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Radiolarian dating of the Mala Palagruža pelagic succession: direct evidence of the Middle Jurassic evolution of the central Adriatic Basin

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Abstract

The Adriatic Basin was one of the pelagic basins of the Adriatic microplate formed as a consequence of Late Palaeozoic–Early Mesozoic extension. However, unlike other pelagic domains of the Adriatic microplate, that have successions exposed in the peri-Adriatic mountain chains, the Lower Jurassic to Miocene deposits of the Adriatic Basin are mostly buried beneath the modern Adriatic Sea. One of the rare places where pieces of this pelagic succession are exposed above sea level is the Palagruža Archipelago in the central Adriatic. There, blocks of pelagic lithologies are brought to the surface by active diapirism of Triassic evaporites. A succession several tens of metres thick, composed of thin-bedded microcrystalline and partially silicified grey dolostone, interlayered with very thin-bedded siliceous siltstone is exposed on the island of Mala Palagruža. This succession is informally named the Mala Palagruža formation, however, it lacks underlying and overlying deposits. Radiolarians extracted from three samples of siliceous siltstone from the Mala Palagruža succession indicate a late Bajocian–Bathonian to possibly early Callovian age. Correlations with the offshore industrial wells drilled in the Adriatic Sea and onshore successions of the central Apennines, indicate that the investigated block is likely to be equivalent to the Calcari Diasprigni Formation, a deep-marine facies deposited in the central part of the Adriatic microplate during a period of eutrophic conditions, which favoured radiolarian productivity. This is the first discovery of Jurassic pelagic deposits above sea level in the central Adriatic.

Keywords: Middle Jurassic, dolostone, siliceous siltstone, biostratigraphy, Mid-Adriatic Ridge, Adriatic foreland, salt diapir

1. INTRODUCTION

Mountain chains of the central Mediterranean region preserve evidence of several Mesozoic deep-water domains, which together with shallow-water carbonate platforms formed a network on top of a small lithospheric block named the Adriatic plate or Adria (BERNOULLI, 1971, 2001; D'ARGENIO et al., 1971; ZAPPATERRA, 1994; VLAHOVIĆ et al., 2005; KORBAR, 2009; SANTANTONIO & CARMINATI, 2011; MASETTI et al., 2012; GORIČAN et al., 2022). This complex topography formed from the Late Palaeozoic through the Early Jurassic as a consequence of widespread and long-lasting extension related to the opening of different oceanic branches of the western Tethyan realm, was well-developed throughout the Jurassic and later became involved in orogenic processes associated with the collision of Adria and Eurasia (CHANNELL et al., 1979; HANDY et al., 2010, 2015; SANTANTONIO & CARMINATI, 2011; VAN HINSBERGEN et al., 2020).

Pelagic domains attributed to the Adriatic plate, including Mesozoic deep-water basins and submarine heights, have been well-documented from the Alps, the Dinarides–Hellenides and the Apennines (BERNOULLI, 1971, 2001; WINTERER & BOSELLINI, 1981; BERTINELLI et al., 2005; BERRA et al., 2009; MARINO & SANTANTONIO, 2010; SANTANTONIO & CARMINATI, 2011; GORIČAN et al., 2012, 2022). Sedimentation in these pelagic domains was controlled by Tethyan-wide fluctuations in plankton productivity, as well as the local supply of material from shallow areas of active carbonate production. As a result, thick continuous sequences of pelagic carbonates, marls and radiolarites, intercalated with carbonate gravity-flow deposits are recorded in basinal areas, while condensed sequences, often punctuated by stratigraphic gaps characterize intra-basinal topographic highs (BAUMGARTNER, 1990, 2013; SANTANTONIO & CARMINATI, 2011; MARINO & SANTANTONIO, 2010). Radiolarians, as often the only fossils providing stratigraphic control, played a major role in understanding the evolution of these pelagic domains.

One of the deep-water basins of the Adriatic plate, the Adriatic Basin, extended approximately in the same position as the present-day Adriatic Sea and separated the Adriatic Carbonate Platform (AdCP) in the northeast from the Apulian platform in the southwest (ZAPPATERRA, 1994; GRANDIĆ et al., 1999; VLAHOVIĆ et al., 2005; Fig. 1d). The basin formed when a pre-existing shallow-marine area drowned in the Early Jurassic and was characterized by pelagic, mostly carbonate sedimentation until the Late Miocene (ZAPPATERRA, 1994; GRANDIĆ et al., 1999, 2002; VLAHOVIĆ et al., 2005; SCISCIANI & CALAMITA, 2009; MASETTI et al., 2012; SANTANTONIO et al., 2013). Unlike other Mesozoic pelagic domains of the Adriatic plate, with successions exposed onshore, the successions of the Adriatic Basin are mostly covered by thick Neogene and Quaternary

deposits beneath the Adriatic Sea, and appear onshore only on Gargano (BOSELLINI et al., 1999). Consequently, its evolution is considerably less understood. Most insights into its evolution come from studying boreholes and seismic profiles produced during hydrocarbon exploration.

The only place where some of the Jurassic units attributed to the Adriatic Basin are exposed above sea level is the islet of Mala Palagruža, part of the Palagruža (Pelagosa in Italian) archipelago in the central Adriatic Sea (KORBAR et al., 2009, 2012; Fig. 1a–c). Here, a large block of pelagic deposits was brought to the surface by active diapirism of Triassic evaporites (GELETTI et al., 2008; KORBAR et al., 2009; CARBONI et al., 2024). However, because of the distance from the mainland, steep slopes and rocky coast, access to the islet is difficult and information about its geology remains sparse. This study presents new biostratigraphic data based on radiolarians from one of the extremely rare outcrops of the pelagic succession attributed to the Adriatic Basin. The new data enable correlation with the other Mesozoic deep-marine basins of the Adriatic plate and provide insights into the evolution of the Adriatic Basin.

2. GEOLOGICAL SETTING

The present-day Adriatic Sea, together with the Po Plain, Apulia and Istria regions, represents the Adriatic foreland (Fig. 1a), a relatively undeformed part of a lithospheric block named the Adriatic microplate or Adria (also referred to as Apulia, e.g., DERCOURT et al., 1986). Although regarded by some authors as a promontory of the African plate (CHANNELL et al., 1979; MUTTONI et al., 2013), Adria is nowadays considered an independent plate, which has undergone and still undergoes motion relative to stable Africa (BATTAGLIA et al., 2004; HANDY et al., 2010, 2015; VAN HINSBERGEN et al., 2020).

Following the Middle Triassic rifting phase related to the opening of the Neotethys Ocean, a vast Late Triassic–earliest Jurassic carbonate platform (Hauptdolomite/Dolomia principale sequence) developed on the Permian to Middle Triassic predominantly clastic basement of the Adriatic plate (VLAHOVIĆ et al., 2005). This unique area of shallow-marine carbonate production was tectonically disintegrated during the Early Jurassic, leading to the formation of the Adriatic Basin as a northwest–southeast striking trough with the AdCP and the Apulian platform on opposite sides (ZAPPATERRA, 1994; GRANDIĆ et al., 1999; VLAHOVIĆ et al., 2005; Fig. 1d). Data from the northern Adriatic region suggest that the deepening occurred along the reactivated longitudinal Triassic normal fault of the Dinaridic strike and that the transition between the AdCP and the Adriatic Basin was characterized by a notably steep slope (GRANDIĆ et al., 1999, 2002; KAMENSKI & KORBAR, 2023). Rapid subsidence along reactivated older extensional faults is also recognized in the transitional area between the Apulian Platform and the Adriatic Basin in the central Adriatic region, where seismic and borehole data indicate topography characteristic of extensional margins, with submarine highs and isolated basins (SANTANTONIO et al., 2013). This platform margin architecture can be traced onshore in the central Apennines (MARINO & SANTANTONIO, 2010).

It is generally accepted that the Adriatic Basin was connected with the Ionian Basin of the Hellenides, the Umbria-Marche Basin of the central Apennines and the Belluno Basin of the Southern Alps (ZAPPATERRA, 1994; GRANDIĆ et al., 1999; VLAHOVIĆ et al., 2005; SANTANTONIO et al., 2013; Fig. 1d). MASETTI et al. (2012) recognized the similarities in stratigraphy between the Belluno Basin and the northern Adriatic Basin but emphasized that the former formed on top of a drowned Late Triassic platform, while the latter evolved on the lowermost Jurassic shallow-water carbonates like the early drowned eastern margin of the Trento Platform.

