Mineralium Deposita (1999) 34: 743–753 

ARTICLE

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# Age and tectonic setting of Bocşa and Ocna de Fier – Dognecea granodiorites (southwest Romania) and of associated skarn mineralisation

Received: 4 August 1998 / Accepted: 20 April 1999

**Abstract** The granodiorite intrusion at Ocna de Fier-Dognecea in the western South Carpathians, Romania, triggered the formation of a classic Fe-(Pb-Zn) skarn deposit. The intrusive is related to the larger composite Bocşa Laccolith five kilometres north that is part of the regional Banatite Suite. Previous work indicated a K/Ar age of 65–57 Ma and postulated an Andean-type subduction related tectonic setting for the intrusions. We report ion probe U/Pb zircon ages of 79.6 ± 2.5 Ma for the Bocşa Laccolith and 75.5 ± 1.6 Ma for the Ocna de Fier Pluton, which date their emplacement. Fission track dating on titanite gives slightly younger ages: 78 ± 4 Ma for Bocşa and 73 ± 4 Ma for Ocna de Fier. Together with zircon and apatite data from the same samples, average cooling rates of 52 °C/Ma and 83 °C/Ma are calculated for the Bocşa and Ocna de Fier intrusives respectively. A post-collision tectonic setting is proposed on the basis of field evidence, the timing of intrusions in the context of regional tectonic evolution, and trace element geochemistry.

Editorial handling: B. Lehmann

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The Fe-(Zn-Pb) skarn deposits of the Ocna de Fier and Dognecea district of Romania are located at the western limit of the South Carpathians in southwest Romania (Fig. 1) and have been almost continuously mined for 4000 years and intensely studied for 200 years. The ore district was known as Vaskö-Moravitza and Dognácska in pre-1918 literature, when Banat Province was part of the Austro-Hungarian Empire. The research history has been reviewed by Codarcea in 1931 and Nicolescu in 1996.

## Regional geology and skarn genesis

The region is part of the South Carpathian fold and thrust belt, related to the Alpine orogeny. The mining district is underlain by retrogressed greenschist facies metamorphic rocks (Codarcea 1931; Iancu 1984, 1985), mainly metapelites, belonging to the Supra-Getic Unit of the South Carpathians (Streckeisen 1934) (Fig. 2).

Based on stratigraphic correlations, Iancu (1984, 1985) assigns an Upper Proterozoic age to the initial, amphibolite facies metamorphism, which was retrogressed, giving rise to greenschist facies assemblages in the Lower Palaeozoic. However, recent $^{40}Ar/^{39}Ar$ data (Dallmeyer et al. 1996), as well as older K/Ar data (Mînzatu et al. 1976) give a Late Carboniferous to Early Permian age (320–280 Ma) for metamorphism in other areas of the Southern Carpathian Supra-Getic Unit.

A narrow, N25°E-trending Upper Jurassic to Lower Cretaceous unit of impure limestone with subordinate dolomite, lies discordantly over the metapelites (Fig. 2). Contact metamorphism and metasomatism together with the associated mineralisation, were triggered by the medium-sized (8 × 3 km) Ocna de Fier calc-alkaline granodiorite pluton which intruded the metapelite and limestone units after their juxtaposition. Hornfelses, skarns and marbles were formed, depending on the composition of the original rocks. The intrusion which caused this mineralisation seems to be related to the large but barren composite Bocşa Laccolith (Fig. 1).

The skarn ore has a zoned distribution. Calcic Fe skarn overprinting subordinate magnesian Fe skarn is developed in the proximal zone at Ocna de Fier, whereas the distal zone occurring in the south of the ore district at Dognecea is dominated by calcic Zn-Pb (Cu) skarn. The initial grade of the iron ore was around 60% FeO. After extensive mining the grade has dropped to 18–25%

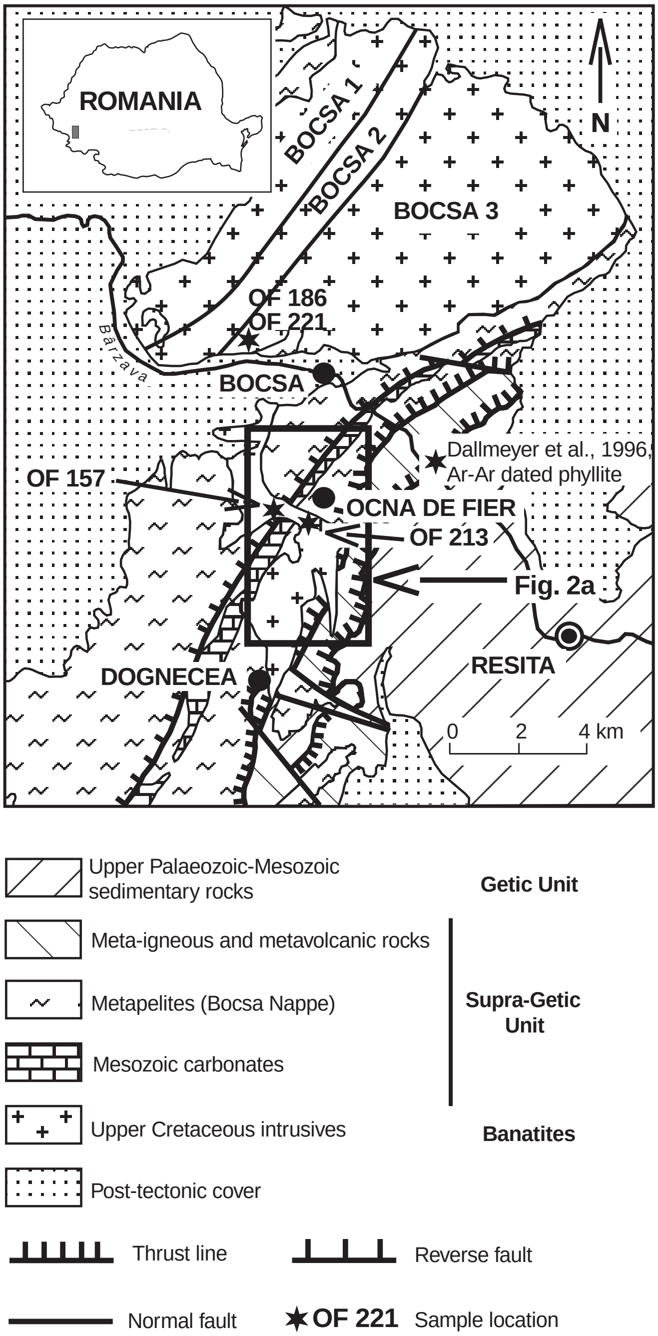


**Fig. 1** Location of the study area in Romania (*inset*) and geology of the study area, simplified after Iancu (1985)

FeO, the only mining activity continuing today being recycling of old mine dumps. Sulphide ore grade was at the level of several percent for each Pb, Zn and Cu, but sulphide mining ceased completely in the early eighties.

