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Dinosaur footprints in the Lower Hauterivian deposits of Palud Cove in Istria, Croatia

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ABSTRACT

Sixteen dinosaur footprints are exposed along the upper-bedding surface of a single Lower Hauterivian limestone layer in Palud cove (western Istria, Croatia). This footprint-bearing horizon is part of the thick Mesozoic stratigraphic succession of the Adriatic-Dinaridic Carbonate Platform. The Palud site section is characterized by peritidal (shallow subtidal to intertidal) limestone with several shallowing-upward cycles composed of mudstone, peloidal wackestone/packstone, peloidal packstone/grainstone and fenestral mudstone/wackestone with common geopetal infill. The Early Hauterivian age of these deposits is based on their microfossil content, which is dominated by ostracods, benthic foraminifera and calcareous green algae (Dasycladales). The footprints are circular to elliptical in shape, with no distinct digit impressions (with one possible exception), and with average length of 26 cm. Most footprints have a well-defined expulsion rim produced by the compression and displacement of the waterlogged substrate caused by the feet of the dinosaurs. All of the footprints are nearly the same shape and size, which indicates that they were produced by the same kind of trackmaker – likely a sauropod dinosaur. These animals left their footprints on the top of an intertidal and shallowing-upward succession during ephemeral subaerial exposure of the fine-grained carbonate sediment.

Keywords: Dinosaur footprints, Sauropods, Lower Hauterivian, Palud, Istria, Croatia

1. INTRODUCTION

This paper represents the first detailed documentation of the Palud dinosaur footprint locality from the Lower Cretaceous (Lower Hauterivian) strata exposed in the southern part of Cape Gustinja in Palud cove, western Istria, Croatia (MEZGA et al., 2007a; Fig. 1). The Palud site is currently subjected to intensive physico-chemical and biological weathering and erosion due to its exposure within the intertidal zone along the coast of the Adriatic Sea (Fig. 2). The site is also located in close proximity to the coastal tourist resorts and is relatively easily accessible. The prospects of site destruction due to possible vandalism and future rise in sea level drive the need for its detailed study and documentation.

Cretaceous strata of the Palud site on the Istrian peninsula are part of the Adriatic-Dinaridic Carbonate Platform succession (ADCP – also referred to as the Adriatic Carbonate Platform, see discussion in VLAHOVIĆ et al., 2005). The ADCP was one of the largest Mesozoic platforms in the Mediterranean region (central Tethys) and its strata now comprise a heavily deformed, 4-6.5 km thick, Lower Jurassic to Paleocene succession of almost pure carbonate deposits. These strata are part of a thicker (4-8.5 km), predominantly carbonate succession deposited over >270 my (from at least the Carboniferous to the Late Eocene), and which forms most of the present-day Croatian Karst (External or Outer) Dinarides. The sedimentary succession exposed in Istria mainly consists of shallow water carbonates with a stratigraphic

