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Campanian *Pseudosabinia* from the Pučišća Formation on the island of Hvar (Adriatic Sea, Croatia)

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Abstract: The Upper Cretaceous carbonates on the Island of Hvar were deposited within the central Tethyan, intra-oceanic Adriatic carbonate platform (*s. str*). The Upper Cretaceous stratigraphy of the platform has been described in detail from the neighbouring island of Brač. Following the intra-platform deeper-water carbonate sedimentation of the Dol Formation, the Campanian Pučišća Formation (the Brač 'Marbles' unit) in the area of the town of Hvar are characterized by massive bioclastic rudist-bearing carbonates deposited in relatively deeper subtidal environments.

Within the uppermost part of the Pučišća Formation we recognized massive rudist valves, characterized by a complex canaliferous inner shell structure, and determined them as *Pseudosabinia klinghardti*. The valves are embedded in massive, light-grey to white, mostly recrystalized peloidal-bioclastic packstone to rudstones, characterized in places by chalky appearance. The macrofossil association comprises various radiolitids, rare hippuritids, plagioptychids and inoceramid bivalves. Microfossil association includes index species of orbitoids and siderolitines. The range of the microfossils, along with results of strontium-isotope stratigraphy, indicate the latest Middle Campanian age of the *Pseudosabinia* horizon. Thus, it is the youngest horizon of the Pučišća Formation in the Adriatic carbonate platform reported to date.

Key Words: carbonate platform, intraplatform basin margin, radiolitid rudist, benthic foraminifera, strontium-isotope stratigraphy

Hvar Adasında (Adriyatik Denizi, Hırvatistan) Pučišća Formasyonu'nundan Kampaniyen *Pseudosabinia*'ları

Özet: Hvar adasındaki Üst Kretase karbonatları, Tetis'in orta bölümünde yer alan ve bir okyanus-içi platform olan Adriyatik karbonat platformunda çökelmiştir. Platformun Üst Kretase stratigrafisi, komşu Brač adasında ayrıntılı bir şekilde tanımlanmıştır. Hvar kasabası alanında, Dol Formasyonu'nun platform-içi derin denizel karbonat tortulları, Kampaniyen yaşlı Pučišća Formasyonu'nun (Brač mermer üyesi), bağıl olarak derin gelgit altı ortamında çökelmiş rudistli masif biyoklastik karbonatları tarafından üzerlenir.

Pučišća Formasyonu'nun en üst bölümlerinde, *Pseudosabinia klinghardti* olarak tanımladığımız ve karmaşık kanallı iç kavkı yapısı ile tanınan, masif rudist kavkıları saptanmıştır. Kavkılar masif, açık gri-beyaz renkli, çoğunlukla rekristalize olmuş ve yer yer tebeşirimsi görünüşlü pelletli-biyoklastik istiftaşı-kabataş içinde yer alır. Makrofosil topluluğu, çeşitli radiolitidler, seyrek hippuritidler, plagioptychids ve inoseramid kavkılarından oluşur. Mikrofosil topluluğu indeks orbitoid ve siderolit türleri içerir. Mikrofosillerin stratigrafik yayılımları, stronsiyum-izotop stratigrafisi sonuçlarıyla da uyumlu olarak, *Pseudosabinia* düzeyinin Orta Kampaniyen yaşlı olduğunu gösterir. Bu nedenle bu düzey, Pučišća Formasyonu'nun Adriyatik karbonat platformunda bugüne değin saptanan en genç düzeyidir.

Anahtar Sözcükler: karbonat platformu, platform-içi havza kenarı, radiolitid rudist, bentik foraminifer, stronsiyum-izotop stratigrafisi

Introduction

The Upper Cretaceous carbonates on the Island of Hvar (Figure 1A, B) are typical of the central Tethyan ('peri-Adriatic', central-northern Mediterranean) intra-oceanic carbonate platforms (Jenkyns 1991; Zappaterra 1994; Pamić *et al.* 1998; Dercourt *et al.* 2000; Tari 2002; Vlahović *et al.* 2005; Korbar 2009). The carbonates were deposited within the southern part of the longlasting (Late Triassic to Eocene) Adriatic-Dinaridic carbonate platform (*sensu lato*, cf. Pamić *et al.* 1998; Korbar 2009), i.e. in the central-southern part of the Adriatic carbonate platform (*sensu stricto*, cf. Jenkyns 1991; Korbar 2009; Figure 1C). The Upper Cretaceous stratigraphy of the Adriatic carbonate platform has been described in detail on the neighbouring island of Brač (Gušić & Jelaska 1990; Cvetko Tešović *et al.* 2001; Moro *et al.* 2002; Steuber *et al.* 2005), and has been subdivided into a few lithostratigraphical units. This lithostratigraphic subdivision includes carbonate deposits ranging in age from Middle Cenomanian to the Maastrichtian (Paleocene?). The Pučišća Formation is subdivided into three superpositional-lateral units; the Brač 'Marbles' unit, the Rasotica unit, and Lovrečina unit (Gušić & Jelaska 1990). Following the intra-platform deeper-water carbonate sedimentation of the Dol Formation, carbonates of the Brač 'Marbles' unit (Santonian to Campanian) were deposited within the relatively deeper subtidal margin of an intra-platform basin. Contemporaneously, the Rasotica unit and the Lovrečina unit were deposited within back-margin peritidal environments. The similar succession is also recognized on the island of Hvar (Jerinić *et al.* 1994).

