UPPER CRETACEOUS WELDED IGNIMBRITES OF THE HAȚEG BASIN (SOUTHERN CARPATHIANS, ROMANIA): INSIGHTS INTO THEIR GENESIS, EMPLACEMENT DYNAMICS, AND STRATIGRAPHIC SIGNIFICANCE

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Abstract. Fragments of Upper Cretaceous eruptive products are exposed across the Hațeg Basin (Southern Carpathians), mostly around Ciula Mică, Peștenița, Criva, Densuș, and Răchitova localities. The location of the volcanic eruptions is currently unknown, since no volcanic centres exist in the Hațeg area. Unlike the Early Campanian Densuș and Răchitova volcaniclastic products, the Ciula Mică, Peștenița, and Criva eruptive products have never been studied so far, so their nature and provenance remained up until now largely unknown. Here we provide detailed lithologic and petrographic analyses that combined with previous geochemical data, show that the eruptive products are fragments of trachytic welded ignimbrites. The ignimbrites were formed from calc-alkaline and high-K calc-alkaline magmas generated during highly explosive, subaerial volcanic activity, probably of Plinian type. Lithological and petrographic features suggest multiple volcanic sources and the volcanic centres were either of caldera or stratovolcano type. The observed moderate to high degree of welding indicate that initially, the ignimbrite fragments were part of high-aspect ratio deposits tens or hundreds of meters thick, typical for large-scale, silicic volcanism. While the Densuș and Răchitova volcaniclastic products, as well as the Criva ignimbrite fragment are in contact only with Upper Cretaceous marine sediments, the Ciula Mică and Peștenița ignimbrites appear as blocks embedded in Upper Cretaceous alluvial deposits. In this paper, we also investigate this rather unusual stratigraphic position of the ignimbrite fragments within the Hațeg Basin and their field relation with the Upper Cretaceous sediments that are in contact with.

Key words: Hațeg Basin, Late Cretaceous, welded ignimbrite, pyroclastic density current, trachyte, Plinian.

Résumé. Des fragments de produits éruptifs du Crétacé supérieur sont exposés dans tout le bassin de Hațeg (Carpates du Sud), principalement autour des localités de Ciula Mică, Peștenița, Criva, Densuș et Răchitova. La localisation des éruptions volcaniques est actuellement inconnue, car aucun centre volcanique n'existe dans la région de Hațeg. Contrairement aux produits volcanoclastiques du Campanien inférieur de Densuș et de Răchitova, les produits éruptifs de Ciula Mică, Peștenița et Criva n'ont jamais été étudiés jusqu'à présent, de sorte que leur nature et leur provenance sont restées jusqu'à présent largement inconnues.Nous fournissons ici des analyses lithologiques et pétrographiques détaillées qui, combinées aux données géochimiques précédentes, montrent que les produits éruptifs sont des fragments d'ignimbrites soudées trachytiques. Les ignimbrites se sont formées à partir de magmas calco-alcalins et calco-alcalins riches en potassium, générés lors d'une activité volcanique subaérienne hautement explosive, probablement de type Plinien. Les caractéristiques lithologiques et pétrographiques suggèrent de multiples sources volcaniques, et les centres volcaniques étaient de type caldeira ou stratovolcan. Le degré de soudure observé, modéré à élevé, indique qu'initialement, les fragments d'ignimbrite faisaient partie de dépôts à rapport d'aspect élevé, épais de plusieurs dizaines ou centaines de mètres, typiques du volcanisme silicique à grande échelle. Alors que les produits volcanoclastiques de Densuș et de Răchitova, ainsi que le fragment d'ignimbrite de Criva, ne sont en contact qu'avec des sédiments marins du Crétacé supérieur, les ignimbrites de Ciula Mică et de Peștenița apparaissent comme des blocs encastrés dans des dépôts alluviaux du Crétacé supérieur. Dans cet article, nous étudions également cette position stratigraphique plutôt inhabituelle des fragments d'ignimbrite dans le bassin de Haţeg et leur relation de terrain avec les sédiments du Crétacé supérieur qui sont en contact avec eux.

Mots-clés: Bassin de Haţeg, Crétacé supérieur, ignimbrite soudée, courant de densité pyroclastique, trachyte, Plinien.

1. INTRODUCTION

Remnants of ancient Upper Cretaceous volcaniclastic deposits and products of different lithology and composition, from basaltic-andesites to high-silica rhyolites, occur in multiple locations across the western and north-western parts of the Haţeg Basin (e.g., Laufer, 1925; Anastasiu and Csobuka, 1989; Anastasiu, 1991; Vornicu *et al.*, 2023). These products resulted mainly from subaerial explosive volcanic activity that took place during the Late Cretaceous and consist of poorly exposed pieces of volcaniclastic successions near Densuş and Răchitova and fragments of eruptive products at Ciula Mică, Peştenița, and Criva (Fig. 1; e.g., Laufer, 1925; Anastasiu, 1991; Popa and Seghedi, 2015; Vornicu, 2024; Vornicu and Seghedi, 2025).

The general tectonic and sedimentary setting of the Haţeg Basin and the fact that no volcanic vents or edifices were discovered in the Haţeg area, have shaped the hypothesis that the volcaniclastic products were initially emplaced in a different, unknown location and later were re-arranged in their present-day position by subsequent tectonic displacements that operated during the Late Cretaceous (e.g., Pătraşcu *et al.*, 1993; Bârzoi and Şeclăman, 2010; Vornicu *et al.*, 2023). Genetically, the eruptive products of the Haţeg Basin are related to the Late Cretaceous, so called 'Banatitic' magmatism that formed the Apuseni-Banat-Timok-Srednogorie (ABTS) belt in Central-Eastern Europe, implying that the magmas were generated within the same geodynamic conditions (e.g., Berza *et al.*, 1998; Popov and Popov, 2000; Vornicu and Seghedi, 2025).

In contrast with the Densuş and Răchitova volcaniclastic successions, which in the latest years were the object of several lithological, geochemical and age studies (e.g., Bârzoi and Şeclăman, 2010; Bojar *et al.*, 2011; Vornicu, 2024), the Ciula Mică, Peştenița, and Criva eruptive products remained so far, essentially, unexplored. The first who mentioned the presence of these eruptive products is Laufer (1925), who described them as porphyritic volcanic products associated in some instances with lithified tuff layers. Genetically, Laufer (1925) suggested that they are igneous intrusions or dikes but as will be shown here, this interpretation could not be proven correct.

Since the study of Laufer (1925), the Ciula Mică, Peştenița, and Criva eruptive products have been hardly re-visited for research purposes. Most of the Ciula Mică, Peştenița, and Criva areas are, at the present time, forested and for this reason, the eruptive products described by Laufer (1925) have now become for the most part inaccessible for field observations. Outcrops of these products only occur as scattered fragments of various size, mostly covered with vegetation. Besides the small surface exposures, studying ancient volcanic or volcaniclastic products can be a real challenge for many other reasons. The first and foremost issue in studying the Ciula Mică, Peştenița, and Criva volcaniclastic products is the fact they represent only small pieces of the total original deposits and cannot be linked to a certain volcanic source. Moreover, ancient eruptive products are commonly affected by post-depositional alteration and weathering that can significantly modify or overprint the initial volcanic textures or composition. In such cases, determining the deposit genetic type and emplacement mechanism can be very complicated. Equally, tectonic movements can have an impact on primary depositional features, such as bedforms, layering or the direction of sedimentation.

Herein we provide a comprehensive field description of the Ciula Mică, Peştenița, and Criva eruptive products and we question their relation with the surrounding Upper Cretaceous deposits that are associated with, with the purpose of understanding the significance of their occurrence within the Haţeg Basin. Despite the above mentioned limitations, we document the lithological characteristics of these products and based on their lithology and petrographic features, we try to identify the compositional and genetic type. We also discuss volcanological aspects such as possible initiation mechanisms and the eruption type. This volcanological and petrographic analysis constitutes the first research study of the Upper Cretaceous Ciula Mică, Peştenița, and Criva eruptive products and can be used as a basis for future, more advanced approaches of these products.

2. GEOLOGICAL BACKGROUND

Haţeg Basin is a syn/post-orogenic, sedimentary depression in the Southern Carpathians of Western Romania (Fig. 1). The metamorphic basement of the Haţeg area is represented by the Variscan Getic-Supragetic and Danubian Units (e.g. Săndulescu, 1984). The formation of the Haţeg Basin began during the Late Cretaceous, with the continent-continent collision between the Getic-Supragetic Units and the Danubian Unit, upon closure of the small Severin Ocean (e.g., Ratschbacher *et al.*, 1993; Berza *et al.*, 1994).

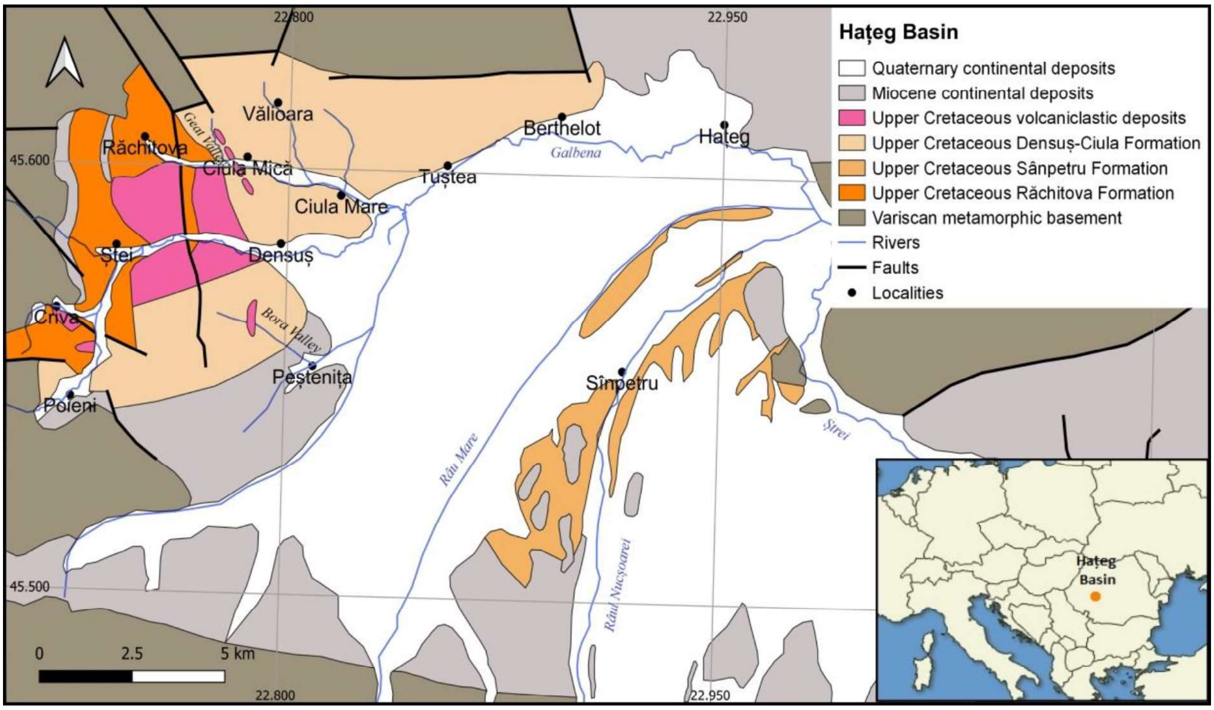

Figure 1. Simplified geological map of the Haţeg Basin (modified after the 1:200.000 Geological Map of Romania of the Geological Institute of Romania – Codarcea *et al.*, 1967, Dessila-Codarcea *et al.*, 1968).

