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Blanka Cvetko Tešović
University of Zagreb

Aleksandar Mezga
University of Zagreb

Bosiljka Glumac
Smith College, bglumac@smith.edu

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Stable isotope analysis of Upper Tithonian limestones with dinosaur footprints from Kirmenjak quarry (Istria, Croatia)

Blanka Cvetko Tešović[1], Aleksandar Mezga[1] and Bosiljka Glumac[2]

[1] Department of Geology, Faculty of Science, University of Zagreb, Horvatovac 102a, HR-10 000 Zagreb, Croatia; (bcvetko@geol.pmf.hr, amezga@geol.pmf.hr)

[2] Department of Geology, Smith College, Northampton, Massachusetts 01063, USA; (bglumac@email.smith.edu)

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ABSTRACT

The Kirmenjak locality of western Istria, Croatia, represents the oldest evidence of a dinosaur presence on the Adriatic-Dinaridic Carbonate Platform (ADCP). In a quarry at this locality, almost a thousand sauropod footprints are recognized in one distinctive trackbearing horizon within the Upper Tithonian limestones. The stable isotopes of oxygen and carbon, in conjunction with microfacies analysis of carbonate rocks exposed in this quarry, unravel details about the marginal marine or coastal environments in which sauropods left their footprints. Rocks from the trackbearing horizon, and laterally adjacent area, represent intertidal fenestral mudstones that form the top of a shallowing-upward succession, capped with a thin peloidal packstone/grainstone layer and overlain by subtidal mudstone. The formation and preservation of footprints was favoured by short-duration exposure of muddy sediment and its rapid burial beneath more mud. The isotopic composition of the sample from the trackbearing horizon is not substantially different from those of an adjacent area without footprints and from the overlying mudstone. Stable isotope analysis supports petrographic observations that the conditions on the carbonate tidal flat during formation of rocks with dinosaur footprints were not unique. Documented variations in stable isotope compositions reflect minor differences in the depositional and diagenetic history of the Kirmenjak quarry succession.

Keywords: Stable isotopes, Palaeoenvironments, Sauropods, Upper Tithonian Limestones, Istria, Croatia.

1. INTRODUCTION

Dinosaur footprints were discovered recently in Upper Tithonian strata exposed in an active quarry near Kirmenjak village (about 2 km south of the Sv. Lovreč–Poreč road) in western Istria, Croatia (MEZGA et al., 2003; MEZGA et al., 2007) (Fig. 1). The Istrian peninsula is in the northwestern part of the Adriatic-Dinaridic Carbonate Platform, (ADCP; also refered to as Adriatic Carbonate Platform, see discussion in VLAHOVIĆ et al., 2005). The sedimentary succession mainly consists of shallow water carbonates with a stratigraphic range from the late Middle Jurassic to the Eocene (VELIĆ et al., 2003), and to a lesser extent of Eocene clastic rocks and Quaternary terra rossa and loess deposits. The Kirmenjak locality represents the oldest evidence of a dinosaur presence on the ADCP to date, with a total of 971 documented footprints. It also represents the largest site with dinosaur tracks discovered on the ADCP so far (MEZGA et al., 2007), with 23 trackways, and other footprints occurring individually or in groups. Based on their overall morphology, the footprints are attributed to sauropod dinosaurs.

The objective of this study was to use stable isotopes of oxygen and carbon in conjunction with petrographic observations of carbonate rocks, to unravel details about the marginal marine or coastal environments in which large quadrupe-

