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Middle Triassic autoclastic deposits in the vicinity of Bosansko Grahovo (SW Bosnia and Herzegovina)

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Abstract

Middle Triassic volcaniclastic rocks have been recognized at several localities in the vicinity of Bosansko Grahovo, in the southwestern part of Bosnia and Herzegovina in the External Dinarides. Peculiar types of autoclastic rocks were investigated. These are **peperites** and **hyaloclastites**. Regarding specific structures, mineral composition and micropetrographic characteristics hyaloclastites observed at section Bosansko Grahovo I represent genetic succession. It was possible to further differentiate hyaloclastites into a) *in situ* hyaloclastites, b) slightly resedimented hyaloclastites and c) resedimented hyaloclastites. Genesis of peperites is related to lava emplacement in unconsolidated water saturated pelagic lime mudstones. *In situ* hyaloclastites and slightly resedimented hyaloclastites were formed due to quenching at the contact of basaltic lava effusions with sea water. Detritus of resedimented hyaloclastites, where volcanic rock fragments are mixed with limestone/chert clasts, imply reworking after fragmentation and redeposition possibly in the vicinity of primary volcanic basalt effusion. All rock types occurred in the deep sea troughs that formed as a consequence of Middle Triassic extensional tectonic and rift related wrench faulting. All investigated rock types represent the first findings of autoclastic deposits in the External Dinarides. Biostratigraphic constraints achieved by means of conodont species *Neogondolella excentrica, Paragondolella excelsa, Paragondolella trammeri* and *Gladigondolella tethydis* indicate Late Anisian to Early Ladinian interval of the autoclastic deposits from Bosansko Grahovo.

Keywords
autoclastites, hyaloclastites, peperites, Middle Triassic, External Dinarides, Bosnia and Herzegovina

1. Introduction

The investigated Middle Triassic volcaniclastic deposits are located in Southwestern Bosnia and Herzegovina (geotectonic unit of the External Dinarides), in the vicinity of Bosansko Grahovo. Investigated rocks crop out along the road cut Knin - Bosansko Grahovo (see **Figure 1)**.

Very specific genetic types of volcaniclastics were described for the first time in the Dinarides. Their discovery helps in understanding the complex tectonic movement in the Middle Triassic that started as rift or half-rift faulting accompanied by volcanic intrusion/effusions but then abruptly ended in the late Middle Triassic ("aborted rifting phase" according to **Ferrarra & Innocenti, 1974; Bechstädt et al., 1978**).

Middle Triassic extensional tectonic and wrench faulting started after a deposition on a passive continental margin in the Early Triassic (**Aljinović et al., 2014**). Already in the Anisian, rifting took place with the intensive lifting of tectonic blocks (**Hrvatović, 2006**). Rifting has been accompanied by emplacement of intrusive and effusive volcanism. Intrusive

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rocks of the Middle Triassic rift phase are represented by the well-known Jablanica gabbro (**Pamić, 1996; Hrvatović, 2006**), while effusive varieties are represented by andesites of Senjska Draga (**Lugović & Majer, 1983**), basalts and volcaniclastic rocks near Pazarište on Velebit Mts. (**Poljak & Tajder, 1942, Smirčić et al., 2015**), and in the vicinity of Sinj (**Belak 2000, Aljinović et al., 2010**). In the vicinity of Pazarište Middle Triassic accretionary lapilli were described by **Marci et al. (1990)**, while volcaniclastic deposits near Sinj were investigated and determined as crystaloclastic or vitroclastic tuffs. These tuffs were deposited as a consequence of strong volcanic eruptions on the land or in very shallow sea but were then redeposited by mass flows to deep marine pelagic settings (**Aljinović et al., 2010**). Recent investigations in the vicinity of Bosansko Grahovo resulted in the rather interesting discovery of volcaniclastic deposits. These volcaniclastics are referred to as autoclastic rocks - specific types of volcaniclastic rocks that occur at the transition of submarine volcanic coherent lavas and volcaniclastic rocks. Their significant petrographic and biostratigraphic features are shown in this paper. Their primary structural characteristics elude different genetic processes emphasizing the peculiarity of their emplacement. The main goal of this investigation is to petrographically document and describe autoclastic deposits found for the first time in the External Dinarides.

