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NEW DINOSAUR TRACKSITE IN THE LATE JURASSIC OF KIRMENJAK QUARRY (ISTRIA)

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Abstract. A new dinosaur tracksite was found in the Kirmenjak quarry in Istria. It is located about one kilometre from an already existing tracksite. The footprints are placed on a slightly inclined bedding plane at the base of the succession represented by heavily stylolitised limestones of the Kirmenjak informal lithostratigraphic unit. The age of the limestones is late Tithonian. Fifteen footprints of circular shape with no clear digit or claw impressions were found at the site and are interpreted to have been formed on a tidal flat during a sea-level fall. All of the footprints belong to sauropod dinosaurs. Pes prints are circular to elliptical in shape, whereas manus prints are more elliptical and of smaller size. The average length of the pes prints is 55 cm, which would correspond to a sauropod of approximately 16 meters in length. The trackway is of narrow-gauge type, where the internal trackway width often has a negative value. The length of the strides indicates slow movement of the individual with a speed of less than 2 km/h. Based on stratigraphic position and footprint morphology, the new and the pre-existing tracksites represent the same trackbearing layer.

Introduction

The Kirmenjak quarry in western Istria (Croatia) is already well known as the locality with the largest dinosaur footprint site in the area of the former Adriatic-Dinaridic Carbonate Platform (abb. ADCP; Fig. 1; Mezga et al. 2003, 2007). It is also the earliest evidence of the presence of dinosaurs, since the age of the footprints is dated as late Tithonian. The Kirmenjak ichnocoenosis consists exclusively of sauropod footprints (Mezga et al. 2007).

A new footprint site was found in the Kirmenjak quarry a few years ago during preliminary investigations of the southern part of the quarry. The new locality (Kirmenjak II) is located on the southern part of the quarry, about one kilometre from the first site (Kirmenjak I; Fig. 2). The newly found footprints are not as abundant as in the Kirmenjak I site, but the footprint sizes indicate a slightly larger animal.

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Geological settings, facies and depositional environment

Istria belongs to the northwestern part of the ADCP. It is mainly formed by shallow water carbonates with a stratigraphic range from the Middle Jurassic to the Eocene (Velić et al. 1995a), and to a lesser extent by Eocene siliciclastic rocks, flysch and calcareous breccias. The depositional succession of Istria can be divided into five sedimentary megasequences separated by important discontinuities – subaerial exposure surfaces of different duration (Vlahović et al. 2005). Those megasequences include sediments deposited during the (1) Bathonian – earliest Kimmeridgian; (2) late Tithonian – early/late Aptian; (3) late Albian – late Santonian; (4) Eocene; (5) Quaternary. The sediments at the Kirmenjak II site belong to the upper Tithonian part of the second (2) sedimentary megasequence and are part of the Kirmenjak informal lithostratigraphic unit [Kirmenjak stylolitised micrite of Velić & Tišljar (1988)].

The dinosaur footprints are preserved on a slightly inclined bedding plane at the base of the stratigraphic succession exposed in the quarry (Fig.

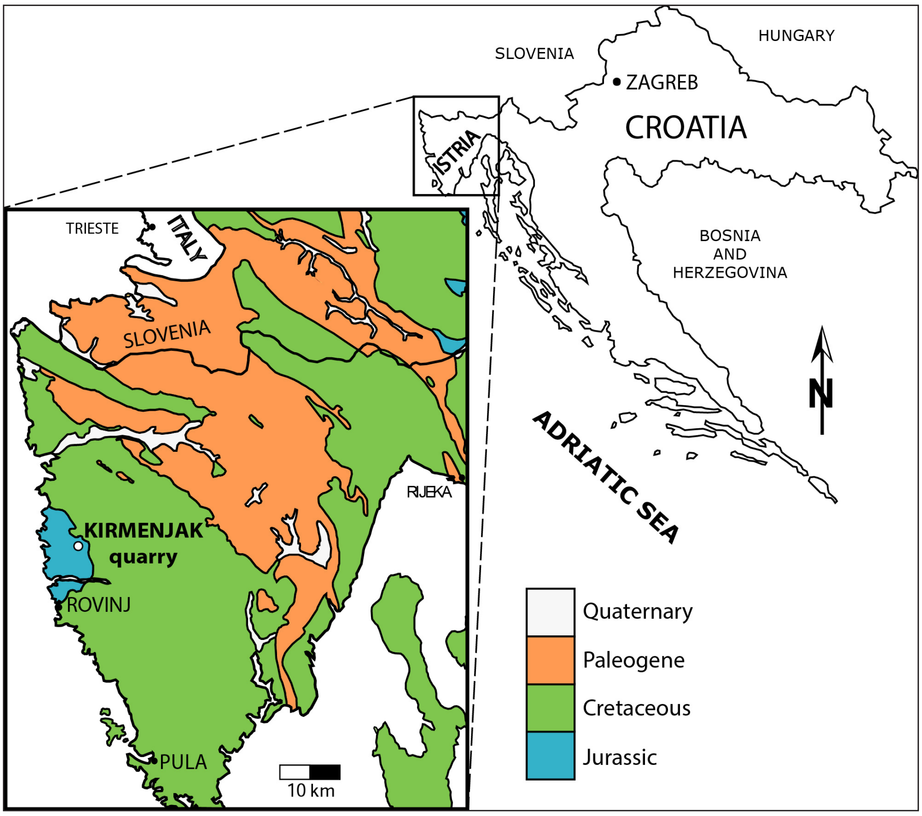

Fig. 1 - Geological setting and geographic position of the new dinosaur tracksite in Istria.

