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# MIDDLE-LATE TRIASSIC $^{40}Ar/^{39}Ar$ HORNBLENDE AGES FOR EARLY INTRUSIONS WITHIN THE DITRAU ALKALINE MASSIF, RUMANIA: IMPLICATIONS FOR ALPINE RIFTING IN THE CARPATHIAN OROGEN

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**Abstract:** Multigrain hornblende concentrates from two samples of massive gabbro and diorite collected within „early“ intrusive phases of the Ditrau Alkaline Complex (Rumania) record well-defined $^{36}Ar/^{40}Ar$ vs. $^{39}Ar/^{40}Ar$ plateau isotope correlation ages of 231.5 ± 0.1 Ma and 227.1 ± 0.1 Ma; 2σ intralaboratory error). These are interpreted as dating relatively rapid post-magmatic cooling at high crustal levels following pluton emplacement in the Middle-Late Triassic. The magmatic activity predated Early Jurassic rifting in the Eastern Carpathian orogen.

**Key words:** Eastern Carpathians, Triassic, alkaline magmatism, rifting.

## Introduction

The Alpine-Carpathian orogen displays only local and limited evidence for magmatic activity during tectonic rifting. Rift-related mantle-plume activity is apparently entirely lacking throughout the Alpine-Carpathian orogen. Most recent models have postulated two distinct phases of Alpine rifting which led to the development of two different oceanic tracts between Laurasia and Gondwana during Mesozoic times (Dal Piaz et al. 1995; Neubauer 1994; Sandulescu 1994; Stampfli et al. 1991; Trümpy 1988). Permian to Middle Triassic rifting resulted in formation of the Middle Triassic Meliata-Vardar and North Dobrogea extended rift and ocean domains. A second rift resulted in the separation of the continental Austroalpine/Southalpine domains from extra-Alpine Europe. Evidence for the latter rift and subsequent passive continental margin formation is widely distributed throughout the Austroalpine, Southalpine, and Dinaric domains although magmatic activity appears to have been minor during the rift phase.

Middle Triassic magmatic activity in the Southalpine-Dinaric units included (Fig. 1): (1) Triassic pegmatite intrusions in westernmost sectors of the Southalpine unit (Hanson et al. 1966) due to crustal extension (e.g. Bertotti et al. 1993); (2) Middle Triassic intrusion of Predazzo-Monzoni suites in the central Southern Alps; and (3) Middle Triassic volcanic activity in the South Tyrolian Dolomites. The variably altered, green tuffs associated with this partly subaerial volcanism („pietra verde“) are widely distributed in Southalpine and Austroalpine units, and the Dinarides. The latter has been interpreted to have related to subduction of oceanic crust rather than to rifting processes (e.g. Bebien et al. 1978; Pe-Piper 1982).

This contribution presents geochronological evidence for a Middle-Late Triassic age of early gabbro and diorite intrusions within the Ditrau Alkaline Massif that occurred close to the opposite margins of the Alpine-Carpathian belt. These data suggest that intrusion of the Ditrau Alkaline Massif was associated with mantle-plume activity which predated Jurassic rifting within the Eastern Carpathian orogen.

## Geological setting

The Ditrau Alkaline Massif is located within westernmost exposure of basement within the Eastern Carpathians or Rumania (Fig. 1). Detailed description of the intrusion complex and general geological relationships may be found in Ianovici (1938), Streckeisen (1952, 1954, 1960), Codarcea et al. (1958), Streckeisen & Hunziker (1974), Anastasiu & Constantinescu (1984), Sandulescu (1984), Anastasiu et al. (1994) and Kräutner & Bindea (1995). The Ditrau Massif is considered to represent an intrusion body with a internal zonal structure, which was emplaced into pre-Alpine metamorphic basement complexes of the Bucovinian Nappe Complex. The center of the Ditrau Massif was formed by nepheline syenite, which is surrounded by syenite and monzonite. Northwestern and norteastern marginal sectors are composed of hornblende gabbro/hornblendite, diorite, monzonite and alkali granite. Hornblende gabbro/hornblendite and diorite represent the earliest intrusive phase, and are embedded within younger syenite and granite. All these rocks are cut by late-stage dikes with a large variety of compositions including tinguaite, microsyenite, and aplite, and later lamprophyre (Streckeisen 1952, 1954; Codarcea et al. 1958; Streckeisen & Hunziker 1974; Anastasiu & Constantinescu 1984; Anastasiu et al. 1994). Lithologies and variations of petrographic compositions suggest that the Ditrau pluton represents an alkaline massif with mantle-plume related origin.

