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Dinosaur footprints from the Thaiat ridge and their palaeoenvironmental background, Jaisalmer Basin, Rajastan, India

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Abstract. Two dinosaur footprints: *Eubrontes* cf. *giganteus* and *Grallator tenuis*, both attributed to theropods, have been found in the Lower Jurassic Thaiat Member of the Lathi Formation at the Thaiat ridge, near Jaisalmer in western Rajasthan, India. The footprints were left in sediments of a tidal origin, located in profile a few meters above a marked transgressive/flooding surface. They show different states of preservation – the smaller *Grallator tenuis* represents a well-preserved concave epirelief footprint on the upper surface of a sandstone containing nerineid gastropod shells, while the bigger *Eubrontes* cf. *giganteus* footprint shows a rare state of preservation as a positive epirelief on the top of a calcareous sandstone bed, where recent erosion exposed the footprint cast by removing the mud above and around the footprint. The Thaiat ridge section has been amended in its lower part, to indicate the marked transgressive surface. Geochemical analyses and calculated weathering indices (such as CIA) show that the hinterland climate was seasonal to semi-arid during deposition of that part of the succession.

INTRODUCTION

The Jurassic rocks in India are very diverse: they range from continental siliciclastic rocks overlying thick coal deposits in the central and eastern parts of the Indian subcontinent (Gondwana Supergroup) to siliciclastic and carbonate facies of the lower shelf in the north (Himalaya). The Jaisalmer and Kachchh basins are located in the states of Rajasthan and Gujarat, respectively, in western India (Fig. 1A) and contain exposures of rocks of the Jurassic period, which originated in connection with the early opening stages of the Indian Ocean and represent continental, marginal-marine, and shallow to offshore marine environments which formed at the southern margin of the Tethys Ocean. Hitherto in Rajasthan, dinosaur bones were identified by Mathur *et al.* (1985) from sediments exposed at the base of the Baba Bhar-

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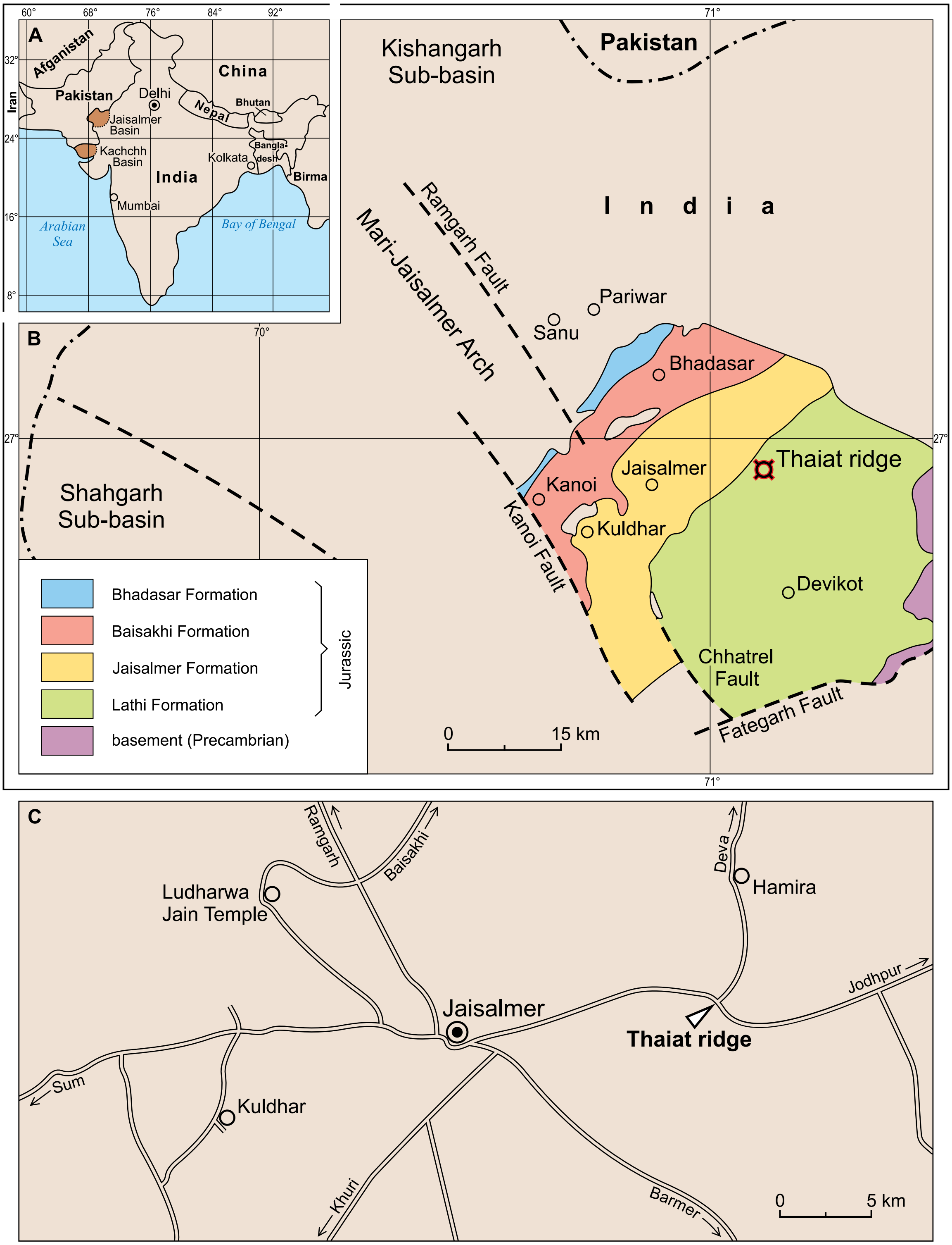

