1 **Peri-Amazonian provenance of the Euxinic Craton components in Dobrogea and of**
2 **the North Dobrogean Orogen components (Romania): a detrital zircon study**

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11 **Abstract.** The Romanian South Carpathians foreland is located southwards of the East
12 European Craton (EEC) and consists of three major tectonic units: the Scythian Platform,
13 the North Dobrogean Orogen and the Euxinic Craton. The Euxinic Craton is represented
14 in the Dobrogea area by two components: (i) Central Dobrogean Shield and (ii) East
15 Moesia. In central-northern Dobrogea, the Trans European Suture Zone (TESZ),
16 including the Teisseyre-Tornquist Zone, presumably strikes below the surface. Because
17 the paleogeographic provenance of the above tectonic units was poorly documented until
18 present, a systematic sampling for detrital zircon has been conducted in all tectonic units
19 except for the Scythian Platform basement which is entirely covered by the Danube
20 Delta. In all, this totals 26 samples and around 1833 analyzed zircon grains. The
21 distribution of zircon grains dates along the time scale for all the sampled terranes
22 suggests that the sampled components of the Euxinic Craton in Dobrogea and the
23 constitutive terranes of the North Dobrogean Orogen have a peri-Gondwanan, peri-

Amazonian provenance. Their ages are Neoproterozoic or younger. In addition, the Euxinic Craton can be depicted as a paleo-Amazonian crustal fragment that was marginally affected by the Avalonian-Cadomian orogenic events. Along with its margin, the Avalonian type terranes accreted or Ganderian type terranes have evolved. Primary relationships between the Amazonian derived terranes and EEC are obscured due to an intricate geologic history exhibited by the North Dobrogean Orogen involving Caledonian, Variscan and Cimmerian orogenic events, while the geologic history of the Scythian Platform is also poorly established. The general distribution diagram of U-Pb detrital zircon ages shows some major zircon sources, shared with those detected at a global scale. They are episodic and coincident along with the time scale, such as those at the end of Archean or those from the Pan-African orogens. Finally, among these discussed tectonic components, only the Scythian Platform can possibly have an EEC provenance.

Keywords: detrital zircon; U-Pb ages; provenance; Dobrogea; peri-Amazonian terranes;

1.Introduction

The Trans European Suture Zone (i. e. TESZ, Gee and Zeyen, 1996) represents a transition zone from the East European Craton (EEC) to central and western Europe, a dominantly post-Cambrian collage of peri-Gondwanan terranes. The TESZ extends across Europe, from the North Sea to the Black Sea (Fig.1), marking a zone of complex relations between the EEC and peri-Gondwanan terranes accreted to its western margin (e.g. Pharaoh, 1999; Pharaoh et al., 2006; Winchester et al., 2006). While the origin and provenance of most terranes accompanying the TESZ in its northwestern part have been

constrained (e.g. Pharaoh et al., 2006; Winchester et al., 2006; Oczlon et al., 2007), there remain some crustal fragments, especially along its southern termination, whose origins, provenance and drifting history are still under debate (Balintoni et al., 2010, 2011). In Romanian geological literature, these are known as the Scythian Platform (Săndulescu, 1984) the North Dobrogean Orogen (Săndulescu, 1984), and the Euxinic Craton (Balintoni, 1997).

One approach to address the provenance and the drifting history of terranes is the study of U-Pb zircons in detrital populations in basement and cover rocks (e.g. Nance et al., 2008; Gehrels, 2014). Limited U-Pb zircon published results (Zelazniewicz et al., 2009; Balintoni et al., 2010, 2011) from the Carpathian foreland in Romania indicate a peri-Gondwanan provenance for one geological unit of the Euxinic Craton in Central Dobrogea (i.e. the Histria Formation) and two geological units of the North Dobrogean Orogen (i.e. Megina and Orliga terranes). Extensive and systematic sampling, targeted all the accessible components of the two domains, in order to allow for a thorough discussion on the provenance of the Euxinic Craton and North Dobrogean Orogen within the larger geotectonic context of the relationship between the EEC and the peri-Gondwanan terranes along the TESZ.

2. Geological setting

2.1 East Moesia component of the Euxinic Craton

The Euxinic Craton (Balintoni, 1997) consists in the Dobrogea area of two blocks: (i) the eastern part of the Moesian Platform, known as the East Moesia, and (ii) the Central Dobrogean Shield (Fig.3). The composite Intra-Moesian transcrustal fault, with

dip southern compartment, is active at least since Cretaceous until present (Săndulescu, 1984). It divides the Moesian platform into East Moesia and West Moesia, (Fig. 3, 4a; Barbu, 1973; Săndulescu, 1984). To the northeast, the boundary between East Moesia and the Central Dobrogean Shield is marked by the Capidava-Ovidiu normal fault of pre-late Cretaceous age. The southern compartment of this normal fault is the hanging wall (Fig. 3; e.g. Ionesi, 1994). Paleozoic sedimentary cover sequences of East Moesia in South Dobrogea begin with Ordovician quartzites, followed by Lochkovian-Emsian shales, Eifelian quartzitic sandstones, Givetian to Visean carbonate rocks and Kasimovian-Gzhelian clastic successions (Răileanu et al., 1966; Iordan, 1967, 1981, 1984, 1992, 1999).

2.2 Central Dobrogean Shield *component of the Euxinic Craton*

The area between the Capidava-Ovidiu fault to the south and the Peceneaga-Camena pre-Cenomanian transform fault that opened the western Black Sea basin to the north (Balintoni and Baier, 1997; Schmid et al., 2008) (Fig. 2, 4-A) defines the limits of the Central Dobrogean Shield (Fig.4). Here is the only place where the Moesian basement is exposed at the surface. The Central Dobrogean Shield consists of two units: (i) the lower Altîn-Tepe Group (e.g., Kräutner et al., 1988), made up of metasediments metamorphosed up to amphibolite facies, and (ii) the upper, very low grade, Histria Formation turbidites (Seghedi and Oaie, 1995).