The Brač 'Marbles' unit of the Pučišća Formation in the town of Hvar (Figure 1B) is disconformably overlain by the inner-platform carbonates of the Sumartin Formation (Herak *et al.* 1976; Sladić-Trifunović 1980; Jerinić *et al.* 1994; Korbar 2003; Figure 2). The Middle Campanian hiatus is a result of a relatively short-term platform emergence (Gušić & Jelaska 1990), related to a regional (global?) sea-level fall (Steuber *et al.* 2005 and references therein) and represents the beginning of a new sequence (Moro *et al.* 2002). The Sumartin Formation is unconformably

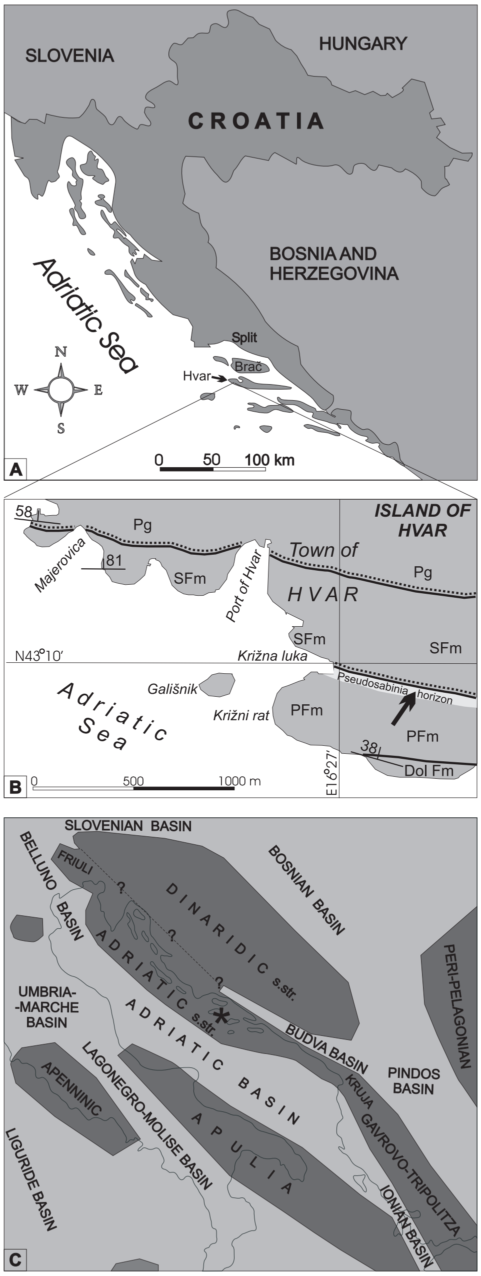

Figure 1. **(A)** Location map of the island of Hvar (arrow). **(B)** Schematic geological map of the town of Hvar: *Pseudosabinia* horizon in the topmost part of the Pučišća Formation (PFm), including the sampled locality (arrow, N43°9′55″/E16°27′17″), is disconformably overlain by inner-platform carbonates of the Sumartin Formation (SFm) which were unconformably overlain by Paleogene carbonates and clastics (Pg). **(C)** Sketch of Late Cretaceous palaeogeography of the wider Adriatic region (dark grey- carbonate platforms, light grey– basins, after Korbar 2009) and the position of the island of Hvar (asterisk).