In the Albian-Campanian period, the area corresponding to the present-day Haţeg Basin functioned as a "piggy-back" basin on top of the Getic-Supragetic units (e.g., Willingshofer *et al.*, 2001), during which a marine environment developed (e.g., Iancu *et al.*, 2005). During the Late Maastrichtian, collapse of the orogen was followed by the installation of an extensional tectonic regime (e.g., Willingshofer *et al.*, 2001), when the marine domain was replaced with a continental environment (e.g., Iancu *et al.*, 2005).

The Răchitova Formation comprises the youngest marine deposits of the Haţeg Basin of Early Campanian age (Ţabără and Slimani, 2019) and crops out in patches across the basin, especially in the north and north-west. The formation is divided into two individual lithological members: Lower and Upper (e.g., Grigorescu and Melinte, 2001; Melinte-Dobrinescu, 2010), mostly containing turbidite deposits (e.g., Grigorescu and Melinte, 2001).

The marine deposits are topped by the continental Upper Cretaceous sedimentary beds of the Haţeg Basin (e.g., Laufer, 1925; Grigorescu and Anastasiu, 1990). These beds are exposed in multiple locations across the basin and are separated into two main lithostratigraphic units: Densuș-Ciula Formation, which is exposed in the north-western parts of the basin, and Sânpetru Formation, which crops out mainly in the central and eastern parts of the area (e.g., Grigorescu, 1992).

Based on lithological criteria, the continental Densuş-Ciula Formation is further split into three different members: Lower, Middle, and Upper (e.g., Grigorescu, 1992; Grigorescu *et al.*, 1990).

Upper Cretaceous volcaniclastic products occur especially in the western and north-western parts of the Haţeg Basin (Fig. 1; e.g., Anastasiu and Csobuka, 1989; Grigorescu and Anastasiu, 1990). Near Densuș and Răchitova, we find multiple, relatively poorly exposed eruptive successions of andesitic, dacitic, and less often rhyolitic composition (e.g., Bârzoi and Şeclăman, 2010; Vornicu and Seghedi, 2025). These successions are over hundred meters thick and represent fragments of former stratovolcanoes, mostly formed from eruptions of phreatomagmatic type (e.g., Popa and Seghedi, 2015; Vornicu, 2024).

The Ciula Mică eruptive products crop out along the Geat Valley, as isolated bodies of similar lithology (Figs. 1, 2; Laufer, 1925; this study). Their dimensions usually range from a few meters up to about 50 meters. Volcaniclastic products of similar size and lithology, also occur near Peștenița, positioned south of Densuș (Fig. 1; Laufer, 1925; this study). These are discontinuously exposed along the Bora Valley, as fragments of various sizes, the largest being approximately 15 meters across. Eruptive products with lithological characteristics identical to those at Peștenița are also exposed near Criva locality (Fig. 1; Laufer, 1925; this study).

The stratigraphic position of the volcaniclastic products within the Haţeg Basin is rather curious and unusual and a similar situation was not observed elsewhere on the Romanian territory. Around Densuș, Răchitova, and Criva the volcaniclastics are in direct contact with the early Campanian marine deposits of the Răchitova Formation, while the Ciula Mică and Peștenița eruptive products crop out as blocks embedded in Upper Cretaceous polymictic conglomerate deposits (Fig. 2; Laufer, 1925; Albert *et al.*, 2025). The conglomerate deposits overlie the same marine sediments of the Răchitova Formation (Fig. 2; e.g., Albert *et al.*, 2025). It was hypothesised that in some areas, such as Densuş, the contact between the marine beds and the continental deposits is of tectonic nature, whereas in other places, such as Ciula Mică, the contact is rather erosional (e.g., Laufer, 1925; Grigorescu and Melinte, 2001; Albert *et al.*, 2025). Over the years, the atypical sedimentary layout of the Haţeg Basin and the lack of volcanic centres have posed many questions about the character and source of the volcaniclastic products.

At Densuş and Răchitova, the Lower Member of the continental Densuș-Ciula Formation is constituted by the volcaniclastic deposits exposed in these areas, as proposed by previous authors (e.g., Grigorescu, 1992; Grigorescu and Anastasiu, 1990). At Ciula Mică and Peștenița, the above mentioned conglomerate deposits are regarded as the Lower Member of this formation (Albert *et al.*, 2025).

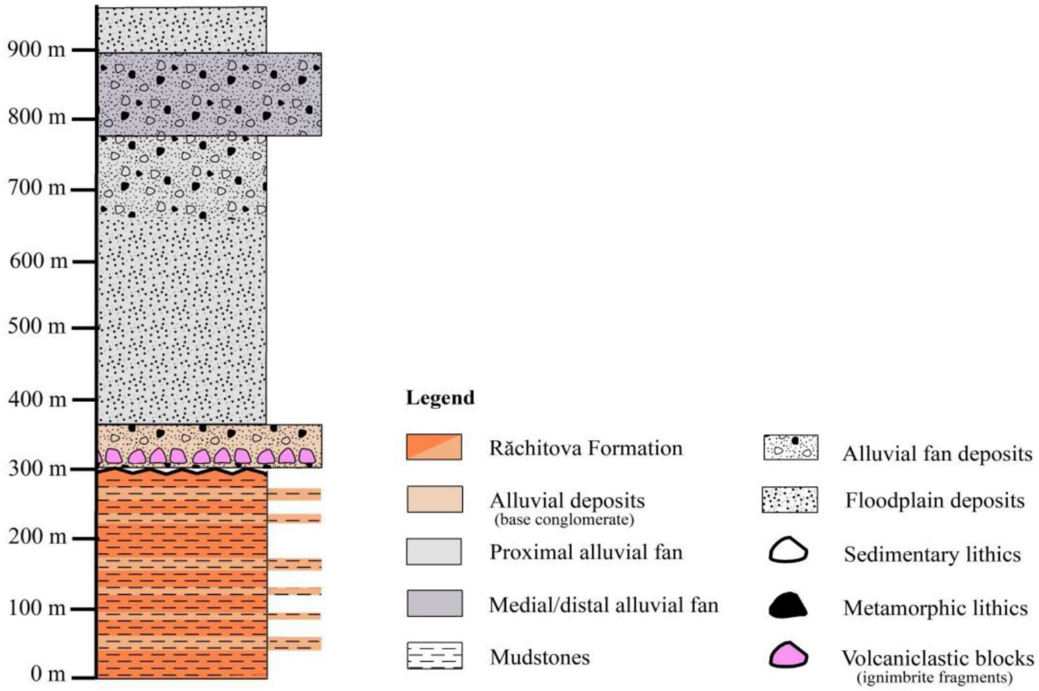

Figure 2. Simplified lithostratigraphic column of the Ciula Mică area (redrawn/modified after Albert *et al.*, 2025); denominations of the continental lithologic units are from Albert *et al.* (2025).

3. METHODOLOGY

This study makes use of detailed field observations and petrographic analyses of the Ciula Mică, Peştenița, and Criva eruptive products with the aim of delivering a complete lithological and petrogenetic description of these products.

Grain-size was established on the basis of White and Houghton (2006) classification system for volcaniclastic sediment and deposit sorting values were determined using the Cas and Wright (1987) classification scheme. Other important depositional features that were examined in this study are texture, grading, bedforms, as well as lateral variations of lithologic characteristics.

Analyses of the juvenile particles targeted specific grain parameters such as grain size, grain size distribution, particle shape and degree of porosity. Particle size was calculated using the formula $(\Phi) = -\log2[d(mm)])$ and the median size was calculated as $Md\Phi = \Phi50$ (Inman, 1952).

Rock samples of the different volcaniclastic products were collected from each location, for petrographic analysis. The composition was determined mainly from petrographic and geochemical analyses. For the Peştenița volcaniclastic deposits, whole-rock major and trace element geochemical data is provided by Vornicu and Seghedi (2025).

Deposit genetic types were determined on the basis of composition and texture, in combination with microscopic elements that can be observed only in thin section and can be essential in establishing the primary or secondary character of certain deposits. Petrographic analysis of thin sections was undertaken using an Olympus BX41 TF petrographic microscope.

In this paper, the lithostratigraphy-related terms are used in agreement with the recommendations of the International Commission on Stratigraphy.

4. RESULTS

4.1. LITHOLOGIC DESCRIPTION OF THE CIULA MICĂ, PEŞTENIŢA, AND CRIVA ERUPTIVE PRODUCTS

4.1.1. Lithological description of the Ciula Mică eruptive products

Five different lithological entities have been found in the Ciula Mică area: **Ciula Mică 1, Ciula Mică 2**, **Ciula Mică 3**, **Ciula Mică 4**, and finally **Ciula Mică 5**.

The Ciula Mică 1 eruptive product crops out inside the Ciula Mică village, as an isolated body of about 40 m long and 7–8 m wide and is partially obscured by anthropic constructions (Fig. 3a; GPS coordinates: 45° 35' 59.7" N/ 22° 46' 53.3" E). It is closely associated in the field with a fine tuff layer that crops out in its proximity as very small-sized fragments.