An important tectonic lineament tracing southwards of the Capidava-Ovidiu fault is the concealed pre-Jurassic Palazu reverse fault (Fig. 5), along which the South Dobrogea basement thrusts over the Histria Formation, confining its occurrence to the north (e.g., Kräutner et al., 1988). The contact between the Altîn Tepe Group and Histria

Formation has been considered as either a stratigraphic unconformity (Giușcă et al., 1967, Mirăuță, 1965, 1968), a low-angle overthrust (Mureșan, 1971, 1972), or a low-angle extensional detachment fault (Seghedi et al., 1999). The Histria Formation is a typical turbiditic succession whose stratigraphic sequence includes three members (i.e. Seghedi and Oaie, 1995; Oaie, 1998). The lower member (Beidaud member) and the upper member (Sibioara member) are dominated by sandstones, interpreted as interbedded channel and depositional lobe sequences, while the middle member (Haidar member), consists of fine grained distal turbidites, mainly purple siltstones and mudstones. The age of the Histria Formation was interpreted to be Ediacaran based on the medusoid *Nemiana simplex Paliș* imprint, identified in the Haidar member (Oaie, 1992). The rocks of the Histria Formation display a characteristic deep green color due to the presence of chlorite and epidote. Zeolites and carbonates also occur as a result of incipient metamorphism.

The Altîn Tepe Group (Fig. 6) occurs in a narrow zone, south of the Peceneaga-Camena fault. Above the low angle tectonic plane that separates this group by the overlying Histria Formation, a narrow zone of retrograde metamorphism and mylonitization develops in the Altîn Tepe Group (Mureșan, 1972). In the exposed part of the Altîn Tepe Group, Mureșan (1972) distinguished three separate lithostratigraphic units: (i) a lower gneiss-mica schist formation, (ii) a middle amphibolite formation, and (iii) an upper quartzite-micaschist formation. The latter formation hosts in its uppermost part an ore member that consists of syngenetic stratiform lenses of pyrite, chalcopyrite, magnetite and barite ores interbedded with the host rock.

2.3 North Dobrogean Orogen

The North Dobrogean Orogen (Fig.7, 8) represents a Cimmerian fold belt (Murgoci, 1912), superimposed on a Variscan orogen. The term "Cimmerian" designates a pre-Cretaceous orogeny that resulted in the closure of the Paleo-Tethys Ocean (Sengor, 1984). This orogenic complex is situated between the Central Dobrogean Shield in the south and the Scythian Platform in the north and is bound by the Peceneaga-Camena and the Sf. Gheorghe faults, respectively (Kräutner et al., 1988). Structurally, it involves four main basement and cover tectonic units (Mirăuță, in Patrulius et al., 1973). From bottom to top, these units are: (i) Tulcea unit, which exposes mainly Triassic and Jurassic deposits and scarce remnants of Paleozoic basement; (ii) Niculițel unit, consisting of Triassic limestones and basalts; (iii) Consul unit, represented by Triassic sediments and acid volcanics; (iv) Măcin unit comprising mainly late Proterozoic to Paleozoic metamorphic, magmatic and sedimentary rocks, covered by Triassic and Jurassic deposits.

The metamorphic rocks comprising the basement of the Măcin tectonic unit (Fig. 8) belong to the Orliga, Megina and Boclugea groups. The relationship between these three metamorphic groups is structural; they represent dismembered relics of Variscan orogenic assemblages, subsequently shuffled by various Cimmerian faults (Seghedi, 2001; Seghedi et al., 1999, 2004). Because of their tectonic relationships, and since each group found its origin in a different tectonic setting and has a specific metamorphic history (e.g., Seghedi, 1999), these groups are considered as parts of different pre-Alpine terranes (Balintoni et al., 2010). The Orliga and Megina groups are medium-grade assemblages with sedimentary and igneous (mafic and acid) protoliths, metamorphosed up to kyanite grade (Seghedi, 1975, 1980). The Boclugea Group is a low-grade

metapelitic-metapsamitic succession that reached the biotite zone. The succession is dominated by mica-rich quartzites, interbedded with quartzitic schists, muscovite schists and phyllites (Seghedi, 1986). An important, relatively continuous sedimentary sequence, are the Priopcea quartzites, considered part of the Boclugea Group for example by Kräutner et al. (1988). However, the quartzite sequence is described as in sedimentary continuity with the overlying Silurian sedimentary deposits on the underlying Megina basement by Mirăuță (1966). In what concerns the temporal placement of the formation of Orliga and Megina groups, there is no clear constraint, yet based on indirect and scarce evidence, a Precambrian age was presumed for these two groups by some authors (Kräutner and Savu, 1978; Seghedi et al., 1980, 1988; Kräutner et al., 1988).

The Paleozoic sedimentary cover of the Măcin tectonic unit has been divided into: (i) the Cerna Formation of Silurian age, represented by sandstones, slates and limestones (Patrulius et al., 1973); (ii) the Bujoarele Formation, of early Devonian age, which consists of slates, quartzites and limestones (Patrulius et al., 1973); (iii) the Carapelit Formation, which is a volcano-sedimentary assemblage of late Paleozoic age, contemporary to the Variscan orogeny (Mrazec and Pascu, 1896; Seghedi and Oaie, 1986; Seghedi et al., 1987). The basement of the Cerna and Bujoarele formations is represented by the Megina terrane. The Carapelit Formation is sourced by Variscan magmatism and material from the Boclugea and possibly from the Megina terranes, yet the relationship between the Carapelit Formation and these terranes is structural, they are separated by Cimmerian (strike-slip) faults (Seghedi, 1983; Seghedi and Oaie, 1994).

The metamorphic basement of the Tulcea unit is temporally unconstrained and crops out across small areas as dismembered patches. The Paleozoic sedimentary deposits

are represented by two Silurian and Devonian formations, known as the Reditu Formation and Beştepe Formation, respectively (Patrulius et al., 1973). A third formation, the Horia Formation, has an uncertain age since it is considered pre-Paleozoic by some authors and Devonian by others (see comments in Ionesi, 1994). The Reditu Formation is predominantly detrital with some calcareous layers interbedded at the lower part. The Beştepe Formation, is ascribed to the Devonian based on conodonts (Mirăuță and Mirăuță, 1965), and consists of pelagic siliceous successions and distal turbidites (Seghedi et al., 1993; Seghedi, 2012).