Fig. 1. A sketch map showing locations of the Kachchh and Jaisalmer basins on the outline map of India (A), Jurassic outcrops in the Jaisalmer Basin (B), and location of Thaiat ridge (C) from where dinosaur foot prints have been recorded (modified after Pandey *et al.*, 2014)

ti Temple Scarp section, 2 km from the center of Jaisalmer city (Pandey *et al.*, 2014). During the post-Congress field excursion of the 9th International Congress on the Jurassic System, the first dinosaur footprints were found in the Jaisalmer Basin by Jan Schlögl and Grzegorz Pieńkowski. The footprints were observed on the Thaiat ridge (precisely, the Thaiat Scarp section) near Thaiat village, 16 km east of Jaisalmer city, on the southern side of the Jaisalmer–Jodhpur highway (co-ordinates: N26°55'50.1", E71°03'54.2"; Fig. 1B, C). This find adds new evidence for the presence of dinosaurs in Rajasthan, western India.

GEOLOGICAL AND PALAEOENVIRONMENTAL SETTING

The rocks exposed along the Thaiat ridge show a clear bi-partite development: the lowermost part of the succession is composed of siliciclastic sediments with a low CaO and MgO content (Fig. 2; beds nos 1, 2, 3 and 5), while upwards (beds 6–16) the profile is more calcareous, containing a more diversified fauna, pointing to a fully-marine environment (nerineid gastropods, heterodont and bakevelliid bivalves, oysters, *Trigonia*, *Eomodion*, rhynchonellid brachiopods, crinoids, and the invertebrate trace fossils *Teichichnus*, *Gyrochorte*, *Rhizocorallium*, *Thalassinoides*, and *Skolithos*; Pandey *et al.*, 2006, 2012, 2014). Interestingly, drift wood and vertebrate bones (including fragments of pterosaur bones) have been found in the upper part of the section (Pandey *et al.*, 2014). Collectively, the whole succession has been assigned to the Thaiat Member of the Lathi Formation, and its age has been estimated to be Early Jurassic to Bajocian (Pandey *et al.*, 2012), based on the occurrence of the characteristic Bajocian coral *Isastraea bernardiana* (d'Orbigny) in the lower part of the overlying Jaisalmer Formation (Pandey *et al.*, 2006).

At the base of the section (Fig. 2; beds nos 1 and 2), a mudstone-claystone succession with lens-shaped ("channelized") sandstone layers is visible. Sample CM-1 was taken from the mudstone. At the top of the lens-shaped sandstone intercalations, numerous rootlets are observed. Immediately above the top of the sandstone with plant roots and neighbouring mudstones/claystones (Fig. 3) a conspicuous bounding surface runs through the whole outcrop. Above this surface, a *c.* 10–15-cm-thick mudstone alternating with silty-very fine sandy streaks (wavy-bedded heterolith) occurs (bed no. 3). This heterolith contains *Rhizocorallium* isp. and other feeding structures (sample CM-2 was taken from this bed). The wavy-bedded heterolith bed passes upwards into a flaser-bedded one (with a stronger sandstone component) with convolute bedding in places (bed no. 3, upper part). Here, both feeding and dwelling structures (*Arenicolites* isp.) occur. The heteroliths are topped by bioturbated sandstones, showing hummocky cross-stratification (Fig. 2; bed no. 4).