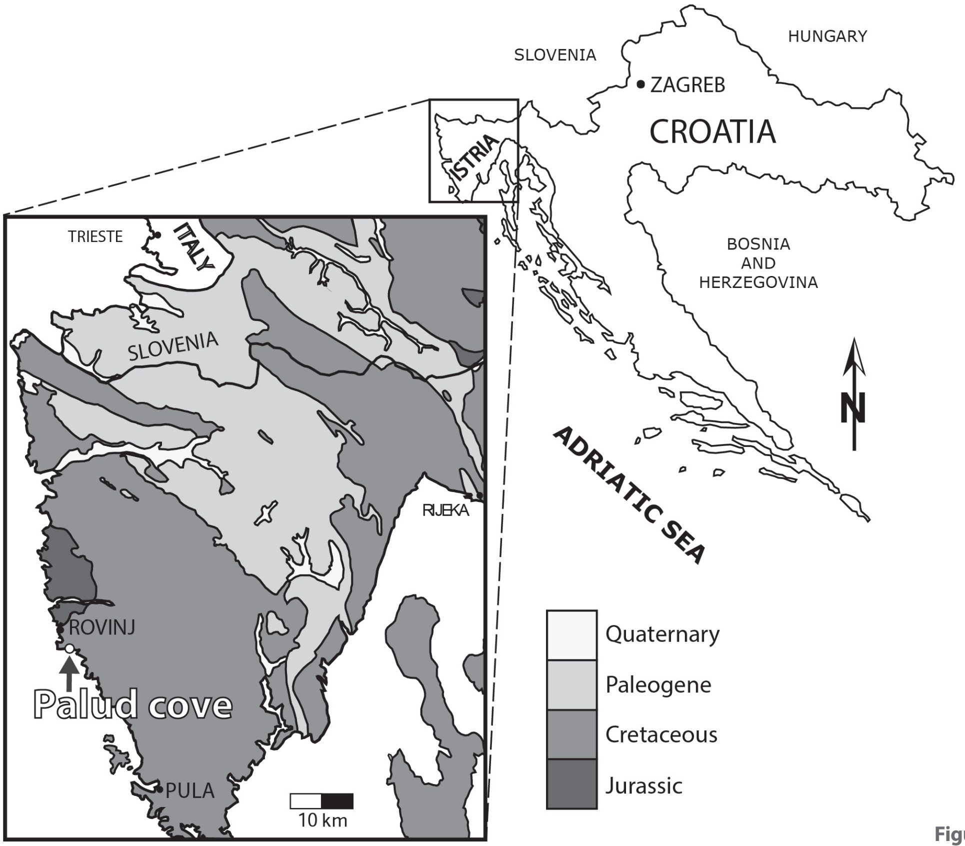

Figure 1: Geographical location of the site.

range from the late Middle Jurassic to the Eocene (VELIĆ et al., 2003).

About twenty dinosaur footprint sites have been discovered to date in Istria (DALLA VECCHIA et al., 1993, 2000, 2001, 2002; DALLA VECCHIA, 1994, 2013; MEZGA & BAJRAKTAREVIĆ, 1999, 2004; DALLA VECCHIA & TARLAO, 2000; MEZGA et al., 2006, 2007b, c). Most of these sites have been examined and described in great detail, but no detailed documentation has yet been published for the Palud site. This paper presents the results of the study on the horizon with footprints produced by a relatively large trackmaker in coastal environments of a large carbonate platform and now exposed in the lower part of the Palud succession. Besides a detailed description of the footprints and their interpretations, this study also includes the petrographic analyses of the carbonate microfacies, and the description of the microfossil as-

Figure 2: The dinosaur footprint site in Palud cove. Arrows mark the extent and location on the upper bedding surface of the footprint bearing layer. The right arrow points to the main exposure with 15 footprints and the left one at the location of the isolated footprint (No. 16) to the northwest of the main area.

semblages as support for the identification of the environments of deposition and the age of the footprint-bearing section.

The Palud cove locality represents a new piece of evidence for the presence of dinosaurs on the ADCP during the Early Cretaceous (Early Hauterivian; MEZGA et al., 2007a). During the 1990's, A. Tarlao had already observed a possible footprint-bearing surface close to the Palud channel (DALLA VECCHIA et al., 2000).

2. GEOLOGICAL SETTING

The Istrian peninsula is located in the northern part of the Adriatic coastal region of Croatia (Fig. 1). Geological literature on Istria covers more than three centuries of research. The first detailed information about the geology of this region was presented in the explanatory notes to the Basic Geological Map of Croatia, the Rovinj Sheet 1:100.000 (POLŠAK & ŠIKIĆ, 1973). Detailed lithofacies and biofacies investigations of shallow water carbonates in Istria started in the 1970s and the list of the most important references can be found in VELIĆ et al. (2003).

The Istrian succession is mainly composed of upper Middle Jurassic to Eocene shallow water carbonates (VELIĆ et al., 2003), and to a lesser extent of Eocene carbonate and siliciclastic rocks, and Quaternary terra rossa and loess deposits. This succession can be divided into four sedimentary sequences or megasequences separated by important discontinuities representing subaerial exposure surfaces (TIŠLJAR et al., 1998; VELIĆ et al., 2003). The oldest Bathonian–lowermost Kimmeridgian megasequence is characterized by shallowing- and coarsening-upward trends and by the appearance of regressive breccias. The Kimmeridgian–Early Tithonian subaerial exposure horizon with bauxite deposits caps this megasequence. The second Upper Tithonian–Upper Aptian megasequence is very complex with regard to its facies heterogeneity and great thickness. Deposition of this megasequence started with an oscillating transgression and the resulting peritidal shallowing-upward cycles. This megasequence is capped by the Upper Aptian deposits, which experienced a relatively rapid shallowing and subaerial exposure (VELIĆ et al., 2003). This regional exposure was a consequence of a relative sea-level fall caused by the interaction of eustatic changes and synsedimentary tectonics in the Istrian part of the ADCP, which resulted in variable duration of shallow-water conditions in different parts of the platform, as well as in the varying intensity of erosion of the Aptian and Barremian deposits (VELIĆ et al., 2003). The end of this megasequence was marked by the deposition of breccias and conglomerates with common blackened pebbles, interbedded with clay layers, representing swamp conditions.

