DISCUSSION AND REPLY

1.57-Ga Magmatism in the South Carpathians: Implications for the Pre-Alpine Basement and Evolution of the Mantle under the European Continent: A Discussion

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Introduction

Drăguşanu and Tanaka (1999) provide intriguing new chemical and isotopic analyses of amphibolites and gneisses from the Cumpăna Group, the oldest lithostratigraphic unit in the Getic-Supragetic unit of the South Carpathians (Balintoni 1975; Pana 1994). Ten amphibolite whole-rock data points form a linear trend in a plot of measured $^{143}Nd/^{144}Nd$ against $^{147}Sm/^{144}Nd$ (Drăguşanu and Tanaka 1999, fig. 3). Drăguşanu and Tanaka interpreted this as a 1.57-Ga isochron. This age corresponds to the oldest determined magmatism in the south Carpathians and, if true, would be instrumental in elucidating the tectonomagmatic evolution of the Carpathian basement, which is obscured by younger orogenic cycles such as the Hercynian (Variscan) and the Alpine.

The Variscan and Alpine events are consistent with a variety of geologic and thermochronologic data from the Getic-Supragetic unit of the South Carpathians (Dallmeyer et al. 1996). In contrast, no geochronologic evidence is available to support the existence of relics of prior orogenic cycles in this unit. It appears that Precambrian metasedimentary rocks are present in the Getic-Supragetic unit, based on Nd model ages performed on a variety of metasedimentary basement rocks (D. Pana and P. Erdmer, unpub. data). However, no pre-Hercynian magmatic events have been determined so far in the Getic-Supragetic unit. The Drăguşanu and Tanaka (1999) data are the first to suggest the existence of relics of an older orogen (e.g., an older accreted terrane?) in the Getic-Supragetic realm.

The purpose of this discussion is to explore alternatives to two main conclusions of the Drăguşanu and Tanaka (1999) paper. First, their whole-rock data may have been originally a mixing line rather than a point and, hence, the inferred age is a potentially inclusive maximum one. Second, the data are equivocal in support of their tectonic interpretation that the Cumpăna metatholeiites represent fragments of an island arc.

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Whole-Rock Data: Isochron or Mixing Line?

The amphibolite Sm-Nd whole-rock data in Drăguşanu and Tanaka (1999, table 1, fig. 3) was interpreted as an isochron reflecting a 1.57-Ga crystallization age. Drăguşanu and Tanaka negate the possibility of two-component mixing, based on lack of mixing relationships between $^{143}Nd/^{144}Nd$ (present-day?) and 1/Nd and indicate a rather small error for the fit (± 85 Ma, MSWD = 0.47). I recalculated the fit of the 10 analyzed amphibolites, using Ludwig's program (1991), and obtained a larger scatter: 1611 ± 245 Ma and MSWD = 1.9. Figure 1 shows that, in detail, the ϵ_{Nd} of the 10 amphibolites analyzed by Drăguşanu and Tanaka (1999) does not converge back to a point in ϵ_{Nd}-time space to better than within ~500 m.yr. Three amphibolites were also analyzed by the authors for mineral geochronology and yielded Sm-Nd ages of 319–354 Ma. These values are Hercynian and are consistent with all other geochronologic determinations on similar rocks from the South Carpathians (see discussion in Iancu et al. 1998). The scatter around the whole-rock isochron age is large enough to cast some doubt on whether this age is meaningful. Clearly, some higher-ϵ_{Nd} rocks have younger model ages (fig. 1, *inset*). This observation suggests that these am-