Above the sandstone, siltstone intercalated with very fine-grained sandstone, in parts slightly calcareous, occurs (Figs 2, 3; composed bed no. 5). The tops of the sandstone beds are covered with linguloid and ladder ripples; in places desiccation cracks can be observed. Additionally, scattered nerineid gastropods and bivalves (*Indocorbula* sp.) can be found on bedding planes. Sample CM-3 was taken from bed no. 5. Dinosaur footprints were found within this interval.

The three rock samples taken from the lower part of the profile (CM-1, CM-2, CM-3; see Figs 2, 3) were analysed for their chemical composition (Tables 1, 2).

Table 2 shows the so-called "simple indices" (Al/K, Al/Na, *etc.*) and the "composed indices", such as the CIA (Chemical Index of Alteration, after Nesbitt, Young, 1982) and the CIA* (after Goldberg, Humayoun, 2010), the index of chemical weathering (CIW), the index of plagioclase alteration (PIA), and the index of compositional variability (ICV). The newly characterized (Garzanti *et al.*, 2014) CIX index does not regard CaO and is particularly useful in a case

Table 1

Main chemical composition of the three rock samples collected at the Thaiat ridge

Sample	SiO_2	TiO_2	Al_2O3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	(SO_3)	(Cl)	LOI	Σ
	%	%	%	%	%	%	%	%	%	%	%	%	%	%
CM-1	61,89	0,896	17,50	5,09	0,023	1,10	0,12	1,10	3,52	0,053	0,01	0,021	8,51	99,86
CM-2	59,03	0,993	20,78	4,79	0,012	1,09	0,28	0,66	3,09	0,043	<0,01	0,019	9,10	99,89
CM-3	84,06	0,654	6,35	2,82	0,014	0,63	0,05	0,45	1,32	0,026	<0,01	0,021	3,53	99,93

