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Uplifted Pleistocene marine sediments of the Central Adriatic Island of Brusnik

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ABSTRACT

The Island of Brusnik, located in the Central Adriatic Sea, is mainly known for its Triassic igneous rocks. However, it also contains Pleistocene conglomerates, limestones and Neptunian dikes, as well as Holocene rock debris, soil, and beach gravels. Quaternary sediments unconformably overlie tectonically disturbed Triassic basement. The majority of Pleistocene limestones, as well as the matrix of the conglomerates, are predominantly bioclastic grainstones and rudstones. Gastropod shells in these sediments retain their original aragonite mineralogy, and may also display their original colours. The majority of the conglomerates and limestones originated in lower beachface and shoreface environments. Similar sediments have not been identified in the surrounding area and the Dinarides in general. Some of the Pleistocene sediments originated during MIS 5e of the Last Interglacial based on radiometric evidence. The island experienced uplift of about 30m during the Middle and Late Pleistocene and this process probably continued in the postglacial period. The combination of uplift and cyclic sea-level changes is envisaged to have resulted in an overall downstepping pattern of the Pleistocene deposits.

Keywords: Central Adriatic Sea, Late Pleistocene, Brusnik Island, conglomerates, bioclastic limestones, tectonic uplift

1. INTRODUCTION

Initial data on the features and age of poorly known Quaternary sediments of Brusnik Island are presented, and discussed, regarding the implications for their origin. Brusnik Island is located within the foreland zone which separates two orogens: the Apennines to the SW and the Dinarides to the NE (MORETTI & ROYDEN, 1988; BIGI et al., 1990; DE ALTERIIS, 1995; among others), (Figs. 1 and 2). As the foreland area of the Central Adriatic Sea including Brusnik Island is almost completely covered by sea, only the islands provide an opportunity to study the exposed rocks of this zone. Hence, understanding of the Brusnik sediments may contribute to the understanding of the geological evolution of this complex and tectonically unstable area. The Brusnik sediments are unique as no comparable deposits have been reported from the surrounding areas, including the sea bed and islands, or from the eastern Adriatic mainland. We show that besides conglomerates which have been reported previously (HAUER, 1867; KIŠPATIĆ, 1892; MARTELLI, 1904), there are also limestones and limestone dykes, all of which store data regarding the island's history. Initial radiometric dating of the Brusnik sediments is also provided.

2. GEOLOGICAL SETTING AND PREVIOUS WORK

The island is about 300x200 m in size, 30 m high, and displays a rocky, rugged topography. It is located in the Central Adriatic Sea (coordinates: 43^{0}00’24’’N, 15^{0}48’02’’E), in the foreland area separating opposite verging Apenninic and Dinaridic orogens (Figs. 1 and 2) (MORETTI & ROYDEN, 1988; BIGI et al., 1990; KRUSE & ROYDEN, 1994; ROYDEN et al., 1987). The foreland is a complex unit, which didn't behave uniformly and includes a variety of tectonic structures (ROYDEN et al., 1987; DOGLIONI et al., 1994; KRUSE & ROYDEN, 1994; DE ALTERIIS, 1995; ARGNANI & FRUGONI, 1997; GRANDIĆ et al., 1997, 2001, 2002, 2010; BERTOTTI et al., 1999, 2001; GRANDIĆ & MARKULIN, 2000; OLDOW et al., 2002; GELETTI et al., 2008; BENNETT et al., 2008; KORBAR, 2009; among others).

Figure 2 shows the location of Brusnik Island within the area bounded by the frontal thrusts of the Dinarides to the NE, and the outer (SW) margin of the persistent Dinaric carbonate platform. The sedimentary succession of the wider area of Brusnik consists of Permian–Lower Triassic red beds with evaporites, Triassic rift successions which comprise various facies deposited in grabens and on horsts also including evaporites, and thick Upper Triassic to Lower Eocene shallow-marine carbonates with evaporites (GRANDIĆ et al., 1997, 2001, 2002). These carbonates may be overlain by Palaeogene, Neogene and Quaternary clastics. Tectonic structures of the area include SW-vergent compressional structures, wrench faults and diapirs (Figs. 2 and 3; GRANDIĆ et al., 1997, 2002, 2010; GRANDIĆ & MARKULIN, 2000; GELETTI et al., 2008). Tectonic deformation in the area has continued until the present (ALJINOVIĆ et al., 1987; FAVALI et al., 1993; KUK et al., 2000; OLDOW et al., 2002; PRELOGOVIĆ et al., 2003; HERAK et al., 2005; BENNETT et al., 2008; see also faults in Fig. 2 based on HERAK et al., 2005).

The Island of Brusnik largely consists of igneous rocks which are regarded to be genetically related to those exposed on the neighbouring islands of Vis and Jabuka, i.e. to Triassic rifting processes (KIŠPATIĆ, 1892; GOLUB & VRAGOVIĆ, 1975; MAMUŽIĆ & RAFFAELLI, 1977; BALOGH et al., 1994; GRANDIĆ et al., 2001, JURAČIĆ et al., 2004). Besides the igneous rocks, there are peculiar conglomerates containing marine fossils which display their original colours (HAUER, 1867, 1882; KIŠPATIĆ, 1892; MARTELLI, 1904; MAMUŽIĆ & RAFFAELLI, 1977; CRNJAKOVIĆ, 1998). HAUER (1867) was the first to report on a conglomerate sample brought to him from Brusnik, which consisted of a cobble of an igneous rock, and carbonate matrix with biogenic particles including a bivalve *Spondylus gaederopus* LINNÉ. The bivalve partly retained its original reddish colour, and after this author, the conglomerate is of an “offenbar ganz recenten Ursprungs” (i.e. obviously of fully recent origin). Recent molluscs in conglomerate matrix, as well as the “very recent” age of its origin and subsequent uplift, have also been mentioned by KIŠPATIĆ (1892) and MARTELLI (1904). More recently, CRNJAKOVIĆ (1998) reported on fissures in igneous rocks which are filled by limestone.