The overlying Upper Albian–Upper Santonian megasequence is more than 1000 m thick. It is composed of variable facies successions, including peritidal and other nearshore environments during the Late Albian, differentiation of sedimentary systems during the Vraconian (latest Albian) and Cenomanian, drowned platform systems during the latest Cenomanian and Turonian (GUŠIĆ &JELASKA, 1993), and re-establishment of the shallow-water sedimentation during the Late Turonian, Coniacian and Santonian (VELIĆ et al., 2003).

The fourth megasequence in Istria comprises a relatively thick succession of carbonate and siliciclastic deposits of Eocene age. The duration of subaerial exposure of the Lower to Upper Cretaceous rocks prior to deposition of the lower Eocene varies from area to area; different parts of the Eocene succession were transgressively deposited on various units of the Cretaceous basement because of the terrain differentiation caused by Late Cretaceous tectonics (MATIČEC et al., 1996). The current study of the Palud footprint site focuses on limestones that belong to the second transgressive–regressive megasequence (Upper Tithonian–Upper Aptian).

Although the Palud site is relatively close (about 1 km) to another dinosaur footprint site (the Gustinja locality; DALLA VECCHIA et al., 2000), a fault zone located at the tip of Cape Gustinja separates the two localities and prevents their correlation. Therefore, Palud and Gustinja are considered to represent two separate and distinct localities.

3. LITHOLOGY AND BIOSTRATIGRAPHY

The Lower Cretaceous carbonate succession of the Palud bay is characterized by peritidal (shallow subtidal to intertidal) limestones with several shallowing–upward cycles (Fig. 3). These cycles are composed of mudstones, peloidal wackestones/packstones, peloidal packstones/grainstones (Fig. 4A) and fenestral mudstones to wackestones (Fig. 4B). The dinosaur footprints are observed in a layer of fenestral mudstone with common geopetal infill (Fig. 4C).

The microfossil assemblage present within these limestones is dominated by ostracods associated with the following foraminifera: *Istriloculina* cf. *elliptica* (IOVCHEVA) (Figs. 4D, E); *Praechrysalidina* cf. *infracretacea* LUPERTO SINNI (Figs. 4F, G); *Vercorsella* sp., *Rumanoloculina* cf. *robusta* (NEAGU) (Fig. 4H); *Mayncina bulgarica* LAUG, PEYBERNÈS & REY, *Glomospira* cf. *glomerosa* EICHER (Fig. 4I); *Pseudonummoloculina* sp. (Fig. 4J); *Arenobulimina* sp., *Vercorsella scarsellai* (DE CASTRO); *Trocholina* sp.; *Montsalevia salevensis* (CHAROLLAIS, BRONNIMANN & ZANINETTI) (Fig. 4K); *Vercorsella wintereri* ARNAUD-VANNEAU & SLITER (Fig. 4L); and the green algae (dasycladales) *Salpingoporella annulata* CAROZZI (Figs. 4M, N) and *Salpingoporella* sp. (Figs. 4O, P).

This assemblage indicates a probable Early Hauterivian age for these strata. The sedimentological characteristics of the strata and the presence of footprints indicate a short period of subaerial exposure of the sediment and suggest an intertidal depositional setting. According to biostratigraphic zonation and subdivision of the Lower Cretaceous (VELIĆ, 2007), which can be used platform-wide, the microfossil assemblage of the Palud section can be assigned to the *Vercorsella camposaurii* Taxon-range Zone (SARTONI & CRESCENTI, 1962). A more accurate age for the Palud succession could be better determined with reference to the underlying strata in which the green alga *Pseudoclypeina*? *neocomensis* (RADOIČIĆ, 1975) was seen (work in progress)