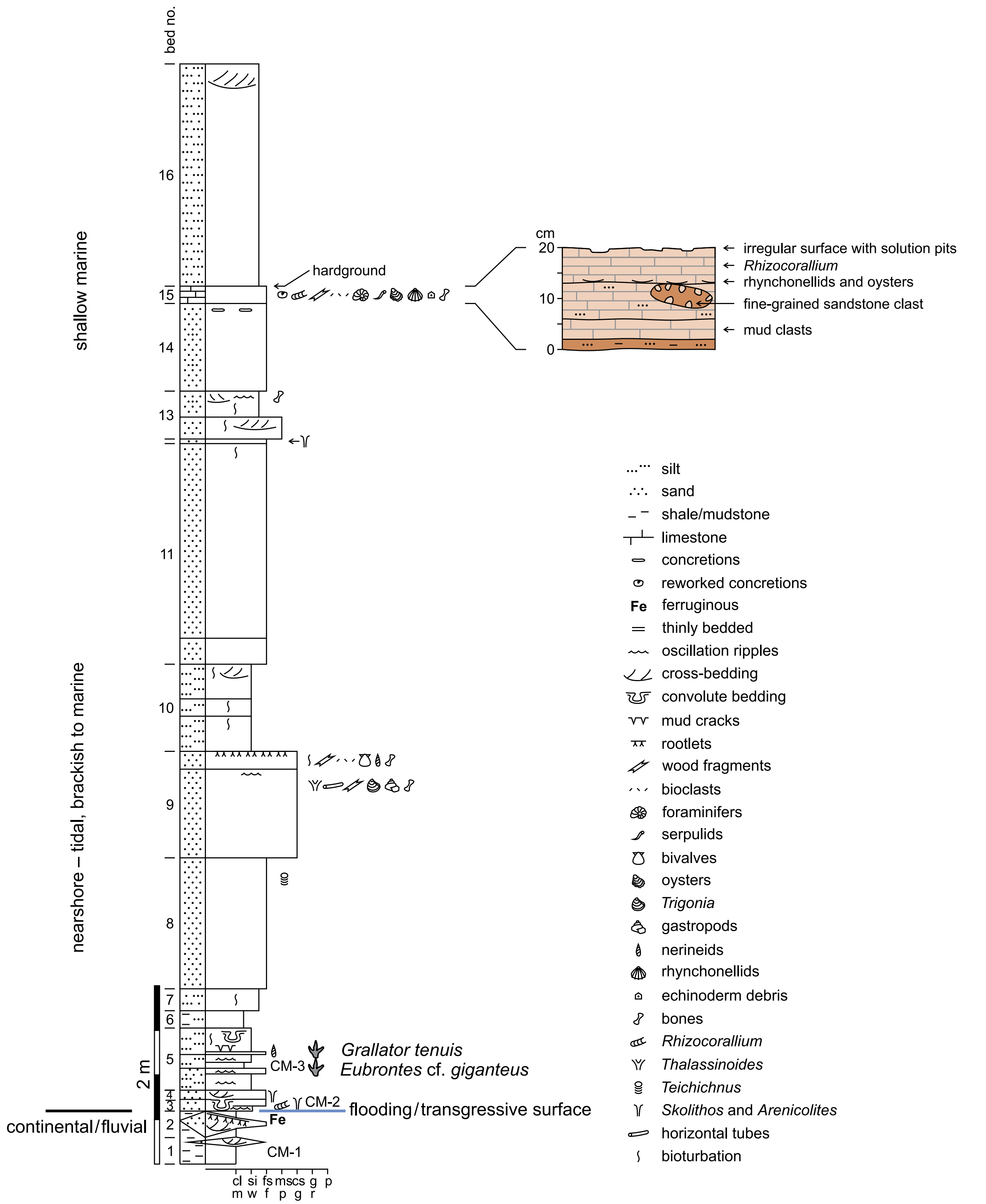

Fig. 2. Litho-log of the Thaiat ridge section showing geochemical samples location (CM-1, CM-2, CM-3) and horizons from where dinosaur footprints have been recorded (profile after Pandey *et al.*, 2014, modified in the lower part)

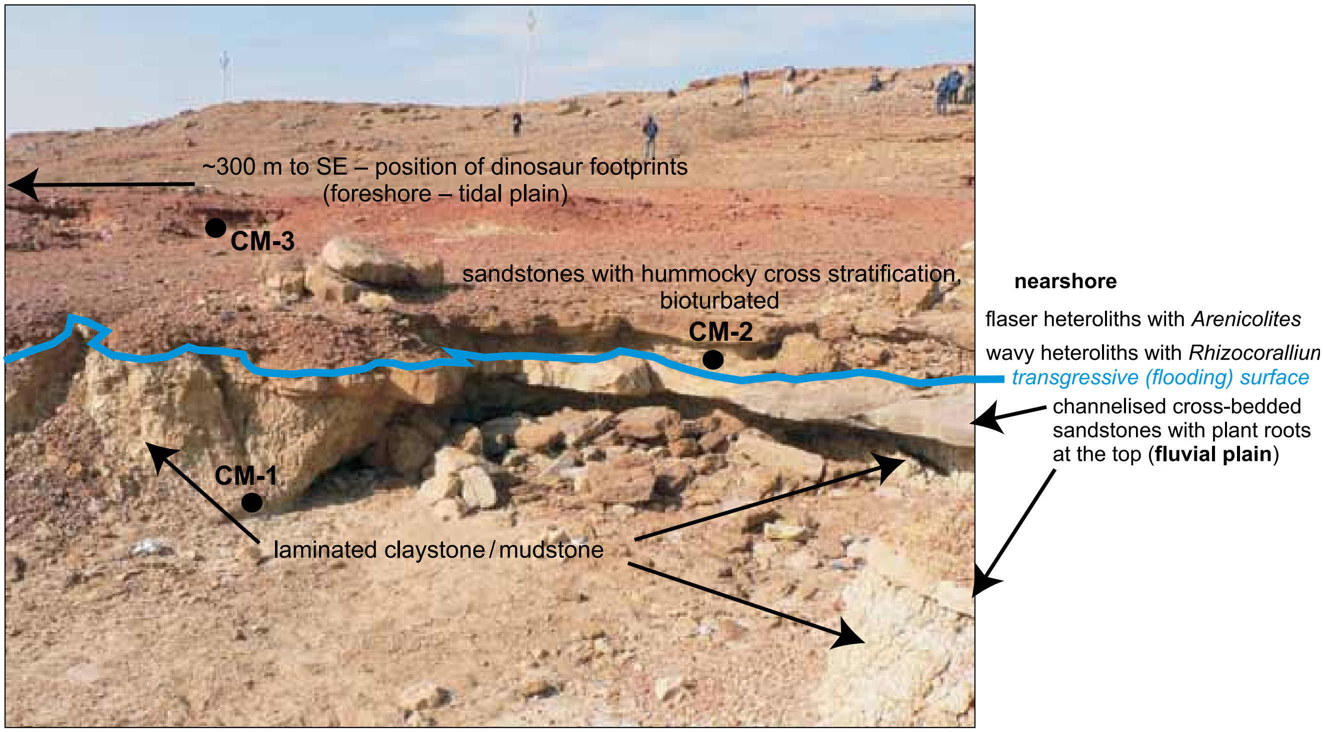

Fig. 3. Field photograph of the Thaiat ridge section showing lens-shaped (channelled) sandstone layers in the lowermost part of the section (interpreted as fluvial deposits), transgressive/flooding surface and nearshore/foreshore sediments above. Dinosaur footprints come from the foreshore/tidal sediments located some 300 m to the SE (arrowed). Location of geochemical samples is marked