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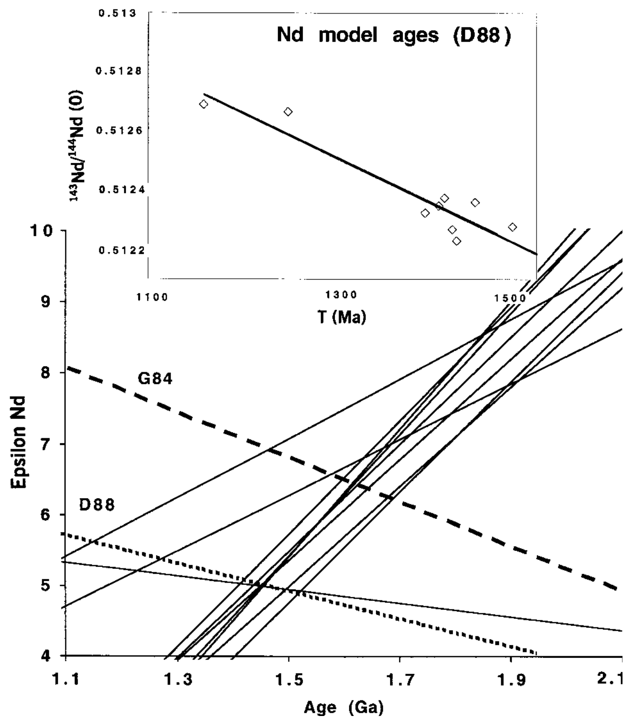

Figure 1. ϵ_{Nd} versus age (Ga) diagram for the 10 analyzed amphibolites (*solid lines*), using the data in table 1 of Drăguşanu and Tanaka (1999). Also shown are depleted mantle evolution curves from DePaolo (1988), dashed line labeled "*D88*," and Goldstein et al. (1984), dashed line labeled "*G84*." The model ages calculated using the DePaolo (1988) model (interceptions of the sample lines with the *D88* line) are plotted against the measured $^{143}Nd/^{144}Nd$ in the Cumpăna amphibolites (*inset*, upper part of figure).

phiboles either did not form from a uniform reservoir or were contaminated as melts.

An alternative interpretation to the correlation of the whole-rock data of Drăguşanu and Tanaka (1999) is that in part they reflect mixing between two end members: a depleted mantle-like component and the local gneisses as contaminants. Assimilation of continental basement by the Cumpăna metatholeiites was also observed by Drăguşanu et al. (1997) in a major element and trace element study of the same group of rocks. The paragneisses hosting many of the amphibolites (e.g., sample PGM of Drăguşanu and Tanaka 1999) have the required Nd isotopic compositions to represent contaminants of mantle-derived basaltic melts.

Figure 2*a* shows a mixing line between the most depleted amphibolite studied by Drăguşanu and Tanaka (1999, sample 48) and sample PGN. The amphibolites clearly lie near this mixing line. Moreover, the Nd isotopes correlate well with Nd concentrations for all but one sample (fig. 2*b*). The anomalous sample is S6 and has an unusually high Sr/Nd ratio of 135 and low Nd concentrations (3.74 ppm) compared with all other Cumpăna amphibolites studied by Drăguşanu and Tanaka (1999) and Drăguşanu et al. (1997). That sample aside, the correlation between $^{143}Nd/^{144}Nd$ and 1/Nd is consistent with a mixing hypothesis. I plotted the Nd isotopes at 330 Ma, the minimum age of this inferred mixing. Present-day Nd isotopic ratios display a somewhat poorer correlation with 1/Nd.