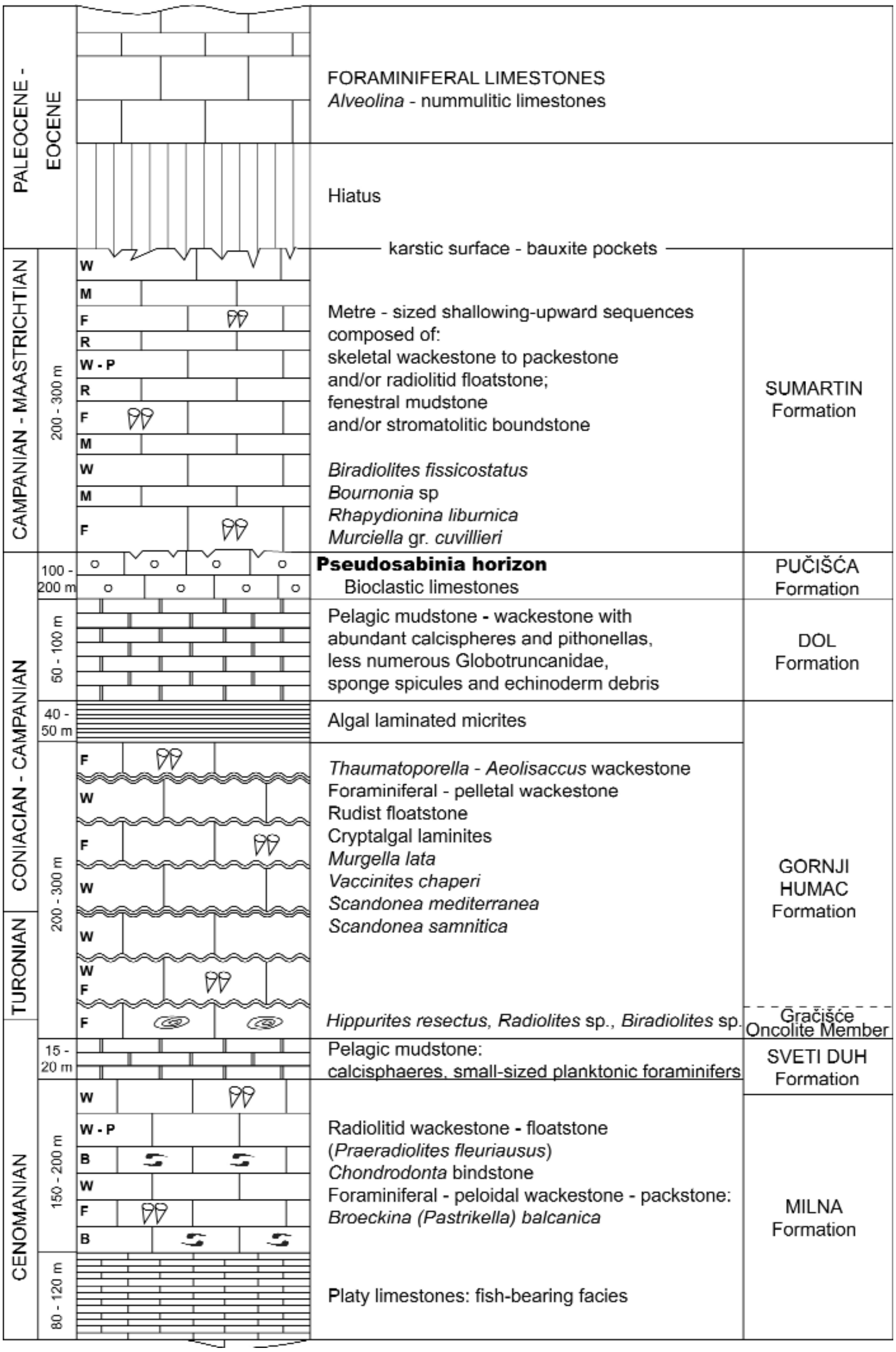

Figure 2. Schematic Upper Cretaceous lithostratigraphic column of the island of Hvar (chronostratigraphy after Borović *et al.* 1975, modified after Jerinić *et al.* 1994 and Mezga *et al.* 2006 with corresponding lithostratigraphic subdivision of Gušić & Jelaska 1990) and position of the *Pseudosabinia* horizon.

overlain by Palaeogene carbonates and clastics (Marjanac *et al.* 1998).

Within the uppermost part of the Pučišća Formation (*Pseudosabinia* horizon, Figures 1B & 2), in the Križna luka locality (town of Hvar, island of Hvar) we recognized abundant shells and collected a few massive rudist valves characterized by a complex canaliferous inner shell structure. Relative shell symmetry, myocardinal arrangements, and cellulo-prismatic structure of the right valve outer shell layer lead us to refer the specimens to the family Radiolitidae.

Massive appearance of the limestones and anthropogenic influence (many buildings, roads and artificial coast) prevented measurements of detailed stratigraphic section of the *Pseudosabinia* horizon.

Description of Specimens

We collected a few massive rudist valves (location map on Figure 1B) which are mostly embedded in pure limestone. The bulk of the material is housed in the Croatian Natural History Museum in Zagreb, one *Pseudosabinia* left valve in the permanent exhibition at the Croatian Geological Survey in Zagreb, and a few shells in the private collection of Ivo Radovanović (town of Hvar, Croatia). The shell structure is highly recrystallized, but nicely preserved.

The right valves (RV) are massive, high-conical in shape and ellipsoidal (oval) in transverse section (Figure 3A). The slightly depressed posterodorsal parts of the shells mark the radial bands. Outer shell layers are mostly eroded, and characterized by typical radiolitid cellulo-prismatic structure (Figure 3B). The inner shell layer is characterized by irregular polygonal canals that get smaller outwards. The ligamental ridge is well developed, with a thin neck and relatively thick oval T-form tip. Sockets of cardinal teeth and myophore scars are developed within the inner shell layer.

The left valves (LV) are also massive, and coiled-conical in shape. The valves are also characterized by well-preserved canaliculate inner shell layer structure, while centrally placed body cavity covers less than a quarter of the transverse section (Figure 3C, D). The inner shell layer has bigger irregular polygonal canals in its thicker inner part and smaller radially elongated canals in its thinner outer part. The ligamental invagination is well developed. The myocardinal apparatus is attached to the inner shell layer construction (Figure 3E).