3). The section is represented by 7.56 m of thick, heavily stylolitised and ivory colored limestones of the Kirmenjak unit (Fig. 4). According to Vlahović (1999) and Vlahović et al. (2003), the Kirmenjak unit is composed of different shallowing upward cycles consisting of three members: (1) in the lower part there is a laterally variable bed of black-pebble breccia with a carbonate, clayey or marly matrix. It was formed by the redeposition of material originating from brackish marsh deposits, enriched in organic matter that was eroded and transported during a relative sea-level rise; (2) in the middle part, there is a thick (1-2 m) stylolitised mudstone with rare bioclasts of *Clypeina jurassica* Favre, *Salpingoporella annulata* Carozzi and *Campbelliella striata* (Carozzi) which was deposited in a low energy sub-

Fig. 2 - Overhead view of the Kirmenjak quarry with the position of two tracksites.

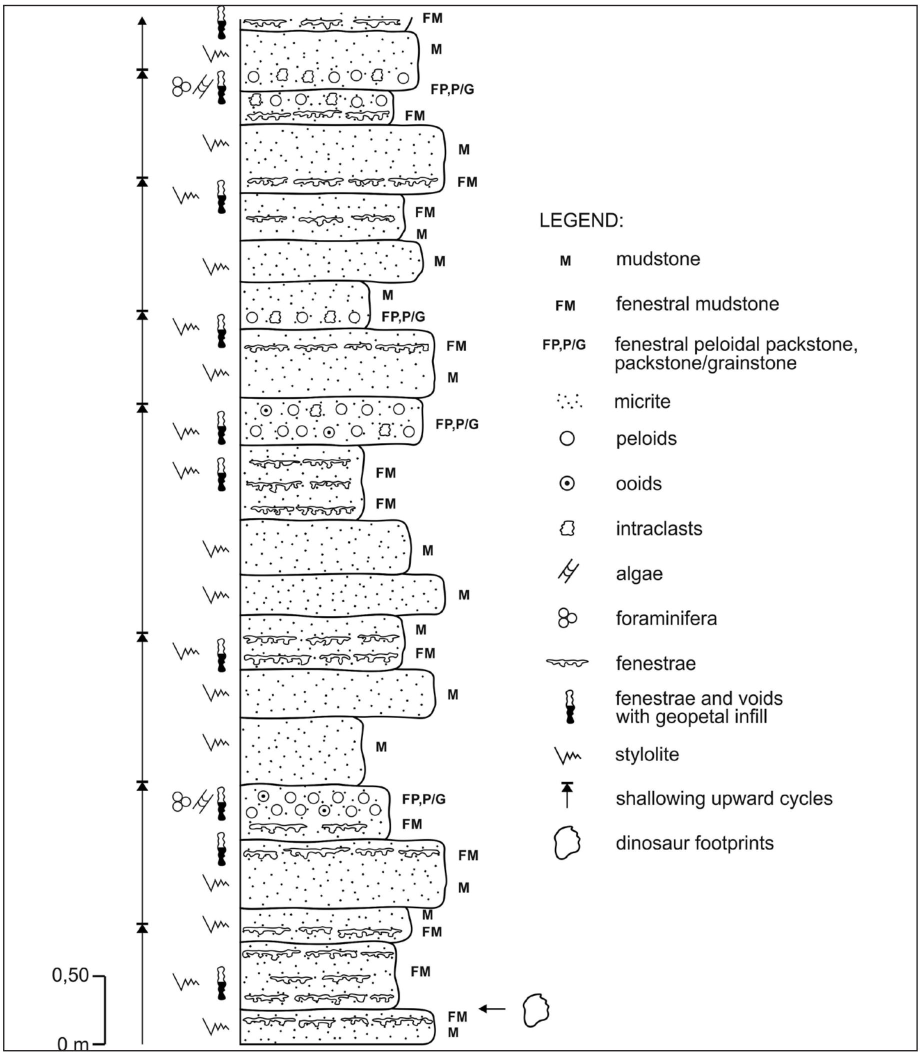

Fig. 3 - Lithostratigraphic column of the Kirmenjak II site.

tidal environment; (3) the upper part of cycles is characterised by variation in thickness, lithology and fabric, and it is predominantly represented by vadose fabric, pisoids, and in places, by stromatolites. The upper bedding surfaces of these beds are usually sharp, irregular with dessication cracks and/or erosion features. They formed in an intertidal and/or vadose zone.

However, in this work, several shallowing-upward cycles were recorded above the dinosaur footprints and none reveals traces of black-pebble breccias (Fig. 3). Each cycle begins with stylolitised mudstone, followed by fenestral mudstone and eventually ending with coarser-grained fenestral peloidal packstones and/or packstone/grainstones. Very similar cycles and facies arrangements have been found above the bed containing abundant dinosaur footprints in Kirmenjak I locality (Mezga et al. 2007). Thus, it is possible that beds containing dinosaur footprints from these neighboring localities were deposited during the same interval of time, representing the same laterally extensive horizon with dinosaur footprints.

Stylolitised mudstones are massive in appearance, purely micritic, and irregularly intercalated by 0.01-0.05 m thick lenses or layers of peloidal packstone/grainstones or grainstones, always separated from the mudstones by a sharp and uneven erosional contact. Tiny echinoid, ostracode (Fig. 5A), bivalve and gastropod bioclasts with micritic envelopes are locally present. In addition, some cryptocrystalline spheroidal-ellipsoidal peloids, crustacean fecal pellets (*Favreina* sp., Fig. 5B) with distinctive internal structure, aggregate grains, flat pebbles as well as undetermined small foraminifera skeletons are sporadically embedded in the calcareous mud. Bioturbation occurs very rarely. The grain composition indicates that these beds were deposited during episodes of low-energy subtidal/lagoon conditions. The presence of sporadic coarser grained peletal packstone/grainstone or grainstone with elongated skeletal fragments oriented, as a rule, parallel to bed-

Fig. 4 - Panoramic view of the Kirmenjak II site.

ding, suggests that the predominantly low energy subtidal environment was periodically affected by storms which winnowed both muddy and coarser-grained material. These storm currents eroded the subtidal sea bottom and removed carbonate mud from the sediment, thus leaving the peloidal packstone/grainstone or grainstone as a "lag deposit".

