Volcaniclastic turbidites of the Coşuştea Nappe: a record of Late Cretaceous arc volcanism in the South Carpathians (Romania)

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Abstract. Sedimentological and mineralogical composition of Upper Cretaceous terrigenous and volcaniclastic sandstones are presented for the Coşuştea Nappe of the South Carpathians, Romania, in order to constrain the provenance and tectonic setting of deposition. Existing geochemical data on volcaniclastic rocks were interpreted using discrimination diagrams in order to get additional information. The Coşuştea Nappe includes terrigenous turbidites, overlain by upward coarsening sequences of volcaniclastic turbidites, both associated with a strongly dismembered mélangé complex. Facies association and vertical facies distribution suggest that terrigenous successions are midfan turbidites, dominated by deposition in suprafan channels. Their sandstone mineralogy indicates that a major sediment source, located on the upper plate, provided detritus of Getic type metamorphic basement and withinplate volcanic rocks, with minor input from the accretionary wedge. Volcaniclastic sedimentation took place as dominantly sandstone deposition in supracone lobes, followed by coarse sedimentation as channelized debris flows. Vertical facies distribution suggests evolution in time from midfan to proximal fan turbidites. Mineralogical composition of volcaniclastic sandstones indicates provenance from a major volcanic source, with minor contributions from the accretionary wedge and from an upper continental plate supplying terrigenous siliciclastic detritus, and suggests that volcaniclastic turbidites accumulated in a trench or a slope forearc basin. Geochemical data indicate resedimented volcanic arc material, with intermediate to basic composition and calc-alkaline geochemistry. The volcanic source was very likely represented by the Maastrichtian volcanism related to the Banatitic Magmatic and Metallogenetic Belt from the western South Carpathians.


Key words: Alpine nappes, turbidites, forearc basin, accretionary wedge, provenance, Late Cretaceous volcanism.

INTRODUCTION

Cover nappes of the South Carpathians are exposed in the Danubian Window between the Getic-Supragetic and Danubian Nappe systems (Fig. 1). In the Mehedinți Plateau, Cerna Mountains and on the southern rim of the Vulcan Mountains, the cover nappes were separated as Severin, Cerna and Coşuştea nappes (Fig. 2). These nappes, emplaced as underthrust units of an accretionary wedge (Seghedi et al., 1995a; Seghedi, Oaie, 1997), were subsequently deformed during the Late Cretaceous collisional events between the Tiszia and Dacia plates.

The Coşuştea Nappe is made of Upper Cretaceous deposits including terrigenous turbidites, volcaniclastic turbidites and a strongly dismembered mélangé complex. The thick, upward coarsening sequences of Upper Cretaceous volcaniclastic turbidites, located on top of terrigenous turbidites, both associated with a mélangé formation, suggest deposition in a trench or slope forearc basin. Sedimentological features and thickness
differences of the turbiditic sequences from Severin and Coşuştea nappes can be explained by trench evolution in time, from a starved trench during the Berriasian, to a moderately supplied trench during the Barremian and an oversupplied trench in the Turonian–Maastrichtian (Seghedi, Oaie, 1997).

Although separated in 1940 by Codarcea as Coşuştea unit, sedimentological and mineralogical studies were not performed on the main sedimentary successions of the Coşuştea Nappe. In order to understand the source areas and the geotectonic setting of the depositional basin, this paper aims to describe the sedimentology and mineralogy of sandstones and conglomerates from the turbiditic successions of the Coşuştea Nappe, and especially the volcaniclastic deposits, and to use the already published geochemical data to establish sandstone provenance.

GEOLOGICAL AND STRUCTURAL BACKGROUND

The Danubian window exposes the geological structure of central South Carpathians consisting of two systems of basement cored-nappes, the Getic-Supragetic and Danubian, with cover nappes in between, as shown in a simplified tectonic sketch (Fig. 1). Crustal thickening and nappe stacking in the South Carpathians is the result of Early to Mid-Cretaceous collision between the Tiszia and Dacia crustal blocks (Berza et al., 1994; Dallmeyer et al., 1996). Gravitational collapse and exhumation as metamorphic core complex followed in the Late Cretaceous (Schmid et al., 1998), triggering the formation of continental ‘Gosau-type’ collapse basins (Willinghofer, 2000; Willingshofer et al., 2001), e.g. in Rusca Montană and Haţeg basins. Magma emplacement adjacent to these basins was favoured by the extensional regime. Subsequent deformation by steeply dipping, right-lateral strike-slip faults affected the area during the Late Cretaceous and Paleocene (Ratschbacher et al., 1993; Willingshofer et al., 2001).

In the southern part of the Danubian window, exposed in the Mehedinţi Plateau, Cerna and Vulcan Mountains, three cover nappes occur between the main Getic and Danubian nappes, designated as Severin, Coşuştea and Cerna nappes (Fig. 2). The image shown
in Fig. 2 is based on the tectonic maps of Berza et al. (1983, 1986, 1988, 1994), completed with the Cerna Nappe after various maps of Codarcea (1940), Pop (1973), Pop et al. (1975), Stan et al. (1979), Marinescu et al. (1989), and with the Coşuştea Nappe modified after Stănoiu et al. (1988, 1992). The tectonostratigraphy of these Alpine units is shown in Fig. 3.

**The Getic Nappe**, first recognized by Murgoci (1905), is represented in the Mehedinți Plateau by the Bahna and Iron Gates outliers, and by the Vâlari klippen in the southern part of Vulcan Mountains. The outliers consist of metamorphic rocks of the Sebeș-Lotru series (Sebeș Group of Iancu, Mărunțiu, 1994) with polycyclic metamorphic history, showing remnants of eclogite facies rocks, Variscan shearing zones in granulite facies and a complex PT evolution of the amphibolite facies rocks (Iancu, Mărășuț, 1994; Iancu et al., 2005, and references therein). Locally, the metamorphic rocks of the Bahna outlier are overlain by a Mesozoic cover of Upper Jurassic-Lower Cretaceous deposits (Codarcea, 1940), while the Upper Cretaceous is designated as the Gura Văii Sandstone (Stănoiu et al., 1979, 1988).

**The Severin Nappe**, situated between the Getic and Danubian nappes, includes ophiolitic rocks associated to the Sinaia, Azuga and Comarnic Beds (Codarcea, 1940). It was subdivided into several tectonostratigraphic units, their internal stratigraphy varying according to each author. Mărășuț (1987) suggested that ophiolitic rocks, which form a tectonic mélange, represent a gravitational slide (i.e. the Obârșia Nappe), while the Severin Nappe would include only the Sinaia and Comarnic Beds with their associated basaltic rocks. Stănoiu et al. (1988) divided the sedimentary successions into at least three units with local names.