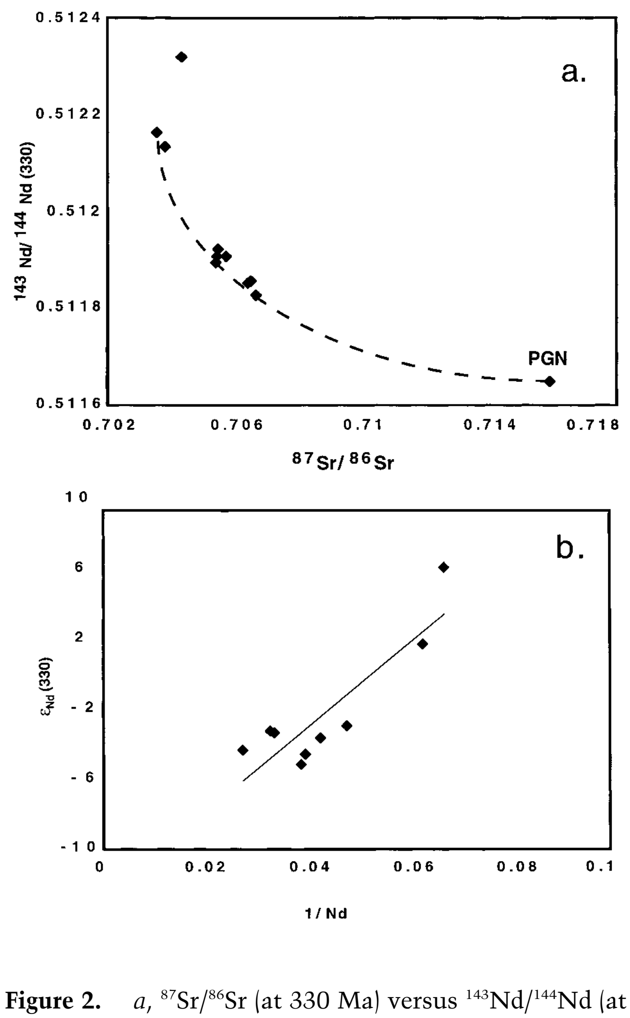

Figure 2. *a*, $^{87}Sr/^{86}Sr$ (at 330 Ma) versus $^{143}Nd/^{144}Nd$ (at 330 Ma) for the 10 amphibolites analyzed by Drăguşanu and Tanaka (1999) and a local metasediment (*PGN*) also analyzed by them. The amphibolites lie along the calculated mixing curve between a more depleted (perhaps mantle-derived) member and the local metasediments. *b*, ϵ_{Nd} (330 Ma) versus 1/Nd diagram showing a broad positive correlation ($R^2 = 0.783$), which is consistent with a mixing hypothesis. Sample S6 was not used in this regression.

Based on these observations, I suggest that at least part of the Nd isotopic heterogeneities measured by Drăguşanu and Tanaka (1999) in the Cumpăna amphibolites are caused by magmatic mixing between mantle and crustal reservoirs.

The crystallization age of these basaltic magmas is constrained to be ~330–1600 Ma. The last major mineral equilibration event affecting the Sm-Nd systematics in these rocks took place in the Hercynian (~320–350 Ma). The slope of the whole-rock amphibolite mixing line in ^{143}Nd/^{144}Nd versus ^{147}Sm/^{144}Nd space puts an upper bound for the crustal emplacement of these rocks at ~1600 Ma.

Many amphibolite lenses in the Cumpăna Group contain cores of relic gabbros and occasionally eclogitic assemblages. Such unmetamorphosed core gabbros are mentioned in papers on Cumpăna Group rocks (e.g., Udubaşa et al. 1988). Drăguşanu et al. (1997, p. 421) mention the presence of such relics. The age of magmatism in the Cumpăna rocks can be constrained by dating these unmetamorphosed gabbros, garnet-bearing gabbros, and/or eclogites. I suggest that the mineral Sm-Nd system could successfully be applied on pyroxenes, plagioclase, amphiboles, and garnet in the unmetamorphosed core assemblages.

Tectonic Interpretations

Drăguşanu and Tanaka (1999) and Drăguşanu et al. (1997) interpret the Cumpăna amphibolites to be the products of an island arc. However, all field data suggest that the Cumpăna tholeiites intruded in the continental basement represented today by various high-grade gneisses (Dimitrescu et al. 1985). In fact, the Cumpăna unit is characterized by a silicic basement to amphibolites surface area ratio of ~10. In several outcrops, blocks of paragneisses are preserved within lenses of amphibolites. Drăguşanu et al. (1997) suggested that the chemistry of Cumpăna amphibolites is consistent with various (up to 68%) proportions of assimilation of local gneisslike metasedimentary material during magmatic emplacement. A "primitive island arc," as Drăguşanu and Tanaka (1999, p. 237) interpret the Cumpăna amphibolites, is represented by a succession of mainly mafic rocks formed in an oceanic subduction environment far removed from a continental margin. If the Cumpăna unit represents some form of an island-arc terrane, then the island arc must have been constructed on an older continental crust. The arguments offered by Drăguşanu and Tanaka for an island-arc origin are largely based on the negative anomalies observed among high-field-strength elements such as Nb and Ta. Given the aforementioned geologic setting, these gabbros could more likely have been intruded near a convergent continental margin, or they may represent extension-related underplated mafic material in a region in which the mantle was previously enriched by subduction.