Although Ciula Mică 1 is generally massively textured, certain segments show normal, fine stratification or lamination. It is highly indurated, non-graded and poorly to moderately sorted, with a sorting value (σ) > 2 (Cas and Wright, 1987). The deposit is pumice-rich, consisting of mostly fine to medium-grained juvenile particles that usually lack porosity and a relatively small amount of volcanic and metamorphic lithic fragments. The volcanic clasts can be cognate or accessory, while the metamorphic lithics are accessory and possibly accidental. It has an apparent porphyritic texture, with larger components up to 2–3 mm in size, within a cryptocrystalline matrix. Due to post-emplacement welding, which represents the compaction of the deposit and the elimination of pore space, pumice and glass shards are often flattened and elongated into structures called *fiamme,* forming an approximately parallel foliation or *eutaxitic* texture (Fig. 3b; e.g., Smith, 1960b; Wilson, 1986; Quane and Russell, 2005a). According to the *fiamme* shape classification of Gifkins *et al.* (2005), these are mostly flame-like and thread-like. The welding process will be discussed in greater detail in the following sections.

Figure 3. **(a)** Outcrop of the Ciula Mică 1 eruptive product, Ciula Mică village, Răchitova locality, Hunedoara county; **(b)** detailed image of the Ciula Mică 1 eruptive products, with deformed and elongated pumice (P), forming *fiamme* structures and eutaxitic texture. The majority of the *fiamme* are visibly altered, due to post-depositional alteration processes of volcanic glass. Author: Violeta M. Vornicu/Maria Vornicu

In the immediate vicinity of Ciula Mică 1, the Ciula Mică 2 eruptive product crops out as fragments of different sizes, usually of under a meter (Fig. 4a). The Ciula Mică 2 product has a gray-greenish colour, is highly indurated, massively textured, non-graded, non-stratified and poorly sorted, with a sorting value (σ) between 2–4 (Cas and Wright, 1987).

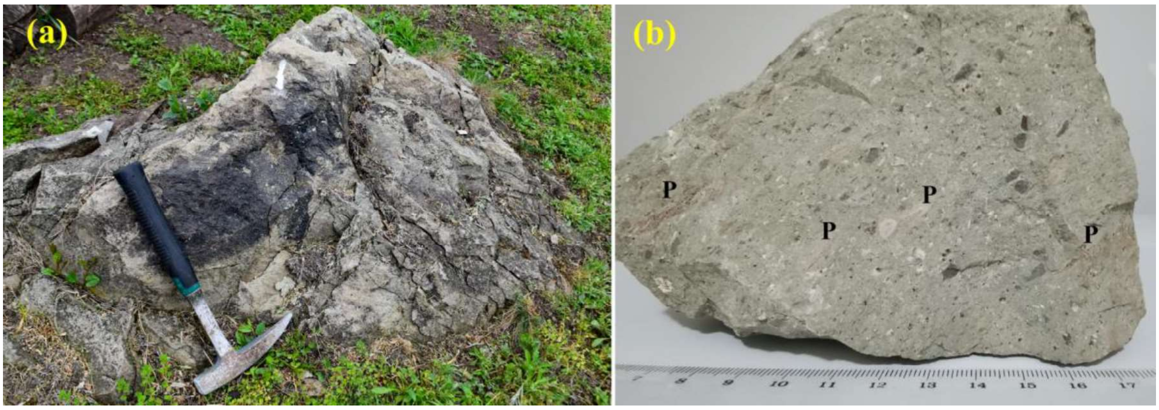

Figure 4. **(a)** Outcrop of the Ciula Mică 2 eruptive product, inside the Ciula Mică village, Răchitova locality, Hunedoara county; **(b)** Detailed image of the Ciula Mică 2 eruptive product, with deformed and elongated vesicular pumice (P), forming *fiamme* and eutaxitic texture. Author: Violeta M. Vornicu

Similar to Ciula Mică 1, it primarily consists of fine to medium-grained juvenile vesicular pumice, glass shards and crystals, together with a small proportion of volcanic and metamorphic lithic fragments, up to a few mm in size. Due to post-depositional welding, the pumice and glass particles are deformed and elongated into *fiamme* up to 4–5 cm long, with vesicular texture and flame-like, lens-like or tread-like shapes (Fig. 4b; e.g., Gifkins *et al.*, 2005).

Just outside the Ciula Mică village, along the Geat Valley, in a wooded area crops out the Ciula Mică 3 eruptive product (Fig. 5a; GPS coordinates: 45° 36" 19.9’ N/22° 46" 35.5’ E). It is about 50 m long and approximately 20 m thick. Ciula Mică 3 is light-coloured and heavily faulted, has a general massive texture, lacks grading and is poorly sorted, with a sorting value (σ) between 2–4 (Cas and Wright, 1987). It is composed of mostly fine to medium-grained juvenile material that lacks porosity and a small amount of volcanic and metamorphic lithic fragments, up to maximum 3 mm in size. This product is rich in crystals and pumice clasts set in a cryptocrystalline matrix, forming an apparent porphyritic texture. The majority of pumice clasts and glass shards are deformed and elongated into *fiamme*, due to post-depositional welding (Fig. 5b). The *fiamme* are maximum 2 cm long and have flame-like, thread-like, and lens-like shapes (Fig. 5b; e.g., Gifkins *et al.*, 2005).

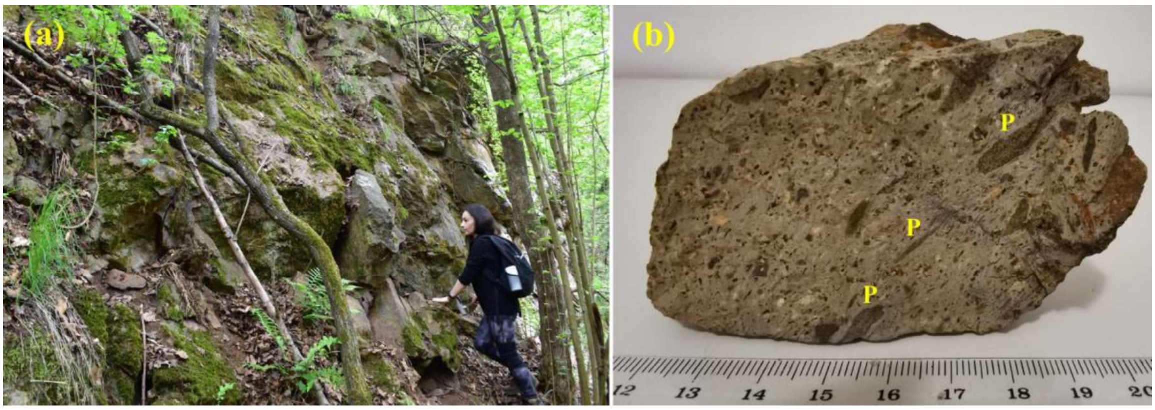

Figure 5. **(a)** Outcrop of the Ciula Mică 3 eruptive product exposed along the Geat Valley, Ciula Mică village, Răchitova locality, Hunedoara county; **(b)** Detailed image of the Ciula Mică 2 eruptive product, with deformed and elongated pumice (P), forming *fiamme* structures and eutaxitic texture. Author: Violeta M. Vornicu/Maria Vornicu

The Ciula Mică 4 eruptive product crops out at a distance of about 1 km of the Ciula Mică village, along the Geat Valley (GPS coordinates: 45º 35' 59" N/ 22º 46' 53" E), as isolated fragments of various sizes, spread out on a distance of about 100 m (Fig. 6a). These bodies are predominantly sub-angular and sub-rounded and are from a few tens of cm up to 5 meters long and up to 2–3 meters wide. Ciula Mică 4 is gray-brownish in colour, highly compacted, massively textured, non-stratified, non-graded and moderately sorted, with a sorting value (σ) between 1–2 (Cas and Wright, 1987). This product is composed of fine to coarse-grained crystals and glass and a relatively small amount of volcanic and metamorphic lithic clasts. Larger crystals and lithic fragments in the lapilli fraction are almost evenly distributed in a cryptocrystalline glassy matrix, forming a conspicuous, apparent porphyritic texture (Fig. 6b). In comparison with Ciula Mică 1, 2, and 3, Ciula Mică 4 is poorer in pumice and does not exhibit eutaxitic texture.

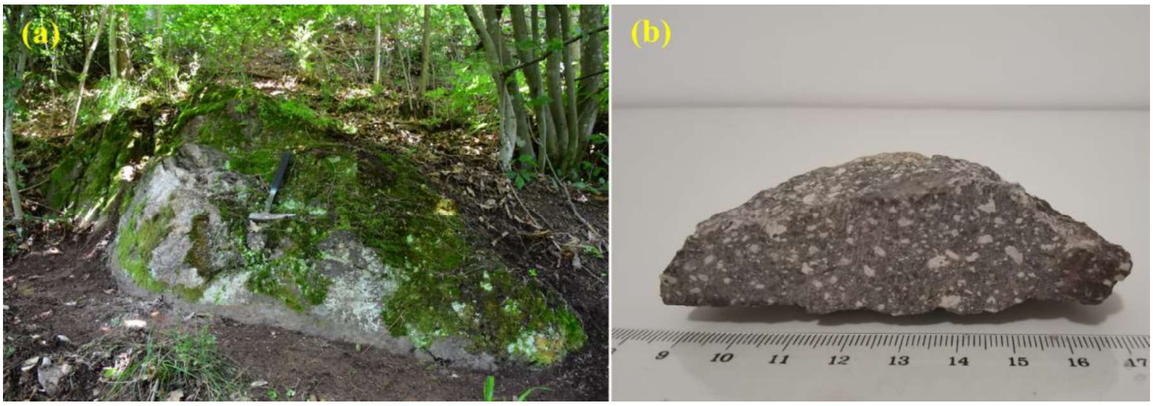

Figure 6. **(a)** Outcrop of the Ciula Mică 4 eruptive product exposed along the Geat Valley, Ciula Mica village, Răchitova locality, Hunedoara county; **(b)** Detailed image of the Ciula Mică 4 eruptive product, with crystals, lithic fragments and less often pumice clasts, set in a cryptocrystalline groundmass, forming a conspicuous apparent porphyritic texture. Author: Violeta M. Vornicu

The Ciula Mică 5 eruptive product is situated south of Ciula Mică, towards Densuș, at a distance of approximately 500–600 m of the Ciula Mică 1 and Ciula Mică 2 outcrops (GPS coordinates: 45° 35" 47.2' N/ 22° 47" 03.8' E). This product is exposed over a distance of about 60–70 m, as fragments of various sizes, from under a meter up to about 10 meters in length (Fig. 7a).

