CORDIERITE IN THE MAGMATIC ROS FROM THE SEBEȘ-CIBIN MASSIF AND THE FĂGĂRAȘ MOUNTAINS (ROMANIA)

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Abstract. The cordierite is first mentioned in the rhyodacites and granodiorites in the northern Sebeș-Cibin Massif, spatially and genetically associated with the Rășinari Shear Zone (RSZ), and in the rhyodacites in north-western Făgăraș Mountains, related to the Intramoesian Fault (IMF). All the rhyodacites are of anatectic origin. The lithic restites of parent rock are of granodiorites in the rhyodacites related to the RSZ, and of cordierite-bearing gneisses in the rhyodacites associated to the IMF. Beside the cordierite, RSZ related mylonites still contain clasts of andalusite, staurolite and garnet. IMF related mylonites frequently contain fibrolitic sillimanite formed at the expense of biotite. There are two generation of cordierite the first (cordierite I) of high temperature and the second (cordierite II) of low temperature, formed at the expense of cordierite I or in subsequent recrystallization processes, post-anatectic in rhyodacites and post-kinematic in mylonites. The cordierite origin is predominantly magmatic in the rhyodacites and the granodiorites in the Sebeș-Cibin Massif and predominantly metamorphic in the rhyodacites in the Făgăraș Mountains.

Keywords: cordierite, granodiorites, gneisses, anatexis, rhyodacites.

Rezumat. Cordieritul din rocile magmatice ale Masivului Sebeș-Cibin și Munților Făgăraș (România). Cordieritul este menționat pentru prima dată în riodacitele și granodioritele din nordul Masivului Sebeș-Cibin, asociate spațial și genetic cu Zona de Forfecare Rășinari (ZFR), și în riodacitele din nord-vestul Munților Făgăraș, asociate Faliei Intramoesice (FIM). Toate riodacitele studiate sunt de origine anatectică. Restitele litice, indicând roca parentală, sunt de granodiorite, în riodacitele asociate ZFR, și de gnaise cu cordierit, în riodacitele asociate FIM. Pe lângă cordierit, milonitele asociate ZFR mai conțin claste de andaluzit, staurolit și granat iar cele asociate FIM conțin frecvent silimanit fibrolitic format pe seama biotitului. Sunt două generații de cordierit, prima (cordierit I) de temperatură înaltă și a doua (cordierit II) de temperatură joasă, formată pe seama cordieritului I sau în procese subsecvente de recristalizare post-anatectică în riodacite, și post-cinematică în milonite. Originea cordieritului este predominant magmatică în riodacitele și granodioritele din Masivul Sebeș-Cibin și predominant metamorfică în riodacitele din Munții Făgăraș.

Cuvinte cheie: cordierit, granodiorite, gnaise, anatexie, riodacite.

INTRODUCTION

The cordierite is a relatively common mineral in peraluminous granitoidic rocks (granites, granodiorites, rhyolites, dacites), chemically characterized by a whole-rock ratio $Al_2O_3/(CaO + Na_2O + K_2O) > 1$. Besides feldspars and quartz, these rocks may contain one or more characteristic phases such as biotite, muscovite, cordierite, garnet, andalusite, sillimanite, mullite, topaz, tourmaline, spinel and corundum (CLARKE, 1981). The PT conditions of the cordierite stability imply relatively low temperature (850-900ºC), low pressure (< 6 kb) and high values of the parameters A/CNK, ($Mg + Fe^{2+}$), Mg/Fe^{2+} and Mg/(Mg+Fe) (CLEMENS & WALL, 1981; CLARKE, 1981, 1995).

In the magmatic rocks in Romania cordierite is mentioned in the dacites of Draica in the Metaliferi Mountains, alongside the sillimanite (IANOVICI, 1938), and in the rhyodacites of Hudin in the Ţibleş Mountains (MAIER, 1962). In the first case, the author explains the formation of cordierite and sillimanite by the interaction between aqueous fluids and magma before its consolidation, suggesting a process of autometasomatism without being defined as such. The second case is much clearer. The cordierite in the rhyodacites of Hudin frequently occurs in the marginal area of the magmatic body, close to the contact with the clayey host rocks that also appear as xenoliths in rhyodacites, in varying degrees of magmatic assimilation. Based on these observations, the author considers the cordierite a contamination product formed at the expense of the excess aluminium in clays.