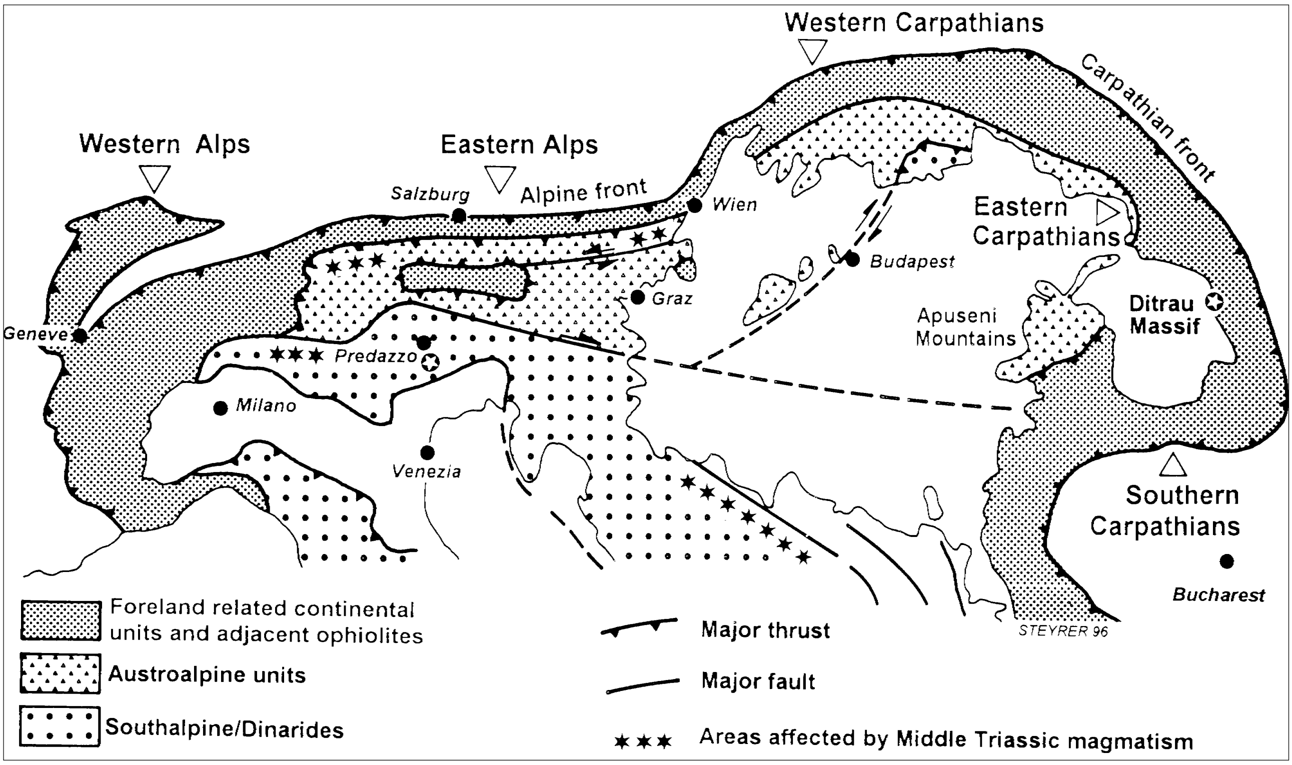


**Fig. 1.** Generalized tectonic map of the Alpine-Carpathian orogen showing Triassic magmatic suites and location of the Ditrau Alkaline Massif in the Eastern Carpathians, Rumania.