of calcareous sediments, which is not the case in the samples studied. The formulas for calculating the indices are as follows:

- CIA = $[Al_2O_3/(Al_2O_3 + CaO^* + Na_2O + K_2O)] \cdot 100$ (Nesbitt, Young, 1982);
- CIA* = $Al_2O_3/(CaO^* + Na_2O + K_2O)$ (Goldberg, Humayun, 2010);
- CIW = $[Al_2O_3/(Al_2O_3 + CaO^* + Na_2O)] \cdot 100$ (Harnois, 1988);
- PIA = $\{(Al_2O_3 - K_2O)/[(Al_2O_3 - K_2O) + CaO^* + Na_2O]\} \cdot 100$ (Fedo *et al.*, 1995);
- CIX = $[Al_2O_3/(Al_2O_3 + Na_2O + K_2O)] \cdot 100$ (Garzanti *et al.*, 2014);
- ICV = $(Fe_2O_3 + K_2O + Na_2O + CaO + MgO + MnO + TiO_2)/Al_2O_3$ (Cox *et al.*, 1995).

The Al_2O_3/TiO_2 index may indicate primary composition of magmatic source rocks (mafic *vs* felsic – Hayashi *et al.*, 1997). Before calculations, percent values were converted into mole values (except for Al_2O_3/TiO_2 and ICV).

Table 2

Geochemical indices of the three rock samples collected at the Thaiat ridge

Sample	Al/K	Al/Na	K/Na	K/Ca	Al_2O_3/TiO_2	CIA	CIA*	CIW	PIA	CIX	ICV
CM-1	4.59	9.69	2.11	17.81	19.5	75.00	3.00	89.66	87.14	75.69	0.68
CM-2	6.21	19.23	3.09	6.56	20.9	80.81	4.21	92.89	91.64	82.44	0.53
CM-3	4.45	8.53	1.92	15.56	9.7	73.73	2.81	88.37	85.49	74.52	0.94

CIA, CIA* – chemical indices of alteration; CIW – index of chemical weathering; PIA – index of plagioclase alteration; ICV – index of compositional variability.

INTERPRETATION OF THE GEOCHEMICAL RESULTS (PALAEOCLIMATE)

Samples CM-1 and CM-2 are mudstones/claystones. Sample CM-3 represents a clayey siltstone to very fine--grained sandstone (high content of SiO_2 and high ICV). Sample CM-2 suggests a relatively elevated degree of chemical weathering (CIA >80, CIW and PIA = 91–93). Relatively high Al/Na and K/Na ratios, as well as elevated CIW and PIA, suggest that weathering processes in the hinterland led to decomposition of the majority of the less resistant plagioclase grains, while many of the more resistant potassium feldspar grains remained intact. Kaolinization of illite and smectite was only partial.

Samples CM-1 and CM-3 show a degree of weathering typical of average fine-grained sediments in the lithosphere (CIA = 70–75). One should bear in mind that the sample CM-3 differs lithologically from CM-1 and CM-2 and the CM-3 result is not fully comparable with those of CM-1 and CM-2.

The Al_2O_3/TiO_2 ratio of CM-1 and CM-2 (*c.* 20) suggests that source rocks were mainly intermediate mafic–felsic rocks, most likely of granodiorite type. The same value for CM-3 (below 10) rather suggests typical mafic rocks.

Probably, the weathering processes occurred in a semiarid climate (the considerable K content suggests a high content of illite and non-kaolinized K-feldspars, the elevated Na and Mg may suggest a smectite content, and the low to moderate Al/K and CIA values with the diversified composition of the samples (relatively high ICV) suggest that the kaolinite content is not dominant). These conclusions should be supplemented with clay mineral studies of the fraction <0.002 mm.

