BABEȘ-BOLYAI UNIVERSITY
FACULTY OF BIOLOGY AND GEOLOGY
DEPARTMENT OF GEOLOGY

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# IELOVA METAMORPHIC SEQUENCE (SOUTH CARPATHIANS) – BOUNDARIES, PETROGRAPHY AND TECTONIC AFFILIATION

Summary of the Doctoral thesis

Luminița ZAHARIA

Scientific supervisor
Prof. Univ. Dr. Ioan BALINTONI

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**KEY WORDS: whole rock geochemistry, U-Pb zircon geochronology, geodynamic modelling, tectonic affiliation, Ielova Metamorphic Sequence, South Carpathians.**


**NOTE: The figure and tables have the original labels, as in the Doctoral thesis.**

# 1. INTRODUCTION

Ielova Metamorphic Sequence[1], belonging to the South Carpathians, is located in the southeastern part of Romania, within Banat territory, between the Danube in the southern part and Mehadica Valley in the north.

Ielova unit has a controversial tectonic affiliation to one of the two main crystalline domains of the South Carpathians. Within this study a complex characterisation of Ielova is intended, in order to clarify its affiliation within South Carpathians. Several studies are to be performed, from petrographic, geochemical and geochronological points of view, to achive the following purposes: (1) to identify the rock types within the Ielova Sequence, and to give a description of each petrographic type; to observe the field relationships between various types of rocks; (2) to characterize geochemically the component rocks, and to discriminate their tectonic setting and protolith features; (3) to constrain the age of the protoliths and of various geological processes involved in "building up" this sequences; (4) to model the geodynamic history of Ielova and to determine the paleogeographical framework of its evolution; (5) and finally, to establish the affiliation of the sequence within the South Carpathians.

# 2. GEOLOGICAL SETTING

## 2.1. Alpine tectonic structure of the South Carpathians

The structure of the South Carpathians is the result of the Alpine orogenic events. The main tectonic units originated in three sedimentary areas: Danubian domain in the east, Getic domain in the western part and Severin domain in between (Codarcea, 1940). According to the tectonic plates model applied to South Carpathians (Rădulescu & Săndulescu, 1973), Severin domain was connected with an oceanic crust-floored basin, along a rift developed between two sialic microplates (named Getic and Euxinic cratons; Balintoni, 1994) which represented the Getic and the Danubian domains.

Within South Carpathians, the Alpine convergence and collision events took place from Cretaceous to Tertiary, including multistage folding/thrusting events, uplift/erosion, extensional stages, development of associated sedimentary basins (Iancu *et al.*, 2005). The resulted nappe pile, consisting of systems of basement-cored overthrusts with cover nappes located in between (Berza *et al.*, 1983, 1994; Iancu *et al.*, 1998, 2005), overthrusted onto the Moesian Platform in the Late Miocene (intra-Sarmatian) (Iancu *et al.*, 2005).

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[1] Ielova Metamorphic Sequence will be named also as Ielova or Ielova Sequence within all this work, unless stated otherwise.

There are three main structural units within South Carpathians, from bottom to top (Fig. 2.3): **Danubian nappe system,** now exposed in a tectonic window within the structurally higher nappes, consists of Proterozoic metamorphic rocks (Berza & Iancu, 1994; Liégeois *et al*., 1996) and low-grade Palaeozoic sedimentary formations, covered by Westphalian-Mesozoic sediments (Berza *et al*., 1988a,b); **Severin nappes,** originating in an oceanic basin squeezed between the Getic and the Danubian (Iancu *et al.*, 1998, Seghedi *et al.*, 1998), and composed of Jurassic ophiolites, alkaline magmatic rocks and flysch deposits (Codarcea, 1940; Iancu *et al.*, 1990); **Getic-Supragetic nappes system** with Getic nappe consisting of Neoproterozoic-Ordovician basement rocks (Balintoni *et al.*, 2009, 2010a) and detrital Late Carboniferous-Permian rocks, with a transgressive Mesozoic cover, and Supragetic nappes consisting of a basement overlain by condensed Jurassic detrital rocks and discontinuous Late Jurassic-Cretaceous carbonates.

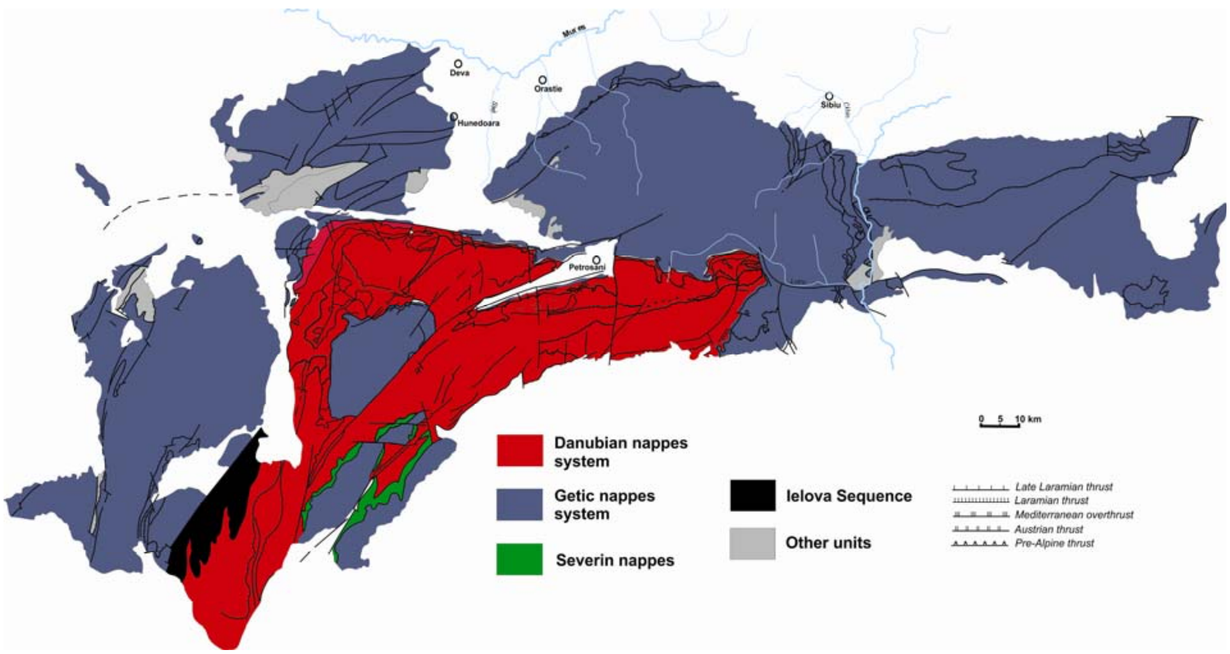



***Figure 2.3.*** *Alpine structural units of the South Carpathians (after Balintoni et al., 1989; Iancu et al., 2005).*

### 2.2. Pre-Alpine metamorphic basement units in the South Carpathians

Several distinct basements units or terranes have been differentiated within South Carpathians (*e.g.* Balintoni, 1997; Balintoni *et al.*, 2009; Liégeois *et al.*, 1996; Kräutner, 1996, 1997).

Representing Avalonian and Ganderian fragments of Gondwana (Balintoni *et al.*, 2011a; Iordan & Stănoiu, 1993; Seghedi *et al.*, 2005), the pre-Variscan metamorphic basement units of the *Danubian domain* are: **Drăgşan** and **Lainici-Păiuş** continental terranes (Liégeois *et al.*, 1996), separated by **Tişoviţa** terrane with oceanic affinity (Mărunţiu, 1984; Kräutner, 1997).

The *Getic–Supragetic basement*, a Cadomian Gondwanan fragment, with Variscan overprints, consists of the following terranes (Fig. 2.4): **Sebeş-Lotru, Făgăraş, Leaota, Padeş** and **Caraş** (Balintoni *et al.*, 2009, 2010a). Among there terranes of the Getic domain, Sebeş-Lotru can be individualized due to its widthness, and to the contained eclogites and/or Neoproterozoic igneous protoliths (Balintoni *et al.*, 2010a), thus having a different geological history.

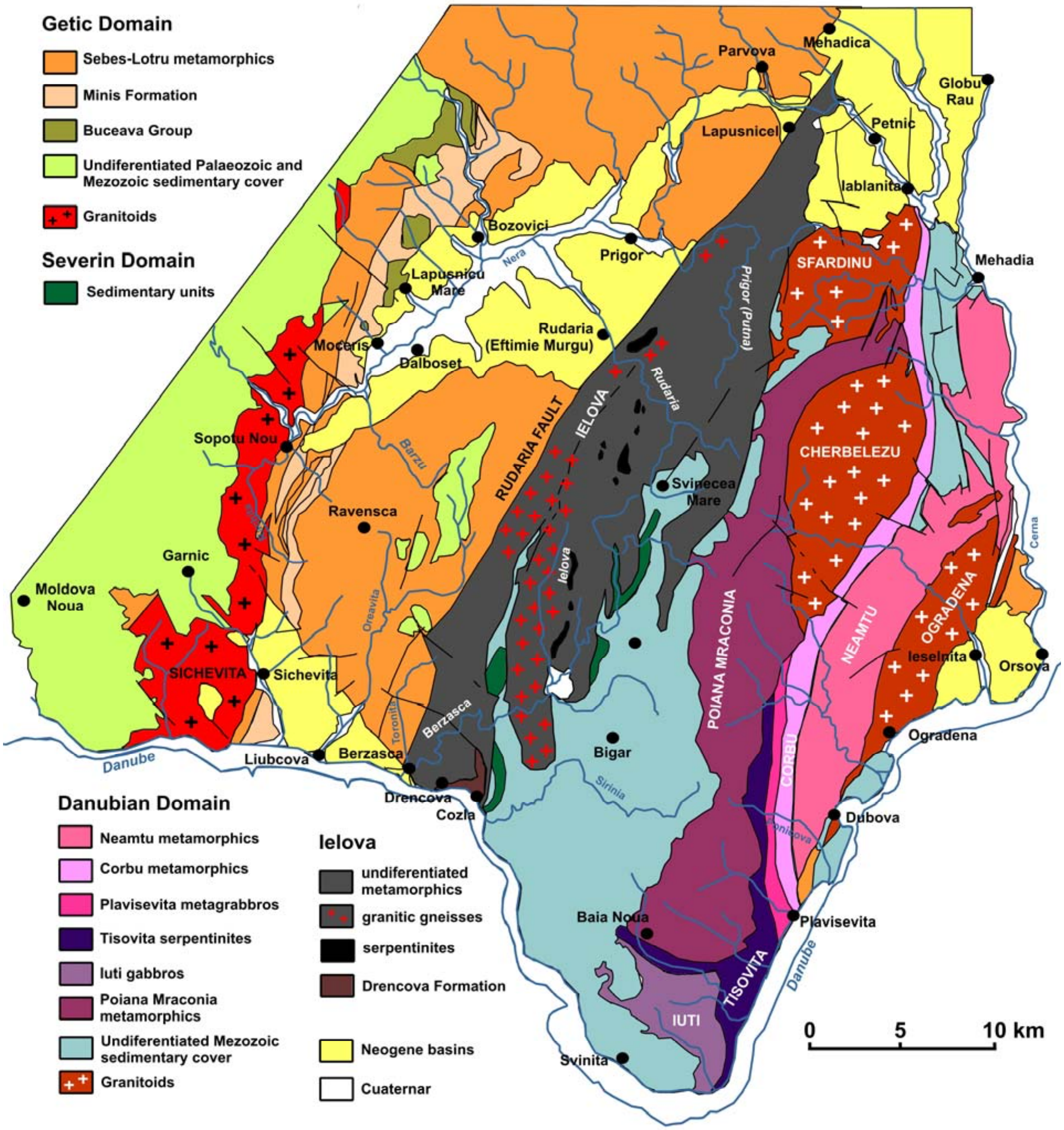



***Figure 2.5.*** *Simplified geological map of the southeastern part of Banat area (modified after Kräutner & Krstić, 2002, 2003).*

### 2.3. Geology of the south-eastern Banat area

In the southeastern Banat, rocks belonging to all three nappe systems occur, although Severin sequences are of a very-reduced size.