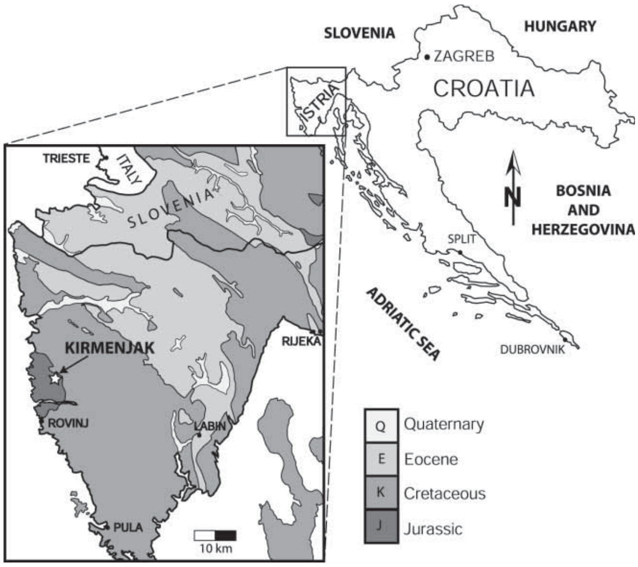

Figure 1: Geographic and geologic setting of the Kirmenjak locality in Istria, Croatia (modified after VELIĆ et al., 1995).

dal sauropod dinosaurs left their footprints during the Late Tithonian (MEZGA et al., 2007). The study was carried out on a portion of the Kirmenjak quarry deposits (Fig. 2) that belong to the informal Kirmenjak unit (VELIĆ & TIŠLJAR, 1988). The focus was on a horizon with abundant dinosaur footprints located approximately in the middle of the succession (Figs. 2, 3).

2. METHODS

Fieldwork involved measuring, describing and sampling of a 14.5 metre thick succession of Upper Tithonian carbonate rocks (Fig. 2) in the Kirmenjak quarry. Petrographic analysis was used to further describe rock types present and to identify samples for stable isotope analysis, which were collected by the drilling of a small amount of carbonate powder with a microdrill mounted on a binocular microscope. All samples for stable isotope analyses were roasted at 380°C for one hour to remove volatile organic matter, reacted with 100% H_3PO_4 at 70°C for 5 minutes and analyzed using an on-line, automated carbonate preparation system (Kiell III) linked to a Finnigan-MAT DeltaXL+ ratio mass spectrometer at the University of Massachusetts, Amherst, USA. Standard isobaric and phosphoric acid fractionation corrections were applied to all results and analytical precision was monitored through daily analysis of a variety of carbonate standards.

3. GEOLOGICAL SETTING

The stratigraphy and the tectonic and geological history of Istria are summarized in the explanatory notes to the Basic Geological Map of Croatia, Sheet Rovinj (POLŠAK & ŠIKIĆ, 1973). Detailed lithofacies and biofacies investigations of shallow water carbonates in Istria were carried out in the 1970s and the list of important references can be found in VELIĆ et al. (2003).

The Istrian stratal succession can be divided into five sedimentary units or large-scale sequences bounded by important discontinuities representing emersion surfaces of varying duration (VELIĆ et al., 2003). These large-scale sequences or megasequences are: (1) Bathonian–lowermost Kimmeridgian, (2) Upper Tithonian–Lower or Upper Aptian, (3) Upper Albian–Upper Santonian, (4) Eocene, and (5) Quaternary.

The investigated strata from the Kirmenjak quarry belong to the second transgressive-regressive megasequence (Upper Tithonian–Lower or Upper Aptian), deposition of which started in the Late Tithonian with shallowing-upward limestone cycles formed in subtidal, intertidal and supratidal environments (VELIĆ et al., 2003; VLAHOVIĆ et al., 2003). This limestone is known as the architectural-building stone »Pietra d'Istria« or »Kirmenjak«.

The deposits of the Kirmenjak unit examined in this study (Fig. 2) represent alternation of metre scale shallowing-upward cycles composed of black pebble breccias or stylolitized mudstone at the base, overlain by fenestral mudstone, and commonly capped by peloidal packstone and/or grainstone (VELIĆ & TIŠLJAR, 1988; TIŠLJAR et al., 1995; MEZGA et al., 2007). The presence of black pebble breccias suggests that strata exposed at the Kirmenjak locality likely belong to the lower part of the Kirmenjak unit, i.e. to the lowermost part of the second Istrian megasequence (VELIĆ & TIŠLJAR, 1988).