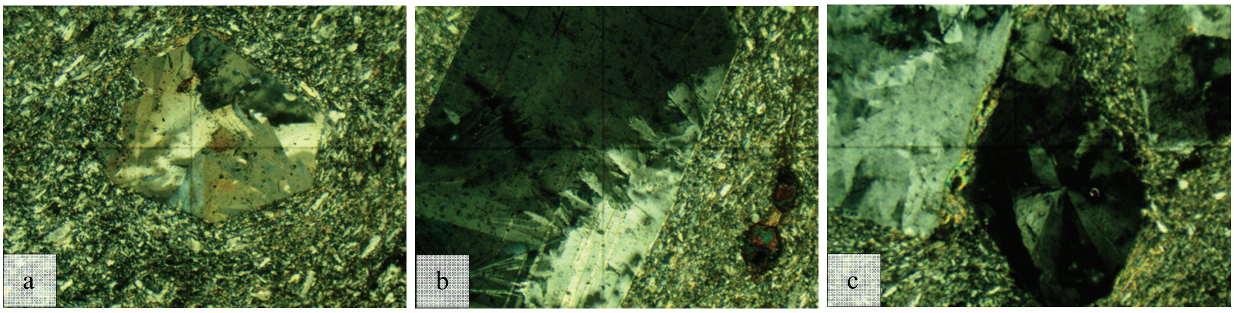

Figure 1. Magmatic cordierite in rhyodacite (Romoșel Valley). a) Cordierite crystal with hexagonal contour, complex twinning, and abnormal birefringence colors in blue and golden tents. b) Prismatic cordierite crystal with complex and polysynthetic twinning. c) Cordierite crystal with radial twinning. Cross-polarized light. The photos width is 1.4 mm (a, b) and 0.7 mm (c).

Here we report the presence of cordierite in the rhyodacites and granodiorites in the northern Sebeș-Cibin Massif as well as in the rhyodacites dykes in the north-western Făgăraș Mountains. Reviewing the petrographic material regarding the igneous rocks, we observed in a rhyodacite thin section crystals with optical characteristics typical for cordierite such as hexagonal contour, complex and radial twinning, and abnormal birefringence colours in blue and golden tints (Fig. 1). Starting from the premise that it cannot be an isolated case, we later searched and we found cordierite in almost all the samples of rhyodacites and granodiorites (148 thin sections).

In both rhyodacites and their parent rocks there are two generations of cordierite, with different refractive indices. The cordierite I, with lower refracive indices, is of high temperature while the cordierite II, with higher refractive indices is of low temperature (HEINRICH, 1965). Cordierite I (high cordierite) is specific to the parent rocks of the rhyodacites. Cordierite I in rhyodacites has a restitic character and cordierite II (hydrous, low cordierite) is recrystallized from the anatectic melt. As a rule, cordierite I shows twinning and good parting while cordierite II is untwinned and without parting. In our samples, cordierite II partially replaces cordierite I.

GEOLOGICAL SETTING

The Sebeș-Cibin Massif. The crystalline basement of the Sebeș-Cibin Massif consist of two metamorphic complexes separated by a cryptic pre-Variscan tectonic plane (STELEA, 2000). The lower complex is metagranitic, of continental crust origin, and the upper complex is leptino-amphibolitic and metapelitic, of oceanic crust origin. The mineral paragenesis and the textural relations highlight two events of regional metamorphism of Cadomian, respectively Variscan age (e.g. MÂNZATU et al., 1975). The Cadomian event (M1) is syn-collisional while the Variscan event (M2) is related to the post-collisional uplift when the tabular regional structure of the metamorphic pile was formed, according to the subhorizontal flattening foliation S2 (STELEA, 2000).

The subsequent Alpine deformations in the Getic Crystalline of the Sebeș-Cibin Massif are localized on the Rășinari Shear Zone (RSZ) which crosscut the north-eastern border of the massif along a large arcuate alignment (STELEA, 2000). The RSZ was active as dip-slip normal fault during the Variscan metamorphism and was intermittently reactivated during the Alpine orogenesis (Lower Jurassic- Upper Cretacous) as sinistral strike-slip fault. In this stage of the fault tectonic activity the favourable conditions of anatexis were achieved at the base of the middle crust (STELEA, 2000). The ascent of the anatectic magma led to the formation of a rhyodacite dykes swarm of including granodiorites bodies, rocks frequently occurring as lithic restites in rhyodacites. Both rhyodacites and granodiorites contain cordierite.