The pelagic stratigraphy of the Adriatic Basin can best be reconstructed by correlating industrial well data from the offshore wells drilled in the Adriatic Sea, with onshore deposits of the Umbria-Marche area in the central Apennines. Information concerning Italian oil exploration, including detailed well logs, has been made publicly available through the ViDEPI project, managed by the Italian Geological Society.

The basement of the pelagic sequence of the Adriatic Basin consists of Permian to Lower Triassic continental sandstones and limestones, Upper Triassic dolomites (Dolomia Principale), dolomites and evaporites of the Burrano Formation, and the lowermost Jurassic shallow-water carbonates of the Calcare Massicio Formation. (GELETTI et al., 2008; FESTA et al., 2014; BRANDANO et al., 2016; BORRELLI et al., 2023). The evaporites of the Burano Formation. are present mainly in the central and southern parts of the Adriatic region and in the Ionian Zone in Albania and Greece (KARAKITSIOS & RIGAKIS, 2007; GELETTI et al., 2008).

Pelagic sequences from wells drilled in the western central Adriatic show very little variability and can be easily correlated with the successions of the central Apennines. Almost identical stratigraphy is also recorded in the northern (Alessandra 1 well, ViDEPI, 2025; GRANDIĆ et al., 1999; ŠPELIĆ et al., 2021) and the southern Adriatic regions (Sparviero 1*bis* and Grifone 1 wells, ViDEPI, 2025; CAZZINI et al., 2015). In several offshore wells, laminated micrites alternating with breccias, informally named the Calcari Anossici (or Calcari di Emma), indicate the existence of spatially limited, intraplatform anoxic basins during the earliest Jurassic (CAZZINI et al., 2015; CAMPANA et al., 2017). In the central Apennines, a succession composed of bituminous dolostone, mudstone and calcarenites, dated with ammonites and radiolarians, provides evidence of a similar earliest Jurassic intraplatform basin (BERTINELLI et al., 2004; BERTINELLI & MARCUCCI, 2011).

The oldest widespread pelagic deposits on top of the shallow-marine Calcare Massicio Formation are the Sinemurian to Toarcian Corniola Formation and the Toarcian Rosso Ammonitico Formation (SANTANTONIO et al., 2013; FESTA et al., 2014; CAZZINI et al., 2015). The Corniola Formation, interpreted as a syn-rift deposit, consists of cherty limestone and contains megabreccias with blocks of the underlying shallow-water carbonate lithologies (GALLUZZO & SANTANTONIO, 2002; MARINO & SANTANTONIO, 2010; SANTANTONIO et al., 2013). Marly limestone of the Rosso Ammonitico Formation was deposited as a response to a drop in the rates of pelagic carbonate productivity during the Toarcian oceanic anoxic event (OAE) and correlates to the

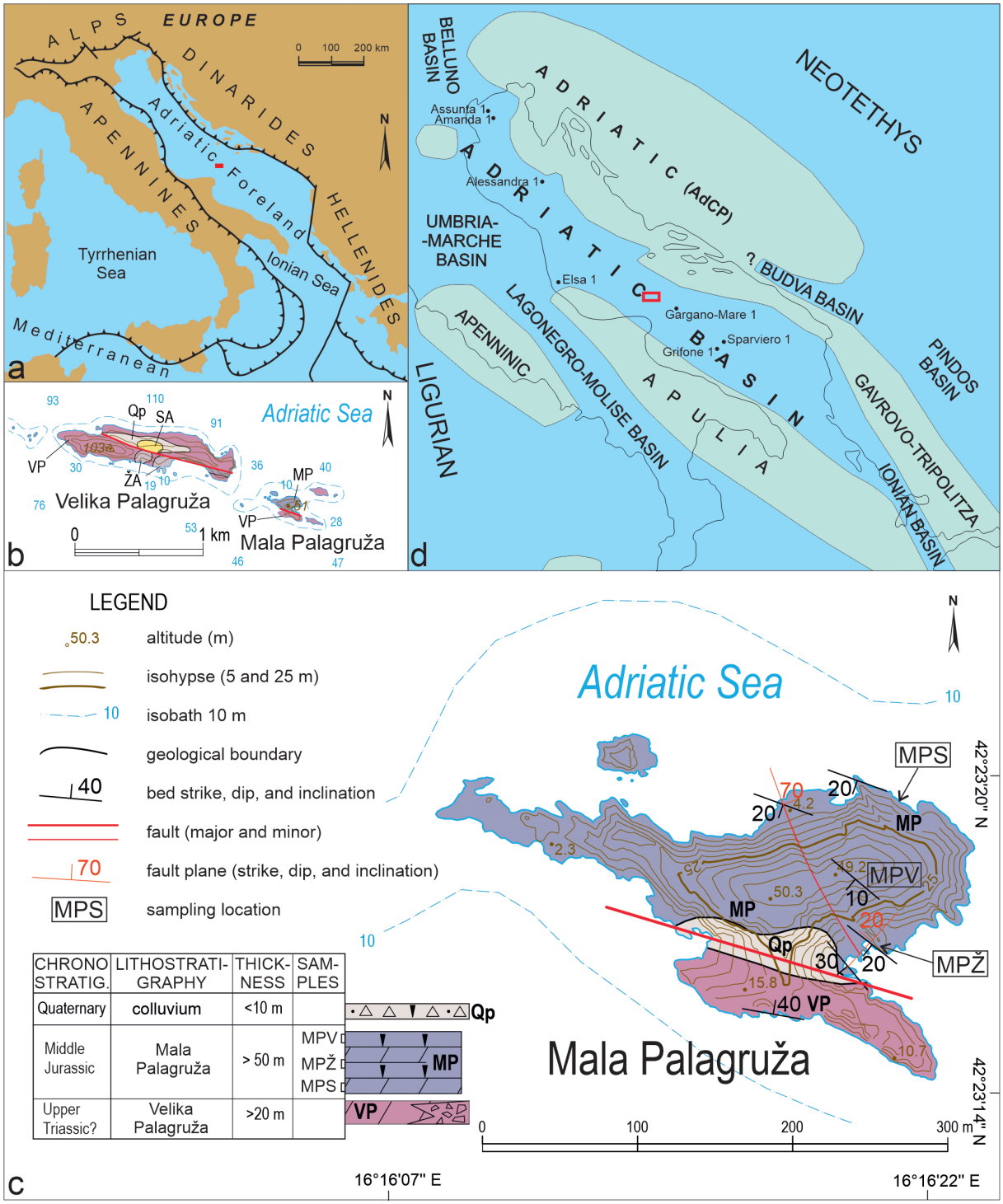


Figure 1. (**a**) Location map of the Palagruža archipelago in the central Adriatic (red rectangle), and the present-day regional peri-Adriatic tectonic setting (KORBAR, 2009); (**b**) A geological map of the Palagruža archipelago (from KORBAR et al., 2012), representing exclusive outcrops of the Mid-Adriatic Ridge; (**c**) A geological map of the Mala Palagruža islet and position of the sampled locations (arrows); (**d**) The paleogeographic position of the Palagruža archipelago during the Middle Jurassic in the central Adriatic Basin (red rectangle) showing a conservative configuration of the peri-Adriatic carbonate platforms and the surrounding basins. Black dots mark selected boreholes (see text).

Marne del Monte Serrone marls in deeper parts of the Umbria-Marche Basin (GALLUZZO & SANTANTONIO, 2002; BARTOLINI et al., 1996). The Marne di Monte Serrone Formation is also documented offshore in the southern Adriatic (Sparviero 1*bis* and Grifone 1 wells, ViDEPI, 2025; CAZZINI et al., 2015).

The Middle to Upper Jurassic Calcari ad Aptici interval from offshore wells is subdivided into three units onshore: the upper Toarcian – Bajocian Calcari e Marne a *Posidonia*, Bajocian/Bathonian – lower Kimmeridgian Calcari Diasprigni, and Kimmeridgian – Tithonian Calcari ad aptici e *Saccocoma* (GALLUZZO & SANTANTONIO, 2002 and references therein). These are generally carbonate lithologies, except for the Calcari Diasprigni, which consists predominantly of radiolarian chert with subordinate cherty limestone. Calcareous resediments occur throughout this entire interval (BAUMGARTNER, 1990;

BARTOLINI et al., 1995, 1996; GALLUZZO & SANTANTONIO, 2002).