## Previous work on the Banatite Suite and skarn deposits

The petrographic identity of intrusive rocks in the area has been much debated. Cotta (1864) visited all the ore deposits of the Banat region which stretch for 80 km from Ocna de Fier in the north to Moldova Nouă on the Danube, and recognised that the intrusives, although petrographically highly variable, are cogenetic and always occur in between the metamorphic basement and limestone. He used the generic name "banatite" for all these intrusive rocks but specified that the term did not describe a new rock type. In modern terms this corresponds to an intrusive suite. Later Codarcea (1931) petrographically described all intrusive rock types in the area, confirmed Cotta's (1864) hypothesis of a cogenetic Banatite Suite, and determined the dominant rock type as granodiorite. Previous studies had assigned the intrusive rocks a variety of names, from syenite, to quartz-trachyandesite and quartz-diorite.

The Bocşa Laccolith (Fig. 1) comprises three different units distinguished by Russo-Săndulescu et al. (1978). The less developed Bocşa 1 and Bocşa 2 units in the western part of the massif are of basic to intermediate composition (gabbro to monzonite). The homogeneous equigranular hornblende-biotite granodiorite Bocşa 3 unit makes up two thirds of the laccolith.

Cotta (1864) understood that the ores were a consequence of contact processes between intrusives and limestones, and classified them as "Contactbildung". However he may have been influenced by the Austrian geologist Karl F. Peters who published a similar classification (Peters 1861) and used the term "Contactgebilde", based on the Băiţa (Bihor) deposit (then known as Rézbánya), genetically similar to the Banat deposits. This is the first mention of igneous contact deposits in the geological literature, according to Nicolescu and Mârza (1989).

## Age of the Banatite Suite

The age of the Banatite Suite, and thus of associated skarn mineralisation has been the subject of debate. An Upper Cretaceous age for the Ocna de Fier Pluton was proposed by Codarcea (1931), while K/Ar biotite dating of the Bocşa Laccolith by Russo-Săndulescu et al. (1986) gave Cretaceous to Palaeocene ages of 65–57 Ma. This is much younger than the Upper Cretaceous 83–72 Ma ages reported for other parts of the Banatite Suite by Soroiu et al. (1986) and Strutinski et al. (1986). The present work has resolved the problem, as discussed in a later section.

## Tectonic setting

The age and tectonic setting of the Ocna de Fier pluton and Banatite Suite is important to economic geology, as it generated one of the most important skarn deposits in the Carpatho-Balkan realm. In a recent paper Vlad (1997) suggests an Andean-type subduction-related tectonic setting for the Banatite Suite in the western South Carpathians. A subduction-related environment is also advocated by other authors such as Jankovic (1997) and Karamata et al. (1997). In this study we review their model in the light of the field evidence, geochemical and age constraints, and we propose a different model which is consistent with all the data.

## Sampling and analytical methods

The Bocşa Laccolith was sampled on the northern bank of the Bârzava river, 200 m upstream of the Moraviţa-Bârzava confluence (samples OF 186 and OF 221, Fig. 1). Two Ocna de Fier granitoid samples, OF 157 and OF 213, were collected from the intrusive body cropping out along Vintilii brook, as shown in Fig. 2a. The two Bocşa samples are equivalent to each other, as well as the two Ocna de Fier ones. The U/Pb zircon ages were obtained on OF 213 and OF 221. A sample of Moraviţa peraluminous granite from a small granitic plug (sample OF 62, Fig. 2a) near Ocna de Fier was also dated.

Approximately 2 kg of each sample was crushed and separated in two aliquots. One was sieved through a 0.2 mm sieve and after standard magnetic and heavy-liquid separation was hand-picked for titanite, zircon and apatite. The other aliquot was powdered in an agate mill for chemical analysis.

