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Dinosaur and crocodylomorph footprints from the Hojedk Formation (Bajocian, Middle Jurassic) of north Kerman, Central Iran

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ABSTRACT

Dinosaur and crocodylomorph tracks are reported from a new Middle Jurassic tracksite in Central Iran. Crocodylomorphs are represented by a single, well-preserved trackway referred to as *Crocodylopodus* isp., whereas dinosaur tracks belong to two different types referred to as *Wildeichnus* isp. and cf. *Anchisauripus*. This is the first report of crocodilian tracks from the Middle East, and one of the few from Asia. Furthermore, the presence of *Wildeichnus* in the Middle Jurassic of Iran is interesting because this ichnogenus has previously been reported from localities of roughly the same age in North and South America, as well as Europe and Northern Africa, and may thus be of global significance.

KEY WORDS: *Dinosaur tracks, Crocodylomorph tracks, Ichnology, Middle Jurassic, Central Iran.*

INTRODUCTION

The coal-bearing Shemshak Group (FÜRSICH *et alii*, 2009; formerly Shemshak Formation, Carnian-Bajocian) was deposited in a foreland basin that developed in the Alborz Mountains and Central Iran during the early to middle Cimmerian orogeny (AGANABATI, 1998). The sediments of this lithostratigraphic unit were deposited in fluvio-deltaic and marginal marine settings (FÜRSICH *et alii*, 2009). All dinosaur footprints known from Iran have been found in deposits belonging to the Shemshak Group, namely in two distinct areas: the Alborz Mountains and the southeast Central Iran zone (Kerman area) (fig. 1). The history of paleoichnological research in this region of the Middle East has been very discontinuous and only recently has the area come into the focus of a renewed interest for its ichnological record. The first discoveries of dinosaur footprints in Iran were reported in the 1970s. LAPPARENT & DAVOUDZADEH (1972) described two track-bearing levels from the Neyzar Valley (Kerman), and LAPPARENT & NOWGOL SADAT (1975) reported a single dinosaur footprint from the Alborz Mountains. For more than 25 years, these two papers have been the only available literature on dinosaur tracks from Iran. Then, a joint Iranian-Brazilian-Italian expedition in 2002 led to the discovery of a third track-bearing level close to the historical site of LAPPARENT & DAVOUDZADEH (1972) and to the finding of a single theropod tooth from the Upper Jurassic/Lower Cretaceous Ravar Formation, still the only known dinosaur body fossil from Iran (KELLNER *et alii*, 2003; MIRZAIE ATAABADI *et alii*, 2005). Recently, all known dinosaur material from Iran has been revised in a comprehensive paper by KELLNER *et alii* (2012), who underlined the great potential for further discoveries in this vast country. In recent years, new dinosaur tracksites have been reported (ABBASSI, 2006; ABBASSI & MADANIPOUR, 2012; ABBASSI & MADANIPOUR, 2014), leading to a significant increase of the existing database. These new discoveries include such important new data as the first report of Middle Jurassic tracks from Northern Iran (Alborz Mountains), including sauropod tracks (ABBASSI & MADANIPOUR, 2014), all previously known material being attributable to Lower Jurassic theropods. In this paper, we report on the first find of Middle Jurassic tracks in Central Iran (Kerman area), including both dinosaur (theropod) and crocodylomorph tracks. The latter represent the first report of non-dinosaurian vertebrate tracks in the Mesozoic of Iran.

GEOLOGICAL SETTING

The stratigraphic position of the Triassic-Jurassic deposits in the Alborz Mountains and Central Iran has recently been revised and the Shemshak Formation was upgraded to a group (AGHANABATI, 1998, 2004; FÜRSICH *et alii*, 2009; WILMSEN *et alii*, 2009). This Shemshak Group contains several formations in the Alborz Mountains as well as in the Tabas and Kerman areas in east Central Iran (AGHANABATI, 1998; FÜRSICH *et alii*, 2009). Sediments of the Shemshak Group include alternations of dark shale, siltstone, sandstone and coal layers. In the Kerman area, the Shemshak Group is divided into the Nayband (Late Carnian-Rhaetian), Ab-e-Haji (Hettangian-Pliensbachian), Badamu (Toarcian-Bajocian) and Hojedk (Bajocian) formations (fig. 2). In this new lithostratigraphic scheme, the dinosaur tracksites in the Neyzar Valley (LAPPARENT & DAVOUDZADEH, 1972) belong to the Ab-e-Haji Formation (KELLNER *et alii*, 2012), which includes quartzitic sandstones and shales with intercalations of calcareous sandstones. Provenance of sandstones from this formation in the Tabas area (north Kerman) emphasize source from plutonic, metamorphic and quartzose sedimentary rocks of the adjacent Yazd and Shotori