3. LABORATORY PROCEDURE FOR U-SERIES DATING

The ^{234}U–^{230}Th dating was done at the Radiogenic Isotope Laboratory, the University of New Mexico, USA. Samples were spiked with a mixed ^{229}Th–^{233}U–^{236}U spike. U and Th were separated using conventional anion exchange chromatography. U and Th isotopes were measured using a Thermo Neptune multi-collector inductively coupled plasma mass spectrometer (MC-ICPMS) which was optimized for U-series analytical work as described by ASMEROM et al. (2006). ^{234}U was measured on a secondary electron multiplier with high abundance filter, while the other isotopes of uranium were measured on Faraday cups with amplifiers that had mixed 10^{10}, 10^{11} and 10^{12} ohm resistors for ^{233}U and ^{236}U, ^{235}U and ^{238}U, respectively. Mass fractionation was monitored using the ^{236}U/^{233}U ratio, while the SEM/Faraday gain was set using sample standard bracketing. A similar procedure was used for Th isotope measurements. We used an ini-

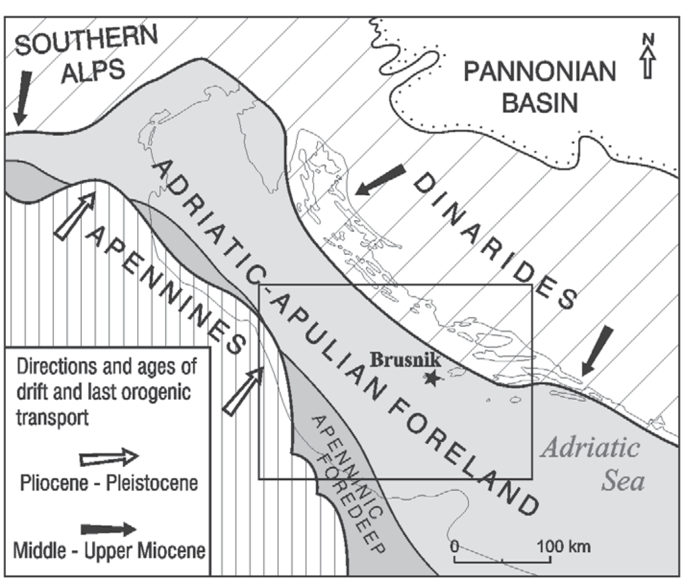

Figure 1: Tectonic sketch showing the Adriatic-Apulian foreland and neighbouring orogens (from BIGI et al., 1990), as well as the location of Brusnik Island. Location of the Dinaridic front is after GRANDIĆ et al. (2001). Framed area is shown in Fig. 2.

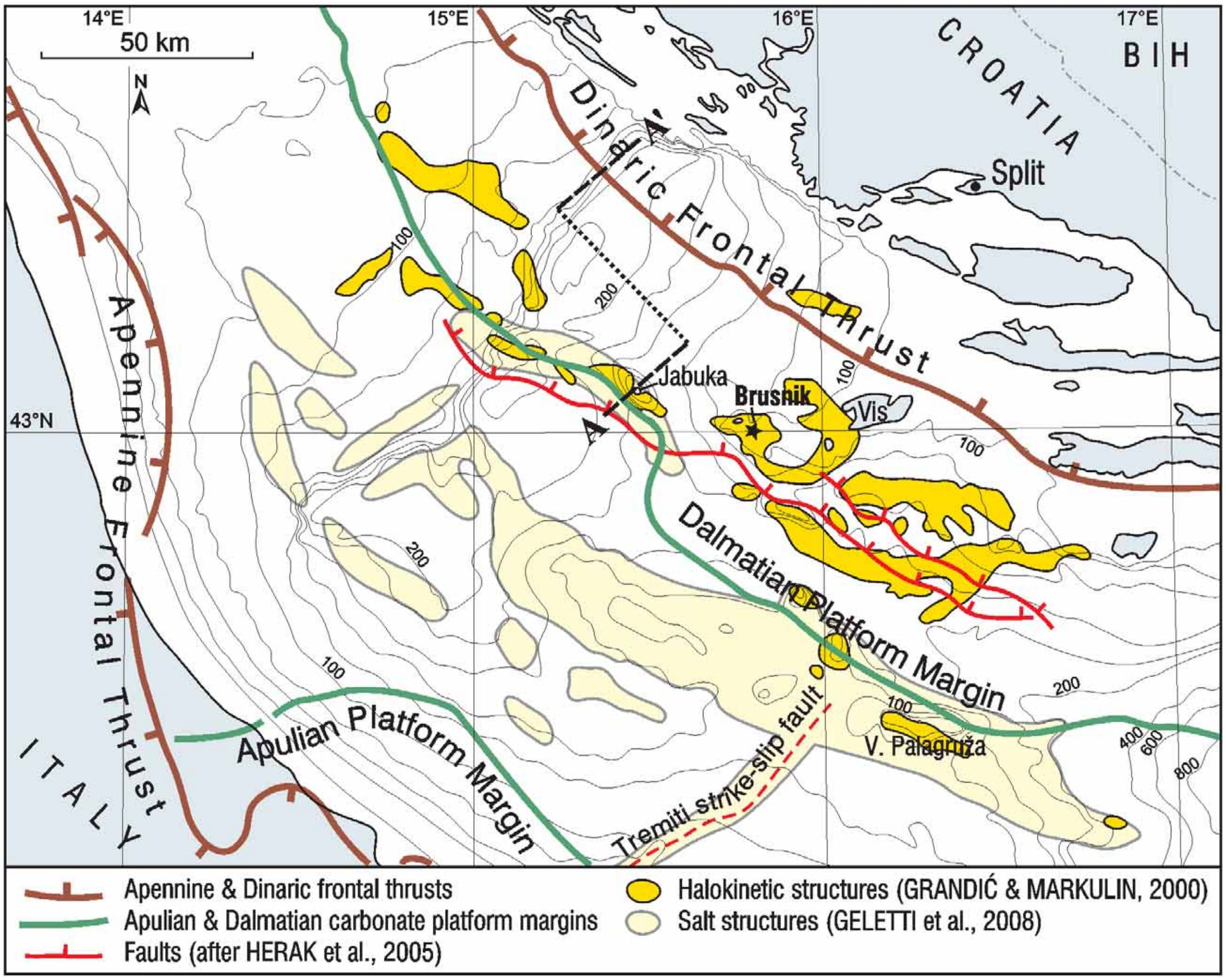

Figure 2: Main structural features of the Central Adriatic Sea. Simplified after GELETTI et al. (2008). Note the position of Brusnik (asterisk) within a diapir-related structure. Dashed line A–A' indicates the position of the cross-section in Fig. 3. For details see text.