Taxonomy and Palaeobiogeography

Classis **Bivalvia** Linné 1758

Subclassis **Heterodonta** Neumayr 1884

Ordo **Hippuritoida** Newell 1965

Superfamilia **Hippuritoidea** Gray 1848

Familia **Radiolitidae** d'Orbigny 1847

Genus ***Pseudosabinia*** Morris & Skelton 1995

Synonymy of the species amended after Morris & Skelton (1995):

Pseudosabinia klinghardti (Boehm 1927) Figure 3A–E.

aff. 1927 *Sabinia klinghardti*: 205, plate 15, figures 1, 2; plate 16, figure 1.

?aff. 1927 *Schiosia bilinguis* Boehm: 2007, plate 18, figures 1a–1c.

aff. 1967 *Pseudosabinia rtanjica* Pejović: 295–97, plate 1, figure 1.

aff. 1986 *Sabinia rtanjica tunisiensis* Philip: 248, 49, plate 1, figures 1–6.

aff. 1996 *Sabinia klinghardti* Laviano: figure 8.

aff. 2008 *Pseudosabinia klinghardti* Schlüter *et al.*: figure 8A–E.

As proposed by Morris & Skelton (1995), a few specimens previously referred to *Sabinia* (Parona 1908) are recognized as a new genus – *Pseudosabinia klinghardti* (Boehm 1927). The species was first described by Boehm (1927) from NW Turkey and the type material is housed in the Natural History Museum in London. Besides, *Pseudosabinia klinghardti* is reported along with some other species