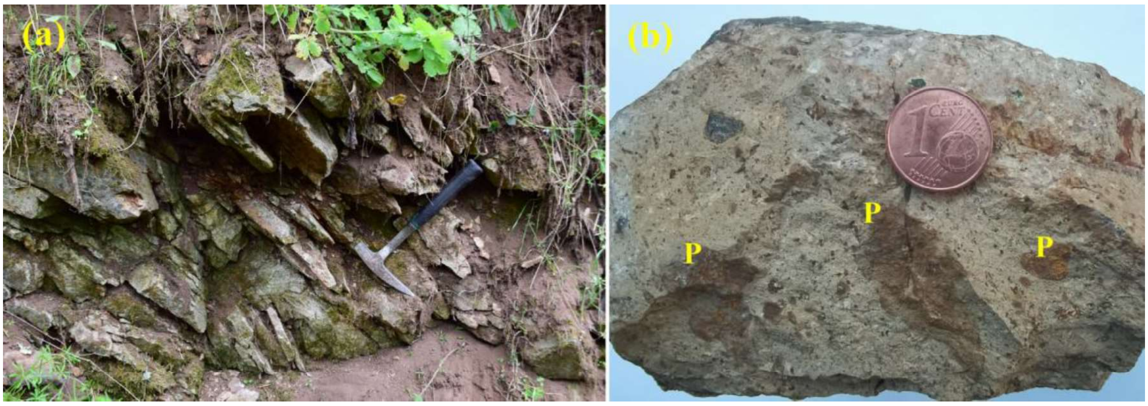

Figure 7. **(a)** Outcrop of the Ciula Mică 5 eruptive product near Ciula Mică village, Răchitova locality, Hunedoara county; **(b)** Detailed image of the Ciula Mică 2 eruptive product, with deformed and elongated pumice (P), forming *fiamme* structures and eutaxitic texture. Author: Violeta M. Vornicu

The Ciula Mică 5 product is heavily faulted and fractured and affected by supergene alteration. It is brownish-yellow, highly indurated, massively textured and poorly sorted, with a sorting value (σ) between 2–4 (Cas and Wright, 1987). Similar to the other eruptive products previously described, it has an apparent porphyritic texture and is primarily composed of fine to medium-grained crystals and moderately vesicular pumice clasts. It also contains a small amount of ash-grained volcanic and metamorphic lithic fragments. Pumice clasts are flattened and deformed into *fiamme*, which are up to 4–5 cm long and usually have lens-like and flame-like shapes (Fig. 7b; e.g., Gifkins *et al.*, 2005).

4.1.2. Lithologic description of the Peștenița and Criva eruptive products

The **Peștenița 1** eruptive product crops out along the Bora Valley, over a distance of about 150 m and individual blocks of this product have a maximum exposure length of about 15 m (Fig. 8a; GPS coordinates: 45° 33' 45" N/ 22° 47' 20" E). Although it has a general massive texture, in certain segments the presence of a parallel, fine stratification can be observed. The individual layers are of variable thickness but usually no thicker than a few cm. Peștenița 1 is dark-gray, non-graded and poorly sorted, with a sorting value (σ) > 2 (Cas and Wright, 1987) but the predominance of fine fraction gives this product a general homogenous aspect. Is has a moderate pumice content, encompassing mostly non-vesicular fine to medium-grained juvenile particles and a relatively small amount of volcanic and metamorphic lithic fragments.

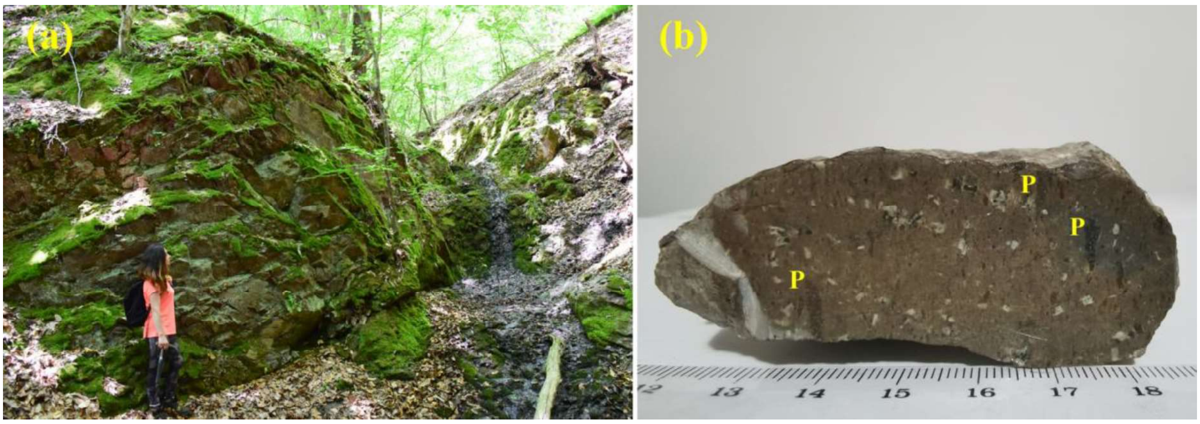

Figure 8. **(a)** Outcrop of the Peștenița 1 eruptive product near Peștenița village, Densuș locality, Hunedoara county; **(b)** Detailed image of the Ciula Mică 2 eruptive product, with flattened and elongated pumice (P), forming *fiamme* structures and eutaxitic texture. Author: Maria Vornicu/Violeta M. Vornicu

Similar to the Ciula Mică eruptive products, larger crystals, pumice, and lithic fragments up to 2–3 mm in size, are embedded in a cryptocrystalline matrix, forming an apparent porphyritic texture. The deposit exhibits eutaxitic texture, formed by post-emplacement welding (Fig. 8b). The *fiamme* are generally flame-like and thread-like in shape (Fig. 8b; Gifkins *et al.*, 2005).

The **Peștenița 2** and **Criva** eruptive products have identical lithological and petrographic characteristics, which indicate that they represent fragments of the same primary volcaniclastic deposit or, at least, they come from different deposits resulted from eruptions of the same volcanic center. For this reason, these products will be treated and described together.

Peștenița 2 crops out in the immediate vicinity of Peștenița 1 and is discontinuously exposed as multiple fragments of various sizes, over a distance of about 50–60 m (Fig. 9a; GPS coordinates: 45° 33' 45" N/ 22° 47' 19" E). The individual fragments are from under a meter up to 10 meters across.

The Criva eruptive product crops out close to the Criva village, as multiple fragments of different sizes, up to a few meters, spread out on a distance of about 40–50 m (Fig. 10a). The fragments are brownish-violet in colour, highly indurated, massively textured, non-stratified and non-graded, and are poorly to moderately sorted, with a sorting value (σ) < 2 (Cas and Wright, 1987).

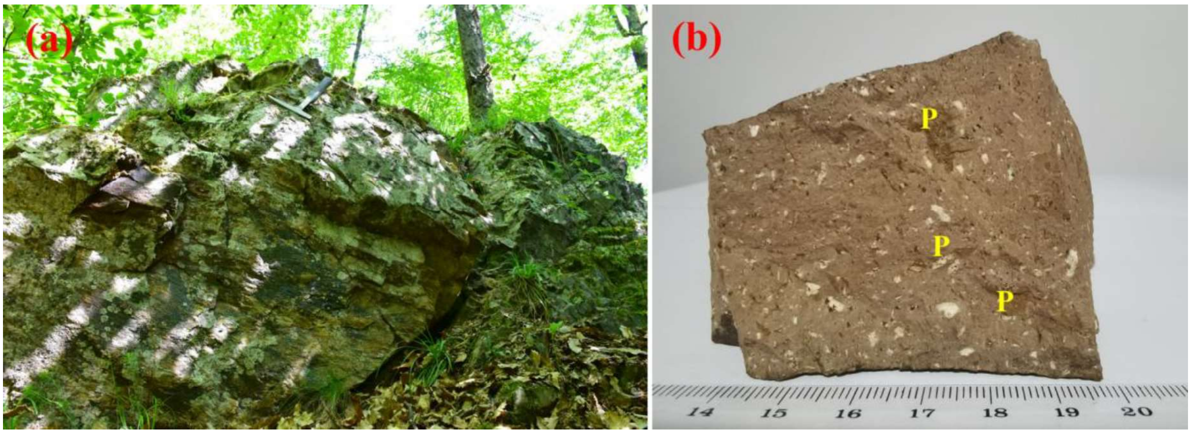

Figure 9. **(a)** Outcrop of the Peștenița 2 eruptive product near Peștenița village, Densuș locality, Hunedoara county; **(b)** Detailed image of the Peștenița 2 eruptive product, with deformed and elongated pumice (P), forming *fiamme* structures and eutaxitic texture. Author: Violeta M. Vornicu

As with Peștenița 1, the Peștenița 2 and Criva eruptive products have a moderate crystal and pumice content, containing fine to medium-grained juvenile material that lacks porosity and a relatively reduced amount of fine-grained volcanic and metamorphic lithic clasts. Because of post-depositional welding, the majority of pumice clasts are deformed into lens-shaped and thread-shaped *fiamme*, up to 1–2 cm long (Figs. 9b, 10b; e.g., Gifkins *et al.*, 2005).

As a general observation, unlike the Ciula Mică eruptive products, Peștenița 1, 2, and Criva are poorer in crystals and pumice and the median size of the juvenile particles is typically smaller. Consequently, the eutaxitic texture is less pronounced and is only locally visible.