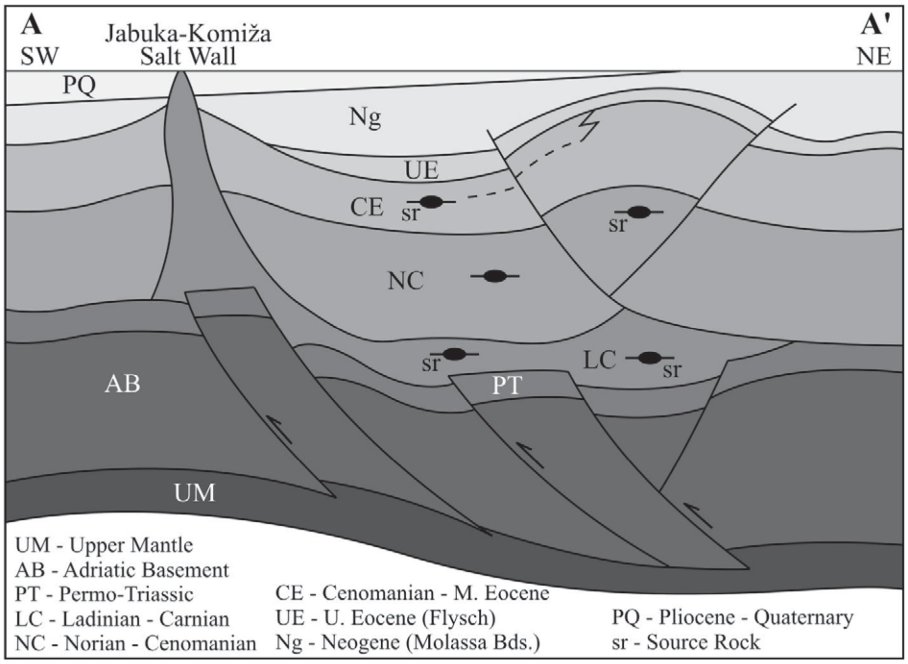

Figure 3: Generalized, SW-NE cross-section located close to Brusnik Island (after GRANDIĆ et al., 2002). Note the character of the „Jabuka-Komiža Salt Wall" (Komiža is located in the W part of Vis Island). Not to scale. For location see Fig. 2. For further explanation see text.

Table 1: Uranium-series data for a bivalve taken from the limestone matrix of a conglomerate (loc. 3 in Fig. 4).

^{238}U (ng/g)	^{232}Th (pg/g)	$^{230}Th/^{232}Th$ activity ratio	$^{230}Th/^{238}U$ activity ratio	measured $\delta^{234}U$ (‰)	initial $\delta^{234}U$ (‰)	uncorrected age (yrs BP)	corrected age (yrs BP)
227 ± 1.2	157 ± 42	3513 ± 931	0.793 ± 0.005	140 ± 2	200 ± 3	125162 ± 1568	**125146 ± 1568**

All errors are absolute 2σ. Subsample powder sizes range from 60 to 160 mg. Initial $^{230}Th/^{232}Th$ atomic ratio used to correct ages is 0.0000044 (activity ratio = 0.81) ± 100%. Yrs BP = years before present, where present = AD 2009.

tial $^{230}Th/^{232}Th$ atomic ratio of $4.4x10^{-6}$ assuming a source of Th with a bulk earth $^{232}Th/^{238}U$ ratio of 3.8. The age errors in Table 1 reflect analytical errors and uncertainties in the value of the initial ratio (± 50%). The laboratory U and Th procedural blanks range from 10–40 pg and 5–20 pg, respectively and were not analytically significant. The CRM145 U isotope standard was measured with the samples obtaining the conventionally accepted $\delta^{234}U$ value of –36.5±0.5‰ (CHENG et al., 2000).

4. DESCRIPTION OF SEDIMENTS

4.1. General data

The most widely encountered sediments on Brusnik Island are conglomerates (KIŠPATIĆ, 1892) which occur in small patches covering Triassic igneous rocks. They occur from 0 to >25m above sea-level (a.s.l.). Small limestone outcrops are observed locally and seem to represent erosional remnants. Limestones also fill fissures in igneous rocks. The sedimentary succession could not be observed clearly due to the isolated character of the smaller outcrops and common surface cover by rock debris. However, there are indications of a close stratigraphic relationship between the conglomerates and limestones. First, the limestone matrix of the conglomerates displays the same features as the majority of the limestones. Furthermore, there are transitional types ranging from igneous clast conglomerates without limestone matrix, to conglomerates with a few molluscs, to conglomerates rich in limestone matrix, to limestones rich in igneous clasts, and finally, to limestones with only rare igneous clasts. In addition, a small outcrop was observed showing a limestone intercalation (possible erosional remnant) in conglomerates (location 1 in Fig. 4).

The sediments cover the irregular igneous basement. The NNE part of the island includes a rather flat surface, gently inclined towards the west which could represent a marine terrace. This feature and its relationship to the Quaternary sediments deserves further study.

Aside from the magmatic basement and sediments mentioned above, the island also displays screes, rock debris, soil and coastal gravels.

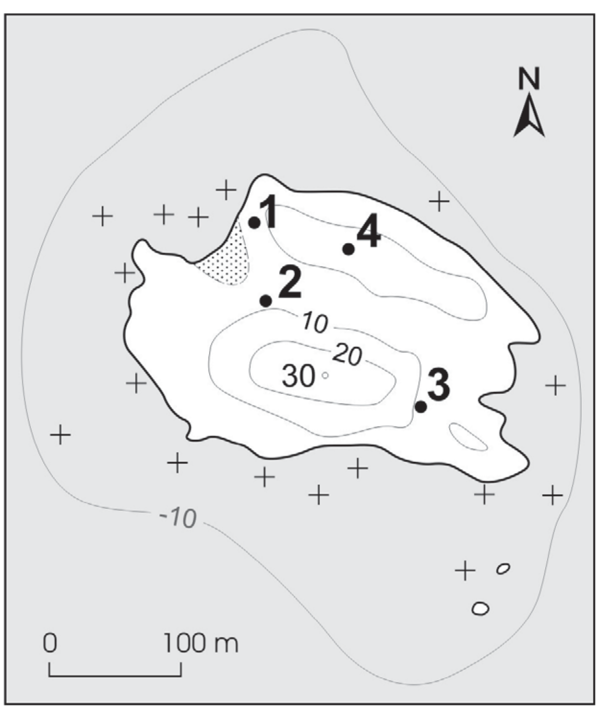

Figure 4: Location of outcrops and samples on Brusnik Island (1–4) mentioned in text and presented in Figs. 5–10. The map has been produced by enlargement of the Topographic Map 1/25000 of the Republic of Croatia (sheet Otok Svetac). Smaller numbers are heights a.s.l. and depth below sea-level (in metres). Crosses in the sea are rocks. Dotted area is a recent gravel beach.

