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The metamorphic basement of Romanian Carpathians: a discussion of K-Ar and $^{40}Ar/^{39}Ar$ ages

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ABSTRACT. More than 600 radiometric K-Ar ages on rocks from the metamorphic basement of the Romanian Carpathians are statistically treated and discussed. The data suggest that the most pervasive Alpine rejuvenation occurred in a belt of about 100-120 km width, within which crystalline rocks were intensely reworked, undergoing a metamorphic remobilisation of Barrovian type before Middle – Late Cretaceous. This *Eo-Alpine metamorphic belt* outcrops on the flanks of the Mureş Zone, *i.e.,* in the Rodna massif to the NE, and in the Northern Apuseni to the west. Away from it, ages get progressively older and outline a broad Variscan metamorphic province. In the most external part of the South Carpathians preserved pre-Variscan ages point to the former extension of the Moesian Plate. Within the study area radiometric K-Ar ages, as well as recently reported fission-track data, do not support reheating above 300°C and corresponding regional metamorphic events during meso- and neo-Alpine times.

Key words: K-Ar dating, Alpine metamorphism, pre-Alpine metamorphism, Romania.

1. INTRODUCTION

In the last four decades of the past century, an impressive number of K-Ar age determinations on metamorphic rocks from the basement of the Romanian Carpathians were carried out, mainly at the geochronological laboratories of the Geological Institute of Romania and the Institute of Physics and Nuclear Engineering in Bucharest.

The great number of analyses allowed us to select the 573 age determinations worked on mineral concentrates – considered to be more accurate than whole rock analyses – and to treat them statistically.

The data were assigned to four age groups more or less arbitrarily delimited and termed as "pre-Variscan" (older than 375 Ma, *i.e.*, pre-Upper Devonian, according to Cowie and Bassett, 1989), "Variscan" (375-251 Ma), "Kimmerian" (250-121 Ma), and "Eo-Alpine" (younger than 120 Ma, *i.e.*, mid-late Cretaceous).

Only four ages slightly crosscutting the Cretaceous-Tertiary boundary were - for the sake of convenience - also included into this latter group.

In addition to the K-Ar ages, 31 recently reported $^{40}Ar/^{39}Ar$ total gas ages from the South Carpathians and Apuseni Mountains (Dallmeyer et al., 1994, 1996, 1998, 1999) were also regarded in the analysis.

All data have been further sorted out by the type of mineral(s) on which they were worked out and then plotted by distinct symbols on a map having the principal tectonic lines as background (Plate I).

To avoid space problems in plotting, some individual ages coming from the same area/unit and having the same characteristics (same age group and processed mineral) have been grouped together and are represented on the map by only one symbol. Accordingly, symbols stand, for their greatest part, for individual ages (244), but also for clusters of 2 – 9 different analyses. It was not possible to differentiate them by size in accordance with their different weights.

The greatest part of analytical data, taken out of papers from the sixties and the seventies of the last century, indicate at best only rock types and mineral concentrates on which K-Ar ages were worked, without making any reference to polyphase mineral growth or possible extraneous argon sources. It is also to be pointed out that K-Ar techniques were at their very beginning at that time and subject to refinement.

Thus, older K-Ar data should be regarded with some caution, particularly in areas where they were not confirmed subsequently. However, it was the aim of our systematizing work to make them available to a greater scientific community and to outline, by statistical analysis, the spatial distribution of metamorphic reworking related to different orogenic epochs in the basement units of the Romanian Carpathians.

On demand, a table with all K-Ar and $^{40}Ar/^{39}Ar$ ages and an appendix reference list with the source of analytical data can be supplied by the senior author.

