GEOLOGICA CARPATHICA, APRIL 2014, 65, 2, 99–115 doi: 10.2478/geoca-2014-0007

Dinosaur tracks from the Jurassic Shemshak Group in the Central Alborz Mountains (Northern Iran)

NASROLLAH ABBASSI[1,✉] and SAEED MADANIPOUR[2]

[1]Department of Geology, Faculty of Sciences, University of Zanjan, Zanjan 45371–138791, Iran; ✉abbasi@znu.ac.ir
[2]Department of Geology, Faculty of Basic Sciences, Tarbiat Modares University, Jalal Ale Ahmad Highway, Tehran, Iran; madanipour.saeed@gmail.com

(Manuscript received October 3, 2013; accepted in revised form December 10, 2013)

Abstract: The Shemshak Group includes alternating layers of coal-bearing shale and siliciclastic sediments in the Baladeh area in the central Alborz Mountains of northern Iran. A diverse and abundant Jurassic dinosaur footprint assemblage is now recognized in the group, which is Toarcian to Bajocian in age in the northern Baladeh. This is the first report of a diverse dinosaur ichnoassemblage from Iran that includes the footprints of sauropods. These tracks can be assigned to three groups of trackmakers: theropods, ornithopods and sauropods. Those of theropods are typically tridactyl in shape, their trackways reflecting bipedal movement. Theropod footprints are very abundant in both northern and western Baladeh. The studied theropod tracks themselves are divided into three major dimensional groups. The medium sized footprints (footprint length, 11–15 cm) are abundant and have a stride length, digit and pace angles like the coelurosaurs footprints and trackway. Theropod footprints were identified as similar to *Schizograllator otariensis*, *Talmontopus tersi* and *Wildeichnus* isp. Ornithopod footprints are tridactyl with rounded and thick toes and belong to bipeds. Some didactyl imprints were also observed. Skin imprints were well preserved in these footprints. The ornithopod tracks resemble *Jiayinosorupus johnsoni*, as well as *Velociraptorichnus sichuanensis* for didactyl footprints. Sauropod footprints found in the western part of Baladeh are assigned here to *Eosauropus* isp., which are pentadactyl pes imprints of a quadruped. The assemblage from Iran resembles similar associations from eastern Asia.

Key words: Jurassic, Iran, Alborz Mountains, ichnology, Dinosaur.

Introduction

Three sites with dinosaur footprints have previously been reported from Iran, all of which belong to the Carnian–Bajocian Shemshak Group (Shemshak Formation of Lapparent & Davoudzadeh 1972). The first reported dinosaur footprint occurrence from the group is from the northern Kerman area of east central Iran (Lapparent & Davoudzadeh 1972; Fig. 1A). The 23 dinosaur footprints discovered in the uppermost layers of the Ab-e-Haji Formation (Kellner et al. 2012) are grouped into five size classes and were attributed to ornithopod and theropod (Coelurosaur) dinosaurs. The second occurrence of dinosaur footprints from Iran is a single tridactyl theropod footprint from the Zirab area in the central Alborz Mountains named *Iranosauripus zerabensis* (Lapparent & Nowgol Sadat 1975; Fig. 1A). Finally, theropod dinosaur footprints have also been described from the vicinity of Harzavil village, the Manjil area in the west Alborz Mountains (Abbassi 2006; Fig. 1A).

Here we present two new dinosaur track sites in Iran, both from the Shemshak Group. The first is located north of the town of Baladeh in the central Alborz Mountains region on the Royan road and is referred to herein as the Royan section (Fig. 1B, and C). The other occurrence was discovered west of Baladeh on the road to Yush and is here referred to as the Bol-Yasel section, after the neighbouring villages (Fig. 1C). Together, the sites preserve an abundant and diverse assemblage of dinosaur tracks, including the first evidence for sauropod dinosaurs in Iran.

Materials and methods

The geometry of the studied footprints was examind using the methods of Thulborn 1990. These dimensions are footprint length (FL), footprint width (FW), pace angulations (PA), stride (S), trackway width (TW) and digit length (DL). The shape of footprints and trackway patterns were mapped on the transparent papers. Some footprints were sampled; including six footprints of horizons 2–4 of the Royan section and two footprints of the uppermost layer of horizon 2 of the Bol-Yasel section. Four plaster casts prepared in the field from the well-preserved footprints of the Royan section include footprint numbers of f_{11-12} in horizon 4 and $5a_1$ from the horizon 5. These samples were deposited in the Geological Museum of the Department of Geology of the University of Zanjan, with code numbers GMZU09-40-49.

Geological setting

Upper Triassic sediments conformably underlay the Lower Jurassic deposits found in the Middle Iranian Plateau (MIP), which includes the Alborz Mountains, central Iran, and the Sanandaj-Sirjan zones (e.g. Assereto 1966; Stöcklin 1974). The Shemshak Group, first described by Assereto (1966) in his study of the Lazin pass area in the north-eastern part of Tehran City in the central Alborz Mountains, can be found as outcrops along the MIP from the north-western parts of the Alborz Mountains to east-central Iran. The Shemshak Group