2.4 Dobrogea terranes.

For the sake of simplicity, in terms of pre-Alpine terranes, we can sketch the following geologic units that make up the entire Dobrogea territory: (i) the East Moesia terrane in South Dobrogea; (ii) the Histria and (iii) Alfin Tepe terranes in Central Dobrogea; (iv) the Boclugea, (v) Megina, (vi) Orliga and (vii) Tulcea terranes in north Dobrogea.

2.5 Scythian Platform

Săndulescu (1984) defines the Scythian Platform as the area comprised between the EEC to the north and Alpine orogens (Great Caucasus, South Crimea, North Dobrogean) to the south, with a Cadomian-Caledonian deformed basement. This author considers the Pre-Dobrogean depression as the foreland of the North Dobrogean Orogen and in 1994 he suggests this orogen to be an unrooted nappes pile thrust over the Scythian Platform margin. In this way, the boundary between the Scythian Platform basement and the Euxinic Craton basement runs along the Peceneaga-Camena fault. According to Seghedi (2012), the Scythian Platform represents the southern margin of the

EEC that was involved in Neoproterozoic deformation before the Vendian, since its undeformed platform cover, described in various bore-holes, starts with Vendian clastic deposits similar to those of the EEC along the Nistru river. Therefore, the Scythian Platform did not suffer Caledonian deformation. New seismic data (Starostenko et al., 2015) reveal a pre-Vendian seismic structure of the Pre-Dobrogean depression basement similar to that of the Western European basement. If this is the case, then the Scythian Platform should be divided into two parts: an eastern part representing the southern margin of EEC; a western part of peri-Gondwanan provenance, docked to EEC during the pre-Vendian time.

3. Analytical methods

Zircon crystals were extracted from samples by traditional methods of crushing and grinding, followed by separation with a Wilfley table. Samples were processed such that all zircons are retained in the final heavy mineral fraction. A large split of these grains is incorporated into a 1" epoxy mount together with fragments of our Sri Lanka standard zircon. The mounts are sanded down to a depth of ~20 microns, polished, imaged, and cleaned prior to isotopic analysis.

U-Pb geochronology of zircons was conducted by laser ablation multicollector inductively coupled plasma mass spectrometry (LA-MC-ICPMS) at the Arizona LaserChron Center (Gehrels et al., 2006, 2008). The analyses involved ablation of zircon with a Photon Machines Analyte G2 excimer laser using a spot diameter of 30 microns. The ablated material was carried in helium into the plasma source of a Nu-HR-MC-ICPMS, which was equipped with a flight tube of sufficient width that U, Th, and Pb

isotopes are measured simultaneously. All measurements were made in static mode, using Faraday detectors with 3×10^{11} ohm resistors for ^{238}U , ^{232}Th , ^{208}Pb - ^{206}Pb , and discrete dynode ion counters for ^{204}Pb and ^{202}Hg . Ion yields were ~ 0.8 mv per ppm. Each analysis consisted of one 15-second integration on peaks with the laser off (for backgrounds), 15 one-second integrations with the laser firing, and a 30 second delay to purge the previous sample and prepare for the next analysis. The ablation pit was ~ 15 microns in depth.

For each analysis, the uncertainties in determining $^{206}\text{Pb}/^{238}\text{U}$ and $^{206}\text{Pb}/^{204}\text{Pb}$ result in a measurement uncertainty of ~ 1 -2% (at 2-sigma level) in the $^{206}\text{Pb}/^{238}\text{U}$ age. The uncertainty in measurement of $^{206}\text{Pb}/^{207}\text{Pb}$ and $^{206}\text{Pb}/^{204}\text{Pb}$ also result in ~ 1 -2% (at 2-sigma level) uncertainty in age for grains that are > 1.0 Ga, but are substantially larger for younger grains due to low intensity of the ^{207}Pb signal. For most analyses, the cross-over in precision of $^{206}\text{Pb}/^{238}\text{U}$ and $^{206}\text{Pb}/^{207}\text{Pb}$ ages occurred at ~ 1.0 Ga.

^{204}Hg interference with ^{204}Pb is accounted for measurement of ^{202}Hg during laser ablation and subtraction of ^{204}Hg according to the natural $^{202}\text{Hg}/^{204}\text{Hg}$ of 4.35. This Hg correction is not significant for most analyses because the Hg backgrounds are low (generally ~ 150 cps at mass 204).

Common Pb correction was accomplished by using the Hg-corrected ^{204}Pb and assuming an initial Pb composition from Stacey and Kramers (1975). Uncertainties of 1.5 for $^{206}\text{Pb}/^{204}\text{Pb}$ and 0.3 for $^{207}\text{Pb}/^{204}\text{Pb}$ were applied to these compositional values based on the variation in Pb isotopic composition in modern crystal rocks.

Inter-element fractionation of Pb/U is generally $\sim 5\%$, whereas apparent fractionation of Pb isotopes is generally $< 0.2\%$. In-run analysis of fragments of a large zircon crystal (generally every fifth measurement) with known age of 563.5 ± 3.2 Ma (2-

sigma error) is used to correct for this fractionation. The uncertainty resulting from the calibration correction is generally 1-2% (2-sigma) for both $^{206}\text{Pb}/^{207}\text{Pb}$ and $^{206}\text{Pb}/^{238}\text{U}$ ages.

Concentrations of U and Th are calibrated relative to the Sri Lanka zircon standard, which contains ~518 ppm of U and 68 ppm Th.

The analytical data are reported in Supplementary Data Table 2. Uncertainties shown in these tables are at the 1-sigma level, and include only measurement errors. Analyses that are >10% discordant (by comparison of $^{206}\text{Pb}/^{238}\text{U}$ and $^{207}\text{Pb}/^{235}\text{U}$ ages) or >5% reverse discordant are not considered further.

The resulting interpreted ages are shown on relative age-probability diagrams using DensityPlotter app (Vermeesch, 2012). The age-probability diagrams are plotted using Kernel Density Estimator function using an appropriate bandwidth for each distribution, and sum all ages from a sample into a single curve. Histograms with 30 Ma binwidth and probability density curves are also plotted on each diagram. The maximum deposition age is appreciated based on the youngest three zircon grains population overlapped at one sigma, and in correlation with some dated ortho-rocks.