4.2. Conglomerates

The conglomerates mostly appear massive, and locally display indistinct bedding (Fig. 5). They show a clast-supported fabric, consist of igneous clasts and matrix represented either by smaller igneous clasts with or without minor biogenic particles (Fig. 6), or are of bioclastic limestone with rare igneous particles. Several specimens of the gastropod *Cerithium vulgatum* BRUGUIERE (based on RIEDL, 1983), exhibiting their original brown colours have been identified in the conglomerate matrix. The clasts are usually pebble to

Figure 5: Poor bedding in conglomerates. Long diameter of the boulder to the right is 40 cm. Loc. 2 in Fig. 4. About 5m a.s.l. Photo by J. VRANIĆ.

cobble-sized, and clasts attaining 0.5 m in diameter are locally present (Fig. 5). Besides, an exceptionally large, angular clast of igneous rock 4 m in diameter has been observed (close to loc. 1, Fig. 4). The conglomerates may consist either of well-rounded clasts, or sub-angular to angular clasts. The limestone matrix closely resembles the limestones which are described below.

4.3. Limestones

The limestone outcrops hitherto studied in our investigations occur in the northern part of the island (e.g. 4 in Fig. 4), and are mainly represented by bioclastic grainstones and rudstones. Biogenic constituents include gastropods, bivalves, bryozoans, corallinaceans, and echinoids (CRNJAKOVIĆ, 1998), as well as rare smaller benthic foraminifera and attached foraminifera. Using RIEDL (1963, 1983) and MILIŠIĆ (1991), who described the recent Mediterranean and Adriatic fauna and flora, it was possible to identify *Gibbula euxinica* ANDRJAVSKI (Fig. 7) and *Bittium reticulatum* DA COSTA (Fig. 8) among several other gastropod species. There was also a limpet, and an oyster. Some gastropod specimens display their original colours, as do the echinoid spines. Igneous clasts are variably present in the limestones and may be rare to common.

After treatment with Fiegl's solution (MILLER, 1988), it was discovered that sections of several gastropod shells displayed their original, aragonite mineralogy. Primary voids, both interskelatal and intraskeletal, are lined by isopachous, acicular fringes of calcite (Fig. 9), which was identified by staining with Alizarin red S, and Fiegl's solution (MILLER, 1988).

4.4. Neptunian dykes

Neptunian dykes in igneous rocks may be observed at several places (Fig. 10). The sedimentary fill of the fractures either consists of limestone containing gastropods and other biogenic particles, or contains various proportions of biogenic particles and igneous clasts.

Figure 6: Igneous clast conglomerate containing many fragments of gastropod tests and debris of other fossils. Largest gastropod is a *Cerithium*. Its preserved portion is 3 cm long. Loc. 1 in Fig. 4. About 3m a.s.l. Photo by J. VRANIĆ.

Figure 7: Gastropod *Gibbula euxinica* ANDRJAVSKI in bioclastic limestone. The test is 8.5 mm wide. Loc. 4 in Fig. 4. About 11m a.s.l.

Figure 8: Gastropod *Bittium reticulatum* DA COSTA in bioclastic limestone. The test is 3.5 mm wide. Loc. 4 in Fig. 4. About 11m a.s.l.

Figure 9: Isopachous, acicular cement lining skeletal particles, including a corallinacean (left) and a gastropod (right). Note voids which remained empty after cementation. Thin section, plane polarised light. Loc. 4 in Fig. 4. About 11m a.s.l.

Figure 10: Neptunian dyke of limestone seen as a light diagonal stripe in igneous rock. The dyke is up to 13 cm thick. Loc. 2 in Fig. 4. About 5m a.s.l. Photo by D. LACKOVIĆ.

5. RADIOMETRIC DATA

Table 1 presents radiometric dating results for a bivalve test extracted from the limestone matrix of the conglomerate found at locality 3, occurring about 9m a.s.l. (Fig. 4).

6. DISCUSSION

6.1. Origin of the sediments

The mollusc species identified in the limestones and conglomerates are known to inhabit the shallow bottoms of the present Adriatic Sea (RIELD, 1963, 1983; MILIŠIĆ, 1991), while the other organisms observed may also inhabit these environments. The dominant grainstone to rudstone textures of the limestones suggest reworking of skeletal material by agitated waters, and deposition within a shallow-water environment, above fair-weather wave base (CRNJAKOVIĆ, 1998). The occurrence of angular igneous clasts in limestones may be related to the vicinity of the rocky coast composed of igneous rocks. The remains of shallow-water organisms in the conglomerates, together with the inferred close relationship between these and the limestones, is interpreted as indicating a similar, shallow marine setting for the conglomerates (see also below).

Isopachous, acicular calcite fringes indicate a phreatic environment, are typically marine, but may also be precipitated from meteoric waters (TUCKER & WRIGHT, 1990). It is suggested, that a meteoric origin of this cement may be excluded, as fresh waters would have probably caused dissolution of gastropod skeletal aragonite, which is not observed. Calcite cements, such as those in the Brusnik limestones, are more common in cooler waters in contrast to aragonite cements, as lower temperatures favour calcite precipitation (e.g. BURTON & WALTER, 1987). This is in accordance with the current mid-latitude position of Brusnik which was also the case during the Pleistocene. A "cool-water" character for the Brusnik carbonates is also supported by the dominance of gastropods, bivalves, bryozoans, and corallinaceans in the composition of the bioclastic limestones (review in JAMES, 1997).

Based on the above data and discussion, it is proposed that the origin of clast-supported conglomerates is related to gravels initially formed within a high-energy, wave-dominated beachface, after which most were mixed with carbonate bioclastic material on the beach and in the upper shoreface zone. As shallow-marine biota which produced skeletal material, i.e. carbonate sediment, presumably dominated the adjacent offshore area, small changes in relative sea level, and/or the local wave patterns may have caused shifts in the shoreline which resulted in the alternation of conglomerates and limestones. The commonly occurring isopachous cement, suggests final deposition was below sea-level. Some of the igneous clasts may have been brought to the shoreface zone dominated by biogenic production by storm-related processes, becoming a subordinate component of the limestone. The processes discussed above reflect a close relationship between the relevant environments which resulted in a close association of lithologic types, as well as in the similarity between the limestone matrix of the conglomerates and limestone sediment. Conglomerates containing large, angular clasts of igneous rocks may have been deposited in the vicinity of rocky, rugged coasts consisting of igneous rocks.

The constituents of the infills of open fractures now representing Neptunian dikes correspond to the composition of the sediments discussed above, which suggests that the opening of the fractures and their filling occurred at the time when conglomerates and limestones were deposited at the relevant locations.