Despite its strongly broken character (Mărășuț, 1987), the Obârșia complex of the Severin Nappe shows important elements of the ophiolitic stratigraphy established by Moores (1982), even if they cannot be observed in their initial succession. The complex shows ultramafic tectonites, non-cumulate massive plutonic rocks (gabbros), pillow lavas and massive basalt flows.

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**Fig. 2.** Tectonic units in the area of southern Vulcan Mountains – Mehedinți Plateau. Modified after Pop et al., 1975; Bercia et al., 1977; Berza, 1978; Berza et al., 1986, 1988; Stan et al., 1979; Stănoiu et al., 1979; Savu et al., 1989; Marinescu et al., 1989; Seghedi et al., 1995a). Red bars represent locations of lithological logs: 1. Valea Socilor; 2. Topicioara cu Apă; 3. right tributary of Gâina Valley; 4. left tributary of Balta Valley.
Fig. 3. Tectonostratigraphy of the Alpine units in Vulcan-Mehedinți area (after Seghedi et al., 1995a).

(Savu, 1985; Mărunțiu, 1987), associated with dominantly siliceous pelagic sediments. Although dykes and ultramafic cumulates are uncertain (Mărunțiu, 1987), elements of layers 4, 2 and 1 of the oceanic crust stratigraphy (Anderson et al., 1982) are recognizable in the Obârșia complex. An additional element to strengthen the presence of oceanic crust derives from geochemical features of basalts, indicating oceanic tholeiites (Cioflica et al., 1981, 1994; Savu, 1985; Savu et al., 1987, 1989, 1992; Mărunțiu, 1987).

The Coșuştea Nappe, defined in the Mehedinti Plateau (Stănoiu et al., 1988; Stănoiu, 1997, 1999, 2000) includes Lower Jurassic terrigenous deposits, mid Jurassic–Lower Cretaceous carbonate successions and deposits largely belonging to an Upper Cretaceous olistostrome. According to Stănoiu et al. (1992), the stratigraphy of the Coșuştea Nappe is different in the Mehedinti Plateau from that in the southern Vulcan Mountains.

Seghedi et al. (1995a, b) ascribed to the Coșuştea Nappe both the Upper Cretaceous deposits previously considered as Danubian cover (Pop, 1973; Pop et al., 1975, 1997; Berza et al., 1986, 1988, 1994) and a large part of the deposits ascribed to this unit by Stănoiu et al. (1988, 1992). However, they excluded from the Coșuştea Nappe the Lower Jurassic ‘Gresten facies’ deposits and the Tithonian to Hauterivian carbonate platform limestones from the Mehedinti Plateau, which represent the Alpine Danubian cover of the Lainici Nappe.

The Cerna Nappe was defined by Codarcea (1940) in both the Mehedinti Plateau and Cerna Mountains as a thin-skinned thrust formed subsequently to the emplacement of the Arjana Nappe. The Cerna Nappe extends eastward on the southern rim of Vulcan Mountains (Pop, 1973; Pop, in Stan et al., 1979; Pop, in Marinescu et al., 1989) and includes Tithonian to Hauterivian limestones overlain by Upper Cretaceous turbidites. In both the Cerna Mountains and southern Vulcan Mountains, the Jurassic–Lower Cretaceous limestones of the Cerna Nappe overlie Upper Cretaceous deposits and only locally they directly overlie the Tithonian–Lower Cretaceous limestones of the Lainici Nappe.

The Lainici Nappe (Berza et al., 1988) is a basement-cored Lower Danubian nappe, involving two distinct pre-Alpine units sharing the same Mesozoic cover. The amphibolite facies metamorphic basement involves metabasic and quartzite-carbonate rocks. The Mesozoic cover consists of terrigenous Lower Jurassic deposits, Upper Jurassic–Lower Cretaceous carbonate rocks and Upper Cretaceous clastics (Berza et al., 1983, 1986, 1988).
The Schela Nappe (Berza et al., 1986, 1988) represents the lowermost structural unit within the Lower Danubian Nappes. Its stratigraphy includes an Upper Precambrian basement (consisting of Lainici-Păuș metamorphic rocks and granitoids) and a Lower Jurassic cover (i.e. the ‘Gresten facies’ Schela Formation) showing a very low-grade to low-grade metamorphism, with neoformations of chloritoid and pyrophyllite.

METHODOLOGY

Samples were collected along four sections shown in Fig. 2. Sedimentological studies were performed on six lithological sections with continuous exposure along these sections. A total of 190 samples were collected, 65 from terrigenous turbidites and sandstones within the mélangé complex, and 125 from the green volcanioclastic sandstones. Thin sections were studied using a petrographic microscope. Previously published geochemical data (Savu et al., 1987) and few unpublished data of Russo-Sândulescu, in Stânoiu et al., 1988 (25 in total) were used to calculate discriminant functions and to draw provenance diagrams for the volcanioclastic sandstones, considering that in matrix-rich rocks, microscopic methods can be enhanced by minor and trace element geochemistry, as only stable minerals are preserved during weathering and diagenesis.

THE COŞUŞTEA NAPPE

The Coşuştea Nappe consists of Upper Cretaceous deposits including the following three lithostratigraphic units: 1) grey calcareous sandstones (brown in weathered surface), siltstones and mudstones, representing terrigenous turbidites ascribed to the Upper Senonian (Middle Campanian–Maastrichtian) based on foraminiferal associations (Stânoiu et al., 1988); 2) green conglomerates, microconglomerates and sandstones, representing volcanioclastic turbidites; and 3) a strongly dismembered mélangé complex (also referred to as olistostrome or wildflysch). The areal development of this nappe is shown in Fig. 2. This image corresponds only partly to the Coşuştea unit as separated by Stânoiu et al., 1988, 1992), and includes exclusively Upper Cretaceous formations. From the lithological column of the Coşuştea Nappe in the Mehedinți Plateau (in the model of Stânoiu et al., 1988) we exclude the Lower Jurassic and Tithonian–Lower Cretaceous deposits, considering that these continental and shallow marine formations cannot represent the basement of trench turbidites, as we interpret the overlying Upper Cretaceous formations.

In the Mehedinți Plateau, Stânoiu et al. (1988) considered the Coşuştea Nappe as including the Dejderiu Sandstone (Codarcea, 1940) and the Balta Formation (olistostrome), ascribed to the Upper Senonian (Middle Campanian–Maastrichtian) based on foraminiferal assemblages.