Fenestral mudstone (Fig. 5C) is characterized by the same compositional features as the underlying beds. Fenestral fabric occurs as two distinctive types, planar shaped fenestrae with uneven bottom and roof, 0.5-3 mm long, with their longer axes oriented parallel to bedding, representing generally unconnected voids which tend to form parallel to individual laminae, and randomly distributed large bubble-shaped voids. Both types are filled with sparite and/or vadose microspar at their bottoms (Fig. 5D). Sporadically, up to few cm-scale, V-shaped vertical to subvertical desiccation cracks and dissolution-enlarged voids, also with vadose

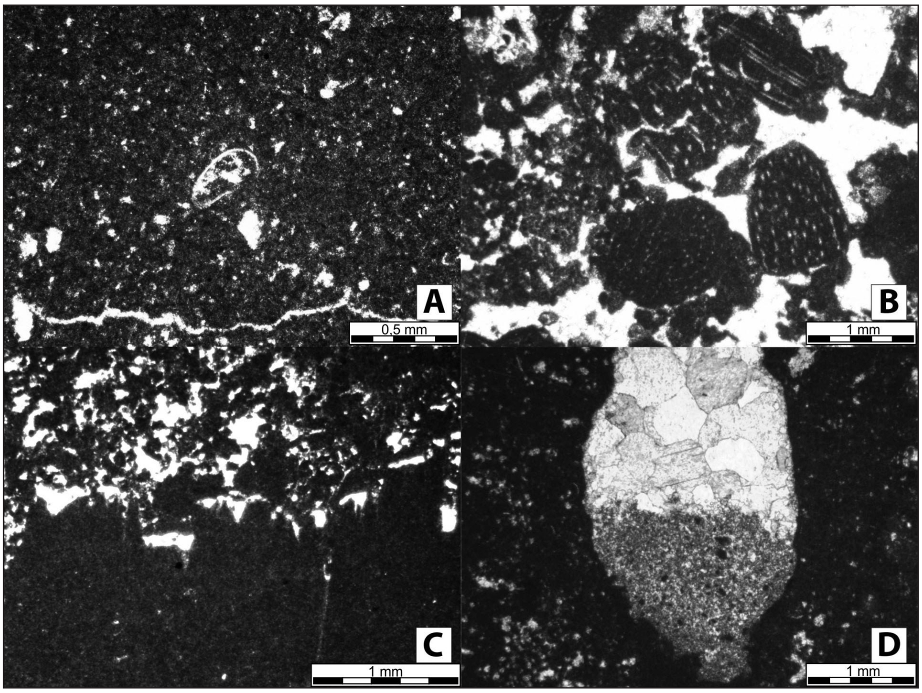

Fig. 5 - A) Longitudinal section of Ostracoda indet. B) Longitudinal and near transverse sections of *Favreina* sp. C) Contact between mudstone and fenestral mudstone. D) Large bubble-shaped void filled with geopetal filling in fenestral mudstone.

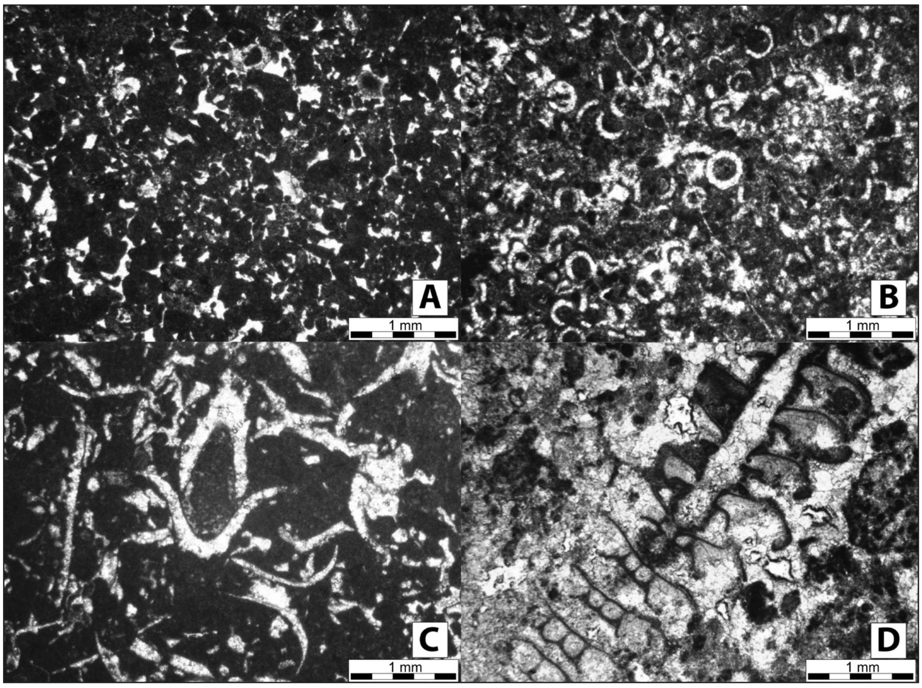

Fig. 6 - A) Fenestral peloidal-intraclastic packstone. B) Numerous thallus fragments and transverse section of *Salpingoporella annulata* Carozzi. C) Longitudinal sections and thallus fragments of *Campbelliella striata* (Carozzi). D) Longitudinal section of *Clypeina jurassica* Favre.

microspar infills, can be recognized. The fenestral fabrics and sporadic geopetal infills within this subunit indicate the intermittent existence of extreme shallow subtidal to intertidal conditions.