6.2. A tentative Quaternary evolution of the island

Radiometric dating provided an age of 125146 ± 1568 years BP which corresponds to Marine Isotope Stage (MIS) 5e. This stage (or Substage) is of global importance for the time correlation of sedimentary, tectonic and eustatic processes based on a variety of evidence collected world-wide (CHAPPEL & SHACKLETON, 1986; MARTINSON et al., 1987; BARD et al., 1990; HOOGHIEMSTRA & MELICE, 1994; PETIT et al., 1999; LYLE et al., 2001; LAMBECK et al., 2002; SHACKLETON et al., 2003; MARTRAT et al., 2004; among others). MIS 5e lasted some 18000 years, corresponds to a warm interval, with its warmest part lasting about 12000 years (SHACKLETON et al., 2003) and embraces the measured date above. The conglomerate including the dated bivalve was probably deposited in the upper shoreface, as discussed previously, and was discovered about 9m a.s.l. If the depositional depth is assumed at -1m, the relative rise of the island amounts to about 10m. As the MIS 5e sea-level is thought to had been several metres higher than today (CHAPPEL & SHACKLETON, 1986; BARD et al., 1990; WAELBROECK et al., 2002; FER-

RANTI et al., 2006), and assuming MIS 5e sea-levels at +6m and +3m, respectively, the conglomerate has been uplifted for some 4–7 m in the last 125000 years. This corresponds to an average uplift rate of between 0.032 and 0.056 mm/year.

Limited data do not allow for direct generalisation of the above data concerning all Pleistocene sediments of Brusnik Island. However, the patchy occurrences of similar but poorly known facies up to >+25m could suggest that higher parts of the island show older Pleistocene sediments presumably deposited during longer and shorter highstand periods and mainly during MIS 7, MIS 9 and possibly MIS 11. It is believed that the oldest deposits occur at the highest portion of the island and that deposition subsequently occurred lower and lower, being younger and younger in the same direction, thus representing an overall downstepping pattern related to overall relative sea-level fall. Deposits younger than MIS 5e might be those occurring in the lowermost part of the island. This would imply a total Pleistocene uplift corresponding approximately to the highest position of Pleistocene sediment, which is +25m. Patches of Pleistocene sediments may be regarded as representing relics which remained after weathering, which started after each highstand depositional period, and increased in extent at lower altitude due to the increasing subaerial surface of the island. Poorly recognizable erosional surfaces at the base of some conglomerates, as well as the flat surface in the NNE part of the island may represent remnants of marine terraces related to different relative sea-levels.

The rise of Brusnik Island may be explained by its structural position within an uplifting structure as mentioned above. The uplift may have been accompanied by extensional deformation and earthquakes responsible for the opening of fractures hosting limestone fills. Another island in the Central Adriatic Sea, Velika Palagruža, displays certain similarities to Brusnik in its geological history, related to its position within an uplift structure which may have resulted either from compression (BERTOTTI et al., 2001) or from diapirism (GRANDIĆ & MARKULIN, 2000; Fig. 2). Velika Palagruža shows probable marine straths and beach deposits at about +75m and +13m, respectively (KORBAR et al., 2009). Also pelagosite, which otherwise grows on wet rocky shores, has been found at different heights, including 6500 year old examples at +6m (based on U/Th dating) (MONTANARI et al., 2007; KORBAR et al., 2009). These features resulted from a recent uplift of this island. Marine straths and beach deposits of Velika Palagruža may possibly correlate with some parts of the Pleistocene evolution of Brusnik. However, this does not imply precise synchroneity in the tectonic activity and uplift of the two islands as they belong to different structures located rather far apart (Fig. 2).

While the Brusnik data provide direct outcrop evidence for a recent uplift trend, the areas surrounding the Adriatic behaved variously during the relevant time period. For example, the NE and NW Adriatic coasts (including islands) are known to have subsided (FERRANTI et al., 2006; ANTONIOLI et al., 2007, with references; SURIĆ & JURAČIĆ, 2010, with references), while the SW Adriatic coast displays uplift related to compressional deformation (FERRANTI et al., 2006; ANTONIOLI et al., 2007). This and other differences in the tectonic evolution of the NE and SW Adriatic belts may be regarded as reflecting the different characteristics of Apenninic versus Dinaric styles of subduction of the Adriatic slab (DOGLIONI, 1994; see also discussion by FERRANTI et al., 2006 and references therein).

6.3. Alternative interpretation for some of the Brusnik sediments?

The data on Pleistocene sediments of Brusnik Island are scattered and only of locally documented character, especially regarding the upper part of the island. In light of this, alternative interpretations of depositional processes for some parts of these sediments may be discussed. Given the difficulties encountered while searching for the type(s) of organisation, fabrics and structures of Brusnik sediments, together with the apparent disorder in the distribution of conglomerates, igneous rocks and limestones, possible deposition by exceptionally high storm waves and tsunami waves is appropriate to be included here. Such processes include sudden, energetic resedimentation event(s), by which shallow-marine, carbonate particles, and the gravel from the beachface and shoreface, are picked up from their original depositional settings, moved, partly mixed together, and displaced to their final depositional sites which may be located onshore, offshore or both. This could occur during one or several, rapid short term depositional events. Storm waves may be discounted as it is unlikely that different parts of the subaerial island surface could have been covered in this way. However, a storm-related origin for modest, locally occurring parts of this detritus might be possible. In contrast, some coarse-grained sediments may have been deposited below sea-level by storm-related processes, as discussed above.

It is known that tsunamis may result in erosion, and transport of sediments from different environments, displacement of large blocks, and deposition of this detritus both below sea level and/or onshore, up to considerable distances and heights (e.g. SHIKI & JAMAZAKI, 1996; FUJINO et al., 2006; BONDEVIK et al., 1997; NICHOL et al., 2003; SCHEFFERS & KELLETAT, 2005; NANAYAMA & SHIGENO, 2006). Deposition of large clasts and the mixing of igneous clasts and skeletal particles on Brusnik bear some similarity to the features resulting from tsunami events. Besides, the unique occurrence of these sediments on Brusnik makes them “anomalous”, which is a feature characterising tsunami deposits compared to “normal” sediments. Alternatively, consideration of a tsunami interpretation should be coupled with the question of whether a tsunami of an appropriate intensity could have occurred in the Adriatic Sea at the relevant time (Middle-Late Pleistocene). This question is relevant as the present Adriatic is a small, semi-closed basin, in contrast to the oceanic domains, where the great majority of tsunamis has been reported including the examples cited above. Even during sea-level highstands of the Pleistocene, the Adriatic was not considerably larger and deeper. Available data from different parts of the Adriatic, for the last 2000 years, include tsunamis of different intensities (TINTI et al., 2004; PAULATTO et al., 2007), and although some of them caused heavy damage and human losses, their intensities were below those of tsunamis known from oceanic domains. This is due to the lower seismicity and shallower water of the Adriatic basin compared to the oceans (PAULATTO et al., 2007). However, the Brusnik sediments are older than the tsunami records, hence, extrapolating these records to earlier, much longer periods, may not be appropriate. The possibility of large tsunami events, which could have occurred during these earlier times, may be supported by tectonic processes which operated, and are still operating, in the Adriatic area. The overall situation includes three surrounding orogens; the Dinarides, Alps, and Apennines, all of which are characterised by tectonic transport towards the Adriatic, which is active in both the onshore and offshore zones, especially along the NE and SW Adriatic coasts (e.g. BIGI et al., 1990; BENNETT et al., 2008). Consequently, numerous tectonic displacement events and earthquakes may be envisaged to have occurred in these areas during the Quaternary, beyond the extent of available records. Active tectonic boundaries and epicentres located close to Brusnik Island (ALJINOVIĆ et al., 1987; FAVALI et al., 1993; KUK et al., 2000; OLDOW et al., 2002; PRELOGOVIĆ et al., 2003; HERAK et al., 2005; BENNETT et al., 2008) may be relevant for tsunamogenic potential.