A contact aureole is well-developed mainly within the otherwise low grade, host metamorphic Tulghes Group metasediments and metavolcanic rocks. The contact aureole displays statically grown andalusite, biotite, and cordierite (Streckeisen 1952; Streckeisen & Hunziker 1974). Neogene volcanic and sedimentary rocks discordantly overlie the complex.

Previous interpretations of the age of intrusion are exclusively based on K-Ar geochronology. K-Ar biotite ages ranging from Late Triassic to Cretaceous have been reported from the intrusive complex (218–103 Ma: Bagdasarian 1972; Streckeisen & Hunziker 1974; Minzauti et al. 1981, unpubl. report: data listed in Kräutner & Bindea 1995; Molnár & Avra-Sós 1995). Recently, Molnár & Avra-Sós (1995) reported K-Ar amphibole ages ranging from 237 to 177 Ma, and K-Ar feldspar ages between 255 and 113. The Ditrau Alkaline Massif was recently interpreted as representing an Early Jurassic incipient intrusion within the Bucovinian intra-continental rift zone of the Eastern Carpathians (Kräutner & Bindea 1995).

## Analytical methods

The techniques used during $^{40}Ar/^{39}Ar$ analysis of the Ditrau hornblende concentrates generally followed those described by Dallmeyer & Gil-Ibarguchi (1990). Optically pure (>99 %) amphibole concentrates were wrapped in aluminium-foil packets, encapsulated in sealed quartz vials, and irradiated for 80 hr in the central thimble position of the TRIGA Reactor in the U.S. Geological Survey, Denver. Variation in the flux of neutrons along the length of the irradiation assembly was monitored with several mineral standards, including MMhb-1 (Sampson & Alexander 1987). The samples were incrementally heated until fusion in a double-vacuum, resistance-heated furnace. Temperatures were monitored with a direct-contact thermocouple and are controlled to ± 1°C between increments and are accurate to ± 5°. Measured isotopic ratios were corrected for total blanks and the effects of mass discrimination. Interfering isotopes produced during irradiation were corrected using factors reported by Dalrymple et al. (1981). Apparent $^{40}Ar/^{39}Ar$ ages were calculated from corrected isotopic ratios using the decay constants and isotopic ratios listed by Steiger & Jäger (1977).

Intralaboratory uncertainties reported here have been calculated by statistical propagation of uncertainties associated with measurement of each isotopic ratio through the age equation. Interlaboratory uncertainties are ca. ±1.25–1.5 % of the quoted age. Total-gas ages have been computed for each sample by appropriate weighting of the age and percent $^{39}Ar$ released within each temperature increment. A „plateau“ is considered to be defined if the ages recorded by two or more continuous gas fractions each representing >4 %, constituting together >50 % of the total $^{39}Ar$ evolved are mutually similar within a ±1 % intralaboratory uncertainty. Analyses of the MMhb-1 monitor indicate that apparent K/Ca ratios may be calculated through the relationship 0.518 (±0.0005) × $(^{39}Ar/^{37}Ar)_{corrected}$.

Plateau portions of the hornblende analyses have been plotted on $^{36}Ar/^{40}Ar$ vs. $^{39}Ar/^{40}Ar$ isotope correlation diagrams. Regression techniques followed methods described by York (1969). A mean square of the weighted deviation (MSWD) has been used to evaluate the isotope correlations.

## Results

Multigrain hornblende concentrates were prepared from two samples of massive gabbro and diorite collected within northern sectors of an „early" gabbroic phase of the Ditrau Complex. Sample locations are indicated in Fig. 2. Coordinates of sample locations and petrographic descriptions of the dated samples are provided in the Appendix. The $^{40}Ar/^{39}Ar$ analytical data are provided in Table 1 and portrayed as apparent age spectra in Fig. 3.