The **Danubian Domain** crystalline rocks constitute the basement of Retezat-Ogradena and Almăj major structural units, and are represented by various metamorphites and magmatic rocks. The major plicative and disjunctive structures as the associated magmatite bodies follow NE-SW alignements (Bercia & Bercia, 1980) (Fig. 2.5). The sedimentary deposits covering the basement are largely displayed within the Mezozoic synclinorium of Bigăr.

**Getic Domain** crystalline rocks occur within the *Semenic Unit*, between the Danubian rocks in the eastern part, and Reşiţa-Moldova Nouă sedimentary area in the west. Getic basement includes Proterozoic polymetamorphic formation (Lotru unit) and slightly metamorphosed rocks (Miniş Formation and Buceava Group), all intruded by Sicheviţa granitoids (Bercia & Bercia, 1975).

**Severin Domain** rocks were mentioned in the area only recently (Pop *et al.*, 1992, in Pop, 1996), including only the sedimentary formations of Severin Nappe: bedded coarse- to fine-grained subarkoses and some massive polymictic conglomerates.

## 3. PREVIOUS STUDIES

### 3.1. Previous knowledge

There are several papers dealing with the metamophic rocks of Ielova Sequence, ranging from mineralogic and petrographic descriptions, geochemical characterisations to short but detailed syntheses (*e.g.* Bercia & Bercia, 1975, 1980; Codarcea, 1940; Gheorghiu, 1951; Kräutner *et al.*, 1988; Mureşan *et al.*, 1974; Zlaratova-Ţop *et al.*, 1971).

Based on identified petrographic types of Ielova, the original material was interpreted as being a volcano-sedimentary pile, with argillaceous sandstones alternating with basic igneous rocks as tuffs and tuffites, as well as ultrabasics and metagabbros as the primary magmatic producs (Bercia & Bercia, 1975; Năstăseanu & Bercia, 1968). The basic rocks were geochemically investigated and considered as the products of the calc-alkaline differentiation of a basic magma (Mureşan *et al.*, 1974; Zlaratova-Ţop *et al.*, 1971). The rocks mineralogy indicates a pre-Devonian regional metamorphism in the amphibolite facies, kyanite (Mărunţiu, 1976) and sillimanite (Andrei & Match, 1976, in Kräutner *et al.*, 1988) being reported, althrough more recent studies indicates eclogite-level metamorphic conditions (Iancu *et al.*, 1996). Along Rudăria fault, dynamic retromorphism affected the rock within the conditions of greenschists facies (Năstăseanu & Savu, 1970).

No reliable radiometric data concerning the Ielova Formation were previously reported (Kraütner *et al.*, 1988). However they are considered as Neoproterozoic – Paleozoic (Năstăseanu & Bercia, 1968). A specific microspore association (and especially genus *Emphanisporites*) constrains the overlaing Drencova age to Upper Devonian (Năstăseanu & Biţoianu, 1970). Thus, Ielova metamorphism was widely considered as surely pre-Devonian.

### 3.2. Tectonic affiliation ideas

Codarcea (1940), the first who individualized the Ielova unit, considered it as part of the Danubian crystalline, and until recently, all the syntheses and papers dealing totally or partially with the Southern Banat geology (*e.g.* Kräutner *et al.*, 1988, Năstăseanu *et al.*, 1988) maintained Ielova as part of the Danubian domain. However, based on some petrographic similarities of Ielova rock with those of neighbouring Lotru group of Getic Domain, there were some ideas that Ielova might be a Getic unit (*e.g.* Codarcea, 1940; Bercia & Bercia, 1980).

Iancu & Mărunţiu (1989) discussed in detail the implications of the possible affiliation of Ielova to Getic Domain, pointing out also some arguments for this possible change. However, the strongest argument was considered the presence of Severin units in several small areas, tectonically overlain by the Proterozoic metamorphites of the Ielova Series, which results in a partially assignment of Ielova Series to the Getic Nappe (Pop, 1996; Kräutner & Krstić, 2002)

In the studies published post-1996, the boundary between the Getic and the Danubian rocks in Banat area is differently traced (according with the cited map/study/authors), thus determining also the boundaries and affiliation of Ielova (Fig. 3.1)

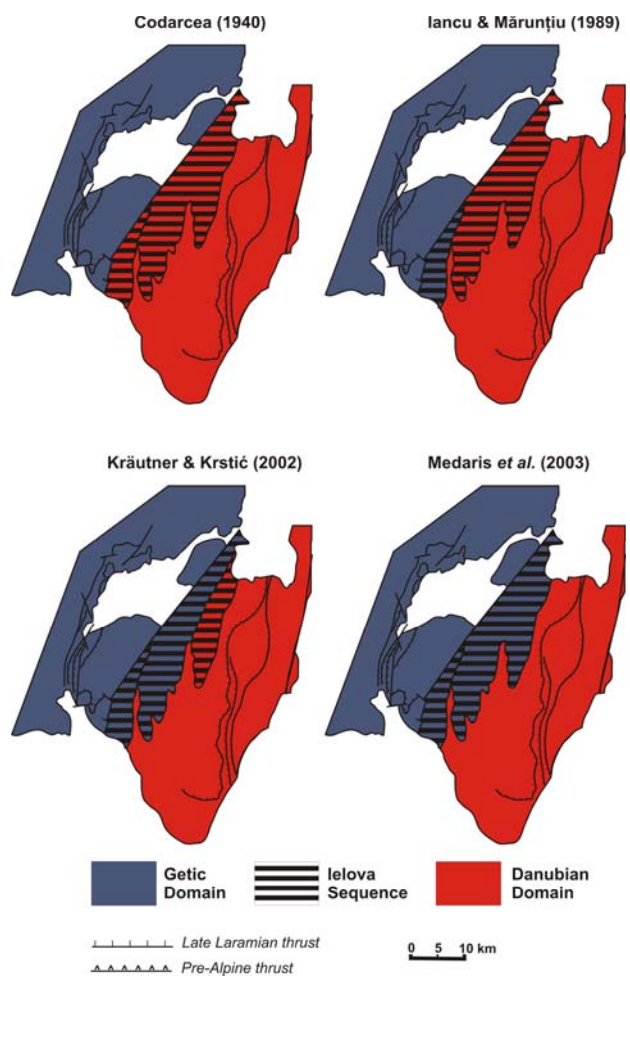



***Figure 3.1.*** *Sketches of the south-eastern Banat area, showing different delimitations between Getic and Danubian domains, according with the literature.*

# 4. PETROGRAPHY OF METAMORPHIC ROCKS

Given the numerous studies on the petrography of Ielova metamorphic rocks, some very detailed (e.g. Bercia & Bercia, 1975, Zlaratova-Ţop *et al.*, 1971), within this work only the main rock types were briefly presented, emphasising the field relationships

**Metasedimentary rocks**, represented by biotitic gneisses with/without garnet, micaceous gneisses (with muscovite and biotite), micaschists, but also amphibolitic gneisses, quartzo-feldspatic gneisses and few quartzites, are exposed in outcrops up to tens meters high.

The **amphibolites** and **amphibolitic orthogneisses** crop out either as elongated bodies (up to few meters long), or as small, more or less continous bands, within more felsic gneisses. According with the field relationships, it can be presumed that the amphibolites rock protoliths represented dike or sills intruding the sedimentary rocks, or were mafic flows, interbeded in sediments.

Ielova **granitic gneisses** crop out as a "belt" in the southern part, cutting transversely (NW-SE) the metasedimentary rocks (Fig. 2.5), and are exposed in large uniform outcrops (several meters width), suggesting that large quantities of magma intruded the layered sediments.

Many elongated bodies of **serpentinites** occur within the Ielova sequence (Fig. 2.5), but they are exposed best in the Rudăria-Urda Mare area. **Migmatites** represent one of the most spectacular characteristics of Ielova. The leucocratic material is injected in gneisses, either concordant or discordant, different types of migmatitic structures occurring. The dikelets and veins show a width ranging from centimeters to meters, in some case also folded. Lenses of various sizes, large boudins within the dikelets or difuse structure can also occur. The rock can be impregnated by the injected material. **Pegmatites** are connected with the very intense migmatisation processes. The quartz-feldspar material, while injected, can crystallize as big grains.

# 5. WHOLE-ROCK GEOCHEMISTRY

## 5.1. Samples and analytical methods

The geochemical study was based on 25 whole-rock determination (major oxides) by means of X-ray fluorescence (XRF) and inductively coupled plasma – atomic emission spectroscopy (ICP-AES). For 20 of these samples also trace and rare-earth elements were measured by inductively coupled plasma – mass spectrometry (ICP-MS). The samples included twelve metasedimentary rocks (micaschists, quartz-plagioclase-biotite and quartz-biotite-hornblende gneisses), and thirteen orthogneisses (a "*mafic orthogneisses group*" consisting of 8 samples, including amphibolites, amphibolites-biotite gneisses and amphibolitic schists and a „*felsic orthogneisses group*" of 5 granitoid gneisses).

## 5.2. Metasedimentary rocks

The investigated rocks were originally immature greywackes and shales. The position of Ielova paragneisses within the A–CN–K diagram (Nesbitt & Young, 1984, 1989) (Fig. 5.4) suggests that the source material is less weathered. None of the samples plots close to A-K line, implying that weathering in the source area was represented only by the breakdown of plagioclase, which corresponds to intermediate chemical weathering according. The constant Zr, Nb, Y and Ta abundances and the unsystematic co-variations observed between LREE and Th, Ta/La and Ti or HREE and Hf (La Flèche & Camiré, 1996), indicate that heavy mineral accumulation does not influence too much the geochemical signature of the Ielova metasedimentary rocks, thus the effect of hydrodynamic sorting during transportation on bulk chemistry may be minor (Nesbitt & Young, 1996).