The Făgăraș Mountains. From a lithologic point of view, the crystalline basement in the north-western area of the Făgăraș Mountains, slightly affected by large Alpine folds, is identical to that of the Sebeș-Cibin Massif (STELEA, 2006). In obvious contrast, the crystalline basement in the rest of the northern area of Făgăraș Mountains is strongly affected by Alpine folding, with tight to isoclinal folds, penetrative axial-plane foliation (S3) and intense retromorphism (M3). From a tectonic point of view, the north-western area represents the western compartment of the Intramoesian Fault (IMF), with trace at the topographic surface in the Făgăraș Mountains (STELEA, 2017).

The IMF in this region is seismically active as dextral strike-slip fault on NW-SE direction. The fault plane has a deep arborescent structure asymmetrically branched (half flower structure) only in its western compartment (STELEA, 2017). Rhyodacites outcrop only in this tectonic compartment, the number of the dykes being unknown, however smaller than in the Sebeș-Cibin Massif. We sampled five of them, enough to observe the anatectic textures similar to those of the rhyodacites in the Sebeș-Cibin Massif. Anatectic processes in thermodynamic conditions close to those in the RSZ could take place only on the IMF branches in this tectonic block. The parent rock in this case, present as lithic restites, is not granodioritic but gneissic. Both rhyodacites and gneissic restites contain cordierite.

MICROSCOPIC STUDY

Cordierite in the Sebeș-Cibin Massif. The rhyodacites in the Sebeș-Cibin Massif consist of a microcrystalline matrix of cordierite II, quartz, albite and K-feldspar (the last two as interstitial phases), with ahedral and subhedral restites of cordierite I, oligoclase, biotite, quartz and epidote, very rare hornblende. Euhedral prismatic or hexagonal cordierite is quite rare. It shows complex twinning (Fig. 1) characteristic for the high temperature cordierite (VENKATESH, 1954). The phenocrysts of magmatic cordierite usually have net boundaries, stable relative to the matrix (Fig. 2a), while the cordierite restites are intensely corroded by the matrix (Fig. 2b). The cordierite in the matrix is subhedral and untwinned (Fig 2a).

The biotite sometimes appears as thin and long sheets with a filiform appearance (Fig. 2c) or as protonodules, especially in the dykes on the central sector of RSZ where the granodiorites with biotite nodules also outcrop (STELEA & GHENCIU, 2021). In the rhyodacites on this tectonic sector the apatite frequently appears, as inclusions in biotite and cordierite I. Out of the fifteen samples in which the cordierite contains apatite inclusions, thirteen are localized on the central sector of the RSZ. Rarely, microblastic sillimanite included in cordierite I also occurs (Fig. 2d). The cordierite I restites are partially pinitized and often contain separations of unaltered cordierite II (Fig. 2b). The lithic restites are of granodiorites with cordierite I (Fig. 2e).

The mineral and the lithic restites preserve a pre-anatectic semi-brittle deformation, materialized in undulatory extinction in quartz and cordierite I, good parting in cordierite I and kink-bands in biotite. Most rhyodacites have undeformed matrix, with massive texture. The deformation contrast between the restites and the matrix is evident in most of the dykes that outcrop outside the shear zone.The dykes inside the RSZ frequently show both pre-cooling plastic deformations and post-cooling cataclastic deformations, affecting both the matrix and the restites.