The two hornblende concentrates display variably discordant apparent age spectra (Fig. 3). The relatively small volume low-temperature gas fractions record considerable variation in apparent ages. These are matched by fluctuations in apparent K/Ca ratios which suggest that experimental evolution of argon occurred from compositionally distinct, relatively nonretentive phases. These could have been represented by: 1) very minor, optically undetectable mineral contaminants in the hornblende concentrates; 2) petrographically unresolvable exsolution or compositional zonation within constituent hornblende grains;

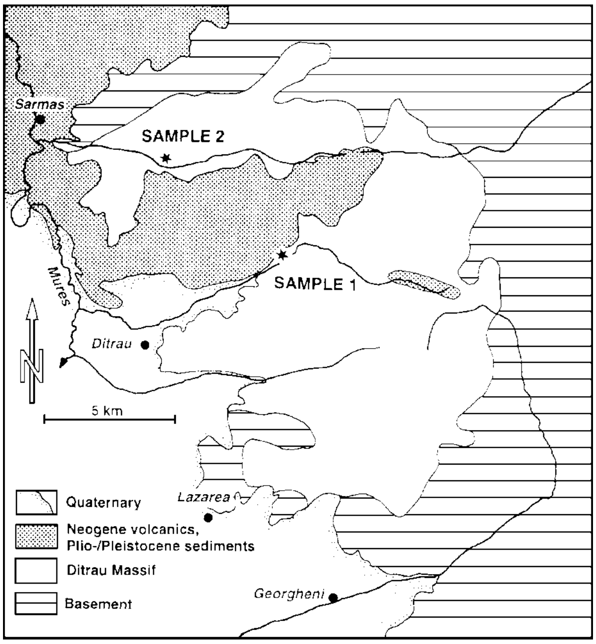


**Fig. 2.** Simplified geological map of the Ditrau Alkaline Massif showing $^{40}Ar/^{39}Ar$ sample locations (strongly simplified after Streckeisen & Hunziker 1974).

**Table 1:** $^{40}Ar/^{39}Ar$ analytical data for incremental heating experiments on hornblende concentrates from gabbros of the Ditrau Massif, Rumania.