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2. ANALYSIS OF THE DATA

Referring to a basement tectonic/tectonostratigraphic unit or group of units within a relatively young, Alpine, orogenic domain like the Carpathians, it must be stated that interpretation of K-Ar age data should be carefully handled and ruled by what we have designated as the rejuvenation law. In accordance with it, there may, but must not be a direct connection between the high frequency of ages belonging to a specific, older, age group and the real importance of thermal events pertaining to that time interval (*e.g.*, Variscan thermal events in the above stated 375-251 Ma span). It is far more realistic to admit only that, the more frequently pre-Alpine ages occur in a region, the less important Alpine thermal rejuvenation was in that particular structural unit. Vice versa, if - on lithostratigraphic grounds - well-established ancient rock sequences constantly indicate Alpine ages, it points to their pervasive thermal, and most probably, structural rejuvenation during Alpine orogeny. Thus, in analyzing K-Ar and $^{40}Ar/^{39}Ar$ age data, which most reliably indicate the last thermal event capable to produce regional metamorphism, it is most important to look for thermal gradients, vertical and horizontal polarities and thermal axes that are expected to be outlined by the spatial arrangement of age groups. With these considerations in mind, we discuss the main characteristics of the units from the Romanian sector of the Carpathians.

2.1. Eastern Carpathians

In the Eastern Carpathians, the frequency of K-Ar radiometric ages as related to the time scale [frequency profile or **F** (frequency) /**T** (time) - diagram] (Fig. 1) shows a broad plateau-like segment in the 260-340 Ma time interval. It is seen that these Variscan ages clearly dominate over Alpine ones that show an apex at about 100-120 Ma. Pre-Variscan ages occur only sporadically, while the so-called “Kimmerian” ages are more or less evenly distributed, but at a low level, over the whole corresponding time span.

On Plate I can be observed that the spatial distribution of the ages is not random, but shows a SW-NE polarity, with a clear predominance of Variscan ages to the north-east, close to the boundary with the sedimentary Mesozoic units of the Outer Dacides, and, reversely, the predominance of Eo-Alpine ages in the western extension of the East Carpathians (Rodna Massif). This distribution, in addition to the aspects shown by the frequency profile, indicates that Alpine rejuvenation increased from north-east to south-west and that the “Kimmerian” ages are, in fact, partially reset Variscan ages, yielded on rocks that have undergone a variably weak Alpine overprint. The broad plateau of Variscan ages and only sporadic occurrence of pre-Variscan ages may suggest a pervasive ?Early Carboniferous tectonothermal event, followed by an Upper Carboniferous - Lower Permian cooling. However, it is conceivable that cooling took place over a much shorter period, and that most of the Permian ages are, like “Kimmerian” ones, geologically meaningless “mixed ages” (see also section 2.2.1). The Alpine ages reported mainly from the south-western Rodna massif are for their greatest part mica cooling ages on lower amphibolite-facies metamorphic rocks, structurally totally transposed and thermally rejuvenated during an event that reached its climax in pre-Albian or even in pre-Aptian times. Fast uplift took place during the Albian and the early Late Cretaceous.

2.2. Southern Carpathians

2.2.1. Getic and Supra-Getic domains

Typical for the basement complexes of these tectonic mega-units is the overwhelming predominance of Variscan K-Ar ages that form a well-evidenced maximum at 310 Ma (Fig. 2).

Pre-Variscan and “Kimmerian” ages show the same characteristics as in the Eastern Carpathians: the former occur isolated, while the latter describe a low-level plateau. The most outstanding feature of the Getic and Supra-Getic domains, as revealed by isotopic K-Ar ages, is, however, the almost total absence of Alpine ages. The few Alpine ages that occur are linked to discrete shear zones. It can be seen on the map (Plate I) that there is no clear spatial relationship between Variscan and “Kimmerian” ages, and, consequently, no zonal distribution is discernible. The metamorphic peak seems to have occurred, like in the Eastern Carpathians, prior to 310 Ma, probably during the Lower Carboniferous, and was followed by a relatively fast uplift during the Upper Carboniferous. Similar conclusions were reached by Dallmeyer et al. (1998).