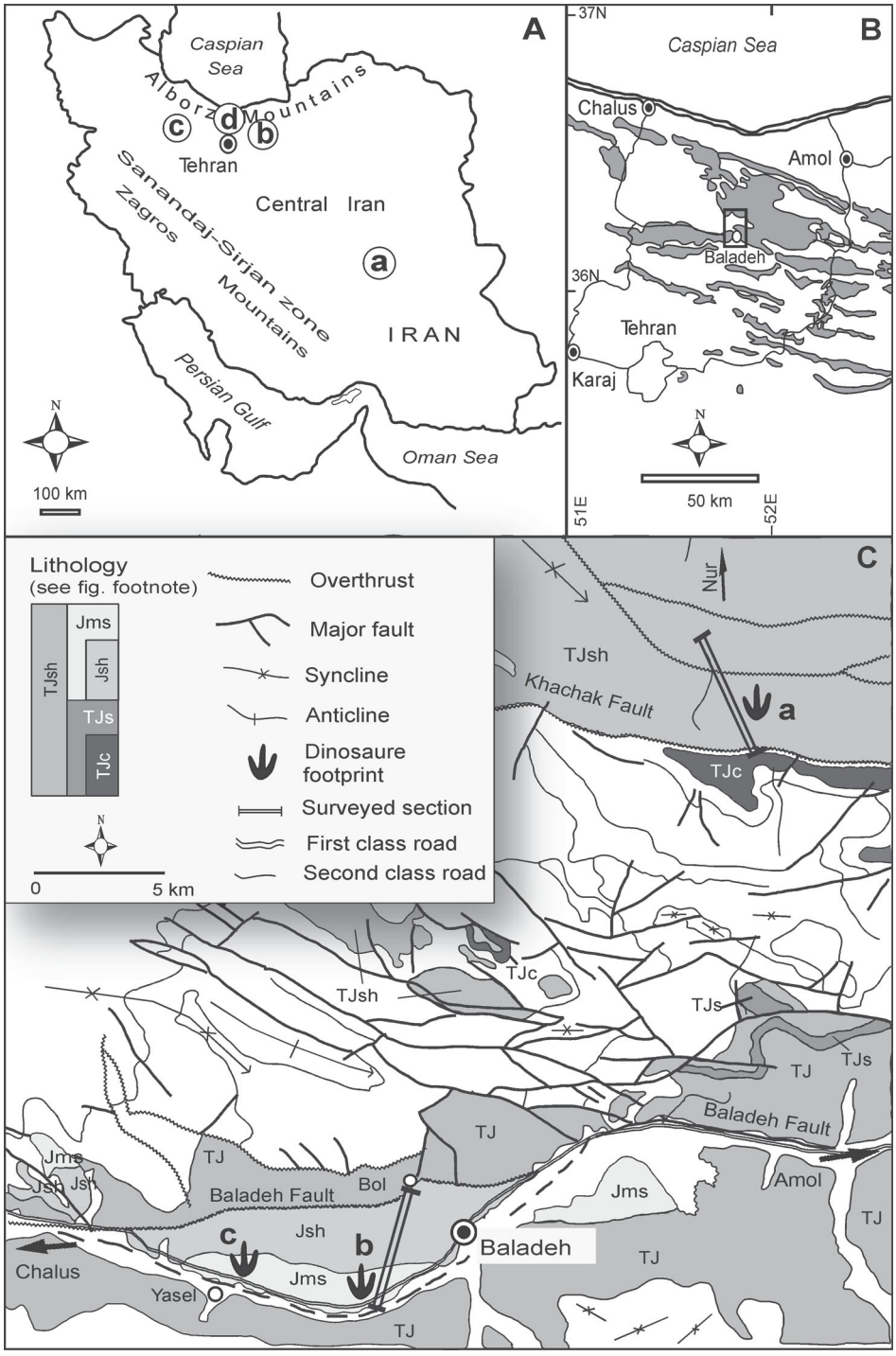


Fig. 1. Geological map and studied sections in Baladeh area, and location of previously reported dinosaur tracks from Iran. **A** — the location map of the Alborz Mountains in the northern part of Iran and previously reported dinosaur tracks from Iran; a — north Kerman, central Iran (Lapparent & Davoudzadeh 1972); b — Zirab area, Central Alborz Mountains (Lapparent & Nowgol Sadat 1975); c — Harzavil area, Manjil district, west Alborz Mountains (Abbassi 2006); d — Baladeh area, central Alborz Mountains (this report). **B** — the outcrop pattern of the Shemshak Group in the central Alborz Mountains and Baladeh region with the position of the study area (quadrangle) (modified after Fürsich et al. 2005). **C** — detail of study area and surveyed sections indicated by footprint icon; a — Royan section, which is accessible by the Baladeh–Nur road; b and c — Bol-Yasel section, accessible by Baladeh–Yush road (modified after Ghasemi & Saeedi 1993). **Abbreviations:** TJ — Shemshak Group (Late Triassic–Middle Jurassic); TJc — Massive-, thick-bedded conglomerate; TJs — Grey sandstone; Jms — Micaceous argilitic sandstone with coal steams; Jsh — Coal bearing shale.

is generally composed of alternating layers of varying thickness (1000–3000 m) of sandstones, siltstones, shales, claystones and coal seams and is Late Triassic to Middle Jurassic in age. The Shemshak Group contains some local formations in the Alborz Mountains or Tabas and Kerman areas in east-central Iran (Aghanabati 1998; Fürsich et al. 2009; Fig. 2).

The Shemshak Group has extensive fault-controlled outcrops in the Baladeh area and is mainly in contact with Upper Paleozoic units such as the Carboniferous Mobarak Formation or the Permian Dorud, Ruteh and Nasan formations (Fig. 1C).

The sedimentary basin of the coal-bearing Shemshak Group (Carnian–Bajocian) was formed in a foreland basin (e.g. Fürsich et al. 2005). The sedimentary environment was a peat bog with predominantly fluvial or deltaic conditions throughout (Wilmeson et al. 2009) but with deep marine conditions still existing in some locations. It was finally infilled with fluvio-deltaic sediments until the Mid Cimmerian orogenic event.

It was under these conditions that the Shemshak Group of Baladeh formed as a fault controlled basin. The Shirindasht Formation (Fig. 2) indicates a continental environment finally

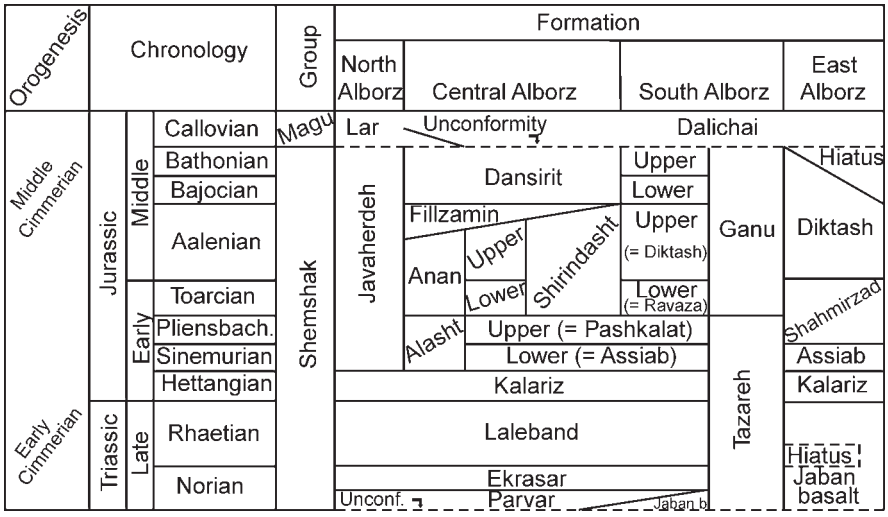


Fig. 2. Lithostratigraphic units of the Shemshak Group in the Alborz Mountains (modified after Aghanabati 1998, with slight changes).