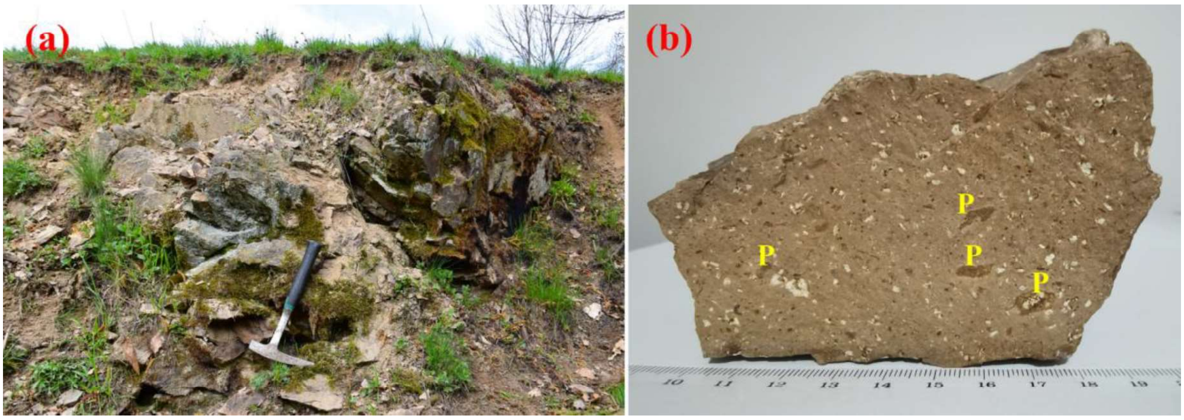

Figure 10. **(a)** Outcrop of the Criva eruptive product near Criva village, Densuș locality, Hunedoara county; **(b)** Detailed image of the Criva eruptive product, with deformed and elongated pumice (P), forming *fiamme* structures and eutaxitic texture. Author: Violeta M. Vornicu

4.2. PETROGRAPHIC ANALYSES

The Ciula Mică, Peștenița, and Criva rock samples largely share the same petrographic characteristics (Fig. 11A–D). The samples display more or less pronounced apparent porphyritic texture with crystals, possibly xenocrystals as well, and pumice particles, set in a glass-rich, cryptocrystalline matrix.

The most abundant minerals types in the analysed rock samples are euhedral alkali feldspar and plagioclase, followed by smaller amounts of hornblende, quartz, and more rarely biotite. The phenocrysts often occur as crystals clots or glomerocrysts, formed from alkali feldspar, plagioclase, and hornblende. Because of magma fragmentation-related processes, the crystals are usually fragmented or fractured, giving the rocks a shattered appearance. Studies have shown that crystal fragmentation is also caused by welding processes (e.g., Zalinge *et al.*, 2018).

The most frequently observed accessory mineral phases are opaques, apatite, zircon, and titanite. The rock samples also contain a moderate proportion of pumice clasts that sometimes are partially or completely devitrified (Fig. 11A–E). In comparison with the other rock samples, Ciula Mică 4 has a lower pumice content. Apart from the juvenile material, the eruptive products also contain a variable, relatively low amount of predominantly sub-angular and sub-rounded volcanic and metamorphic lithic clasts, randomly scattered throughout the rock mass.

The mesostasis is basically hypohyaline, composed of pumice and abundant angular or blocky glass shards, which are evident in the matrix and microlites and crystals fragments (Fig. 11A–F). The glass shards dominate the groundmass and often exhibit a fluid flow pattern or texture, noticeable especially around crystals (Fig. 11A–F).

The composition of the Ciula Mică eruptive products is dominated by alkali feldspar, which mostly occurs as sanidine, followed by plagioclase. Quartz, hornblende, and biotite are found in small amounts or as accessory minerals (Fig. 11A–D). The crystal content is estimated at around 40–50%. Poikilitic textures sometimes occur, involving mostly plagioclase (Fig. 11E–F).

The most abundant mineral phases in the Peștenița 1, Peștenița 2, and Criva rock samples are alkali feldspar and plagioclase, accompanied by lesser amounts of hornblende and quartz. In these samples phenocrysts often occur as glomerocrysts. The estimated crystal content is of about 35–45 %.

The Ciula Mică, Peștenița, and Criva rock samples generally display different degrees of alteration of both the crystalline and the vitric components. Alkali feldspar is usually altered to phyllosilicates, such as sericite or kaolinite. Plagioclase is sometimes replaced by sericite or chlorite. Mafic minerals, hornblende, and biotite are commonly transformed to chlorite. Hornblende crystals are sometimes altered to pyroxene, biotite, and magnetite displaying opacitized margins or are completely opacitized.

Fissures and cracks that run through the groundmass of some of the Ciula Mică and Peştenița samples are filled with calcite or quartz. Fissures of plagioclase and alkali feldspar are often filled with iron oxides. The predominantly vitric groundmass is at times altered to chlorite and shows high-temperature devitrification textures, such as micropoikilitic. Both the pumice clasts and the glass-rich matrix are locally replaced by a mosaic of plagioclase and quartz crystals formed by devitrification, which can be interpreted as granophyric texture (Fig. 11C, D).

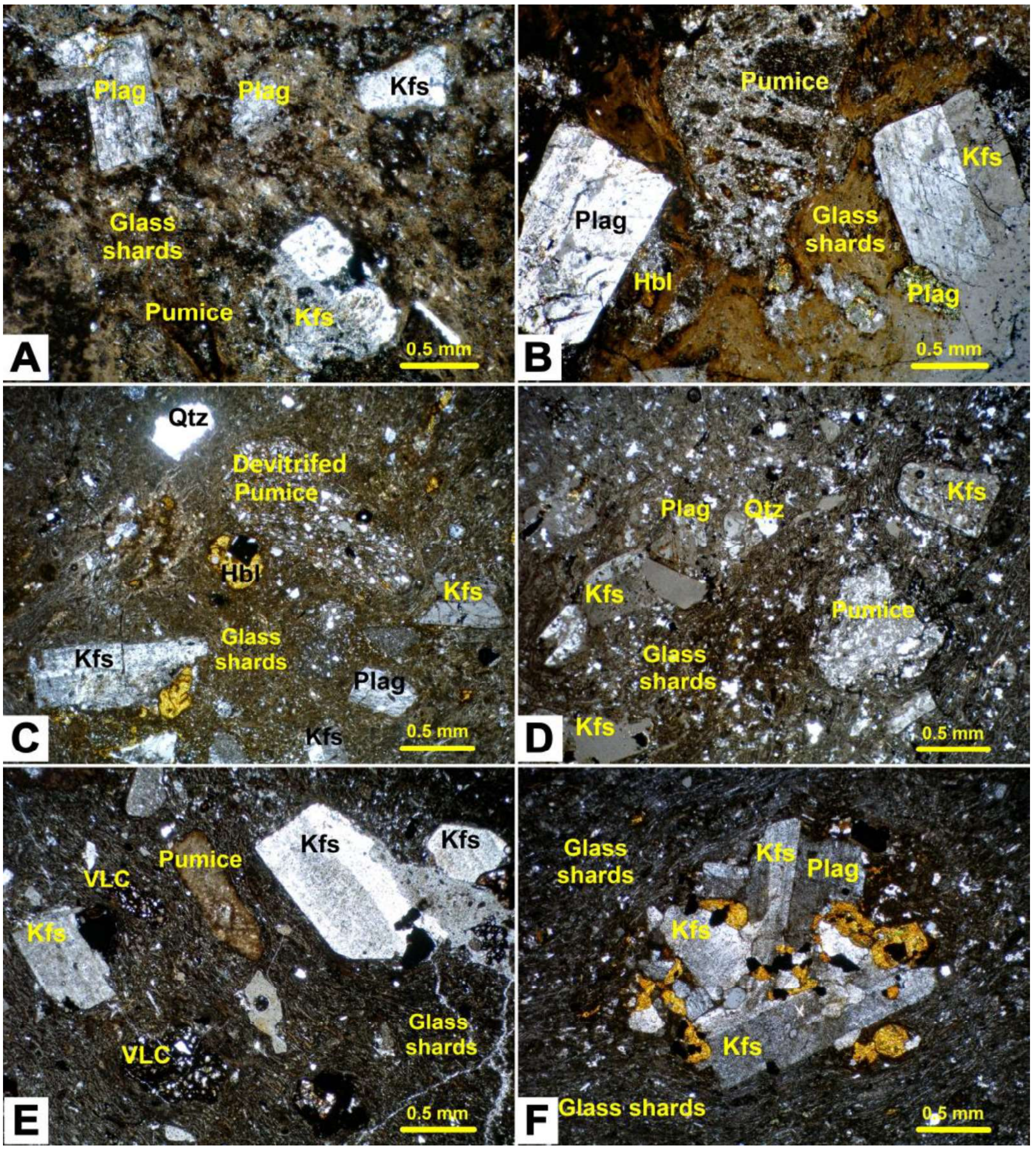

Figure 11. Microscopic image of the: **(A)** Ciula Mică 1 eruptive product; **(B)** Ciula Mică 2 eruptive product; **(C)** Ciula Mică 3 eruptive product; **(D)** Ciula Mică 4 eruptive product; **(E)** Peştenița 1 eruptive product; **(F)** Peştenița 2 eruptive product (cross-polarized light). Abbreviations: Plag–plagioclase feldspar, Kfs–potassium feldspar, Qtz–quartz, Hbl–hornblende, VLC– volcanic lithic fragment.

5. DISCUSSION

5.1. GENETIC INTERPRETATION OF THE CIULA MICĂ, PEŞTENIȚA, AND CRIVA ERUPTIVE PRODUCTS

Lithological and petrographic characteristics of the Ciula Mică, Peştenița, and Criva eruptive products indicate that they represent fragments of primary volcaniclastic deposits resulted from explosive volcanic eruptions. More specifically, they are fragments of ignimbrite deposits. Ignimbrites are produced by pyroclastic density currents (PDCs), which are dense, highly-mobile, hot currents of dispersed gas and particles, generated by magma fragmentation during highly explosive volcanic activity (e.g., Wright and Walker, 1981; Cas and Wright, 1987; Branney and Kokelaar, 2002; Lube *et al.*, 2020).

Whole-rock geochemical data showed that the Peştenița 1 ignimbrite is of trachytic composition (Vornicu and Seghedi, 2025). The chemistry of the Ciula Mică and Criva products has not been determined as yet. However, by using the compositional properties of Peştenița 1 as a reference, in combination with analysis of the mineral types and their proportions, we established that the Ciula Mică, Peştenița 2, and Criva ignimbrites also have an intermediate to acidic composition that corresponds to the trachyte category.