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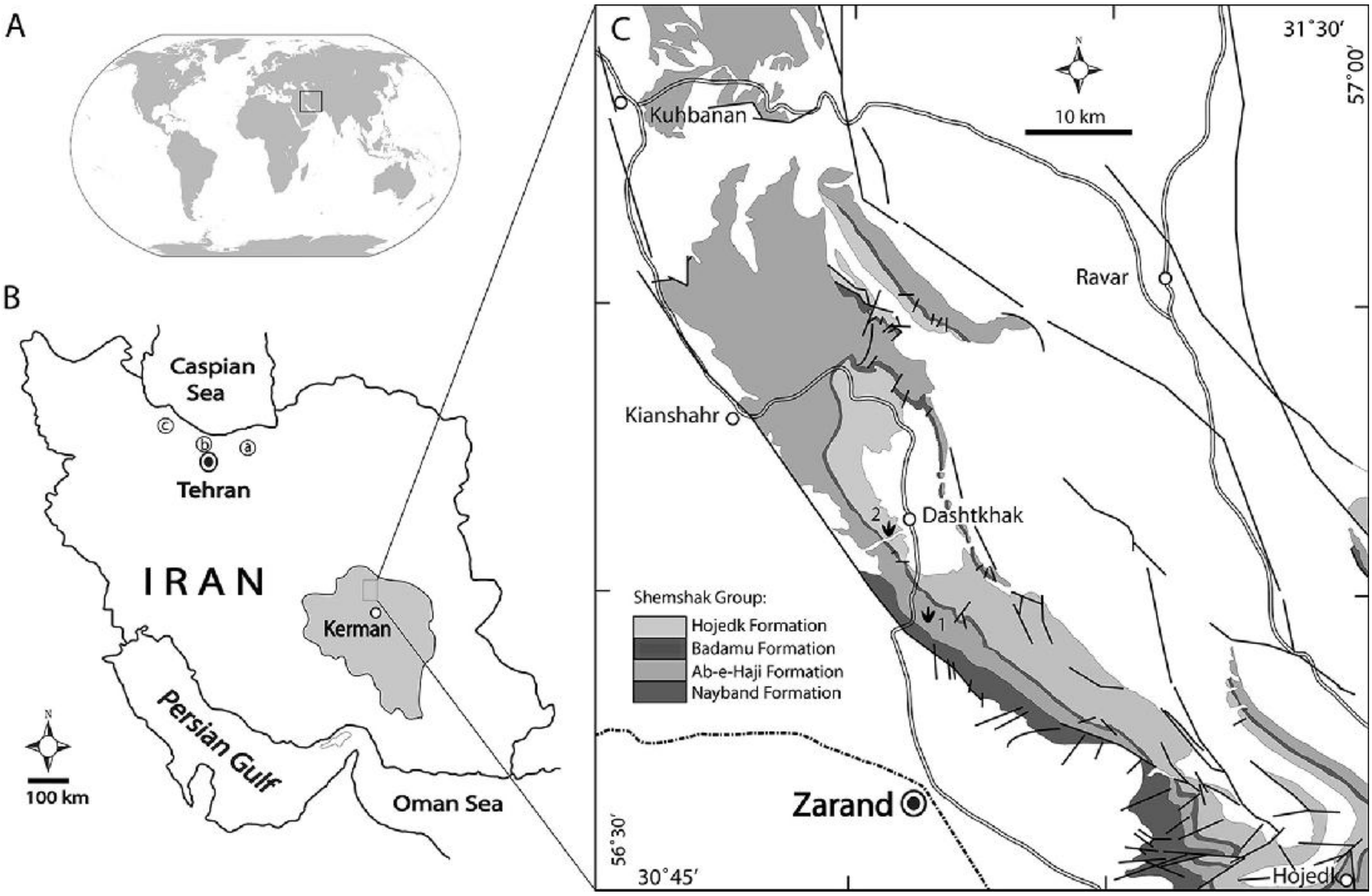

Fig. 1 - A) location of Iran in the world map; *B*) location of Zarand area in the north Kerman province and reported dinosaur footprints sites from Alborz Mountains in the north Iran, including Zirab (*a*: LAPPARENT & NOWGOL SADAT, 1975), Baladeh (*b*: ABBASSI & MADANIPOUR, 2014) and Harzvil (*c*: ABBASSI, 2006); *C*) Shemshak Group outcrops in the Zarand area, north Kerman with dinosaur footprints of Ab-e-Haji Formation in the Neyzar valley, north Kerman (1, LAPPARENT & DAVOUDZADEH, 1972) and Hojedk Formation in the southwest Dashtkhak village, north Kerman (2, this report).

blocks (SALEHI *et alii,* 2014). The overlying Badamu Formation is made up essentially of fossil-bearing oolitic limestones with a few sandstone layers. Its ammonite assemblage has been attributed to the Toarcian-Bajocian (SEYED-EMAMI, 1967). An extensive and thick sequence of coal-bearing terrigenous sediments overlies the marine Badamu Formation, known as Hojedk Formation and dated to the Bajocian (WILMSEN *et alii*, 2009; SEYED-EMAMI *et alii*, 2004). This formation represents the uppermost unit of the Shemshak Group in Central Iran. The Hojedk Formation is formed mainly by an alternation of sandstones and sandy to argillaceous shales with dull green-grey to brown-green colours. Reworked shale particles are found in the sandstone layers and intercalations of coal and carbonaceous shale occur at the base of the formation (STÖCKLIN & SETUDEHNIA, 1991). The Hojedk Formation is overlain by the basal conglomerate of the Bidu Formation (Bathonian-Callovian; SEYED-EMAMI, 1999) (fig. 2). The sediments of the Hojedk Formation are considered to have accumulated in a fault-controlled, river-dominated delta and in meandering river systems (LASEMI & KHERADMAND, 1999).

Geologists of the Geology Management and Mining Exploration of South East Iran (GMMESEI) in Kerman recently found a dislocated fine-grained sandstone slab that contains numerous vertebrate tracks on both its upper and its lower bedding planes. The slab was collected in 1976 by a local villager from an outcrop in the Hojedk Formation, about 5 km southwest of the village of Dashtkhak (95 km north Kerman, fig. 1). This slab is the subject of this paper.