accumulated by marine sediments the Fillzamin Formation in the western Baladeh. The Shemshak Basin returned to continental conditions by deposition of the sediments of the Dansirit Formation. The marine conditions of the Fillzamin Formation do not seem to extend to the hanging wall of the Baladeh thrust (Royan section). Since the dinosaur tracks of Baladeh were found in a fluvial-deltaic environment, they are scattered, and rare in the Shirindasht Formation. Nevertheless, abundant and diverse dinosaur tracks were found in the northern and western sections of the Dansirit Formation of Baladeh.

In the following two chapters, we will describe the geological characteristics of both the Royan and Bol-Yasel sections of the Shemshak Group.

Royan section

The Shemshak Group in the outcrop at kilometer 18 of the Baladeh–Nur Road is conformably reposed on the light grey limestone and yellow marl of the Elika Formation, which is Triassic in age. Dinosaur footprints were studied in sections of this outcrop from this locale to the first thrust fault 8.3 kilometers south of Loos village (point a in Fig. 1C). The coordinates of this section are 36°17′16″N–51°48′59″E to 36°10′41″N–51°45′17″E. At the site on the Baladeh–Nur Road, the Shemshak Group is 1655 m thick and consists of green and grey sandstones, grey shales, coal veins, and conglomerates (Fig. 3). Plant macrofossils in this section including two florizone assemblages indicate that the Royan section sediments are probably Early to Middle Jurassic in age (?Hettangian–Toarcian to Bajocian) (Vaez Javadi & Abbassi 2012).

The lower units of the Royan section (1110 m in thickness) are comparable to the Shirindasht Formation (Fürsich et al. 2009; Wilmsen et al. 2009), which is probably Toarcian–Aalenian in age based on its plant macrofossil assemblage. Beneath the sandstone cross-beds lies a basal conglomerate comprised of alternating layers of sandstone, shales, and darker, thickly-bedded shales-bearing plant fossils. These sediments correlate with the Dansirit Formation that is Aalenian–Bajocian in age. There is no evidence of the deep marine shales commonly found in the Fillzamin Formation between the Shirindasht and Dansirit Formations in the northern Baladeh area. The dinosaur footprints described below were found within five horizons of the Royan section of the Shemshak Group. Three horizons in the Shirindasht Formation yield single footprints, while two other horizons in the Dansirit Formation's basal layers contain dinosaur trackways (Fig. 3).

Bol-Yasel section

The lower faulted boundary of the Shemshak Group at this section (820 m in thickness), which is located west of Bol Village, is restricted to the Ruteh Formation (Upper Permian) (Fig. 1C). The coordinates of this section are 36°11′48″N–51°46′14″E to 36°10′53″N–51°46′52″E. The footwall splays of the Baladeh fault successively repeat the sediments of the Shemshak Group at this section. Sandstone and shale make up the lower parts of the Bol-Yasel section, while the top units are composed predominantly of thick-bedded sandstone layers containing plant fossils and coal veins (Fig. 4). The dinosaur tracks found in the upper layers of this section (b and c points in Fig. 1C) are common and comprise sauropod, ornithopod, and abundant theropod footprints. There are no biostratigraphic relevant plant fossils and other paleontological data for this section, but its lithofacies correlates with the Shirindasht (Pliensbachian–Aalenian), Fillzamin (Aalenian) and Dansirit (Aalenian–Bajocian) Formations (Fig. 4). No invertebrate body fossils were discovered in the Bol-Yasel section.

Dinosaur footprints

Royan section

Dinosaur footprints of the Royan section occur in five distinct horizons (Fig. 3). Here we give a description of footprints and footprint layers (see also Table 1).

Horizon 1 — The first horizon, between 710–720 m, is composed of green silty shale layers containing *Protovirgularia* isp., *Cochlichnus* isp. and plant fossils. Within this horizon, there is a poorly preserved, single tridactyl dinosaur footprint (Fig. 5A,B). It shows thin digits with irregular margins, rounded tips and wide divarication angles obviously due to the substrate conditions. The mean height measured at hip ($\bar{h}$) of the trackmaker is estimated at 72.2 cm according to the known methods of Avnimelech (1966), Alexander (1976), Lockley et al. (1983) and Thulborn (1990).

Horizon 2 — This horizon, located at 845 m, provided two dinosaur footprints of differing size (Fig. 5C,D). The first is a small, fully-preserved concave epirelief footprint that is