Tsunamogenic processes in the Adriatic may have also been related to large-scale, submarine sliding. Such processes are known to have occurred in the SW Adriatic in the Pleistocene, and are taken as an indicator for possible, future large slides and related tsunamis (MINISINI et al., 2006).

The possibility that important tsunami waves did hit Brusnik Island cannot be excluded based on this discussion. However, onshore deposition by tsunami(s) for a part of Brusnik sediments is unlikely. This is because an extremely high tsunami run up would be required to transport large clasts to heights above 20 m (and much more during periods of sea-level lowstands) where they occur at present, and because tsunami deposits have not been observed on neighbouring islands where they would be expected in the case of a large tsunami(s).

7. SUMMARY AND CONCLUSION

Aside from the Triassic igneous rocks, the Island of Brusnik, Central Adriatic, displays Pleistocene conglomerates and limestones, as well as Holocene rock debris, soil and beach gravels. Pleistocene sediments unconformably overlie tectonically disturbed Triassic basement igneous rocks, and also occur as Neptunian dykes. Based on radiometric evidence, some of the Pleistocene sediments originated during MIS 5e. The conglomerates were predominantly deposited on a high-energy beachface below sea-level, and in the uppermost shoreface, while the limestones accumulated within the same environments and in the shoreface. The limestones, as well as the limestone matrix of the conglomerates are predominantly composed of bioclastic grainstones and rudstones. Gastropods occurring in the limestones and conglomerate matrix retain their original skeletal aragonite and may show original colours. Cementation in most limestones, as well as the limestone matrix of the conglomerates occurred in phreatic conditions and resulted in acicular, isopachous calcite fringes. The island experienced uplift of about 30m during the Middle and Late Pleistocene and uplift process probably continued in the postglacial period. It is proposed that the combination of uplift and cyclic sea-level changes produced an overall downstepping pattern of Middle and Late Pleistocene deposits.

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Samples shown in Figs. 7 and 8 are stored in the Croatian Natural History Museum, Collection of Sedimentary Rocks, under codes BS-96-3 and BS-96-6, respectively.

REFERENCES

ALJINOVIĆ, B., PRELOGOVIĆ, E. & SKOKO, D. (1987): Novi podaci o dubinskoj geološkoj građi i seizmotektonskim aktivnim zonama u Jugoslaviji.– Geol. vjesnik, 40, 255–263.

ANTONIOLI, F., ANZIDEI, M., LAMBECK, K., AURIEMMA, R., GADDI, D., FURLANI, S., ORRÙ, P., SOLINAS, E., GASPARI, A., KARINJA, S., KOVAČIĆ, V. & SURACE, L. (2007): Sea-level change during the Holocene in Sardinia and in the northeastern Adriatic (central Mediterranean Sea) from archaeological and geomorphological data.– Quaternary Sci. Rev., 26, 2463–2486.

ARGNANI, A. & FRUGONI, F. (1997): Foreland deformation in the Central Adriatic and its bearing on the evolution of the Northern Apennines.– Ann. Geofis., 40/3, 771–780.

ASMEROM, Y., POLYAK, V., SCHWIETERS, J. & BOUMAN, C. (2006): Routine high-precision U-Th isotope analysis for paleoclimate chronology.– Geochim. Cosmochim. Ac., 70, p. A24.

BALOGH, K., COLANTONI, P., GUERRERA, F., MAJER, V., RAVASZ-BRANYAI, I., RENZULLI, A. VENERI, F. & ALBERINI, C. (1994): The medium-grained gabbro of the Jabuka islet (“Scoglio del Pomo”, Adriatic Sea).– Giorn. Geol., Bologna, (3a), 56/2, 13–25.

BARD, E., HAMELIN, B. & FAIRBANKS, R.G. (1990): U-Th ages obtained by mass spectrometry in corals from Barbados: sea level during the past 130.000 years.– Nature, 346, 456–458.

BENNETT, R.A., HREINSDÓTTIR, S., BUBLE, G., BAŠIĆ, T., BAČIĆ, Ž., MARJANOVIĆ, CASALE, G., GENDASZEK, A. & COWAN, D. (2008): Eocene to present subduction of southern Adria mantle lithosphere beneath the Dinarides.– Geology, 36, 3–6.

BERTOTTI, G., CASOLARI, E. & PICOTTI, V. (1999): The Gargano Promontory: a Neogene contractional belt within the Adriatic plate.– Terra Nova, 11, 168–173.

BERTOTTI, G., PICOTTI, V., CHILOVI, C., FANTONI, R., MERLINI, S. & MOSCONI, A. (2001): Neogene to Quaternary sedimentary basins in the south Adriatic (Central Mediterranean): Foredeeps and lithospheric buckling.– Tectonics, 20/5, 771–787.

BIGI, G., COSENTINO, D., PAROTTO, T., SARTORI, R. & SCANDONE, P. (1990): Structural Model of Italy, 1:500,000.– Consilio Nazionale delle Riccerche. Roma.

BURTON, E.A. & WALTER, L.M. (1987): Relative precipitation rates of aragonite and Mg calcite from sea water: temperature or carbonate ion control?– Geology, 15, 111–114.

BONDEVIK, S., SVENDSEN, J.I., MANGERUD, J. (1997): Tsunami sedimentary facies deposited by the Storegga tsunami in shallow marine basins and lakes.– Sedimentology, 44, 1115–1131.