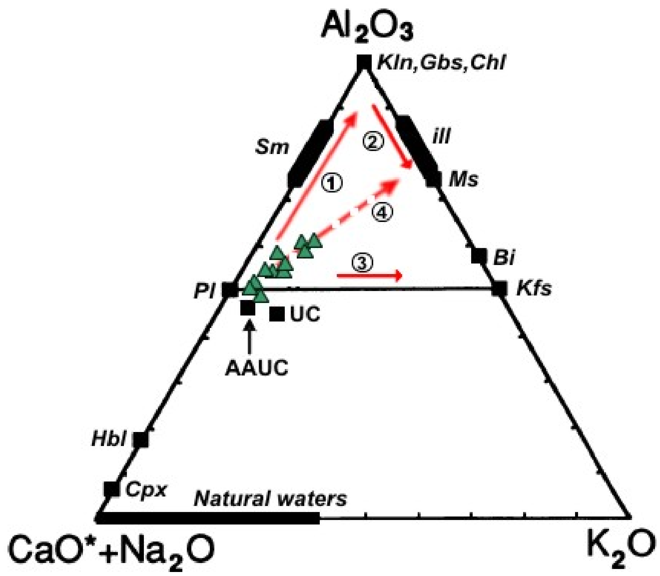



***Figure 5.4.*** *A–CN–K (CIA) ternary diagram (mol%) after Nesbitt & Young (1982) showing composition of metagreywackes of the Ielova area. Compositions of average Archean upper crust (AUCC) and average upper crust (UC), respectively, are after Taylor & McLennan (1985). (1) Weathering trend, (2) Metasomatic trend, (3) Replacement of plagioclase by K-feldspar trend, (4) Ielova metasedimentary rocks trend.*

The compositions of the Ielova metasediments suggest derivation mainly from felsic igneous rocks with minor mafic input (Fig. 5.9.). The trace element-geochemistry (ternary diagrams La–Th–Sc, Th–Co–Zr and Th–Sc–Zr, Bhatia & Crook, 1986; Fig. 5.11) of the Ielova paragneisses shows that their deposition took place on a convergent margin in a continental volcanic arc setting, thus in a sedimentary basin located in the inter-arc, back-arc and fore-arc environments of volcanic arcs developed over thin continental crust.

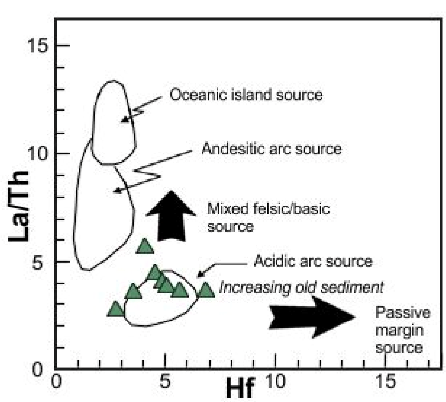



***Figure 5.9.*** *La/Th vs. Hf diagram for discriminating source (Floyd & Leveridge, 1987).*

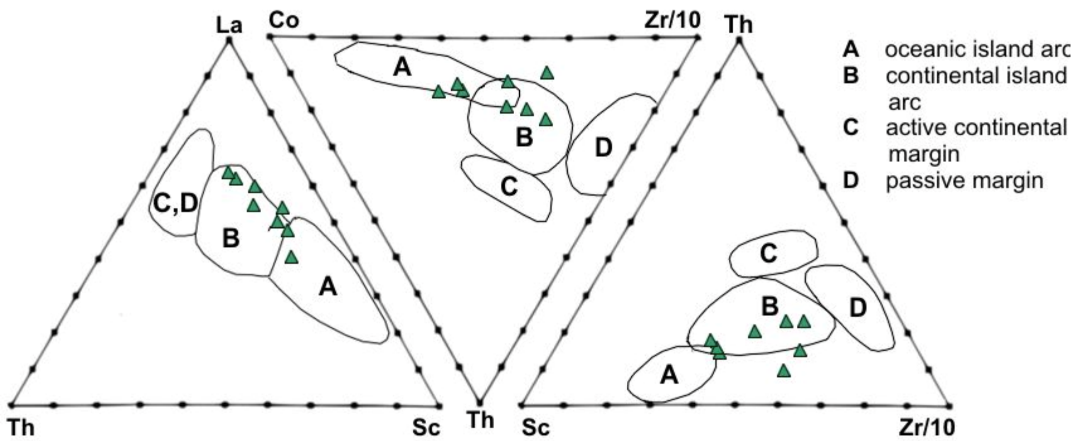



*Figure 5.11.* *Tectonic setting discrimination diagrams for the Ielova metagreywackes: based on trace elements (after Bhatia & Crook, 1986).*

## 5.3. Mafic orthogneisses

Ielova mafic orthogneisses are subalkaline, dominant calc-alkaline and metaluminous. The protoliths of most amphibolites can be classified as gabbros (group Ib) and diorites (group IIb), while trace elements reveal andesite affinities for group IIb, and basaltic andesite and subalkalic basalts affinities for group Ib.

The Zr vs. Zr/Y diagram (Pearce & Norry, 1979; Pearce, 1983) constrains the **tectonic setting** for all Ielova mafic orthogneisses as being within-plate (Fig. 5.22.a), related to a continental arc (Fig. 5.22.b). The Ti/V ratio >20 shows an oceanic affinity for Ielova mafic orthogneisses rather then an arc origin, all the samples plotting more or less within the “back-arc basin and MORB” field, although for the intermediate ones (group IIb) a “calc-alkaline” relation can be constrained too, more consistent with previous discriminations.

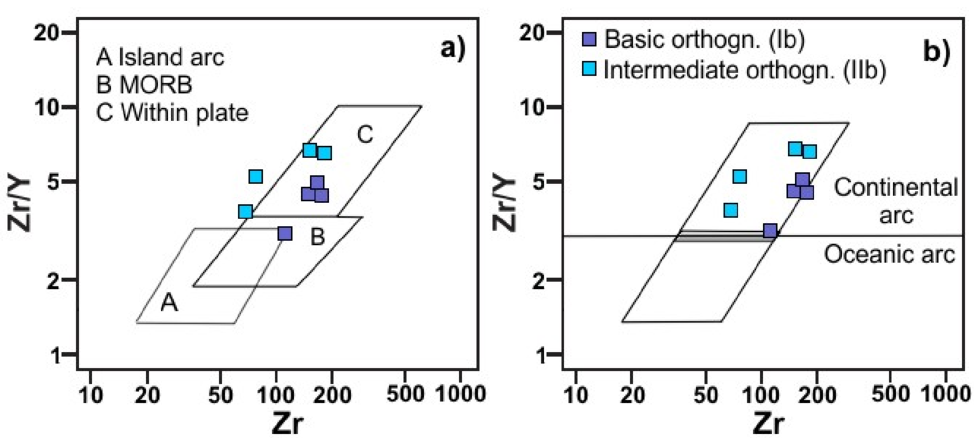



*Figure 5.22.* *Tectonic setting discrimination diagrams for Ielova mafic orthogneisses after* ***a)*** *Pearce & Norry (1979) and* ***b)*** *Pearce (1983).*

Overall, the "basalts" (Ib) are more consistent with a see-floor origin, proceeding from a slightly enriched MORB-like magma. This, together with the subduction-related signature, is consistent with a marginal basin, most probably a back-arc basin, where the MORB-like magma can be chemically influenced by the subducted slab (either as slab-derived melts or fluids). The "andesites" (IIb) are characterized by both, subduction and within-plate features, consistent with a magmatic arc origin.

In summary, the geochemical data suggest that Ielova mafic orthogneisses were placed in a within-plate, most probably a continental arc-back arc basin setting.

### 5.4. Felsic orthogneisses

Applying different petrographic classifications Ielova felsic orthogneisses are granites, the mafic sample (#44) is a granodiorite, while diagrams based on incompatible element ratio show rhyodacite and dacite-affinities for all Ielova granitoids. Ielova felsic gneisses are subalkaline, and more precisely, calc-alkaline, mildly peraluminos (the granites) or metaluminous (the granodiorite).

The chemical characteristics of Ielova granitic gneisses, as high $SiO_2$, $Na_2O$ + $K_2O$, Fe/Mg, Ga/Al, Zr, Nb, Ga, Y and Ce, and low CaO, are fitting with those of an A-type granite, confirmed by the discrimination diagrams proposed by Whalen *et al.* (1987), no matter if they make use of major or trace elements.

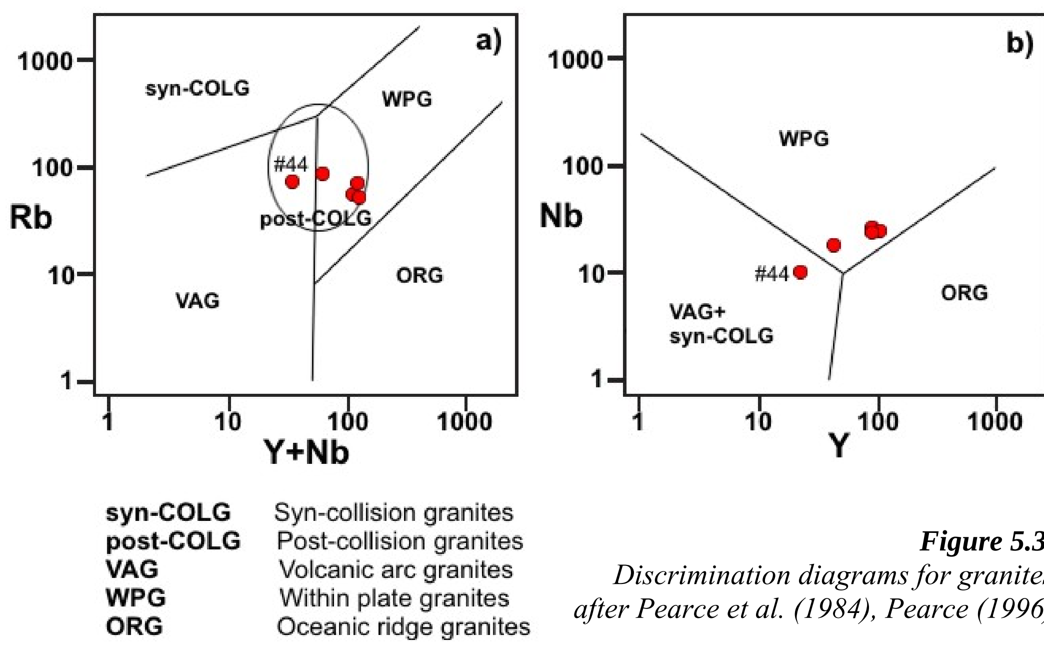



***Figure 5.30***
*Discrimination diagrams for granites, after Pearce et al. (1984), Pearce (1996).*

In Rb vs. (Y+Nb) and Y vs. Nb diagrams of Pearce *et al.* (1984) (Fig. 5.30), the Ielova granitic gneisses plot to within-plate field, while the granodioritic sample #44 is a volcanic arc granitoid. Pearce (1996) modified the Rb vs. (Y+Nb) diagram of Pearce *et al.* (1984), adding a post-collisional field (Fig. 5.30.a), which includes all analyzed Ielova felsic orthosamples.