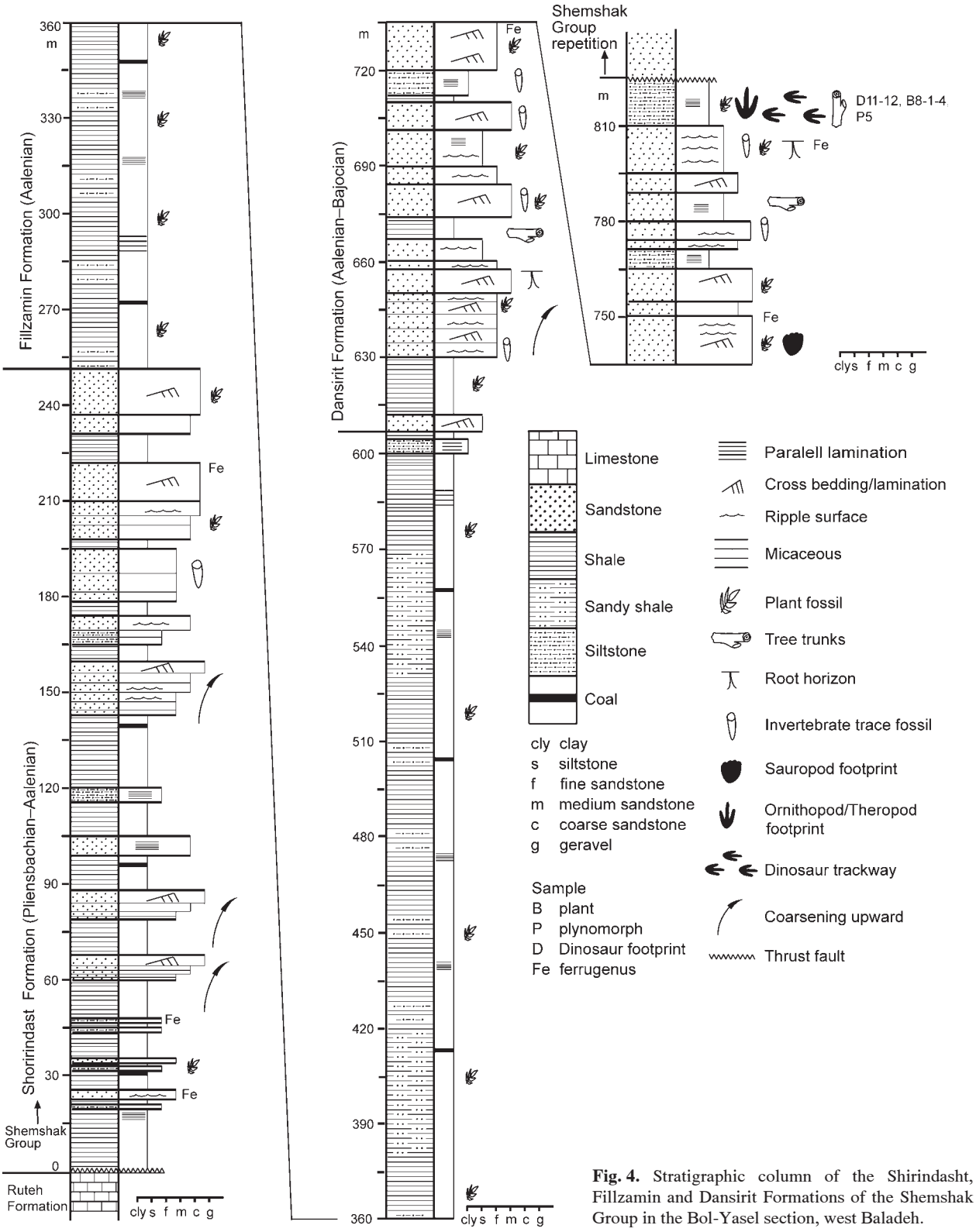


Fig. 4. Stratigraphic column of the Shirindasht, Fillzamin and Dansirit Formations of the Shemshak Group in the Bol-Yasel section, west Baladeh.

dactyl pes print preserved as a convex hyporelief and found on ripple-marked, grey shale containing plant fossils (Fig. 5E). Digits are more deeply impressed and broad, tapering at their distal ends and an elongated metapodium imprint. They show indistinct, rounded pad impressions and lack discernible claws. Although there are no manus imprints, this footprint is attributed to an ornithopod on the basis of the shape and size of digits and metapodium shape (Thulborn 1990 and Lockley 1991). The ratio of footprint width (FW) to length (FL) is 1.19. The estimated mean height from the base of the