Coarser-grained calcareous particles are much more common within the fenestral peloidal packstone and/or packstone/grainstone of the upper beds. They include micritic spheroidal-ellipsoidal peloids, subspheroidal micritic and/or micritic-peloidal intraclasts (Fig. 6A), *Favreina* sp. pellets and sporadic small gastropod, bivalve and echinoid bioclasts. Occasionally, coarser bioclasts as well as some peloids are recrystallized. Ooids can be found sporadically in these beds. They have peloidal and, much more rarely, bioclastic nuclei, surrounded by a clearly visible radial-fibrous fabric. However, crushed and/or regenerated ooids with fragmented ooid nuclei are the most common. Horizontal laminations are poorly visible, as well as sharp and uneven erosional contacts of beds with the lower ones.

A rich dasycladacean algal assemblage of *Salpingoporella annulata* Carozzi (Fig. 6B) and *Campbelliella striata* (Carozzi) (Fig. 6C) can be found in some beds, while occurrences of *Clypeina jurassica* Favre (Fig. 6D) are rare. This dasycladacean assemblage of the Kirmenjak unit was also recorded by previous researchers (e.g. Velić et al. 1995b; Mezga et al. 2007); it corresponds to the *Campbelliella striata* taxon-range zone of late Tithonian age in the Istrian area (Velić et al. 1995b).

This consecutive succession of shallowing-upward cycles clearly points to periodical variation of the platform depositional environments, ranging from low-energy subtidal/lagoon to intertidal (tidal flat) and more rarely to higher-energy intertidal to supratidal environments. Therefore, these shallowing-upward cycles are interpreted to have been formed in response to oscillations of sea-level. During sea-level rises, transgression and submergence of intertidal (tidal flat) environments occurred when the lower beds were deposited in subtidal/lagoon environments. During sea-level falls and progradation of adjacent tidal flats over the neighboring subtidal/lagoon, middle subunits originated. It is just on these tidal flats, during the sea-level falls and deposition of fenestral mudstone, that the animals left their footprints. Coarser-grained upper beds were deposited during periods when higher energy waves and tides eroded the subtidal/lagoon bottom and transported semi-lithified micritic material and bioclasts. The lagoon was surrounded by oolitic sand barriers since the ooids can be found sporadically in these units. Thus, during higher energy wave and tide conditions the ooids derived from the sand barriers were mixed with the subtidal/lagoonal carbonate material and transported on the adjacent tidal flat. Following these conditions, all the coarser grained particles were subjected to subaerial exposure and