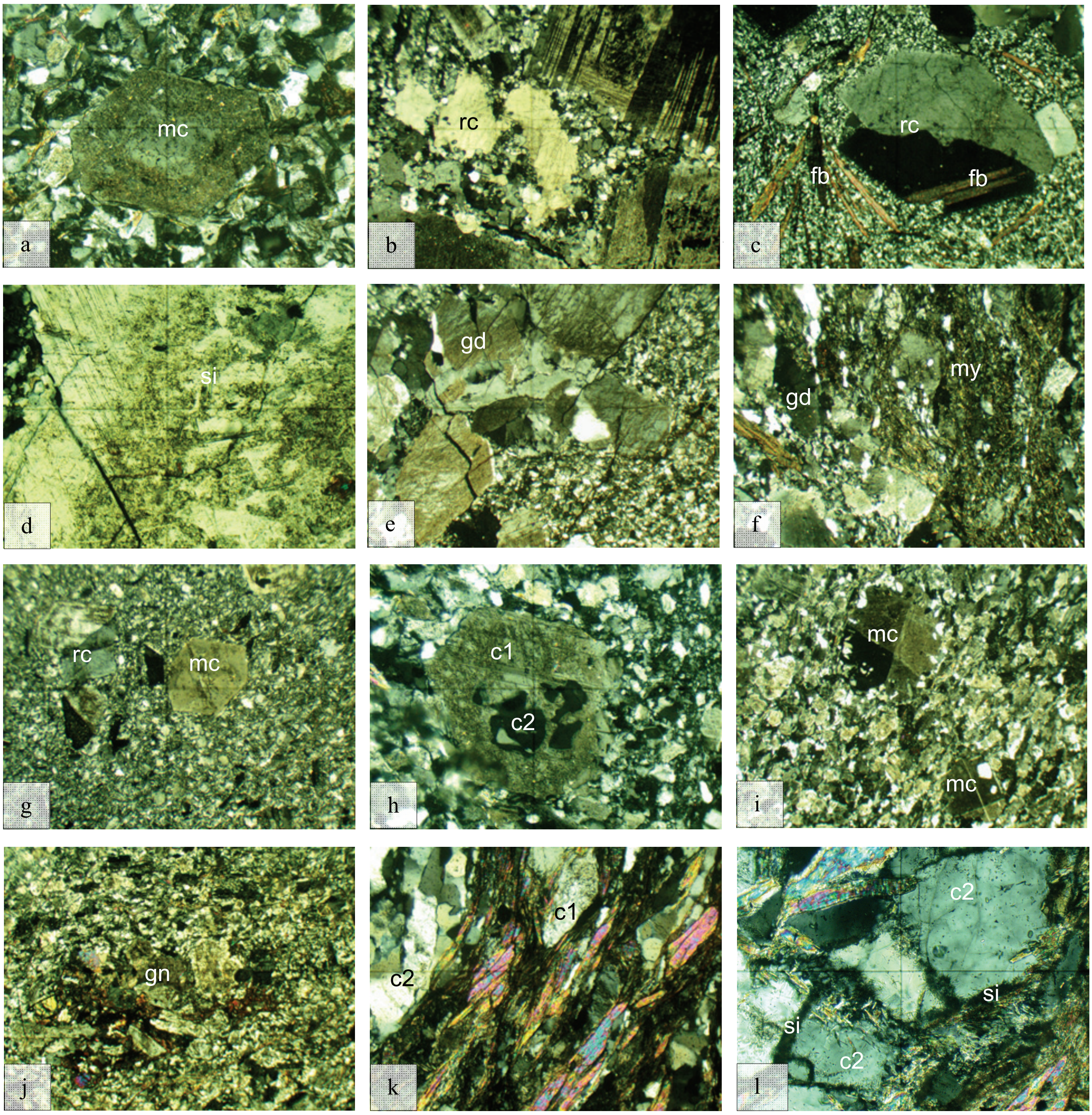

Figure 2. Cordierite from the Sebeș-Cibin Massif (a-f) and the Făgăraș Mountains (g-l). a) Rhyodacite with magmatic cordierite (mc) in a matrix of subhedral cordierite, quartz and albite. b) Rhyodacite with corroded restitic cordierite (rc). c) Rhyodacites with restitic filiform biotite (fb); note that the restitic cordierite contains inclusions of filiform biotite. d) Cordierite with sillimanite inclusions (si) in a granodiorite affected by incipient anatexis. e) Lithic restite of cordierite-bearing granodiorite (gd) in a rhyodacite. f) Mylonite xenolith (my) with clasts of cordierite in a cordierite-bearing granodiorite (gd); note the intergranular anatexis in granodiorite. g) Rhyodacite with magmatic (mc) and restitic (rc) cordierite. h) Restitic cordierite I with good parting (c1) and separations of cordierite II (c2), without parting, in rhyodacite. i) Magmatic cordierite (mc) with sector (upper) and simple (lower) twins in rhyodacite. j) Lithic restite of biotite gneiss with cordierite (gn) in rhyodacite. k) Mylonitized biotite gneiss with clasts of cordierite I (c1) and post-kinematically recrystallized aggregates of cordierite II (c2) and quartz. l) Mylonitized cordierite gneiss with nests of fibrolitic sillimanite (si) between the grains of cordierite II (c2). Cross polarized light.
The photos width is 4.2 mm (a, c, e, f, g, h, i, j), 1.4 mm (b, d, k) and 0.7 mm (l).