MATERIAL AND METHODS

The Dashtkhak sandstone slab (95×58 cm) displays tracks on both bedding planes. Twenty-five convex hyporelief imprints ("natural casts") are preserved on the lower bedding plane and three concave epirelief footprints are preserved on the upper bedding plane (fig. 3 and fig. 4). The slab has been consigned to the GMMESEI office in Kerman without coding number; a plaster cast of the whole lower surface of the slab was deposited in the geological museum of the University of Zanjan under the repository code GMZU-09-38.

The footprints on the lower bedding plane of the slab are arranged in seven track lines (trackways *a-g* in fig. 3B), while the three isolated footprints visible among ripple marks on the upper bedding plane are considered as belonging to as many trackways (trackways *h-j* in fig. 4), although two of them are aligned. Measurements of these footprints were obtained using standard methods (THUL-

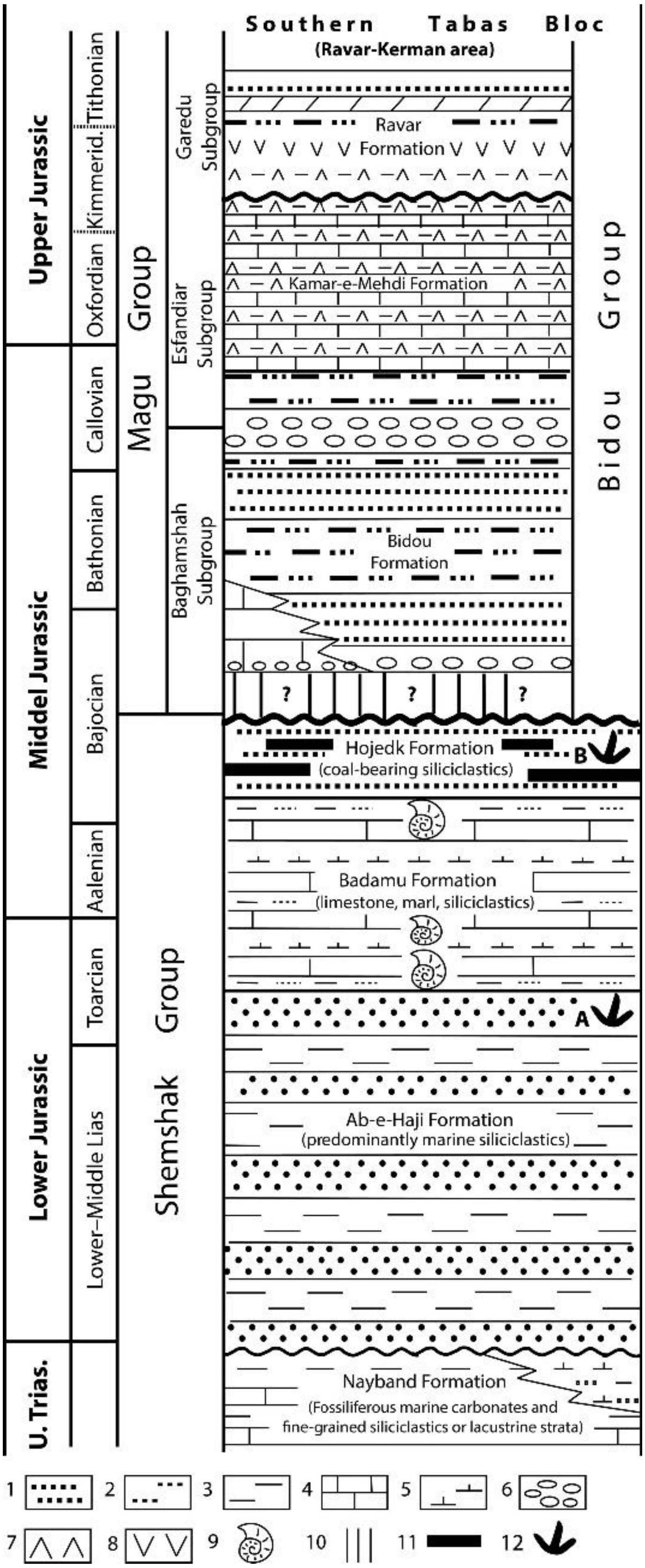

Fig. 2 - Jurassic lithostratigraphy units of the southern Tabas block, north Kerman (modified from WILMSEN *et alii*, 2009) showing position of the vertebrate footprints: 1) sandstone; 2) siltstone; 3) clay; 4) limestone; 5) marl; 6) conglomerate; 7) gypsum; 8) volcanic, 9) ammonite data; 10) hiatus; 11) coal; 12) vertebrate footprints: *A*) dinosaur tracks (LAPPARENT & DAVOUDZADEH, 1972; KELLNER *et alii*, 2012); *B*) dinosaur and crocodylomorph tracks (this report).

BORN, 1990; LOCKLEY, 1991), which include footprint length (FL), footprint width (FW), digital length (DL), interdigital angles (IA), pace (P), pace angulations (PA), stride (S), and trackway width (TW).

DESCRIPTION OF THE TRACKS

The fossil tracks preserved on the Dashtkhak slab are different in size, digit divarication, number of digits in the *pes* and presence/absence of a *manus* track. Two distinct morphological patterns are clearly identifiable: a single trackway of a tiny quadruped accompanied by a clear tail drag mark and a group of bipedal tridactyl footprints, which can be further differentiated (see below). In the following we will refer to this material informally as "type 1" (quadrupedal trackway), and as "type 2" and "type 3" (tridactyl footprints). Tabs. 1 and 2 summarize the average linear and angular data of these footprints.