In the $A_1$-$A_2$ discrimination plots of Eby (1992) (Fig. 5.34), all Ielova granitic gneisses lie within $A_2$ field, defined as an apparent crustal source that is not sedimentary in origin. $A_2$ granitoids can be emplaced in a variety of tectonic settings, including post-collisional and true anorogenic environments (Eby, 1992). Nevertheless the precursor granitoids were emplaced within an extensional setting. Regarding the magma source, the $A_2$ character of granitic gneisses suggests that the magmas were generated from crust that has been through a cycle of subduction or continent-continent collision.

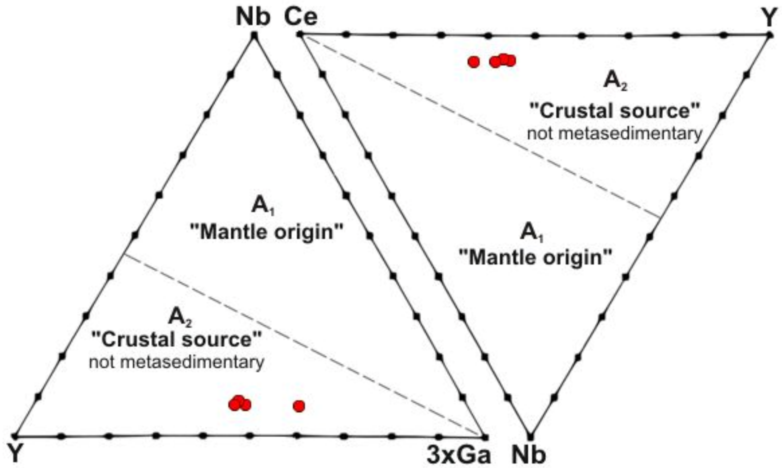
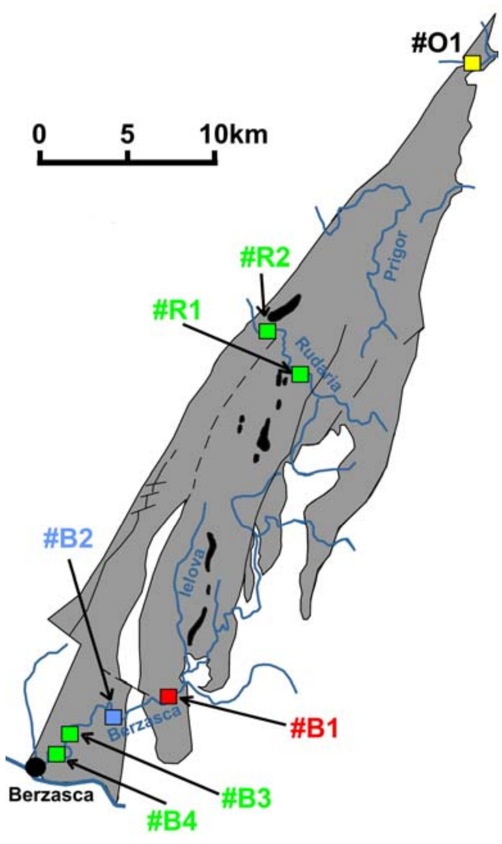



***Figure 5.34.*** *Triangular plots for discriminating between $A_1$ and $A_2$ granitoids (after Eby, 1992).*

# 6. U-Pb ZIRCON GEOCHRONOLOGY




## 6.1. Samples and analytical methods

Seven samples were selected for dating (Fig. 6.2). While from Globu sample (#O1), only few low-quality zircon grains were obtained, which were not analysed, the other six samples provided numerous zircons. From these six, two were orthogneisses (#B1 – granitic gneiss and #B2 – amphibolithic orthogneiss) and four paragneisses (#B3 – chlorite-sericito schist; #B4 amphibolitic paragneiss; #R1 – micaceous gneiss; #R2 – quartzo-feldspatic gneiss).

***Figure 6.2.***
*Sampling points from Ielova, for U/Pb zircon dating. Yellows square represents the sample with low-quality zircons, the green squares indicate metasedimentary rocks, while the blue and the red ones represent orthogneisses.*

Isotopic ages were determined by U-Pb analyses on zircons by laser ablation – inductively coupled plasma – mass spectrometry (LA-ICP-MS). The selected grains were imaged by cathodoluminiscence (CL) to reveal their internal structures in order to select the areas to be ablated. The data were processed and various age plots were created.

### 6.2. U-Pb zircon ages

In case of orthogneisses, the analyses which didn't felt between 90-110% concordancy were rejected, while for paragneisses the selected interval was 85-105% concordancy. For zircons younger than 1000 Ma, $^{206}Pb/^{238}U$ ages are preferred because of the better precision, while for grains with ages greater than 1000 Ma the $^{207}Pb/^{206}Pb$ ages are preferred since they yield results that are more representative of the true ages for older zircons (*e.g.* Balintoni *et al.*, 2009).

**Orthogneisses**

**Sample #B1** zircon ages show predominance in a very narrow range of 474-523 Ma, not clustering within the age span, which however is rather discrete, but range continuously between the mentioned values (Fig. 6.9). **Sample #B2** have the same characteristics as #B1, the $^{206}Pb/^{238}U$ ages span continuously the time interval of 559-615 Ma, with one exception, the oldest value (a $^{206}Pb/^{208}U$ age of 615 ± 10 Ma, with a concordia age of 612.3 ± 3.4 Ma) (Fig. 6.9).

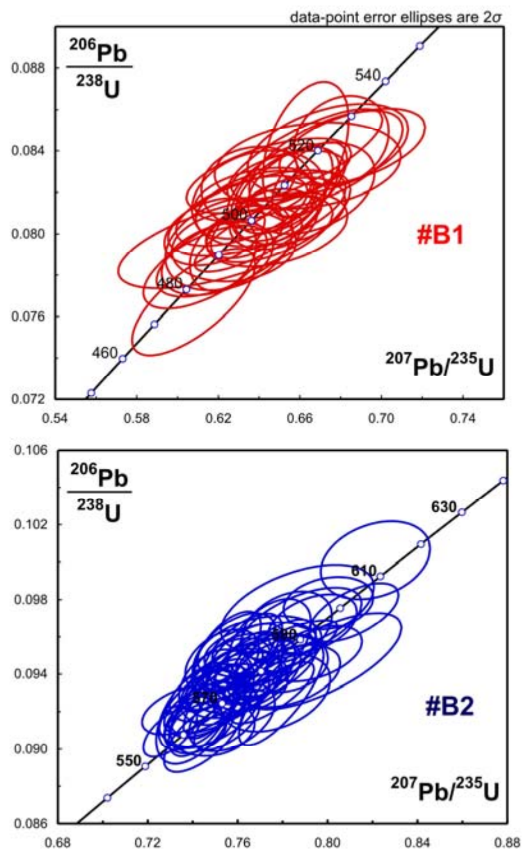



***Figure 6.9.*** *U–Pb concordia diagram showing the results of U–Pb dating of zircon in the samples #B1 and #B2.*

**Paragneisses**

All four dated **metasedimentary samples (#B3, #B4, #R1 and #R2)** have large zircon age spectra, with the youngest ages obtained from (usually high-U) rims, while the oldest from Paleoproterozoic and even Archean inherited cores (Table 6.1).

**Table 6.1.** *The detrital zircon ages of Ielova metasedimentary samples, sorted ascending.*

| Sample #B3 Age (Ma) | ± (Ma) | Sample #B4 Age (Ma) | ± (Ma) | Sample #R1 Age (Ma) | ± (Ma) | Sample #R2 Age (Ma) | ± (Ma) |
|---|---|---|---|---|---|---|---|
| *362* | *7* | *383* | *5* | *404* | *13* | *389* | *7* |
| 437 | 9 | *387* | *4* | 526 | 9 | *451* | *19* |
| 443 | 12 | *388* | *4* | 535 | 16 | *483* | *8* |
| 445 | 13 | *391* | *5* | 557 | 9 | 521 | 8 |
| 458 | 14 | *393* | *4* | 562 | 14 | 526 | 14 |
| 475 | 2 | *396* | *5* | 565 | 10 | 529 | 12 |
| 486 | 9 | *400* | *5* | 572 | 10 | 533 | 7 |
| 489 | 11 | *402* | *7* | 584 | 12 | 535 | 9 |
| 495 | 10 | *404* | *5* | 592 | 7 | 547 | 7 |
| 498 | 10 | *451* | *10* | 622 | 18 | 581 | 9 |
| 499 | 7 | 490 | 9 | 640 | 15 | 594 | 11 |
| 512 | 7 | 491 | 7 | 642 | 17 | 605 | 11 |
| 519 | 15 | 507 | 6 | 1712 | 36 | 607 | 10 |
| 521 | 5 | 514 | 9 | 1960 | 34 | 650 | 11 |
| 531 | 20 | 524 | 10 | 2138 | 42 | 764 | 11 |
| 531 | 10 | 536 | 9 | | | 843 | 23 |
| 542 | 8 | 537 | 9 | | | 1194 | 30 |
| 542 | 7 | 540 | 5 | | | 1216 | 28 |
| 546 | 16 | 542 | 9 | | | 1526 | 48 |
| 548 | 10 | 581 | 17 | | | 1966 | 32 |
| 553 | 10 | 608 | 12 | | | 2002 | 34 |
| 553 | 9 | 623 | 15 | | | 2008 | 52 |
| 556 | 9 | 630 | 13 | | | 2028 | 20 |
| 557 | 6 | 641 | 7 | | | 2046 | 30 |
| 561 | 13 | 658 | 12 | | | 2048 | 26 |
| 568 | 10 | 718 | 13 | | | 2052 | 56 |
| 569 | 11 | 729 | 7 | | | 2058 | 30 |
| 570 | 17 | 1130 | 22 | | | 2060 | 28 |
| 576 | 12 | 1984 | 32 | | | 2062 | 24 |
| 582 | 5 | 1986 | 22 | | | 2072 | 22 |
| 587 | 15 | 1986 | 18 | | | 2074 | 32 |
| 595 | 11 | 1986 | 18 | | | 2078 | 26 |
| 617 | 11 | 2000 | 18 | | | 2078 | 22 |
| 617 | 11 | 2010 | 22 | | | 2086 | 30 |
| 623 | 10 | 2016 | 18 | | | 2150 | 22 |
| 648 | 19 | 2046 | 46 | | | 2210 | 20 |
| 934 | 9 | 2056 | 28 | | | 2220 | 30 |
| 935 | 19 | 2072 | 22 | | | 2366 | 20 |
| 1994 | 28 | 2074 | 22 | | | 2498 | 20 |
| 2014 | 38 | 2090 | 32 | | | 2520 | 20 |
| 2024 | 40 | 2350 | 18 | | | 2542 | 26 |
| 2106 | 48 | 2478 | 42 | | | 2554 | 24 |
| | | 2592 | 16 | | | 2556 | 20 |
| | | 2602 | 16 | | | 2638 | 10 |
| | | 2606 | 22 | | | 2662 | 22 |
| | | 2628 | 12 | | | 2950 | 22 |
| | | 2720 | 16 | | | | |
| | | 2826 | 14 | | | | |

Devonian
Silurian
Ordovician
Cambrian
Neoproteoz.
Mezoproteroz.
Paleoproteroz.
Archaean

* ages written in italic are obtained from rims

## 6.3. Age significance

**Metaigneous protolith ages**

Two are the dated metaigneous samples, representing different rock types. For the granitic **sample #B1**, the protolith age can be considered around 500Ma, as indicated by the statistical coherent group of 21 apparent ages (fig. 6.18).