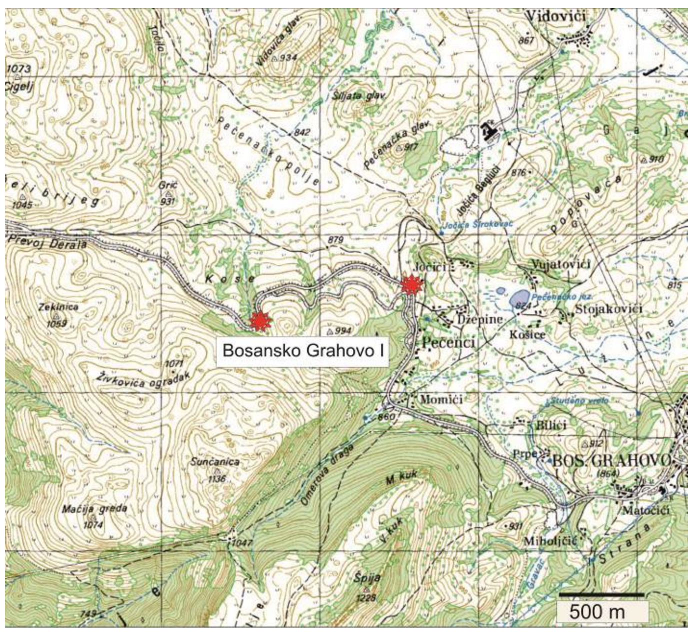

Figure 1. Location map. Outcrops of the autoclastic deposits are marked with an asterisk. Section Bosansko Grahovo I is noted on the map (**DGU, 2007**).

2. Geological setting

According to **Hrvatović (2006)** investigated outcrops belong to the Southwestern Bosnia unit where **Papeš (1985)** differentiated nine smaller tectonic units. Southwestern Bosnia includes several high mountains and several karst valleys (Glamoč, Duvno and Livno). Its southwestern boundary with Dalmatia is defined by the Mts. Dinara and Kamešnica.

The occurrence of volcaniclastic rocks near Bosansko Grahovo was not mapped on the Basic Geological Map SFRY 1:100 000 (**Grimani et al., 1972, 1975**). Anisian and Ladinian sedimentary rocks unconformably overly Early Triassic „Campiller beds“ (**Jelaska et al., 2003**). **Grimani et al.,** (**1975**) supposed that volcanic activity had started after a deposition of „Otarnik breccia“ at the beginning of Anisian, as pyroclastic deposits and first basalt flow. The second basalt flow occurred in the younger volcanogenic-sedimentary complex. Ladinian strata (mostly clastic deposits intercalated with limestones and dolostones) represent transgressive deposits overlying limestones and dolostones ofAnisian age. In the Ladinian marls, limestones, volcanogenic sediments, sandstones, breccias, conglomerates and organic rich clayey deposits have been deposited. The occurrence of Middle Triassic volcaniclastics along with sedimentary rocks indicate an extensional tectonic trend - rift phase formed by normal faulting. Due to normal faulting, several deep sea basins/troughs/rifts occurred with the deposition of pelagic sediments mainly cherts and shales (**Kovács et al., 2010**). At the same time, uplifted blocks envisaged the shallow marine deposition of limestones with algae (*Diplopora*), and dolostones (**Kovács et al., 2010**). Intensive magmatism (intrusive and effusive rocks) accompanied rifting especially in the pelagic realms.