QUADRUPEDAL FOOTPRINTS

"Type 1" tracks are represented by a single trackway (trackway *a* in fig. 3B) made up of eight consecutive tiny footprints (average FL = 4.6 cm) coupled with *manus* impressions that are just over half that size (average ML = 2.7 cm) (fig. 5). The quality of preservation of the tracks is suboptimal, as the sediment was probably very wet at the time of indentation. The seventh footprint of "Type 1" is partly obscured by a larger tridactyl track, but its position is still recognizable between the digits of this trace. The upper portion of the trackway (footprints 5 to 8) is better preserved than the lower one. No skin impressions have been noticed on the footprints, and this might be in favour of interpreting them as under-prints. This standing, many features are clearly discernible, allowing a detailed description of the shape of the traces. The *pes* is tetradactyl, with digits II, III and IV being almost equal in length (digit III is only slightly longer than II and IV), digit I is the shortest, but still functional. The posterior margin of the foot mark is randomly preserved, and, when present, it appears as a rounded heel, more or less on the same axis of digit IV, from which it is separated by a gap. Digit divarication in the *pes* decreases from the inner digits to the outer ones, so that the angle between digits I and II is the highest, whereas digit divarication in the *manus* is higher between digits III and IV. The trackway is fairly wide (TW about 3FW). There is an almost continuous, sinuous tail drag impression along the midline of the trackway. The width of this impression varies from 0.3 to 0.8 cm. The average *pes* pace angulation is 108° (see tab. 1 for details). *Pes* rotation as measured from the axis of digit III with respect to the midline of the trackway is almost zero, but *manus* imprints show outward rotation (or negative rotation) up to 26° (hand-print *6a*). However, hand rotation is difficult to assess due to the overall poor preservation of the digits. The *manus* shows a tetradactyl pattern (I-IV) with group I-IV directed anteriorly. The presence of a fifth digit cannot be ascertained with confidence. The *manus* trace lies relatively close to the tip of the *pes*, but *manus* and *pedes* traces never overlap, remaining clearly separated by a gap along the entire sequence. The position of the *manus* is usually internal to the lateral border of the *pes* trace. The average

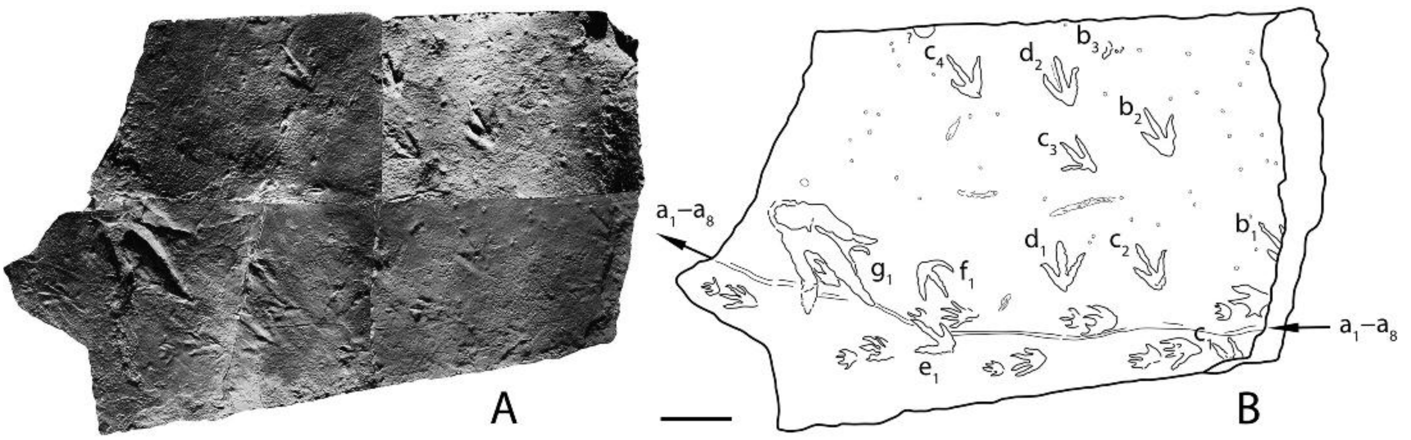

Fig. 3 - Photograph (*A*) and sketch (*B)* of the lower bedding plane of the Dashtkhak slab, with trackways *a-g*, preserved as convex hyporeliefs. Scale bar is 10 cm.

pace angulation for the *manus* is 110° (see tab. 1 for details). Fig. 5 shows a composite photograph of the trackway and an interpretive sketch.

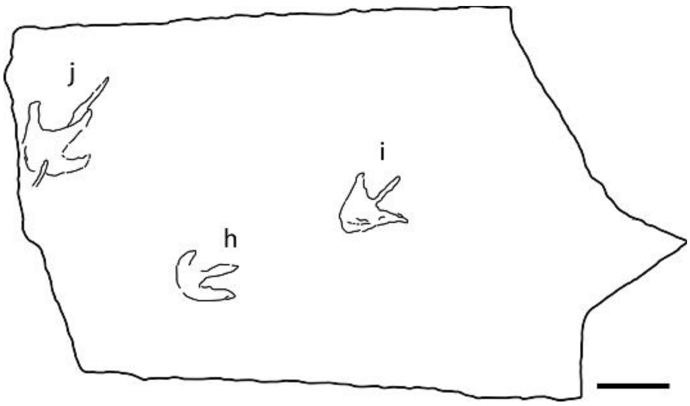

Fig. 4 - Footprints from the upper bedding plane of the studied slab, preserved as concave epireliefs. Scale bar is 10 cm.

