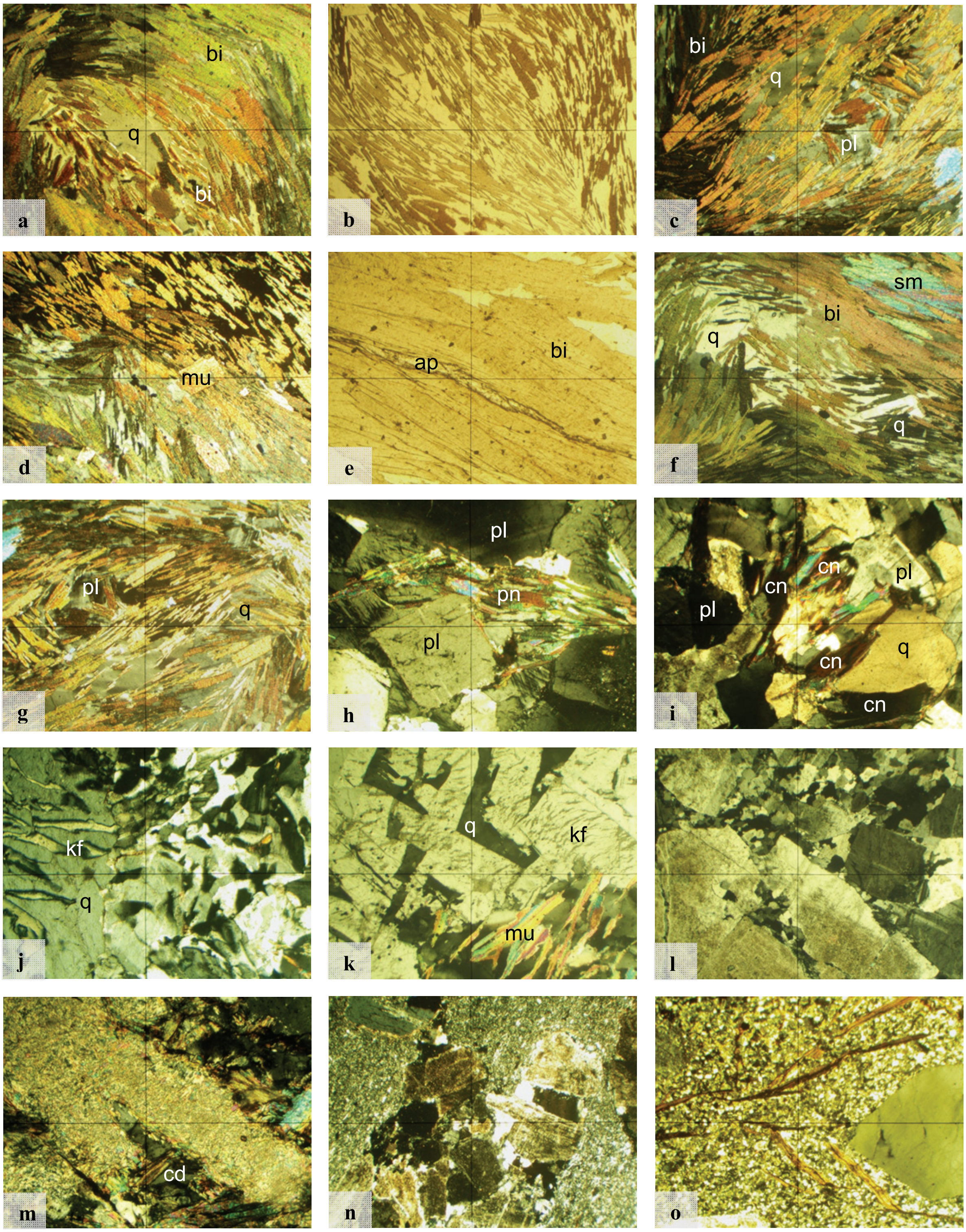

Figure 3. **a, b, c**) Biotite (bi) intergrows with quartz (q) and plagioclase (pl) in the central core of a biotite nodule. **d, e, f**) Compact shells of biotite with transverse magmatic muscovite (mu), thin interstratification of apatite (ap) along the cleavage and secondary post-magmatic muscovite (sm). **f, g**) Secondary cores with clusters of biotite associated with quartz (q) and plagioclase (pl) in polycentric biotite nodules. **h**) A collapsed biotite proto-nodule (pn) squashed between two coarse grains of plagioclase. **i**) Remnants of a biotite nodule collapsed in advanced stage of development (cn). **j**) Pegmatitic microstructure (quartz-K-feldspar) near a biotite nodule . **k**) K-feldspar-quartz graphic structure and muscovite-quartz intergrown in a pegmatite segregation in the granodiorite on the Sibișel Valley. **i**) Intergranular incipient step of anatexis in the granodiorites on the Sasu Valley. **m**) Pinitized cordierite (cd) in the country rocks near the contact with a granodiorite body on the Sasu Valley. **n**) Lithic restite of granodiorite in a rhyodacite dyke on the Romoșel Valley. **o**) Filiform biotite restites in a rhyodacite dyke on the Cugirul Mic Valley.
Cross-polarized (a, c, d, f-o) and plane-polarized (b, e) light. The photos width is of 4.2 mm (a-d, f-l, n, o) and 1.4 mm (e, m).