In the case of **sample #B2**, a larger coherent group of 33 analyses gives a TuffZirc age of 581 ± 3Ma (95% confidence), while a maximum of 584Ma is visible on the probability density curve (fig. 6.18). Thus, most probably, the #B2 andesitic orthogneiss has a crystallization age as around 584Ma

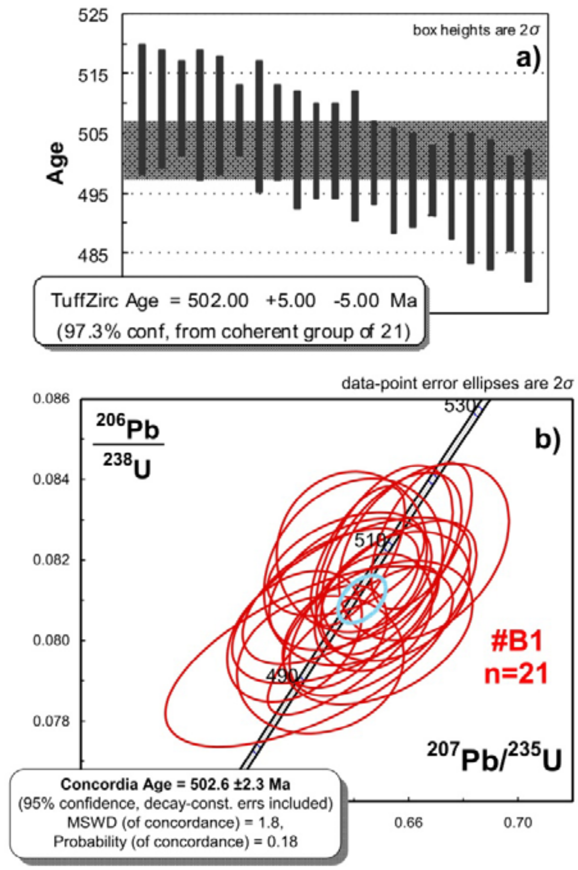



***Figure 6.18. a)*** *Robust median statistical analysis of the $^{206}Pb/^{238}U$ ages corresponding to a group of 21 analyses of zircons from the granitic gneiss sample #B1.* ***b)*** *Concordia diagram and Concordia age for the same group of 21 analyses.*

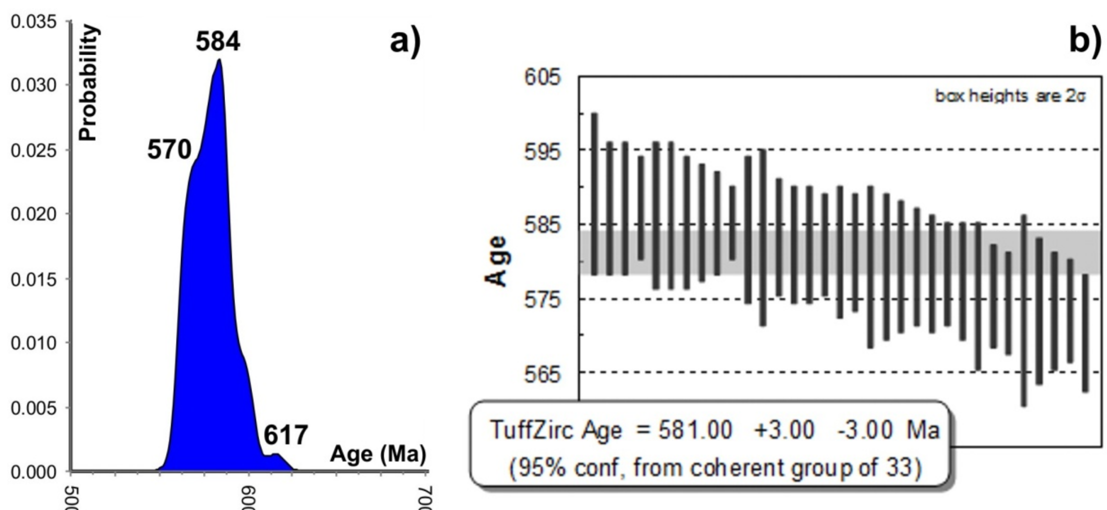



***Figure 6.19. a)*** *Probability density curve all zircon ages and* ***b)*** *robust median statistical analysis of the $^{206}Pb/^{238}U$ ages corresponding to a group of 33 analyses of zircons from the orthogneisss sample #B2.*

**Age of metamorphic/thermal events**

Ielova metasedimentary rocks contain a large number of complex zircon grains. From the dataset, without exception, all the youngest ages have very low Th/U ratio, <0.1, commonly considered characteristics of metamorphic and recrystallized zircons (*e.g.* Schaltegger *et al.*, 1999; Hoskin & Black, 2000; Rubatto *et al.*, 2001; Rubatto, 2002; Hoskin & Schaltegger, 2003).

The youngest ages, specific for all four samples, are related to Devonian-Ordovician times. These dark±dull rim areas can be interpreted as metamorphic recrystallized zircons, whose ages have been only resetted by the tectonothermic event (Fig. 6.20). Their repeated appearance indicates clearly that there are some tectono-metamorphic events, which affected Ielova metasedimentary rocks around 437-483Ma (Ordovician-Silurian) and 362-404Ma (Devonian).

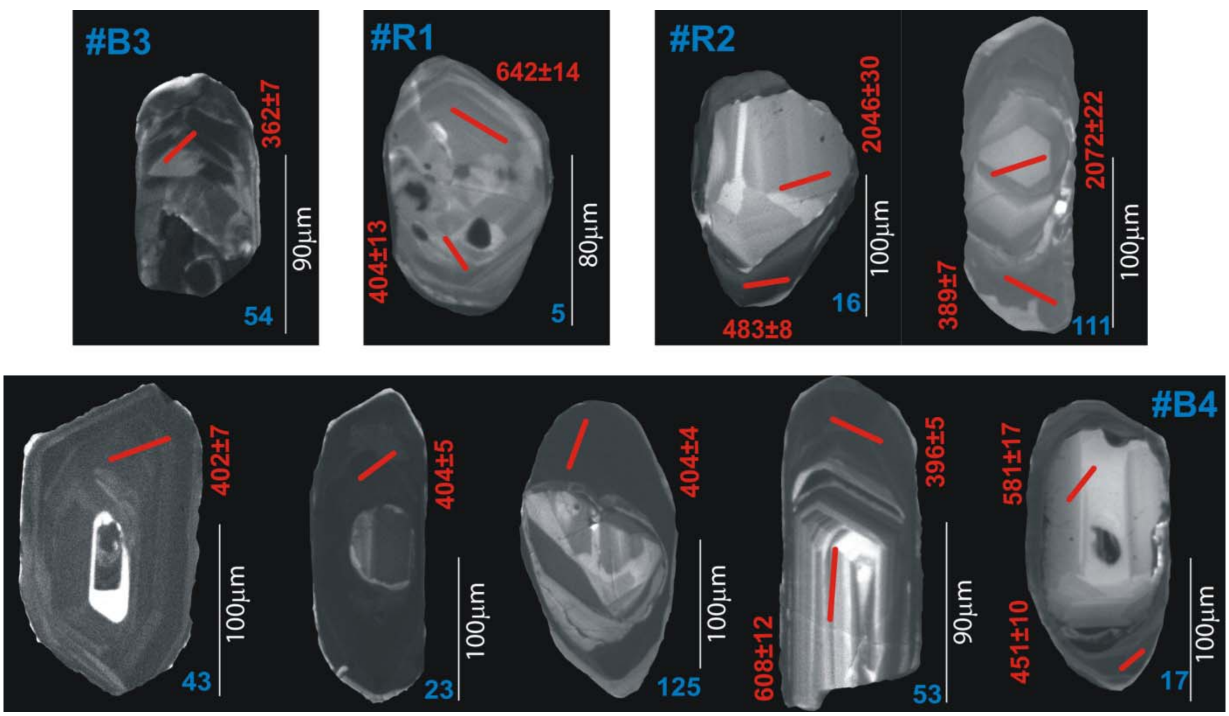



***Figure 6.20.*** *CL images of selected zircons from Ielova paragneises, showing the youngest ages obtained from grain rims (blue number indicates the grain; red line marks the ablation area, while red number indicates the obtained age in Ma)*

**Age of sedimentary deposition**

In principle, the maximum age of deposition for a sedimentary rock is estimated based on the youngest detrital zircon age. However, given the statistical uncertainty of a single analysis, the maximum depositional age can be better approximated based on the average age of the youngest zircon population (*e.g.* Kontinen *et al.*, 2007; Diez Fernández *et al.*, 2010) or even of the largest group of youngest zircons (*e.g.* Fuenlabrada *et al.*, 2010), all <10% discordance.

As shown, the youngest ages for each of the four samples are dating mainly rims and show features of recrystallized/metamorphic/reset zircons, therefore they will not be considered for the next discussion regarding the depositional age, based entirely on the grains with ages less than 10% discordant (Table 6.2). The time of sedimentation processes for Ielova metasedimentary rock can be estimated as taken place in two stages, one intra-Cambrian, between 532-525 Ma and 500Ma, and the other in Upper Cambrian – Ordovician, 493-491Ma and 451Ma.

***Table 6.2.***
*Various estimates of maximum depositional age for each dated Ielova metasedimentary samples.*

| ***Metasedimentary rock*** | ***Maximum depositional age estimates (Ma)*** | | |
|---|---|---|---|
| | ***Youngest grain*** | ***Youngest population*** | ***Largest youngest population*** |
| **#B3** | 475±2 | 493 | 555 |
| **#B4** | 490±9 | 491 | 540 |
| **#R1** | 526±9 | 528 | 564 |
| **#R2** | 521±8 | 525 | 532 |

# 7. PALEOGEOGRAPHIC IMPLICATIONS

## 7.1. Gondwana and Cadomian-Avalonian belt

The amalgamation of the Gondwana Supercontinent took place during the late Neoproterozoic as the result of continental collision processes and formation of interior orogens (Drost *et al.*, 2011). The over 5000 km long magmatic belt, known as Cadomian-Avalonian belt, was build up along the northern margin of Gondwana (Fig. 7.2) and represents one of the outboard orogens formed around 750-540 Ma.