In the Southern Vulcan Mountains, the Coşuştea Nappe includes the Cernișoara Formation (Pop, 1988), interpreted as a wildflysch facies (Pop, 1966) and ascribed to the Upper Turonian–Senonian, based on the assumed discordant position on top of the Cenomanian–Middle Turonian shales (Nadanova Formation) and on the presence of inoceramids. In the interpretation of Stânoiu et al. (1992), the Upper Cretaceous succession in the southern Vulcan Mountains includes both the Balta and Dejderiu formations of the Coşuştea Nappe, and the Mehedinți Formation (an olistostrome located at the top of the Cerna Nappe cover).

Geometric relations always indicate that the green sandstones lie on top of the grey sandstone successions, forming prograding, upward coarsening and thickening successions. In the southern Vulcan Mountains (on Topicioara cu Apă, Valea Bătrâna, and Valea Socilor), the green sandstones overlie a succession of grey sandstones with facial characteristics of mid-fan turbidites, dominated by overbank deposits (Fig. 4). The springs area of Gaîna Valley in the Mehedinți Plateau exposes green sandstones building such a sequence overlying about 100 m thick distal cone turbidites with rare decimeter interbeds consisting of grey sandstones (Fig. 5a).

Terrigenous turbidites

Separated in the Mehedinți Plateau as Dejderiu Sandstone (Codarcea, 1940), grey sandstone dominated successions are found within the Cernișoara Formation on Valea Bătrâna, Topicioara cu Apă, and the right tributaries of the Bulba Valley. On small areas, they also occur on the right tributary of Motrușor Valley and sometimes in the main river banks. These rocks are also found eastward, in the Parâng Mountains (i.e. the Cernăda flysch of Berza et al., 1988). On Topicioara cu Apă, the grey sandstones are better exposed and although there is no continuous outcrop area, their relationships with the volcanioclastic sandstones can be clearly seen.

The grey terrigenous sandstones show the same mineralogical composition as the Lower Cretaceous sandstones in the Sinaia Beds of the Severin Nappe (Seghedi et al., 1995a).

In Topicioara cu Apă, the grey sandstones occur as metric sequences of the upward fining B2-D facies type, characteristic of the Sinaia Beds in the Coşuştea Valley. Typical sedimentary structures are convolute laminations and flame structures in the base of the
Fig. 4. Lithological logs in the turbidites of the Coșuştea Nappe from the south Vulcan Mountains.
massive sandstone facies, suggesting a sedimentary basin with active tectonics and seismicity. Such conditions are typical for trench basins. Cross- and parallel lamination of heavy minerals placers suggest the possibility that the lithofacies Tc and Td represent contourites. The facies association represents mid-fan turbidites, accumulated in supraconce channels.

The mineralogy of the terrigenous sandstones is dominated by quartz, plagioclase, K-feldspar, with rare lithoclasts of trachyte, chert and muscovite quartzite; frequent laminations with heavy minerals occur consisting of opaque minerals, such as tourmaline, garnet, and leucoxene. The mineralogical composition suggests a terrigenous continental source that yielded clasts of muscovite-rich metamorphic rocks and withplate type magmatic rocks along with accretionary wedge type source. Such sources usually feed trench or forearc type basins (Dickinson, 1970). Locally, in the Mehedinți Plateau, the grey sandstones overlay red-purple clasts similar to the Azuga Beds. Along with the sedimentological and mineralogical features, this genetic relationship suggests that the grey sandstones represent trench turbidites, accumulated on the external trench wall, on top of pelagic siliceous sediments typical of a subducting oceanic plate.

**Volcaniclastic turbidites**

First noticed in Romania by Manolescu (1937) and Codarcea (1940) on the southern slope of the Vulcan Mountains, then by Kalenić, Dordević (1969) in the Miroć Plateau of Eastern Serbia, this unusual magmatic record is still not well understood in its genesis, significance and provenance.

The green volcaniclastic rocks from the Southern rim of Central South Carpathians have been described under various names and even associated with the basalts from north of Curpenu, which actually represent a small outlier of Obârja Nappe. These rocks were described by Pop (1966) as ophiolitic rocks including basalts, serpentinites, basic rocks similar to basalts, diabase tuffites variably contaminated with terrigenous material, and green tuffitic sandstones. The green volcaniclastic rocks are figured on the 1:50 000 scale map of Romania in the area of Sohodol Valley – Topicioara cu Apă (north of Bâlta and Runcu localities) as veins and dykes within the Upper Cretaceous flysch formation and some are described as volcaniclastics and basaltic rocks (Pop, in Marinescu et al., 1989). Pop (1973) presented a map of the distribution of ophiolitic rocks in the entire area of Cernișoara Formation. Stănoiu et al. (1992) figured these rocks as thin layers of epiclastic deposits in the Dejderiu sandstone and Balta olistostrome from the southern Vulcan Mountains.

In the Balta olistostrome from Mehedinți Plateau, the green sandstones are figured as lens-shaped bodies and described as volcano-sedimentary facies with gabbro-diorites (belugites and belugite-porphyrites) on the Criva Valley tributaries, and as dykes of pyroxene and amphibole anidesites on Balta Valley (Mercus, in Stănoiu et al., 1979). On the lithological map in scale 1:25 000 Balta sheet, the green sandstones are figured as lens-shaped successions of psammitic epiclastic rocks, very rich in magmatic rock fragments, suggesting the possibility that they represent olistoliths of olistostate type (Stănoiu et al., 1988). Those authors did not preclude that they might belong to the Balta Formation. Emphasizing the false intrusive aspect of the rocks, Savu et al. (1987) described the green rocks as crystalloclastic, seldom vitroclastic tuffs, with rare fragments of rocks, such as basalts and basaltic andesites, while northward, in the Bâlta and Curpenu areas, the green rocks are associated with tuffites and sandstones with tuffogenous material.

The green sandstones represent successions of variable thicknesses. Maximum thickness of 300 m was observed in the Balta area of the Mehedinți Plateau. North of Vâlari, the green sandstones show only 150 m thickness in outcrop. Both in the southern Vulcan Mountains and Mehedinți Plateau areas, the green sandstones always lie on top of the grey terrigenous sandstones, with no visible discontinuity (Figs. 4, 5a).

**The mélange complex**

The mélange complex can be described as a dismembered or broken formation, as defined by Hsü (1974). It represents a unit with internal fragmentation but lacking exotic blocks, within which the reconstitution of the stratigraphic succession and bed continuity is no longer possible. On the largest part of the outcrop area, it contains lenses, blocks and fragments of brown sandstones which locally preserve ripple-cross laminations, graded bedding, parallel laminations, and even Tcde Bouma divisions.