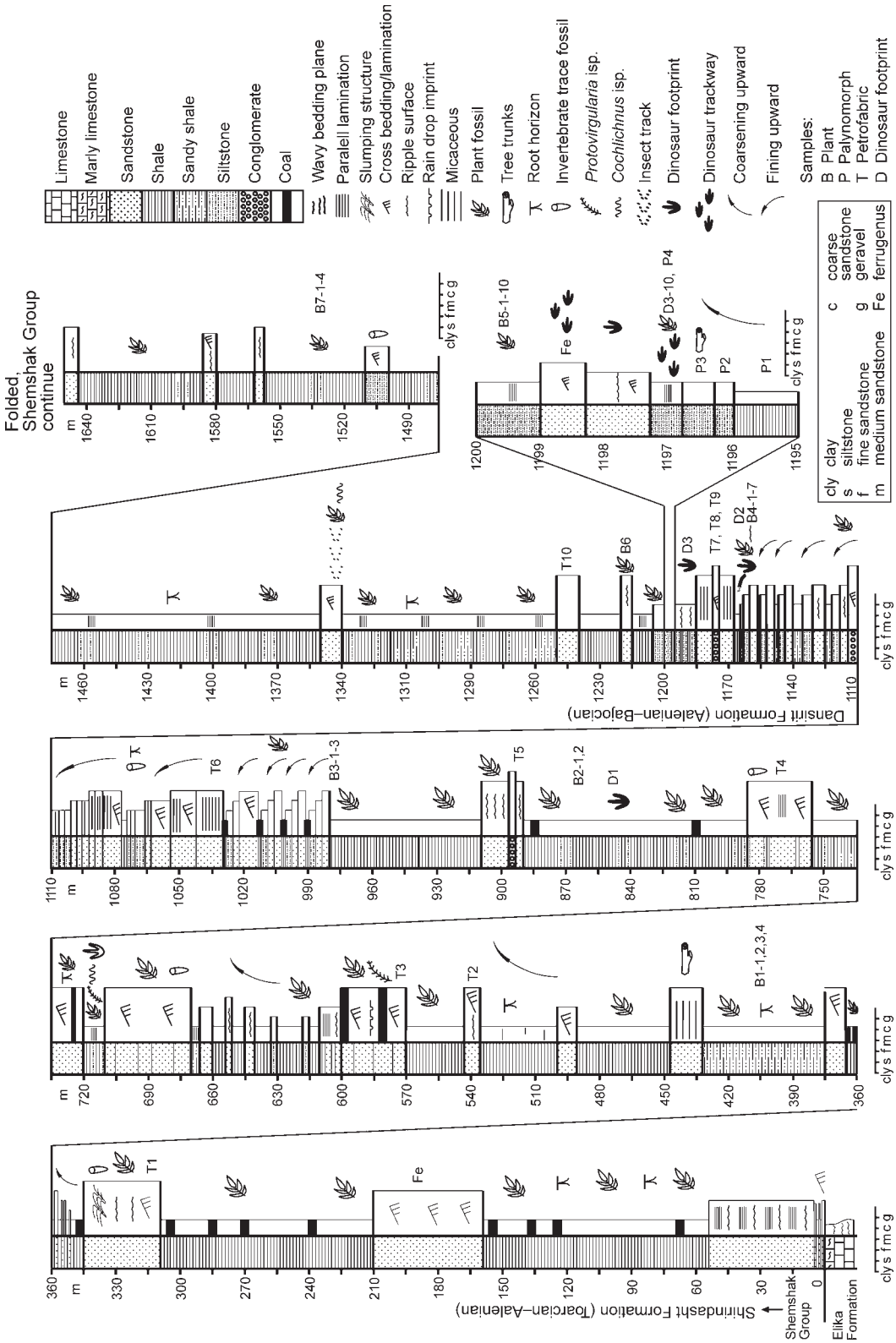


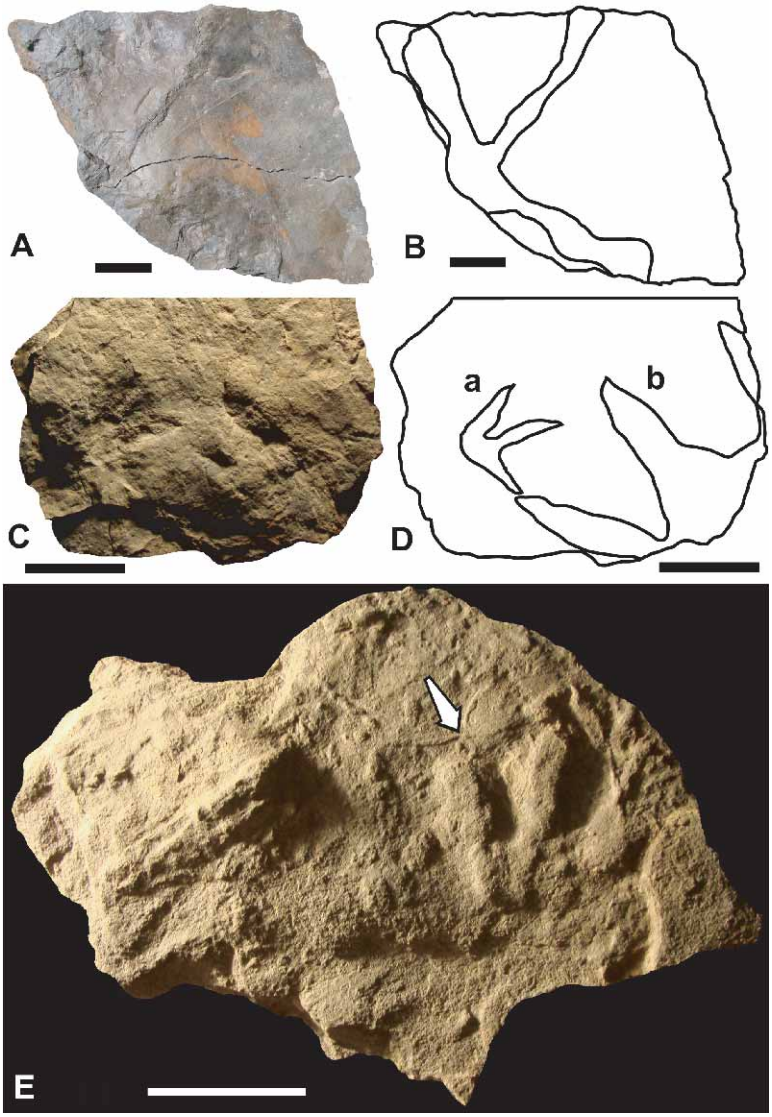
Fig. 3. Stratigraphic column of the Shirindasht and Dansirit Formations of the Shemshak Group, Royan section, north Baladeh.

symmetrical and tridactyl with pointed digits and a semicircular metapodium area (Fig. 5Da). The digits show longitudinal skin drag marks and no phalangeal pads. In contrast, only the digits are preserved in the large, incomplete footprint (Fig. 5Db). These show sharp pointed tips. The parameter of $\overline{h}$ in the small footprint of the second horizon is about 25.8 cm.

Horizon 3 — This horizon is located in the middle of the stratigraphic section (~1165 m) and belongs to the Dansirit Formation. The dinosaur footprint from this horizon is a tri-

Table 1: Geometry of measured dinosaur footprints of the Royan section. Dimensions are in cm and angles are in degrees. **Abbreviations:** F — frequency, FL — footprint length, FW — footprint width, P — pace, PA — pace angulations, S — stride, T — trackway, TW — trackway width.

Horizon	T	F	S	P	PA	TW	FL	FW	Interdigital angles	
									II-III	III-IV
1	a	1	–	–	–	–	16	20	64	70
2	a	1	–	–	–	–	6	6	53	43
	b	1	–	–	–	–	–	15	35	–
3	a	1	–	–	–	–	6.3	7.5	42	42
4	a_1	6	68.9	37.8	162	16.1	11.3	11.8	44	47
	a_2	2	–	35	–	27	12.7	10.6	33	33
	a_3	5	55.8	28.6	158	25	15	12.9	30	41
	a_4	2	–	46	–	25	13	11.2	55	28.5
	b_1	12	60.8	34.8	128	28	12.6	11.7	36	46
	b_2	2	–	39.5	–	–	11.5	12.2	45	49
	c	21	–	–	–	–	12	11.3	41	42
	d	1	–	–	–	–	10	12	60	75
	e	5	59.7	32	135	–	11.6	10.6	32	43
	f	12	57.5	32	125	25	13.3	11	43	44
	g	1	–	–	–	–	11.9	13	25	85
5	a	5	85	43	149	28	18	18	50	57
	b	1	–	–	–	–	20	19	56	62



hip is about 27 cm, indicating that it was likely made by a small ornithopod.