4. Results

A brief description of all new samples presented in this paper, together with the GPS coordinates of the sampling locations can be found in the supplementary data Table 1. The results are, in short, characterized using some terms proposed by Link et al. (2005). According to these authors, *defining populations* form more than 50% of the zircon in a sample and they dominate and define the first order drainage systems. *Major*

populations are present at the 10% to 50% level in the second order drainage systems. The *small populations*, less than 10% in an ages group, characterize the third order drainage systems and are important for provenance because they persist through multiple episodes of dilution and recycling. In accordance with our experience, all the populations can be paleogeographical important and the defining and major populations can also be present in a single sample from a very large drainage system of third order, as for example the Parana River (Rino et al., 2008). There are singular zircon sources localized in large paleogeographic areas, and generally speaking, in provenance studies, more than a single sample is collected from the zone of interest. The fact that the mountains ranges do not persist over 500 Ma is critical in judging the zircon sources. But during the same time, out of the sedimentary sources, shield areas can provide very old zircons from primary sources. Briefly, the detrital zircon age distribution in a collected sample depends on: (i)-the source type (magmatic, metamorphic or sedimentary; (ii)-the source age; (iii)-the geographical arrangement of sources; (iv)-the accessibility of sources; (v)-the age of the sources that supplied zircons in sediments; (vi)-the supercontinent configuration during the sedimentary sources deposition.

4.1 East Moesia (samples 5082, GM-087)

The youngest peak of zircon grain ages of 448 Ma from the sample 5082-Mangalia drill-core (Fig. 4a), indicates an early Silurian, late Llandovery (Telychian) maximum age for the intercepted sediments. The most important major population (~34% of all the ages) is situated around 629 Ma. Other significant minor populations are spread along the Mesoproterozoic, Paleoproterozoic and Neoproterozoic.

In the Gârla Mare drill-core (sample GM-087), there is a defining population around 620 Ma, including 88% of all the ages. The maximum age of sediments intercepted by this drill-core should be less than 560 Ma, the age of the Cocoşu volcanogenic formation situated in its basement (e.g. Mutihac, Mutihac, 2010).

The detrital zircon ages from the two drill-hole cores are projected in Figs. 9a, b (individual sample projections), and c (cumulative projection of both samples). The two individual histograms are broadly similar, with the main difference in the number of ages older than ca. 1.1 Ga. The main age concentration in both samples is confined to the interval of 552-683 Ma and includes 119 ages, or 64 % of the total. There are 19 Mesoproterozoic ages (10 % of total), 21 Paleoproterozoic ages (11 % of total), and only 10 Archean ages (5 % of the total). There are remarkable gaps between 0.8 and 1.05 Ga, and between 2.2 and 2.4 Ga.

4.2 Central Dobrogea

For a good comparison with the detrital zircon age distribution in the AlŃn Tepe Group, new projections are shown of the previously published data for the Histria Formation (Balintoni et al., 2011).

4.2.1 Histria Formation (samples 346A, 346B)

The youngest peak of 623 Ma, recorded in the coarse-grained sandstones of the upper Sibioara member (Fig. 4b, 10), confirm an Ediacaran age of the Histria Formation suggested by Oaie (1992), based on the *Nemiana simplex Palij* medusoid imprint. The detrital zircon ages from the two samples are projected in Figs. 10a, b (individual sample projections) and c (cumulative plot of both samples). The two diagrams are quite similar and characterized by a great number of Archean ages. There are minor significant

populations in Neoproterozoic, around 1.5 Ga, around 2.0-2.1 Ga and in Neoarchean. The entire Archean population includes 97 ages or ~54 % of the total. A gap can be noticed between 0.75 and 1.0 Ga and only three ages appear between 2.2 and 2.5 Ga.

4.2.2 Altın Tepe Group (samples 12-495, 12-496, 172 GPS)

The youngest detrital zircon ages peak of 575 Ma suggest a maximum late Neoproterozoic deposition age for the Altın Tepe Group (Fig. 6, 11) meta-sedimentary protoliths. Therefore, the rocks of the Altın Tepe Group are slightly younger than those of the Histria formation, proving without doubt that the tectonic relationship between the two geological units is contractional and not extensional.

The detrital zircon ages from the three samples are projected in Figs. 11a, b, c (individual sample projections), and d (cumulative plot of all samples). Out of the three samples, the sample 12-495 was not sourced with zircon grains older than 1.8 Ga. The other two samples show a significant number of zircon grains older than 1.8 Ga, including Archean ages. The youngest minor populations lay between 510 and 743 Ma and contains 60 ages, or 30 % of the total. There are significant minor populations along the Mesoproterozoic and Paleoproterozoic intervals, with a major population around 2.1 Ga. Some minor populations are also visible in Neoarchean. Only two ages exist in the 0.8-1.05 Ga interval and another three between 2.2 and 2.5 Ga.

4.3 Age spreading patterns of the Euxinic Craton

Figures 12a, b, and c, shows the cumulative plots for the Paleozoic of East Moesia, the Histria Formation of Central Dobrogea and the Altın Tepe Group, together with a general cumulative plot for all the samples (Fig. 12d). A striking similarity is obvious among the samples. The general histogram is especially suggestive, since it

shows clearly the dominance of zircons from interval centered around 616 Ma. The remaining age groups, i.e. 1.2 Ga 1.5 Ga; around 2.1 Ga, 2.7 Ga, and 2.9 Ga are subordinate.

4.4 North Dobrogea, the Măcin unit

In-depth analysis of U-Pb detrital zircon ages of samples from the Orliga Group, Boclugea Group, and Priopcea quartzites was already carried out (Balintoni et al., 2010). Unfortunately, without addressing zircon ages from the magmatic protoliths, the Priopcea quartzites were discussed together with the Boclugea Group mica-rich quartzites. Subsequent U-Pb zircon dating of granite intrusions in the Boclugea Group rocks (i.e. Hamcearca and Chietros bodies, Balintoni et al., 2013) yielded ca. 600 Ma crystallization ages. These results explain the absence of ages younger than 600 Ma in the Boclugea mica-quartzites, otherwise well represented in the Priopcea quartzites, and confirm the previous assertion (i.e. Mirăuță, 1966) about the probable Ordovician age of the Priopcea quartzites and their sedimentary continuity with the Silurian deposits on the Megina Group. In accordance with the new information that the Boclugea mica-quartzites and the Priopcea quartzites represent distinct units, the respective U-Pb detrital ages are re-projected separately (Figs. 13, 16) and commented in the general context of the Măcin unit. In the same discussion (i.e. Balintoni et al., 2010), based on the data from a single metaquartzite sample, the authors proposed a Cadomian provenance for the Orliga Group. Yet, the new data from a paragneiss and three sets of inherited zircons found in migmatized paragneisses, change this image, since the Mesoproterozoic zircon is relatively abundant in these samples. Consequently, all data from the Orliga Group will be revised.