The coarse sandstones are composed of various lithoclasts, including corpuscular and peletal micritic limestone, fine-grained calcareous sandstone and siltstone, radiolarian chert (with radiolarians replaced by fibrous chaledony), trachyte, quartz-muscovite schist with mylonitic fabric, and quartzitic sandstone. The sandstones also contain clasts of quartz, rutile, detrital muscovite and biotite (discoloured or partly replaced by chlorite). The fine-grained sandstones and siltstones consist of clasts of quartz, feldspar, muscovite and biotite, sometimes with calcite monocrystals suggesting replacement of foraminiferal bioclasts or other types of microfauna. The petrographic and mineralogical composition of sandstone clasts and lenses within the mélange-type matrix also suggests input from accretionary wedge (of Sinaia and Azuga-type formations), as well as terrigenous siliciclastic input from the metamorphic rocks of the upper plate.

In the Coșuțtea Valley, downstream of Isverna, and in Brebina Valley, downstream of Obârja Cloșani,

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Fig. 5. Lithological logs in the turbidites of the Coșuştea Nappe from the Mehedinți Plateau. Note the upward coarsening sequence in the Valea Găina section and the coarse conglomeratic facies rich in limeclasts in log c. Same legend as in Fig. 4.
in the sheared pelitic matrix rare decimetric layers occur consisting of very coarse white calcirudites made of angular and subangular limestone clasts. The lens-shaped geometry of this facies and the absence of internal structure suggest deposition from mass-flows of debris-flow type; its association with pelitic sediments indicates proximal turbidite fan deposits, where calcirudites represent the submarine canyon facies and the pelitic rocks represent pelagic sediments specific to the depositional basin. The clast petrography of calcirudites is dominated by pelagic Calpionella limestones, corpuscular limestones with microfaunal debris and pelletal limestones with usually recrystallized bioclasts. The subordinate siliciclastic material consists of quartz, strongly albitized and calcitized K-feldspar and lithoclasts of quartz-muscovite-carbonate schists (suggesting greenschist facies mylonites). This facies was derived from the erosion of a carbonate platform, with minor input of terrigenous siliciclastic material from the upper plate. The absence of arc volcanic material suggests that reeal limestones might have formed on the crest of the accretionary wedge, either emerged, or located very close to the surface.

In several localities (e.g. in Brebina Valley between Mărășești and Bratilovu, and in Cerna Valley at Bâile Herculane), the mélangé complex contains decimetric to metric (or even larger) blocks of strongly brecciated basalts, sometimes associated with pink limestones. The angular basalt clasts are completely unsorted and show a recrystallized cement of calcite. They have been previously considered olistoliths of basalts from the Severin Nappe (Stănoiu, in Pop et al., 1975). However, the mineralogical and petrographic features of basalts show strong similarities with alkali basalts: presence of lithophyses, abundance of chloritized glass, cavities filled with secondary calcite, and presence of alkali feldspar in the recrystallized ground mass. In several localities (e.g. in Pârâu Socilor and Brebina Valley), in the sheared matrix of the mélangé complex greenish layers occur, which in thin sections were identified as slightly mylonitic trachytes.

The presence of alkali basalts and trachytes within the mélangé complex and in the composition of the brown sandstones suggests that they originated from a common source area. Such rocks represent the products of whinplate magmatism and occur both in the Arjana Nappe and in the cover of the Getaic Nappe in the Eastern Carpathian bend zone (Russo-Sândulescu, in Conovici et al., 1988, and in Kräutner et al., 1990).

GREEN VOLCANICLASTIC SANDSTONES OF THE COȘUȘTEA NAPPE

Sedimentology

The main sedimentological features of the green sandstones are shown in Table 1. The lithofacies have been determined according to bed internal structure and grain-size, using the classes and facies codes proposed by Pickering et al. (1989).

**Facies and facies associations**

In the southern Vulcan Mountains, green sandstones dominate as beds with thicknesses varying between decimetric to 1-2 m. Beds frequently show an irregular, erosive base; rocks are normally graded (from medium- or fine-grained sandstones to very coarse sandstones, locally microconglomerates, to medium- and fine-grained sandstones with parallel laminations at top). Beds with coarser bases often contain centimetric-subcentimetric intraclasts of mudstone or laminated black siltstone, as well as rare clasts of carbonate rocks, brownish in weathering surface. Since usually these carbonate clasts are partly or entirely leached, the rocks show typical cavernous appearance. The colour of sandstones varies from dark green in the coarse-grained and very coarse-grained facies to light green to olive in the fine-grained, horizontally laminated sandstones. On the dark green background of the coarse basal layers, sub-centimetric lithoclasts of feldspathic eruptive rocks occur, usually andesites.

The sandstone beds are separated by fine intervals consisting of Tcde or Tde Bouma divisions. They form centimetric rhythms, superimposed in decimetric, seldom metric sequences (Figs. 4, 5). Convolute laminations and flame structures frequently occur at the base of coarse sandstone beds.

**Vertical facies distribution**

In the Mehedinți Plateau, south of Balta, two types of upward coarsening successions were recorded.

On tributaries at the springs of Găina Valley, east of the road to Balta, distal terrigenous turbidites showing grey sandstone interbeds are overlain by a 200–250 m thick succession dominated by green sandstones (column a in Fig. 5). The green sandstones occur as beds 2–4 m thick, massive or graded and almost always showing parallel laminations at the top. The base of sandstone beds is coarser, made of coarse sandstones or microconglomerates, often with dark green-blackish clasts of chloritized glass. In the main valley, the sandstone beds are separated by decimetric or metric banks of distal turbidites (interchannel deposits), to become amalgamated toward the top of the sequence. Northward, the succession grades up to massive sandstone, or graded-bedded sandstone with laminated top (column b in Fig. 5), well exposed on the tributary of the Găina Valley.

On a left tributary of Balta Valley, an upward coarsening sequence is exposed on several tens of meters. The succession shows the transition from amalgamated massive sandstones with parallel laminated tops to coarse strata of conglomerates, showing a clast-supported to matrix-supported texture.
Table 1.
Sedimentological features of the volcaniclastic sandstones of the Coșuştea Nappe; Facies codes after Pickering et al. (1989)