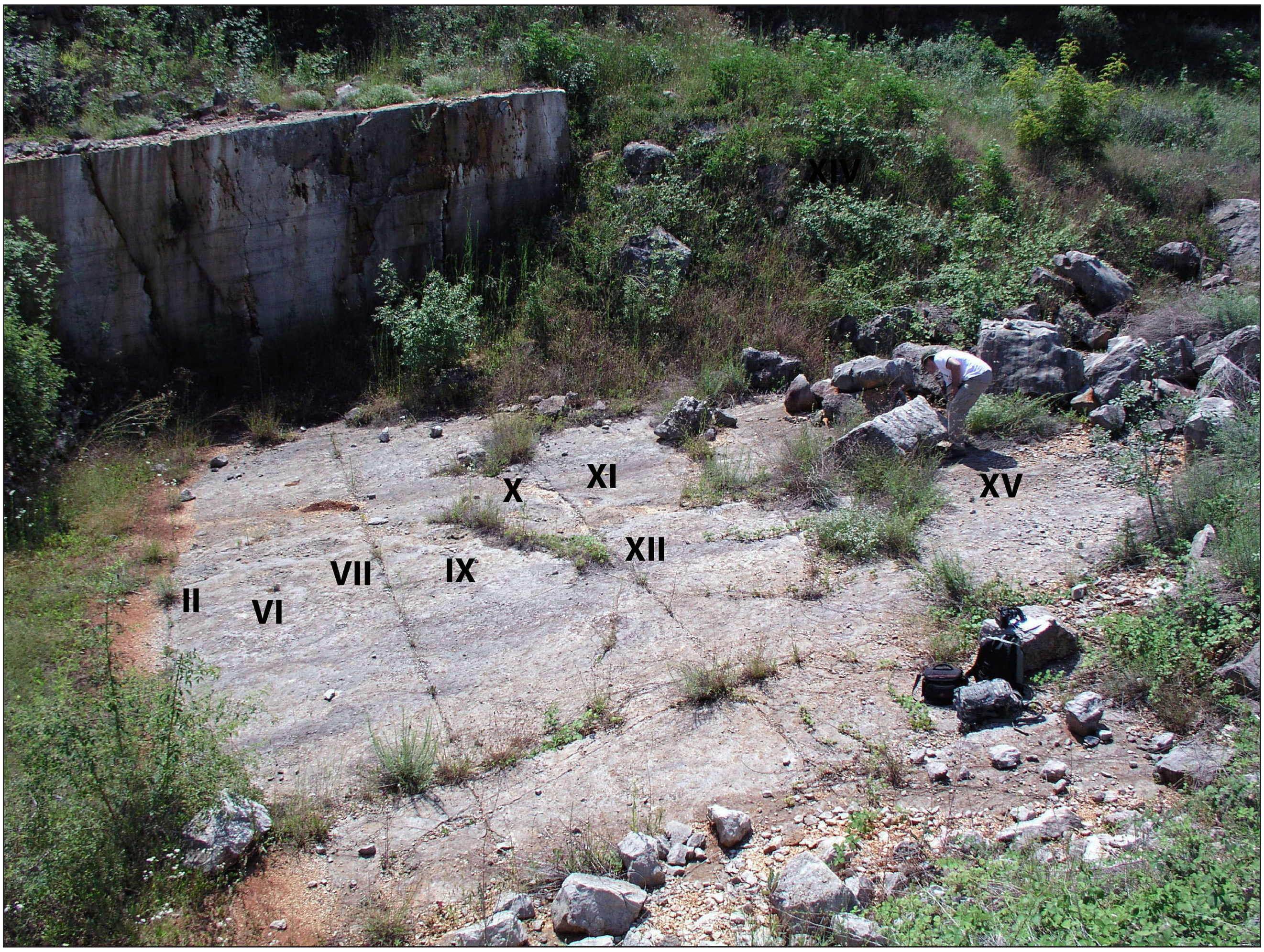

Fig. 7 - The upper bedding plane of the Kirmenjak II tracksite (with footprint labels).

meteoric water influence on the tidal flats or even maybe in the supratidal environments. The observed footprints are placed inside the intertidal fenestral mudstones within the middle part of the first determined shallowing-upward cycle.

Material and methods

The measurements of the footprints were taken as follows: the length of the footprints was measured from the anterior to the posterior part of the print along its axis and the width was measured as a maximum width perpendicular to the length. In prints with pronounced expulsion rims the measures were taken only of the inner part of the prints (excluding the expulsion rims). The depth of the footprints was measured in the center of the prints (also excluding the height of the expulsion rims). In prints without expulsion rims the measures were taken from the edge of the depression margin. The measurements of the footprints without expulsion rims should be regarded with caution due to the erosion and corrosion of the sediment, so the possibility of exaggeration of measurements cannot be excluded. The reference points from which pace, stride and distance were measured are the footprint centres.

The dimension of the dinosaur which left the footprints is calculated using the hip height estimates. The hip height was predicted using Alexander's (4FL; 1989) and Thulborn's (5.9FL; 1990) ratios. The speed of the Kirmenjak II dinosaur was estimated using the Alexander's formula $v = 0.25g^{0.5} \times SL^{1.67} \times h^{-1.17}$ (Alexander 1976). The average walking speed (AWS) was calculated using the formula $v=1.675h^{0.129}$ (Thulborn 1990) and compared to the data from Table 10.3 from Thulborn (1990).

Ichnology

The footprints discovered at the Kirmenjak II site are preserved as imprints (epichnia or negative epirelief) on the upper-bedding plane of the mudstone bed (Fig. 7). The track association includes 15 footprints (Fig. 8) the majority of which form one trackway (footprints VII – XV in Fig. 8). Footprints I – VI forms an irregular group of different-sized tracks. On the basis of their morphological characteristics, it is concluded that the footprints belong to dinosaurs. There are two different types of footprints at the site; larger circular-