A "Cadomian provenance" for a terrane means that it originated along the Gondwana margin and was affected by the Cadomian orogeny (Pharaoh, 1999). Despite the more developed classifications of these terranes (*e.g.* Nance *et al.*, 2008), from a simple point of view, two major groups have been separated: Avalonian and Cadomian.

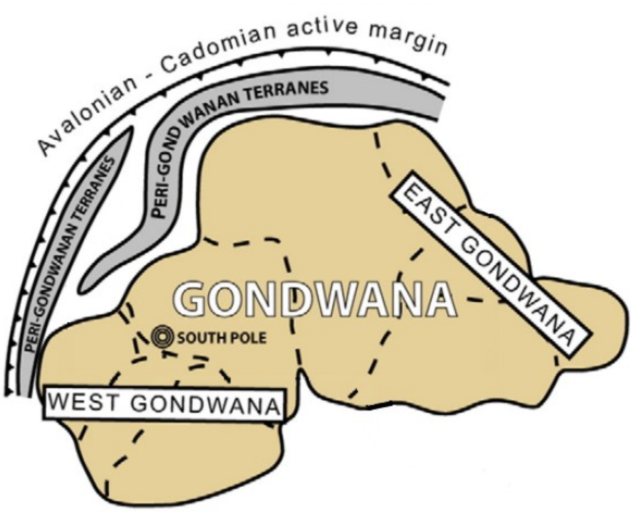



**Figure 7.2.** *Simplified paleogeography of Gondwana and related peri-Gondwanan realm at cca 570 Ma (from Díez-Fernández et al., 2010).*

## 7.2. Ielova detrital zircon ages

The large number of zircon detrital ages obtained from the four metasedimentary samples of Ielova can be interpreted in terms of populations and age components. The whole detrital data set for Ielova is listed in table 6.1, and graphically represented in figure 7.5.

**Pre-Mezoproterozoic ages** are present in various proportions, in all the studied sedimentary rocks. From the large dataset of pre-Mesoproterozoic ages, 54 concordant analyses (85-105%) were obtained (Fig. 7.5). These data are consistent with the existence of Palaeoproterozoic (1.6-2.5Ga) and Archean (2.5-3.0Ga) components in the Ielova unit.

**Unusual Mesoproterozoic ages.** One of the most striking features of the Ielova detrital ages is the almost complete absence of Mesoproterozoic (1.0-1.6Ga) zircons, only three grains yielding four such ages (Fig. 7.4).

**Paleozoic-Early Neoproterozoic ages.** The largest part of the ages falls in the interval 500-650Ma, with peaks around 525, 540, 555, 580, 590, 623 and 640Ma (Fig. 7.5). These indicate the main zircon-forming magmatic events, and they are quite similar for all four metasedimentary samples.

Dating U-rich zircon rims, the youngest ages are Devonian (362-404Ma), and point to a superposed metamorphism, as well as some of the Silurian-Ordovician ages (437-483Ma) that indicate another tectonothermic event affecting the Ielova detrital zircons.

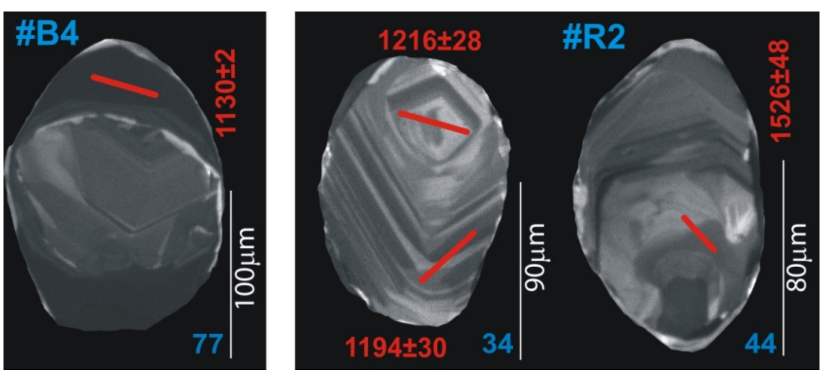



***Figure 7.4.*** *CL images of Mesoproterozoic zircons from Ielova paragneises (blue number indicates the grain; red line marks the ablation area, while red number indicates the obtained age in Ma)*

## 7.3. Peri-Gondwanan affiliation of Ielova unit

The largest part of the Ielova detrital ages fall in the interval 500-650Ma, with peaks around 525-555Ma (maximum at 540Ma) (Fig. 7.5), and represents a distinctive peri-Gondwanan signature, being related to the magmatic processes in the Cadomian (-Avalonian) orogenic belt (Baltica is known to be magmatically inactive during this period). The belt was the site of arc volcanism and calc-alkaline plutonism between 540 and 700 Ma ago, with a maximum at 600-540 Ma. This confirms without doubts the Gondwanan-related position of Ielova sequence.

The main characteristics of Ielova detrital spectrum are the almost complete absence of Mesoproterozoic (1.0-1.6 Ga) zircons and the large number of Paleoproterozoic ages falling in the 1.95-2.4 Ga and 2.5-2.75 Ga intervals. The minimum/abundance of zircon ages within 2.45–2.05 Ga is considered a robust signature for deciphering the Avalonian/Cadomian-related terranes (Samson *et al.*, 2005). Thus, Ielova unit, with very abundant zircons in this interval, together with the lack of consistent Mezoproterozoic zircons, shows a Cadomian affinity in the peri-Gondwanan realm.

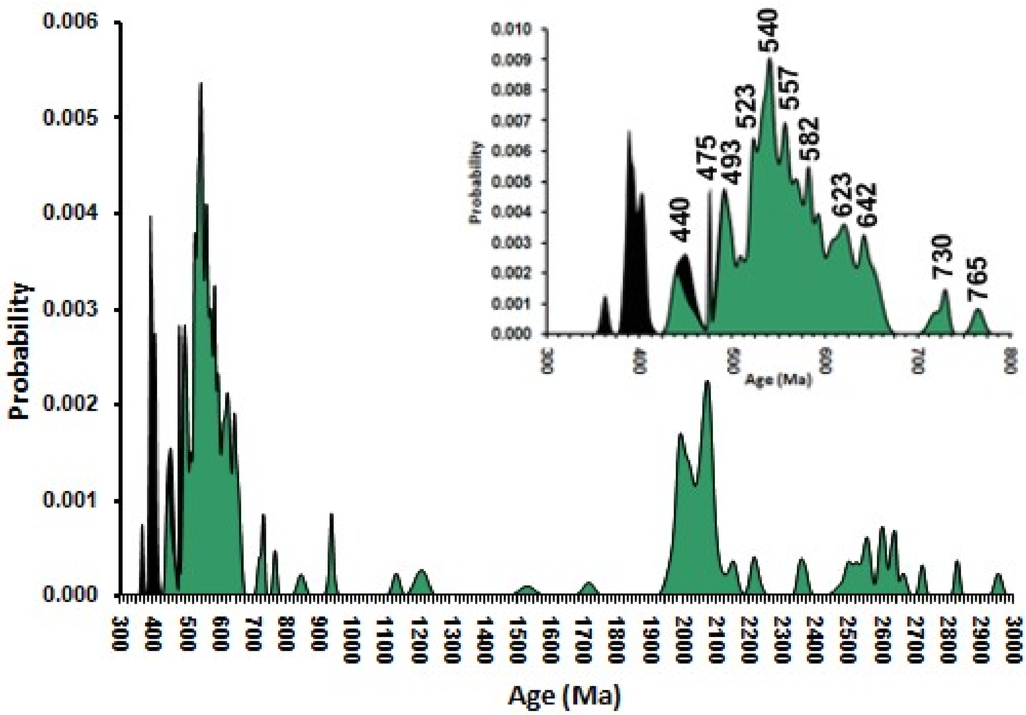



***Figure 7.5.*** *Probability density distribution plots of all Ielova detrital zircon grains (85-105% conc.): black – rim ages, green – the rest of ages. Inset shows enlarged interval of 300-800 Ma.*

Cadomian terranes are positioned along western and northern African margin, the marginal African cratons being also the main zircon suppliers. However, according with the exact location of the Cadomian terranes, incomes from Amazonia (for westermost terranes), as well as from India (for the eastern ones), are also expected.

Based on the presence of the few Mezoproterozoic zircons, two are the possible positions of Ielova unit: (1) adjacent to West Africa, but still close enough to Amazonia to receive Mezoproterozoic zircons from it or (2) north-eastern part of Africa, with sources as Saharan craton and Arabian-Nubian shield (Fig. 7.6). The presence of a consistent cluster of ages spanning between 2.4-2.7Ga, with a peak around 2.6Ga, as well as by the few ages between 750 and 900Ma (characteristics of northern and north-eastern Africa suppliers, while they lack in the Amazonian craton) clearly indicates a paleogeographical position of Ielova in the north toward north-eastern part of Africa (northeastern Gondwana).