3. Methods

Investigation was carried out by field and laboratory methods. It was conducted on several outcrops where autoclastic rocks crop out (see Figure 1.) but characteristic of the columnar section Bosansko Grahovo I will be presented in this work. Samples of typical autoclastic rocks were selected for further mineralogical and micropetrographical analysis. Thin sections were stained by standard procedure with K-ferricyanide and Alizarine red S. Volcaniclastic rocks were determined according to the classification proposed by **McPhie et al.,** (**1993**). In this classification, structural (macroscopic) rock features infer from their genesis and are taken into account. Genetic classification is related to the volcanic processes, emplacement of magma, erosion and resedimentation of volcaniclastic material. Classification emphasizes differences between deposits produced by coherent lava flows and explosive volcanic events. Genetic terminology differentiates between coherent lavas, synvolcanic intrusions and very densely welded pyroclastic deposits.
Biostratigraphic dating has been made by means of conodonts. Conodont analyses have been conducted in the Geological Survey of Slovenia. Carbonate parts of peperites from the base of the investigated section were collected. Each sample weighed between 5 and 7 kg. Samples were crushed into small pieces (few centimeters) and dissolved in acetic acid. Insoluble residue was further separated in bromoform that has a density of 2,88 g/cm^3. Apatite conodont fragments were then examined under the stereo microscope so conodont elements could be picked from the rest of the heavy mineral assemblage. Separated conodont elements were further examined using a Scanning Electron Microscope JEOL JSM 6490LV at the Geological Survey of Slovenia.

4. Results

4.1. Petrography

Autoclastic rocks that we observed at Bosansko Grahovo I section will be presented in this work (see **Figure 3)**.
According to the macro- and micropetrographical features following types of autoclastic deposits were recognized: **peperites** (see **Figure 4 a, b**) and **hyaloclastites** (presented by the three varieties: ***in situ*** **hyaloclastites**, **slightly resedimented hyaloclastites – Figure 4 c, d**) and **resedimented hyaloclastites (see Figure 11 a, b)**. Although a short covered interval occurred between peperites to hyaloclastites, we consider Bosansko Grahovo I section as continuous **(see Figures 2, 3).**

Figure 2. Outcrop of autoclastic deposits at Bosansko Grahovo I section. Contact between peperites in the lower part (right) and hyaloclastic deposits in the upper part (left) is marked by red line.