BIPEDAL FOOTPRINTS

Two morphotypes of bipedal footprints are distinguished. They are provisionally referred to as "type 2" and "type 3" tracks, as opposed to the quadrupedal "type 1" trackway.

"Type 2" tracks include trackways *b*, *c*, *d*, *e* and probably *f*, altogether 8 complete footprints (fig. 3B). They are tridactyl, with slender digits, sometimes ending in sharp points (fig. 6). The average *pes* length is just over 7 cm, the *pes* width averages 5.5 cm. Individual pads can be identified, but are not very clear, so that it is difficult to assess the phalangeal formula. Total divarication angle is around 60°. Where more than one footprint is preserved (trackways *b*, *c* and *d*), the trackway appears to be narrow, with a long step. Digit slenderness varies depending on the footprint, and also on different portions of the same footprint. It appears that the central digit (digit III) is usually the most slender, whereas the lateral ones might be stouter. In most cases the proximal region of the digit prints is far more marked into the sediment than the distal one. This standing, taphonomy seems not to affect the relative length of the digits to any extent. The traces display a rather short protrusion of the third digit over the lateral ones, while digits II and IV are almost equal in length and have a tendency to converge strongly posteriorly, giving an overall "arrowhead-shape" to the footprint. The mark of digit II is sometimes isolated by a gap from digits III and IV, which are always joined. The overall shape is highly symmetrical, as the divarication angles II-III and III-IV are nearly equal.

A single, isolated footprint on the lower surface is here interpreted as a different morphotype (Type 3; fig. 7). This track is characterized as follows: tridactyl, footprint length 20.5 cm, footprint width 10.3 cm, total divarication angle 33°, pads well developed, slender digits ending in sharply pointed claw marks.

A few tracks are difficult to assign to any of these three morphotypes. The three tridactyl footprints on the

TABLE 1

Measurement data of the Dashtkhak crocodylomorph footprints ("Type 1"); abbreviations: BP) bedding plane; DL) digit length; F) frequency; FL) footprint length; FT) footprint type; FW) footprint width; IA) interdigital angle; LBP) lower bedding plane; m) *manus*; P) pace; PA) pace angulation; p, *pes*; S) stride; TN) trackway number; TW) Trackway width. Data in millimeters.

BP	FT	TN	F		FW		FL		DL								IA						P		S		PA	TW
									I		II		III		IV		I–II		II–III		III–IV							
LBP	Type 1	a	p	m	p	m	p	m	p	m	p	m	p	m	p	m	p	m	p	m	p	m	p	m	p	m	108	96
			8	8	36	24	48	23	14	9	24	11	28	12	19	10	25	21	20	21	18	28	121	121	232	232		

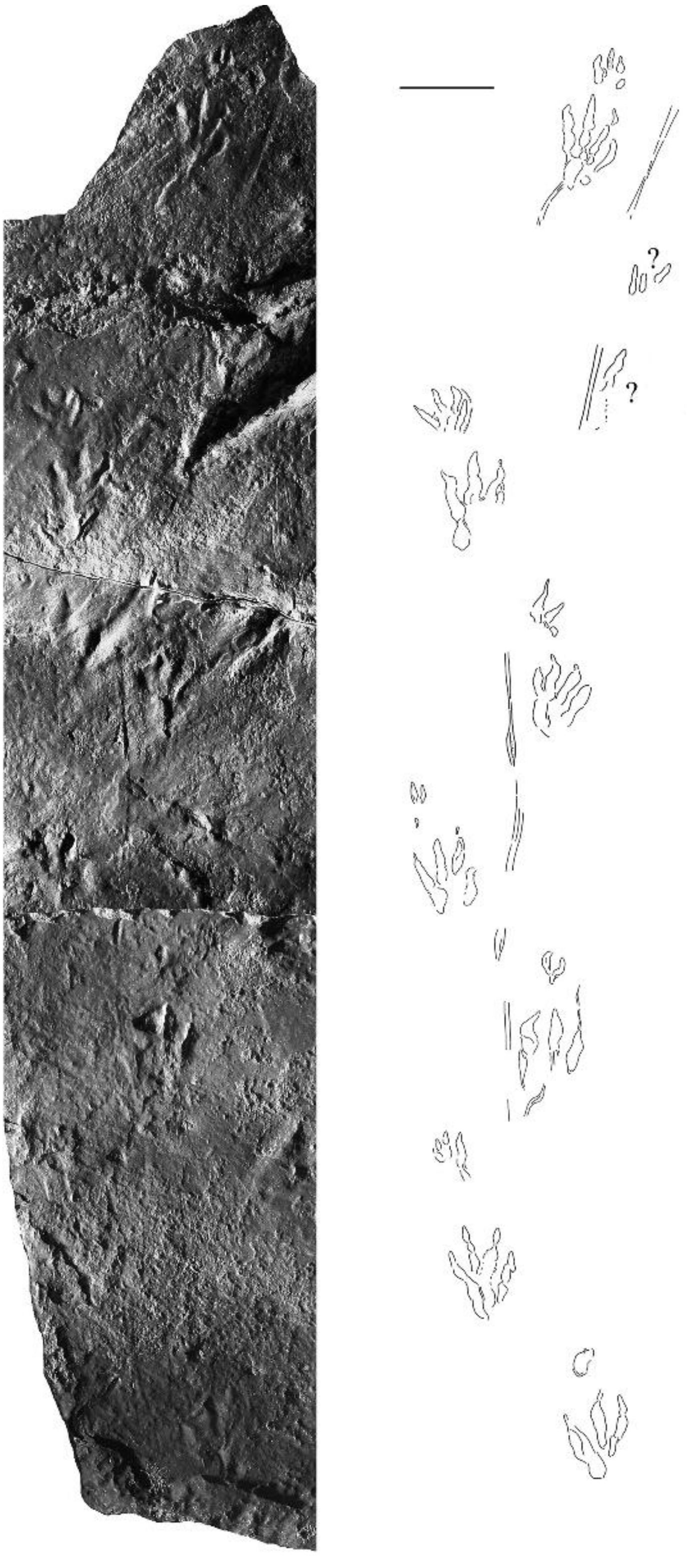

Fig. 5 - Photograph and sketch of the crocodylomorph trackway "Type 1", showing *manus* and *pes* prints and the tail drag mark. Scale bar is 5 cm.