Anatectic textures in early stages of partial melting also appear in the bodies of granodiorites that outcrop on the central sector of the RSZ. The pre-anatectic deformation is present in all the rock mass, except for the intergranular spaces where the strain was removed by melting and recrystallization. In their marginal zone, the granodiorite bodies with biotite nodules contain pegmatitic segregations with large cordierite I with separations of cordierite II or mylonite xenoliths with biotite and cordierite (Fig. 2f). Cordierite is also present in the mylonites along the RSZ as clasts of cordierite I and post-kinematically recrystallized aggregates of cordierite II. Some cordierite mylonites in the central sector of the RSZ contain clasts of andalusite, staurolite and garnet.

Cordierite in the Făgăraș Mountais. The matrix of the rhyodacites in north-western Făgăraș Mountains has a mineralogical composition close to that of the rhyodacites in the Sebeș-Cibin Massif, with the mention that the hornblende is missing. In addition, it contains clinozoisite, muscovite, chlorite (on biotite), xenotime and zircon, minerals that also appear as inclusions in cordierite I. Fine sillimanite needles sometimes appear included in cordierite I. The restites of cordierite I have various size (Fig. 2g, h), the larger granules having separations of cordierite II without parting in their central area (Fig. 2h). Rarely occurs euhedral magmatic cordierite, with hexagonal contour and clear boundaries, slightly corroded by the matrix (Fig. 2g). Cordierite I, anhedral or subhedral and partially pinitized, shows pre-anatectic deformations and sometimes contains separations of undeformed cordierite II (Fig. 2i). A lithic restite of gneiss with cordierite I, biotite, clinozoisite and epidote appears in a sample (Fig. 2j), representing the parent rock of the rhyodacites in the Făgăraș Mountains.

The host rocks of the rhyodacites dykes in the Făgăraș Mountains are biotite gneisses with cordierite and fibrolitic silimanite, more or less mylonitized. These show obvious compositional banding, with wavy alignments of microblastic biotite and lenticular aggregates of quartz and cordierite II post-kinematically recrystallized (Fig. 2k). Deformed clasts of cordierite I, biotite, garnet and staurolite, rarely kyanite, appear on the biotite alignments. Cordierite I, partially pinitized, has good parting and contains nests of fibrolitic sillimanite formed on the expense of the biotite between the cordierite granules and of the biotite inclusions (Fig. 2l). Apatite, tourmaline and zircon inclusions are also common. The cordierite II is unaltered and sometimes shows abnormal birefringence colours in blue and golden tints. Both generations of cordierite also appear as inclusions in the garnet and staurolite clasts.

DISCUSSIONS AND CONCLUSIONS

The anatectic origin of the rhyodacites in the northern Sebeș-Cibin Massif has been argued, based on the eutectic composition of the matrix and the restitic character of the phenocrysts (ȘECLĂMAN & LUPULESCU, 1986). The necessary conditions for anatexis were achieved along the RSZ (STELEA, 2000). At the base of the middle crust (20-22 km) the granodioritic parent rocks reached temperatures of 600-650ºC and lithostatic pressures of 5-6 Kb, very close to the melting physical conditions of the granites saturated in water. The presence of magmatic cordierite in the rhyodacites indicates higher temperatures by 200ºC. The tectonically induced rise of temperature and the presence of excess fluids determined the anatexis of the granodioritic rocks affected by shearing. The low effective pressure due to high fluid pressure allowed the melt to rise at higher crustal levels (STELEA, 2000; STELEA & GHENCIU, 2021). The presence of andalusite in the mylonites on the central sector of the RSZ attests effective local pressures of less than 4 Kb.