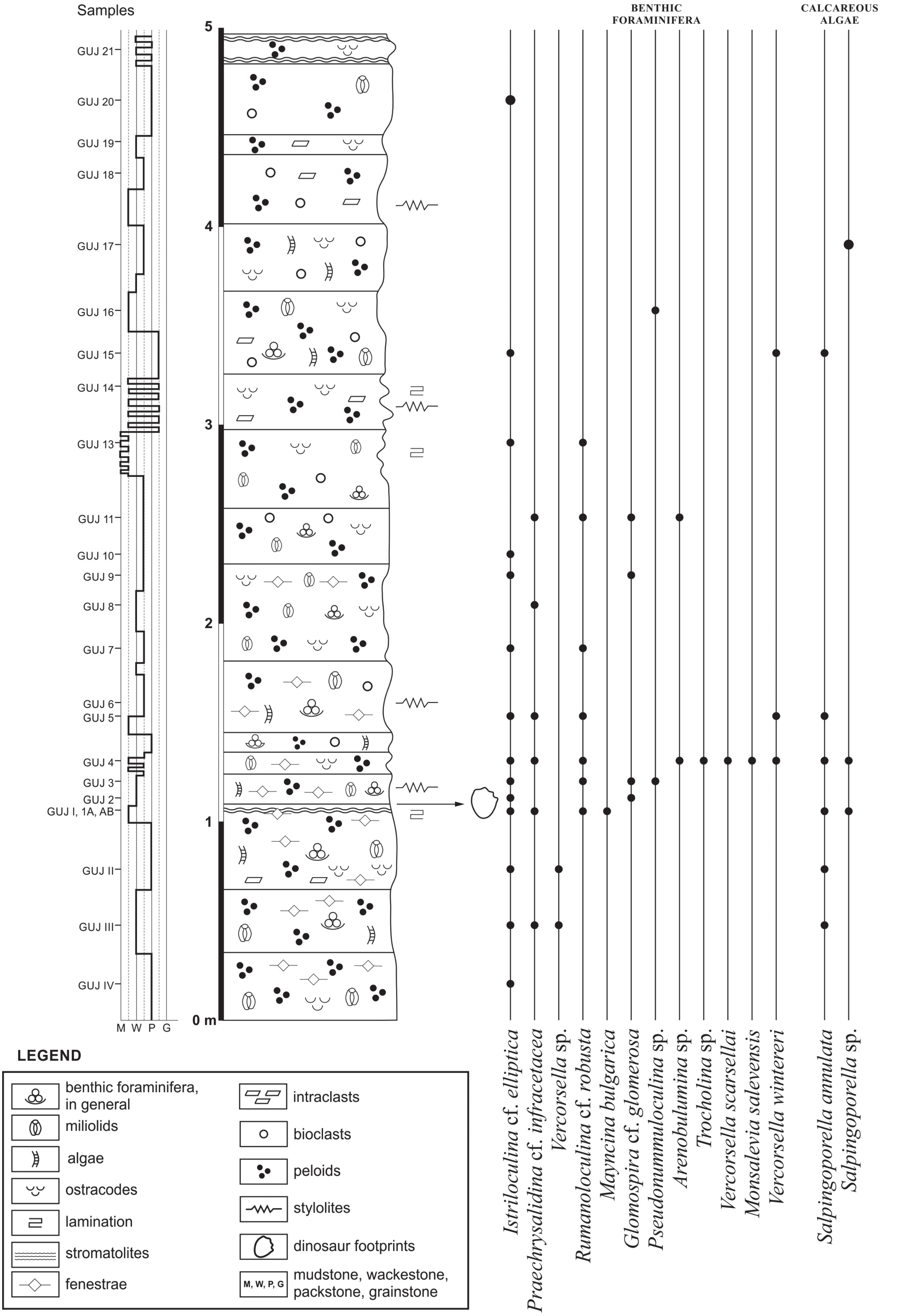

Figure 3: A stratigraphic column of the section exposed at Palud cove.