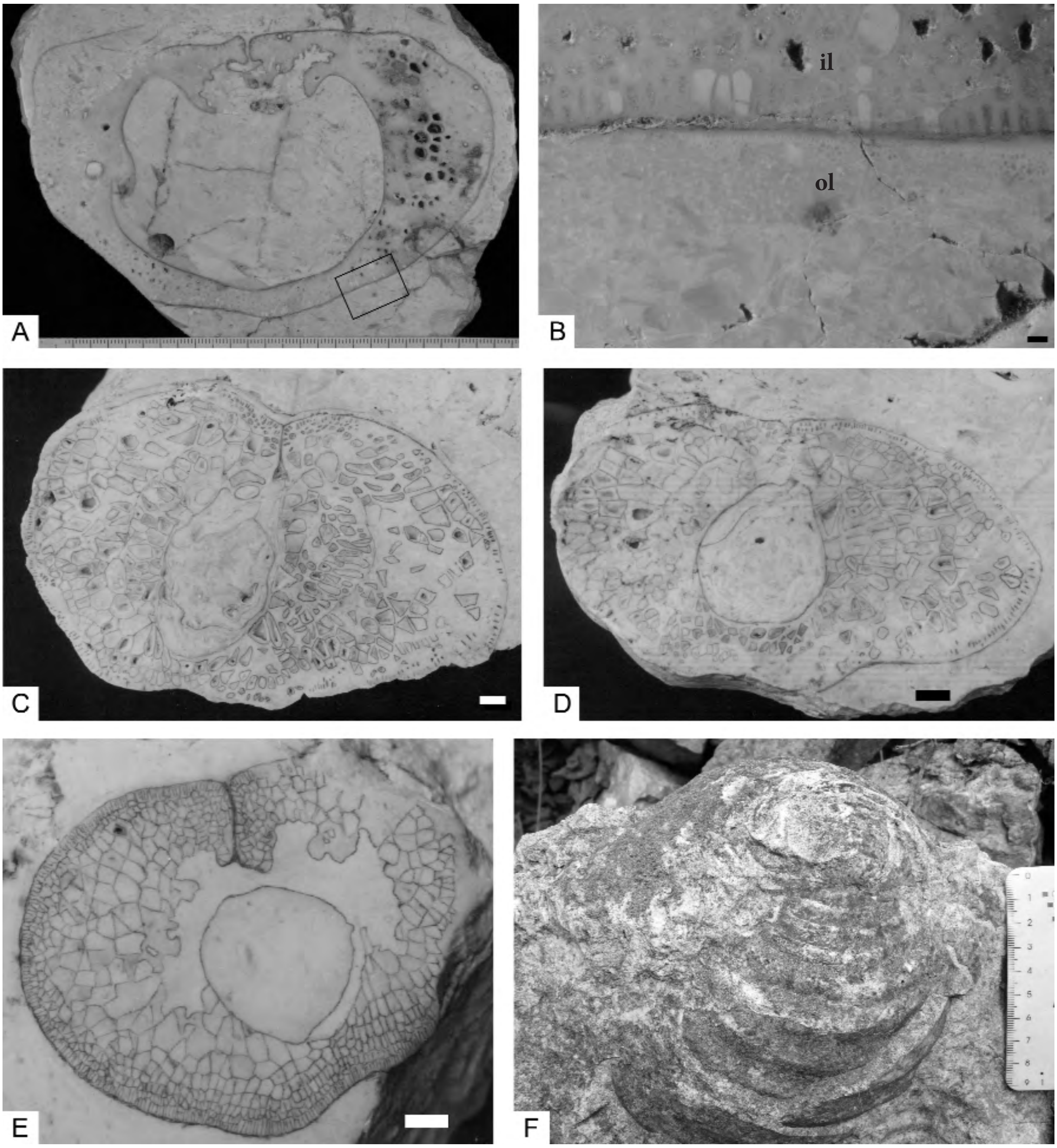

Figure 3. **(A–E)** *Pseudosabinia klinghardti* (Boehm 1927) **(A)** RV transverse section showing inner shell layer structure, ligamental ridge, and contours of teeth and myophores. See figure 3B for detail. Scale bar in mm. **(B)** Detail of Figure 3A showing atypical inner (il) and typical radiolitid cellulo-prismatic RV outer (ol) shell layers. Scale bar 1 mm. **(C)** LV transverse section close to the commissure. Scale bar 1 cm. **(D)** LV transverse section close to the apex (of the same valve as on Figure 3C). Scale bar 1 cm. **(E)** LV transverse section showing a contour of the cardinal apparatus. Scale bar 1 cm. **(F)** Inoceramid bivalve from the *Pseudosabinia* horizon. Scale bar in cm.

of the genus by Özer (1986, 2002, 2008), Fenerci (1999), Özer *et al.* (2008) and Steuber *et al.* (2009) from the wider region of Turkey.

In Arabia, the species was reported from the Qahlah Formation of Jebel Huwayyah as well as in the 'red jebel' limestones of Qarn Mileiha, west of Jebel Faiyah (Morris & Skelton 1995; Skelton & Smith 2000).

From Apulia (Italy) the species is reported from Campanian S. Cesarea Limestone of Salento Peninsula (Laviano 1996; Schlüter *et al.* 2008).

Fossil Association, Biostratigraphy, Lithology, and Environment

The *Pseudosabinia* valves are embedded in massive, light-grey to white, mostly recrystalized peloidal-bioclastic packstone to rudstones, characterized in places by chalky appearance. Associated macrofauna is characterized by various radiolitids (including *Pseudopolyconites*), rare hippuritids (including *Vaccinites* sp.), *plagioptychid Mitrocaprina* sp. and inoceramid bivalves (Figure 3F).

The association comprises also abundant foraminifers, including index species of orbitoids and siderolitines. The investigated microfossil assemblage (Figure 4A–F, sampling location marked by arrow on Figure 1B) is composed of *Praesiderolites* sp., *Pseudosiderolites vidali* (Douvillé), *Orbitoides tissoti* Schlumberger, *Orbitoides douvillei* (Silvestri) (*O. tissoti* var. *O. douvillei* in Neumann 1972; forms with lacking lateral layers). The orbitoids and siderolitines are forms with well studied and documented phyletic lineage (for a review see van Gorsel 1978).

The association of *O. tissoti* and *P. vidali* assemblage undoubtedly indicates the Campanian age. The association is referred to the 'middle' or early Late Campanian (Gušić & Jelaska 1990), and is recalibrated by strontium isotope stratigraphy to Middle Campanian (Steuber *et al.* 2005).

Regarding the recent research the investigated *Pseudosabinia* horizon belongs to the Pučišća Formation. Massive appearance of the limestones, abundant rudist debris, accompanied by other mollusk, echinoderm, coral and stromatoporid fragments in the bioclastic packstone-floatstones containing siderolitines and orbitoids – so called 'proximal' type of the Brač 'Marbles' unit (Gušić & Jelaska 1990), indicate deposition in a relatively deeper subtidal environment (Moro *et al.* 2002).

Strontium Isotopes Stratigraphy

Samples for geochemical analyses were obtained with tungsten drill bits from polished surfaces of rudist shell bioclasts (brown coloured compact outer shell layer). Three samples from the horizon were taken (HIR-1, HIR-2 and HIR-3, sampling location marked by arrow on Figure 1B). The samples were prepared and processed at Ruht-University (Bachum, Germany) according to the standard procedure described by Steuber *et al.* (2005). Sr was separated from the remaining splits by standard ion-exchange methods. Sr-isotope ratios were analyzed on a Finnigan MAT 262 thermal-ionisation mass spectrometer and normalized to an $^{86}Sr/^{88}Sr$ value of 0.1194. The $^{87}Sr/^{86}Sr$ ratios of samples are adjusted to a value of 0.709175 of modern seawater (USGS EN-1), to be consistent with the normalisation used in the compilation of the 'look-up' table of McArthur *et al.* (2001) which was used to derive numerical ages. This normalisation is critical for the precise derivation of numerical ages, and was assessed by interlaboratory comparison of samples, including latest Cretaceous biological calcite. The results are shown in Table 1 and Table 2.

Assessment of the preservation of the original seawater $^{86}Sr/^{88}Sr$ value in the analysed material is most important for the derivation of precise numerical ages. Although high Mn and Fe concentrations in skeletal calcite are considered to indicate recrystallization in reducing environments, involving the partial or complete equilibration of the Sr-isotope ratio with that of the diagenetic fluid, also resulting in low Sr concentrations, specific diagenetic environments can result in different patterns (Steuber 2003). Nearly concordant Sr isotope values in different samples from one stratigraphic level provide strong evidence for the retention of the original seawater value, because diagenesis typically proceeds patchily, and different diagenetic phases tend to have different Sr isotope values related to the evolution of diagenetic fluids (McArthur 1994).