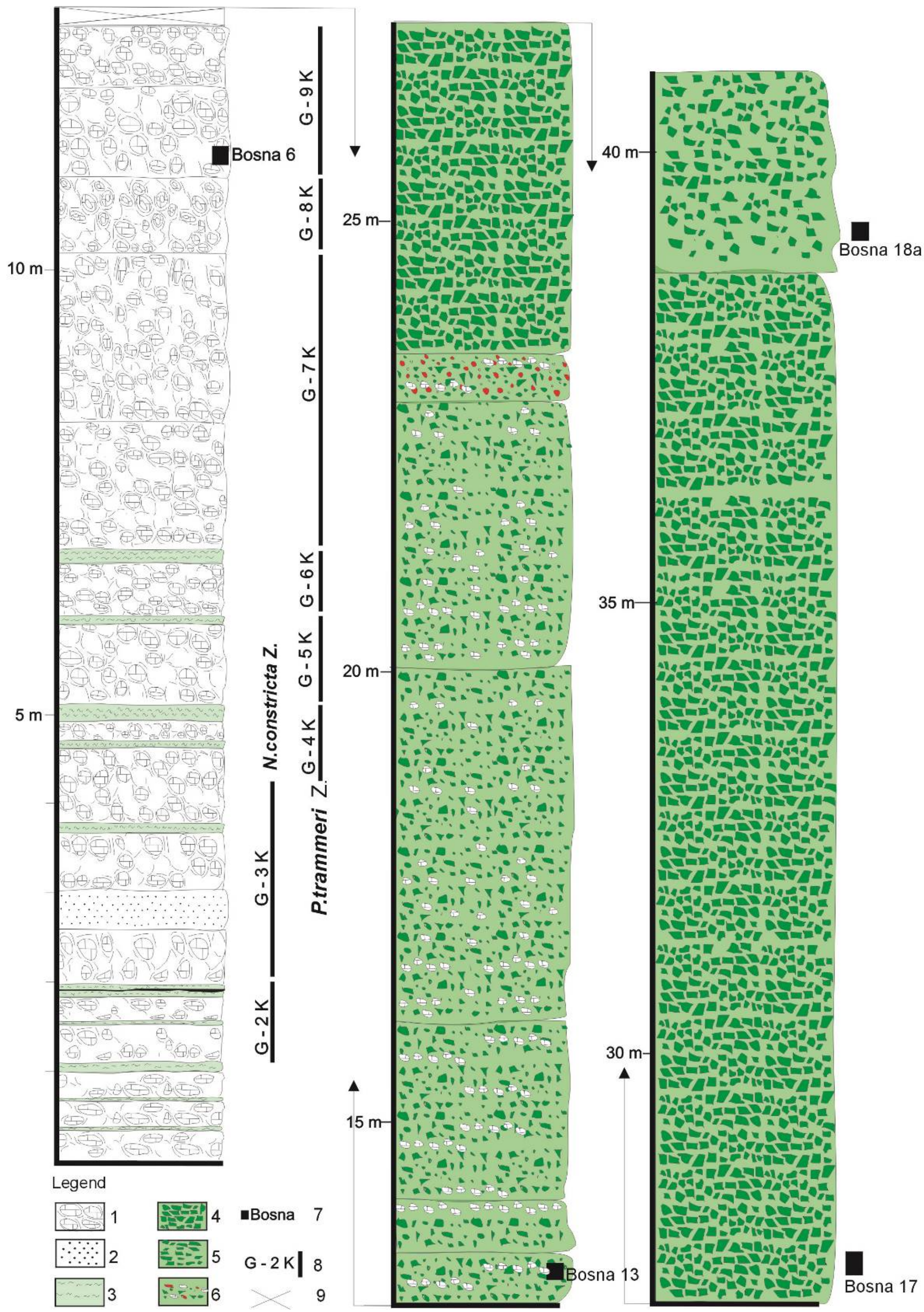

Figure 3. Bosansko Grahovo I section. Legend: 1) limestone fluidal peperite; 2) volcanogenic sandstone; 3) altered volcanic glass; 4) in situ hyaloclastite 5) slightly resedimented hyaloclastite; 6) resedimented hyaloclastites; 7) petrographic samples presented in this paper; 8) conodont samples, vertical lines mark sampled intervals; 9) covered interval.

4.1.1. Peperites

In the outcrops peperites can be recognized as irregular layers, sometimes nodule-like forms of limestone that were formed in contact with magma (see **Figure. 4 a, b**). However, a crude bedding can be observed in the peperites **(see Figure 3)** that are sometimes pronounced by thin interlayers of unconsolidated clay, glass and quartz material. In the hand specimen (see **Figure. 5**) nodule-like forms are separated by a green matrix of magmatic origin. Nodule-forms display white rims which gradually change colour towards red-brown interior. Nodule-forms are well rounded, irregular, ranging from 1 to 3 cm. Transition from nodule-forms to matrix is also gradual. Micropetrographically, clasts consist of calcite (limestone) (see **Figure 6,** top). They are very often silicified and in the interior of clasts tiny crystals of quartz, up to 0.5 mm in size, can be seen. Contact of clasts and matrix is characterized by an intensive green colour stem from the composition of matrix i.e. a large amount of chlorites. Apart from chlorite the matrix contains unaltered volcanic glass or glassy parts are altered to a polymorphic modification of SiO_2.

Interpretation: Emplacement of magma is related to effusion or intrusion, occasionally to pyroclastic material to water saturated sediment. **Busby-Spera & White** (**1987**) identified two textural types of peperites. Peperites of Bosansko Grahovo I according to observed characteristics can be determined as fluidal or globular peperites. Textural differences between fluidal/globular and blocky peperites are a function of grain size, porosity and permeability of a host rock and therefore structurally different peperite types occurred. It can be concluded that the most likely peperites from Bosansko Grahovo I were formed by an interaction of hot lava and wet unconsolidated fine grained mud rich limestone.