upper bedding plane of the slab (trackways *h-j* in fig. 4) are less well preserved than the natural casts on the lower surface, but given their size they may belong to type 3. On the lower bedding plane, footprint *f1* differs from the other tracks assigned to type 2 in being shorter (FL about 5.5 cm instead of 7), all other parameters being equal. We consider its relative shortness to be an artifact due to its unclear posterior limit, which makes the assessment of FL difficult. Therefore, we assign *f1* to type 2.

TABLE 2

Measurement data of dinosaur footprints of Dashtkhak specimen "Type 2" and "Type 3"; abbreviations: BP) bedding plane; DL) digit length; F) frequency; FL) footprint length; FT) footprint type; FW) footprint width; IA) interdigital angle; LBP) lower bedding plane; P) pace; S) stride; TN) trackway number; TW) trackway width; UBP) upper bedding plane. Data in millimeter.

BP	FT	TN	F	FW	FL	DL			IA		P	S	TW
						II	III	IV	II–III	III–IV			
LBP	Type 2	b	2	49	76	35	48	32	37	25	230	---	70
		c	4	56	71	34	43	28	40	24	188	367	75
		d	2	60	74	39	52	31	30	29	260	---	95
		e	1	55	75	34	51	20	40	27	---	---	---
		f	1	56	53	44	40	25	27	18	---	---	---
	Type 3	g	1	103	204	70	130	63	13	20	---	---	---
UBP	? Type 2	h	1	85	88	25	65	50	40	20	---	---	---
		i	1	98	110	35	52	45	30	60			
		j	1	115	120	40	70	45	40	30	---	---	---

DISCUSSION

"Type 1" tracks, represented by the single trackway *a*, clearly belong to a small, quadrupedal animal. From an ichnotaxonomic point of view, the set of characters that have been observed in this material allows to assign it to the ichnofamily Batrachopodidae (LULL, 1904). Albeit as a general rule there is no straightforward relationship between ichnotaxa and trackmakers, the biological significance of these ichnites relies on their well-established zoological attribution to the Crocodylomorpha. Identification of a lower ichnotaxonomic level within the Batrachopodidae might be a difficult task. A first differentiation should concern those ichnotaxa that represent the tracks of walking animals and those representing a buoyant trackmaker (swim tracks). We will focus on the former, as the studied trackway is clearly a walking trace. Among known ichnotaxa, the "type 1" material might be compared to *Batrachopus* from the Lower Jurassic of North America (HITCHCOCK, 1845, 1858; OLSEN & PADIAN, 1986; LOCKLEY *et alii*, 2004) and to *Crocodylopodus* from the Upper Jurassic and Lower Cretaceous of Spain (FUENTES VIDARTE & MEIJIDE CALVO, 1999; AVANZINI *et alii*, 2007; AVANZINI *et alii*, 2010). Classic *Batrachopus* (comparison has been made with the type specimen 26/5 in the Pratt Museum, Amherst College) has broader, "fleshier" digits and a higher degree of outward rotation in both *pes* and *manus* tracks than the Dashtkhak slab "type 1" trackway. Some degree of overlap (*pes* beyond the *manus*) is present in the type material