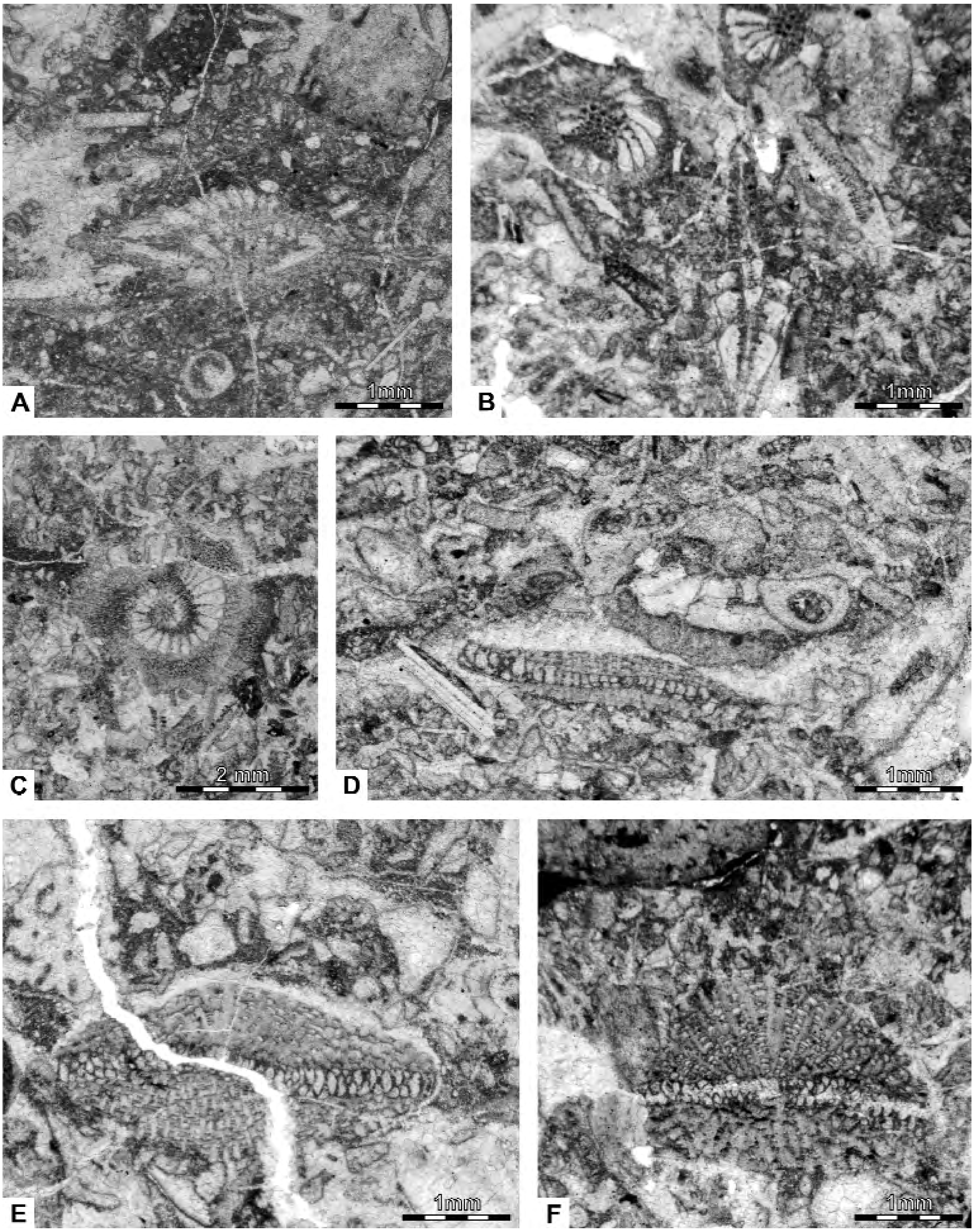

Figure 4. (**A**–**F**) Microphotographs of thin-sections of bioclastic packstone-rudstones containing siderolitines and orbitoids. **(A)** *Pseudosiderolites vidali* (Douvillé), axial section; **(B)** different sections of *Pseudosiderolites vidali* (Douvillé); **(C)** *Pseudosiderolites vidali* (Douvillé), equatorial section; **(D)** *Orbitoides douvillei* (Silvestri) (*O. tissoti* var. *O. douvillei*; with the addition of lateral layers evolved into *O. tissoti*), subaxial section; **(E, F)** *Orbitoides tissoti* Schlumberger, subaxial section.

Table 1. Elemental concentrations of HIR samples (*Pseudosabinia* horizon, see Figure 1B for the location) of the Pučišća Formation in the town of Hvar.