Ignimbrites are defined as generally massively textured and poorly sorted pyroclastic flow deposits, which consist of variable amounts of crystals, pumice, and lithic clasts of various sizes, within a glass-rich, fine-grained matrix (e.g., Sparks, 1976; Wilson, 1986; Cas and Wright, 1987; Branney and Kokelaar, 2002).

The ignimbrite nature of the Ciula Mică, Peştenița, and Criva products is evidenced by textural properties such as the massive texture, poor sorting and the lack of stratification and grading, which define this type of pyroclastic rocks (e.g., Wilson, 1986; Branney and Kokelaar, 2002; Brown and Andrews, 2015; Douillet *et al.*, 2015; Báez *et al.*, 2020).

The Ciula Mică 2, 5, and Peştenița 1 ignimbrites do locally show some normal, fine stratification and lamination, suggesting that at the initial moment of emplacement they were, at least, partially stratified. The occurrence of local stratification implies a transitory, unsteady flow regime or the interference of multiple pulses of flow during the eruption (e.g., Sigurdsson *et al.*, 1984; Sulpizio *et al.*, 2007; Brand *et al.*, 2016) that was probably controlled by paleotopography (e.g., Cas *et al.*, 2011).

Compositional properties of the Ciula Mică, Peştenița, and Criva ignimbrites that were discussed in detail in previous sections, are in good agreement with the typical compositional profile of ignimbrites, as per the above definition. Based on grain-size parameters, that is the particle diameter coefficient (Φ) = 2 and particle median size MdΦ = 0.25, the ignimbrite fragments are products rich in fine ash corresponding to size fraction category D (Fig. 12).

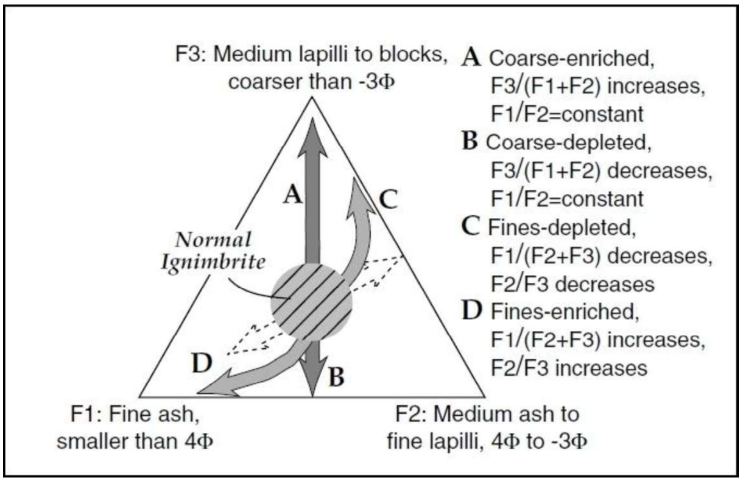

Figure 12. Illustration of selective enrichment and depletion of certain grain size fractions in ignimbrite deposits (from Freundt *et al.*, 2000).

The general massive texture and poor sorting, as well as the high content of fine ash and low abundance of ground surface lithic (accidental) clasts indicate highly concentrated and less energetic pyroclastic flows that were characterised by low levels of turbulence and mobility, as well as low erosional capacity of surface material (e.g., Cas *et al.*, 2011). These assumptions are also supported by the high emplacement temperature and the degree of welding (see below).

Based on textural characteristics, ignimbrite deposits can be welded or non-welded (e.g., Riehle, 1973; Wilson, 1986). Welding consists of post-depositional cohesion and deformation of juvenile particles at temperatures above the glass-transition threshold, resulting in the complete elimination of pore space and compaction of the deposit (e.g., Smith, 1960a; Wilson, 1986; Cas and Wright, 1987). As shown above, the plastic deformation of hot, viscous pumice particles and glass shards with high temperature and viscosity, produces flattened and deformed structures called *fiamme* and the deposit acquires a texture that is defined as eutaxitic (e.g., Smith, 1960b; Wilson, 1986; Quane and Russell, 2005a). The degree of welding of ignimbrites mainly depends on their composition, emplacement temperature, and deposit thickness (e.g., Ragan and Sheridan, 1972; Moon, 1993; Quane and Russell, 2005b; Brown and Andrews, 2015).

The Ciula Mică, Peștenița, and Criva ignimbrites are generally characterised by the lack of porosity and the occurrence of welding texture, implying that at the moment of deposition the temperature, composition, and deposit thickness criteria were fully met, allowing the initiation of the welding process. In the case of the Ciula Mică 4 ignimbrite there are no visible *fiamme,* even though it completely lack porosity and is highly cemented. A possible explanation can be the reduced pumice content, so the post-depositional welding or compaction was primarily achieved by elimination of the pore space.

We attempted to measure the degree of welding of the Ciula Mică, Peștenița, and Criva ignimbrites by using the strain ratio or the horizontal (a) to vertical (b) axis ratio of pumice and vitric shards (Fig. 13; Sheridan and Ragan, 1976). By observing this ratio, we assess that the Ciula Mică 1, 2, 3, and 5 ignimbrites are moderately to densely welded, whereas Ciula Mică 4 displays a rather moderate degree of welding. The Peștenița 1, Peștenița 2, and Criva ignimbrites are characterized by a moderate degree of welding, with defined eutaxitic texture.

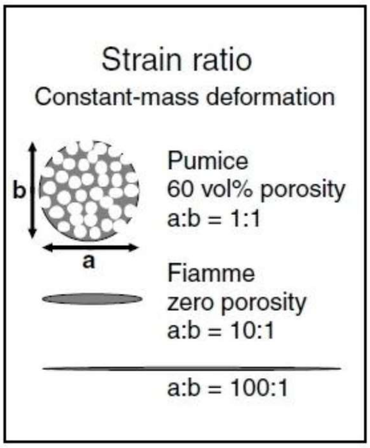

Figure 13. A measure of the strain ratio using the horizontal (a) to vertical (b) axis ratio of *fiamme* and vitric shards in ignimbrite deposits (Sheridan and Ragan, 1976); the image is from Frundt *et al.* (2000).

In this paper, in order to evaluate the degree of welding of the Ciula Mică, Peștenița, and Criva ignimbrite blocks, we use the welding intensity scale by Quane and Russel (2005a). This classification scheme comprises six ranks, from I to VI, that are distinguished by certain microscopic and macroscopic physical characteristics. As per the above classification, the degree of welding of the

Ciula Mică 1, 2, 3, and 5 ignimbrites can be described by rank IV-V, while that of the Ciula Mică 4 ignimbrite can be assigned to rank III-IV, corresponding to moderate up to relatively high welding (Fig. 14). The degree of welding of the Peştenița 1, Peştenița 2, and Criva ignimbrites is rather moderate and corresponds to rank IV of this classification scheme (Fig. 14).

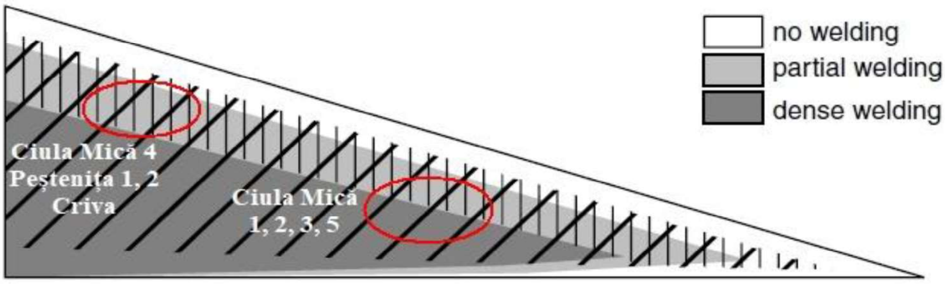

Figure 14. Welding and crystallisation zones in a schematic section through a welded ignimbrite (from Freundt *et al.*, 2000).

Ignimbrite deposits are typically characterised by particular microscopic textures that are not normally present in other types of primary volcaniclastic deposits. In the case of the Ciula Mică, Peştenița, and Criva ignimbrites, we observe the occurrence of glass shards, spherulites, and patterns that closely resemble granophyric texture (see section 4.2.; e.g., McPhie *et al.*, 1993). These textures are direct evidence that the ignimbrites were originally deposited as high-temperature pyroclastic products, because they are exclusively formed from glass devitrification at high temperatures (e.g., Smith, 1960b; McPhie *et al.*, 1993).

5.2. INITIATION MECHANISMS AND DEPOSITIONAL CHARACTERISTICS

Pyroclastic flow deposits or ignimbrites are formed during large-scale explosive volcanic events and can be produced by multiple initiation mechanisms, of which the most common are: the collapse of the ash column, laterally or low-angle directed explosions and caldera-forming collapse (e.g., Sparks and Wilson, 1976; Hoblitt *et al.*, 2000; Neri *et al.*, 2002; Kandlbauer and Sparks, 2014). The largest and most voluminous PDCs are formed from highly viscous, silicic calc-alkaline magmas, during eruptions that cause caldera-forming collapse (e.g., Wilson *et al.*, 1980; Cas and Wright, 1987).

When dealing with very old volcanic products that are affected by various types of alteration or tectonic processes, accurately establishing the eruption-related processes that generated them can be difficult. Nevertheless, certain lithological features such as composition, grain parameters or some textural characteristics such as welding, are useful in restraining the emplacement mechanism and the general eruption style (e.g., Wright *et al.*, 1980).

Brief descriptions of Laufer (1925) suggest that the Ciula Mică, Peştenița, and Criva ignimbrites are in some instances associated with fallout deposits, although the presence of fallout deposits could not be confirmed by field observations in the case of each ignimbrite block. The occurrence of fallout deposits could mean that during the eruptions, the conditions allowed the formation of a sustained eruption plume, from which volcanic ash directly accumulated. This aspect suggests that the ignimbrites could have been produced by ash column collapse, corresponding to an initial Plinian phase, which may have led to caldera-forming collapse. Anyway, the process of caldera-forming collapse cannot be determined with absolute certainty only from the lithology of the available ignimbrite fragments. The occurrence of multiple volcanic events closely related in space and time dominated by ignimbrite-forming eruptions, indicates a period of intense silicic volcanism, known as an ignimbrite flare-up (e.g., Coney, 1978; de Silva and Gosnold, 2007).