The uppermost Jurassic and Cretaceous deposits of the Adriatic Basin consist of the upper Tithonian – Barremian/Aptian Maiolica cherty limestone, overlain by Aptian – Cenomanian marls of the Marne a Fucoidi Formation. and the Cenomanian to Oligocene Scaglia limestone (Scaglia Calcarea and Scaglia Cinerea). Miocene (Aquitanian to Tortonian) marls and clayey limestones of the Bisciario and the Schlier formations are the youngest pelagic deposits of the Adriatic Basin bellow thin Messinian evaporites, which separate the pelagic succession from the thick overlying Pliocene to Quaternary sequence of the Adriatic foreland (GALLUZZO & SANTANTONIO, 2002; FESTA et al., 2014; SANTANTONIO et al., 2013).

Salt doming of Triassic evaporites has been active in the central Adriatic since the Miocene (GELETTI et al., 2008; FESTA et al., 2014; PIKELJ et al., 2015). Some diapiric structures are aligned with an area of crustal uplift named the Mid-Adriatic Ridge (GRANDIĆ et al., 1997; GELETTI et al., 2008; SCISCIANI & CALAMITA, 2009) or the Palagruža rise (BERTOTTI et al., 2001). Tectonic inversion of Mesozoic extensional structures along the ridge, accommodated compressional deformations transferred from two opposite-verging orogens, the Dinarides and the Apennines (ARGNANI et al., 1994; BERTOTTI et al., 2001; GELETTI et al., 2008; SCISCIANI & CALAMITA, 2009). The main orogenic phases in the outer Dinaridic and Apenninic zones occurred during the Palaeogene and the Pliocene, respectively (KORBAR, 2009; SCISCIANI & CALAMITA, 2009, and references therein), with compression still possibly active (SCROCCA, 2006; CARBONI et al., 2024). Locally, diapirs pierce the overlying sedimentary sequence (SCISCIANI & ESESTIME, 2017) and are exposed above sea level on some islands (KORBAR et al., 2012). Halokinetic tectonics in the central Adriatic region were presumed to have also induced the exhumation of magmatic bodies (JURAČIĆ et al., 2004; PIKELJ et al., 2015; KORBAR et al., 2012). Similar diapirism of the Triassic evaporites linked to compressional structures is also recognized in the Ionian Zone (VELAJ, 2002; VAKALAS et al., 2023).

The Palagruža archipelago is the only part of the Mid-Adriatic Ridge exposed above sea level (Fig. 1b). It is likely placed on top of a deep-rooted diapiric structure that is still undergoing uplift (GRANDIĆ et al., 1999; GELETTI et al., 2008; KORBAR et al., 2009; CARBONI et al., 2024). The archipelago is built predominantly of sedimentary and some evaporitic rocks of Mesozoic and Cenozoic ages. Four units are recognized on the island of Velika Palagruža (KORBAR et al., 2009). The oldest, Žalo unit (ŽA on Fig. 1b), is composed of Triassic siliciclastics and gypsum. This unit is likely in diapiric contact with the Lanterna unit (Velika Palagruža formation (VP) in KORBAR et al., 2012; Fig. 1b, c), comprising thick-bedded dolostone with local occurrences of chert and dolomitic breccia of presumably Late Triassic age, and is capped by Miocene biocalcarenites of the Salamandrija unit (SA on Fig. 1b). Talus, landslide deposits, and humic soil make up the youngest unit of Velika Palagruža (KORBAR et al., 2009).

3. DESCRIPTION OF MALA PALAGRUŽA OUTCROPS

The islet of Mala Palagruža is built predominantly of a unique succession of thin-bedded siliceous dolomites alternating with chert, that is recognized as a specific lithostratigraphic unit – the Mala Palagruža formation (Figs. 1c, 2, 3), tentatively assigned a Late Triassic to Early Jurassic age (KORBAR et al.,

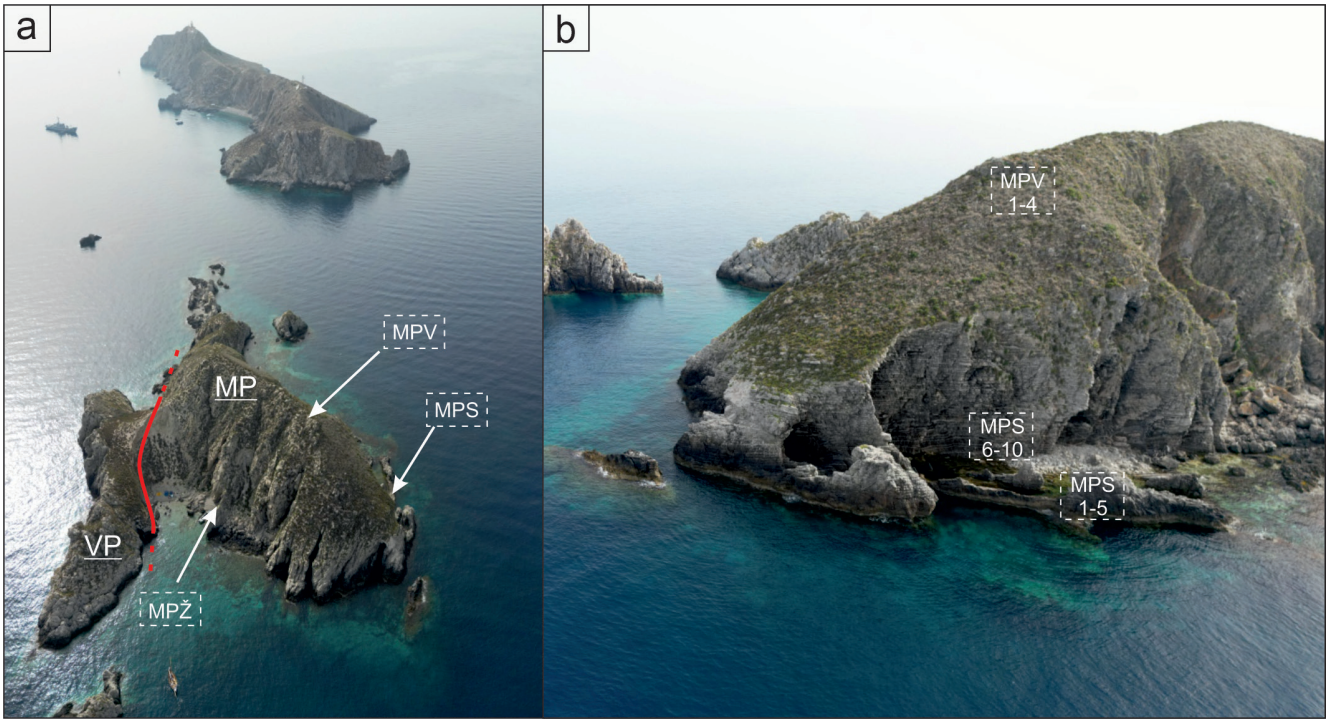


Figure 2. (**a**) A panoramic photograph from the east to the islet of Mala Palagruža, (Velika Palagruža is in the background on the west), with interpretation of the main geological elements and the sampling locations MPS, MPŽ and MPV. VP – Velika Palagruža formation, MP – Mala Palagruža formation; (**b**) A panoramic photograph from the north, showing a typical thin-bedded pelagic succession of the Mala Palagruža formation exposed on the northern cliff of the islet and the sampling locations.

2012). The WNW–ESE striking Palagruža fault separates the crystalline dolomites and breccia of the Velika Palagruža formation, on the smaller southern ridge of the islet, from the thin-bedded siliceous deposits of the Mala Palagruža formation that form the larger northern ridge (Fig. 1c). The fault zone is covered by the strongly tectonically crushed surrounding rocks that form a colluvium deposited along the fault (Fig. 2a).