Elem	Avg	Units	Stddev	%RSD
HIR 1				
Elem	Avg	Units	Stddev	%RSD
Ca3179	390800,00	ppm	4102,57	1,05
Fe2382	23,74	ppm	2,12	8,91
Mg2852	1721,00	ppm	8,02	0,47
Mn2576	5,89	ppm	0,69	11,78
Sr4215	699,40	ppm	4,12	0,59
HIR 2				
Elem	Avg	Units	Stddev	%RSD
Ca3179	393200,00	ppm	5377,04	1,37
Fe2382	6,30	ppm	1,11	17,68
Mg2852	1756,00	ppm	9,42	0,54
Mn2576	4,25	ppm	0,58	13,64
Sr4215	809,70	ppm	3,44	0,42
HIR 3				
Elem	Avg	Units	Stddev	%RSD
Ca3179	393100,00	ppm	6513,01	1,66
Fe2382	0,43	ppm	0,54	126,18
Mg2852	1757,00	ppm	13,47	0,77
Mn2576	2,95	ppm	0,75	25,37
Sr4215	1204,00	ppm	10,48	0,87

Fe and Mn concentrations in all but one sample (HIR-1) are below the analytical detection limit of 18 µg/g and 30 µg/g Mn, respectively. Thus, the concentrations of these elements should not be used for screening of diagenetic alteration of rudist calcite. Furthermore, according to the discussion of Steuber *et al.* (2005), Sr concentration of 800 µg/g (ppm) is considered as a threshold value, and samples with lower concentrations should not be considered for the derivation of numerical ages. The Fe concentration in sample HIR-1 do not exceed 55 µg/g Fe (Table 1), but the Sr concentration is below the threshold value. However, Frijia & Parente (2008) use also the samples with nearly the same Sr concentrations as reliable for the numerical ages.

Noteworthy, in our samples, even those with concentration of 700 µg/g Sr (HIR-1), shows similar $^{87}Sr/^{86}Sr$ values as those samples with higher Sr concentrations (samples HIR-2 and HIR-3, 800 and 1200 µg/g Sr, respectively, Table 2).

A mean value of $^{87}Sr/^{86}Sr$ for all three samples is 0.707585. According to the 'look-up' table of McArthur *et al.* (2001), the horizon is placed within latest Middle Campanian (Figure 5).

Noteworthy, the age of the most famous Apulian *Pseudosabinia* horizon (S. Cesarea Limestone) is of

Table 2. $^{87}Sr/^{86}Sr$ values of HIR samples (*Pseudosabinia* horizon, see Figure 1B for the location) of the Pučišća Formation in the town of Hvar.

#	sample number	$^{87}Sr/^{86}Sr$ measured	± 2 s $_{mean}$	$^{87}Sr/^{86}Sr$ normalized to NBS 987 values bracketing the samples and corrected for deviation from value stated by McArthur	$^{87}Sr/^{86}Sr$ normalized to USGS EN-1 values bracketing the samples and corrected for deviation from value stated by McArthur	$^{87}Sr/^{86}Sr$ normalized to NBS 987 mean value Bochum and corrected for deviation of the mean value from NBS 987 Value stated by McArthur	$^{87}Sr/^{86}Sr$ normalized to USGS EN-1 mean value Bochum and corrected for deviation of the mean value from USGS EN-1 Value stated by McArthur	**mean value**
1	NIST NBS 987	0.710237	0.000007	0.710247	0.710259	0.710248	0.710257	
2	HIR-1	0.707569	0.000007	0.707579	0.707591	0.707580	0.707589	
3	HIR-2	0.707561	0.000007	0.707571	0.707583	0.707572	0.707581	**0.707585**
4	HIR-3	0.707566	0.000007	0.707576	0.707588	0.707577	0.707586	
5	USGS EN-1	0.709153	0.000007	0.709163	0.709175	0.709164	0.709173	