The biotite nodules and the host granodiorites. The biotite nodules have a central core of thin and long sheets of biotite ("filiform biotite") intergrow with quartz and plagioclase (Fig. 3a-c). The marginal zone consists of compact shells of biotite (Fig. 3d-f) with clusters of filiform biotite associated with quartz (Fig. 3d, f) and plagioclase (Fig. 3g) and K-feldspar sometimes. However, almost all the biotite in the central zone of the large nodules (2.5-3 cm) has a filiform habitus (Fig. 3a-c, f, g).

The internal structure of the nodules is the vortex-like one, quasi-concentric around the central core. It is a very dynamic structure, suggestive for a turbulent bubbling magma. The large nodules usually have a polycentric structure, with two or three secondary centers around the core (Fig. 3f, g. In this case, the trends of the biotite sheets inside the nodule are much more sinuous, and the biotite does not show internal deformations. A subhedral magmatic muscovite transverse to the biotite trends (Fig. 3d) crystallized after the nodule formation from Fe-depleted fluids, probably at the same time as the fibro-radial muscovite in the pegmatite segregations within the granodiorite on the Sibișel Valley (Fig. 3k). Pegmatitic microstructures sometimes appear right next to the biotite nodules (Fig. 3j).

The biotite content of the nodules is 40-70 percent. Like in the host granodiorite, the biotite is either brown-green (Fe^{2+}) or reddish-brown (Fe^{3+}, Ti) suggesting some variations of the oxygen fugacity in the melt. It is partially replaced by secondary post-magmatic muscovite (Fig. 3f), sphene, epidote and clinozoisite, sometimes by chlorite, especially on the marginal area of the nodules. Except for the magnetite, the accessory minerals are the same that occur in the host granodiorite: apatite and zircon, the apatite being more abundant than in the host granodiorite. The apatite sometimes shows unusual physiographic features, at least for us, as very thin interstratifications (films) along the cleavage planes of the biotite (Fig. 3e).

The microscopic study of the host granodiorites revealed various stages of nodules development. The clusters of biotite-quartz intergowths without shell probably represent proto-nodules or prematurely collapsed nodules. The proto-nodules are sometimes squashed between the coarse grains of quartz and plagioclase during the cooling of the magma (Fig. 3h). Crystallization pressure and contractions due to the cooling also explain the wrinkled external surface of the biotite nodules (Fig. 2f). Some crowded flakes of relatively coarse biotite are remnants of a biotite nodule collapsed in advances stages of development (Fig. 3i).

Anatectic processes in granodiorites. Several granodiorite bodies on the central sector of RSZ were affected by partial melting during the Alpine phase of tectonic activity. As result of the rapid cooling of the anatectic melt, the original equigranular texture of the granodiorites on the Sibișel and Sasu valleys become more or less inequigranular suggesting various steps of anatexis, from early intergranular (Fig. 3l) to the relatively advanced steps when the rock texture tends to become porphyritic.

Generalized anatectic processes to the erosion surface are characteristic only for rhyodacites (CIOFLICĂ et al, 1981; ȘECLĂMAN & LUPULESCU, 1986; STELEA, 2000). The lithic restites of granodiorite recently found in rhyodacites are clear evidence for their anatectic origin and for the granodioritic nature of the parent rock (Fig. 3n). More subtle evidence could be the filiform biotite restites in rhyodacites (Fig. 3o), probably resulting from the disintegration of the biotitic nodules in the parental granodiorite during the anatexis. We make here the due rectification to our initial hypothesis (STELEA, 2000) regarding the granito-gneissic nature of the parental rock of the rhyodacites in the northern Sebeș-Cibin Massif. The thermobaric considerations and the definition of the tectonic context made at that time remain valid.