The Mala Palagruža formation consists of thin-bedded (10–25 cm) microcrystalline and partially silicified grey dolomites interlayered with very thin-bedded (<15 cm) light grey to greenish "floury" biogenic siliceous siltstone (Fig. 3). The bedding surfaces are predominantly flat and parallel, but there are also wavy surfaces between the underlying siliceous siltstone and overlying dolomite beds that are characterized by wavelengths and amplitudes of a few centimetres (Fig. 3b). The siliceous siltstone is within the beds laterally diagenetically altered to cryptocrystalline (amorphous) chert (Fig. 4), especially close to the main fault on the southern part of the islet. Although the succession of the Mala Palagruža formation appears continuous, since it dips monoclinally, gently to the SW (Fig. 1c), there are small faults measured in the central part of the islet (Fig. 3c), together with intraformational folding

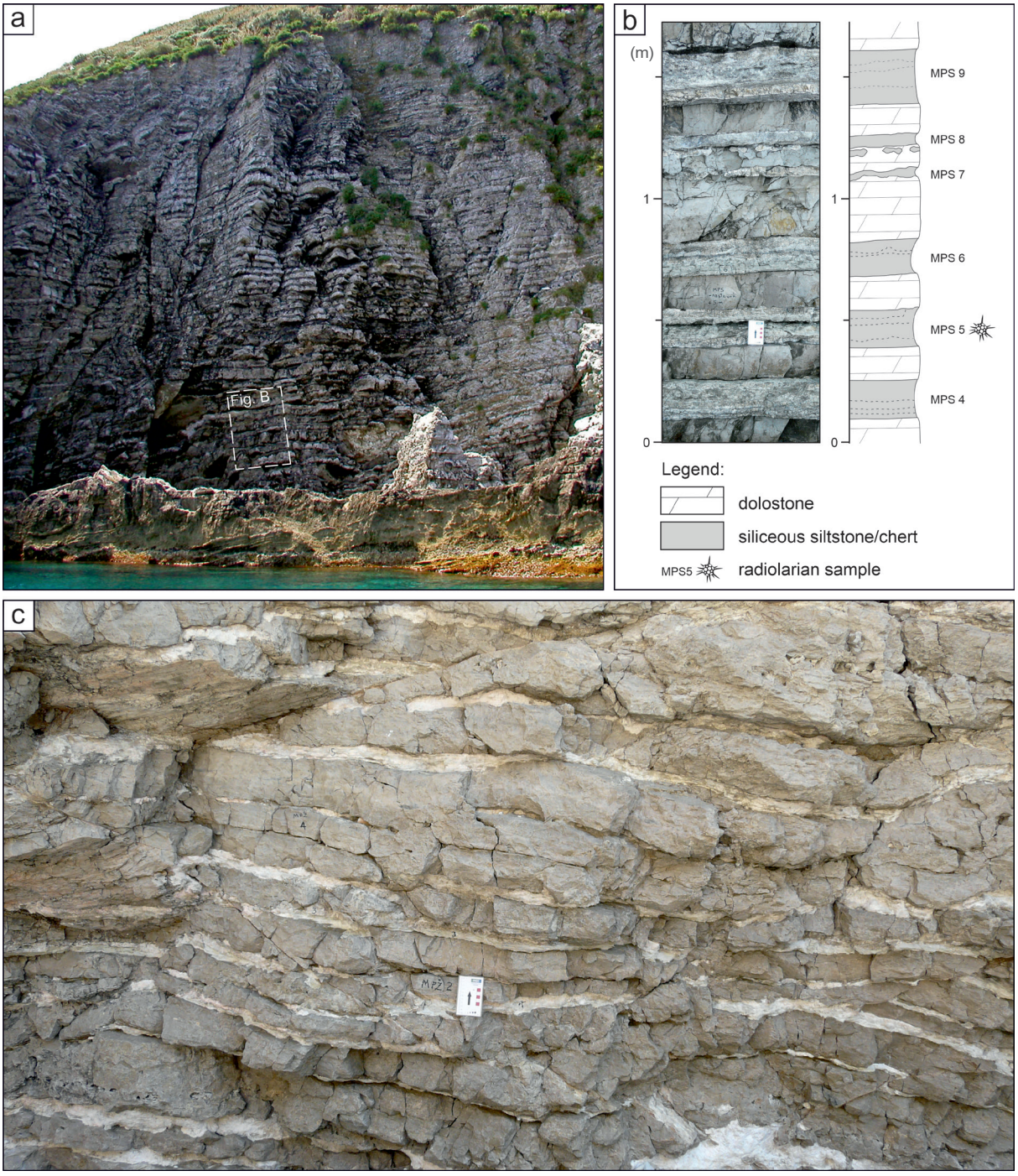


Figure 3. (**a**) A typical succession of the Mala Palagruža formation on the northern cliff of the islet and a schematic drawing of decimetric alternation of dolomite and chert; (**b**) Sampling points on the MPS location in the lower part of the Mala Palagruža succession (location marked by a rectangle on (a); (**c**) Sampling point Mala Palagruža žalo (MPŽ, location on Figs. 1c, 2a) that is characterized by a metre thick very thin-bedded succession bounded by two small faults.

(a package several metres thick) in the central part of the succession. Due to such a tectonic disturbance, it was impossible to measure and sample a continuous stratigraphic column within a generally 50 m thick succession of pelagic deposits assigned to the formation. Therefore, undisturbed packages only several metres thick within the succession were imaged and sampled in detail for biostratigraphic analyses (Fig. 1c). The MPS package is measured in the lowermost part, MPŽ in the middle, and MPV in the uppermost part of the exposed succession of thin-bedded pelagic deposits recognized as the Mala Palagruža formation (Figs. 1c, 2 and 3).

4. RADIOLARIAN DATING

A poorly preserved radiolarian fauna was extracted from three siliceous siltstone samples after treatment with diluted hydrofluoric acid (HF, 8%) following the procedure of PESSAGNO & NEWPORT (1972) and DE WEVER et al. (2001). Scanning electron micrographs of radiolarians were obtained using a JEOL JSM-IT 100 scanning electron microscope at the Ivan Rakovec Institute of Palaeontology ZRC SAZU in Ljubljana. The identified radiolarian taxa and their stratigraphic ranges are listed in Table 1 and illustrated in Figure 5. Sampling positions are shown in Figures 2 and 3. Generic designations follow the catalogue of Mesozoic radiolarian genera (O'DOGHERTY et al., 2009) and more recent taxonomic work on Middle to Late Jurassic radiolarians (O'DOGHERTY et al., 2017). The assemblages are dated using the zonation of BAUMGARTNER et al. (1995a) based on unitary associations, which divided the Middle to Late Jurassic period (Aalenian to Tithonian) into 13 united association zones (UAZ). Additional references are provided for those species featured in this zonation, the stratigraphic