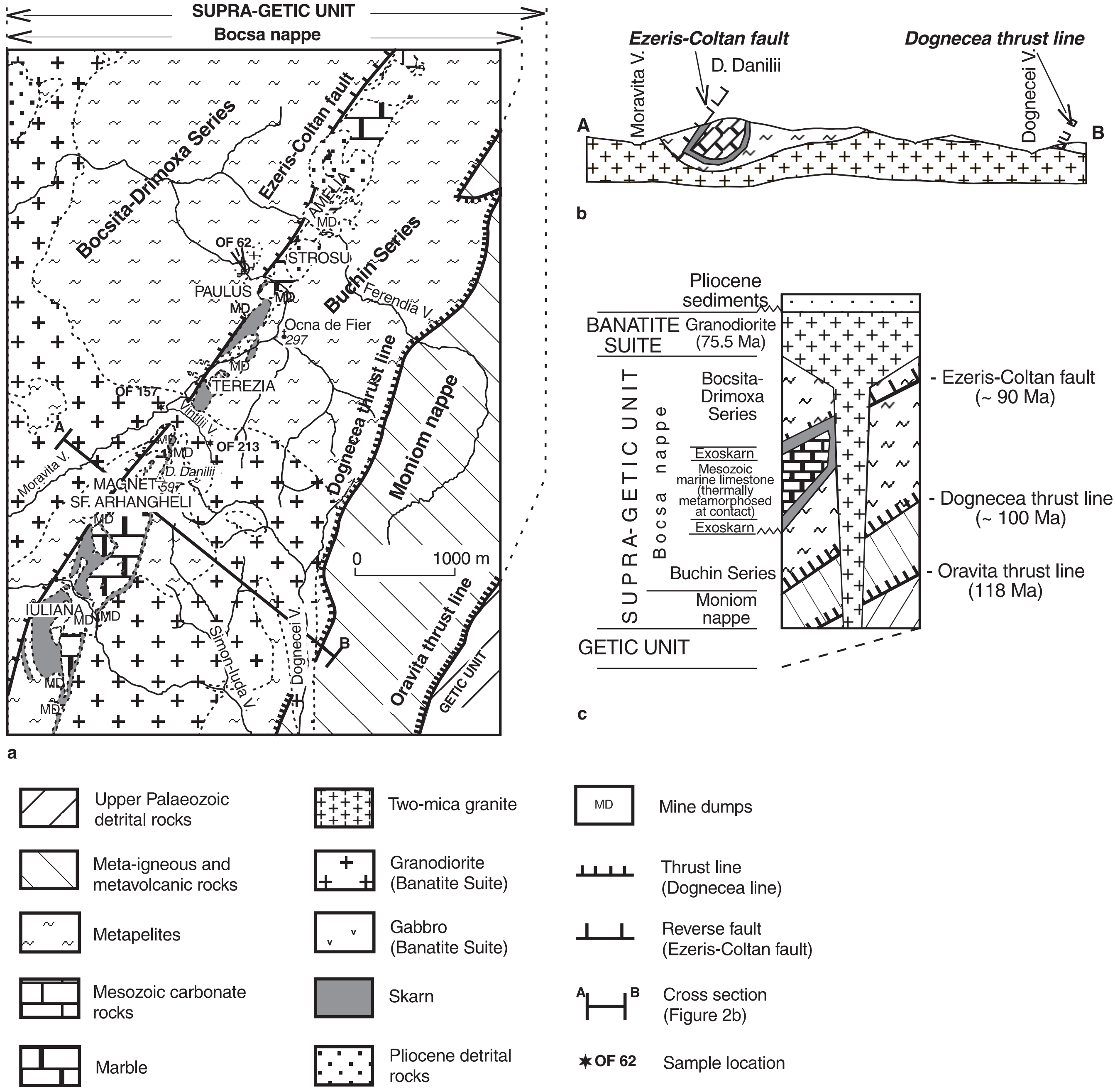


**Fig. 2** **a** Geological map of the Ocna de Fier skarn deposit (simplified after Codarcea 1931, and modified according to Iancu 1984). **b** Cross section along line *A-B* in **a**. **c** Schematic lithostratigraphic column for the Ocna de Fier skarn deposit

*Secondary ion mass spectrometry (SIMS) U/Pb zircon dating*

This was done using the NORDSIM CAMECA IMS 1270 ion microprobe at the Swedish Museum of Natural History in Stockholm. Zircon grains were mounted in epoxy resin and diamond polished to expose grain sections, then gold coated for ion probe analysis. The 1065 Ma Geostandards 91 500 zircon characterised by Wiedenbeck et al. (1995) was used as standard throughout this work. Cathodoluminescence (CL) images were collected before and after SIMS analysis to choose and check the ~30 μm analytical spots, and to avoid analysing possibly older cores or metamorphic rims. Details of the NORDSIM analytical method and empirical U-Pb calibration are given by Whitehouse et al. (1997). Due to the young age of our samples, and the low abundance of $^{235}$U, the $^{207}$Pb/$^{235}$U and $^{207}$Pb/$^{206}$Pb methods are inappropriate and only $^{206}$Pb/$^{238}$U dates are used in this work. The SHRIMP ion-probe dating of young rocks is discussed by Claoué-Long et al. (1995).

Because the NORDSIM instrument has mainly been used to date Precambrian zircons, an accuracy test on young rocks was made using a conventionally dated zircon sample, kindly provided by F. Oberli (ETH, Zürich, Switzerland), from a volcanic tuff at Possagno, Italy. It was conventionally dated at 35.47 ± 0.10 Ma by Fischer et al. (1989). Our NORDSIM age was 35.1 ± 2.2 Ma, in good agreement with Fischer et al.'s (1989) date, and confirming the reliability of the instrument and U-Pb calibration.

For increased sensitivity, the Banatite Suite samples were analysed using oxygen flooding of the sample chamber, which increased Pb yields and improved the counting statistics.

*Fission track dating*

This investigation of titanite, zircon and apatite was performed at the Institut für Geologie und Paläontologie, Graz, Austria. The method is based on the natural fission of uranium contained in minerals. During a natural fission event of $^{238}U$, two heavy nuclei and about 200 MeV of energy are released. The two heavy nuclei traverse the mineral lattice in opposite directions and leave a fission track. The dating is based on the determination of fission track density on polished surfaces.

Different sample preparation methods were used for different minerals. Both apatite and titanite were mounted in epoxy resin. To reveal the tracks in apatite, the crystals were etched in a 7% $HNO_3$ solution for 35–40 s at 20 °C, whereas titanite crystals were etched in a mixed $HNO_3$-HCl-HF solution for 20–30 minutes following Gleadow (1978). Zircon crystals were mounted in PFA Teflon and etched at 220 °C in a NaOH-KOH eutectic melt (Gleadow et al. 1976).

Age determinations were made by the external detector method. Mineral samples together with an external detector and mineral standards were irradiated at the reactor of the Atominstitut der österreichischen Universitäten. Neutron flux was monitored using CN glasses and results are given in Table 3. Ages were calculated using the standard fission track age equation (Hurford and Green 1982) and the zeta calibration recommended by Hurford (1990).

*Major and trace element analyses*

These were made at the Centre de Recherche Pétrographiques et Géochimiques, Vandoeuvre les Nancy, France. Approximately 300 mg of sample powder was mixed with 900 mg of lithium tetraborate flux and fused in a tunnel furnace, followed by dissolution in nitric acid. Major elements were analysed by inductively coupled plasma atomic emission spectrometry, while trace element concentrations were determined by inductively coupled plasma mass spectrometry. Results are given in Table 1.

## Age of the intrusive rocks

### U/Pb zircon data

As shown in the cathodoluminescence (CL) images of Fig. 3, the zircon from Banatite Suite samples proved to be homogeneous, with magmatic oscillatory zoning and no xenocrystic cores. Zircons from the OF 62 peraluminous granite revealed CL-bright (low U) cores surrounded by dark (high U) CL rims.