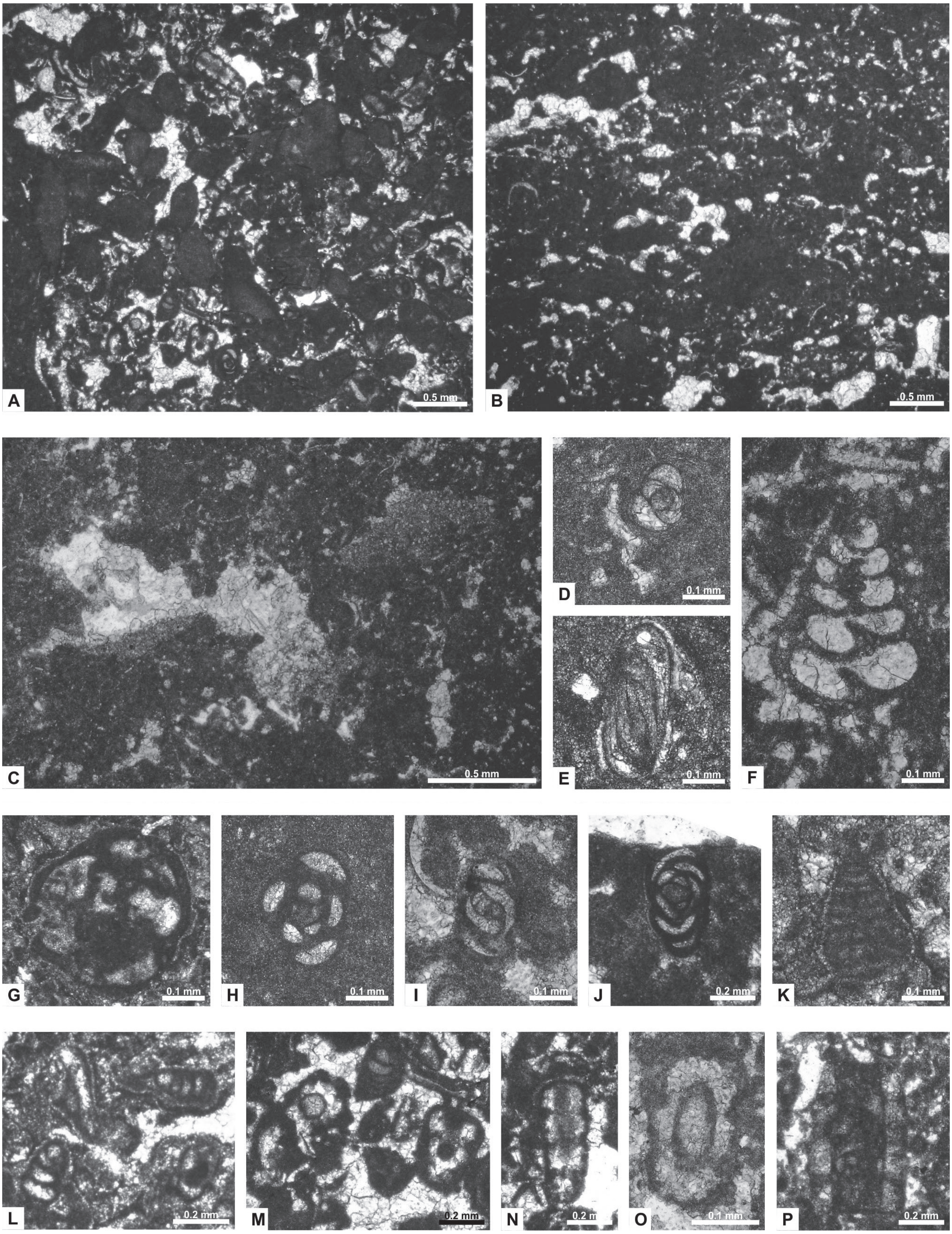

Figure 4: The microfacies and microfossil assemblage of the section exposed at Palud cove. A peloidal packstones/grainstones with different sections of *Salpingoporella annulata* (GUJ 1A). B fenestral mudstones to wackestones (GUJ 1). C fenestral mudstone with geopetal infill (GUJ AB). D, E *Istriloculina* cf. *elliptica*; transverse (D) and longitudinal (E) section (GUJ 1B, GUJ IV). F, G *Praechrysalidina* cf. *infracretacea*; approximately longitudinal (F) and transverse (G) section (GUJ 4). H *Rumanoloculina* cf. *robusta*; subtransverse section (GUJ 1A). I *Glomospira* cf. *glomerosa*; oblique section (GUJ 3). J *Pseudonummoloculina* sp.; oblique section (GUJ 2). K *Montsalevia salevensis*; longitudinal section (GUJ IV). L *Vercorsella wintereri*; longitudinal section (GUJ 10). M, N *Salpingoporella annulata*; transverse, oblique (M) and longitudinal section (N). O, P *Salpingoporella* sp.; oblique (O) and longitudinal section (P).