If one compares the frequency profiles from the Eastern Carpathians and from the Getic and Supra-Getic domains of the Southern Carpathians, then a striking difference is observed as regards the shape of the Variscan “peak”. It has a well-pronounced bell-shape in the case of the Getic and Supra-Getic domains, whereas in the Eastern Carpathians it forms the above-mentioned plateau-like feature. The reason for this difference might be the more intense Alpine rejuvenation that affected the Eastern Carpathian basement. This rejuvenation possibly created a much wider spectrum of opening of the K-Ar isotopic systems, being witnessed not only by the “Kimmerian” ages, but also by the leveling of the Variscan “peak”, that has become flattened and broadened over an unlikely large time span. This feature gives credit to the idea that, at least partly, Permian isotopic ages are, like the “Kimmerian” ones, “mixed ages” of no real geologic significance. Alternatively, they could represent distinct shear zones, as assumed by Dallmeyer et al. (1998).

2.2.2. Danubian domain.

In the basement rocks of the Danubian domain a Variscan “peak” is no more discernible in the **F**/**T** diagram (Fig. 3), even though the importance of the Variscan tectonothermal evolution is indisputable. It seems that in this mega-unit an even more advanced leveling than in the Eastern Carpathians has occurred. Here the plateau-like aspect of the segment corresponding to the Variscan orogeny spans the interval between 320 and 190 Ma. Partial opening of the K-Ar systems due to variable Alpine overprinting seems to be, here too, the most plausible cause. Eo-Alpine ages are frequent only in the most internal parts of the mega–unit, where they possibly point to a “hidden” Alpine metamorphic belt. The external, geometrically most inferior units of the Danubian domain are, on the contrary, characterized by the widespread occurrence of pre-Variscan ages. The frequency profile for these units clearly evidences that pre-Variscan ages have a greater importance than the

Variscan ones (Fig. 4), forming two small peaks at about 430 and 510 Ma, respectively.

2.3. Northern Apuseni Mountains

The frequency profile of K-Ar age data from the basement of the Northern Apuseni shows a little Variscan "peak" at 320 Ma and an important Alpine one at 90 Ma (Fig. 5).

As seen on Plate I, an ill-defined polarity in the distribution of ages can be recognized, particularly in the most westerly unit, the Bihor Autochthonous. This may be regarded as the mirror image of the Eastern Carpathians' polarity, as here the oldest (Variscan) ages are to be found to the west and southwest, while the younger Alpine ages occur to the east and northeast. The K-Ar and $^{40}Ar/^{39}Ar$ ages worked on rocks of the Biharia and Baia de Arieş units are almost all Eo-Alpine.

The situation is somewhat complicated by the Codru system, located between the eastern part of the Bihor Autochthonous and the Biharia unit, as here determinations on mainly amphibolitic rocks yielded Variscan and even older ages. However, isolated pre-Variscan ages were obtained also on rocks from adjacent areas to the west, belonging to the Bihor Autochthonous, as well as to the east, in the Biharia unit. Here, a U/Pb isotopic age of ca. 490 Ma on granite indicates a Late Cambrian age as time of emplacement (Pană and Balintoni, 2000). These ages draw a much more complex picture in this sector of the Northern Apuseni Mountains, as compared to the polarity evidenced in the Eastern Carpathians. It may possibly point to the existence of a core complex in the region, exhumed during later stages of Variscan orogeny, and that acted as a rigid mass during Alpine times.

2.4. Transylvanian Basin

The relatively few data on rocks of the submerged metamorphic basement and of the metamorphic "islands" that frame the basin to the northwest indicate almost comprehensively the Eo-Alpine tectonothermal event. Thus, in the north-western part of the basin only three out of 31 determinations indicate Upper Jurassic – Lower Cretaceous ages, the remaining 28 falling all in the Eo-Alpine group and forming a well-defined peak at about 90-92 Ma (Fig. 6).

Three isolated ages worked on well cores coming from the eastern and southern parts of the Transylvanian Basin are consistently older (belonging to the Variscan and "Kimmerian" age groups, respectively), and correlate well with the ages from the adjacent inner units of the Eastern and Southern Carpathians.