**Table 1** Major (ICP-AES) and trace element (ICP-MS) composition of Bocşa and Ocna de Fier granitoids[a]

| Rock type<br>locality<br>Spl. # | Granodiorite<br>Bocşa 3<br>OF 186 | Granodiorite<br>Ocna de Fier<br>OF 157 | Granodiorite<br>Ocna de Fier<br>1374 | Granodiorite<br>Ocna de Fier<br>1148 | Two-mica granite<br>Ocna de Fier<br>OF 62 |
|---|---|---|---|---|---|
| Major elements (%) | | | | | |
| $SiO_2$ | 63.96 | 62.71 | 63.22 | 62.14 | 72.53 |
| $Al_2O_3$ | 16.60 | 15.96 | 15.15 | 14.36 | 14.44 |
| $Fe_2O_3$ | 4.63 | 5.09 | 2.75 | 3.77 | 0.85 |
| FeO | n.d.[b] | n.d. | 1.65 | 2.55 | 2.42 |
| MnO | 0.06 | 0.07 | tr.[b] | 0.03 | 0.02 |
| MgO | 1.78 | 2.83 | 3.62 | 2.70 | 0.83 |
| CaO | 3.63 | 4.91 | 4.50 | 5.89 | 1.70 |
| $Na_2O$ | 3.83 | 3.63 | 2.85 | 3.37 | 2.30 |
| $K_2O$ | 3.82 | 2.90 | 3.34 | 3.25 | 2.43 |
| $TiO_2$ | 0.55 | 0.62 | 0.95 | 1.02 | 0.56 |
| $P_2O_5$ | 0.30 | 0.23 | 0.50 | 0.26 | 0.20 |
| LOI[b] | 0.51 | 0.77 | 0.76 | 0.70 | 1.68 |
| Total | 99.67 | 99.72 | 99.29 | 100.04 | 99.96 |
| Source: | This work | This work | Codarcea (1931) | Codarcea (1931) | Codarcea (1931) |
| Trace elements (ppm) | | | Rare earth elements (ppm) | | |
| | OF 186 | OF 157 | | OF 186 | OF 157 |
| Ba | 563.0 | 530.0 | La | 36.83 | 28.22 |
| Be | 2.4 | 1.6 | Ce | 70.36 | 53.51 |
| Co | 63.1 | 75.3 | Pr | 7.05 | 5.76 |
| Cr | 18.6 | 31.4 | Nd | 26.94 | 23.82 |
| Cu | 115.0 | 20.5 | Sm | 4.89 | 4.41 |
| Ga | 18.0 | 17.5 | Eu | 1.17 | 1.25 |
| Nb | 9.8 | 9.6 | Gd | 3.71 | 3.55 |
| Ni | 8.0 | 16.0 | Tb | 0.56 | 0.50 |
| Rb | 143.0 | 96.2 | Dy | 2.93 | 2.61 |
| Sc | 7.9 | 10.1 | Ho | 0.65 | 0.64 |
| Sr | 492.0 | 453.0 | Er | 1.61 | 1.55 |
| Th | 18.8 | 11.8 | Tm | 0.25 | 0.23 |
| V | 95.5 | 117.0 | Yb | 1.73 | 1.68 |
| Y | 17.4 | 17.0 | Lu | 0.28 | 0.26 |
| Zn | 42.2 | 45.7 | | | |
| Zr | 255.0 | 157.0 | Total | 158.96 | 127.99 |
| | | | $(La/Lu)_N$ | 13.65 | 11.27 |
| | | | $(Ce/Ce^*)_N$ | 1.05 | 1.01 |
| | | | $(Eu/Eu^*)_N$ | 0.84 | 0.97 |

[a] Analyses performed at CRPG, Vandoeuvre les Nancy, France
[b] n.d. – not determined; tr. traces; LOI – loss on ignition

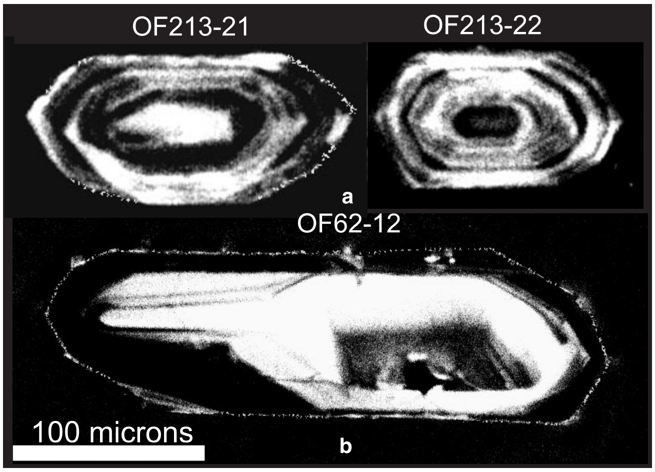


**Fig. 3a, b** Cathodoluminescence (*CL*) images of zircon grains from **a** Banatite Suite granodiorite *OF 213* and **b** two-mica granite *OF 62* from Ocna de Fier

*Bocşa Laccolith sample OF 221*

The sample represents the homogeneous equigranular hornblende-biotite granodiorite Bocşa 3 unit which makes up two thirds of the Bocşa Laccolith. Sixty zircon grains were mounted from this sample and no xenocrysts were observed. Ion microprobe U-Pb data are given in Table 2.

The weighted mean age of the 8 spots analysed in six grains is 79.6 ± 2.5 Ma (2σ, MSWD = 0.19), as shown in Table 2. This is significantly older than the 65-57 Ma K/Ar age of Russo-Săndulescu et al. (1986).

*Ocna de Fier Pluton sample OF 213*

This rock type is similar in fabric, mineralogy and chemical composition to that of Bocşa 3. Previous researchers suggested that the two rock types should be coeval, based on their mineralogical and chemical similarity. The 23 zircon grains mounted from this sample show similar morphologies and CL characteristics to those of the Bocşa sample.

The weighted mean age of the nine spots analysed in 8 grains is 75.5 ± 1.6 Ma (2σ, MSWD = 1.16, Table 2). It is also apparent from Table 2 that the Ocna de Fier zircons are 6 to 10 times richer in U, Th and Pb than the zircons in the Bocşa sample. However, the measured Th/U ratios in both samples are similarly high and characteristic of magmatic zircons, whereas metamorphic zircons are much poorer in Th (Th/U < 0.2, Cornell et al. 1998).

*Two-mica Moraviţa granite sample OF 62*

The small two-mica granitic plug cropping out in Moraviţa valley at the northern end of the deposit (Fig. 2a) is interesting because *P-T* data from the surrounding hornfelses and particularly a xenolith in the plug, showed disequilibrium parageneses (Nicolescu and Cornell 1999). This suggests two periods of contact

**Table 2** U-Pb analytical data and derived ages for the Bocşa and Ocna de Fier banatites. Note: individual analyses for zircons from each sample are ranked by increasing age.