Figure 5: The southeastern part of the Palud site with the main footprint concentration.

that corresponds to the *Pseudoclypeina*? *neocomensis* to *Campanellula capuensis* unfossiliferous interval (Early Hauterivian) recognized on Mljet Island (HUSINEC & SOKAČ, 2006).

4. FOOTPRINT DESCRIPTION

The Palud site is located along the coast within the intertidal zone and is repeatedly flooded. This affected the preservation of the footprints and complicates their study. Sixteen large footprints of circular to elliptical shape, with an average length of 26 cm, without clearly identifiable digit impressions, and with a rather indistinct morphology have been discovered at this site (Figs. 5, 6; Tab. 1). Fifteen footprints are close to each other while a single track is several tens of metres away to the northwest (Fig. 2). The observed stratigraphic relationships indicate that all footprints belong to the same horizon located along the upper bedding surface of a single layer. They are true footprints and most of them have a clearly defined expulsion rim, which allows their unmistakable identification as footprints despite substantial weathering and erosion of the outcrop. The pronounced height of the expulsion rim indicates that the substrate on which the trackmakers were walking was very soft. All footprints are of approximately the same shape and size, suggesting that they were all made by the same type of animal. The morphology of the footprints is very poorly defined in this karstified outcrop, which does not allow their referral to an ichnotaxon.

The length of the footprints was measured from the anterior to the posterior part of the print along its axis and the

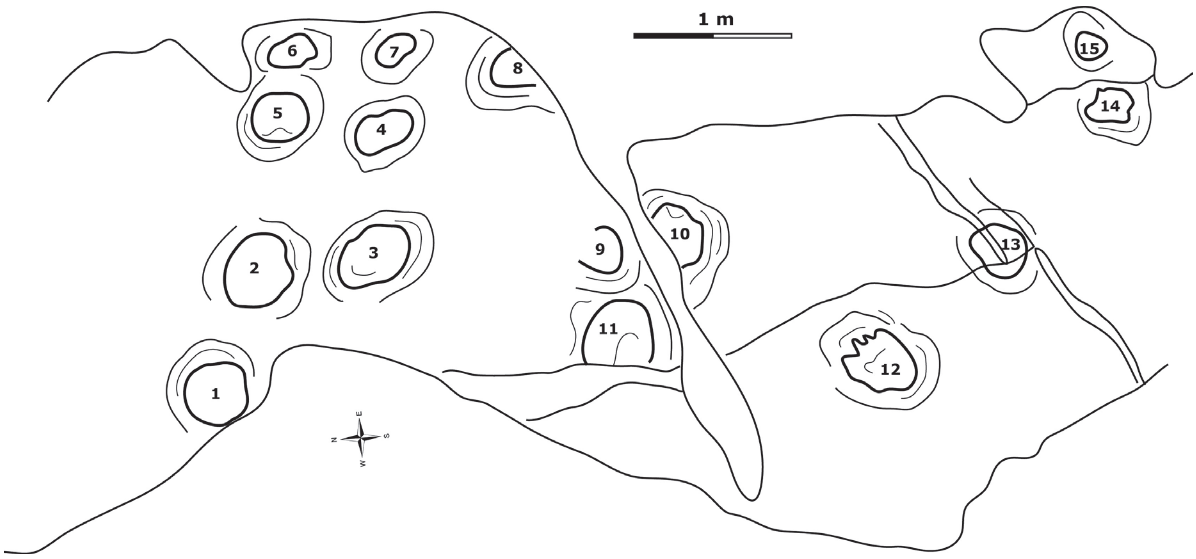

Figure 6: A map showing the distribution of footprints 1-15 at the Palud site.

Figure 7: Dinosaur footprint at the Palud cove locality (No. 12 on Fig. 5). Scale bar = 22 cm.

Table 1: Footprint measurement (all measurements in cm; FL = footprint length; FW = footprint width)

footprint no.	expulsion rim	FL	FW
1	+	29.5	28.5
2	–	32.5	31
3	+	31.5	32
4	+	28	31
5	+	29	31.5
6	+	23.5	27
7	+	21	26
8	+	–	–
9	+	–	–
10	+	31	31.5
11	–	–	–
12	+	30	29.5
13	–	27	27.5
14	+	18	19
15	+	15.5	15
16	+	24	20

width was measured as a maximum width perpendicular to the length. On the prints with pronounced expulsion rims, the measures were taken only on the inner part of the prints (excluding the expulsion rims). On the prints without the expulsion rims, the measures were taken from the beginning of the depression margin.