4.4.1 Boclugea Group (sample 347)

The youngest four ages between 890 and 960 Ma from the Boclugea mica-rich quartzite (Fig. 8, 13), coupled with the ca. 600 Ma crystallization ages of the aforementioned granites, suggest a Neoproterozoic age for the Boclugea Group rocks. The age distribution plot (Fig. 13) shows that along with the Mesoproterozoic span, there are several scattered zircon populations including 44 ages or ~45 % of the total, while the Paleoproterozoic zircon populations contain 42 ages, or ~43 % of the total. Within the Archean there are 6 ages. Regarding the age spreading pattern, we can observe the similarity with that found for the East Moesia and Central Dobrogea, except for the absence of the late Neoproterozoic ages.

4.4.2 Megina Group (samples 344, 171GPS))

A minor detrital zircon population of 683 Ma suggests a maximum Cryogenian age for the Megina Group (Fig. 8, 14). However, three Megina orthogneisses yield protolith ages of 506-511 Ma, which attest to its Cambrian age (unpublished data of the authors), which supports the assumption that the Megina Group is younger than the Boclugea Group.

The detrital zircon age distributions are projected in Figs. 14a, b (individual sample projections), and c (cumulative plot of both samples). The two individual histograms are similar and characterized by a great number of Mesoproterozoic ages. Along this time span, there are 125 ages or 69 % of the total, divided in six minor populations. The Paleoproterozoic includes 43 ages or ~24 % of the total, and the Archean is represented by three ages only, or 1.6 % of the total. The great resemblance between the Megina and Boclugea age spreading pattern is easily observable.

4.4.3 Orliga Group (samples 335, 337, 167GPS, 168GPS, 339)

The youngest minor population of 536 Ma from the Orliga Group metaquartzite (Fig. 8, 15) suggests a maximum Cambrian age for the metasedimentary protoliths. Therefore, the Orliga Group also appears to be younger than the Boclugea Group.

The U-Pb detrital zircon ages are projected in Figs. 15 (a - the metaquartzite, b - the unmigmatized paragneiss zircon ages together with the ages from the three migmatized paragneiss samples, and c - cumulative plot of all the ages). The Orliga Group age distribution is close to that of the Histria Formation, especially due to the important number of Archean ages. Significant minor populations are spread out along all the Proterozoic Era divisions, as well as the Neoproterozoic.

4.4.4 The Paleozoic of the Măcin unit

The Priopcea quartzites sampled in four places (samples 336, 338, 340, 345; Fig.8), mark the base of the slightly metamorphosed cover of the Megina Group. Considering the Cambrian age of the Megina Group, we appreciate a maximum Middle Ordovician age for the Priopcea quartzites.

The U-Pb detrital zircon age distributions are projected in Figs. 16a, b, c, d (individual sample projections), and e (cumulative plot of all the ages). The age distribution among the individual samples is similar, while the cumulative plot shows the same distribution as the East Moesia and Central Dobrogea together. We can suppose either that these terranes acted as main zircon suppliers for the Priopcea quartzites, or at least the Priopcea quartzites shared common sources with those terranes. The most important set of ages is located between 500-700 Ma. The Mesoproterozoic ages are also

well represented, there are numerous Paleoproterozoic ages, as well as an important Archean set of ages.

The youngest U-Pb detrital age group zircon grain from the Silurian sandstone of the Cerna Formation (sample 12-512; Fig.8) is centered around 544 Ma. Nevertheless, the youngest grain yields 435 Ma, which is in agreement with the Silurian paleontological age of the Cerna Formation. This age suggests a post Llandovery deposition for the Cerna sandstone. The age distribution shows that the Mesoproterozoic ages are best represented, while there is a single Archean age (Fig. 17a).

The late Paleozoic Carapelit Formation was sampled in two points (samples 12-508 and 12-510; Fig.8). The U-Pb detrital zircon age distributions are shown in Figs. 17 b, c (individual samples projection) and d (cumulative plot together with Cerna Formation). Characteristic to the Carapelit samples is that they reveal proximal Variscan zircon sources around 300 Ma. Another important set of ages is located between 500 and 600 Ma and there are several Meso- and Paleoproterozoic ages. The cumulative histogram for the Cerna and Carapelit samples shows similarities in the distribution of ages with that revealed by the Priopcea quartzites cumulative histogram, except for the Paleozoic post-Cambrian sources, abundant in the Cerna and Carapelit formations.

A cumulative age distribution plot that summarizes all the data from the Macin unit is presented in Fig. 18. The diagram is quite suggestive since it shows the dominance of Variscan ages (0.3 to 0.4 Ga), Pan-African ages (0.5 to 0.7 Ga), and Grenvillian ages (0.9 to 1.3 Ga). Many other ages cluster into important groups along the Mesoproterozoic to the late Archean (1.3 to 2.2 Ga and 2.6 to 2.8 Ga).

4.5 North Dobrogea, the Tulcea unit.

412 *4.5.1 Horia Formation (samples 12-498, 12-499)*

413 The youngest minor population from the sample 12-499 of 387 Ma suggests a
414 maximum late Devonian age for the deposition of the Horia Formation (Fig. 2, 19). The
415 U-Pb detrital zircon age distributions projected in Figs. 19a, b, show the main age
416 concentrations in the 550-650 Ma, 1.95-2.2 Ga and 2.6-2.75 Ga intervals. There are only
417 4 ages in the Mesoproterozoic.