| Grain # | [U] ppm | [Pb] ppm | [Th] ppm | Th/U meas. | $^{206}Pb/^{204}Pb$ | $^{206}Pb^a/^{238}U$ | ±1σ% | $^{206}Pb/^{238}U$ age ± 1σ (Ma) |
|---|---|---|---|---|---|---|---|---|
| OF 221 (Bocşa granodiorite) | | | | | | | | |
| 4 | 95 | 2 | 80 | 0.840 | 3970 | 0.01204 | 4.65 | 77 ± 4 |
| 45a | 204 | 3 | 169 | 0.829 | 1970 | 0.01236 | 3.84 | 79 ± 3 |
| 45b | 266 | 4 | 246 | 0.925 | 4750 | 0.01230 | 2.66 | 79 ± 2 |
| 53b | 191 | 3 | 167 | 0.879 | 3890 | 0.01238 | 4.15 | 79 ± 3 |
| 38a | 254 | 4 | 153 | 0.601 | 2520 | 0.01248 | 4.43 | 80 ± 4 |
| 38b | 128 | 2 | 66 | 0.518 | 1380 | 0.01254 | 3.56 | 80 ± 3 |
| 54a | 202 | 3 | 187 | 0.923 | 3700 | 0.01272 | 3.36 | 81 ± 3 |
| 53a | 327 | 6 | 301 | 0.921 | 2360 | 0.01282 | 9.52 | 82 ± 8 |
| Weighted mean: | | | | | | | | 79.6 ± 2.5 |
| MSWD: | | | | | | | | 0.19 |
| OF 213 (Ocna de Fier granodiorite) | | | | | | | | |
| 10b | 620 | 8 | 396 | 0.639 | 6750 | 0.01068 | 7.78 | 68 ± 5 |
| 17 | 561 | 8 | 440 | 0.785 | 9270 | 0.01118 | 5.86 | 72 ± 4 |
| 10a1 | 614 | 9 | 383 | 0.624 | 5240 | 0.01149 | 1.71 | 74 ± 1 |
| 16a | 450 | 7 | 1859 | 4.134 | – | 0.01179 | 1.86 | 76 ± 1 |
| 19b | 720 | 11 | 531 | 0.738 | 3270 | 0.01183 | 1.54 | 76 ± 1 |
| 14 | 644 | 9 | 484 | 0.751 | 120 | 0.01198 | 2.32 | 77 ± 2 |
| 18 | 675 | 11 | 532 | 0.788 | 3000 | 0.01228 | 3.17 | 79 ± 2 |
| 13 | 682 | 11 | 538 | 0.788 | 1630 | 0.01241 | 5.24 | 79 ± 4 |
| 11 | 396 | 7 | 338 | 0.855 | 1090 | 0.01248 | 4.99 | 80 ± 4 |
| Weighted mean: | | | | | | | | 75.5 ± 1.6 |
| MSWD: | | | | | | | | 1.16 |

[a] $^{206}Pb$ is corrected for common lead using the model of Stacey and Kramers (1975)

metamorphism, which could not be explained if the plug was coeval with the banatites. Its two-mica mineralogy and peraluminous chemistry (Table 1) show it to be different from the banatites, which are metaluminous, high-K calc-alkaline rocks.

Zircon CL images in Fig. 3b show different characteristics from the two Banatite Suite samples. Although most of the grains show magmatic zoning, some of them have CL-bright cores and dark rims, suggesting metamorphic reworking. An imprecise ion probe dating of this sample indicates an age around 415 Ma. This confirms Codarcea's (1931) and our own interpretation that the two-mica granite is much older than the Banatite Suite.

## Fission track (FT) data

To constrain the cooling history of the plutons, titanite, zircon and apatite fission track data were collected on the same samples which were U/Pb dated. The data are listed in Table 3 and sample locations are given in Figs. 1 and 2a.

In comparison with other dating methods for which a closing temperature is defined, fission tracks are metastable in a temperature interval known as the partial annealing zone. To interpret these ages in term of cooling rates, a short discussion on the partial annealing limits of these minerals is required. Literature data report values of 225 ± 30 °C for zircon (Zaun and Wagner 1985; Hurford 1986) and around 290 ± 40 °C for titanite (Harrison and McDougall 1980), but recent experimental studies in combination with geological constraints on FT annealing in zircon estimate the upper limit of zircon annealing at about 300 °C (Tagami et al. 1998). Moreover, fission track studies on zircon and titanite from the same rock sample give titanite ages older than or concordant with zircon ages (Fitzgerald and Gleadow 1988). Thus, the upper annealing limit of titanite is above that of zircon and close to the K-Ar closing temperature of biotite (Andriessen and Reutter 1994). According to these data, in our study we opted for closing temperatures of around 300 °C for zircon and 330 °C for titanite. For apatite the annealing limits are well established between 120–60 °C (Naeser and Faul 1969; Green et al. 1986).

U/Pb zircon ages combined with FT data on titanite and apatite allow the construction of cooling curves and estimation of intrusive cooling rates, as shown in Fig. 4. Intrusive emplacement temperatures are from Nicolescu and Cornell (1999), while the exhumation time (at least 10–5 Ma) is estimated based on the presence of Pliocene detrital sediments in the area. Apatite FT data suggest that cooling below 120 °C occurred in the Upper Cretaceous. Length measurements on horizontally confined tracks indicate that cooling stopped at temperatures over 60 °C by the end of the Cretaceous. These results are concordant with data from the Getic crystalline basement, about 300 km south-east of Bocşa-Ocna de Fier (Bojar et al. 1998) which also support a Late Cre-

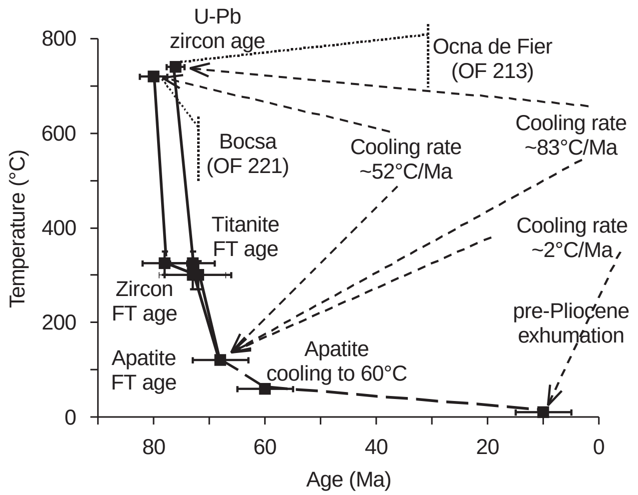


**Fig. 4** Age versus temperature plot of U/Pb zircon and fission track (*FT*) data for the Bocşa Laccolith and the Ocna de Fier Pluton showing cooling curves of the intrusions. The post-Cretaceous cooling is tentative, being based on poorly constrained data

**Table 3** Fission track analytical data and derived ages in Bocşa and Ocna de Fier banatites

| Mineral/number of grains analysed | $\rho_s$ (×10$^6$ cm$^{-2}$) ($N_s$) | $\rho_i$ (x10$^6$ cm$^{-2}$) ($N_i$) | $\rho_d$ (x10$^6$ cm$^{-2}$) ($N_d$) | Age ±1σ (Ma) | P($X^2$) Probability (%) | U (ppm) | Mean track length (μm) | Standard deviation (μm) |
|---|---|---|---|---|---|---|---|---|
| OF 221 (Bocşa granodiorite) U/Pb zircon age = 79.6 Ma | | | | | | | | |
| Tnt:9 | 5.682 (1136) | 5.357 (1071) | 0.417 (2523) | 78 ± 4 | 78 | 70 | | |
| Zrn:13 | 3.994 (1464) | 1.727 (633) | 0.519 (3138) | 73 ± 6 | 99 | 86 | | |
| Ap:20 | 0.128 (493) | 0.144 (551) | 0.417 (2523) | 68 ± 5 | 94 | 3 | 12.88 ± 0.25 (41) | 1.63 |
| OF 213 (Ocna de Fier granodiorite) U/Pb zircon age = 75.5 Ma | | | | | | | | |
| Tnt:10 | 5.437 (1079) | 5.482 (1088) | 0.417 (2523) | 73 ± 4 | 95 | 97 | | |
| Zrn:10 | 14.972 (851) | 6.562 (373) | 0.519 (3138) | 72 ± 6 | 99 | 124 | | |
| Ap:17 | 0.228 (555) | 0.252 (613) | 0.417 (2523) | 68 ± 5 | 99 | 6 | 13.89 ± 0.19 (40) | 1.19 |