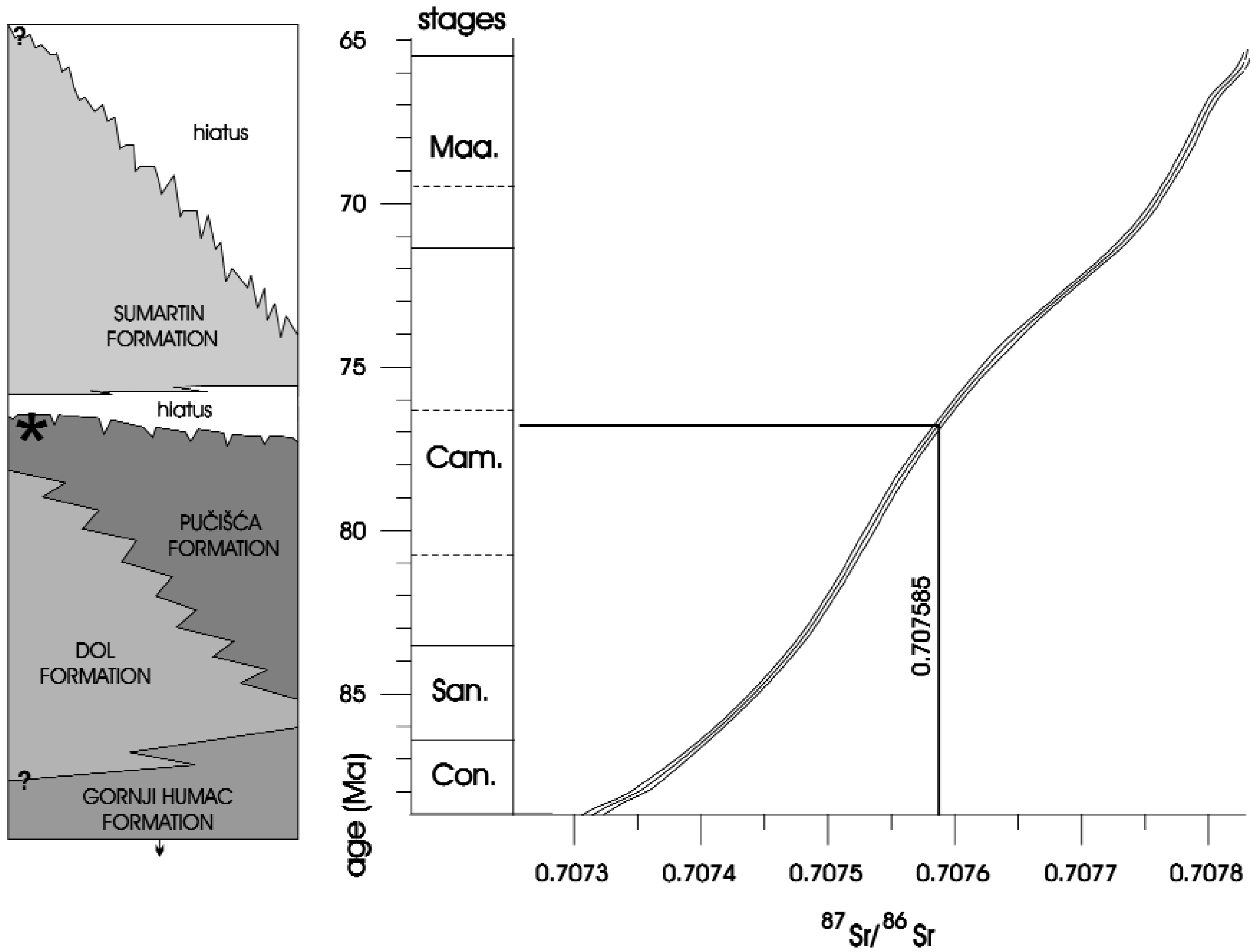

Figure 5. Scheme of the Upper Cretaceous lithostratigraphic units of the Adriatic carbonate platform (modified after Steuber *et al.* 2005) showing the position of the *Pseudosabinia* horizon (asterisk) within Pučišća formation of the town of Hvar according to the numerical age derived from $^{87}Sr/^{86}Sr$ value and 'look up' table of McArthur *et al.* 2001). Intrastage boundaries after McArthur *et al.* 2000).

similar age (Schlüter *et al.* 2008 and references therein), and also directly underlies Middle to Upper Campanian disconformity. The disconformity is related to regional (global?) relative sea level fall (Steuber *et al.* 2005 and references therein).

Conclusions

The Upper Cretaceous carbonates on the Island of Hvar (Figure 1A, B) are typical of the central Tethyan ('peri-Adriatic', central-northern Mediterranean) intra-oceanic carbonate platforms. The carbonates were deposited within the southern part of the Adriatic-Dinaridic carbonate platform (*sensu lato*), i.e. in the central-southern part of the Adriatic carbonate platform (*sensu stricto*, Figure 1C). The Upper Cretaceous stratigraphy of the Adriatic carbonate platform has been described in detail from the neighbouring island of Brač, and has been subdivided into a few lithostratigraphical units. The Pučišća Formation in the area of the town of Hvar (the island of Hvar) is represented exclusively by the Brač 'Marbles' unit, that is disconformably overlain by the inner-platform peritidal carbonates of the Sumartin Formation (Figure 2).

Within the uppermost part of the Pučišća Formation we recognized and collected a few massive rudist valves, characterized by a complex canaliferous inner shell structure (Figure 3A–E). Relative shell symmetry, myocardinal arrangements, and cellulo-prismatic structure of the right valve outer shell layer lead us to refer the specimens to the family Radiolitidae, i.e. to the *Pseudosabinia klinghardti*.

The valves are embedded in massive, light-grey to white, mostly recrystallized peloidal-bioclastic packstone to rudstones, characterized in places by chalky appearance. The macrofossil association comprise various radiolitids (including *Pseudopolyconites*), rare hippuritids (*Vaccinites* sp.), *Mitrocaprina* sp. and inoceramid bivalves (Figure 3F). Microfossil association includes index species of orbitoids and siderolitines: *Pseudosiderolites vidali*, *Orbitoides tissoti* and *O. douvillei* (Figure 4A–F).

The range of the microfossils, along with results of strontium-isotope stratigraphy (Tables 1 & 2; Figure 5), indicate the latest Middle Campanian age of the horizon. Thus, these are the youngest deposits of the Pučišća Formation on the Adriatic carbonate platform reported to date.

The *Pseudosabinia* limestones in the town of Hvar were deposited in a relatively deeper subtidal environment. The deposits were affected by regional (global?) Middle to Late Campanian sea-level fall, relatively short platform emergence, and subsequent deposition of the inner-platform peritidal carbonates referred to as the Sumartin Formation.

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