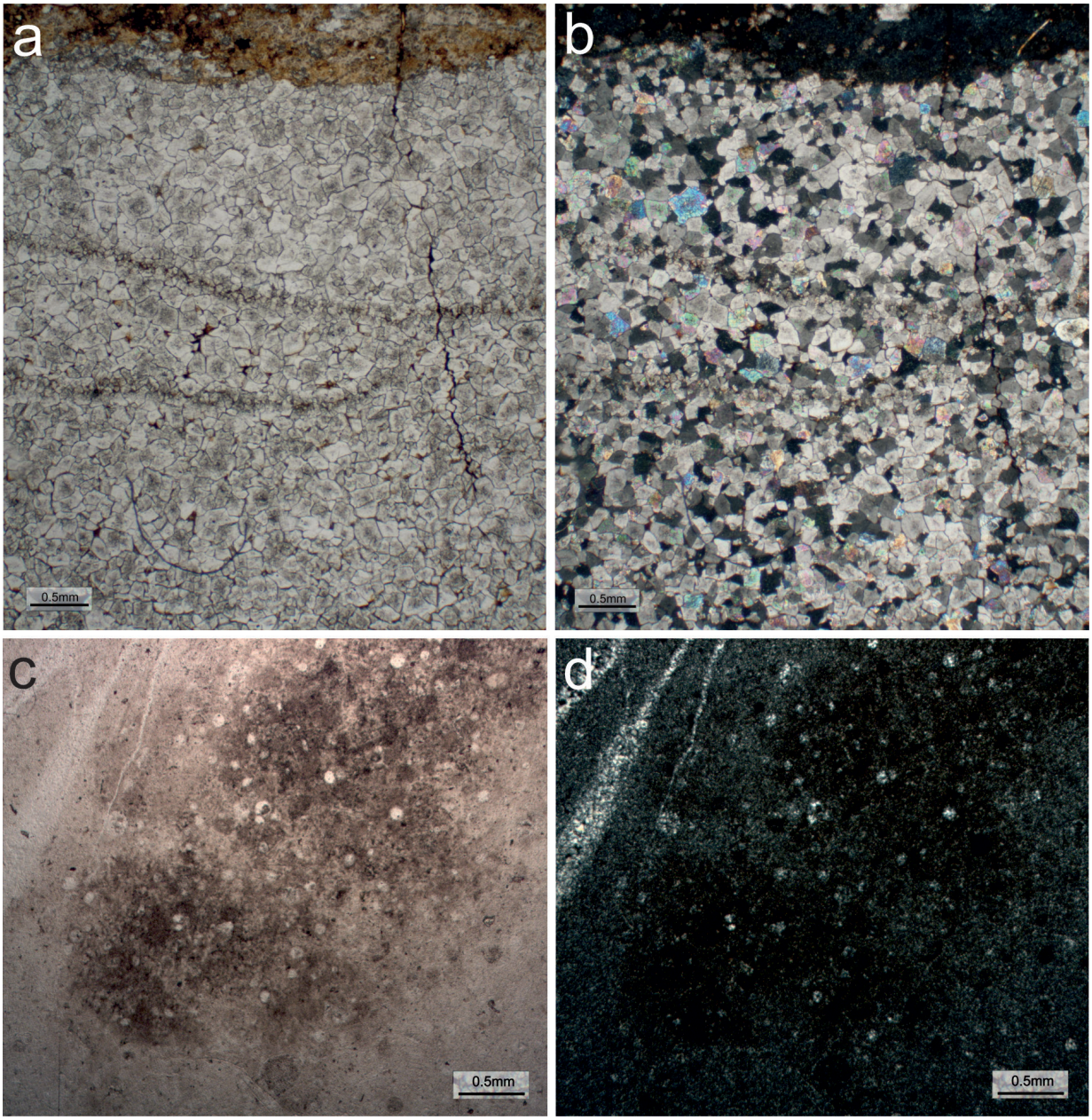


Figure 4. (**a, b**) Photomicrographs of a contact of microcrystalline partly siliceous dolomite (lower part) and chert (on top), with (left) and without polarizer (right). Sampling locality MPV; (**c, d**) Photomicrographs of amorphous chert, with (left) and without polarizer (right). Tiny, rounded spheres are probably diagenetic relicts of radiolarians. Sampling locality MPŽ.

Table 1. Occurrence of radiolarian species in three analysed samples. The second column gives ranges of the species according to the zonation of BAUMGARTNER et al. (1995a). The arrows indicate that the ranges have been subsequently extended (see the text for references).

Radiolarians	UA Zones	Samples		
		MPŽ-5	MPS-5	MPV-2
Archaeodictyomitra sp.	–	•		
Archaeodictyomitra patricki KOCHER	–	•		
Canoptum krahsteinense (SUZUKI & GAWLICK)	–	•		
Eoxitus baloghI KOZUr	–	•		
Eucyrtidiellum unumaense (YAO)	3-8	•	•	•
Eucyrtidiellum sp.	–		•	
Hemicryptocapsa buekkensis (KOZUR)	–	•	•	
Hemicryptocapsa nonaginta O'DOGHERTY, GORIČAN & GAWLICK (was *Tricolocapsa* sp. S in BAUMGARTNER et al., 1995c)	4-5	cf.	•	
Homoeoparonella elegans (PESSAGNO)	4-10			cf.
Mizukidella kamoensis (MIZUTANI & KIDO)	3-7 →	•		•
Parahsuum sp.	–	•		
Parvicingulid gen. et sp. indent.	–		•	
Praewilliriedellum convexum (YAO)	1-11	•		
Praewilliriedellum sp.	–			•
Protunuma turbo MATSUOKA	4-7		cf.	•
Quarticella cicciona (CHIARI, MARCUCCI, & PRELA)	–	cf.		
Quarticella sp.	–		•	
Stichomitra ? *takanoensis* AITA	3-7	•		•
Striatojaponocapsa synconexa O'DOGHERTY, GORIČAN & DUMITRICA (was *Tricolocapsa plicarum* ssp. A in BAUMGARTNER et al., 1995c)	4-5 →		•	
Transhsuum brevicostatum (OŽVOLDOVA)	3-11	•		
Transhsuum maxwelli (PESSAGNO)	1-10	•		
Unuma darnoensis KOZUR	–	•		
Unuma typicus YAO	3-4	cf.		
Age (UAZ Baumgartner et al., 1995a)		**4-5**	**4-5**	**4-7**

ranges of which were later extended, as well as for those species not featured in the zonation.

Although radiolarians are generally abundant in the analysed samples, their preservation is mostly very poor. This selective preservation allowed, in some cases, only tentative determinations of radiolarians at a higher taxonomic level. The extracted assemblages are composed almost exclusively of Nassellarians. Rare sponge spicules, mostly rhax microscleres, are also present. Sponge spicules are more abundant only in sample MPV-2, however, not more abundant than radiolarians.

None of the three analysed samples contain species or a pair of species characteristic of a single UAZ. Instead, the extracted assemblages allow only a relatively broad age assignment. Several species identified in the samples as *confer* due to poor preservation would allow for a more precise age assignment, however, this should be considered with caution.

Sample MPŽ-5 (late Bajocian–latest Bajocian/early Bathonian; UAZ 4-5)

The age assignment of sample MPŽ-5 is based on the co-occurrence of *Unuma darnoensis* KOZUR and *Canoptum krahsteinense* (SUZUKI & GAWLICK). *U. darnoensis* was not featured in the zonation of BAUMGARTNER et al. (1995a). It has been reported from Middle Jurassic assemblages of Europe (KOZUR, 1991; GORIČAN, 1994; HALAMIĆ et al., 1999; ŠMUC & GORIČAN, 2005), Iran (ROBIN et al., 2010) and Japan (*Unuma (Unuma)* sp. in OWADA & SAKA (1982). According to the zonation of GORIČAN (1994), the range of this species is UA 6-8, which corresponds to UAZ 4 or UAZ 5 (see BAUMGARTNER et al., 1995a, p. 1037). This range was later extended to UAZ 5 (ŠMUC & GORIČAN, 2005). HALAMIĆ et al. (1999) reported *U. darnoensis* from a relatively broadly dated sample (UAZ 5-7), meaning that *U. darnoensis* possibly ranges up to UAZ 7. The range of the genus *Canoptum* does not extend beyond the late Bajocian (O'DOGHERTY et al., 2009, 2017), which means that sample MPŽ-5 cannot be younger than UAZ 5. If we take into consideration the ranges of *Unuma typicus* Yao (UAZ 3-4) and *Hemicryptocapsa nonaginta* O'DOGHERTY, GORIČAN & GAWLICK (was *Tricolocapsa* sp. S in BAUMGARTNER et al., 1995c; for complete synonymy, see O'DOGHERTY et al., 2017) (UAZ 4-5), both identified as *confer* in this sample, the sample is limited to UAZ 4 (late Bajocian). Although this would give the shortest age assignment for this sample, it should be considered tentative due to the poor preservation of radiolarians.

In summary, the age assignment of sample MPŽ-5 is late Bajocian–latest Bajocian/early Bathonian (UAZ 4-5), based on the occurrence of *U. darnoensis* KOZUR and *C. krahsteinense* (SUZUKI & GAWLICK).

Sample MPS-5 (late Bajocian–latest Bajocian/early Bathonian; UAZ 4-5)

The age assignment of sample MPS-5 is based on the occurrence of *Hemicryptocapsa nonaginta* O'DOGHERTY, GORIČAN & GAWLICK in the sample. The stratigraphic range of *Striatojaponocapsa synconexa* O'DOGHERTY, GORIČAN & DUMITRICA (*Tricolocapsa plicarum* ssp. A in BAUMGARTNER et al., 1995c) identified in this sample was extended from UAZ 4-5 to include UAZ 6-7 (PRELA et al., 2000; O'DOGHERTY et al., 2006).