Tnt: titanite; Zrn: zircon; Ap: apatite; ρ = track density; s, i, d = spontaneous, induced tracks and tracks in the fluence monitor glass, respectively. N = number of tracks counted

Note: samples were dated using the external detector method (Hurford and Green 1982). Ages were calculated using (a) $\zeta_{titanite}$ = 354.0 ± 10 and CN5 glass; (b) $\zeta_{zircon}$ = 121.7 ± 4 and CN2 glass; (c) $\zeta_{apatite}$ = 367.1 ± 10 and CN5 glass. Details on zeta calibration are available from A.-V.B.

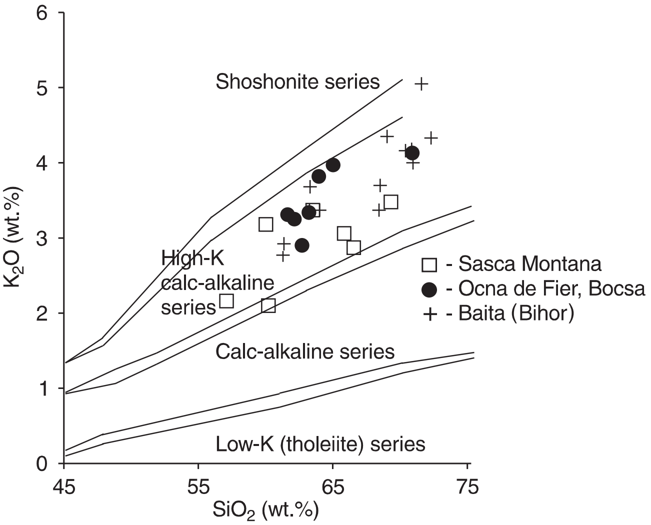


**Fig. 5** $K_2O$ versus $SiO_2$ diagram (Pecerillo and Taylor 1976 in Rickwood 1989) showing the high-K calc-alkaline nature of Romanian banatites. Data for Sasca Montană from Constantinescu (1980) and for Băiţa (Bihor) from Stoici (1983)

taceous regional cooling event affecting the South Carpathian realm.

Based on these data, a cooling rate of ~52 °C/Ma is calculated for Bocşa 3, while at Ocna de Fier the cooling rate was ~83 °C/Ma. The slower cooling of Bocşa 3 in comparison with the Ocna de Fier Pluton is explained by the much larger size of the former intrusion.

## Granodiorite geochemistry and tectonic setting

### Major element geochemistry

The Bocşa 3 and Ocna de Fier rock types have similar major element concentrations, as shown in Table 1. Moreover, analyses along the entire Banatite Suite show a consistent high-K calc-alkaline character. Figure 5 illustrates this feature for samples from Bocşa, Ocna de Fier, Sasca Montană (central Banat – 60 km south of Ocna de Fier) and Băiţa (Bihor Mountains – 150 km north-east of Ocna de Fier). The classification schemes of Streckeisen (1973) and Barker (1979) confirm that the samples are granodiorite (Fig. 6). Both Bocşa and Ocna de Fier samples, can be classified as I-type (Table 4), metaluminous granodiorites. The Palaeozoic two-mica granite is peraluminous, being different not only in age, but also in composition and petrogenesis.

### Trace element geochemistry

If not combined with other geological evidence, discrimination diagrams alone are not very useful for distinguishing between subduction-related volcanic arc, syn-collision and post-collision granitoid tectonic settings, as pointed out by many authors such as Harris et al. (1994), Roberts and Clemens (1993) and Seymour et al. (1996).

Major element discrimination diagrams (Maniar and Piccoli 1989; Rogers and Greenberg 1990; Agrawal 1995) applied to the Bocşa and Ocna de Fier granitoids gave inconclusive results and are not considered further. The trace element diagrams proved to be more useful. Plotting the samples on the Rb versus (Y + Nb) diagram of Pearce (1996) (Fig. 7), all data fall in the post-collision or volcanic arc fields. The Bocşa and Ocna de Fier samples plot much closer to the post-collision Omani and Adamello granitoids than to the Andean volcanic arc or syn-collision ones shown for comparison.

Chondrite-normalised rare earth element (REE) patterns of Bocşa and Ocna de Fier granodiorites are similar to those of the southern Adamello (Re di Castello group) granodiorites and of the Omani granites (Fig. 8). REE abundances are similar, with moderate light rare earth element enrichment ($La/Lu_N$ =

**Fig. 6 a** AQP diagram showing the dominantly granodioritic nature of Ocna de Fier banatites (Streckeisen 1973). Data from Codarcea (1931). **b** Plot of Bocşa-Ocna de Fier granitoids on the normative An-Ab-Or ternary diagram (Barker 1979 in Rollinson 1993)