4. ICHNOLOGY

The investigated site is very rich in dinosaur footprints: almost a thousand individual prints have been observed on the trackbearing layer exposed in the Kirmenjak quarry (MEZGA et al., 2007; Fig. 3). Most of the footprints have an oval or horseshoe shape without clearly visible digit impressions (Fig. 4), and are relatively shallow (1–2 cm). The oval-shaped prints represent pes prints and the horseshoe-shaped prints are manus prints (Fig. 4). The footprints are of various dimensions: the manus prints have a length ranging from 5.5–26.5 cm, and the pes prints from 23–52 cm. The calculated hip height ranges from 153–306 cm. There are 23 trackways documented at this site and they frequently overlap. The trackways show characteristics of a narrow-gauge type (Fig. 5). The pace and stride lengths indicate slow walking individuals. The main direction of dinosaur movement is towards the NE and because there are many parallel trackways it may be concluded that some of the individuals were moving together in a herd (indication of gregarious behavior).

Although the state of preservation is far from ideal, the prints belong to sauropod dinosaurs based on their overall morphology (MEZGA et al., 2007). The footprints are similar to *Parabrontopodus* ichnogenus and the ichnocoenosis is assigned to the *Brontopodus* ichnofacies, which is characterized by sauropod footprints in carbonate platform environments.

5. LITHOLOGY AND MICROFOSSIL ASSEMBLAGE

Several shallowing-upward cycles are distinguished in the investigated succession, ranging in thickness from 0.3 to 2 m