The mineral assemblages of the rhyodacites in the north-western Făgăraș Mountains, as well as the tectonic context in which these outcrop, indicate that PT conditions favourable to anatexis were achieved on the Intramoesian Fault. At the present level of erosion, the host rocks of the rhyodacite dykes in the western compartment of the fault are mylonitic gneisses with cordierite and fibrolitic sillimanite, formed in PT conditions similar to formation conditions of the mylonites in RSZ but not identical. In the north-western Făgăraș Mountains was not a shear zone concentrated on a single alignment but shears distributed on a set of faults without significant fluid input to causing the effective pressure decrease at the depth favorable to anatexis. This may also explain the low amount of anatectic magma, expressed in the small number of rhyodacite dykes.

In part, the cordierite in the marginal zone of granodiorite bodies in the Sebeș-Cibin Massif, with cordierite-bearing xenoliths, is a contamination product of metamorphic origin. Therefore, some cordierite restites in rhyodacites may also be of metamorphic nature. The cordierite in the central zone of the granodiorite bodies can only be of magmatic nature. This means that most of the restitic cordierite in rhyodacites is of magmatic nature. Characteristic for this primary high temperature cordierite are the separations of low cordierite. Obviously, the euhedral cordierite directly crystallized from the anatectic magma is also magmatic, but it seems to be sometimes high cordierite, sometimes low cordierite, probably due to some different cooling rates of the anatectic melt.

Given the small number of dykes, not many comments can be made on the rhyodacites dykes in the Făgăraș Mountains. We can only say that in three of the five dykes all cordierite is of metamorphic nature, inherited from the gneissic parent rock. Quasi-hexagonal phenocrysts of cordierite grown from anatectic magma, with abnormal birefringence and twins also appear in two dykes (Figs. 2g, i).

REFERENCES

CLARKE D. B. 1981. The mineralogy of peraluminous granites: a review. *Canadian Mineralogist*. GeoScienceWorld. **19**: 3-17.

CLARKE D. B. 1995. Cordierite in felsic igneous rocks: a synthesis. *Mineralogical magazine*. GeoScienceWorld. **59**: 311-325.

CLEMENS J. D., WALL V. J. 1981. Cryatallization of some peraluminous (S-type) granitic magmas. *Canadian Mineralogist*. GeoScienceWorld. **19**: 111-131.

HEINRICH E. W. 1965. *Microscopic identification of minerals*. McGraw-Hill Book Company. 414 pp.

IANOVICI V. 1938. Étude pétrographique et chimique des dacites de Draica (département de Hunedoara). *Annales Scientifiques de l'Université de Jassy*. **24**(2): 303-314.

MAIER O. 1958. Geologia și petrografia Masivului Hudin (Munții Țibleș). *Dări de Seamă ale Comitetului Geologic.* Institutul Geologic. București. **45**: 89-110.

MÂNZATU S., LEMNE M., VÂJDEA E., TĂNĂSESCU A., IONCICĂ M., TIEPAC I. 1975. Date geocronologice obținute pentru formațiuni cristalofiliene și masive eruptive din România. *Dări de Seamă ale Institutului de Geologie și Geofizică*. București. **41**(5): 85-111.

STELEA I. 2000. *Blastomylonitic formations in the Sebeş Mountains* (In Romanian). Ph.D. Thesis. Univesity of Bucharest. 115 pp.

STELEA I. 2006. Corelări litostructurale in fundamentul cristalin al Carpaţilor Meridionali Centrali şi de Est. *Anuarul Institutului Geologic al României*. Bucureşti. **74**: 208-211.

STELEA I., 2017. Intramoesian Fault in the Făgăraş Mountains area. *Oltenia. Studii și comunicări*. *Științele Naturii*. Muzeul Olteniei Craiova. **33**(2): 7-12.

STELEA I., GHENCIU M. 2021. The granodiorites with biotite nodules in the northern Sebeș Mountains (South Carpathians). *Oltenia. Studii și comunicări*. *Științele Naturii*. Muzeul Olteniei Craiova. **37**(1): 7-12.

ȘECLĂMAN M., LUPULESCU M. 1986. Anatectic restites in magmatic rocks and their genetic significance (with reference to the Romanian territory). *Revue Roumain de Géologie, Géophysique, Géographie, série Géologie*. Academia Română. București. **30**: 31-40.

VENKATESH V. 1954. Twinning in cordierite. *American Mineralogist*. **39**: 636-436.

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