2.5. Pannonian Basin

In boreholes between Oradea and Satu Mare, as well as on the Hungarian side of the border, K-Ar isotopic datings yielded Eo-Alpine ages that define a peak around 90 Ma, seen in Fig. 7.

In more southerly sectors of the Pannonian Basin on Romanian territory the K-Ar datings indicate mostly "Kimmerian" ages that scatter over a great time span and are yielded most probably, like in Carpathian units discussed above, on rocks thermally overprinted to variable degrees during the Eo-Alpine event.

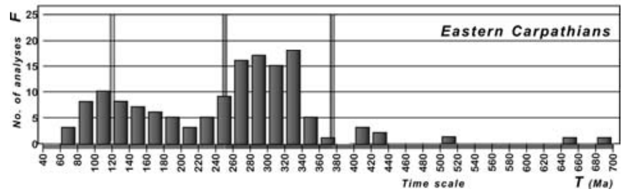

Fig. 1. *F/T diagram of radiometric ages from the basement of the Eastern Carpathians.*

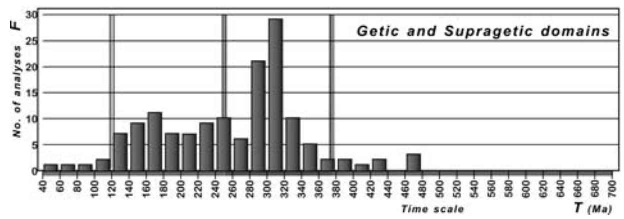

Fig. 2. *F/T diagram of radiometric ages from the basement of the Getic and Supragetic domains.*

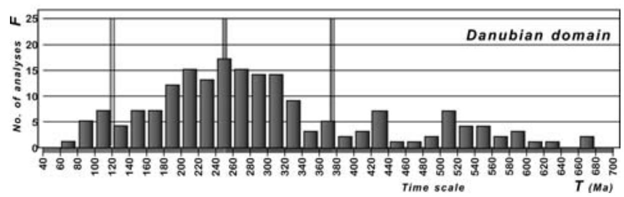

Fig. 3. *F/T diagram of radiometric ages from the basement of the Danubian domain.*

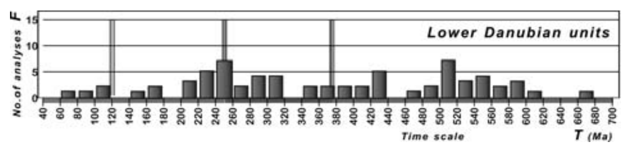

Fig. 4. *F/T diagram of radiometric ages from the basement of the Lower Danubian units.*

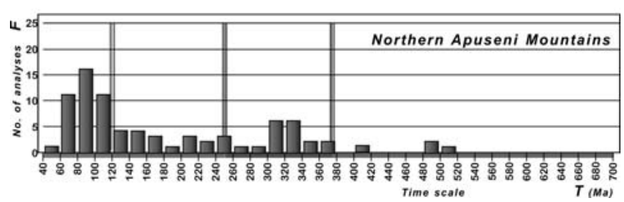

Fig. 5. *F/T diagram of radiometric ages from the basement of the Northern Apuseni Mountains.*

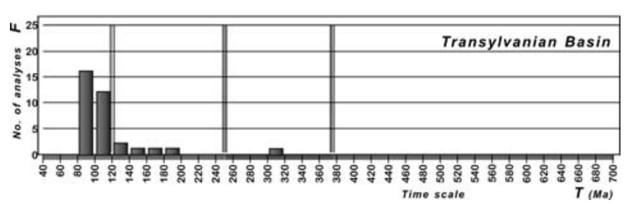

Fig. 6. *F/T diagram of radiometric ages from the basement of the Transylvanian Basin.*