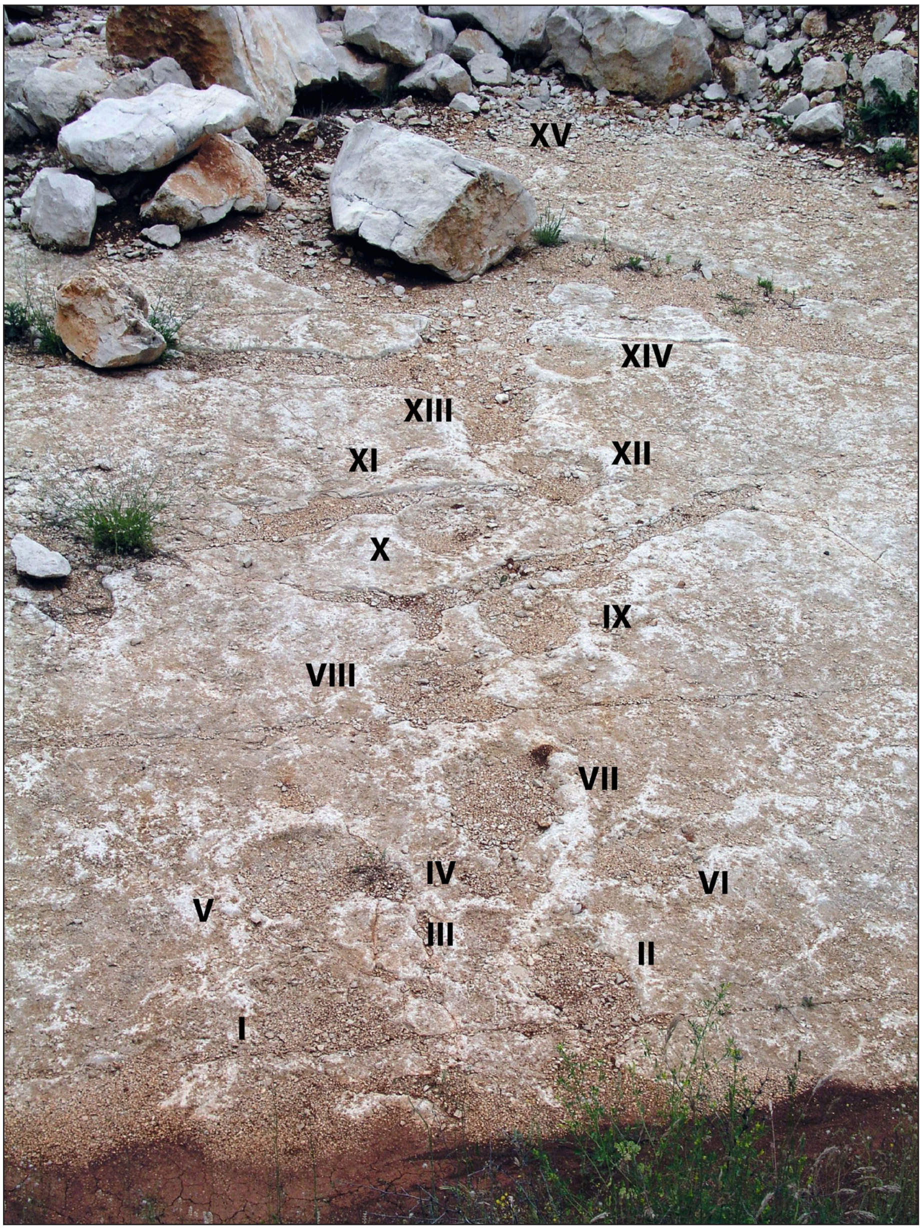

Fig. 8 - The footprint association of the Kirmenjak II tracksite (with footprint labels).

elliptic ones and smaller semicircular ones. Given that both types of print occur in the same trackway, they are interpreted as belonging to the same animal. Around some of the footprints, an expulsion rim is visible, representing compressed waterlogged sediment squeezed from the print by the weight of the dinosaur. Such rims are usually more prominent than the footprints themselves. Most footprints reveal clearly pronounced 'ragged' bottom, a feature that is most likely due to adherence of unconsolidated mud to the animal foot. The arrangement of the footprints in the trackway and differences in the size and shape clearly indicate that the trackways were left by quadrupedal animals. The smaller semicircular footprints represent the manus prints (Fig. 9A) and the larger circular ones the pes prints (Fig. 9B). The length of the manus averages 22.3 cm whiles the pes length averages 55 cm. The footprints are attributed to sauropod dinosaurs on the basis of their morphology i.e. oval–circle shape of the pedal prints and semicircular shape of the manus prints. The state of footprint preservation is rather poor, similar to the Kirmenjak I site; in fact it is difficult to find a footprint with clearly pronounced morphology where the digit impressions are also recognizable. With respect to their dimensions, footprints are rather shallow. Footprint depths range from 1 to 2 cm, with the footprint XI being the deepest one. The measured parameters of the footprints are given in Table 1.

The arrangement and morphology of the footprints indicate that they belong to the same

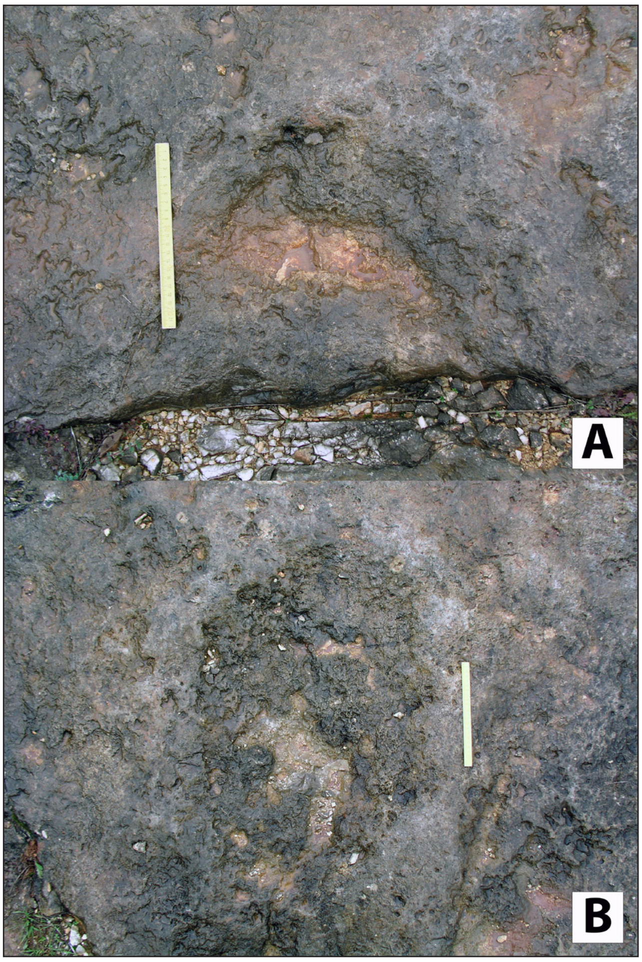

Fig. 9 - A) Footprint XI (for the position see the map on Fig. 10; scale bar = 22 cm). B) Footprint VII (for the position see the map on Fig. 10; scale bar = 22 cm).

footprint	FL	FW	footprint	SL	PL	distance
I	-	48	VII-IX	136		
II	51	38	IX-XII	155		
III	22	20	XII-XIV	151		
IV	24	25	XIV-XV			314
V	55	54	VIII-X	159		
VI	49	46	X-XIII			130
VII	59	49	VII-VIII		82	
VIII	54	44	VIII-IX		79	
IX	57	45	IX-X		98	
X	58	53	X-XII		84	
XI	21	28	XII-XIII			83
XII	57	49	XIII-XIV			96
XIII	49	40	II-V			116
XIV	58	45	II-VI			85
XV	59	51	V-VII			95
			VI-VII			78
			II-VII			123
			VI-VIII			159
			I-VII			153
			V-VIII			152
			I-V			86

Tab. 1 - Measurements of the footprints of the Kirmenjak II tracksite. (All measurements in cm; FL = footprint length; FW = footprint width; SL = stride lenght; PL = pace length).