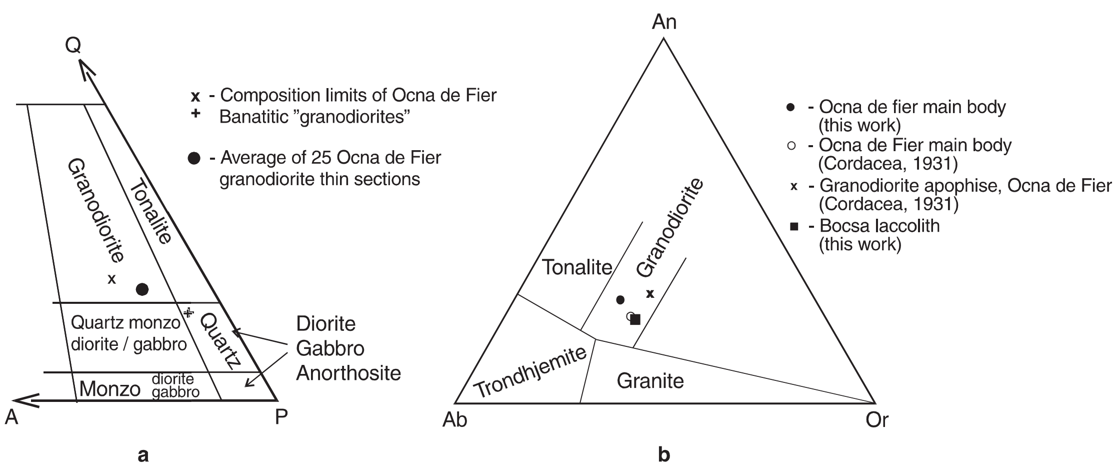

**Table 4** I-Type granitoid characteristics of Ocna de Fier granodiorites

| Characteristic | I-type granitoids (Raymond 1995) | 1 OF 186 | 2 OF 157 | 3 1148 | 4 1374 |
|---|---|---|---|---|---|
| $SiO_2$% | 53–76 | 63.96 | 62.71 | 62.14 | 63.22 |
| Mol. $Al_2O_3/(Na_2O + K_2O + CaO)$ | <1.1 | 0.97 | 0.88 | 0.73 | 0.92 |
| $Na_2O$% in silicic rocks | >3.2 | 3.83 | 3.63 | 3.37 | 2.85 |
| $K_2O/Na_2O$ | Low | 1.00 | 0.80 | 0.96 | 1.17 |
| $Fe^{3+}/(Fe^{2+} + Fe^{3+})$ | >0.2* | n.d. | n.d. | 0.57 | 0.43 |
| Eu (ppm) | Low–high | 1.17 | 1.25 | n.d. | n.d. |
| Cr, Ni (ppm) | Low | 18.6, 8.0 | 31.4, 16.0 | n.d. | n.d. |
| Main enclaves | Amphibolite, diorite | – | Amphibolite, diorite | – | – |
| Key CIPW minerals | <1%C | 0.18 | 0.00 | 0.00 | 0.00 |
| Key modal minerals | Hbl, Bt, Tnt, Mag | Hbl, Bt, Tnt, Mag | Hbl, Bt, Tnt, Mag | Hbl, Bt, Tnt, Mag | Hbl, Bt, Tnt, Mag |

n.d. – not determined; Hbl – hornblende; Bt – biotite; Tnt – titanite; Mag – magnetite
* Ohmoto (1986)
1 – Bocşa laccolith (this work); 2 – Moraviţa valley, Ocna de Fier (this work); 3 – Ţiganului brook, Ocna de Fier (Codarcea 1931); 4 – Ferendia valley, Ocna de Fier (Codarcea 1931)

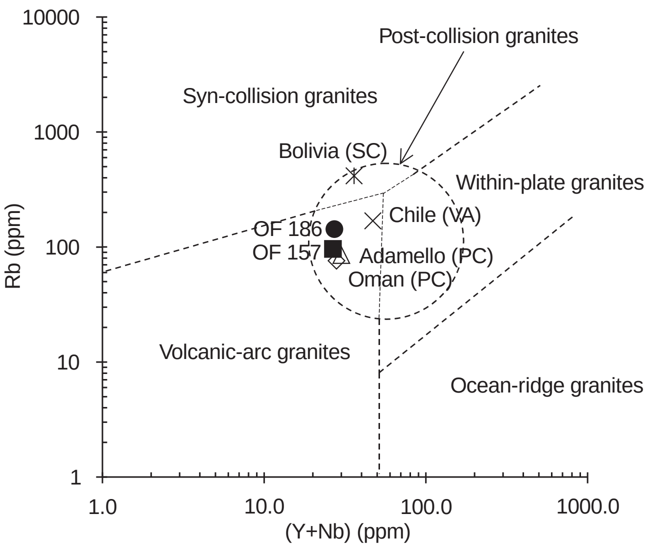


**Fig. 7** Updated Rb versus (Y + Nb) granitoid tectonic setting discrimination diagram (Pearce 1996), suggesting the post-collision character of the Bocşa and Ocna de Fier granodiorites. The original diagram of Pearce et al. (1984) did not discriminate between post-collision (*PC*), syn-collision (*SC*), volcanic arc (*VA*) and within-plate granitoids. Granitoids from known tectonic settings (Chile – volcanic-arc, Pearce et al. 1984; Bolivia – syn-collision Pearce et al. 1984; Oman – arc-continent post-collision, Pearce et al. 1984; Re di Castello group of the Adamello massif, Italy – continent-continent post-collision, Dupuy et al. 1982; Kagami et al. 1991) are plotted for comparison

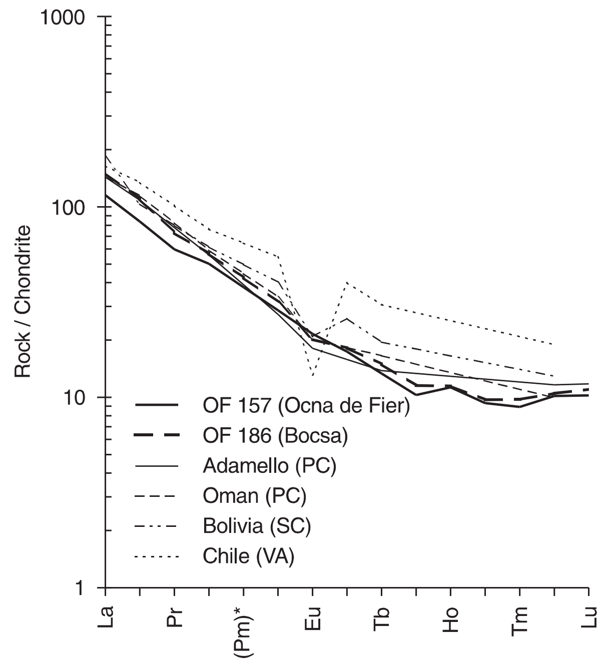


**Fig. 8** Chondrite normalised REE patterns showing the post-collision signature of the Bocşa and Ocna de Fier granodiorites (chondritic values of Evensen et al. 1978). Same samples from known tectonic settings shown in Fig. 7, are plotted for comparison

$12.91 \pm 1.46$, Table 1) and virtually no Eu anomaly ($Eu/Eu^*_N = 0.87 \pm 0.07$). REE profiles of the Chilean and Bolivian granitoids differ markedly in having slightly higher total REE abundances and moderate (0.65) to strong (0.28) negative Eu anomalies.

In conclusion, the geochemical data point to a subduction or post-subduction tectonic setting, but do not easily distinguish between them. This is mostly because the same rocks are involved in granitoid generation both during and after subduction events, as discussed by Pearce et al. (1984), Roberts and Clemens (1993) and Förster et al. (1997).

## Discussion

### Critical discussion of previously published data

#### *Age of the intrusive rocks*

Russo-Săndulescu et al.'s (1986) K/Ar dating of the composite Bocşa laccolith gave different ages for the three petrographic units that make up the laccolith. The Bocşa 1 and Bocşa 2 units gave 88 and 80 Ma respectively, while two samples analysed from Bocşa 3 gave 65 and 57 Ma, differing by more than the estimated error of about 2.4 Ma. These dates were questioned by Pătraşcu et al. (1992), because they were also much younger than the 83–72 Ma K/Ar ages (Campanian to Maastrichtian of Upper Cretaceous) obtained for Banatite intrusives at Oraviţa and Moldova Nouă to the south by Soroiu et al. (1986) and by Strutinski et al. (1986) in the Poiana Ruscă Mountains to the north. Pătraşcu et al. (1992) considered that alteration of Bocşa biotites had caused argon loss and therefore too-young ages.