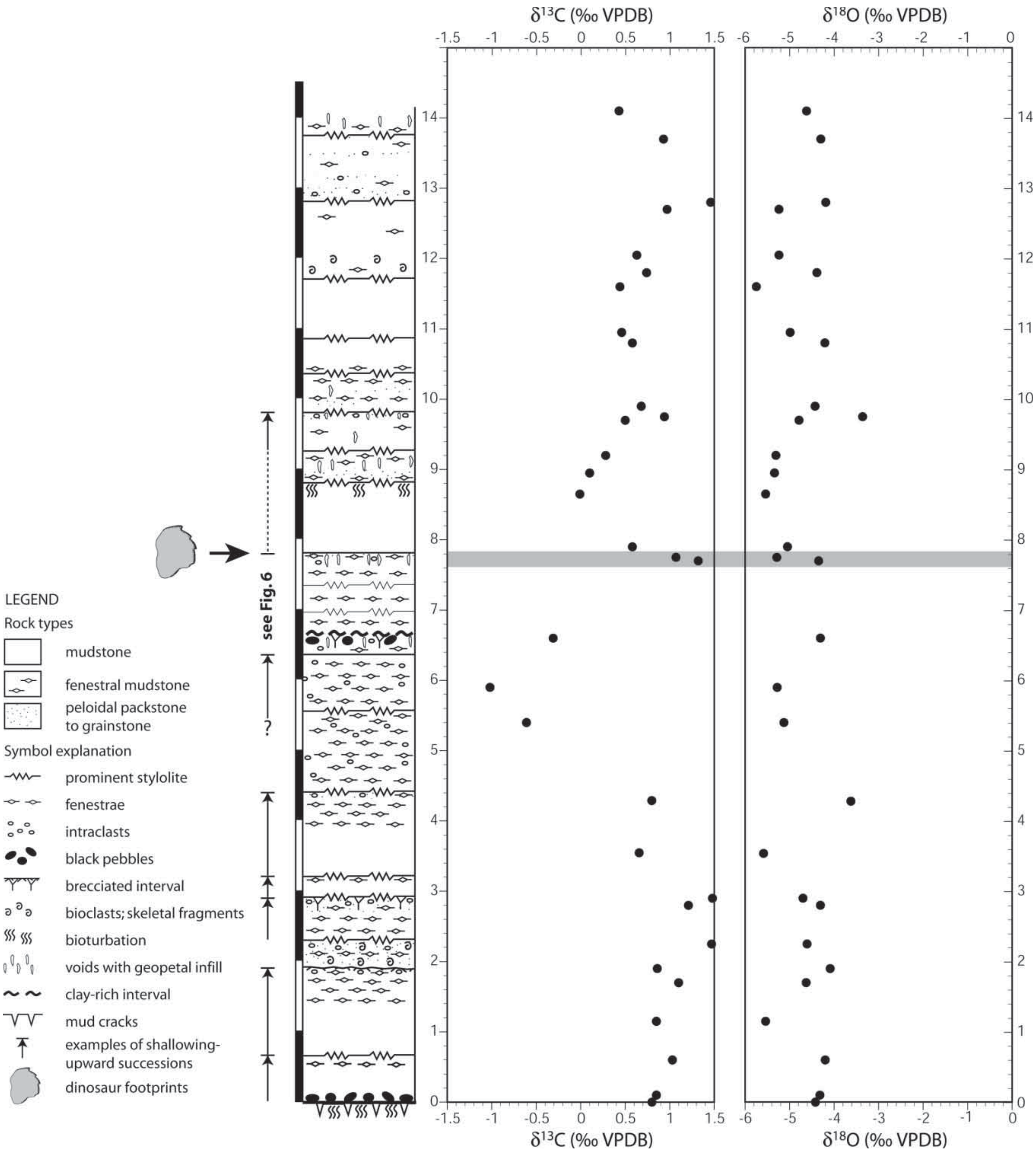

Figure 2: Schematic lithologic column of the measured Kirmenjak quarry succession with measured $\delta^{13}C$ and $\delta^{18}O$ values. Only examples of prominent shallowing-upward succession tops are indicated on the stratigraphic column.

(Fig. 2). The shallowing-upward cycles begin with black pebble breccia (in two cycles) or stylolitized mudstones, followed by fenestral mudstone, and commonly end with peloidal packstone/grainstones and grainstones (Fig. 6). The mudstones are massive, highly stylolitized (Fig. 6), occasionally bioturbated, rarely laminated, light yellowish gray in colour, and in places interbedded with lenses and layers of peloidal packstone to grainstone. Rare fossils include ostracods, green algae, gastropods, small foraminifera and crustacean pellets *Favreina*. These deposits are interpreted as representing a subtidal environment, probably a restricted lagoon. Black pebbles (Fig. 6) incorporated in the base of some mudstone horizons suggest reworking of marsh deposits during sea-level rise. Mudstones commonly grade upward into fenestral mudstone (Figs. 2 & 6).

The fenestral mudstones (Fig. 6) are in places also interbedded with lenses and layers of peloidal packstone to grainstone with mm-scale muddy intraclasts. Common mm-scale

Figure 3: Panoramic view of the trackbearing horizon in the Kirmenjak quarry.

fenestral voids are filled with sparite and are mainly irregular in shape, whereas laminar fenestrae or sheet cracks are not as abundant. Subvertical to irregular mm- to cm-scale desiccation and dissolution-enlarged voids with geopetal infills of vadose silt and coarse-crystalline clear equant calcite cement are present in some of the fenestral mudstones (Fig. 6). The fenestral mudstones rarely form *in situ* brecciated shallowing-upward cycle tops with reworked muddy intraclasts. The fenestral mudstones are interpreted as having formed in restricted shallow subtidal to intertidal environments and they commonly grade upward into peloidal grainstone (Fig. 6).