Figure 4. Varieties of autoclastic rocks investigated near Bosansko Grahovo. A – part of the succession with limestone peperites (samples G-1K, G-2K), hammer for scale (33 cm); B – Close up view of limestone peperite (samples G-1 K). Limestone parts are rounded, irregular, nodular or layer shaped; C – *in situ* hyaloclastite, with typical *jigsaw-fit* texture where angular, polyhedral clasts tightly fit. Space between the clasts is filled with calcite (white); Pencil for scale 8 cm; D – slightly resedimented hyaloclastite. Clasts are slightly rounded. *Jigsaw-fit* texture is deformed. There is more space between the clasts, recognized by white calcite in the pore space; Glasses for scale 13 cm.

Figure 5. Rounded forms of carbonates (light and red-brown) forming as fluidal/globular peperite (sample Bosna 6).

Figure 6. Photomicrograph of fluidal peperite (sample Bosna 6). Carbonate clast is seen at the top and the matrix (green) formed by a reaction between lava and carbonate sediment. The carbonate origin of the clast can be observed at its edge (arrow) while the clast interior is strongly silicified

4.1.2. Hyaloclastites

There are three types of hyaloclastites that have been differentiated: a) *in situ* hyalaoclastites, b) slightly resedimented hyaloclastites and c) resedimented hyaloclastites.

***In situ* hyaloclastites** (see **Figure 4c**) are massive, green coloured. In their composition, angular clasts occur (see **Figure 7)**. Clasts are sometimes hardly recognizable. Space between clasts is filled with macrocrystalline calcite. Samples of in situ hyaloclastites (as can be seen in sample Bosna 17 - see **Figure 7 and Figure 4c)** exhibit *jigsaw-fit* texture - tightly packed angular fragments/clasts that fit together. Clasts are approximately 3 cm in size, polyhedral and usually not rounded. All clasts have a porphyritic texture, and their mineral composition points to a basaltic origin. Large phenocrystals of ortho- and clinopyroxene as well as plagioclase are immersed in a fine crystalline matrix composed of plagioclase and chlorite (see **Figure 8)** rarely of calcite. Calcite in the clast composition represents a diagenetic alteration of primary composition.

Interpretation: The basic characteristic of this rock type is the presence of angular fragments/clasts and their tight fit forming a *jigsaw-fit* texture. Clasts are formed by the quenching of hot basaltic lava in contact with chilled water. Quenching occurs on the margins of lava domes or the coherent core of lava flows (**McPhie et al., 1993**). *Jigsaw-fit* texture suggests that quenched fragments have not been transported; therefore they can be considered *in situ* hyaloclastites. This interpretation is supported also by the massive appearance of *in situ* hyaloclastites. According to **McPhie et al.** (**1993**) hyaloclastites formed *in situ* can be restricted to narrow areas on the margins of lava flows. These types of hyaloclastites are not stratified, they are strictly monomict, and are in gradual contact with coherent lava. Although direct contact with coherent lava has not been discovered in the Bosansko Grahovo I section, the described features (massive appearance *jigsaw-fitting* and monomict composition) enable the conclusion that this rock type was formed by *in situ* fragmentation, or nonexplosive fragmentation of basaltic lava in contact with water.

Figure 7. Sample of *in situ* hyaloclastite in which a tight fit can be seen (*jigsaw-fit* texture) (sample Bosna 17).

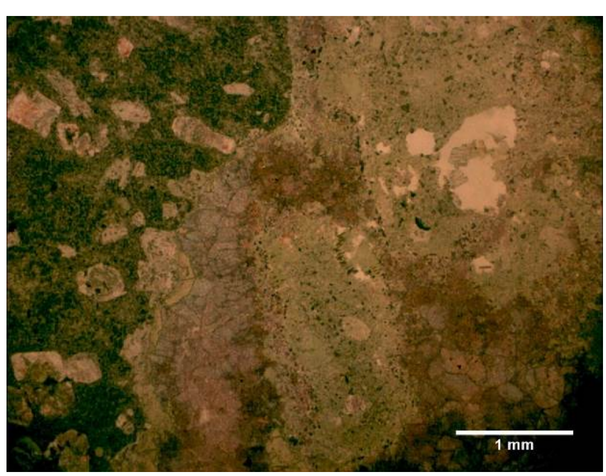

Figure 8. Porphyritic texture in the fragments of *in situ* hyaloclastite (left and right). Calcite (stained pink, middle of microphotograph) represents infill between the clasts (sample Bosna 17)