The palaeoenvironmental conditions can be summarized as follows:

The lowermost part of the profile (Figs 2, 3; beds 1 and 2) represents a fluvial plain environment with sandy channel deposits and fine-grained overbank sediments. A palaeosol horizon occurs at the top of this succession. Geochemical indices point to a seasonal climate, while thicker sandstone lithosomes, and the palaeosol occurrence might point to a slightly intensified hydrolic cycle in the uppermost part of bed 2. Above bed 2 there is a major bounding surface (Fig. 3), interpreted as a transgressive/flooding surface. Heteroliths above that surface contain a fairly diverse trace fossil assemblage, pointing to a nearshore/shoreface environment. The elevated degree of chemical weathering just above the transgressive surface (sample CM-2) tends to confirm the intermittent humidification of climate, observed already at the top of bed 2. Beds 3 and 4 exhibit a coarsening-upward character; the sandstones with hummocky cross-stratification contain dwelling structures (*Arenicolites*, *Skolithos*) pointing to a high-energy, nearshore (upper shoreface) environment. The shallowing trend continued and bed no. 5 (Fig. 2), besides the presence of scattered nerineid shells, shows numerous linguoid ripples (developed under high-velocity currents), ladder-like ripples (formed by interference of waves in very shallow ponds) and desiccation cracks, which collectively point to a foreshore-intertidal environment. The degree of chemical weathering (sample CM-3) seems to indicate the return of a seasonal (?semi-arid) climate, although geochemical indices of this sample are not fully comparable to the previous ones. In the middle part of this interval, the dinosaur footprints were found – *Eubrontes* cf. *giganteus* and, slightly higher, *Grallator tenuis* (Fig. 4).

SYSTEMATIC DESCRIPTION OF THE DINOSAUR FOOTPRINTS AND DISCUSSION ON THEIR PRESERVATION

Grallator tenuis Hitchcock, 1858 – Fig. 4

Description. – Small, 5.5 cm long, functionally tridactyl ichnite in which the digit length ratios are III/II = 1.6 and III/IV = 1.1, respectively. The length to width ratio is about 1.5. Two phalangeal pads are visible in digit II, three in digit III and three in digit IV. Divarication angle of outer digits is relatively wide – about 50°.

Discussion. – Similar small theropod tracks from Poland have been described (Gierliński, 1995; Gierliński, Pieńkowski, 1999) as *Grallator tenuis* with length ratios close to those given by Olsen *et al.* (1998) for the foot skeleton of "*Syntarsus*" (*Megapnosaurus*) and not so close to those of *Grallator parallelus* Hitchcock, 1858, the type ichnospecies of *Grallator*, revised by Olsen *et al.* (1998). The wide divarication angle is also atypical of *Grallator* described by Olsen *et al.* (1998), but is identical to the *Grallator* illustrated by Gierliński and Pieńkowski (1999) and Lucas *et al.* (2006). Its assignment to *Grallator tenuis* (based on the formula by Weems, 1992) seems to be correct, although using ichnospecies identification can be regarded as premature, until all the ichnospecies belonging to *Grallator*, *Anchisauripus*, and *Eubrontes*, shown by Olsen *et al.* (1998) as poorly defined, are thoroughly revised. Of note is that the discussed ichnite shows a few features which stay just on the boundary of the *Grallator* standards. The digits are very narrow with very long slender claws, the toes are relatively widely divaricated and the size is twice as small as typical *Grallator* ichnites. All these features resemble the Early Jurassic diminutive grallatorid named *Stenonyx*. However, these small grallatorids distinguished from the Navajo Sandstone of the western US, alternatively labeled as *Stenonyx* by