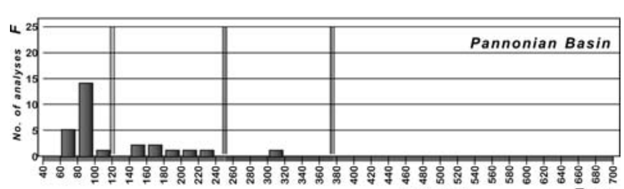

Fig. 7. *F/T diagram of radiometric ages from the basement of the Pannonian Basin.*

3. DISCUSSION

The statistical analysis of more than 600 K-Ar and $^{40}Ar/^{39}Ar$ mineral ages coming from practically all major basement units constituting the Romanian Carpathians permits to draw some important conclusions.

3.1. Pre-Variscan Ages

These ages are meaningful – due to their widespread occurrence – only in the lower units of the Danubian domain. Here they outline an old province that has been ascribed to the Cadomian tectonothermal event (Liégeois et al., 1996; Dallmeyer et al., 1998). The ages are in perfect agreement with those from the metamorphic basement of the Moesian Platform, situated immediately to the south (Paraschiv et al., 1982, 1983). Irrespective of the possibility that the ages might represent only "mixed ages", due to different degrees of remobilization during Variscan and, eventually, Alpine tectonothermal events, their high frequency, as compared to that of Variscan and quite more of Alpine ages, strongly suggests, that these events have not been very intense in this sector of the Carpathians, or, in other words, that we are here in the outskirts of the Variscan as well as Alpine systems. Besides, it is reasonable to assume that parts of the lower Danubian units structurally belonged, perhaps until the Late Cretaceous, to the Moesian Platform, and was only afterwards integrated in the Alpine nappe system.

3.2. Variscan Ages

The group of Variscan ages is the most numerous in basement rocks of the Romanian Carpathians. The real extent of Variscan reworking is by far more impressive if we ascribe to it also the so-called "Kimmerian" ages - as we indeed do - because there is really no convincing evidence in favor of a Kimmerian or other pre-Aptian thermal event in the whole Carpathian realm. Therefore the data permit to assume that the Carpathians are for their greatest part superimposed on an old Variscan structure that probably belonged to the Variscan system extending in extra-Alpine areas through Central and Western Europe. It is of interest to note that Variscan ages are widespread in practically all basement sectors of units where a Permian – Cretaceous sedimentary cover more or less unaffected by Alpine metamorphism still exists. (Rarău nappe in the Eastern Carpathians; Leaota, Sirinia, Reşiţa-Moldova Nouă zones in the Southern Carpathians; Bihor unit in the Northern Apuseni). This is in our view, according to the rejuvenation law, an important criterion in the assessment of a polarity in the reheating/metamorphic history of the Eo-Alpine tectonothermal event. However, isotopic data so far reported do not permit to assess a polarity for the Variscan tectonothermal event itself. Criteria that might be taken into consideration in order to identify a Variscan thermal axis are the existence of metamorphosed Palaeozoic magmatic and sedimentary rocks and the indication of a Mid-Upper Paleozoic suture, characterized by large amounts of meta-ophiolitic rocks. Such petrographic and tectonic elements are to be found in the north-central part of the Rodna Massif (Eastern Carpathians) and in the Getic and Supra-Getic domains of the South Carpathians (*e.g.*, Locva and Poiana Ruscă mountains).

The possibility to regard the Biharia and Codru units of the Northern Apuseni as a suture-magmatic belt pair of the Variscan orogeny was stressed by Pană et al. (2002). It is likewise possible that eclogites, which have recently been reported in the Leaota and Lotru Mountains of the South Carpathians (Mărunţiu et al., 1997; Săbău, 2000; Săbău and Massonne, 2003) may represent deep-level exposures of a Variscan suture.