The best preserved footprint (No.12) represents an exception (Figs. 7, 8). Like most other tracks, it has a circular shape (length = 30 cm; width = 29.5 cm) and a well-defined and continuous expulsion rim that is up to 2 cm high. Along its W-E axis there is a continuous fissure caused by rock fracture. What distinguishes this footprint from the others is the presence of four V-shaped, pointed grooves along its north-eastern part that resemble digit impressions (Fig. 7). These grooves are wider proximally and taper distally; this gives them an acutely pointed appearance. It is possible that these features do not actually represent digit impressions but were instead produced by selective corrosion that altered and modified the primary footprint.The running waters flowing into the footprint along the fractures could have been the cause for their formation where the erosion enlarged the fractures. Similar features have already been recorded in sauropod footprints exposed to tidal weathering in the Fenoliga islet (MEZGA & BAJRAKTAREVIĆ, 1999: Fig. 2D; DALLA VECCHIA et al., 2001: Fig. 18).

It is interesting that only footprint 12 has such large pointed grooves as footprints 1 to 10 have expulsion rims of

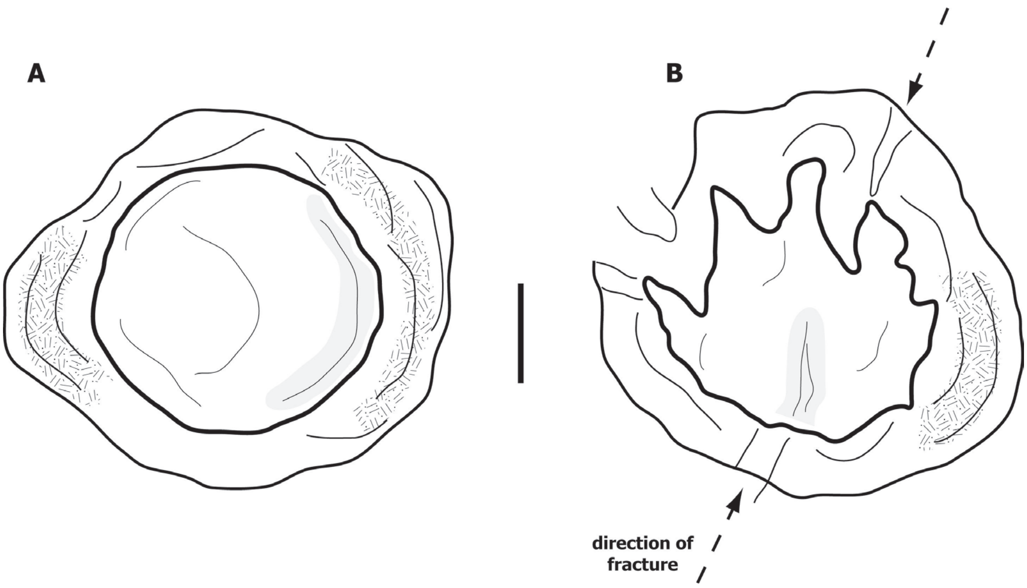

Figure 8: Interpretative sketches of footprints 1 (A) and 12 (B). Scale bar = 10 cm.

Figure 9: Isolated footprint No. 16 from the Palud cove locality (scale bar = 22 cm).

similar height and shape, suggesting that they were impressed at approximately the same time. This may support an erosional modification as an explanation for the unique morphology of footprint 12. The fact that there is no other footprint with such features could be explained by the selectivity of the erosion process.

Although isolated from the main group of footprints, footprint 16 is very similar in shape and size to the rest of the tracks (Figs. 8, 9), which once again suggests it was produced by the same kind of trackmaker. Footprints 1 to 7 are fairly eroded, but appear to be organized in two parallel lines indicative of a trackway trending 95°–275°. The prints cannot be interpreted as impressions of left or right feet with certainty and their interpretation as belonging to the same trackway is doubtful. Along with the other footprints they could represent several parallel trackways of similarly sized animals. It is possible that footprints 8, 10 and 12 also form a trackway because they are aligned (Fig. 10), but the trend is questionable.