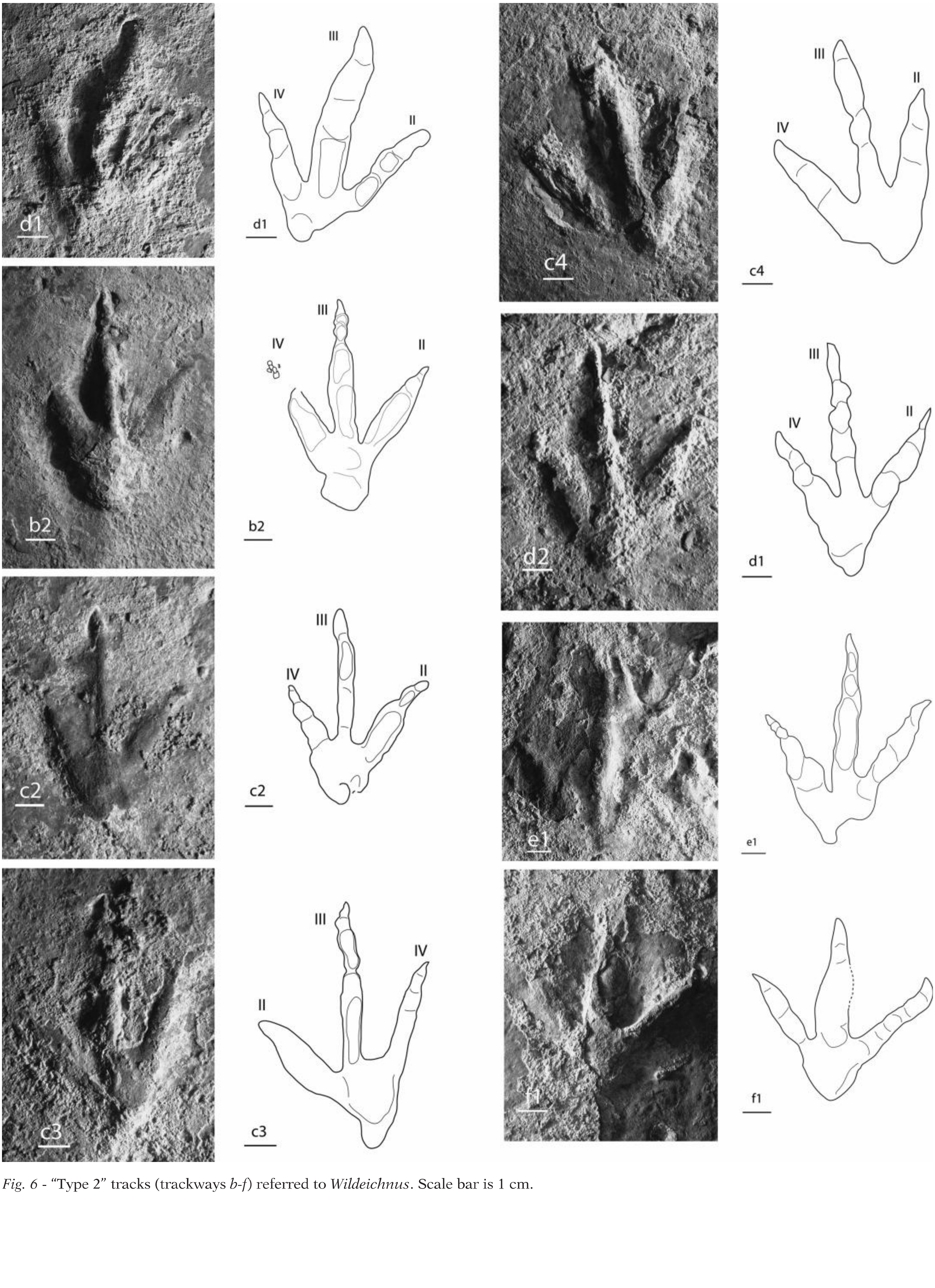

Fig. 6 - "Type 2" tracks (trackways *b-f*) referred to *Wildeichnus*. Scale bar is 1 cm.

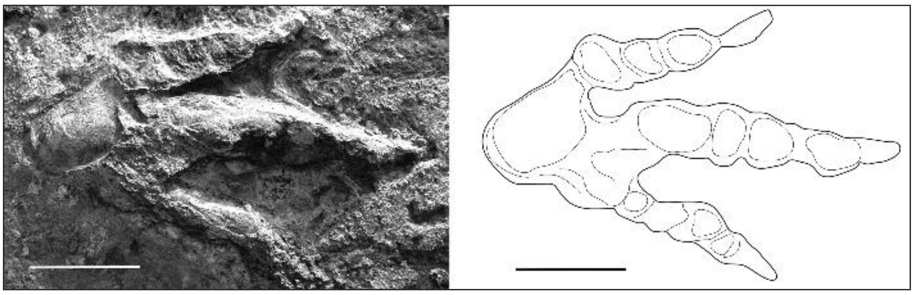

Fig. 7 - "Type 3" tracks (trackway g), cf. *Anchisauripus*. Scale bar is 5 cm.

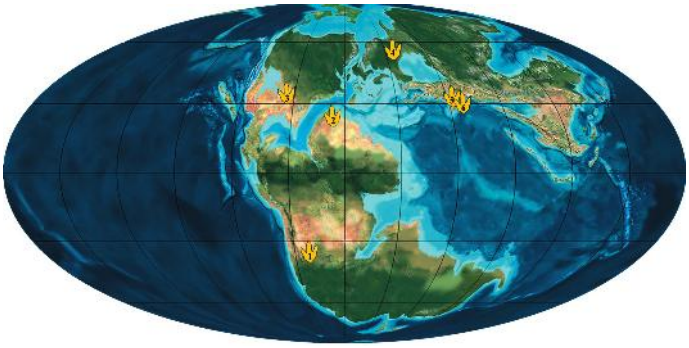

Fig. 8 - The Middle Jurassic paleogeographic distribution of *Wildeichnus*: 1) Argentina (Casamiquela, 1964; Leonardi, 1994); 2) United States (Lockley *et alii*, 2007); 3) Poland (Gierliński *et alii*, 2009b); 4) Morocco (Gierliński *et alii*, 2009a); 5) northern Iran (Abbassi & Madanipour, 2014); 6) Central Iran (this report). Word base map by R. Blakey (Colorado Plateau Geosystems, 4102 E Cortez St, Phoenix, Az 85028 http://cpgeosystems.com/paleomaps.html).