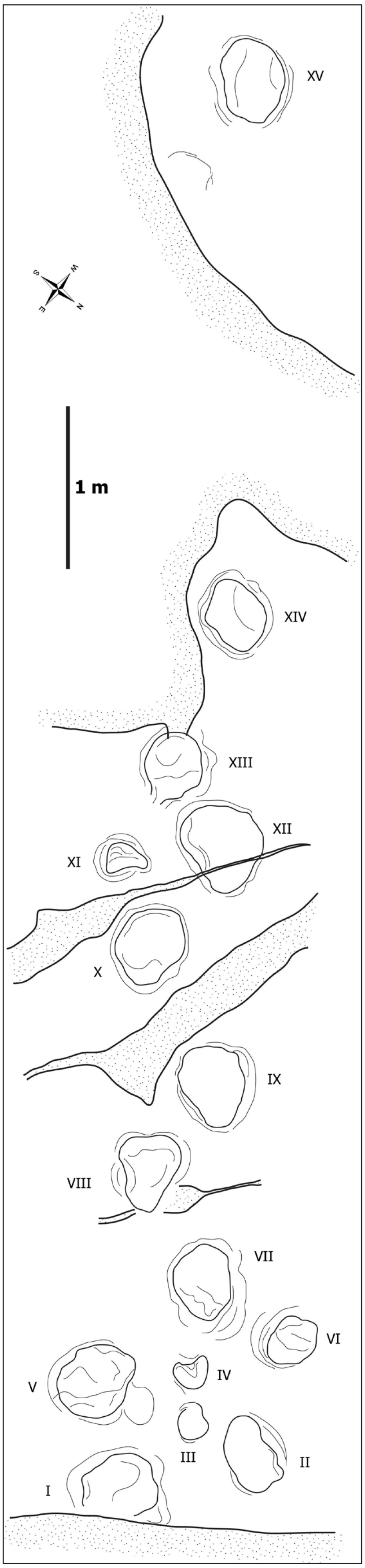

Fig. 10 - Ichnological map of the Kirmenjak II tracksite.

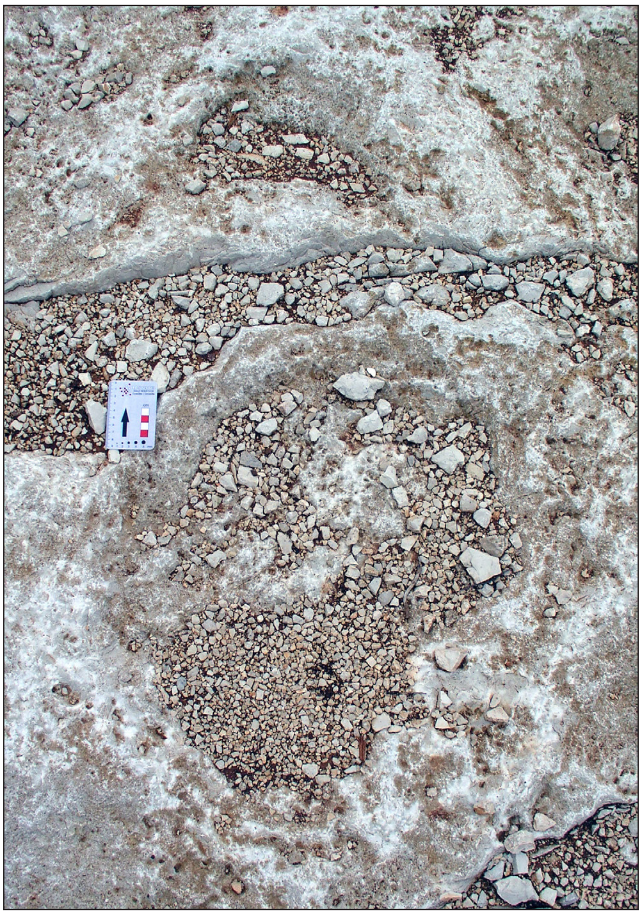

Fig. 11 - Set of pes (footprint X) and manus (footprint XI) prints.

trackway which is directed towards the south-west (Fig. 10). The orientation of the trackway is 240° and its visible length is 9.1 m. Footprints X and XI represent the only clearly discernible pair of manus and pes prints (Fig. 11). The best preserved part of the trackway is between footprints VII and XII, where clearly alternating footsteps could be tracked. There is a huge gap between footprints XIV and XV caused by gravel infill which obviously ruined a couple of tracks. The assignment of footprint XV to the trackway seems reasonable since it lies on the trackway midline and the distance between it and footprint XIV match to approximately two stride lengths. The area at the beginning of the trackway (i.e. NE side) is somewhat problematic regarding how to ascribe particular footprints to the trackway. It seems possible that the footprints of two individuals are present since there is no clear footstep alternation or they represent some complex movements of the same individual.

The trackway is of the narrow-gauge type, as the internal trackway width has often a negative value (*sensu* Lockley et al 1994a). Pes trackway ratio (*sensu* Romano et al. 2007) varies between 51.4% and 53.1%, which also indicate narrow-gauge trackway.

Discussion

Since there are no significant differences of morphology and size between the Kirmenjak I and Kirmenjak II tracks, we could infer that the footprints belong to the same type of sauropods. Narrow-gauge trackways, prominent heteropody and outward manus rotation, are characteristics of the ichnogenus *Parabrontopodus* (Lockley et al. 1994a). Manus prints of *Parabrontopodus* are characterized by width greater than the length, a semicircular shape, and a much smaller size compared to its pes prints; also they lack clear digit impressions. Pes prints of *Parabrontopodus* are characterized by length greater than the width and the long axis rotated from the middle axis of the trackway. The Kirmenjak II footprints, which clearly characterized by the abovementioned features, can be therefore attributed to the ichnogenus *Parabrontopodus*. The Kirmenjak site ichnocenosis consists of sauropod footprints formed on a shallow carbonate platform and is therefore attributed to the *Brontopodus* ichnofacies *sensu* Lockley et al. (1994b). Tithonian sauropod footprints have been known in Europe from Switzerland, Portugal and France (Lockley & Meyer 1999; Curry Rogers & Wilson 2005), but, as said in a previous work (Mezga et al. 2007), they differ from the Kirmenjak ichnites most notably because they are of the wide-gauge types.