S**lightly resedimented hyaloclastites** directly overly *in situ* hyaloclastites (represented by sample Bosna 18a). These rocks are also green in colour but clasts are clearly visible and separated by calcite infill – see F**igures 4d & 9.** Clasts are slightly varying in mineral composition and are sub-rounded with diffuse edges. The largest clasts are around 4 cm in size, and the smallest are around 0.5 cm. *Jigsaw-fit* texture is absent in this rock type. In each clast porphyritic texture is clearly seen, with crystals of orthopyroxene, clinopyroxene and plagioclase in a fine crystalline plagioclase and chlorite groundmass implying a basaltic origin (see **Figure 10**). Between the clasts macrocrystalline calcite has been determined (see **Figure 10**).

Interpretation: The described characteristics imply that this variety of hyaloclastic rock type was formed by the accumulation of volcanic clasts. The monomict composition of the clast still prevails but slight variations in mineral composition occurred. According to **McPhie et al.** (**1993**) in the slightly resedimented volcaniclastic deposits texturally unaltered juvenile clasts are dominant, with only slight variations in clast types. The absence of the *jigsaw-fit* texture implies that clasts were slightly moved/resedimented which differs from the *in situ* hyaloclastites. Calcite infill has been interpreted as a primary calcite precipitate (see **Figure 10**).

Figure 9. Slightly resedimented hyaloclastite with a significant presence of clearly distinct volcanic clasts and calcite infill between them. *Jigsaw-fit* texture is absent (sample Bosna 18a)

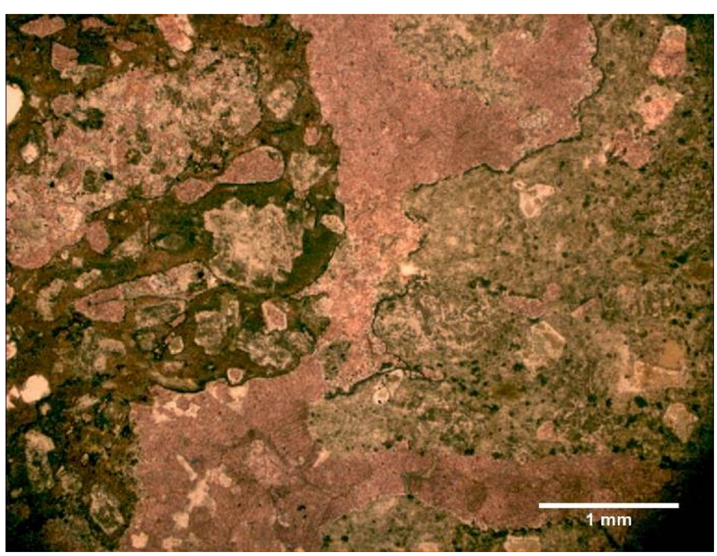

Figure 10. Photomicrograph of the slightly resedimented hyaloclastite. Space between clasts is wider in comparison to the *in situ* hyaloclastite type and filled with macrocrystalline calcite – pale red (sample Bosna 18a)

Resedimented hyaloclastites form more or less distinct layers **(see Figure 2)**. The main characteristic of this hyaloclastic variety is that it consists dominantly of well-rounded cm-size clasts of magmatic origin, but subordinately limestone or chert clasts occur (cm size) **(see Figure 11 a, b)**. The important constituents of resedimented hyaloclastics are fine grained crystaloclasts and volcanic glass accumulated as matrix. Crystaloclasts are mainly plagioclase. Volcanic glass in the matrix is altered to chlorite.