of *B. deweyi*, a feature not shared with the Iranian material. When "type 1" is compared to other material referred to *Batrachopus*, such as a set of Lower Jurassic crocodile tracks with slender digits from France (Demathieu & Sciau, 1995), the differences highlighted above appear to be less marked. Another formally named ichnogenus that is worth mentioning is *Antipus* (Hitchcock, 1858). Though included as a synonym of *Batrachopus* by Olsen & Padian (1986), this form has been re-considered as a distinct ichnogenus by Coombs (1996) and Lockley & Meyer (2004) on the basis of its slender digits and wider trackway. Notwithstanding the ichnotaxonomic status of the ichnogenus *Bratachopus* and its possible synomyms (i.e., *Antipus*) and the referred material from Europe (Demathieu & Sciau, 1995), all these forms share the character of a marked outward rotation of both *manus* and *pes* tracks. Lockley & Meyer (2004) consider this character as useful for distinguishing *Batrachopus* from *Crocodylopodus*, which has *pes* tracks nearly parallel to the trackway midline. The "type 1" trackway from Dashtkhak has a minimal outward rotation of the *pes*, which is in the range of *Crocodylopodus* but differs from *Batrachopus* and *Antipus*. The slender digits of "type 1" are also in agreement with *Crocodylopodus*. Thus, we refer the trackway to this ichnogenus. There is no similarity between this *Crocodylopodus* isp. from Iran and the few previously described crocodile tracks from Asia. The Chinese forms *Kuangyuanpus* and *Laiyangpus* both display short, near parallel digits and probably represent swim tracks with only the tip of the *pes* impressed (Lockley *et alii*, 2010a). Early Cretaceous crocodile trackways from Thailand described by Le Loeuff *et alii* (2010), have short blunt toes, a marked outward rotation and narrow trackway and thus bear a striking resemblance to *Batrachopus*, despite being much younger than other reported occurrences of this ichnotaxon.

"Type 2" and "Type 3" tracks clearly belong to bipedal dinosaurs. We assign both types to theropod trackmakers on the basis of their slender, sharply pointed digits, presence of a postero-medial indentation behind digit II, low digit divarication (type 3) and narrow trackway with long steps (type 2). Small Jurassic theropod tracks are most commonly referred to the ichnogenus *Grallator*. The use of this ichnotaxonomic label, however, should not be too liberal. Since its original description by Hitchcock (1858), about 20 ichnospecies have been assigned to *Grallator* and many more specimens have been reported as *Grallator* isp., often sharing nothing more than their small size. In revising the type material of *Grallator parallelus* Olsen *et alii* (1998) diagnose this ichnogenus as being less than 15 cm long, having a length/width ratio near 2, a high projection of digit III beyond the tips of digits II and IV and a total divarication between 10° and 30°. Comparison of the Dashtkhak slab "type 2" tracks with well-determined *Grallator* tracks from North America (Weems, 1992; Olsen *et alii*, 1998; Lockley *et alii*, 1998a; Milner *et alii*, 2006) shows significant differences. The Iranian tracks have less marked pads, are only slightly longer than wide, have a lesser projection of digit III and a considerably higher total divarication angle. Therefore, we regard them as distinct from *Grallator*. Some similarity is given with the ichnogenus *Toyamasauripus* from the Lower Cretaceous of Japan (Matsukawa *et alii*, 1997) that shares some characters with the Dashtkhak slab "Type 2" tracks, namely a comparable size, very slender digits with unclear digital pads and comparable projection of digit III. However, the total divarication angle is much higher than in the Dashtkhak material, averaging 90° with a range of 60°-135° (Matsukawa *et alii*, 1997). The highest similarity is given with the two ichnogenera *Wildeichnus* and *Carmelopodus*, and it may be no coincidence that both have a similar age in common with the Dashtkhak tracks. *Wildeichnus* was originally reported from the Middle Jurassic of Argentina (Casamiquela, 1964) and successively from the Middle Jurassic of North America (Lockley *et alii*, 2007) and Alborz Mountains, north Iran (Abbassi & Madanipour, 2014) (fig. 8), whereas *Carmelopodus* was described from the Middle Jurassic of North America (Lockley *et alii*, 1998b). Both share many characters with the "Type 2" tracks from Dashtkhak, namely a comparable size, total divarication angle around 60˚, digits with pads that are less evident than in typical *Grallator* specimens. *Carmelopodus* is characterized by a lack of the most proximal pad in digit IV, resulting in an almost symmetrical track that is nearly as wide as long (Lockley *et alii*, 1998b). We think that the "Type 2" tracks from the Dashtkhak slab are within the morphological range of *Wildeichnus* and refer them to this ichnogenus. The isolated footprint *g1* ("type 3") matches the diagnosis given by OLSEN *et alii* (1998) for the ichnogenus *Anchisauripus*, to which we tentatively refer the specimen.

CONCLUSIONS

The vertebrate tracks on the Dashtkhak slab are significant in that they are the first evidence of a Middle Jurassic tetrapod fauna in Central Iran. The presence of a crocodylomorph and two different theropod morphotypes, probably representing two different ichnotaxa and provisionally referred to *Wildeichnus* isp. and cf. *Anchisauripus*, is a relatively high diversity for such a small surface. The presence of *Wildeichnus* or a closely resembling form from the Hojedk Formation is interesting because this taxon has been reported from the Middle Jurassic of Argentina (CASAMIQUELA, 1964; LEONARDI, 1994), the United States (LOCKLEY *et alii*, 2007), Poland (GIERLIŃSKI *et alii*, 2009b), Morocco (GIERLIŃSKI *et alii*, 2009a) and northern Iran (ABBASSI & MADANIPOUR, 2014). This points to the possibility that small (5-10 cm) theropod tracks with slender digits and a divarication angle around 60° may be recurrent in the Middle Jurassic track record worldwide. Trackway *a* (*Crocodylopodus* isp.) represents another important specimen, as reports of crocodilian trackways from Asia are extremely rare. LOCKLEY *et alii* (2010b) cite only four known localities from the continent, two in China and two in Thailand. None of the specimens previously reported from Asia can be assigned to *Crocodylopodus*, which herein we report for the first time outside Europe.

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