Horizon 4 — The fourth horizon contains more than 160 tridactyl dinosaur footprints preserved as concave epireliefs and found in medium-bedded, finely laminated, coarse-grained siltstone located in the Dansirit Formation at 1197 m (Fig. 6A). Unfortunately, the steep slope of the bed was destroyed by a large landslide in the spring of 2011 (Fig. 6B), forcing us to rely on the partial map and photographs provided in the summer of 2010 (Fig. 6C,D). Mapped trackways include 69 footprints of a_{1-4}, b_{1-4}, c, d, e, f, and g track lines (Figs. 6D, and 7). These footprints were traced as 16 trackways and have been classified into two major sets: (a) A group of tracks (a_{1-4} trackways in Fig. 6D) that show abundant, overlapping prints (c in Fig. 6D). There are also some trackways radiating from point c towards the south or north (b_{1-4} trackways in Fig. 6D). (b) The remaining trackways arranged in different directions (mainly east–west or north–south trending). These trackways are marked by the letters d to o in Fig. 6D. The footprints are similar in shape,

Fig. 5. Tridactyl theropod footprints from the Shirindasht Formation in the Royan section. **A** — large, convex hyporelief tridactyl footprint of horizon one with wide digit imprints; **B** — graphed footprint of Fig. 4A; **C** — large and small sized tridactyl footprints from horizon two, preserved as concave epirelief ; **D** — graphed footprint of Fig. 4C, that shows position of small (a) and large (b) footprints; **E** — tridactyl ornithopod footprints of horizon three in the Dansirit Formation, as convex hyporeliefs. Scale bar equals 5 cm.

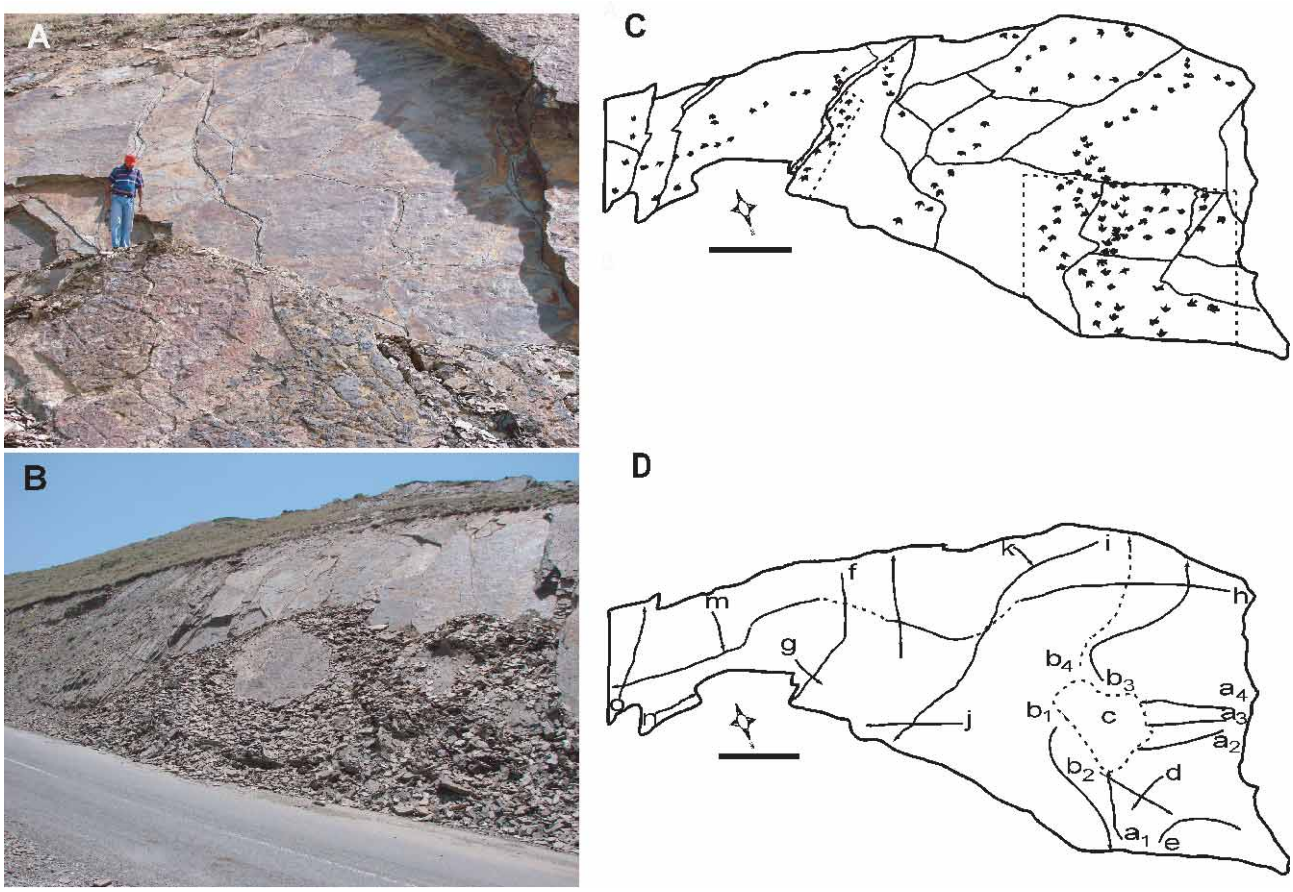


Fig. 6. Tridactyl bipedal theropod footprints from horizon four. **A** — outcrop of central and western parts of horizon four; **B** — horizon four damaged by mass landslide in spring 2011; **C** — map redrawn from Fig. 5A showing the general scattering of the footprints, with mapped footprints areas in the dashed polygons; **D** — trackways indicated by a–o letters. Scale bar equals 1 m.