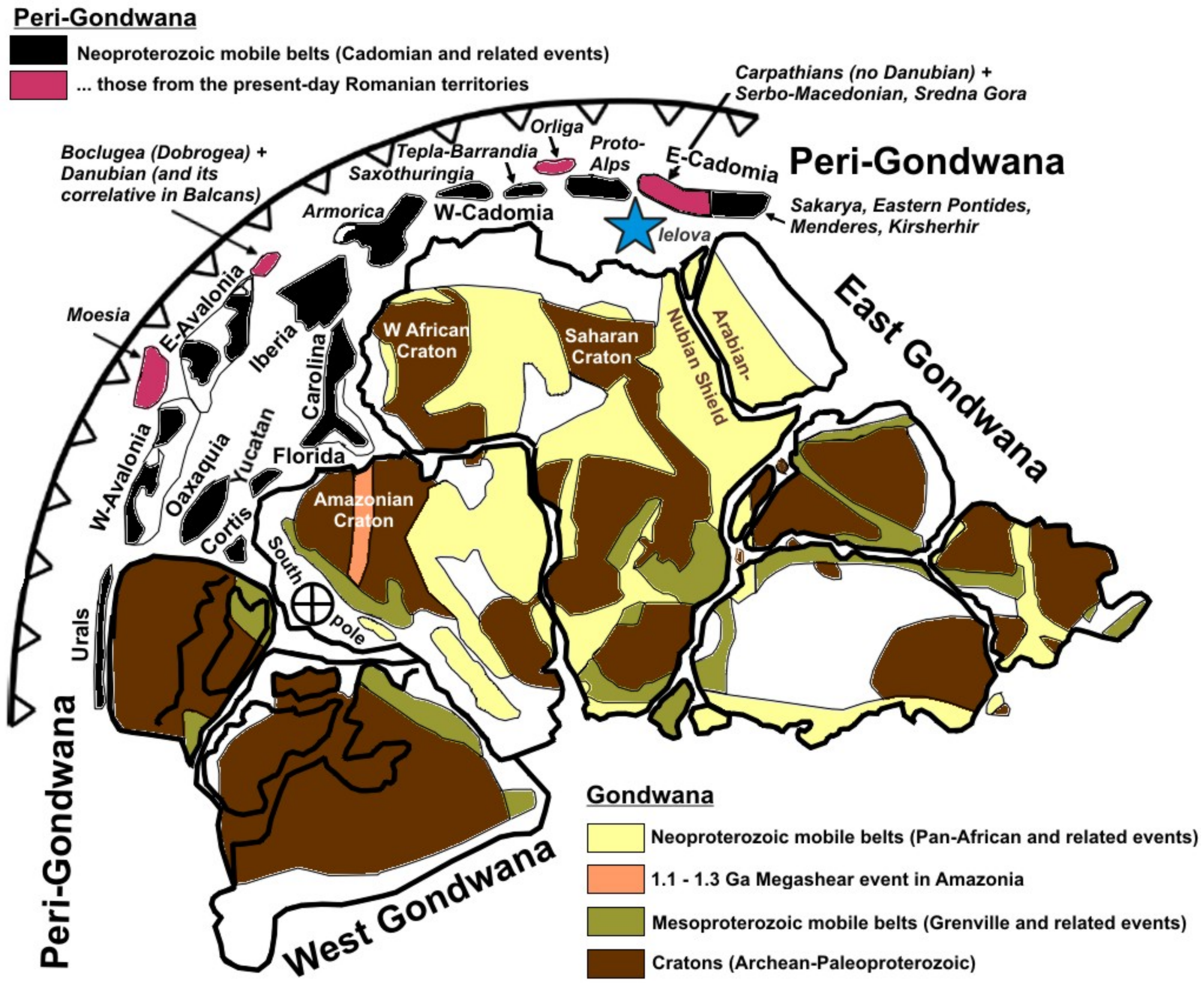



***Figure 7.8.***
*Position of Ielova Metamorphic Sequence (blue star) within the paleogeographical arrangement of the peri-Gondwanan terranes at cca 570 Ma. (after Linneman et al., 2004; Balintoni et al., 2010b)*

### 7.4. Detrital zircon sources

The largest part of the ages, concentrated in the interval 500-650Ma, is attributed to the event representing the assembly of Gondwana and the subsequent orogenic belts from its northern part during Late Proterozoic (Nance & Murphy, 1994) (*e.g.* Pan-African or Cadomian orogenic belts). Those few ages between cca 0.9 and 1.1-1.2 Ga can be interpreted as originating in Arabian-Nubian Shield or Kibaran Orogen from Central Africa, due to Grenvillian orogeny (*e.g.* Himmerkus *et al.*, 2007, Linnemann *et al.*, 2004). For the 1.5-2.0 Ga zircons, Trans-Saharan Belt, Saharan metacraton and Arabian-Nubian Shield, and less Anti-Atlas, are plausible sources, while for older zircons, >2.0Ga Eburnean and Liberian-Leonian orogens can be suspected. The ages of 2.75-2.25 Ga are most probable derived from Saharan metacraton.

### 7.5. Post-Cambrian ages

The majority of the ages younger than Cambrian are provided by zircon rims, usually U-rich, Ordovician-Silurian (437-483Ma) and Devonian (362-404Ma), both indicating superposed tectonothermic events. Additionally, some Ordovician grains, with high degree of discordance, as well as lack of any magmatic structures, are interpreted as suffering from Pb-loss.

Given the location of the Ielova in the northeastern African part of Gondwana, most probably "Caledonian North African orogenic events/orogeny" (Balintoni *et al.*, 2011b) generated the Ordovician rims on the older detrital grains, as well as radiogenic Pb loss of some older detrital zircons. The Devonian metamorphic event, indicated by the zircon rims, is interpreted as the result of a superposed metamorphism, related to Variscan orogeny, which largely affected all the Romanian Carpathians up to eclogitic facies (Balintoni *et al.*, 2009, 2010a and the reference therein).

## 8. TECTONIC SETTING AND EVOLUTIVE IMPLICATIONS

Reconstruction of Ielova sequence tectonic history is possible assembling all the obtained data for each principal rock type which constitute it. Thus, the tectonic setting in where the geological processes took place, as well as the timing of this evolution, can be inferred.

### 8.1. Tectonic setting

As shows by the metasediments and orthogneisses whole-rock geochemistry, a continental margin implied in a subduction process is the large tectonic setting in which Ielova sequence originated.

The basin in which detritic material has been deposited is of forearc-, intraarc- or backarc-type and developed on a thin continental basement. Based on the thinkness of Ielova sedimentary unit, and on the presence of mafic magmatic intercalations, fore-arc basin as the depositional place for Ielova metasediments is excluded. In turn, modern back-arc and intra-arc basins are associated with extension, typically accompanied by rift-related mafic magmatism, and may receive thick accumulations of sediments from the adjacent arcs. Hence, a back-arc or an intra-arc basin should be considered the most likely depositional environment for the Ielova metasediments.

The mafic orthogneisses are characterized by both subduction-related and within plate features, respectively, which is consistent with the emplacement in an extensional basin, as a back-arc one. This is further supported by the $A_2$-type granitic gneisses, because such felsic magmas are normally produced during the rapid development of island arc/back-arc basin system via extension within the margin of a pre-existing older continental crust.

## 8.2. Timing

The U-Pb zircon LA-ICPMS data indicate (a) a volcanic-arc activity – at about 580Ma, (b) the zircon- forming magmatic events – 493, 510, 523, 540 (the highest peak), 557, 570, 582, 592, 623 and 642Ma., (c) the onset and duration of sediments deposition – from 532-525 Ma, up to 500Ma., and from 493-491Ma. (d) the emplacement of granitic magma – at *cca* 500Ma and (e) subsequent two thermotectonic events which affected the rocks – a Devonian (362-404Ma) and an Ordovician-Silurian one (437-483 Ma), respectively.

There is a peculiar situation, related to the presence of a 580Ma-old protolith (sample #B2) within younger sediments. Considering the petrographical and geochemical characteristics, an andesite or an andesitic tuffite can represent the protolith of #B2. It can represent a rock slice tectonically emplaced in a younger sedimentary basin or a sedimentary rock which reached the basin with essentially no dilution from other sources, during transport.

## 8.3. Geodynamic evolution model of ielova unit

Given the proved paleogeographical position of Ielova sequence in the peri-Gondwanan realm, and more precisely in the north-eastern part of Gondwana, and its Cadomian affinity, it is expected to share at least partially the geodynamic history with the other Cadomian units. Except for the most recent geochronologically-recorded events, clearly due to the Variscan and Caledonian ("North African") orogenies, all the other ages, of Neoproterozoic – Upper Paleozoic, can be related to Cadomian orogenic processes and their continuum to the opening of the Rheic Ocean (Fig. 8.4)

In Neoproterozoic (590-542Ma), Cadomian arc was one of the main sources for the future Ielova Cambrian metasediments, which were deposited in the associated back-arc basin (Fig. 8.5). According with the Cadomian-Rheic evolutive model of Linnemann *et al.* (2007, 2008), all these rocks and detritus have been later thrusted and folded (545-540Ma) in a convergence regime, and constituted the Cadomian basement, intruded at *cca* 540Ma by anatectic magmas. No clear evidences for the convergent regime have been found within Ielova rocks, but the 540Ma-old magmatic zircons represent the largest population within the detrital grains.

The Ielova sequence has been "born" during Middle Cambrian. Its "birth place" has been a basin developed through extension on the Northeastern Gondwanan continental margin, basin in which the Ielova Cambrian sediments have been deposited between *cca* 520Ma and and up to *cca* 480Ma. They recycled local sources, represented by the Cadomian arc-related rocks and post-Cadomian magmatic activity (as igneous rocks and/or their detritus), within a rapid cycle of erosion-transport-deposition. Besides these, detritus from Palaeoproterozoic and Archean crust reached the basin. In the same time, the within-plate basaltic protoliths of Ielova amphibolites have been emplaced.

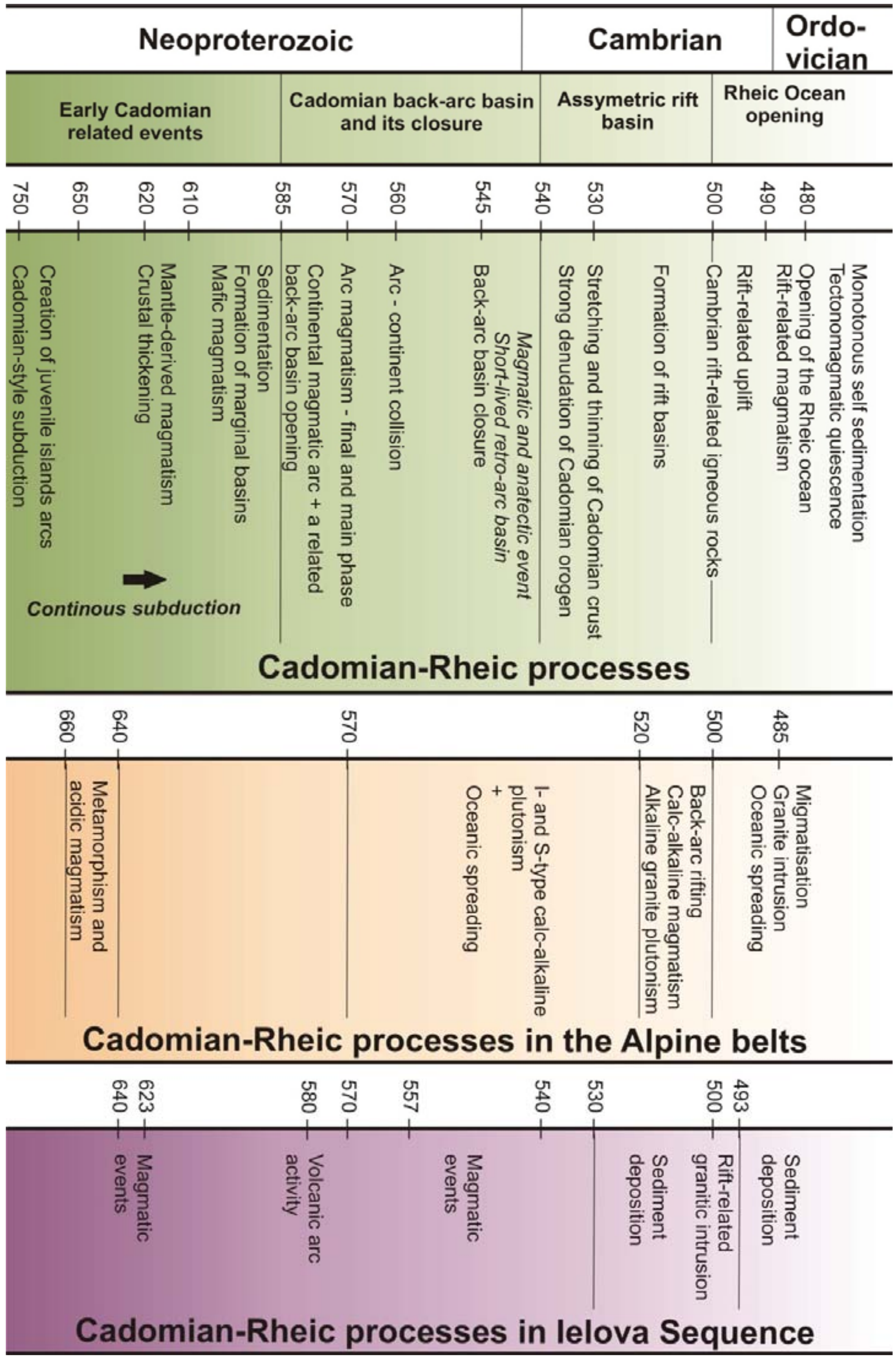



***Figure 8.4.***
*Scheme of tectonic evolution stages of Cadomian-Rheic processes, and the correspondent events in the Alpine belts and Ielova Sequence.Cadomian Rheic events after Linnemann et al. (2007, 2008); Cadomian-Rheic processes in the Alpine belts after Neubauer (2002).*

The continuous forcing of extension has led eventually to a doming of the astenosphere and a thinning of the crust, which has promoted crustal melting and intrusion of granitic magma at about 500 Ma. While the basin extended, leading eventually to the opening of the future Rheic ocean, the sedimentation continued after 493Ma.