3.3. Eo-Alpine Ages

Contrary to basement units, which yielded almost exclusively Variscan and/or "Kimmerian" isotopic K-Ar ages and which preserved, at least in part, their un-metamorphosed cover, the basement units in which Eo-Alpine ages predominate are practically devoid of a sedimentary cover of Late Paleozoic - Early Cretaceous age. However, indications exist, that a post-Variscan cover is locally present; but as it underwent a Barrovian-type metamorphism during Alpine evolution, being now tightly intermingled with (older) poly-metamorphic sequences, it cannot be distinguished from the latter on petrographic grounds alone.

There is still the debate on the stratigraphic age of the Vulturese–Belioara Group from the Northern Apuseni, a slightly metamorphosed sequence of conglomerates, quartzites, limestones and dolostones. According to some authors (Dimitrescu in Ianovici et al., 1976; Balintoni, 1996), the group represents a Triassic sequence similar to the Foederata-Struzenik Series from the Western Carpathians. Still others regard it as a Lower Carboniferous formation, ascribing its metamorphism - without proof – to the Variscan orogeny (Pitulea et al,. 1983; Solomon et al., 1984).

Basement rock sequences, which yielded Eo-Alpine ages and are devoid of a sedimentary pre-Upper Cretaceous cover, are those from: a) the south-western part of the Rodna Massif (Eastern Carpathians), b) the eastern part of the Bihor unit, and from the Baia de Arieş nappe (Northern Apuseni), and c) those cropping out in the "islands" situated at the north-western border of the Transylvanian Basin. Some authors, considering the absence of cover rocks and ignoring or disregarding the Eo-Alpine ages, thought of those "old" terrains as thresholds or barriers between the Tethyan realm and the Bihor platform (Preluca and Highiş "thresholds" of Patrulius in Ianovici et al. (1976); the Preluca "median massif" of Mutihac (1990) or the "landmass" from where the Baia de Arieş nappe originates, according to Balintoni (1996).

Petrography of all these basement rocks shows, that the evolution culminating with the Eo-Alpine event was not merely a thermal, but instead – a tectonothermal one, as they all have a tectonitic structure (Strutinski, 1998; Strutinski and Mosonyi, 1996, 1997, 1998) and were not only statically reheated, as different authors supposed (*e.g.*, Kräutner et al., 1976; Zincenco et al., 1990).

The units with intensely reworked basement yielding Eo-Alpine ages are flanking on both sides the mega-unit of the Transylvanides (or the so-called Mureş Zone), as well as its submerged prolongation to the north and south-west. Numerous authors have interpreted this important geostructure, in which the ophiolite suite is largely developed, as a prime order suture within the Alpine-Carpathian-Dinaric system (*e.g.*, Săndulescu, 1984). It consists, beside ophiolites, of different Mesozoic sedimentary sequences, the older, mainly Jurassic ones, of platform type, the younger - starting in the Neocomian and sometimes even earlier -, of trough character. Flysches and wildflysches are widespread, as are Cretaceous and Neogene magmatites.

Apart from some local metamorphic aureoles in connection with the relatively late magmatic activities, in certain districts weakly metamorphosed ophiolitic and sedimentary rocks occur (Seghedi et al., 1996) that suffered their metamorphism most probably prior to the Late Cretaceous.

As a whole, the Transylvanides are, however, regarded as an un-metamorphosed domain, at the present outcrop level at least. Nevertheless, as it is bordered on both sides by basement suites, that have pervasively been reworked thermally, as well as mechanically, up to the late Early Cretaceous, it seems clear that the only reason for the almost total absence of metamorphism within it is its present-day lowered position.

In contrast to this, the flanking "shoulders" witness, during the Eo-Alpine event, exhumation and rapid cooling (the greatest part of the analyzed K-Ar and $^{40}Ar/^{39}Ar$ ages are considered to be cooling ages). This situation fits well with the scenario favored by Sanders (1998) for the evolution of the whole Carpathian orogeny, based on $^{40}Ar/^{39}Ar$ and fission track data. According to Sanders, widespread thick skinned deformation in the mid Cretaceous produced a high mountain chain. The thermal equilibration of the thickened lithosphere subsequently caused orogenic collapse, giving rise to a topography consisting of alternating uplifted metamorphic domes and subsiding basins. In this way the generation of "post-tectonic" Gosau basins is explained.