The accessory metamorphic lithic content is indicative of a high degree of explosiveness of the eruptions because dislodging rock fragments from the crystalline basement is a process that requires a great amount of energy, suggesting large-magnitude eruptive events (e.g., Houghton and Nairn, 1991; White, 1991; Houghton *et al.*, 2000a).

The intensity of the eruptions is also reflected in the high degree of magma fragmentation, which can be estimated by the median size of the juvenile particles and grain-size distribution (e.g., Zimanowski *et al.*, 1997; Cioni *et al.*, 2000; Alatorre-Ibargüengoitia *et al.*, 2010). The abundance of fine-grained material is an important indicator of volcanic events of Plinian type (e.g., Cioni *et al.*, 2000). A possible interaction between magma and water from an external source during the eruptions cannot be completely ruled out because in comparison with pure magmatic eruptions, phreatomagmatic events produce a higher proportion of fines (e.g., Self and Sparks, 1978; Houghton and Wilson, 1989; Morrissey *et al.*, 2000). It is important to mention that grain-size distribution in ignimbrites can be modified by dynamic processes such as: (1) fragmentation in the vent, (2) segregation of certain components during pyroclastic material transport and emplacement, (3) fragmentation and abrasion during transport or incorporation of surface material (e.g., Freundt *et al.*, 2000). In the case of the Ciula Mică, Peştenița, and Criva ignimbrites the general assessments of these parameters is not possible however, we can make rough estimations based on observations of the available material.

Compositional analyses showed that all ignimbrite fragments from the three locations are mostly composed of fine ash, with the largest part of the ignimbrite volume being represented by the cryptocrystalline fraction. There are no significant changes in grain-size with the type of deposit or location but it was observed that the juvenile clasts in the Peştenița and Criva ignimbrites have a lower median size (see section 4.1.2.). The juveniles are usually platy or angular and the pumice clasts exhibit different degrees of porosity, from low to high. The pumice particles in Ciula Mică 2 and 5 have the highest degree of porosity.

The Ciula Mică, Peştenița, and Criva eruptive products are welded ignimbrites. The welding process depends primarily on deposit composition and the temperature at the moment of sedimentation, including the cooling rate of the pyroclasts (e.g., Smith, 1960b; Wilson, 1986). Whole rock geochemical analyses have shown that the Densuş, Răchitova, and Peştenița eruptive products belong to the calc-alkaline and high-K calc-alkaline magma suite (e.g., Vornicu and Seghedi, 2025). Although the chemistry of the Ciula Mică and Criva ignimbrites has not been determined as yet, given their similar lithology and petrography, we assume that they were also produced by calc-alkaline melts, generated by a similar magmatic source. For calc-alkaline magmas, typical minimum temperatures for deposit welding are in the range 500–700ºC (e.g., Walker, 1983; Freundt *et al.*, 2000). Using the chemical data of Peştenița 1, we employed the zircon saturation thermometry in order to calculate the magma crystallisation temperature (Watson and Harrison, 1983; Harrison *et al.*, 2007). Calculations yielded an estimated temperature of approximately 750ºC, which is in accord with the accepted values for calc-alkaline magmas. Some temperature drop takes places between magma fragmentation and emplacement, due to air entrainment in the eruption column or during the flow, the interaction with surface water or incorporation of accidental lithic clasts and vegetation (e.g., Branney and Kokelaar, 2002; McClelland *et al.*, 2004; Todesco *et al.*, 2006). McClelland *et al.* (2004) and Lesti *et al.* (2011), for instance, estimated that the maximum temperature loss from magmatic temperature due to the above mentioned reasons is of around 200ºC. As far as the Ciula Mică, Peştenița, and Criva ignimbrites are concerned, there is no clear evidence of the interaction of the flow with surface water or significant ingestion of vegetation or accidental lithic fragments. Therefore, we infer that the emplacement temperature could not have been much lower than the magmatic temperature. The estimated temperature of around 600ºC, is in good agreement with the emplacement temperature of some large-volume, calc-alkaline ignimbrites, such as Cerro Galán in Argentina (e.g., Lesti *et al.*, 2011).

Deposit thickness is amongst the most important factors that control the degree of welding in ignimbrites. The greater the thickness, the larger the rate of welding. Although the Ciula Mică, Peşteniţa, and Criva ignimbrites are small-sized fragments, to achieve the observed degree of welding from moderate to relatively high, their initial thickness must have been much higher especially near the vent, perhaps of a few hundreds of meters. These thicknesses correspond to large-volume ignimbrites generated by volcanic systems distinguished by a high output rate (e.g., Riehle, 1973; Sparks and Wilson, 1976; Freundt *et al.*, 2000; Neri *et al.*, 2002).

The shape of ignimbrites is usually described by their aspect ratio, which is the ratio of the average deposit thickness to their total extent and depends mainly on the velocity of the PDC (e.g., Walker *et al.*, 1980; Wilson and Walker, 1981, 1982). High-aspect ratio ignimbrite deposits are thick and usually restricted to smaller areas surrounding the volcanic vent, whereas low-aspect ratio ignimbrites are thin and affect large areas (e.g., Walker *et al.*, 1980). The degree of welding of the Ciula Mică, Peşteniţa, and Criva ignimbrites suggests that these were originally part of high-aspect ratio deposits.

No vertical variations in composition, texture, density or degree of welding have been observed anyway, as highlighted in the text, the studied ignimbrites represent only small fragments of the total deposits. Simple zonation and the lack of variation in the degree of welding describe a *simple cooling unit* (e.g., Smith, 1960b; Freundt *et al.*, 2000). The Ciula Mică ignimbrites likely represent simple cooling units and were probably emplaced in a short period of time. For instance, the ignimbrite generated by the 186 AD Taupo eruption in New Zealand, was emplaced in about 400 seconds (Wilson, 1985). We infer that each individual ignimbrite fragment of the Ciula Mică area may have been part of different eruptive units associated to a singular volcanic source but because of the current stratigraphic context of these fragments, the number of volcanic sources cannot be established with certainty. The Peşteniţa 1 and 2 ignimbrites are found in the same location and share almost identical lithological characteristics. Although the contact between the two ignimbrites is not visible, their field position suggests that Peşteniţa 1 is partially overlain by Peşteniţa 2. This means that the two eruptive products were likely produced by the same volcanic source and are considered different lithologic units, as well as different cooling units. The Criva ignimbrite has a lithological profile that is identical to that of Peşteniţa 1 (see section 4.1.2.), meaning that most probably they are pieces of the same ignimbrite deposit.

In the proximity of the volcanic vent, ignimbrite deposits are especially rich in lithic breccia and lithic fragments detached from the crystalline basement and conduit walls that can have a wide range of sizes, from millimetre-sized fragments to meter-sized boulders (e.g., Druitt and Sparks, 1982; Walker, 1985). Is has been shown that the size of the lithic fragments, as well as that of the juvenile particles, decreases exponentially with distance from the vent (e.g., Druitt and Sparks, 1982; Freundt *et al.*, 2000). Therefore, the size of the accessory lithic fragments can be used to roughly estimate the outflow distance from the source, in situations in which the vent was destroyed or obscured. Based on the size criterion, we interpret that the fragments constituted the distal facies of the former volcanoes.

5.3. RELATIONSHIP BETWEEN THE CIULA MICĂ, PEŞTENIŢA, AND CRIVA IGNIMBRITE FRAGMENTS AND THE SURROUNDING UPPER CRETACEOUS CONTINENTAL AND MARINE DEPOSITS

The Ciula Mică 1, 2, 3, 4, and 5 welded ignimbrites that were considered in detail in this paper are exposed in different locations inside the Ciula Mică village and along the Geat Valley, near Ciula Mică (Fig. 1). As discussed, they are characterised by a peculiar stratigraphic position, occurring as blocks incorporated in thick, coarse-grained conglomerates striking NW-SE, which crop out over relatively large areas around Ciula Mică (Figs. 2, Appendix-A1; Laufer, 1925; Albert *et al.*, 2025).

The same conglomerate deposits also crop out in the Peştenița area and the Peştenița 1 and 2 ignimbrites appear as blocks embedded in these deposits. Interestingly enough, unlike Ciula Mică and Peştenița ignimbrites, the Criva ignimbrite is in direct contact with the marine Răchitova Formation (Fig. 1).

These greyish, basal conglomerate beds discordantly overlay the marine Răchitova Formation (Fig. 2) and predominantly consist of poorly sorted sedimentary and metamorphic lithic clasts, set in a sandy, loosely consolidated matrix and their thickness ranges from a few m to tens of m (Fig. 15a; Albert *et al.*, 2025). The lithic fragments are mostly sandstones, siltites, quartzites, and schists and cover a wide range of sizes, from a few mm up to a few tens of cm and commonly are sub-angular and sub-rounded (Fig. 15b). Albert *et al.* (2025) interpreted the coarse-grained conglomerate beds as alluvial deposits and are overlain by other types of sedimentary deposits of alluvial type, with comparable lithological characteristics (Fig. 2).

Figure 15. **(a)** Coarse-grained conglomerate deposits of alluvial type that crop out in the Ciula Mică and Peştenița areas of the Hațeg Basin; **(b)** Close-up image of the alluvial deposits, which predominantly consist of sedimentary and metamorphic lithic fragments, set in a poorly consolidated matrix.

Albert *et al.* (2025) carried out zircon U-Pb dating of three samples of reworked volcanic material (LL16, LL17 and LL18) exposed along the Geat Valley, near the base of the alluvial deposits, close to the boundary with the Răchitova Formation. Although it crops out in the proximity of the Ciula Mică 4 ignimbrite (Appendix–Fig. 1A), since there is no visible contact in the field it is not clear whether there is a genetic relationship between the dated volcanogenic material and the ignimbrite blocks. The geochronology analyses of Albert *et al.* (2025) yielded ages of 79.75 ± 0.69, 79.10 ± 0.73 and 72.96 ± 0.97 Ma. These results are partially in agreement with the absolute ages of the Densuş and Răchitova volcaniclastic successions, of about 80–82 Ma, which were dated via zircon U-Pb and K-Ar radiometric methods (Bojar *et al.*, 2011; Vornicu *et al.*, 2023).