<table>
<thead>
<tr>
<th>Facies class</th>
<th>Facies code</th>
<th>Description</th>
<th>Transport</th>
<th>Depositional mechanism</th>
<th>Facies associations</th>
</tr>
</thead>
<tbody>
<tr>
<td>A conglomerate, sandstone with large clasts</td>
<td>A11 – clast supported conglomerate</td>
<td>conglomerate with no internal structure; metric beds; erosional, irregular base; sharp or graded top; weak sorting; angular to subangular, seldom rounded clasts;</td>
<td>debris-flow</td>
<td>mass deposition due to slope decrease and intergranular friction</td>
<td>A11&gt;A14&gt;B11&gt;C23 A11&gt;B11&gt;A14&gt;B11</td>
</tr>
<tr>
<td></td>
<td>A14 – matrix-supported conglomerate</td>
<td>pebbly sandstones; no internal structure; 1-3.50 m thick beds; sharp base, flat top; unsorted to moderately sorted; angular to subrounded clasts; sandstone matrix, medium to coarse</td>
<td>high concentration flow</td>
<td>rapid deposition of clasts-matrix mixture; intergranular friction increases due to decelerating flow</td>
<td>B21&gt;B11&gt;A14 A11&gt;A14&gt;B11&gt;C23</td>
</tr>
<tr>
<td></td>
<td>A27 – graded sandstone</td>
<td>pebbly sandstones, graded bedding; 1-4 m thick beds; sharp base and top; intraclasts or rare limestone clasts concentrated at base; graded bedding</td>
<td>high concentration flow; grains are partly tarate on the bottom or transported in suspension</td>
<td>grain to grain deposition with rapid burial</td>
<td>A27&gt;B21&gt;C23&gt;A27&gt;B21</td>
</tr>
<tr>
<td>B sandstone (no Bouma sequence)</td>
<td>B11 – massive sandstone</td>
<td>massive sandstone; bed thickness 0.5-7 m; sometimes with levels of intraclasts or limestone clasts in the lower part; massive appearance</td>
<td>high concentration flow</td>
<td>rapid “grain by grain” deposition, favoured by intergranular friction</td>
<td>B21&gt;B11&gt;A14 B11&gt;B21&gt;D23</td>
</tr>
<tr>
<td></td>
<td>B21 – planar laminated sandstone</td>
<td>planar laminated sandstone; bed thickness 0.1-2 m; sharp base and top; seldom ripple laminations at top; normal or reverse grading</td>
<td>high concentration flow</td>
<td>cessation of flow at the base; intergranular friction produces imbrication and grading</td>
<td>B21&gt;B11&gt;A14 B11&gt;B21&gt;D23</td>
</tr>
<tr>
<td>C2 alternating fine grained sandstone/siltstone/mudstone (with Bouma sequence)</td>
<td>C23 – fine grained sandstone/siltstone/mudstone</td>
<td>horizontal and cross laminated fine-grained sandstone/siltstone/mudstone; bed thickness 0.4-3.5 m; disposed in 3-10 cm thick Tcde, Tcd, Tce Bouma sequences</td>
<td>diluted turbidity currents or contour currents</td>
<td>deposition from suspension (“grain by grain” for Td and Te) and by bottom traction (for Tc)</td>
<td>A27&gt;C23 B11&gt;C23 A11&gt;A14&gt;B11&gt;C23</td>
</tr>
<tr>
<td>D alternating siltstone/mudstone</td>
<td>D23 – laminated siltstone and mudstone</td>
<td>siltstones and mudstones as graded/laminated units, with continuity along strike; sharp and flat base and top; 0.70-1.80 m thickness</td>
<td>suspensions</td>
<td>deposition from diluted turbiditic or hemipelagic suspensions</td>
<td>B11&gt;B21&gt;D23 A27&gt;D23</td>
</tr>
<tr>
<td>F deformed beds</td>
<td>F21 – deformed sandstone, siltstone</td>
<td>Convolute laminated sandstone and siltstone; bed thickness 30-80 cm; flat and smooth sliding surface; internal bedding of convolute-type</td>
<td>Intraformational sliding</td>
<td>-</td>
<td>B11&gt;F2</td>
</tr>
</tbody>
</table>
Individual conglomerate beds are 4-6 m thick, while clasts are represented by pebble- to boulder-sized white limestone. Clast-supported beds consist of coarse-grained to very coarse-grained sandstones with a pellicular matrix. 

Analysis of facies associations revealed both aggrading and prograding stacking patterns of the III-rd order (Shanmugam, 1980), 3-10 m thick, controlled by the dynamics of the sedimentary processes specific to the depositional basin.

The thinning and fining upward sequences (column c in Fig. 5) consisting of facies types A1.1 – A1.4 – B1.1 – C2.3 reflect processes of gradual abandonment of channels, while upward coarsening and thickening sequences (B2.1 – B1.1 – A1.4 type) in the same location define reactivation of erosional processes.

The sandstone dominated sequences (B1.1 – B2.1) associate with finer-grained facies (D2.3) form B1.1 – B2.1 – D2.3 type sequences (Fig. 4, Socilor and Topicioara cu Apa valleys). These reflect the processes forming depositional lobes within complex systems of turbidite fans.

Sedimentological features and vertical facies association suggest that in the Mehedinti Plateau the volcaniclastic sedimentation evolved in time from arenite-dominated in suprafan lobes to rudite-dominated, as channel-deposited debris flows, the vertical succession indicating transition from median to proximal cone.

Sandstone mineralogy

Previous mineralogical descriptions of the volcaniclastic successions are given by Savu et al. (1987) and Russo-Sândulescu (in Stănoiu et al., 1988), who were the first to prove that the formerly considered lava layers or dykes in the Mehedinti Plateau (Balta area) and in the southern Vulcan Mountains (Runcu-Balta area) represent in fact tuffs or volcanic agglomerates.

Our study based on 125 representative samples shows, as expected, that the mineralogical constitution varies significantly from the coarse members (coarse, very coarse sandstones and microconglomerates) to the medium- and fine-grained, parallel laminated sandstones.

Coarse-grained to microconglomeratic sandstones are clast-supported rocks with local carbonate cement and a pellicular matrix strongly recrystallized into oriented phyllosilicates. Green sandstones are compositionally immature rocks consisting dominantly of unstable volcanic material, such as plagioclase feldspar, usually euhedral and zoned; clinopyroxene, brown hornblende, and biotite. Magmatic rock fragments are frequent, representing mainly porphyritic andesites with microcrystalline groundmass and plagioclase, hornblende and pyroxene phenocrysts. Geochemical data (Savu et al., 1987) indicate that such lithoclasts are andesites and basaltic andesites. Clasts of acid volcanic rocks are rare.

Resedimented carbonate material includes micritic limestones, often rich in microfauna. The influx of carbonate material is more reduced in the southern Vulcan Mountains, but is locally very abundant in the proximal turbidites from Balta region (Mehedinti Plateau). Radiolarian cherts occur in small amounts. Terrigenous detritus, consisting of quartz, muscovite, biotite and garnet is less common. Rare grains of glauconite were observed in Balta region.