Conclusion

Further tests need to be aimed at deciphering the age and tectonic setting in which the Cumpăna metatholeiites were formed. An important key to deciding the arc versus nonarc controversy for the basement units in the South Carpathians is to test (e.g., using Nd provenance studies) whether their metasediments are proximal to a nearby continent, the East European shield, for example, or are exotic. A combination of major element and trace element studies with isotopic studies of the same samples (the amphibolite samples analyzed for isotopes and select trace elements in Drăguşanu and Tanaka 1999 do not appear to be the same as those analyzed for major and trace elements in Drăguşanu et al. 1997), especially the least metamorphosed relics, can yield better quantitative information on the nature of primary magmas, their crustal differentiation, and perhaps the tectonic setting in which they formed.

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1.57-Ga Magmatism in the South Carpathians: Implications for the Pre-Alpine Basement and Evolution of the Mantle under the European Continent: A Reply

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Isochron Fitting and Model Ages

First, Ducea (1999, fig. 1, in this issue) recalculates the fit of our 10 analyzed amphibolites and asserts that they "[do] not converge back to a point in ϵ_{Nd}-time space to better than within ~500 m.yr." (Ducea 1999, p. 733). However, fitting is dependent on the weighting procedures and on the weights themselves. Ducea's new calculated value (1611 ± 245 Ma) is coeval within the error of our original value (1572 ± 85 Ma). Other outputs of our regression, after weighting, confirm both the goodness of fit given by the MSWD and the adequacy of the model used in the least squares fit (t statistic for constant = 6370, t statistic for slope = 19, the overall $F_{(1,\ 8)}$ statistic = 344, and the Durbin-Watson statistic = 1.54).

The uncertainty of the model ages derives from the fact that the source pool is unknown. Depending on the model of the source, the model ages can be more or less convergent to a certain range of ages. For example, if the source liquid has a higher $^{147}Sm/^{144}Nd$ than the mantle, then it is possible to intercept the source at a more reasonable range of ages. This appears as permissive if we compare the parental liquids of Cumpăna, Drăgşan, and the Pennine Nappe (Drăguşanu and Tanaka 1999, fig. 4).

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Exclusion of Sample S6 and Reservoir Uniformity

The chemical data and petrographic characteristics in Drăguşanu et al. (1997), consistent with those of Udubaşa et al. (1988) and Gandrabura et al. (1992), reveal the consanguinity of the amphibolites from the base of the Cumpăna Group. The extending of sampling over two of the lowest stratigraphic formations (up to 88 amphibolites) confirmed the consistency of the data. Even so, for the safety of our assumptions concerning the geological time and the reservoir, samples used for whole-rock geochronology were taken from the same stratigraphic level, the Valea Bolovanului amphibolites. When possible, samples with different Sm/Nd ratios were selected to minimize isochron error. Therefore, plagioclase-rich layers were not avoided in the manner often adopted for liquid descent modeling. Sample S6, a possible cumulate, is one such plagioclase-rich layer; there is no geological reason for its exclusion.

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Whole-Rock Data: Isochron or Mixing Line?