Because the ages of the Ciula Mică, Peştenița, and Criva ignimbrites have not been determined as yet, the temporal relationship between these and the Densuş and Răchitova volcaniclastic successions is not clear. Nonetheless, geochemical and petrogenetic data combined with comparative studies, suggest that all volcaniclastic products of the Hațeg Basin are genetically related (Vornicu and Seghedi, 2025), so they should be of about the same age, maybe with small differences, regardless of location or genetic type. The recent geochronology data of Albert *et al.* (2025) suggests that, in comparison with the Densuş and Răchitova eruptive successions, the Ciula Mică welded ignimbrites might be somewhat younger. In any case, as specified, the genetic link between the dated volcanogenic material and the ignimbrite blocks that represent the object of this study is not fully understood.

In summary, field observations indicate that the Ciula Mică, Peştenița, and Criva welded ignimbrites are remnants of primary volcaniclastic deposits with much greater initial thickness and were, most likely, detached from a proximal volcanic source. The location of the volcanic centres is unknown. We favour an interpretation that the re-sedimentation of these fragments took place long after the cessation of volcanic activity because, once volcanism comes to a complete halt, it can take from a few thousand up to millions of years for the volcanic structures to disintegrate (e.g., Singer *et al.*, 1997; Davidson and De Silva, 2000). Similarly, the Densuş and Răchitova volcaniclastic successions and products are small-sized fragments of former volcanic edifices and volcaniclastic deposits that were presumably tectonically transported and re-arranged in their current position during the Late Cretaceous. However, unlike the welded ignimbrite fragments, they are not directly associated with other types of continental deposits.

The processes that allowed the mobilisation and re-sedimentation of the Upper Cretaceous ignimbrite fragments, resulting in their their present-day stratigraphic position, as blocks associated with alluvial deposits, are still a matter of debate. At first sight, the alluvial deposits and the ignimbrite blocks appear to have been deposited during a single event but the mechanisms behind such a scenario cannot be easily explained. As an alternative hypothesis, we suggest that the Upper Cretaceous alluvial deposits may have been deposited after the re-sedimentation of the ignimbrite blocks. Erosion processes would have later exposed the upper parts of the ignimbrite blocks. This view implies that the Ciula Mică and Peştenița ignimbrite blocks, similar to the Criva ignimbrite and the Densuş/Răchitova volcaniclastic products, are also in direct contact with the marine Răchitova Formation, although the contact is not visible in the field. The general absence of smaller-sized volcaniclastic fragments throughout the conglomerate accumulations supports this idea. This interpretation would also explain why the Criva ignimbrite is in contact with the marine deposits, while the Peştenița 2 ignimbrite is embedded in the conglomerate beds, since both appear to be fragments of the same primary pyroclastic deposit.

As mentioned, the volcaniclastic successions and products of the Haţeg Basin are regarded by some authors as the Lower Member of the continental Densuş-Ciula Formation. The ages of the Middle and Upper Members of this formation were estimated to Lower and Upper Maastrichtian (e.g., Vasile *et al.*, 2011a, b; Csiki-Sava *et al.*, 2016; Botfalvai *et al.*, 2021). The Early Campanian ages and the stratigraphy of the volcaniclastic products, as well as certain volcanological aspects that were addressed here, indicate that the Late Cretaceous volcanic activity developed much earlier, most probably in a geodynamic environment that is different from the one that enabled the sedimentation of the largely Maastrichtian continental deposits of the Densuş-Ciula Formation. However, the sedimentation of the continental beds within the Haţeg Basin may have been indeed a continuous process. The volcaniclastic products, at least in the Densuş and Răchitova localities, may represent a different lithostratigraphic unit, a hypothesis already advanced by Vornicu *et al.* (2023). This view is reinforced by the occurrence of the Ciula Mică, Peştenița, and Criva ignimbrites as re-sedimented deposit fragments, suggesting that the actual Late Cretaceous volcanism may not be related with the sedimentation of the younger Densuş-Ciula Formation.

6. CONCLUSIONS

Multiple fragments of Upper Cretaceous eruptive products crop out in the Ciula Mică, Peştenița, and Criva areas of the Haţeg Basin. These products are genetically related with the volcaniclastic successions and products that are exposed in several other locations within the basin, such as Densuş and Răchitova, and are of about the same age. There are no volcanic centres in the Haţeg area so these eruptive products cannot be linked to a specific volcanic source and the location of the Late Cretaceous volcanism is not yet known.

Detailed lithologic and petrographic analyses showed that the Ciula Mică, Peştenița, and Criva eruptive products represent small-sized pieces of welded ignimbrite deposits produced by high-temperature PDCs during large-scale, silicic volcanic manifestations of Plinian type. The ignimbrite deposits were likely produced by multiple volcanic events closely related in space and time, pointing to a period of ignimbrite flare-up. The volcanic centres were probably of caldera type, fed by large volumes of calc-alkaline melts.

Lithological features strongly suggest that the initial ignimbrites were high-aspect ratio deposits, tens or even hundreds of meters thick. The Ciula Mică, Peştenița, and Criva ignimbrite fragments were likely part of the distal facies of the pyroclastic deposits.

The Ciula Mică and Peştenița welded ignimbrites fragments are found in an unusual, rarely observed stratigraphic position, occurring as blocks associated with coarse-grained alluvial deposits. The fragments were detached from primary pyroclastic deposits and re-sedimented after the cessation of volcanic activity yet, the processes involved are not fully understood. A possible interpretation of the stratigraphic configuration of the Ciula Mică and Peştenița areas is that the sedimentation of the alluvial deposits post-dates the emplacement of the ignimbrite fragments. However, to confirm this assumption further investigations are required.

Geochemical and petrographic data showed that all Upper Cretaceous volcaniclastic products of the Haţeg Basin are genetically related and should have similar ages. The occurrence of the Ciula Mică, Peştenița, and Criva ignimbrites as re-sedimented pieces of larger volcaniclastic deposits associated with conglomerate deposits, indicates that the volcanic activity that produced them took place time before the formation of the largely Maastrichtian continental deposits that are now grouped into the Densuș-Ciula Formation.

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APPENDIX

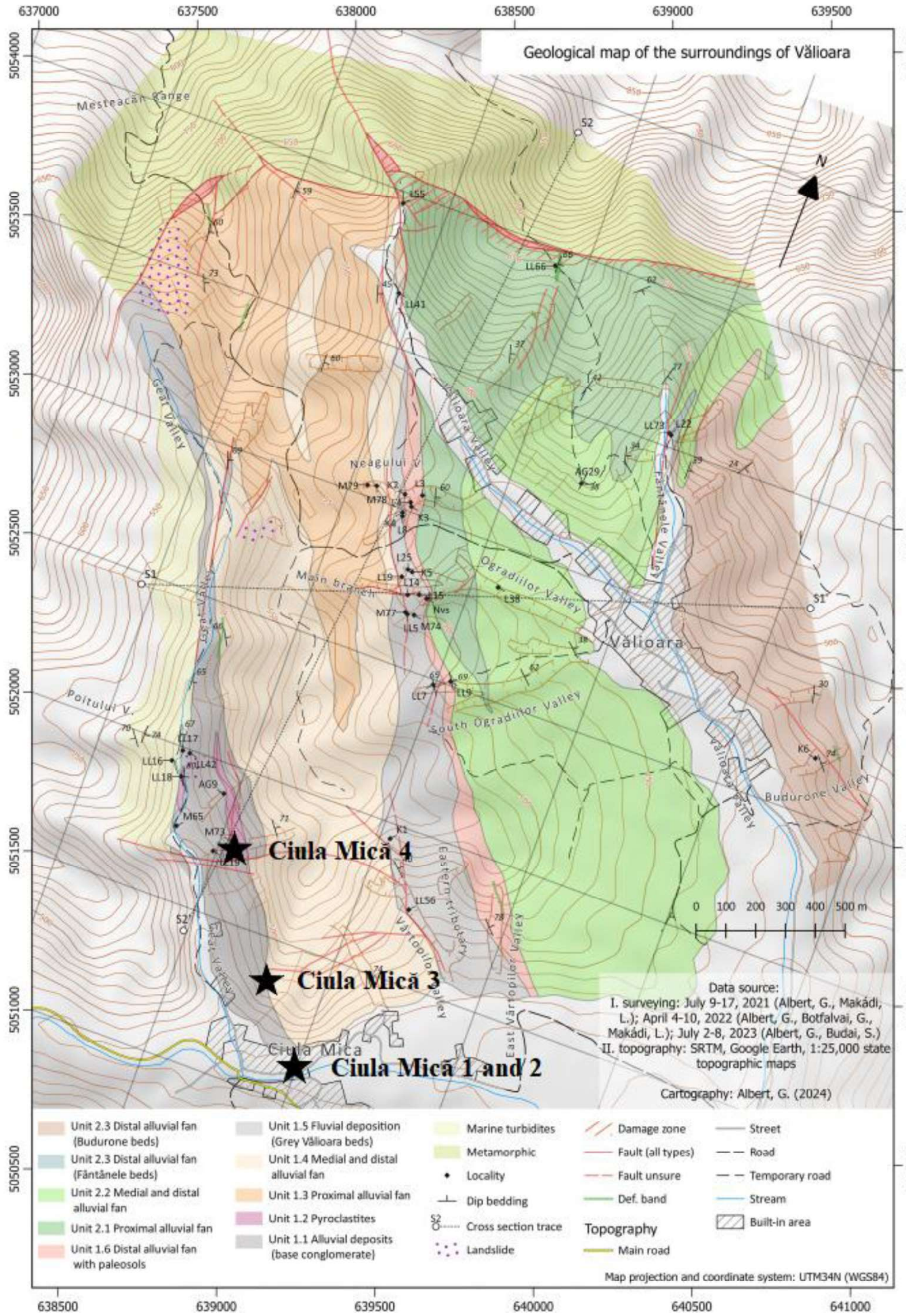

Fig. A1 Detailed geological map of the Ciula Mică and Vălioara areas of NW Hațeg, showing the main depositional units (from Albert *et al.*, 2025). The location of the Ciula Mică 1, 2, 3, and 4 welded ignimbrites is marked with a black star. The location of Ciula Mică 5 ignimbrite is outside the mapped area.