and the measured dimensions of the mapped footprints are presented in Table 1. Most of the well-preserved footprints exhibit tridactyl symmetry and have digit IV that are fused into a semi-rounded metapodium area with no clear evidence of pad imprints. Nevertheless, there is a wide extramorphological (substrate-related) variation of the footprints affecting the absence/presence or shape of claw impressions as well as the imprint width and morphology of digits (Fig. 8). Some digits exhibit asymmetry and digits are straight to strongly curved outward or inward. In some prints, three digit pads are visibly conjoined to the metapodium area, while others show two conjoined digit pads, some with a rim around them. The digits vary in width, metapodium marks are visible in most but not all of the footprints. These metapodium marks also vary in width and often exhibit a semicircular, but occasionally triangular, posterior rim. Marks were found in some footprints as a result of the third digit dragging or the heel sliding across the sediment. This horizon includes numerous theropod footprints that appear to have been left coevally based on their arrangement, preservation style, and crosscutting relationship. For example, track numbers a_{16} and b_{21} in the a and b trackways are crosscutting each other (Fig. 8), and have the same imprint depth and preservation. The footprints were likely produced by 16 theropod dinosaurs. The mean stride length to footprint length (SL/FL) ratio is calculated at 4.81, a value similar to that of carnosaurs (Thulborn 1990; Table 2). However, these footprints more closely resemble coelurosaur footprints in both size and morphology.

Horizon 5 — Horizon five is located near horizon four at 1198 m and contains six tridactyl pes imprints preserved as concave epireliefs, five of which belong to one trackway, the others left by individual dinosaurs (Fig. 9). Footprints within trackways are symmetrical in shape and have either rounded or pointed tips of digits, with all digits showing full contact

Table 2: Footprint proportions in the surveyed a_1–a_4, b_{1-2}, and c–g trackways of fourth horizon of Royan section. **Abbreviations:** FL — footprint length, FW — footprint width, $\bar{h}$ — mean height at hip in cm, SL — stride length.

	a_1	a_2	a_3	a_4	b_1	b_2	c	d	e	f	g
FW	1.04	0.83	0.86	0.86	0.92	1.06	0.94	0.94	0.91	0.82	1.09
FL											
SL	6.08	–	3.72	–	4.81	–	–	–	5.12	4.32	–
FL											
FL $\bar{h}$	52.2	58.5	68.1	58.6	57	52.2	54	54	53.3	59.8	54.3

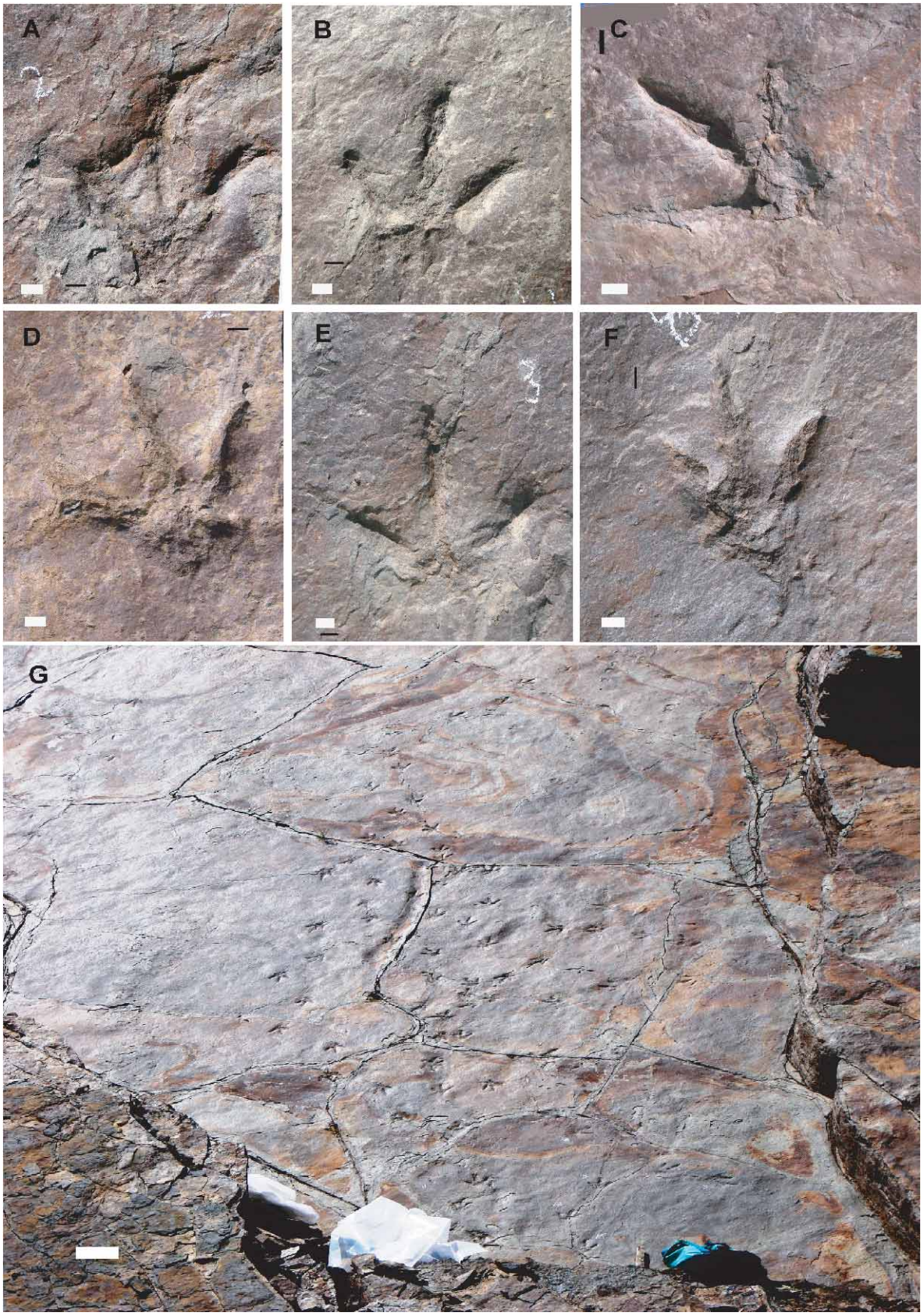


Fig. 7. Photographs of some theropod footprints from horizon four of the Royan section. **A–F** — footprint numbers respectively are a_{12}, c_9, a_{35}, b_{22}, a_{13} and c_2; **G** — close-up of mapped north-western part with the footprints from horizon 4 (right polygon of Fig. 6C). Scale bar of Fig. A–F equals 1 cm, scale bar of G equals 1 m.