418 *4.5.2 Beştepe Formation (samples 12-500, 12-503)*

419 The four ages around 450 Ma from the samples 12-500 and 12-503 attest a
420 maximum late-Ordovician age for the Beştepe Formation rocks (Fig. 2, 19). The U-Pb
421 detrital zircon age distributions are projected in Figs. 19c, d. The two individual
422 histograms are similar and characterized by a large number of Mesoproterozoic ages.
423 There are 18 ages between 530 and 639 Ma, or ~14 % of the total. Along with the
424 Mesoproterozoic, there are 56 ages scattered (~43 % of the total). The Paleoproterozoic
425 includes 38 ages, or ~29 % of the total, and the Archean is represented by 10 ages or
426 almost 8 % of the total.

427 All data from the Tulcea Unit are projected in Fig. 19e. The most important age
428 set is around 600 Ma. Similar to the Măcin unit (Fig. 18), ages between 1.05-1.2 Ga form
429 an important group. The Mesoproterozoic zircon sources older than 1.2 Ga are
430 significant, and there are also notable age concentrations around 2.0 and 2.7 Ga.

431 Putting together the age distributions for the Euxinic Craton (i.e. East Moesia and
432 Central Dobrogea shield), and North Dobrogea Orogen (Fig. 20a, b) it becomes obvious
433 that these domains share common zircon sources, located around 0.6, 1.2, 1.5, 2.0-2.1 and
434 2.7 Ga.

435

436 **5.Discussion**

437 *5.1 Provenance of Dobrogea terranes.*

438 Our general data plot (Fig. 21a) is presented against the U-Pb detrital zircon data
439 plots (Figs. 21b - f), reported for modern sediments from the mouth of great rivers from
440 several continents (e.g. Condie and Aster, 2010, Rino et al., 2008, Safonova et al., 2010,
441 Iizuka et al., 2013). It allows a comparison between the Neoproterozoic-Paleozoic zircon
442 suppliers of the future crustal components of Dobrogea, and the present-day zircon
443 suppliers accessible to the great rivers in Africa, Baltica, South America, and Laurentia.
444 An inspection on the figure reveals that: (i) the Pan-African sources (650-550 Ma), very
445 well represented in Africa, South America and Dobrogea, are missing in Laurentia and
446 Baltica; (ii) the important zircon sources between 1650 Ma and 1450 Ma from Dobrogea
447 are missing in Africa but present in South America, and (iii) the Transamazonian sources
448 (2.2-2.0 Ga) are also poorly represented in Laurentia, Baltica and Africa. The above
449 observations eliminate Laurentia, Baltica and Africa as possible provenance territories for
450 the Dobrogea's crustal components. Consequently, a peri-Gondwanan provenance with
451 the initial location close to the South America is more likely for all Dobrogean crustal
452 fragments. The important peaks, around ca. 1250-1150 Ma and ca.1650-1450 Ma from
453 Dobrogea coincide with the clusters found in the paragneisses from the Coedana and
454 Malvern complexes, southern Britain, of peri-Amazonian provenance (Strachan et al.,
455 2007). A very interesting feature is that the age patterns recorded by the Dobrogea
456 terranes are more similar with that of the Parana River pattern for the Pan-African time
457 interval, and with that of the Amazon River for the Transamazonian time interval. Some

common features shared by the Dobrogea U-Pb detrital age distribution histogram with the Laurentia U-Pb detrital age distribution histograms in the 1500-1000 Ma interval, can be explained by the position of Laurentia close to the South American cratons in the Rodinia supercontinent (e.g., Rino et al., 2008; Li et al., 2008). Therefore, the Laurentian sediments could have been deposited on the South American cratons and reprocessed later.

5.2 What type of Peri-Amazonian terranes?

According to Nance et al. (2008) the Peri-Amazonian terranes can be classified into (i) Avalonian type terranes, (ii) Ganderian type terranes, and (iii) cratonic type terranes. The Avalonian type terranes developed juvenile crust upon 1.3-1.0 Ga or younger, and then accreted to the Amazonian margin of Gondwana by ca. 665-650 Ma. Conversely, the Ganderian type terranes recycled Avalonian and older crust along the Amazonian margin of Gondwana. The third type of terranes, the cratonic terranes, simply represents the displaced Amazonian portions of the cratonic Gondwana. As the boreholes in South Dobrogea intercept a banded iron formation (BIF) and the Palazu Mare Formation (Kräutner et al., 1988), of 1853 to 1673 Ma age (K-Ar ages on mica and feldspar, Giuscă et al., 1967), the affiliation of South Dobrogea (i.e. East Moesia) to the Avalonian type terranes is not sustainable. Instead, the East Moesia basement shows rock assemblages similar to those of the Amazonian craton. Concomitantly, the rock assemblages in Central Dobrogea (Histria Formation, Alftin Tepe Group) attest an Avalonian-Cadomian orogenic history. Considering the great surface of the **Euxinic Craton** (i.e. more than 150,000 km²), together with its compositionally complex basement that comprise Archean, Paleoproterozoic, Neoproterozoic and early Paleozoic rock

assemblages with Avalonian-Cadomian orogenic imprints in some places, we suggest that it represents an Amazonian cratonic fragment, marginally involved in the Avalonian-Cadomian orogenic events. It is in fact a cratonic-type terrane, with Ganderian and possibly Avalonian components.

Regarding the North Dobrogea terranes, their features suggest a more probable Ganderian provenance. These terranes cannot be directly correlated with the Euxinic Craton due to the bounding of the Peceneaga-Camena transform fault. However, they could have evolved as marginal components of the Euxinic Craton during the late Neoproterozoic-early Paleozoic time. The initial relationship between the Euxinic Craton and Baltica has been totally effaced by the Paleozoic and Alpine orogenic events, including the Variscan and Cimmerian ones. However, the Euxinic Craton and North Dobrogea are situated inboard of the Carpatho-Balkan terranes of NE African provenance, a position that directly explains their peri-Amazonian provenance as previously wandering terranes.