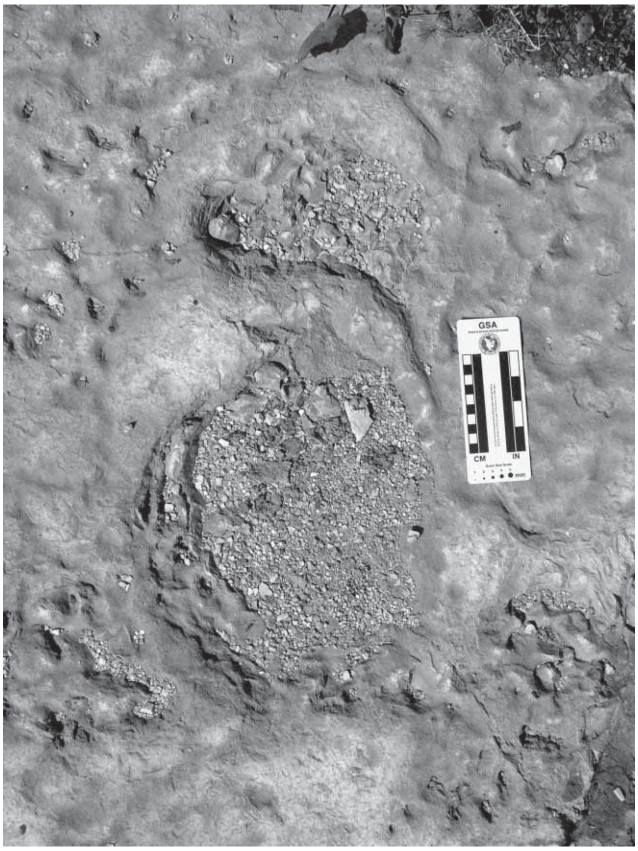

Figure 4: An oval-shaped pes print (lower part of the photograph) and a horseshoe-shaped manus print (upper part of the photograph) of the sauropod dinosaur from the Kirmenjak quarry.

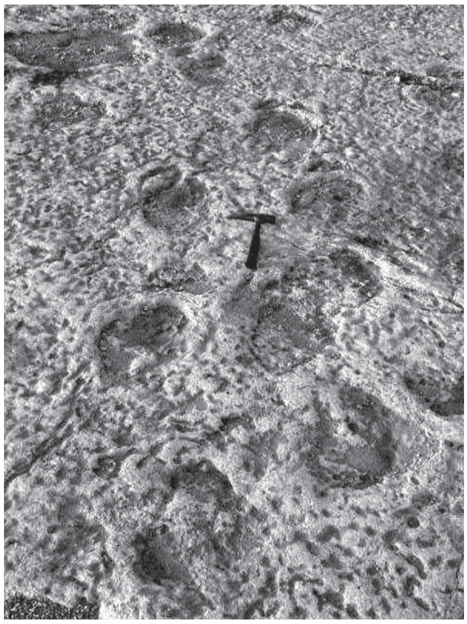

Figure 5: A narrow-gauge trackway of a sauropod dinosaur from the Kirmenjak quarry.

The peloidal packstone/grainstones to grainstones (Fig. 6) are characterized by abundant irregular fenestrae and common intervals with mm-scale intraclasts that form darker grayish to brownish coloured shallowing-upward cycle tops with *in situ* brecciation. These cycle tops are also characterized by darkened clasts (black pebbles), mm- to cm-scale desiccation and dissolution-enlarged voids with geopetal infills (Fig. 6), thin calcrete crusts, and cm-scale clay-rich caps. The peloidal packstone/grainstones to grainstones from the uppermost parts of shallowing-upward cycles are interpreted as deposits of intertidal to supratidal environments formed by high energy storm waves and tides. Modifications under subaerial exposure conditions produced characteristic cycle tops.

Samples from the trackbearing horizon and adjacent area without footprints are lithologically very similar. They consist of mudstones with small fenestrae, faint lamination and rather large subvertical to irregular desiccation cracks and voids. The uppermost part of both consists of a thin layer of peloidal packstone/grainstone (Fig. 6). Layers directly overlying the footprint horizon, on the other hand, are quite different – they are massive stylolitic mudstones. The presence of fenestrae and desiccation features suggests that the rocks with dinosaur footprints were formed in an intertidal environment. The lack of fenestrae and other indicators of subaerial exposure in the mudstones above the footprints suggest formation in a subtidal environment. Thus, the footprints formed on top of a shallowing-upward succession (Fig. 6), which is overlain by deeper, subtidal deposits.

Palaeoenvironmental conditions during deposition of the Kirmenjak quarry succession were not optimal for high biotic productivity. Microfossil remains include only a few taxa of calcareous algae, while benthic foraminifera are very rare. The microfossil assemblage (Fig. 7) consists of *Campbelliella* *striata* (CAROZZI) (Fig. 7A), *Favreina* sp. (Fig. 7B) and *Salpingoporella annulata* CAROZZI (Fig. 7C-D), as well as other unidentified foraminifera, gastropods, ostracods and echinoids. The identified microfossil assemblage, typical of the Kirmenjak unit, confirms a Late Tithonian age.