CHAPPELL, J. & SHACKLETON, N.J. (1986): Oxygen isotopes and sea level.– Nature, 324, 137–140.

CHENG, H., EDWARDS, R.L., HOFF, J., GALLUP, C.D., RICHARDS, D.A. & ASMEROM, Y. (2000): The half-lives of uranium-234 and thorium-230.– Chem. Geol., 169, 17–33.

CRNJAKOVIĆ, M. (1998): Volcanoes on the Adriatic islands?– Croat. Nat. History Museum, Zagreb, 39 p.

DE ALTERIIS, G. (1995): Different foreland basins in Italy: examples from the central and southern Adriatic Sea.– Tectonophysics, 252, 349–373.

DOGLIONI, C. (1994): Foredeeps versus subduction zones.– Geology, 22, 271–274.

DOGLIONI, C., MONGELLI, F. & PIERI, P. (1994): The Puglia uplift (SE Italy): An "anomaly" in the foreland of the Apenninic subduction due to buckling of a thick continental lithosphere.– Tectonics, 13/5, 1309–1321.

FAVALI, P., FUNUCIELLO, R., MATTIETTI, G., MELE, G. & SALVINI, F. (1993): An active margin across the Adriatic Sea (central Mediterranean Sea).– Tectonophysics, 219, 109–117.

FERRANTI, L., ANTONIOLI, F., MAUZ, B., AMOROSI, A., DAI PRA, G., MASTRONUZZI, G., MONACO, C., ORRÙ, P., PAPPALARDO, M., RADTKE, U., RENDA, P., ROMANO, P., SANSÒ, P. & VERRUBBI, V. (2006): Markers of the last interglacial sea-level high stand along the coast of Italy: Tectonic implications.– Quat. Int., 145–146, 30–54.

FUJINO, S., MASUDA, F., TAGOMORI, S. & MATSUMOTO, D. (2006): Structure and depositional processes of a gravelly tsunami deposit in a shallow marine setting: Lower Cretaceous Miyako Group, Japan.– Sed. Geol., 187, 127–138.

GELETTI, R., DEL BEN, A., BUSETTI, M., RAMELLA, R. & VOLPI, V. (2008): Gas seeps linked to salt structures in the Central Adriatic Sea.– Basin Res., 20, 473–487.

GOLUB, LJ. & VRAGOVIĆ, M. (1975): Igneous rocks of the Dalmatian islands (In Croat., Engl. Summary).– Acta Geol., 8/4, Zagreb, 19–63.

GRANDIĆ, S. & MARKULIN, Z. (2000): Triassic synrift euxinic basins as a factor of exploration risk in the Croatian offshore area.– Proceedings of International Symposium of Petroleum Geology, April 22–24, 1999, Nafta, Spec. Issue, 41–50.

GRANDIĆ, S., BOROMISA-BALAŠ, E. & ŠUŠTERČIĆ, M. (1997): Exploration concept and characteristics of the stratigraphic and structural models of the Dinarides in Croatian offshore area.– Nafta, 48/8–9, 249–266.

GRANDIĆ, S., BIANCONE, M. & SAMARŽIJA, J. (2001): Geophysical and stratigraphic evidence of the Triassic rift structuration in the Adriatic offshore area.– Nafta, 52/12, 383–396.

GRANDIĆ, S., VESELI, V. & KOLBAH, S. (2002): Hydrocarbon potential of Dugi otok basin in offshore Croatia.– Nafta, 53/6–7, 215–224.

GRANDIĆ, S., KRATKOVIĆ, I. & RUSAN, I. (2010): Hydrocarbon potential assessment of the slope deposits along the SW Dinarides carbonate platform edge.– Nafta 61/7–8, 325–338.

HAUER, F.v. (1867): Prehnit von Comisa auf der Insel Lissa und Eruptivgesteine aus Dalmatien.– Verhandl. Geol. Reichsanst., 1867/4, 89–91.

HAUER, F.v. (1882): Der Scoglio Brusnik bei St. Andrea in Dalmatien.– Verhandl. Geol. Reichsanst., 1882/5, 75–77.

HERAK, D., HERAK, M., PRELOGOVIC, E., MARKUSIC, S. & MARKULIN, Z., 2005 Jabuka island (Central Adriatic Sea) earthquakes of 2003.– Tectonophysics, 398, 167–180.

HOOGHIEMSTRA, H. & MELICE, J.L. (1994): Pleistocene evolution of orbital periodicities in the high-resolution pollen record Funza I, Eastern Cordillera, Columbia.– Sp. Publ. Int. 19, 117–126.

JAMES, N. (1997): The cool-water carbonate depositional realm.– In: JAMES. N.P. & CLARKE, J.A.D. (eds.): Cool-Water Carbonates. SEPM Sp. Publ., 56, 1–20.

JURAČIĆ, M., NOVOSEL, A., TIBLJAŠ, D. & BALEN, D. 2004: Jabuka Shoal, a new location with igneous rocks in the Adriatic Sea.– Geol. Croat., 57, 81–85.

KIŠPATIĆ, M. (1892): Eruptivno kamenje u Dalmaciji.– Rad Jugosl. akad., 111, Zagreb, 158–190.

KORBAR, T. (2009): Orogenic evolution of the External Dinarides in the NE Adriatic region: a model constrained by tectonostratigraphy of Upper Cretaceous to Paleogene carbonates.– Earth-Sci. Rev., 96/4, 296–312.

KORBAR, T., MONTANARI, A., KOCH, G., MARIANI, S., DePAOLO, D., TURCHYN, A.V., MIKNIĆ, M. & TARI, V. (2009): Geologic reconnaissance of the island of Velika Palagruža (central Adriatic, Croatia).– Geol. Croat., 62/2, 75–94.

KRUSE, S.E. & ROYDEN, L.H. (1994): Bending and unbending of an elastic lithosphere: The Cenozoic history of the Apennine and Dinaride foredeep basins.– Tectonics, 13/2, 278–302.

KUK, V., PELOGOVIĆ, E. & DRAGIČEVIĆ, I. (2000): Seismotectonically active zones in the Dinarides.– Geol. Croat., 53/2, 295–303.

LAMBECK, K., ESAT, T.M. & POTTER, E-K. (2002): Links between climate and sea levels for the past three million years.– In: ZIEMELIS, K. (ed.): Nature Insight – Climate and Water. Nature, 419, 199–206.

LYLE, M., HEUSSER, L., HERBERT, T., MIX, A. & BARRON, J. (2001): Interglacial theme and variations: 500 k.y. of orbital forcing and associated responses from the terrestrial and marine biosphere, U.S. Pacific Northwest.– Geology, 29, 1115–1118.