| Release temp. (°C) | $(^{40}Ar/^{39}Ar)$* | $(^{36}Ar/^{39}Ar)$* | $(^{37}Ar/^{39}Ar)^c$ | $^{39}Ar$ % of total | $\%^{40}Ar$ non-atmospheric $^+$ | $^{36}Ar_{Ca}$ % | Apparent age (Ma) and analytical error (Ma) ** |
|---|---|---|---|---|---|---|---|
| Sample 1: J = 0.009792 | | | | | | | |
| 600 | 55.10 | 0.10548 | 1.475 | 0.77 | 43.64 | 0.38 | 381.7 ± 0.3 |
| 700 | 19.27 | 0.02223 | 0.957 | 0.41 | 66.28 | 1.17 | 212.7 ± 0.3 |
| 800 | 14.12 | 0.00364 | 2.567 | 9.10 | 93.79 | 19.16 | 220.2 ± 0.1 |
| 850 | 13.85 | 0.00154 | 2.752 | 25.59 | 98.26 | 48.53 | 226.0 ± 0.1 |
| 875 | 13.80 | 0.00135 | 2.798 | 32.64 | 98.70 | 56.36 | 226.1 ± 0.1 |
| 900 | 13.79 | 0.00129 | 2.892 | 22.20 | 98.88 | 60.93 | 226.4 ± 0.1 |
| 925 | 13.81 | 0.00202 | 3.319 | 7.37 | 97.55 | 44.52 | 223.9 ± 0.1 |
| 950 | 14.32 | 0.00281 | 6.965 | 1.47 | 98.08 | 67.52 | 233.3 ± 0.1 |
| Fusion | 15.66 | 0.01041 | 14.453 | 0.44 | 87.74 | 37.77 | 229.6 ± 0.4 |
| Total | 14.19 | 0.00259 | 2.920 | 100.00 | 97.48 | 50.54 | 226.7 ± 0.1 |
| Total without 600-700 °C, 950 °C -fusion | | | | 96.91 | | | 225.4 ± 0.1 |
| Sample 1: J = 0.009862 | | | | | | | |
| 600 | 30.22 | 0.05297 | 1.309 | 0.81 | 48.54 | 0.67 | 239.8 ± 0.3 |
| 700 | 12.64 | 0.00849 | 0.366 | 3.16 | 80.34 | 1.17 | 169.1 ± 0.1 |
| 740 | 12.63 | 0.00843 | 0.694 | 2.18 | 80.66 | 2.24 | 169.7 ± 0.1 |
| 770 | 12.72 | 0.00733 | 1.516 | 1.87 | 83.88 | 5.62 | 177.5 ± 0.2 |
| 800 | 13.32 | 0.00379 | 2.316 | 3.82 | 92.94 | 16.62 | 204.5 ± 0.1 |
| 825 | 13.65 | 0.00298 | 2.466 | 12.29 | 94.95 | 22.47 | 213.5 ± 0.1 |
| 850 | 14.30 | 0.00301 | 2.707 | 13.26 | 95.26 | 24.46 | 223.9 ± 0.1 |
| 875 | 14.34 | 0.00214 | 2.891 | 18.29 | 97.18 | 36.82 | 228.7 ± 0.1 |
| 900 | 14.17 | 0.00163 | 3.044 | 20.14 | 98.29 | 50.93 | 228.6 ± 0.2 |
| 930 | 14.18 | 0.00179 | 3.245 | 16.70 | 98.07 | 49.35 | 228.2 ± 0.1 |
| 960 | 14.23 | 0.00156 | 4.421 | 3.98 | 99.23 | 77.29 | 231.8 ± 0.2 |
| Fusion | 15.16 | 0.00330 | 7.116 | 3.49 | 97.31 | 58.74 | 241.9 ± 0.1 |
| Total | 14.18 | 0.00312 | 2.924 | 100.00 | 95.41 | 37.20 | 221.7 ± 0.1 |
| Total without 600-825 °C, 960 °C -fusion | | | | 68.39 | | | 227.6 ± 0.1 |

* measured

c corrected for post-irradiation decay of $^{37}Ar$ (35.1 day ½-life)