6. STABLE ISOTOPE RESULTS

Stable isotope values of the 32 samples analyzed from the studied succession (Figs. 2 & 8) are lower than the estimated values of Upper Jurassic unaltered marine calcite ($\delta^{18}O$ = -2 to -1‰; $\delta^{13}C$ = +3 ‰; LOHMANN & WALKER, 1989). All samples have positive $\delta^{13}C$ values except for the three whole-rock samples of peloidal packstone-grainstone from below a prominent subaerial exposure horizon with black pebbles in the middle of the section (Fig. 2). The rest of the data points show a general covariance between $\delta^{13}C$ and $\delta^{18}O$ values, and an overlap between compositional fields representing different rock types (Fig. 8). Mudstones, however, tend to cluster towards more negative $\delta^{13}C$ and $\delta^{18}O$ values, and fenestral mudstones and peloidal packstone-grainstones plot towards more positive values (Fig. 8). Exceptions are one fenestral mudstone sample ($\delta^{13}C$ = 0.28 ‰) and one mudstone sample ($\delta^{13}C$ = 1.48 ‰) from the base of a shallowing-upward succession. The sample with dinosaur footprints is not substantially different from those of the adjacent area without footprints and from the overlying mudstone (Fig. 8).

7. DISCUSSION

Petrographic observations do not explain why there are no footprints along the same intertidal horizon in different places in the quarry. It is possible that the footprint distribution reflects minor differences in water depth, which are not reflected by lithological changes. It is also possible that footprints were not observed in other similar rock types in the quarry because most of the other tops of the shallowing-upward successions are now capped by prominent stylolites and thus the footprints, if they were there, may have been obliterated by pressure dissolution along stylolites.

Bed-parallel stylolites are extremely abundant in the Kirmenjak deposits, and locally these strata are commonly referred to as the stylolitic limestones. The observed abundance and morphology of stylolites all point towards a potentially substantial magnitude of pressure dissolution and thickness reduction of the Kirmenjak strata during burial diagenesis. Amplitude of stylolites suggests that the primary thickness of these Tithonian limestones may have been reduced by about 20–23% (TIŠLJAR, 1978).

Furthermore, it may be significant that the shallowing-upward succession with dinosaur footprints terminated in fenestral mudstone (with only a very thin cap of peloidal packstone/grainstone; Fig. 6) rather than in thicker shallow intertidal to supratidal grainstone deposits with substantial evidence for modification during subaerial exposure. Footprints likely have a better potential of being produced and preserved in muddy (rather than grainy) sediment that was dried out during a rather brief period of exposure in an interti-