The narrow-gauge nature of Kirmenjak II trackway hints at diplodocoids rather than titanosaurians as possible track makers (Lockley et al. 1994a; Wilson & Carrano 1999). The size of the Kirmenjak II tracks is relatively larger when compared to those of the Kirmenjak I site (Mezga et al. 2007). With an average pes length of 55 cm they correspond to the largest footprints found on the first site. Applying the obtained values of the hip height to the reconstructed skeleton of *Dicraeosaurus* (a non-titanosaurian Late Jurassic African sauropod) *sensu* Paul (2010), a length of 13.5 and 20 m respectively was calculated. What can be concluded on the basis of these calculations is that the trackmaker of Kirmenjak II was a medium-sized sauropod, approximately 16 m in length. It was somewhat larger than the largest sauropods from Kirmenjak I site (Mezga et al. 2007).

The speed of Kirmenjak II sauropod varies from 1.45 to 1.88 km/h which reflects the typical walking speed of sauropods. The AWS is 3.45 km/h which is in agreement with calculated speed predicted for sauropods (3.45-3.67; Thulborn 1990). Low values for SL/h and SL/FL indicates that the Kirmenjak II sauropod walked by taking relatively short strides. The footprints found in Kirmenjak II site are, generally speaking, shallow for their dimensions, which implies that the carbonate mud in which they were formed had high imprint resistance. Despite their overall shallowness and unpronounced morphology, they are not preserved as undertracks. Clearly visible expulsion rims around the tracks verify their preservation as true tracks. The manus prints are rarely preserved in the Kirmenjak II track assemblage; this is in agreement with the Kirmenjak I site where the manus prints are less abundant in the assemblage. The rarity of the manus prints in the Kirmenjak II trackway could be due to the overlapping by the pes prints. It is less probable a preservation bias since the only clearly discernable pair of the footprints in the trackway shows no sign of different preservation. The Kirmenjak II assemblage represents the pes-dominated trackway left by a sauropod with a more posteriorly located centre of mass in a cohesive substrate *sensu* Falkingham et al (2012).

The finding of the new tracksite in the Kirmenjak quarry about one kilometre far from the already existing site could be very intriguing. Since the sedimentary succession and footprint morphology closely correspond to each other, it could be inferred that the trackbearing beds on both sites represent the same one. This would imply the presence of a vast tidal flat area open for roaming dinosaurs. Since the quarry is still active, it should not be surprising if more dinosaur tracks are discovered in this area in the future. The whole Kirmenjak quarry could be regarded as a one large tracksite since the trackbearing horizon spread through the whole of its length. Kirmenjak sauropod tracksites together with Mattinata theropod tracks (Conti et al. 2005) represent so far the only known footprints of Tithonian age in the peri-Adriatic area.

From palaegeographic perspective, the Kirmenjak II tracks (as well as Kirmenjak I) further strengthen the hypothesis that the ADCP during the Tithonian had connections with other peri-Adriatic carbonate platforms (Nicosia et al. 2007; Sacchi et al. 2009; Zarcone et al. 2010). A southern provenance (i.e. a connection with Africa) for the Tithonian ADCP sauropods seems most likely (see also discussion in Mezga et al 2007) since the other routes (from north, east and west) were blocked by the presence of large oceanic areas or deep basins (Nicosia et al. 2007; Turco et al 2007; Zarcone et al. 2010). A possible route for the sauropods migration from Africa could have been the Panormide Platform walkway as suggested by Zarcone et al. (2010).

The taxonomic affinity of the Kirmenjak sauropods can be determined by considering the distribution of the Upper Jurassic sauropod records. The African sauropod fauna is much more diverse than the European one (Weishampel et al. 2004). The only known Early Cretaceous dinosaur bone site on the former ADCP yielded sauropod bones with clear African affinities (Dalla Vecchia 1998). The Kirmenjak footprints probably belong to the diplodocid sauropods and this supports once more that in the Late Jurassic the ADCP was, in some way, connected with the African continent. A rich sauropod fauna was found at the Mkoawa Mtwara site in Tanzania. The locality belongs to the Upper Jurassic Tendaguru Formation, where several genera of the Diplodocoidea have been identified (Weishampel et al. 2004). Regarding the footprint dimensions of the Kirmenjak sauropods, they more likely resemble those produced by smaller genera like *Dicraeosaurus* rather than other larger African genera.

Conclusion

A new locality with dinosaur footprints has been discovered in the Kirmenjak quarry in western Istria, about one kilometre from an already known one. The age of the trackbearing limestones is late Tithonian. The footprints are located within fenestral mudstones and were formed on a tidal flat during a sea-level fall. Fifteen footprints of circular to semicircular shape with no clear digit or claw impressions were found at the site. The footprint preservation is rather poor, but most of the footprints reveal clearly pronounced expulsion rims. Based on their morphology, the footprints belong to sauropod dinosaurs; the average length of the pes prints indicates that the length of the individual was around 16 m. The preserved trackway is of narrow-gauge type and pes-dominated, probably made by a sauropod with a posteriorly located centre of mass in a cohesive substrate. The length of the strides indicates slow movement of the individual. Based on stratigraphic position and footprint morphology, it is concluded that both tracksites (Kirmenjak I and II) represent the same trackbearing horizon, a much larger tracksite surface than previously thought. A proposed southern provenance for the Kirmenjak sauropods suggests a link between the ADCP and Africa across the peri-Adriatic carbonate platforms during the late Tithonian.

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