\+ $[^{40}Ar_{tot.} - (^{36}Ar_{atmos.}) (295.5)] / ^{40}Ar_{tot.}$

** calculated using correction factors of Dalrymple et al. (1981); two sigma, intralaboratory errors.

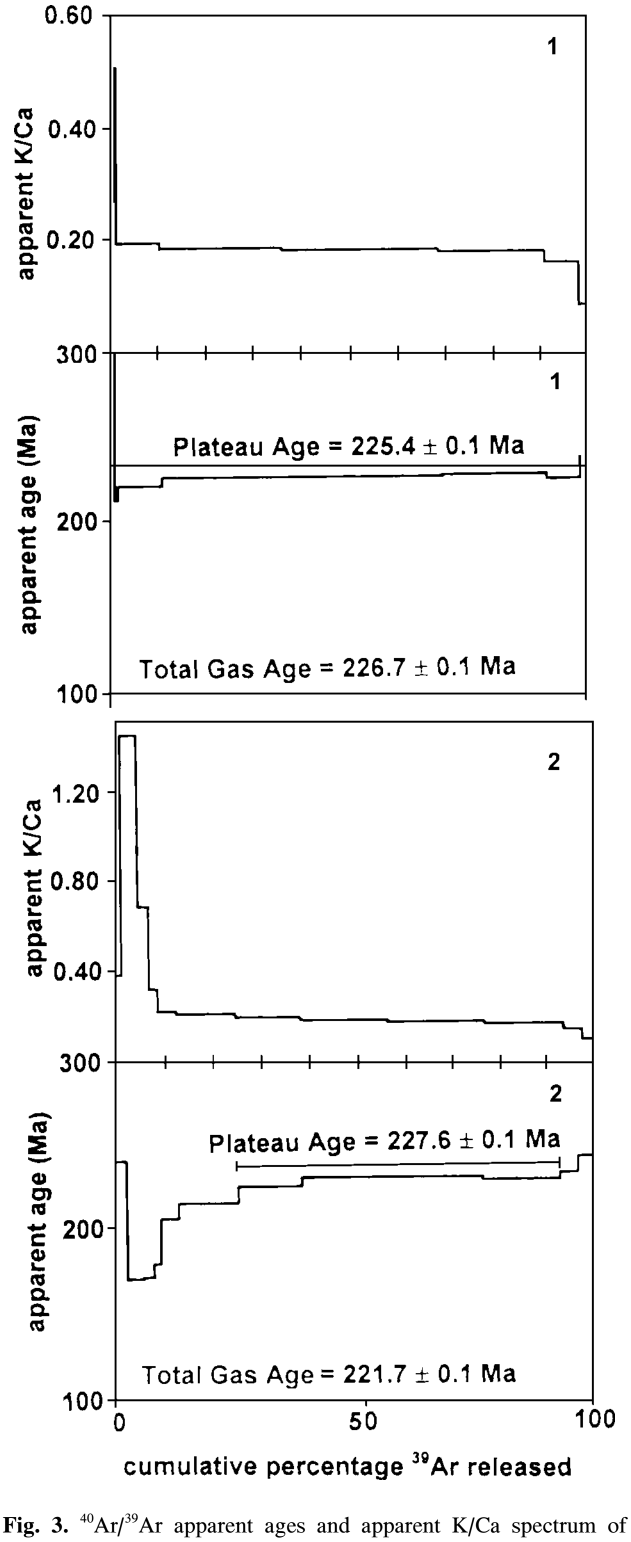


**Fig. 3.** $^{40}Ar/^{39}Ar$ apparent ages and apparent K/Ca spectrum of multigrain hornblende concentrates from the Ditrau Alkaline Massif. Analytical uncertainties (two sigma, intralaboratory) represented by vertical width of bars. Experimental temperatures increase from left to right. Note that plateau ages are listed. For discussion of ages, see text.

3) minor chloritic replacement of hornblende; and/or intracrystalline inclusions. Most intermediate- and high-temperatures gas fractions display little intrasample variation in apparent K/Ca ratios, suggesting that experimental evolution of gas occurred from compositionally uniform sites. The intermediate- and high-temperature gas fractions experimentally evolved from sample 1 record generally similar apparent $^{40}Ar/^{39}Ar$ ages which define a plateau age of 225.4±0.1 Ma. $^{36}Ar/^{40}Ar$ vs. $^{39}Ar/^{40}Ar$ isotope-correlation of the plateau data is well-defined (MSWD = 1.38), and defines an inverse ordinate intercept ($^{40}Ar/^{36}Ar$ ratio) of 293.6. This is similar to that of the present-day atmosphere, and suggests no significant intracrystalline contamination with extraneous („excess“) argon components. Using the inverse abscissa intercept ($^{40}Ar/^{39}Ar$ ratio) in the age equation yields a plateau isotope-correlation age of 227.1±0.1 Ma. Because calculation of isotope correlation ages does not require assumption of a present-day $^{40}Ar/^{36}Ar$ ratio, they are considered more significant than those directly calculated from the analytical data. The 227 Ma isotope-correlation age recorded by the hornblende concentrate from sample 1 is considered geologically significant, and is interpreted to date post-magmatic cooling temperatures required for intracrystalline retention of argon in constituent hornblende grains. Harrison (1981) suggested ca. 500±25 °C are appropriate for argon retention within most hornblende compositions in the range of cooling rates likely to characterize most geological settings. In view of the high-level intrusive character of the Ditrau Complex, it is likely that post-magmatic cooling was relatively rapid. Therefore the ca. 227 Ma isotope-correlation age is interpreted as probably closely dating initial pluton emplacement.