Interpretation: Resedimented hyaloclastic deposits were formed due to the resedimentation of fragmented magmatic rocks that mixed with fragments of limestone or chert. Limestone fragments most likely were derived from peperites. An abundance of crystaloclastic and glassy material in the matrix suggests intensive fragmentation of the source magmatic effusion and subsequent resedimentation. The main difference between resedimented and slightly resedimented hyaloclastics is in the composition of the matrix and clasts: a) there are no limestone/chert clasts in the slightly resedimented hyaloclastics; b) the matrix in resedimented hyaloclastics is a mixture of crystaloclasts and volcanic glass while in the slightly resedimented hyaloclastics space between the fragments consists of precipitated calcite.

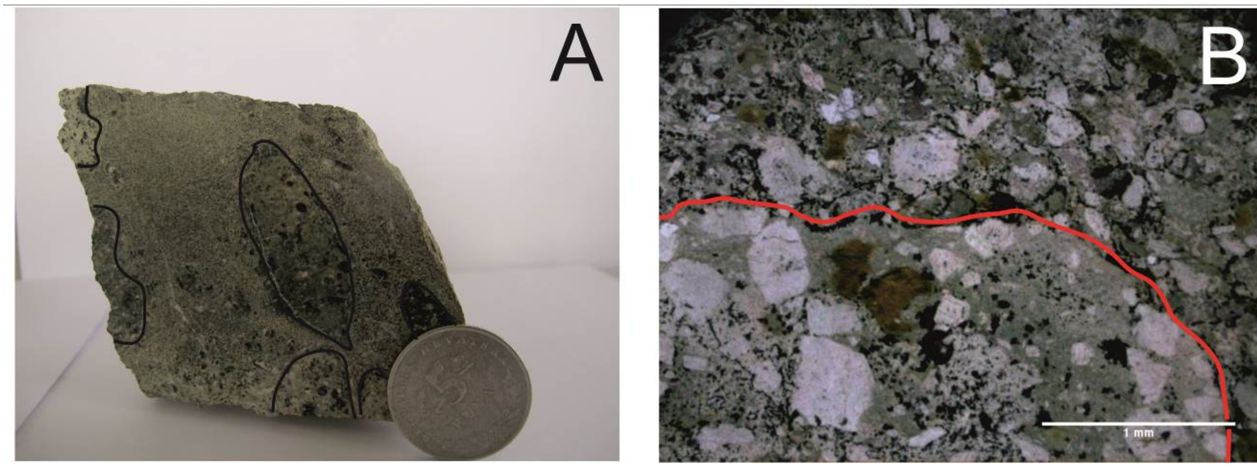

Figure 11. A) Hand specimen of resedimented hyaloclastite (sample Bosna 13). Some of the visible magmatic clasts are outlined (black line). B) Microphotograph of the sample Bosna 13. Magmatic clast with phenocrystals of plagioclase is outlined (red line). Matrix with abundant crystaloclasts is visible above the clast (upper part of microphotograph).

4.2. Biostratigraphic constraints

Biostratigraphic data was available due to the analysis of conodont assemblage from lime parts of the sections (peperites). Conodont elements revealed several conodont species. Samples G2 and G3 (see **Figure 3**) contain *Neogondolella excentrica, Paragondolella excelsa* and *Gladigondolella tethydis* conodont species which determine the *N.constricta* conodont zone. In samples G4 to G9 species *Neogondolella excels, Paragondolella trammeri* and *Gladigondolella tethydis* are discovered characteristic for the *P.trammeri* conodont zone. These conodont species point to the Late Anisian and the Early Ladinian interval.

5. Conclusion

In the External Dinarides, near Bosansko Grahovo (Southwestern Bosnia and Herzegovina) interesting occurrences of volcaniclastic rock types have been investigated. These are autoclastic rocks that have been described for the first time in the External Dinarides. Their macro- and microstructural characteristics imply their specific genesis. The recognized types are **peperites** and **hyaloclastites.** Among the hyaloclastites two varieties were determined: ***in situ*** **hyaloclastites**, **slightly resedimented hyaloclastites** and **resedimented hyaloclastites.**