Sample MPV-2 (latest Bajocian/early Bathonian–late Bathonian/early Callovian; UAZ 4-7)

The age assignment of sample MPV-2 is based on the occurrence of *Protunuma turbo* MATSUOKA, which ranges from UAZ 4 to UAZ 7. *Stichomitra*? *takanoensis* AITA, also

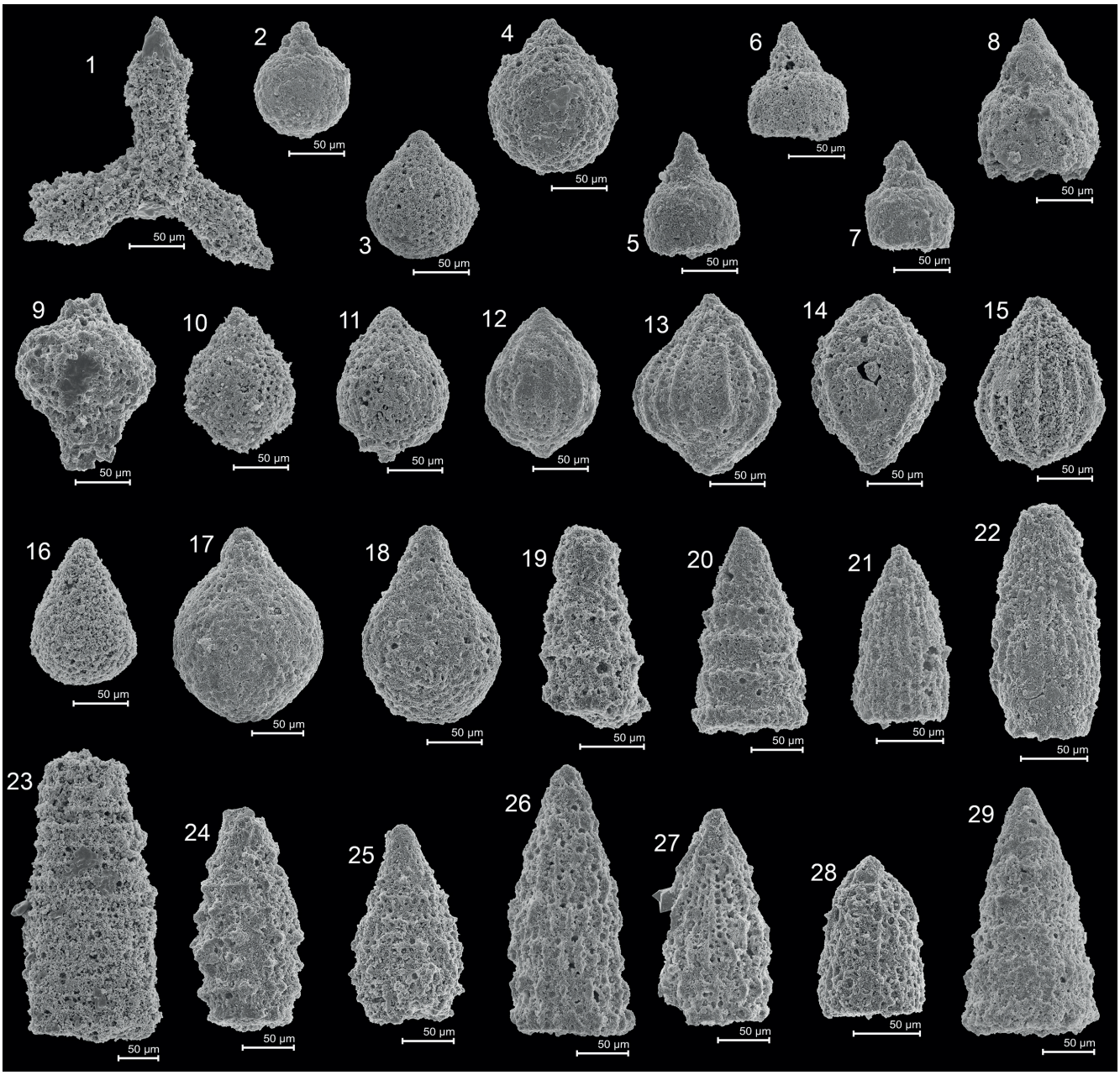


Figure 5. Middle Jurassic radiolarians from the Mala Palgruža succession. For each illustration, sample number and scanning electron micrograph number is indicated. **1 –** *Homoeoparonella* sp. cf. *H. elegans* (PESSAGNO), MPV-2, MPV2_0019; **2 –** *Hemicryptocapsa buekkensis* (KOZUR), MPŽ-5, MPZ5_0032; **3 –** *Hemicryptocapsa nonaginta* O'DOGHERTY, GORIČAN & GAWLICK, MPS-5, MPS5_0015; **4 –** *Hemicryptocapsa* sp. cf. *H. nonaginta* O'DOGHERTY, GORIČAN & GAWLICK, MPŽ-5, MPZ5_0022; **5**-**7 –** *Eucyrtidiellum unumaense* (YAO), 5 – MPŽ-5, MPZ5_0016, 6 – MPV-2, MPV2_0013, 7 – MPŽ-5, MPZ5_0017; **8 –** *Eucyrtidiellum* sp., MPS-5, MPS5_0003; **9 –** *Quarticella* sp. cf. *Q. cicciona* (CHIARI, MARCUCCI, & PRELA), MPŽ-5, MPZ5_0037; **10 –** *Quarticella* sp., MPS-5, MPS5_0009; **11 –** *Striatojaponocapsa synconexa* O'DOGHERTY, GORIČAN & DUMITRICA, MPS-5, MPS5_0021; **12**, **13 –** *Unuma darnoensis* KOZUR, 12: MPŽ-5; MPZ5_0026, 13: MPŽ-5, MPŽ5_0019; **14 –** *Unuma* sp. cf. *U. typicus* YAO, MPŽ-5, MPZ5_0036; **15 –** *Protunuma turbo* MATSUOKA, MPV-2, MPV2_0010; **16 –** *Praewilliriedellum* sp., MPV-2, MPV2_0024; **17**, **18 –** *Praewilliriedellum convexum* (YAO), 17 – MPŽ-5, MPŽ5_0040, 18 – MPŽ-5, MPZ5_0031; **19 –** *Stichomitra* ? *takanoensis* AITA, MPŽ-5, MPZ5_0009; **20 –** *Mizukidella kamoensis* (MIZUTANI & KIDO), MPŽ-5, MPZ5_0027; **21 –** *Archaeodictyomitra patricki* KOCHER, MPŽ-5, MPZ5_0004; **22 –** *Archaeodictyomitra* sp., MPŽ-5, MOZ5_0006; **23 –** Parvicingulid gen. et sp. indent., MPS-5, MPS5_0019; **24**, **25** – *Eoxitus baloghi* KOZUR, 24 – MPŽ-5, MPZ5_0012, 25 – MPŽ-5, MPZ5_0035; **26 –** *Transhsuum brevicostatum* (OŽVOLDOVA), MPŽ-5, MPZ5_0008; **27 –** *Transhsuum maxwelli* (PESSAGNO), MPŽ-5, MPZ5_0034; **28 –** *Parahsuum* sp., MPŽ-5, MPZ5_0033; **29** – *Canoptum krahsteinense* (SUZUKI & GAWLICK), MPŽ-5, MPZ5_0011.

has its last appearance in UAZ 7, further suggesting that the sample is not younger than UAZ 7. *Mizukidella kamoensis* (MIZUTANI & KIDO) also ranges to UAZ 7 according to BAUMGARTNER et al. (1995c) but has been recently described from a late Oxfordian–early Kimmeridgian assemblage (VUKOVSKI et al., 2023).