Most workers regard the Mureş ophiolites as remnants of the Tethyan domain, particularly of its northernmost extension, known as the "Vardar Ocean" (*e.g.*, Săndulescu, 1984), that in their opinion was subducted essentially during Cretaceous times. Moreover, recent studies emphasize that intra-oceanic subduction in the "Vardar Ocean" began even earlier, in the Late Jurassic (Bortolotti et al., 2002; Nicolae and Saccani, 2003). One should be cautious, however, with assumptions put forth to fit a theory. In the sixties and seventies of the last century many authors considered the equivalence of ophiolitic rocks with old oceanic crust to be highly improbable. In an overview on the Phanerozoic Tethys, Sonnenfeld (1981) pointed out that, as a rule, ophiolites are found in narrow belts of vertical instability between more rigid platforms. Most frequently they are emplaced during wrench faulting through submerged and thinned continental crust and do not represent obducted oceanic crust.

As regards the ophiolites of the Mureş Zone, their tight spatial and temporal relationship with calc-alkaline rocks tentatively supposed to have formed in an intra-oceanic island-arc environment (Bortolotti et al., 2002), as well as the fact that sedimentary rocks interstratified with some of the basaltic lava flows show prevalence of continental plant remains over marine ones (Lupu et al., 1995), are clearly favoring an origin in accordance with Sonnenfeld's statements.

Likewise, interpretation of Eo-Alpine metamorphism as a consequence of collision and nappe tectonism is unlikely because of the cooling ages (120 - 90 Ma) which prove that this metamorphism is sensibly older than Late Cretaceous nappe stacking. In fact, it must be considered contemporaneous to the forerunning stage of "thick-skinned tectonics" (*e.g.*, Sanders, 1998; Iancu et al., 2005) whatever this syntagm may signify.

Our alternative interpretation of the Mureş Zone is, that it functioned during most of the Mesozoic time as a transcurrent *alignment* which successively passed through a transtensive (Jurassic – earliest Cretaceous), and then transpressive (Early – Late Cretaceous) phase. Heat generated during this long time span by motion and deformation caused the Eo-Alpine metamorphism and initiated diapiric processes (probably the "tick-skinned tectonics" of several authors, see above). These caused the rising of the "shoulders" of the Mureş Zone, or - more probably - of an extended Mureş Zone, whose central part subsequently sagged down. However, according to this view, based on the distribution of K–Ar ages in the basement units and on the assumption of the originally straight course of the Mureş Zone, it is precisely this zone that contains the *thermal axis* attributable to the Eo-Alpine event.

A tentative draft of its trace is shown in Plate I. It also represents the axis of the ***Eo-Alpine Metamorphic Belt***, that has likewise been sketched in Plate I, and that, on the outcrop level, has a width of 100-120 kilometers. This belt, which is now for the first time outlined, extends to the south-west into the Vardar region, while to the north it may be supposed to occur in the basement of the Pannonian Basin.

The dispersed, however, not accidental Eo-Alpine cooling ages reported from different parts of the Upper Danubian and from adjacent locations within the Getic domain seem to outline another Eo-Alpine partly hidden metamorphic belt, that may have formed in connection with suturing of the Severin trough. The present state-of-the-art does not permit to draw more precise conclusions on this topic.

Scarcity of Late Cretaceous-Paleogene isotopic potassium-argon ages as well as fission-track data (Bojar et al., 1998; Sanders, 1998) are not in favor of meso- or neo-Alpine reheating processes and metamorphism within the Romanian Carpathians, a feature that is different to the thermal evolution of the Alps (Frey et al, 1999).