5. DISCUSSION

The poor preservation of the footprints makes the identification of the trackmaker difficult to establish. From their shape and orientation within the possible trackways, it is even uncertain whether they were produced by bipedal or quadrupedal animals. In fact, no clearly defined manus-pes pairs that would be indicative of a quadrupedal trackmaker can be identified in the sample. However, the circular shape of the Palud footprints suggests that the author of the tracks was a quadrupedal animal because all Early Cretaceous potential bipedal trackmakers were theropod and ornithopod dinosaurs with three digits in the pes. Crocodyliforms and turtles are potential trackmakers for quadrupedal tracks in an Early Cretaceous coastal setting; they can be plausibly excluded by the large size of the footprints (unless they were impressed by giant individuals of these groups). Crocodyliforms can be also excluded because of their marked heteropody (the pes is much larger than the manus). Among quadrupedal dinosaurs, potential trackmakers include the Marginocephalia, Thyreophora and Sauropoda. Quadrupedal Marginocephalia (essentially the neoceratopsians) are not a likely candidate because the Palud footprints are all similar in size without size differences between the prints of manus and pes (i.e. a lack of heteropody). Furthermore, neoceratopsians are extremely rare in the Cretaceous of Europe and are not reported from the Lower Cretaceous (WEISHAMPEL et al., 2004; ŐSI et al., 2010). The Thyreophora include the basal tyreophorans, the Stegosauria and the Ankylosauria. Stegosaur footprints have well de-

Figure 10: The southeastern part of the Palud site showing a possible trackway in the foreground.

fined heteropody and their pes prints are tridactyl (THULBORN, 1990). Furthermore, stegosaur remains are uncommon in the Lower Cretaceous (WEISHAMPEL et al., 2004). Ankylosaurs do not have such pronounced heteropody as stegosaurs, and their pedal prints have impressions of four digits (THULBORN, 1990), similar to the only Palud footprint with possible digit impressions (Fig. 7). The Palud footprints, however, cannot be interpreted as made by ankylosaurians with certainty given their poor state of preservation and rather indistinct morphology. Furthermore, ankylosaurian footprints are not reported in the palaeoichnological record of Istria (see literature cited above). Sauropods present heteropody, with the usually crescentic manus print that is always smaller than the oval to triangular pes print (THULBORN, 1990; LOCKLEY et al., 1994). Although the Palud footprints do not match perfectly with the morphology of the footprints produced by the sauropods, it is possible that they belong to sauropod dinosaurs because such sauropod footprints were observed at the neighbouring and nearly coeval Gustinja site (DALLA VECCHIA et al., 2000). Their referral to small sauropods is the most plausible conclusion considering that the footprints of those dinosaurs are relatively common in the Cretaceous of Istria (DALLA VECCHIA, 2005) and so far most of the footprints with a subcircular outline in Istria have been referred to this group.The Upper Hauterivian-Lower Barremian site of Kolone (Bale municipality) located just 2.5 km south of Palud cove, yielded abundant skeletal remains of sauropod dinosaurs, but no ankylosaurians or stegosaurians (DALLA VECCHIA, 1998).

6. CONCLUSIONS

The Lower Cretaceous carbonate succession of Palud cove is characterized by shallow-water limestones deposited in peritidal environments (shallow subtidal to intertidal) with several shallowing–upward cycles. Those cycles are composed of mudstones, peloidal wackestones/packstones, peloidal packstones/grainstones and fenestral mudstones to wackestones with geopetal infill. The microfossil assemblage, which is dominated by ostracods associated with foraminifera and green algae (dasycladales), suggests an Early Hauterivian age for this section. Sixteen large circular-elliptical footprints lacking further morphological details have been observed on the upper bedding surface of a single layer of limestone. Footprints are surrounded by a pronounced expulsion rim indicating that the substrate was waterlogged when the trackmakers walked on it. The footprints are of approximately the same shape and size, which is suggestive of the same kind of trackmaker for all of them. There are no clearly visible digit impressions and the average length is 26 cm. The most plausible trackmakers are small-sized sauropod dinosaurs. The track-bearing layer is fenestral mudstone with numerous geopetal infills; this together with the presence of footprints of a terrestrial animal, is evidence of short term exposure of the sediment to meteoric conditions and is indicative of an intertidal environment of deposition.

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