5.3 The Trans European Suture Zone (TESZ).

According to Pharaoh (1999) and Pharaoh et al. (2006) the TESZ is located between two major lines. On one side is the Sorgenfrei-Tornquist Zone with its southeastern prolongation the Teisseyre-Tornquist Zone towards the EEC, and on the other side is the Thor suture continued with other suture lineaments, in its southeastern extension towards West Europe (Fig.1). Eastwards of the Teisseyre-Tornquist Zone the drill-hole data and the geophysical information confirm the EEC basement. Westwards of the Thor suture (formerly described as the Caledonian deformation front, Berthelsen, 1998), and of the other suture lineaments in its southeastern extension, the same type of

information attests the West Europe Basement, at least up to the Carpathians Alpine front. Between the above limits, the TESZ incorporates (e.g. Pharaoh et al., 2006): the Avalonia margin superposed over the thinned EEC margin; possible peri-Gondwanan terranes docked to the EEC during the late Neoproterozoic (i.e. Holy Cross Mountains in Poland); other terranes of unclear provenance in the Romanian Carpathians foreland. In their Fig. 1 the above authors trace the Teisseyre-Tornquist Zone between the Sf. Gheorghe and Peceneaga-Camena faults in a rather unclear context. According to this model, the Scythian Platform represents the thinned EEC margin, but no equivalent of the Thor suture or any suture relation is mentioned. The Thor suture is late Ordovician in age (i.e. the time when Avalonia docked to Baltica), but its southeastern extension, the Krakow-Lubliniec Zone, is mid-Cambrian in age (i.e. the time when Moravo-Silesia docked to the Baltica and the Holy Cross Mountains terranes). In its general lines, the above model persisted over time, as is recently illustrated, for example, by Grinc et al. (2013). Nevertheless, by placing the Teisseyre-Tornquist Zone in the Central Dobrogea, between the Peceneaga-Camena and Capidava-Ovidiu faults (Bocin et al., 2013), the model is changed. Our data undoubtedly allow the peri-Gondwanan provenance of the Central Dobrogea and the North Dobrogean Orogen terranes. Therefore, neither the TESZ nor the Teisseyre-Tornquist Zone can be placed in Central or in North Dobrogea. If indeed, the Scythian Platform represents the margin of the EEC, then a reworked equivalent of the Thor suture is buried along the Peceneaga-Camena fault and the notion of TESZ or Teisseyre-Tornquist Zone loses its meaning in Dobrogea. However, if the Scythian Platform has a peri-Gondwanan provenance in the Pre-Dobrogean depression

basement (Starostenko et al., 2015) then the TESZ or the Teisseyre-Tornquist Zone may be kept in relationship with it.

6. Conclusions.

1. The sampled components of the Euxinic Craton in Dobrogea and the constitutive terranes of the North Dobrogean Orogen have a peri-Gondwanan, peri-Amazonian provenance. Their ages are Neoproterozoic or younger.

2. The Euxinic Craton can be depicted as a paleo-Amazonian crustal fragment, marginally affected by the Avalonian-Cadomian orogenic events. Along with its margin, the Avalonian type terranes accreted or Ganderian type terranes evolved.

3. The primary relationships between the Amazonian derived terranes and Baltica are obscured, since the North Dobrogean Orogen exhibits an intricate geologic history, involving Variscan and Cimmerian orogenic events, and the geologic history of the Scythian Platform is not well established.

4. The general distribution diagram of U-Pb zircon ages shows some common great zircon sources with those detected at a global scale, that is an episodic and coincident distribution along with the time scale. These common zircon sources reflect unique thermo-tectonic events at a global scale as for example those from the end of Archean or the Pan-African ones.

5. Only the Scythian Platform can have a Baltican provenance. However, we favor a peri-Amazonian provenance for its Pre-Dobrogean part. Consequently, the Scythian Platform can be considered a component of the TESZ or Teisseyre-Tornquist

Zone, which makes any discussion about the presence of the TESZ or Teisseyre-Tornquist Zone in Dobrogea, southward of the Sf. Gheorghe fault, outdated.

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817 **Figure captions**

818 Figure 1. Sketch map of the TESZ and adjacent areas. Compiled from Săndulescu (1984),
819 Balintoni (1997), Pharaoh (1999). 1-East European Craton (a-Ukrainean Shield,
820 b-platform cover); 2-Trans European Suture Zone; 3-Euxinic Craton; 4-Cadomia;
821 5-Avalonia; 6-North Dobrogean Orogen-Crimea (a-cropping out, b-covered); 7-
822 Scythian Platform; 8-Carpathian Foreland Basin; 9-Holy Cross Mountains; 10-
823 Alpine Front; 11-Rheic Suture; 12-Variscan Front. Boxed area is detailed in
824 Figure 3.

825 Figure 2 Geological map of Dobrogea area. Compiled according to the Geological Map
826 of Romania 1:200.000 scale, Focsani sheet (Saulea et al, 1967), Braila sheet
827 (Murgeanu, et al., 1967); Tulcea sheet (Ianovici et al., 1967a); Sulina sheet
828 (Ianovici et al., 1967b); Calarasi sheet (Liteanu et al., 1966); Constanta sheet
829 (Chiriac et al., 1968). Marked areas on the map are detailed in Figs. 6, 7 & 8. Four
830 pointed stars and attached numbers represents the sampling location and sample
831 codes.

832 Figure 3. General simplified structure of the Euxinic Craton. CDS-Central Dobrogean
833 Shield. Compiled and modified after Seghedi et al. (2005). See Figure 1 for
834 location on the regional map.

835 Figure 4. a - General geology of the Central Dobrogean Shield and East Moesia in South
836 Dobrogea; b - Structure of Histria Formation. Compiled and modified after Oaie
837 et al. (2005).

838 Figure 5. Cross-section through the southernmost part of Central Dobrogea and northern
839 part of South Dobrogea, showing the overthrust relationship of the East Moesia
840 basement and the Histria Formation. Compiled and modified after Seghedi et al.
841 (2005). See Fig. 4 for cross section location on the general map.

842 Figure 6. Alfin Tepe Group. 1 - Quartz-Micaschist Formation (a-ore-member); 2 -
843 Amphibolite Formation; 3 - Gneiss-Micaschist Formation; 4 - Histria Formation
844 overthrust; 5 - Sample locations. Compiled and modified after Kräutner et al.
845 (1988). See Fig. 2 for location on the general geology map.