If one assumes, as Ducea asserts, that what we call an isochron is in fact a mixing line, we should see the same distribution trend for the Rb-Sr isotopes. However, no array could be defined in the space $^{87}Sr/^{86}Sr$-$^{87}Rb/^{86}Sr$. Moreover, the restored Sr isotopic ratios do not correlate well with 1/Sr at any time in the past. This would mean that the Sr isotopic ratios are disturbed for the reasons stated in Drăguşanu and Tanaka (1999); hence, regardless of the restoration time, the dependence that would appear in the $^{143}Nd/^{144}Nd$-$^{87}Sr/^{86}Sr$ domain is meaningless. This is best illustrated by sample S6 itself, which was used by Ducea as an end member of the mixing line at 330 Ma (Ducea 1999, fig. 2*a*—in fact, the calculation was done for ~500 Ma?) and then omitted in figure 2*b*. If sample S6 is a true end member, it should lie in the region around the edges of the line drawn in Ducea's figure 2*b* or in its continuation, and not aside, as it really does. The excluding of sample S6 "improved" the correlation between ϵ_{Nd} and 1/Nd, expressed by the correlation coefficient (r), but their distributions do not keep enough convergent moments (easily seen in their histograms—the tails are long enough). This statistical descriptor is rather poor and cannot be used alone to decide whether the observed correlation is statistically significant because it does not consider the distribution of values in the two strings. If the joint probability distribution of the two variables is different from a binormal distribution, the r statistic becomes irrelevant (Press et al. 1986). The null hypothesis (H_0), that is, ϵ_{Nd} and 1/Nd are uncorrelated, cannot be disregarded by removing samples. If we assume that we can reject H_0, then proving that a mixture between two end members with different isotopic ratios is the cause of an initial scattering is difficult, mainly because the time of the mixing is unknown. In certain cases, such as those of liquids derived by fractional crystallization of mineral assemblages having the same bulk partition coefficient or mixtures caused by the remelting of crystals in the magma chamber, $^{143}Nd/^{144}Nd$ strongly correlates with 1/Nd, except for around the time of the initial ratio, when r is zero. The "linear" array in Ducea's (1999) figure 2*b* can be explained by our sampling procedure: to avoid scattering over a large span of time, samples were collected from the same stratigraphic level. The disadvantage of this procedure is that rocks having similar chemical compositions can match in groups in which the Nd fractionation is very small.

Our Sm and Nd data (Drăguşanu and Tanaka 1999) demonstrate that the chosen samples cannot be only simple mixing products. It is impossible to observe crossing REE patterns if mixing occurred between a crustal component and a depleted one with a higher Sm-Nd ratio. In our case, the mechanism of REE fractionation involves fractional crystallization and partial resorption of crystals in the magma chamber. Similar patterns were described and modeled by Drăguşanu et al. (1997), who did not find any evidence of assimilation processes. What mixing was found was mechanical, resulting in tuffs. Obviously, the metatuffs were carefully avoided in selecting samples for whole-rock geochronology.

It is a real problem to find the age of the protolith of polymetamorphic rocks. An isochron on minerals from unmetamorphosed rocks, as Ducea suggested, would be the alternative to a whole-rock isochron. However, the coexistence of preserved unmetamorphosed mafic or ultramafic rocks, together with eclogites in the same regional medium- to high-grade terrane questionable. Drăguşanu et al. (1997) mentioned the existence of relic gabbroic textures, that is, allotriomorphic-granular textures and phantoms of crystals, such as olivine, mostly replaced by serpentine. Therefore, getting an isochron on primary materials is very improbable, if not impossible.

Tectonic Interpretation

Although not unique, our tectonic model of island-arc origin for the Cumpăna Group amphibolites draws attention to possible regional interpretations of the Precambrian rocks from the Carpathians. Our model is not based only on the high field strength (HFS) anomaly but also considers the distribution of large ion lithophile (LIL) elements and REE. Furthermore, small fractions of melting of a depleted mantle in a dynamic environment suggest the proximity of subduction processes. A comprehensive discussion on the nature of primary magmas that produced the Cumpăna Group mafic rocks is found in Drăguşanu et al. (1997). Their conclusions, derived from quantitative modeling of major elements and REE, have been used as a base for our tectonic interpretation.

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