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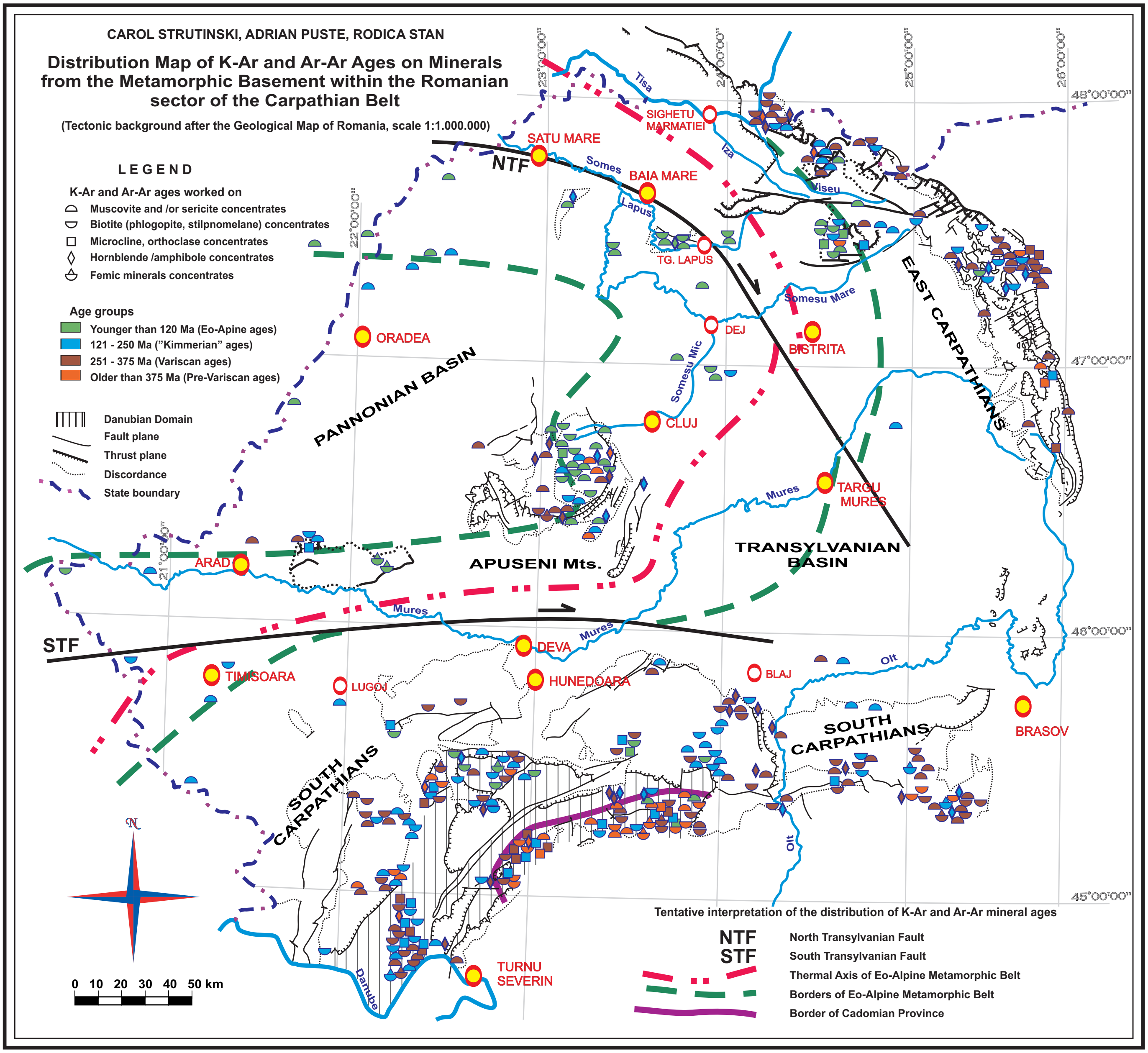

Plate I. *Distribution of K-Ar and Ar-Ar mineral ages in the basement units of the Romanian Carpathians and their tentative interpretation.*