The hornblende concentrate prepared from sample 2, a hornblende diorite, displays more extensive internal spectra discordance. However, the 850–930 °C increments record similar apparent ages which define a plateau of 227.6±0.1 Ma. Isotope-correlation of the plateau data is well-defined (MSWD = 1.88) with an inverse ordinate intercept of 294.7. A plateau isotope-correlation age of 231.5±0.1 Ma is defined. This is also interpreted as dating a relatively rapid post-magmatic cooling following pluton emplacement.

Considered together the plateau isotope-correlation ages defined by the two hornblende concentrates suggest emplacement of early magmatic suites of the Ditrau Complex occurred at ca. 232–228 Ma. These correspond to the Middle-Late Triassic boundary following the time-scale calibration of Gradstein et al. (1994).

## Discussion

The continental portion of the Eastern Carpathian orogen, represented by the Bucovino-Getic microcontinent, has been separated from stable Europe by Early Jurassic rifting (e.g. Sandulescu 1984, 1994; Debelmas & Sandulescu 1987; Trümpy 1988) which is expressed by general subsidence associated with extension of stable continental lithosphere. The Ditrau Alkaline Massif is interpreted, therefore, as having developed as a result of mantle-plume activity within continental crust (South European margin; now Bucovinian Nappe Complex) predating the onset of Jurassic rifting (Fig. 4a). On this continental crust a sedimentary sequence records subsequent rift and passive continental margin formation (Fig. 4b). Deep water and oceanic sequences structurally occur both beneath