Our zircon data are equally precise as the K/Ar data and less easily affected by low-temperature processes. Based on the test of Possagno zircons described above, we regard our dating as accurate within the precision. Thus we have accurately dated the Bocşa 3 unit at 79.6 ± 2.5 Ma and the Ocna de Fier Pluton at 75.5 ± 1.6 Ma, which shows that Banatite magmatism at Bocşa did not extend into the Palaeocene. Our Bocşa and Ocna de Fier ages differ at the $1\sigma$ level, but they just overlap at the $2\sigma$ or 95% confidence level. The fission track dates on titanite also suggest an age difference but with less than 65% confidence, while the zircon and apatite ages from the two intrusions show no differences. We conclude that the Ocna de Fier Pluton might be younger by about 4 Ma, but that the intrusions had similar cooling histories as shown in Fig. 4.

### *Tectonic setting*

Vlad (1997) suggests an Andean subduction-related setting for all banatites. The subduction related environment is also advocated by other authors such as Jankovic (1997) and Karamata et al. (1997). However, field evidence in the Ocna de Fier and Dognecea areas suggests a different interpretation.

In the Moraviţa valley the Ocna de Fier Pluton cuts through the Ezeriş-Colţan reverse fault which separates the Bocşiţa-Drimoxa and Buchin Series of the Bocşa nappe, while along Dognecea valley it also cuts through the Dognecea thrust line that separates the Supra-Getic Bocşa and Moniom nappes (Fig. 2). Both tectonic lines are Mid-Cretaceous in age: the Ezeriş-Colţan reverse fault is intra-Turonian (90 Ma), while the Dognecea thrust is Austrian in age (~100 Ma) (Iancu 1986). The Supra-Getic/Getic thrust, running through the eastern part of the study area, has been shown by Iancu (1986) to be contemporaneous with the Dognecea thrusting. Recent $^{40}Ar/^{39}Ar$ whole-rock data by Dallmeyer et al. (1996) for phyllites along a Supra-Getic/Getic thrust at Moniom (Fig. 1), about 4 km north-east of Ocna de Fier, date this major thrusting event at 118–119 Ma, confirming its Austrian stratigraphic age. In Dognecea valley Banatite Suite granitoids crop out less than 500 m from the Supra-Getic/Getic thrust, and if they were pre- or syntectonic, they should show evidence of deformation, which is not the case. This field evidence clearly shows that the Banatite Suite was intruded into the region after the major tectonic and thrusting events, and is thus post-tectonic. This is further substantiated by our new emplacement ages of the intrusives, which post-date all documented tectonic events in the area. For these reasons they cannot be subduction-related, as subduction would have ceased after the collision event which accompanied the compressional tectonic movements (Dallmeyer et al. 1996). A post-collision setting is thus demonstrated for the Banatite Suite. Our geochemical data are consistent with a post-collision setting, having similar geochemical signatures to other post-collision related intrusives in the Tethyan realm, in the Italian Alps (Adamello) and Oman (Figs. 7 and 8).

We conclude that the Bocşa Laccolith and Ocna de Fier Pluton were generated in a post-collisional environment, following the Lower Cretaceous subduction of the Severin oceanic plate (Russo-Săndulescu in Ilinca et al. 1993).

### Relevance to skarn genesis

The age determinations and tectonic setting proposed in this work are important to the understanding of skarn genesis at Ocna de Fier. The skarn and associated mineralisation at Ocna de Fier and Dognecea were generated as a direct consequence of the emplacement of the Ocna de Fier Pluton. Thus, the age of the intrusive also represents the age of mineralisation. The intrusive ages reported here reconcile the age of the Ocna de Fier-Dognecea skarn deposit with that of other banatite-related skarns in Romania i.e., 83–72 Ma (Soroiu et al. 1986; Strutinski et al. 1986).

The tectonic context in which banatite intrusion and associated mineralisation took place is also relevant for regional mineral exploration. The post-collision tectonic setting suggested in this work offers a criterion when looking for similar mineralisations in other parts of the Carpathians.

## Conclusions

As part of the Carpathian chain of the Alpine-Himalayan belt, the Bocşa and Ocna de Fier granitoids were formed in an orogenic environment related to the closure of the Tethys Ocean.

Our results give a new and realistic picture of how and when the intrusions of the Romanian Banatite Suite formed. They were emplaced in a post-collision environment, after the subduction of the Severin oceanic plate and the subsequent collision of the Getic and Danubian microplates. First the barren Bocşa Laccolith was emplaced 79.6 Ma years ago, followed about four million years later by the similar but smaller Ocna de Fier Pluton, which gave rise to skarn and hydrothermal mineralisation.

Fission track dates reported in Table 3 correlate well with U/Pb zircon dates, suggesting a slightly slower cooling rate from magma intrusion to apatite closure temperatures for the Bocşa Laccolith (~52 °C/Ma) compared to the Ocna de Fier Pluton (~83 °C/Ma). This is in agreement with the much larger rock volume in the Bocşa Laccolith.

Our U/Pb and titanite fission track age determinations suggest that contrary to previous models, the Bocşa and Ocna de Fier-Dognecea intrusives, although petrologically related, are not exactly contemporaneous. However, the age differences of about 4 Ma are only significant at the 65% confidence level.

According to our zircon U/Pb age of ca. 415 Ma, the two-mica granite cropping out at the northern end of the deposit is much older than the banatites and thus not related to the main Alpine intrusions. In combination with the *P-T* data reported elsewhere (Nicolescu and Cornell 1999), which demonstrates that the intrusives were emplaced at a depth of ~10 km in the crust and that the peak temperature during intrusion reached 700 °C, this work contributes to a better understanding of the genesis of one of the classic skarn deposits.

**Acknowledgements** We acknowledge the outstanding work done in the area more than half a century ago by Alexandru Codarcea (1900–1974). He was the first to state that the Ocna de Fier-Dognecea skarn deposit formed in an Upper Cretaceous, post-tectonic environment, and made field observations which are still relevant today. The NORDSIM team (Martin J. Whitehouse, Jessica Vestin and Tornbjörn Sunde) at the high-resolution ion microprobe facility in Stockholm, jointly financed by the Nordic Countries, is acknowledged for its support during U/Pb data collection for this study. F. Oberli at ETH Zürich, Switzerland, kindly provided the Possagno zircon sample. Ali Firoozan assisted with zircon separation.

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