5. DISCUSSION

The investigated block of pelagic thin-bedded dolostone interlain with siliceous siltstone on Mala Palagruža likely represents a fragmented piece of the Adriatic Basin succession, brought to the surface by active diapirism along the Mid-Adriatic Ridge (GELETTI et al., 2008; KORBAR et al., 2012; CARBONI et al., 2024). Jurassic pelagic deposits are not recorded on the neighbouring Velika Palagruža island, or the other central Adriatic islands (KORBAR et al., 2009, 2012), making this the first discovery of pelagic deposits of this age above sea level in the central Adriatic. With underlying and overlying strata missing, the only inference on the provenance of the investigated succession can be obtained by correlation with the data from commercial wells in the Adriatic area, as well as with the neighbouring pelagic domains that are well documented onshore, i.e., the Umbria–Marche–Sabina area in the central Apennines, the Ionian Zone in the Hellenides and the Belluno Basin succession in the Sothern Alps (Fig. 6). A paleogeographic connection between these areas and the Adriatic Basin has already been proposed (ZAPPATERRA, 1994; GRANDIĆ et al., 1999; VLAHOVIĆ et al., 2005; SANTANTONIO et al., 2013; Fig. 1d). The Budva Basin in the External Dinarides is another Mesozoic pelagic domain of the Adriatic plate, however, it existed as a deep-water basin from the Middle Triassic and was separated from the Adriatic–Ionian Basin by shallow-marine areas of the Dalmatian and Gavrovo–Tripolitza units (GORIČAN, 1994; GORIČAN et al., 2022; Fig. 1d).

The closest offshore well to Mala Palagruža is the Gargano-Mare 1 approximately 45 km to the southeast (42°09'13.00'' N, 16°43'12.00'' E; ViDEPI, 2025; Fig. 1d). In this well, dolomites and evaporites of the Burrano Formation underlie a thick, Jurassic to Pleistocene, mostly carbonate succession. In an approximately 50 m thick interval of the succession below the Maiolica Formation, loosely assigned to late Early Jurassic to Late Jurassic, dolostones alternating with chert are documented. In the upper part of this interval, aptychi and *Saccoccoma* occur. This can be considered as the lateral extension of the fragmented succession, part of which is exposed on Mala Palagruža.

Comparable lithologies to the ones investigated on Mala Palagruža, with no precise stratigraphic control are reported from the Elsa 1 well in the western central Adriatic. There, medium- to fine-grained dolostones, intercalated with dolomitized mudstone/wackestone with chert, of Middle to Late Jurassic age, have been recognized from a pelagic carbonate platform margin (SANTANTONIO et al., 2013).

The correlation with the Umbria–Marche area in the central Apennines suggests the investigated block on Mala Palagruža is a part of the Calcari Diasprigni Formation. This formation overlies the Calcari e Marne a *Posidonia* Formation and is overlain by the Calcari ad aptici e *Saccocoma* Formation. The Calcari Diasprigni Formation is composed of radiolarian chert and subordinate cherty limestone with thin shale interbeds. Locally, carbonate resediments occur within the formation (BARTOLINI et al., 1995). Radiolarian dating indicates a late Bajocian/Bathonian to early Tithonian age for

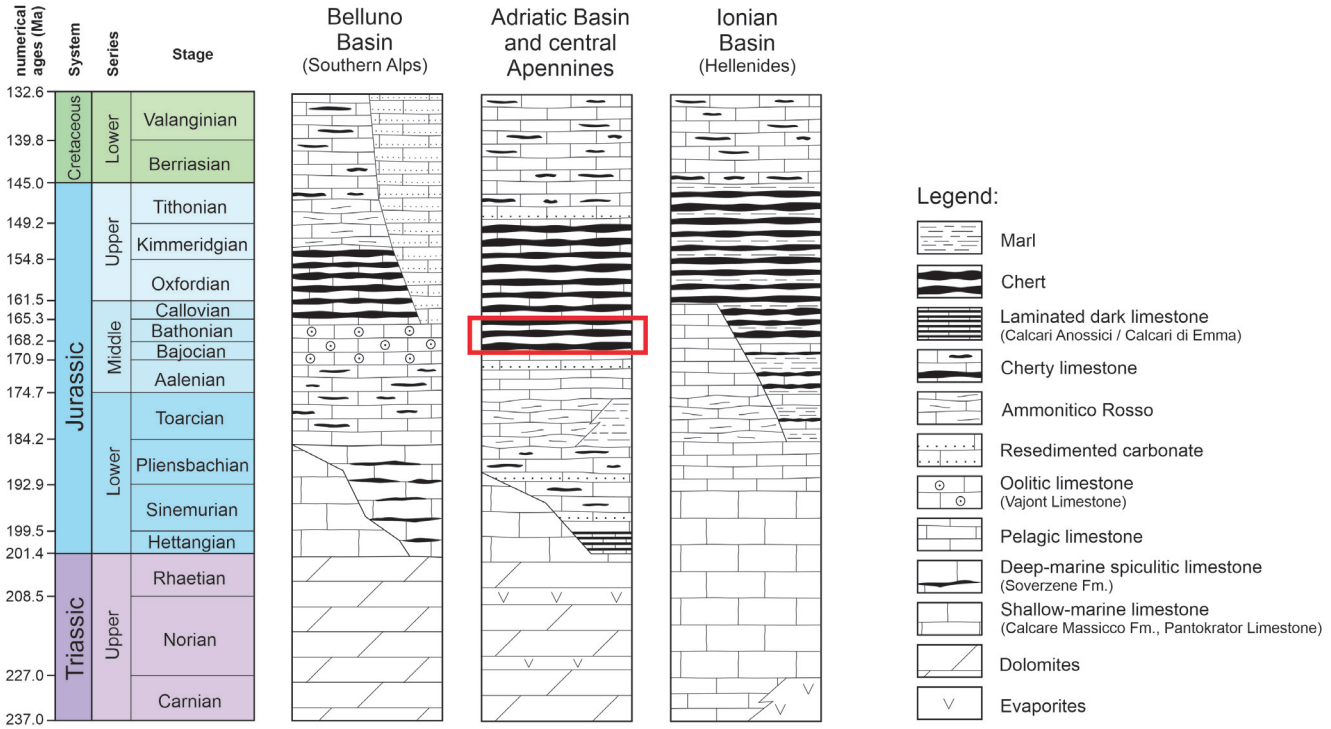


Figure 6. Chronostratigraphic overview of the Upper Triassic to lowermost Cretaceous formations of the Belluno Basin, the Ionian Basin, and the Adriatic Basin (which is similar to the Umbria–Marche basin of the central Apennines). For details and references, see text. The red rectangle marks the range of the investigated Mala Palagruža formation.

the Calcari Diasprigni (BAUMGARTNER, 1990; BARTOLINI et al., 1995). However, this range can vary depending on the placement of the formation boundaries. GALLUZZO & SANTANTONIO (2002) limited the Calcari Diasprigni Formation to the interval between the last occurrence of posidoniids and the cherty limestones bearing *Saccoccoma* (late Bajocian/Bathonian to early Kimmeridgian). In the commercial wells of the Adriatic offshore, all three formations are often grouped into the Calcari ad Aptici unit (ViDEPI, 2025; FESTA et al., 2014; CAZZINI et al., 2015).

The Mala Palagruža succession corresponds in age and general lithology to the Calcari Diasprigni Formation (Fig. 6) with a notable difference in the occurrence of diagenetic microcrystalline dolomite instead of limestone. Considering the difference, the Mala Palagruža succession could be recognized as a new formation, although the lower and upper boundaries are not exposed, and therefore, its complete thickness is unknown. Resediments occurring locally in the Calcari Diasprigni Formation have not been observed on Mala Palagruža, either because they are missing or were destroyed by the dolomitization. However, wavy surfaces observed between the underlying chert and overlying dolomite beds (Fig. 3b) resemble small erosional channels or loading structures, which would imply a distal gravity flow mechanism of the fine-grained carbonate sediment.

Dolomitization of a pelagic sequence correlative to that of the Adriatic Basin has been documented in the northern Apennines. There, pelagic limestone of the Corniola Formation (Sinemurian – earliest Toarcian), underwent several recrystallization and stabilization events under increasing temperatures and in the presence of seawater-derived fluids (RONCHI et al., 2003). MOZAFARI et al. (2019) attributed the dolomitization to two fault-related events that occurred before and during the Apenninic orogeny, with the Mg-rich fluids most likely originating from underlying evaporites of the Upper Triassic Burano Formation. Both the Corniola Formation and the Burano evaporites have been well documented in the Adriatic wells as a part of the Adriatic Basin succession and its basement (SANTANTONIO et al., 2013; FESTA et al., 2014; BORRELLI et al., 2023). Therefore, the same mechanism of dolomitization could be envisioned for the Mala Palagruža succession, however, this is beyond the scope of the present study.