CONCLUSIONS

The geotectonic context in the northern Sebeș Mountains is somewhat comparable to that described by REAVY (1987) in the Castanheira region from northern Portugal. In both regions there are transcurrent shear zones and biotite nodules granodiorites intruded along them, Hercynian shear zone in Porugal (Sierra da Freita Shear Zone) and Alpine but with Hercynian history shear zone in the Sebeș Mountains. However, the mineralogical assemblage of the biotite nodules granodiorites in the Sebeș Mountains is closer to the assemblage described by VAN DIEVER (1970) in the biotite nodule granite of Crafstbury, except for the calcite and rutile: plagioclase, quartz, biotite, muscovite, apatite, sphene and zircon.

The vortex structure of the biotite nodules and the polycentric structure of the large nodules indicate a bubbling volatile-rich magma which allowed the nodules formation around the gas bubbles (H_2O, Cl and F in this case) and their upward migration according to the hypothesis of VAN DIEVER (1970). Most likely the volatile elements Cl and F are present in the apatite inside the nodules and the host granodiorite. Unfortunately, we don't have chemical analysis on this apatite. The pegmatite segregations inside the biotite nodules granodiorites within the northern Sebeș Mountains attest the low viscosity of magma. Microscopic quartz-K feldspar or quartz-albite graphic structures sometimes occur in the host granodiorite right next to the biotite nodules.

The lack of large areas of crowded nodules indicates an erosion level below the ceiling of the magmatic chamber. Few nodules of undeformed biotite, proto-nodules and remnants of collapsed nodules are found at this level. The small agglomerations of nodules in the granodiorite on the Cugirul Mare Valley probably accumulated on a margin of the magmatic body.

The present erosion level could also explain the lack of biotite nodules in the other granodiorite bodies in the north of the Sebeș-Cibin Massif. We can assume that more significant agglomerations of biotite nodules could be in the ceiling of the deep batholith of granodiorite that generated the apophyses exposed to the erosion surface.

ACKNOWLEDGEMENTS

The authors thank an anonymous reviewer for constructive comments and suggestions that helped us to improve the quality of this paper.

REFERENCES

DALLMEYER R.D., NEUBAUER F., FRITZ H., MOCANU V. 1998. Variscan vs. Alpine tectonothermal evolution of the Southern carpathian orogen: constraints from $^{40}Ar/^{39}Ar$ ages. *Tectonophysics*. Elsevier. **290**: 111-135.

DOBRESCU ANCA & SMITH P. 1998. 40Ar/39Ar laser probe dating on single crystals from trondhjemitic dikes from Sebeș-Cibin Mts. (South Carpathians)-Romania. *XVI Congress of Cartatho-Balkan Association, Abstracts volume*. Vienna. 135 pp.

CIOFLICĂ G., ANASTASIU N., CONSTANTINESCU E., POPESCU G., ŞECLĂMAN M., MĂRUNŢIU M. 1981. *Studiul formaţiunilor metamorfice şi magmatice din partea de nord a Munţilor Sebeş (zona Sibişel-Căpâlna.* Raport geologic. Arhiva Universității din București. 120 pp.

PASSCHIER C. W., MYERS J. S., KRÖNER A. 1990. *Field Geology of High-Grade Gneiss Terrains*. International Union of Geological Sciences. Commission on Tectonics. Springer-Verlag. 150 pp.

REAVY J. R. 1987. *An investigation into the controls on metamorphism and syn-tectonic plutonism in the Sierra da Freita region, northern Portugal*. Ph. D. Thesis, University of St. Andrews. Scotland. 210 pp.

REAVY J. R., HUTTON D. H. W., FINCH A. A. 1993. The nodular granite of Castanheira, north central Portugal: origin of the nodules and evidence for diapiric mobilization of granite. *Geological Magazine*. **130** (2): 145-153.

STELEA I. 2000. *Formaţiuni blastomilonitice în Munţii Sebeş*. Ph. D. Thesis. University of Bucharest. Romania. 115 pp.

ŞECLĂMAN M. & LUPULESCU M. 1986. Anatectic restites in magmatic rocks and their genetic significance (with reference to the Romanian territory). *Révue Roumain de Géolgie Géophysique et Géographie, série Géologie*. Academia Republicii Socialiste România. București. **30**: 31-40.

VAN DIEVER B. B. 1970. Origin of biotite orbicules in "Bullseye Granite" of Craftsbury, Vermont. *American Journal of Sciences*. **268**: 322-340.

Stelea Ion
Geological Institute of Romania
1st Caransebeș Street, 012271 - Bucharest, Romania.
E-mail: ionstelea@yaho.com

Ghenciu Monica
Geological Institute of Romania
1st Caransebeș Street, 012271 - Bucharest, Romania.
E-mail: monica_ghenciu@yahoo.com

Received: April 15, 2021
Accepted: August 12, 2021