The mineralogical composition suggests that the proper term for these rocks is epiclastite, as used by Russo-Sândulescu (in Stănoiu et al., 1988), meaning volcaniclastic debris resulted from erosion and redeposition of volcanic or volcaniclastic rocks in terrigenous material (Cas, Wright, 1988). Considering the small amount of terrigenous material (below 5%), the green sandstones are better defined as volcaniclastic turbidites with both sedimentologic and provenance significance.

The more distal, parallel laminated fine-grained sandstones show a different mineralogy. Such rocks, rich in detrital micas (both muscovite and biotite) and quartz, contain sporadic feldspar, tourmaline and garnet. They also contain various amounts of radiolarians, carbonate replaced microfossils and rare spicules replaced by fibrous chaledony. Clasts are set in a clayey matrix, recrystallized into colourless phyllosilicates and cement recrystallized into sparry calcite.

Volcaniclastic sandstones show mineral assemblages of low-temperature Alpine metamorphism (Seghedi et al., 1995b). The newly formed mineralogical assemblage indicates low temperature (200-250°C) and low pressure (2-3 kb) conditions for the Alpine metamorphism of the Coșştnea Nappe, in the prehnite-pumpellylite zone of sub-greenschist facies conditions (Seghedi et al., 1995b; Ciulavu, Seghedi, 1997). This type of metamorphism preserves the initial rock fabric, replacing in various degrees the primary minerals of sandstones (Fig. 6).

GEOCHEMISTRY

The geochemistry of the volcaniclastic sandstones is known from a total of 25 analyses of samples from both study areas: 22 analyses published by Savu et al. (1987) (13 from Bâlta area in the Vulcan Mountains, and 9 from Balta region in the Mehedinti Plateau) (Tables 2 and 3), and 3 unpublished analyses from the Balta region (Russo-Sândulescu, in Stănoiu et al., 1988).

Analysing chemical composition and using various diagrams for magmatic rocks, Savu et al. (1987) concluded that rocks show basalt and basaltic andesite composition; they represent a medium K type calc–alkaline series, as indicated by their contents of rare
Fig. 6. Mineralogy of the Upper Cretaceous volcaniclastic sandstones of the Coșuştea Nappe. a) microphotograph showing magmatic clinopyroxene completely replaced by pumpellyite aggregates, Balta Valley; b) fractured magmatic clinopyroxene replaced by pumpellyite; c) plagioclase with calcic core replaced by compact aggregates of microcrystalline pumpellyite (Pmp) showing intense green color; d) plagioclase (Pl) and a lithoclast in coarse volcaniclastic sandstone, showing a microcrystalline aggregate of pumpellyite (Pmp) completely replacing a clinopyroxene (Cp) clast and partly the groundmass. All photographs are taken in plane polarized light, ×90; width of images is 1 mm.
Table 2
Major element concentration (wt. %) of the Upper Cretaceous volcaniclastic sandstones of the Coșuştea Nappe (after Savu et al., 1987)

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<thead>
<tr>
<th>Sample</th>
<th>SiO₂</th>
<th>Al₂O₃</th>
<th>Fe₂O₃</th>
<th>FeO</th>
<th>MnO</th>
<th>MgO</th>
<th>CaO</th>
<th>K₂O</th>
<th>Na₂O</th>
<th>TiO₂</th>
<th>P₂O₅</th>
<th>CO₂</th>
<th>S</th>
<th>H₂O</th>
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<td>4.12</td>
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<td>0.88</td>
<td>0.36</td>
<td>4.96</td>
<td>0.21</td>
<td>2.90</td>
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<td>4.71</td>
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<td>4.45</td>
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<td>2.02</td>
<td>3.00</td>
<td>0.64</td>
<td>0.44</td>
<td>2.08</td>
<td>0.33</td>
<td>2.33</td>
<td>100.11</td>
</tr>
<tr>
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<td>7.16</td>
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<td>4.67</td>
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<td>99.48</td>
</tr>
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<td>2.97</td>
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<td>0.40</td>
<td>3.20</td>
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b - basalt; ab - basaltic andesite. Grey shade - samples from South Vulcan Mountains; not shaded - samples from Mehedinți Plateau.
Table 3.

*Trace element and rare earth element concentrations (ppm) for sandstones of Coșuțea Nappe (after Savu et al., 1987)*

<table>
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<th>Sample</th>
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<th>Cr</th>
<th>V</th>
<th>Sc</th>
<th>Y</th>
<th>Nb</th>
<th>Zr</th>
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<th>Sr</th>
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elements normalized to chondrites, suggesting provenance from a depleted upper mantle. In the tectonic discrimination diagrams (Li/Y – Ti/Y and Ti-Zr) of Savu et al. (1987), rocks plot relatively grouped in the fields of island arc basalts and andesites, therefore the authors considered them the products of island arc volcanism, resulted during a proposed subduction of the Moesian Plate beneath the Transylvanian Plate.

Based on her own data and on analyses published by Savu et al. (1987), Russo-Săndulescu (in Stănoiu et al., 1988) emphasized the compositional variation from quartz-bearing hawaiites to quartz-bearing alkaline trachytes due to the presence of terrigenous material, concluding that chemical analyses are not relevant for such rocks, which could be attributed to a calc-alkaline, alkaline and even ocean floor magmatism.

**Discrimination diagrams**

As volcaniclastic sandstones are resedimented deposits, we tried to use the chemical analyses from Savu et al. (1987) and Stănoiu et al. (1988) in discrimination diagrams for clastic sediments, which seem more adequate considering the sedimentological and petrographic features of the volcaniclastic sandstones.

Discrimination diagrams for sedimentary rocks are based on the assumption that there is a strong connection between the geotectonic setting and provenance. The best results were yielded from immature rocks rich in lithic clasts (Rollinson, 1993). A great source of uncertainty derives from the fact that some sediments were transported from their initial setting and re-deposited in a basin from a different tectonic environment (McLennan et al., 1990).

Diagrams use major elements, trace elements and the REE to infer the provenance of sandstones. For their relatively low mobility during sedimentary processes and short residence times in seawater, several trace and REE are considered more useful in discriminating source rock compositions and tectonic setting, as they are probably transferred quantitatively into clastic sediments during weathering and transportation, reflecting the signature of the parent materials (Bhatia, Crook, 1986; McLennan, 2001).

For geochemical separation of sedimentary rocks having as primary source either a mafic, intermediate or felsic magmatic source, or a quartzose sedimentary source, diagrams of the discriminant function based on Ti, Al, Fe, Mg, Ca, Na and K oxides were constructed (Roser, Korsch, 1988). These diagrams were designed to discriminate among four sedimentary provenances: mafic source – ocean island arc; intermediate source – mature island arc; felsic source – active continental margin; recycled source – granitic-gneissic or sedimentary source. The problem of biogenic CaCO₃ and silica is eliminated, as the diagram uses projections where the discriminant function is based on the distribution of TiO₂, Fe₂O₃ (tot), MgO, Na₂O and K₂O to Al₂O₃. On the discriminant diagram in Fig. 7a, the analyses plot in about similar proportions in the island arc fields, 11 analyses indicating an intermediate magmatic source and 13 – a mafic magmatic source.