846 Figure 7. Cimmerian structure of the North Dobrogean Orogen, as known from surface
847 geology and drill-holes. 1 - Babadag late-Cretaceous cover (post- Peceneaga-
848 Camena fault); 2 - Măcin nappe; 3 - Consul and Niculițel nappes; 4 - Tulcea
849 nappe; 5 - Sf. Gheorghe fault (North Dobrogean Orogen front). Compiled and
850 modified after Săndulescu (1984). See Fig. 2 for location on the general geology
851 map.

852 Figure 8. Geological Map of the North Dobrogean Orogen. Inset shows the Bugeac
853 promontory. Compiled according to the Geological Map of Romania 1:50.000
854 scale (Seghedi et al., 1980; Savu et al., 1988; Mihăilescu et al., 1988), and
855 1:200.000 scale (Ianovici et al., 1967a); and completed with the authors data. See
856 Fig. 2 for location on the general geology map.

857 Figure 9. Detrital zircon U-Pb age distribution for the East Moesia Paleozoic. a) – second
858 order drainage system, b) – second order drainage system. The main source of
859 detrital zircon was the Avalonian-Cadomian Orogen. In the sample 5082 are well

860 represented the pre-Grenvillian Mesoproterozoic sources, characteristic to the
861 peri- Amazonian terranes.

862 Figure10. Detrital zircon U-Pb age distribution for the Histria Formation (third order
863 drainage system), Central Dobrogea Shield. The Avalonian-Cadomian and the
864 Mesoproterozoic Amazonian sources are present, but especially the
865 Paleoproterozoic and the Neoarchean-Mesoarchean sources are important.

866 Figure 11. Detrital zircon U-Pb age distribution for the Altın Tepe Group, Central
867 Dobrogea Shield. a) and c) – third order drainage system; b) – second order
868 drainage system. All three samples reveal that the Avalonian-Cadomian and the
869 Mesoproterozoic Amazonian sources are important. In the samples 12-496 and
870 172GPS dominate the sources around 1.2 Ga.

871 Figure 12. Cumulative detrital zircon U-Pb age distribution for the East Moesia, Histria
872 Formation and the Altın Tepe Group. The general detrital zircon U-Pb age
873 histogram for the Euxinic Craton in its eastern part it is also plotted. Although
874 each component of the Euxinic Craton has its dominant detrital zircon sources, the
875 provenance characteristic sources are the same. These sources are represented by
876 the Avalonian - Cadomian Orogen, the Grenvillian Orogen and the
877 Mesoproterozoic Amazonian complex sources. The most important zircon source
878 for the Euxinic Craton was the Avalonian-Cadomian Orogen, but also the sources
879 around 2.1 Ga as well as the Archean ones are quite significant.

880 Figure13. Detrital zircon U-Pb age distribution for the Boclugea Group (third order
881 drainage system). A characteristic feature of this distribution is the absence of the

882 Avalonian-Cadomian sources. However, the Grenvillian and the Amazonian pre-
883 Grenvillian sources are well represented.

884 Figure 14. Detrital zircon U-Pb age distribution for the Megina Group (second order
885 drainage system). Although present, the Avalonian-Cadomian sources are poorly
886 represented. Alternatively, the Grenvillian and the Amazonian pre-Grenvillian
887 sources are well represented.

888 Figure 15. Detrital zircon U-Pb age distribution for the Orliga Group (third order
889 drainage system). The Avalonian-Cadomian sources are also poorly represented
890 as in the Megina group. Two ages only, from the sample 339, fall along the
891 Mesoproterozoic. However, in the other samples the Mesoproterozoic Amazonian
892 sources are significant.

893 Figure 16. Detrital zircon U-Pb age distribution for the Priopcea quartzites (Măcin unit,
894 Ordovician). a) – third order drainage system; b), c), d) – second order drainage
895 systems. All four samples show similar patterns. The Avalonian-Cadomian
896 sources are well represented, as well as the Grenvillian and the Amazonian pre-
897 Grenvillian ones. A good similarity can be observed between the Euxinic Craton
898 cumulative plot and the Priopcea quartzites plot.

899 Figure 17. Detrital zircon U-Pb age distribution for the post-Ordovician Paleozoic of the
900 Măcin Unit. a) – third order drainage system; b), c) – second order drainage
901 systems. Besides the Avalonian-Cadomian sources, the Carapelit Formation
902 preserves a significant zircon population pointing to Variscan sources.

Figure 18. Cumulative detrital zircon U-Pb age distribution for the Măcin Unit. This diagram is highly similar to the Euxinic Craton age distribution plot, what suggests common zircon sources. In addition to the Avalonian-Cadomian sources, highly significant are the Grenvillian ones (around 1.2 Ga) and the one around 1.5 Ga, typical Amazonian.

Figure 19. Detrital zircon U-Pb age probability density plots for the Tulcea unit, Paleozoic of the North Dobrogean Orogen. a), b) – second order drainage systems; c), d) – third order drainage systems. There are some differences between the Horia Formation samples and the Beştepe Formation samples, the first ones being poor in Mesoproterozoic zircons. However, the cumulative diagram does not significantly differ by the Măcin one.

Figure 20. Cumulative detrital zircon U-Pb age probability density plots for the Euxinic Craton and North Dobrogean Orogen. Their aspect suggests common zircon sources for both domains.

Figure 21. Comparative age distributions between the cumulative detrital zircon U-Pb age probability density plot of all Dobrogea data (a), and data for Africa (b); the EEC (c); Laurentia (e); and Amazonia (d, f). From the EEC and Laurentia, the Avalonian-Cadomian sources are lacking, while from Africa the sources are absent around 1500 Ma. By combining the data for Amazon and Parana rivers, the zircon sources for Dobrogea can be detected. Data from Iizuka et al. 2013 (b); Safonova et al. 2010 (c); Condie and Aster, 2010 and Rino et al. 2008 (d, f); Condie and Aster, 2010 (e).

925 Figure 22. Comparative age distribution between Dobrogea and all continents. Data for
926 continents are compiled from Condie and Aster (2010) and Condie, 2014.
927 Common peaks between the two patterns are: Pan-African, Trans-Amazonian, and
928 late Archaean. The patterns also share gaps around 2.2-2.4 Ga and 0.7-0.9 Ga.
929 The episodic character of crustal production is obvious. The quantitative
930 parameters of zircon sources vary from place to place as a function of many
931 variables, while timing of their deposition is relatively constant.

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