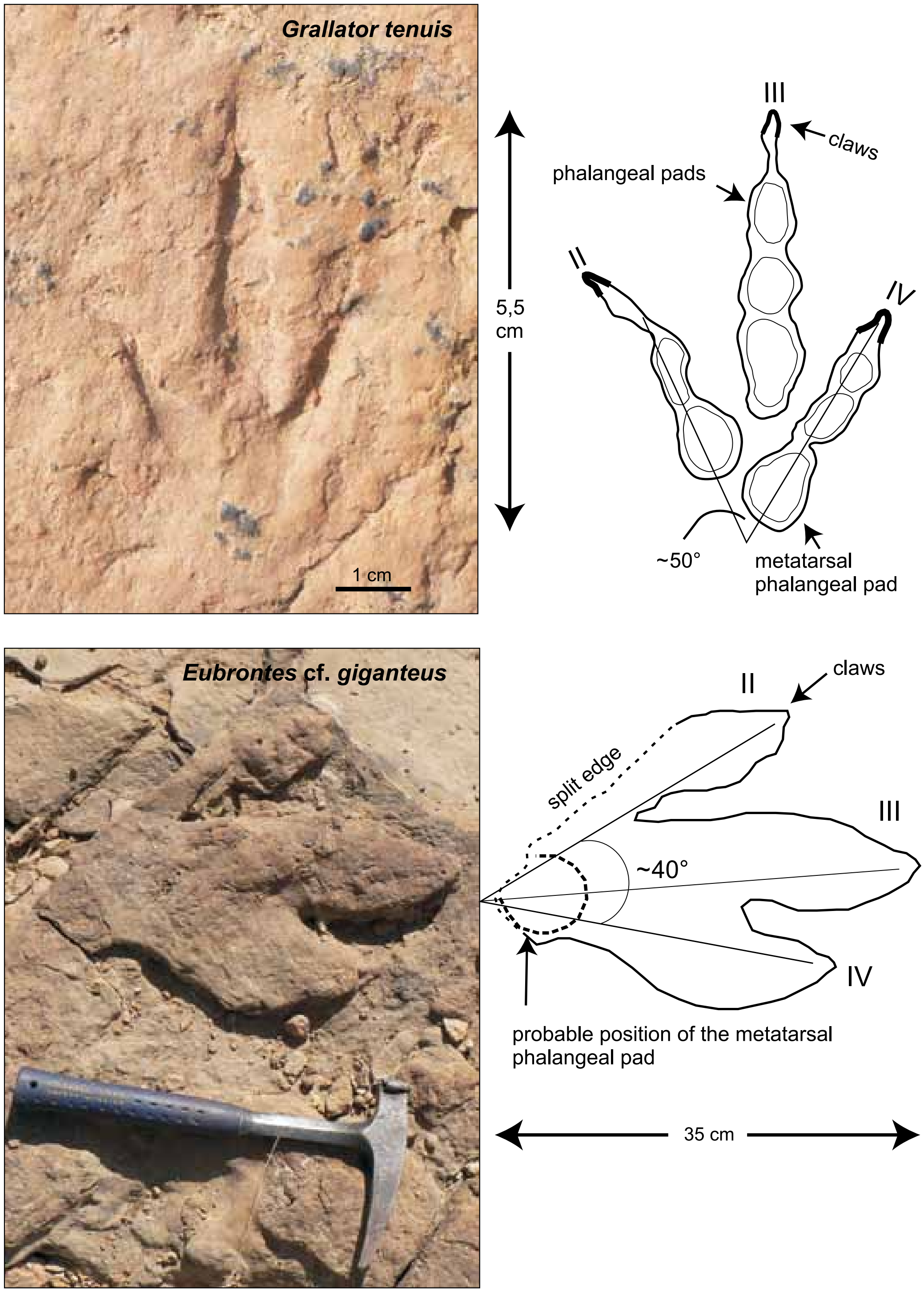

Fig. 4. Field photographs and drawings showing ichnological details of the two dinosaur footprints determined as *Eubrontes* cf. *giganteus* and *Grallator tenuis*

Digits are marked as II, III, IV (digit II was closest to the trackway axis)