The succession, similar to the central Appennines is recorded in the Ionian Zone in the Hellenides (BAUMGARTNER et al., 1993; DANELIAN, 1995; KARAKITSIOS, 1995; DANELIAN et al., 1997). The pelagic *Posidonia* beds have been deposited in the Ionian Basin throughout the Jurassic. The Lower *Posidonia* beds, deposited during the Early and early Middle Jurassic, are composed of marl, marly shaly limestone and chert, and are the basinal equivalent of the Ammonitico Rosso (DANELIAN, 1995). The Upper *Posidonia* beds are composed of ribbon chert and thin layers of siliceous argillites with cherty limestone occurring at the base. This unit was dated with radiolarians as the latest Bajocian – early Bathonian to latest Tithonian – earliest Berriasian (DANELIAN, 1995). Locally, a pelagic Lamellibranch limestone, composed of well-bedded limestone with thin marly interlayers and chert, is present (DANELIAN, 1995). Radiolarian dating indicates a late Bajocian to Bathonian age for the youngest levels of this unit (DANELIAN, 1995). Based on this age assignment, the Mala Palagruža succession is a correlative of the lower part of the Upper *Posidonia* beds, or the upper part of the Lamellibranch limestone.

The Belluno Basin in the Southern Alps is considered as the northern continuation of the Adriatic Basin. This basin evolved from the Early Jurassic between the Adriatic (Friuli) Carbonate Platform and the Trento Platform, which drowned at the end of the Pliensbachian and became a submarine high with condensed sedimentation (WINTERER & BOSELLINI, 1981; BERTOTTI et al., 1993; MARTIRE, 1996; PICOTTI & COBIANCHI, 2017). During the Middle Jurassic (late Bajocian–Bathonian), the oolitic Vajont limestone is recorded in the Belluno Basin and is interpreted as a deep-sea fan that was fed from the productive platform margin of the AdCP (BOSELLINI et al., 1981; PICOTTI & COBIANCHI, 2017). The pelagic Fonzaso Formation (Calcare Selcifero di Fonzaso) was deposited on top of the Vajont limestone in the Belluno Basin as well as on the eastern part of the submerged Trento plateau. The formation is composed of cherty limestone and marl, rich in grey and red chert, interbedded with turbiditic calcarenites (PICOTTI & COBIANCHI, 2017). Diverse radiolarian assemblages indicate a middle Bathonian to late Oxfordian–early Kimmeridgian age (BAUMGARTNER et al., 1995b; BECCARO et al., 2002, 2008; BECCARO, 2006). This range was extended to the early Tithonian with nannofossils (PICOTTI & COBIANCHI, 2017 and references therein). The Rosso Ammonitico Superiore overlies the Fonzaso Formation on the Trento Plateau and in the Belluno Basin (BECCARO et al., 2008; BAUMGARTNER, 2013), however, a direct contact with the Maiolica Formation is also described (PICOTTI & COBIANCHI, 2017). Therefore, the age-equivalent deposits of the Mala Palagruža succession in the Belluno Basin are the Vajont limestone and the lower part of the Fonsazo Formation. Pelagic cherty limestone of the Fonzaso Formation can also be regarded as the lithological equivalent of the Mala Palagruža succession. In the northern Adriatic Basin, the occurrence of the Vajont limestone has been documented in offshore wells (Amanda 1 and Assunta 1, MASETTI et al., 2012). Resedimented ooids do occur in the Lower Jurassic part of the central Adriatic Basin succession but not in so significant quantity and are interpreted as originating from the Apulian platform margin (SANTANTONIO et al., 2013).

The pelagic succession of the Adriatic Basin seems to reflect regional patterns of facies distribution recognized in other deep-water basins of the western Neotethyan region. Before the latest Jurassic calcareous nannoplankton bloom (BORNEMANN et al., 2003), the supply of fine-grained carbonate to deep-water basins bounded by large active carbonate platforms is attributed to the redeposition of platform-derived lime mud (BERNOULLI & KÄLIN, 1984). Abundant thin-shelled bivalves ("posidoniids" or "filaments") appear as rock-forming organisms during the Toarcian to early Bajocian in western Neotethyan successions (BAUMGARTNER, 1990; CONTI & MONARI, 1992; FLÜGEL, 2010) and are recognized in the Adriatic Basin as well (SANTANTONIO et al.,

2013). After the Tithonian, calcareous nannoplankton became a significant source of carbonate in pelagic realms. Consequently, the facies known as Maiolica (also referred to as Biancone or Oberalm), was deposited in all pelagic domains of the Adriatic plate (WEISSERT, 1981; MISSONI & GAWLICK, 2011; GORIČAN et al., 2012, 2022; BAUMGARTNER, 2013; ROŽIČ & REHAKOVA, 2024). The equivalent of this facies in the Ionian Zone is named the Vigla Limestone and its deposition also began in the late Tithonian (DANELIAN et al., 1997).

The frequent occurrence of chert in the Middle and Upper Jurassic pelagic successions of the western Neotethyan realm is well documented. Cherty limestone and/or radiolarian chert were deposited on the deeply submerged parts of the continental margins, as well as on the oceanic crust of both Neotethys and Alpine Tethys (BAUMGARTNER, 1987, 2013; DE WEVER et al., 2014; GORIČAN et al., 2022). In recent decades, ocean fertility and plankton productivity have been recognized as primary factors controlling the distribution of pelagic sediments (BARTOLINI et al., 1999; BORNEMANN et al., 2003; BAUMGARTNER, 2013). Increased radiolarian productivity during the Middle and Late Jurassic is linked to eutrophic conditions attributed to palaeoclimatic factors (BARTOLINI et al., 1996, 1999; BAUMGARTNER, 2013). River discharge (BAUMGARTNER, 2013) and monsoon-driven upwelling (DE WEVER et al., 2014; IKEDA et al., 2017) have been proposed as potential causes of increased nutrient supply during this period.

Increased abundance of chert in the Middle to Late Jurassic interval of a carbonate-dominated succession of the Adriatic Basin recognized in this study is also recorded in offshore wells (ViDEPI, 2025). However, it seems that radiolarian chert is not a dominant facies in any part of the succession as is the case in most successions originating from deeply submerged parts of the Adriatic plate during the Middle and Late Jurassic (e.g., BAUMGARTNER, 2013). This predominance of pelagic limestone over radiolarian chert can be attributed to the potentially shallower depths of the basin floor compared to other deep-water basins of the Adriatic plate. Another explanation can be that a relatively narrow Adriatic Basin, bounded on both sides by active carbonate platforms, received larger amounts of fine-grained carbonate, which diluted the contribution of plankton skeletons. The onset of the Maiolica-type sedimentation, simultaneous with other basins of the Adriatic plate in the latest Jurassic is also well recorded from offshore wells (ViDEPI, 2025; SANTANTONIO et al., 2013). These regional patterns of bioproductivity reflected in the pelagic sediments of the Adriatic Basin testify to the connection of the Adriatic Basin with the open Neotethys Ocean.

6. CONCLUSION

The investigated pelagic succession on Mala Palagruža represents a fragmented piece of the Adriatic Basin pelagic sequence brought to the surface by active diapirism along the Mid-Adriatic Ridge. Radiolarian assemblages, extracted from siliceous siltstone intercalated within a dolomitic sequence, indicate a late Bajocian–Bathonian to possibly early Callovian age for this block, making it the first discovery of Jurassic pelagic deposits above sea level in the central Adriatic. Correlations with the offshore commercial wells of the central and southern Adriatic and onshore successions of the central Apennines indicate that the investigated block is likely an equivalent of the Calcari Diasprigni Formation of the central Apennines, composed of chert and cherty limestone. However, in the Mala Palagruža formation, the limestone is completely diagenetically altered to microcrystalline dolomite. Anyway, this formation represents deep-marine facies deposited in the central part of the Adriatic microplate in a time of eutrophic conditions favouring radiolarian productivity. Comparable coeval deposits are well-known from other deeply submerged parts of the microplate exposed today in the peri-Adriatic mountain chains. Regional patterns of plankton productivity recognized in pelagic sediments of the Adriatic Basin strongly support a connection with the open Neotethys Ocean.

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