After deposition, the Ielova rocks were thermo-tectonically affected by two events, one Ordovician-Early Silurian, 437-483 Ma, assigned to the "Caledonian North African" orogenic events (Balintoni *et al.*, 2011b), and to the younger, Devonian one, 362-404 Ma, part of the Variscan orogeny. No Alpine fingerprint has been geochronologically deciphered.

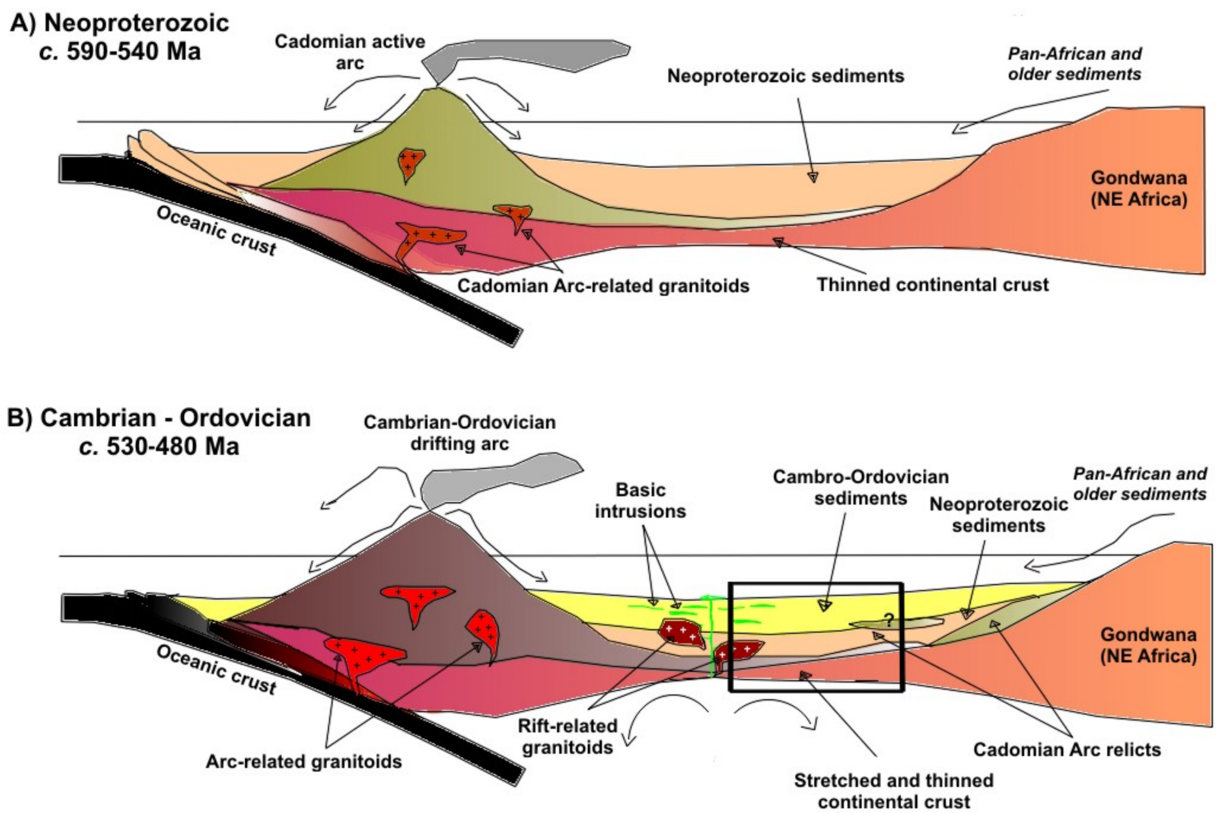



***Figure 8.5.***
*Model of the Ielova sequence evolution during A) Neoproterozoic and B) Cambrian-Ordovician times. The black square depicts a hypothetical "birth" place for Ielova sequence.*

## 8.4. Tectonic affiliation within South Carpathians

As mentioned, the Ielova sequence is a border unit, between the two main domains of South Carpathians, the Getic and the Danubian, and more precisely between the Sebeş-Lotru and the Drăgşan terranes respectively. As the whole **Getic Domain**, Sebeş-Lotru terrane has a proved north-eastern Gondwanan zircon source (Balintoni *et al.*, 2009, 2010a), and it was interpreted as a fragment of the

Cadomian Gondwana eastern extension. In the case of the **Danubian Domain** basement, arguments for an Avalonian location of Danubian terranes were brough by Iordan & Stănoiu (1993), Seghedi *et al.* (2005), Winchester *et al.* (2006) and Balintoni *et al.* (2011a), the latter based on U-Pb zircon ages.

The Cadomian affinity of **Ielova sequence**, as constrained by geochronological data, plead for a similarity with the Sebeş-Lotru terrane, and consequently, for a tectonic affiliation to the Getic Domain (Zaharia & Jeffries, 2010). This is also supported by the north-eastern position of Ielova within peri-Gondwanan realm, where also the Sebeş-Lotru terrane was placed (Balintoni *et al.*, 2009, 2010a).

The Sebeş–Lotru terrane comprises a lower, Neoproterozoic metamorphic unit (Lotru) and an upper, Ordovician metamorphic unit (Cumpăna), juxtaposed during the Variscan orogeny (Balintoni *et al.*, 2010a). Thus, Lotru unit has zircon crystallization ages of about 550-587Ma, while Cumpăna is characterized by much younger protoliths, of 455-470Ma., intruded in sediments which started to be deposited soon after 500Ma, as reported by Balintoni *et al.* (2010a). Ielova ages fit geochronological characteristics of both structural units of the Sebeş–Lotru terrane: if #B2 protolith age of 584Ma is consistent with Lotru unit, the sediments depositional ages are in agreement with those for Cumpăna (although slightly older, but statistically better constrained). Taking into account these new data, the "entrance" of #B2 protolith in Ielova Upper Cambrian – Ordovician sediments took place most probably during or post-Variscan, and it can represent a slice of Lotru basement. However, more data are required for a better constraint. In conclusion, Ielova Metamorphic Sequence is part of the upper Cumpăna unit of the Sebeş–Lotru terrane.

# 9. CONCLUSIONS

Ielova Metamorphic Sequence represented one of most controversial units from the South Carpathians. The controversy was related to its tectonic affiliation to one of the two main domains of the South Carpathians, Getic and Danubian, several tectonic "theories" being known and applied.

Few statements may be drawn from this study, which can be summarized as follows:

**(1)** Ielova sequence is a gneiss-dominated unit, comprising mainly various types of paragneisses and amphibolitic rocks, together with consistent granitic gneisses, migmatites and serpentinites.

The precursor material for metasedimentary rocks, originating from acidic rocks with minor mafic imput, was rapidly transported and deposited in a back-arc basin, thus suffering no intensive weathering. The deposition took place during Late Neoproterozoic – Ordovician.

The protoliths of the amphibolites with basalt affinities are related to a "within plate" setting, being emplaced in the same basin. Large volumes of granites (now as a continouslly transversal belt of granitic gneisses), with characteristics of post-orogenic $A_2$-type entered the basin at about 500Ma. Also, arc-related rocks (as andesite/andesitic tuffs, or granitoid bodies) are part of the Ielova sequence. A 584Ma "exotic" orthogneiss was found within the much younger metasediments.

The material was reworked during the "Caledonian North African" orogenic event (Balintoni *et al.*, 2011b) and subsequent Variscan thermotectonic processes.

**(2)** The detrital age spectra, obtained for four different metasedimentary rocks, revealed that Ielova was part of the peri-Gondwanan realm, having a Cadomian affinity. Its paleogeographical position was established along north eastern part of Africa. The consistent imputs of old material (Paleoproterozoic and Archaic) in the basin have several North-African sources, as Pan-African Orogen, Arabian-Nubian Shield, Kibaran Orogen, West African Craton (Eburnean Orogen and Liberian-Leonian Orogens) and Saharan metacraton.

**(3)** The above-mentioned results allowed a comparison and an integration of Ielova Sequence in the more general model of the Cadomian-Rheic processes, and also constrained its geodynamic evolution.

**(4)** Regarding Ielova tectonic affiliation in the South Carpathians, its Cadomian affinity, and its position in the northeastern Gondwana indicated a relationship with the Getic Domain, and, more precisely with Sebeş-Lotru terrane, thus no tectonic affiliation to the Danubian basement being deciphered. In a more detailed view, Ielova sequence proved to be part of Cumpăna, the tectonically-upper unit of the Sebeş-Lotru terrane, while the 584Ma "exotic" orthogneiss was presumed as originating in the lower unit, Lotru.

**(5)** From the various affiliation "models", the field distribution of the dated metasedimentary samples (Fig. 6.2) confirms the Ielova tectonic affiliation to Getic Domain, according with the Kräutner & Krstic (2002) model. However, given the geochemical consistency of all collected samples (even those from north-eastern part – not included within "Kräutner & Krstic (2002)" Ielova boundaries), we consider that Ielova unit is part of the Getic Domain in its largest extend.

In the present work, a tectonic "problem" was solved through a complex geochemical and geochronologic investigation. Although geochemical results were previously reported (*e.g.* Mureşan *et al.*, 1974; Zlaratova-Ţop *et al.*, 1971), we provided additional consistent information about the various rock types, about protoliths characteristics or tectonic setting. A detailed geochronological study was performed for the first time on the Ielova rocks, six samples being dated by LA-ICPMS, and a time-related evolution pattern was provided.

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