MAMUŽIĆ, P. & RAFFAELLI, P. (1977): Geology of the sheet Svetac (In Croat., Engl. summary).– In: BOROVIĆ, I., MARINČIĆ, S., MAJCEN, Ž., MAGAŠ, N., RAFFAELLI, P. & MAMUŽIĆ, P.: Explanatory notes for sheets Vis, Jelsa, Biševo, Svetac, and Jabuka. Basic Geological Map of Yugoslavia, 1:100000. Institute of Geological Research, Zagreb. Federal Geological Institute, Beograd, 49–60.

MARTELLI, A. (1904): Osservazioni geographico-physiche e geologiche sull'isola di Lissa (I).– B. Soc. Geol. Ital., 4/5, 530–550.

MARTINSON, D.G., PISIAS, N.G., HAYAS, J.D., IMBRIE, J., MOORE, T.C. JR. & SHACKLETON, N.J. (1987): Age dating and the orbital theory of the ice ages: development of a high-resolution 0 to 300,000-year chronostratigraphy.– Quat. Res., 27, 1–29.

MARTRAT, B., GRIMALT, J.O., LOPEZ-MARTINEZ, C., CACHO, I., SIERRO, F.J., FLORES, J.A., ZAHN, R., CANALS, M., CURTIS, J.H. & HODELL, D.A. (2004): Abrupt temperature changes in the Western Mediterranean over past 250,000 years.– Science, 306, 1762–1764.

MILIŠIĆ, N. (1991): Školjke i puževi Jadrana.– Logos, Split, 302 p.

MILLER, J. (1988): Microscopical techniques: I. Slices, slides, stains, and peels.– In: TUCKER, M. (ed.): Tech. in Sedimentology, Blackwell, Oxford, 86–107.

MINISINI, D., TRINCARDI, F. & ASIOLI, A. (2006): Evidence of slope instability in the Southwestern Adriatic Margin.– Nat. Hazards Earth Sist. Sci., 6, 1–20.

MONTANARI, A., BICE, D., DRUSCHEL, G., MARIANI, S., MARSHALL, C., OLCOTT, A., SHARP, W., TIGUE, T. & VUCETIC, M. (2007): Rediscovering pelagosite: a Mediterranean "microstromatolite" recording recent climate cycles.– Geoph. Res. Abstracts, 9, 01555, 2007.SRef-ID: 1607-7962/gra/EGU2007-A-01555. European Geoscience Union.

MORETTI, I. & ROYDEN, L. (1988): Deflection, gravity anomalies and tectonics of doubly subducted continental lithosphere: Adriatic and Ionian seas.– Tectonics, 7, 875–893.

NANAYAMA, F. & SHIGENO, S. (2006): Inflow and outflow facies from the 1993 tsunami in southwest Hokkaido.– Sed. Geol., 127–158.

NICHOL, S.L., LIAN, O.B. & CARTER, C.H. (2003): Sheet-gravel evidence for a late Holocene tsunami run-up on beach dunes, Great Barrier Island, New Zealand.– Sed. Geol., 155, 129–145.

OLDOW, J.S., FERRANTI, L., LEWIS, D.S., CAMPBELL, J.K., D'ARGENIO, B., CATALANO, R., PAPPONE, G., CARMIGNANI, L., CONTI, P. & AIKEN, C.L.V. (2002): Active fragmentation of Adria, the north African promontory, central Mediterranean orogen.– Geology, 30, 779–782.

PAULATTO, M., PINAT, T. & ROMANELLI, F. (2007): Tsunami hazard scenarios in the Adriatic Sea domain.– Nat. Hazards Earth Sist. Sci., 7, 309–325.

PETIT, J.R., JOUZEL, J., RAYNAUD, D., BARKOV, N.J., BARNOLA, J.-M., BASILE, I., BENDER, M., CHAPPELLAZ, J., DAVIS, M., DELAYGUE, G., DELMOTTE, M., KOTLYAKOV, V.M., LEGRAND, M., LIPENKOV, V.Y., LORIUS, C., PÉPIN, L., RITZ, C., SALTZMAN, E. & STIEVENRD, M. 1999): Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antractica.– Nature, 399/3, 429–436.

PRELOGOVIĆ, E., PRIBIČEVIĆ, B., IVKOVIĆ, Ž., DRAGIČEVIĆ, I., BULJAN, R. & TOMLJENOVIĆ, B. (2003): Recent structural fabric of the Dinarides and tectonically active zones important for petroleum-geological exploration in Croatia.– Nafta, 55, 155–161.

RIEDL, R. (1963): Fauna und Flora der Adria.– Paul Paray, Hamburg, 640 p.

RIEDL, R. (1983): Fauna und Flora der Mittelmeeres. 3. Ed.– Paul Paray, Hamburg, 836 p.

ROYDEN, L., PATACCA, E. & SCANDONE, P. (1987): Segmentation and configuration of subducted lithosphere in Italy: An important control on thrust-belt and foredeep-basin evolution.– Geology, 15, 714–717.

SCHEFFERS, A. & KELLETAT, D. (2005): Tsunami relics on the coastal landscape west of Lisbon, Portugal.– Sci. Tsun. Hazards, 23, 3–16.

SHACKLETON, N.J., SÁNCHEZ-GOÑI, M.A. PAILLER, D. & LANCELOT, Y. (2003): Marine Isotope Substage 5e and the Eemian Interglacial.– Global Planet. Change, 36, 151–155.

SHIKI, T. & JAMAZAKI, T. (1996): Tsunami-induced conglomerates in Miocene upper bathyal deposits, Chita Peninsula, central Japan.– Sed. Geol., 104, 175–188.

SURIĆ, M. & JURAČIĆ, M. (2010): Late Pleistocene-Holocene environmental changes – records from submerged speleothems along the Eastern Adriatic coast (Croatia).– Geol. Croat., 63/2, 155–169.

TINTI, S., MARAMAI, A. & GRAZIANI, L. (2004): The New Catalogue of Italian Tsunamis.– Nat. Hazards, 33, 439–465. http://www.ingv.it//italiantsunamis/tsun.html

TUCKER, M.E. & WRIGHT, V.P. 1990: Carbonate Sedimentology.– Blackwell, Oxford, 482 p.

WAELBROECK, C., LABEYRIE, L., MICHEL, E., DUPLESSY, J.C., MCMANUS, J.F., LAMBECK, K., BALBON, E. & LABRACHERIE, M. (2002): Sea-level and deep water temperature changes derived from benthic foraminifera isotopic records.– Quaternary Sci. Rev., 21, 295–305.

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