The occurrence of autoclastites indicates the emplacement of lava in the submarine environment and/or indicates that intrusion took place into the water-saturated sediment. Basaltic hyaloclastites are a major component of ancient and recent submarine rifting sequences. On a local scale, they form several tens of meters thick layers of oceanic crust (**McPhie et al., 1993**). The occurrence of hyaloclastites at the localities near Bosansko Grahovo can also be interpreted as effusions

of basaltic lava in the deep marine environment, supported by the assumption that relatively deep (pelagic) rift basins formed in the Middle Triassic in the External Dinarides (**Marjanac, 2000; Hrvatović, 2006**).
Hyaloclastites of deeper marine areas are typically associated with peperites. Peperites are formed by the mixing of coherent lava or magma with unconsolidated, wet sediment. Peperite is characterized by a clastic texture in which each component can form matrix. Peperites are an important component of mixed sedimentary and volcanic sequences, especially in submarine environments where magma comes into contact with wet unconsolidated sediment while ascending to the surface. In these types of environments they can form effusion or synvolcanic intrusions with peperites occurring at the outer boundaries, which we supposed was the case in the described section of Bosansko Grahovo I.
Peperites from the lower part of the section enabled the analyses of conodont assemblage. The analysed conodont material revealed five species of conodonts occurring in the part of the section with peperites, *Paragondolella excelsa, Gladigondolella tethydis, Neogondolella excelsa* and *Paragondolella trammeri.* The mentioned species indicate a Late Anisian to Early Ladinian interval of the autoclastic deposits in the vicinity of Bosansko Grahovo. Since Late Anisian species were recovered from the peperites, it can be concluded that volcanic activity had already started at the end of the Anisian and continued during the Early Ladinian.

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Sažetak

Srednjotrijaske autoklastične naslage u okolici Bosanskog Grahova (jugozapadna Bosna i Hercegovina)

U okolici Bosanskoga Grahova u jugozapadnome dijelu Bosne i Hercegovine (vanjski Dinaridi) istražen je specifičan tip vulkanoklastičnih stijena – autoklastične stijene srednjotrijaske starosti. Izdvojena su dva osnovna tipa autoklastičnih naslaga: **peperiti** i **hijaloklastiti**. Geneza peperita povezana je s procesima smještanja lave u nekonsolidirane, vodom zasićene vapnenačke madstone koji imaju karakteristike taloženja u pelagičkome okolišu. S obzirom na specifičnu teksturu, mineralni sastav i mikropetrografske karakteristike hijaloklastiti predstavljaju genetski slijed na opisanome lokalitetu Bosansko Grahovo I, te su podijeljeni na a) *in situ* hijaloklastite, b) neznatno pretaložene hijaloklastite i c) pretaložene hijaloklastite. *In situ* hijaloklastiti i neznatno pretaloženi hijaloklastiti nastali su fragmentacijom užarene lave bazaltnoga sastava u doticaju s hladnom morskom vodom, dok pretaloženi hijaloklastiti predstavljaju dominantno vulkanski detritus s kojim je pomiješana mala količina klasta vapnenaca i/ili rožnjaka, te se smatra da je detritus pretaložen nakon fragmentacije, vjerojatno, u blizini primarnih magmatskih izljeva bazaltne lave. Svi tipovi stijena označavaju magmatsku aktivnost u dubokomorskim jarcima formiranim kao posljedica srednjotrijaske ekstenzije i normalnoga rasjedanja asociranoga s procesima nastajanja rifta. Opisane autoklastične stijene prvi su pronalazak autoklastičnih naslaga u vanjskim Dinaridima. Biostratigrafska odredba temeljena na nalazima konodontnih vrsta iz vapnenaca peperita (*Neogondolella excentrica*, *Paragondolella excelsa*, *Paragondolella trammeri* i *Gladigondolella tethydis*) upućuje na kasnoanizičku do ranoladiničku starost autoklastičnih naslaga Bosanskoga Grahova, a time i na početak vulkanske aktivnosti već u aniziku.

Ključne riječi
autoklastične stijene, hijaloklastiti, peperiti, srednji trijas, vanjski Dinaridi, Bosna i Hercegovina