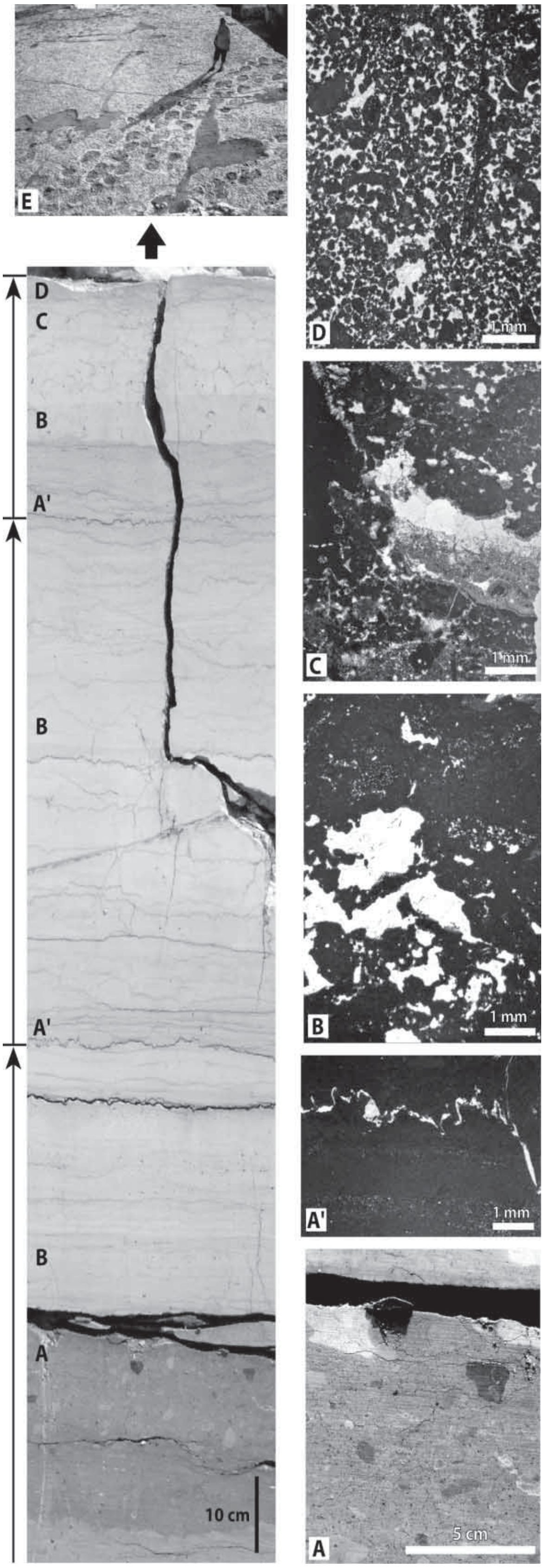

Figure 6: Details of shallowing upward cycles from the central part of the measured Kirmenjak succession (see also Fig. 2). The cycles begin with black pebble breccias (A) or stylolitized mudstone (A'), overlain by fenestral mudstone (B) and peloidal-intraclastic-fenestral packstone with geopetal infill (C), and capped with thin peloidal-intraclastic grainstone (D) with dinosaur footprints (E).

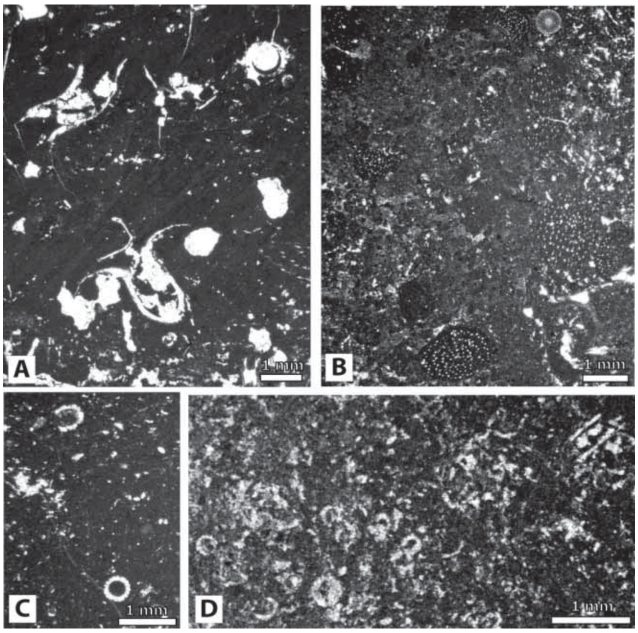

Figure 7: Microfossil assemblage of the Kirmenjak unit from the Kirmenjak quarry. A, longitudinal and transverse sections of *Campbelliella striata* (CAROZZI); B, fenestral mudstone with common *Favreina* sp.; C, algal mudstone with transverse sections of *Salpingoporella annulata* CAROZZI; and D, algal mudstone with various sections of *S. annulata* CAROZZI.