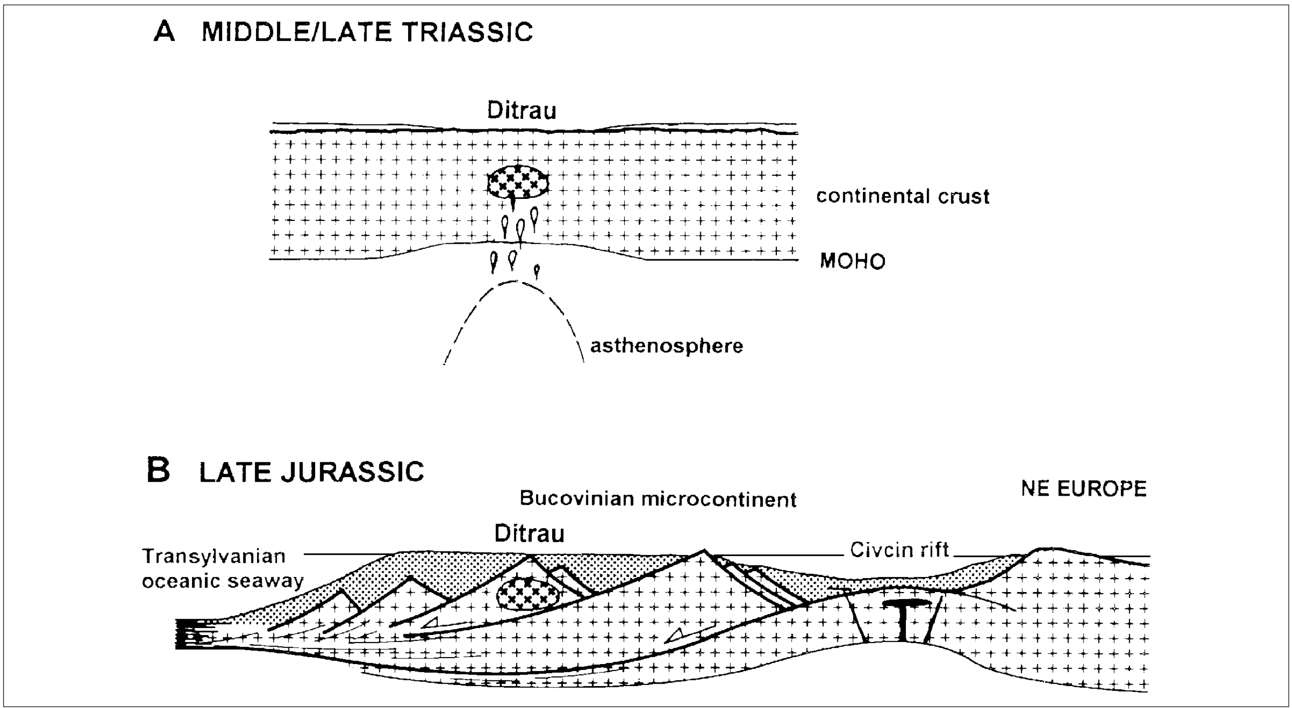


**Fig. 4.** Schematic tectonic cross-sections illustrating: **A** — Triassic magmatism associated with mantle-plume uprise in the Eastern Carpathians; **B** — Jurassic detachment of the Bucovinian microcontinent from Europe (extensional allochthon) during opening of the Civcin rift. The Bucovian microplate was isolated from intra-Tethyan microplates by the Mures-Persani-Haghimas-Rarau (Transylvanian) oceanic seaway.

the present Bucovinian Nappe Complex (e.g. deep water sediments and basalts within the Black Flysch and Ceahlau nappes within the sedimentary Civcin rift that widened towards the south within the Southern Carpathians) and above it, within the oceanic elements that are exposed in the Transylvanian nappes and in the Bucovinian wildflysch sequence of the Haghimas, Rarau and Persani mountains (Sandulescu 1984; 1994; Burchfiel 1976, 1980). The latter correlate with the Jurassic Mures ophiolite sequence that is exposed in the southern Apuseni mountains. Therefore, the Bucovino-Getic microplate is now structurally interleaved with Jurassic oceanic sequences. We interpret the Bucovino-Getic microcontinent as representing an extensional allochthon which was only detached from the European continent during Jurassic rifting.

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## Appendix 1: Sample descriptions

**Sample 1**. Coordinates of location: 46° 50′ 02′′ N, 25° 34′ 19′′ E; ca. 7 km east of Ditrau town on the road to Tulghes. Medium-grained (average grain size between 1 and 2 mm) massive gabbro. Main constituents are brown amphiboles and plagioclase. The amphibole is mostly free of inclusions, some grains include large magnetite, carbonate, and biotite crystals. In a few amphibole grains crystallographically oriented exsolution of sphene occur. In the center rare clinopyroxene inclusions occur. Plagioclase is often optically zoned, and includes some fine inclusions in the center as the product of post-magmatic alteration. Fine-grained phyllosilicates may occur along plagioclase grain boundaries. Further constituents are biotite, nepheline, clinopyroxene, rare alkali feldspar, and zircon.

**Sample 2.** Coordinates of location: 46° 52′15′′ N; 25° 30′ 01′′ E; Sarmas-Jolotca mine in the Sarmas Valley NE of Ditrau. Sligthly deformed and altered, medium-grained massive hornblende diorite. The main constituents are predominant plagioclase and subordinate amphibole, biotite, clinopyroxene, minor constituents alkali feldspar, opaque minerals, sphene, calcite and epidote. Plagioclase occurs in irregularly zoned, sometimes cataclastically deformed grains. These are sometimes altered into a fine aggregate of phyllosilicates. Biotite is kinked and contains amphibole and clinopyroxene inclusions, and sagenite exsolutions. Amphibole occurs in three textural types: 1) large greenbrown crystals with some narrow rims; 2) medium-grained, isometric crystals with straigth grain boundaries; these crystals are free of inclusions, and form aggregates; and 3) some minor actinolite.

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