Calculating the discriminant function based on the ratios of major elements (Fig. 7b), 18 analyses plotted in the field indicating magmatic mafic origin, whereas only 7 show intermediate magmatic origin. This diagram is less efficient for discrimination than the former (Rollinson, 1993).

![Discriminant diagrams using major elements. Provenance fields are after Roser, Korsch (1988).](image)
Major element contents of green sandstones were used to calculate discriminant functions for binary diagrams according to Bhatia (1983), with four fields corresponding to distinct sedimentary basins separated by Bhatia, Crook (1986). As seen in Fig. 8, most samples (19) plot within the ocean island arc, and 4 samples are scattered outside the fields. This suggests the possibility that green sandstones accumulated in a forearc or back-arc basin located in the vicinity of a volcanic arc developed on oceanic, or thinned continental crust. In the diagram in Fig. 8b, based on TiO₂ versus Fe₂O₃+MgO, most of analyses again plot in the ocean island and continental arc fields, while 6 are scattered.

The ternary diagram discriminating the tectonic setting by using trace elements La-Th-Sc shows that all samples but one fall in the oceanic arc field (Fig. 9a). In the Th-Sc – Zr/10 diagram (Fig. 9b), more samples fall outside the ocean island field.

**DISCUSSION**

The mineralogical composition of volcaniclastic sandstones indicates provenance of resedimented material from a major volcanic source, with minor input from the accretionary wedge (micritic limestones, radiolarian cherts, and scattered radiolarian tests) and from an upper plate continental source (which produced mica-rich metamorphic rock fragments). Debris derived from such sources can be deposited either in trenches, or in forearc basins (Dickinson, 1970, 1974).

Dominantly coarse volcaniclastic turbidites, lacking fine-grained facies, can be deposited in several settings, either as trench fans, on the internal part of the forearc, or on the external wall of the accretionary wedge (Dickinson, Szczerbinka, 1979, Dickinson et al., 1983). Facies analysis indicates that volcaniclastic sandstones formed as channel-levée-overbank and sheet systems. Such systems are characteristic for trench fans fed by large submarine canyons, respectively by un-channelized turbidity currents (Pickering et al., 1989). Debris flows in submarine canyons, as well as un-channelized turbidity currents, may attain enough speed to cross the forearc and transport sediments directly into the trench (Underwood, 1986).

Both in the Mehedinți Plateau and in southern Vulcan Mountains, the succession of the Upper Cretaceous deposits is of upward coarsening type, thus corresponding to the stratigraphy of underthrust units of an accretionary wedge formed in an oversupplied trench. In such trenches, detachment planes propagate within the turbiditic trench fill (Thornburg, Kulm, 1987), and the entire succession of an underthrust unit has the same age due to high sedimentation rate (Einsele, 1992).

Geochemical data indicate magmatic intermediate and mafic source for volcaniclastic sandstones. This conclusion is consistent with petrographic observations and the calc-alkaline geochemistry of some “medium K” andesites, as resulted from the diagrams for magmatic rocks (Savu et al., 1987). Tectonic

![Fig. 8. Discriminant diagrams for sandstone provenance (after Bhatia, 1983).](image-url)
discrimination diagrams indicate an oceanic island arc, or a continental arc provenance. We can use these to strengthen the conclusions derived from mineralogy that volcaniclastic turbidites accumulated most likely in a forearc basin, adjacent either to oceanic island arc formed on thinned continental crust, or to a volcanic arc formed on thick continental crust or thin continental margin. However, this does not preclude further transportation into a trench of the forearc basin.

Ignoring ambiguities resulted from some diagrams and considering the sedimentological and mineralogical data, as well as the regional geotectonic framework, the volcaniclastic turbidites may be interpreted as resedimented deposits of an oceanic island arc or a continental margin magmatic arc. Several lines of evidence suggest that the volcanic source was very likely represented by the Maastrichtian volcanism related to the Banatitic Magmatic and Metallogenetic Belt from the western South Carpathians (Seghedi, Oaie, 1997): resedimented arc material with intermediate to basic composition and calc-alkaline geochemistry; spatial association of volcaniclastic turbidites with terrigenous turbidites and a mélangé complex which possibly includes olistostromes, suggesting accumulation in a trench basin. The complete absence of volcanic feeder systems (dykes, necks) in the Mesozoic covers of the Danubian units, as well as the geotectonic model of the Danubian lower plate in collision with the Getic-Supragetic upper plate, suggest the provenance of the volcanic material from the coeval Late Cretaceous magmatic belt developed on the upper Getic-Supragetic plate in Banat, Timok and Srednogorie (Berza, 1999; Berza, Ilinca, 2014). Based on the calc-alkaline geochemistry and features of island arc volcanics, partly contaminated (Rb/Sr ratios of 0.26 and 0.56 and Sr$^{87}$/Sr$^{86}$ ratios of 0.704 and 0.708), Savu et al. (1987) proposed a geotectonic model by subduction in the collision zone between the Moesian and Transylvanian plates. The authors postulate formation of an outer arc as a consequence of Andean-type subduction of the Moesian Plate beneath the Transylvanian Plate (represented by Danubian units), followed by underthrusting of the Moesian Plate during a Himalaya-type collision.

The source area of the volcanism is a question to be answered, as Late Cretaceous volcanism is not known in the Danubian Window. The closest magmatic and volcanic rocks of Late Cretaceous age occur in the inner zone of the western South Carpathians, in Banat area, as well as in the Rusca Montană and Haţeg Basin along the north-western border of the Danubian Window. Both in the Banat and Rusca Montană basins, shallow intrusives were emplaced in the Getic-Supragetic Nappes and their sedimentary cover. First referred to as “banatites” in Banat area of the western South Carpathians (von Cotta, 1864), these intrusives were considered components of the Banatitic Magmatic and Metallogenetic Belt (BMMB) (Berza et al., 1998, and references therein), or of the Apuseni-Banat-Timok-Srednogorie Belt (ABTS) (Popov et al., 2002).