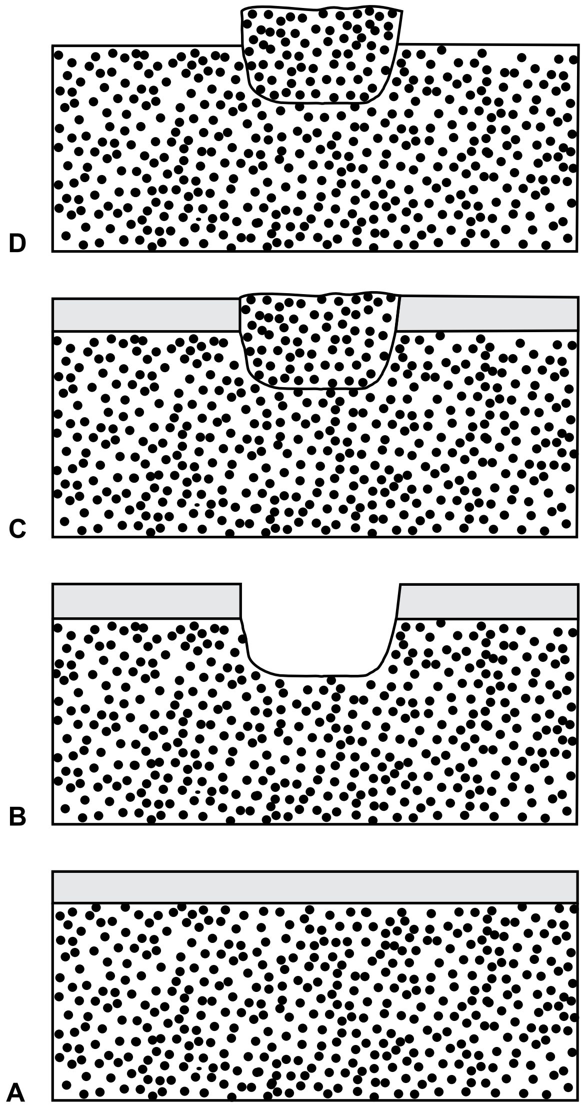

Fig. 5. Model illustrating preservation of a convex epirelief of *Eubrontes* cf. *giganteus* (Hitchcock, 1836) at the top of a sandstone bed of the Thaiat ridge section

Gierliński and Niedźwiedzki (2002), are also classed as *Grallator* by Lockley (2011). The ichnogenus *Grallator* is connected with a variety of bipedal theropod dinosaurs. The oldest *Grallator*-like footprints have been found in formations dating from the late Middle Triassic, but are most abundant in the Late Triassic and Early Jurassic formations of the northern Pangaea.

Eubrontes cf. *giganteus* (Hitchcock, 1836) – Fig. 4

Description. – Large (*c.* 35 cm long), broad, functionally tridactyl footprint. Toes thick, sharply terminated, digit III relatively short. Projection of digits II and IV along the axis of digit III about equal. Divarication angle of digits II – IV = *c.* 40 degrees (for systematic discussion and comparison to type specimen see Olsen *et al.*, 1998). Preserved as a convex epirelief (epi-, hyporelief nomenclature after Seilacher, 1964) on top of a sandstone bed (the epirelief is 2–3 cm higher than the sandstone bed).

Discussion. – The typical *Eubrontes* print is 30–40 cm long, with three toes that terminate in sharp claws. It belongs to a biped that must have been over one metre high at the hip and 5–6 metres long. Vertebrate footprints are usually preserved as depressions on the surface of sedimentary beds (concave epirelief) or as convex casts on undersurfaces (convex hyporelief). Thus, the preservation of the *Eubrontes* cf. *giganteus* footprint from the Thaiat ridge as a convex epirelief on the top of a sandstone bed is peculiar, although has been noted in the literature before (Huerta *et al.*, 2012). The formation of the footprint from Thaiat ridge can be explained in the following way (Fig. 5):

1. The dinosaur stepped on a thin cohesive mud layer, its foot sinking to the top part of an underlying sand layer, producing a negative relief.
2. The mud was squeezed out sidewise so that the surface of the sand layer formed the base of a depression, its walls consisting in its upper part by cohesive mud, thus voids are left in the cohesive mud.
3. Subsequently sand similar in texture and composition to the underlying sand layer filled the depression.
4. Diagenesis turned the sand into sandstone and the mud layer into mudstone.
5. Present-day erosion and weathering exposed the footprint cast by removing the softer mudstone around the sandstone infilling the footprint.

CONCLUSIONS

The trace fossils described herein are the first known dinosaur footprints in the Jurassic strata of the Jaisalmer Basin, India, further proving the presence of dinosaurs in this region during Jurassic times, following reports on the presence of dinosaur bone fragments (Mathur *et al.*, 1985). These finds add new evidence to the global distribution of dinosaurs during Early Jurassic times. The larger *Eubrontes* cf. *giganteus* footprint shows an unusual state of preservation as a positive epirelief. Some features of the *Grallator tenuis* footprint (wide divarication angle of digits, very narrow toes with long claws and very small size), all bearing strong similarities to the Early Jurassic ichnogenus of *Stenonyx* Hitchcock (1865), would support an Early Jurassic age of the strata in the lower part of the Thaiat ridge section. However, this may just be variation – perhaps a taxonomic variation – between *Grallator* tracemakers from North America and India rather than variation due to the geological age. The section shows a continental (fluvial) environment, passing upwards into marginal-marine (tidal flat) and near-shore-marine environments. Geochemical indices point to a seasonal climate in the lowermost part of the section, becoming slightly more humid upwards and again seasonal in the higher part of the section. A major bounding surface between the fluvial and marginal-marine part of the section was identified as a transgressive/flooding surface. Dinosaur footprints were found in the marginal-marine (tidal, foreshore) part of the section, in the interval showing a seasonal climate.

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