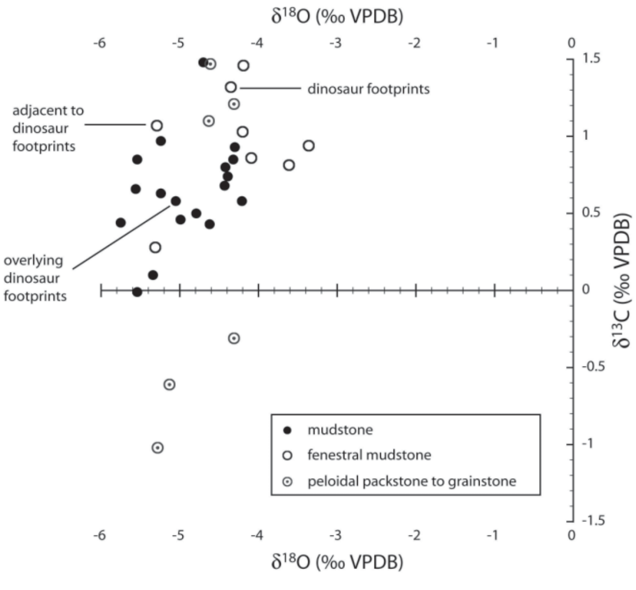

Figure 8: $\delta^{13}C$ vs. $\delta^{18}O$ values of the analyzed samples.

dal environment and was then rapidly covered by subtidal mud. The absence of substantial pressure dissolution (stylolites) along the bedding plane with footprints, unearthed by quarry operations, further aided footprint preservation.

Stable isotope results support petrographic observations that the horizon with dinosaur footprints does not represent a unique rock type. Comparison with unaltered Jurassic marine cements and the covariance between $\delta^{13}C$ and $\delta^{18}O$ values (Fig. 8), suggest post-depositional or diagenetic modifications in the presence of meteoric waters. This is also supported by the presence of dissolution enlarged voids and their occlusion by vadose silt and meteoric calcite cement (Fig. 6). Negative $\delta^{13}C$ values recorded in the peloidal packstone-grainstone (Figs. 2 & 8) associated with the exposed surface with black pebbles, reflect diagenesis under subaerial conditions in the presence of terrestrially derived decaying organic matter. Variations in $\delta^{13}C$ and $\delta^{18}O$ values in other analyzed samples (Fig. 8) are likely a function of minor variations in conditions during deposition (temperature, salinity, organic productivity), and the extent of diagenetic modifications. The observed overlap of compositional fields suggests that the overall conditions during deposition and diagenesis of various rock types did not vary greatly indeed. The clustering of fenestral mudstones (and the rest of the peloidal packstone to grainstone samples) towards slightly more positive values, may reflect their lithification from waters that experienced enhanced exchange with the atmosphere (including evaporation) during their residence on the carbonate tidal flat. On the other hand, clustering of mudstone towards slightly more negative values may indicate lithification in the presence of a somewhat greater amount of organic matter in these restricted subtidal/lagoonal deposits.

The beginning of deposition of the Kirmenjak unit is marked by an oscillatory transgression over the emerged relief (TIŠLJAR et al., 1995; VELIĆ et al., 2003). Deposits in the lower part of the Kirmenjak unit indicate the presence of coastal marsh environments, which represent the source for black pebble breccias (VLAHOVIĆ, 1999). With continuing transgression, these marshes were gradually replaced with shallow, protected lagoon environments surrounded by wide tidal flats where dinosaurs left their footprints.

8. CONCLUSION

The Kirmenjak quarry in western Istria, Croatia, is currently the largest dinosaur footprint site on the ADCP with almost a thousand individual footprints preserved in Upper Tithonian limestones. Dinosaur footprints were produced on the top of a shallowing-upward succession in intertidal fenestral mudstones, capped with a thin peloidal packstone/grainstone layer, and overlain by subtidal mudstone. Footprint formation and preservation was favoured by short-lasting exposure of muddy sediment and its rapid burial beneath more mud. The absence of substantial pressure dissolution (stylolites) along the bedding plane with footprints, unearthed by quarry operations, further aided footprint preservation. The results of petrographic and stable isotope analysis did not provide any direct evidence that the conditions on the carbonate tidal flat during formation of the deposits with dinosaur footprints were unique. Documented variations in stable isotope compositions, on the other hand, reflect minor differences in the depositional and diagenetic history of strata from this stratigraphic succession.

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