According to reliable geochronological evidence, the “banatitic” magmatism, associated to various porphyry and hydrothermal deposits, has been emplaced between 92 and 72 My (Santonian-Campanian), as indicated from U-Pb zircon, Re-Os molybdenite, and Ar$^{39}$/Ar$^{40}$ (reviewed by Berza, 2004). Their tectonic setting was interpreted variously: subduction-related (detailed overviews of such models are given in Berza et al., 1998; Ciobanu et al., 2002; Zimmermann et al., 2008); extensional (Popov, 1981; Popov et al., 2002; Berza et al., 1998; Berza, 1999, 2004; Willingshofer, 2000); post-subduction/collisional setting (Popov, 1981,
post-collisional (Nicolescu et al., 1999), or post-collisional slab-tear model (Neubauer, 2002; Neubauer et al., 2003); roll back of the subducting slab (von Quadt et al., 2007), extension on the upper plate with intra-arc rifting (Georgiev et al., 2012). In the western South Carpathians, intrusive banatites (in the Getic-Supragetic Nappes) range from gabbros to leucogranites, but the most widespread are granodiorites, (quartz) diorites, and (quartz) monzodiorites (Dupont et al., 2002). Dykes consist of basalts, andesites, dacites, rhyolites and relatively diverse lamprophyres. These intrusive and subvolcanic rocks show largely calc-alkaline, high-K calc-alkaline to shoshonitic compositions, with subordinate tholeiitic and alkaline facies (Dupont et al. 2002). BMMB magmatic rocks show active margin-type calc-alkaline compositions (Dupont et al. 2002; Chambefort et al., 2007) which characterize subduction-related settings (Bocaletti et al., 1974; Berza et al., 1998).

All volcanic complexes from the Romanian part of the BMMB are dominated by medium and high-K andesites and dacites (Ilincă et al., 2011). In Rusca Montană basin, volcanic rocks are interbedded into the Cretaceous deposits of the basin fill (Strutinski, Bucur, 1986). The oldest volcanic rocks identified are andesitic tuffs interbedded in marine sediments with mid-Turonian microfauna (92-90 Ma) while a second tuffaceous level was dated as basal Coniacian (89-90 Ma) (Strutinski, Bucur, 1986). Here, Kräutner et al. (1972, 1990) mapped two volcano-sedimentary andesitic formations, separated by a rhyolitic ignimbrite and dated as Late Maastrichtian. The Late Maastrichtian andesitic volcanic activity is coeval with the banatitic magmatic activity, as well as with the emplacement of volcaniclastic turbidites from the Coșuştea Nappe (Ilincă et al., 2011).

Eastward from Rusca, in the Hațeg basin, volcano-sedimentary deposits have also been described in the Coniacian-Campanian Densuș-Ciula Formation (Anastasiu, Csoobuka, 1989), with volcaniclastic conglomerates and sandstones in its middle member dated on dinosaur remains (Grigorescu et al., 1990). A petrographic and geochemical study of these rocks (Bârzoii, Şcheiman, 2010) revealed a pyroclastic nature of the volcaniclastic rocks, dominated by andesite clasts (amphibole- and pyroxene-andesites), acid products occurring less frequently, with rhyolites restricted to the lower part of the succession. The authors concluded that the volcanism was explosive, based on the angularity of volcanic clasts and rich-hornblende content, while poor sorting and little reworking of the pyroclastic material indicates short distance of transport and deposition in the vicinity of the eruption center. An island arc situated close to an active continental margin is considered the depositional environment of the Hațeg basin volcanoclastics (Bârzoii, Şcheiman, 2010).

In the Timok area from Eastern Serbia, part of the BMMB (Berza et al., 1998), Upper Cretaceous volcaniclastic-sedimentary formations are located in the Getic unit and include andesitic and andesitic-basaltic volcanic rocks (Kräutner, Krstić, 1996). They were recently dated on planktonic foraminifera zones as Upper Albian/Cenomanian to Campanian/Maastrichtian (Ljubović-Obradović et al., 2011). Volcanism started with Turonian–Coniacian) andesitic rocks, followed by Coniacian–Maastrichtian andesitic-basaltic volcanic rocks (Milovanović et al., 2005).

Considering the large areal development of the BMMB in the Alpine belt from Romania, Serbia and Bulgaria, it is highly probable that explosive, andesitic type volcanism represented the source area of the volcaniclastic turbidites of Coșuştea Nappe, according to the model cross section of Berza (1999) (Fig. 10). A genetic model of regional underplating with basic magma at the base of the crust was postulated for the Late Cretaceous magmatism recorded in SE Europe (Berza, Ilincă, 2014), with volcanic-sedimentary successions accumulated in Gosau type basins filled with continental and marine deposits.

![Fig. 10](image.png)

Fig. 10. Cross-section between Africa and Europe at 75 Ma, 20-23°N, 18°E, a potential model for the source area of the volcaniclastic turbidites in the Coșuştea Nappe (after Berza, 1999; and Berza, in Ilincă et al., 2011).
CONCLUSIONS

Facies association and vertical facies distribution suggest that the terrigenous successions of the Coșuştea Nappe represent midfan turbidites, dominated by deposition in suprafan channels. Sandstone mineralogy indicates that a major sediment source, located on the upper plate, provided detritus of Getic type metamorphic basement and alkaline volcanic rocks, with minor input from the accretionary wedge.

Upper Cretaceous volcanioclastic turbidites (green sandstones and conglomerates) represent upward coarsening sequences, accumulated on top of the grey terrigenous turbidites. Volcaniclastic sedimentation took place as dominantly sand deposition in supraceone lobes, followed by coarse sedimentation as channelized debris flows. Vertical facies distribution suggests evolution in time from midfan to proximal fan turbidites. The thick, upward coarsening sequences of Upper Cretaceous volcanioclastic turbidites, located on top of terrigenous turbidites, both associated with a mélangé formation, suggest deposition in a forearc basin, trench basin situated on the inner slope, in a forearc slope basin, or even in a remnant ocean basin.

Mineralogical results indicate that the volcanioclastic rocks of the Coșuştea Nappe are compositionally immature, consisting dominantly of unstable volcanic material of feldspatolithic type. The mineralogical composition of volcanioclastic turbidites suggests provenance from a major volcanic source, possibly a migmatic arc, as well as contributions from the accretionary wedge and from a continental source supplying terrigenous siliciclastic detritus. Material with such provenance accumulates in trenches or forearc settings, both associated with a mélange formation, suggest deposition in a forearc basin, trench basin situated on the inner slope, in a forearc slope basin, or even in a remnant ocean basin.

Geochemical results indicate provenance from a reworked volcanic arc material, with intermediate to basic composition and calc-alkaline geochemistry. The potential candidate for the volcanic source is the Maastrichtian volcanism related to the Banatitic Magmatic belt from the western South Carpathians or other areas of the BMBM.

Acknowledgments

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REFERENCES


Carpathians. *Studii și cercetari geologice* 45, Romanian Academy (in Romanian).


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