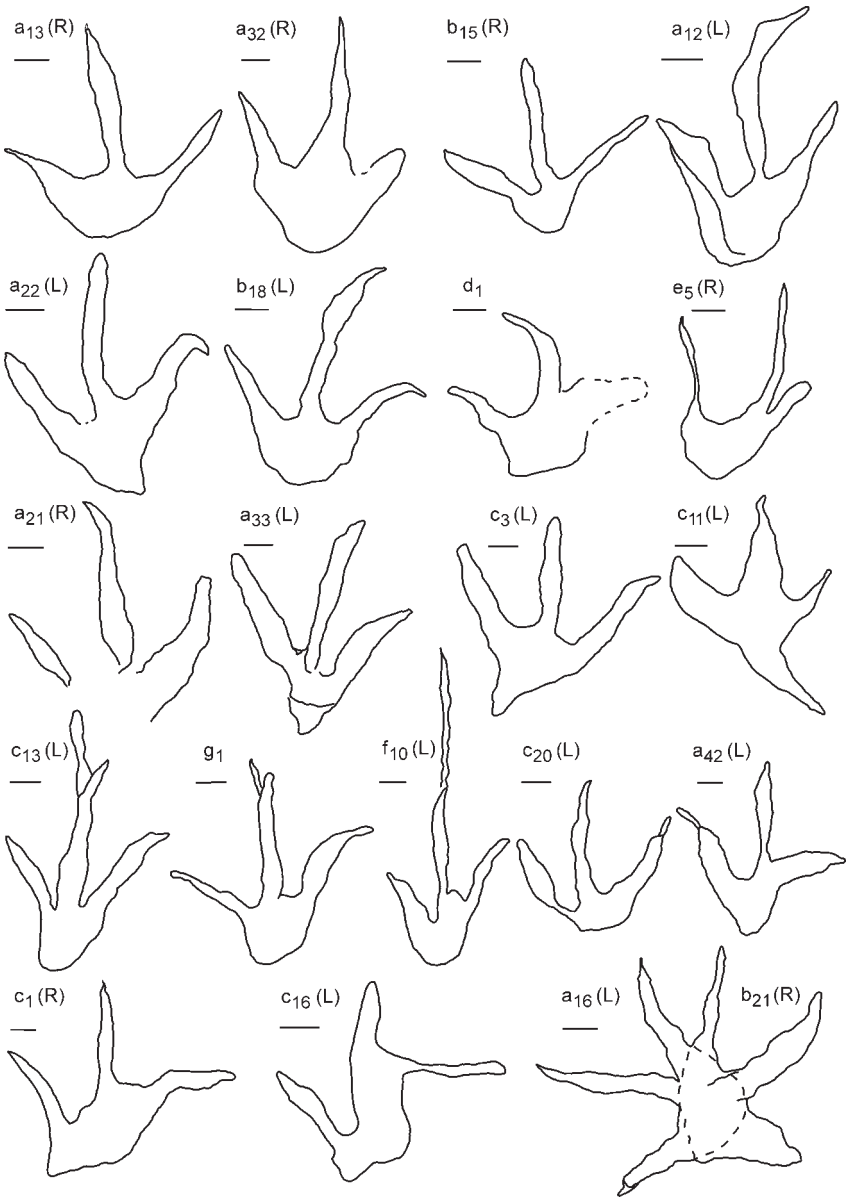


Fig. 8. Some graphed theropod footprints of horizon 4 of the Royan section. Trackways are labelled by letters, footprints by numbers. Footprints are tridactyl with right digits and rounded or sharp tips (a_{13}, a_{32}, b_{15}); curved digits (a_{12}, a_{22}, b_{18}); asymmetric digits (d_1, e_5), no metapodium mark (a_{21}); with slipped heel imprint (a_{33}, c_3, c_{11}) or dragged mid-digit (c_{13}, g_1, f_{10}) or lateral digit (c_{20}, a_{42}); deformed (c_1, c_{16}) and crossing each other (a_{16}, b_{21}). **Abbreviations:** L — left, R — right. Scale bar equals 2 cm.

with the metapodium. Heel imprints are extended and round. An isolated footprint in this bed is tridactyl and exhibits evidence of sliding and radial striations. The dimensions of the footprints are presented in Table 1. The ratio of FW/FL and the $\bar{h}$ value are respectively 1.01 and 79.5 cm in this trackway.

Bol-Yasel section

The upper and lower boundaries of this section are marked by zones of faulting and include the Shirindasht, Fillzamin and Dansirit Formations of the Shemshak Group. An abundant and diverse array of footprints, like those found in the Royan section, were discovered in the uppermost beds of the surveyed sections of the Dansirit Formation. Table 3 shows the dimensions of these footprints. The two horizons of the Bol-Yasel section where footprints were found are separated as follows:

Horizon 1 — This horizon is located at 750 m and is accessible 24 km west of the Baladeh to Yush road. It contains three excellently preserved narrow-gauge sauropod trackways with concave epirelief footprints located on a steep outcrop of thickly-bedded sandstone (Fig. 10). The first trackway is oriented in a southwest–northeast direction, and the two other adjacent trackways run northeast–southwest. We studied the southwest–northeast ward trackway in detail (track line a; Fig. 10A) because of its relatively good preservation. Forty-four tracks (22 pes-manus sets) of a sauropod are visible in this trackway, although the seventh left and right tracks were damaged by a large joint in the slab. Nine pairs of tracks have been outlined, photographed, and measured (Figs. 10B–D, 11). The pes imprints are large, with the impressions of five rounded digits with a distinctive front edge visible on each and a circular rim around the prints caused by the displacement of the sediment. The boundaries between digits are often indistinct, making it difficult to differentiate between three or four digits present on certain prints. Although no claw imprints were found, the tips of some digits (e.g. digit I of first right pes imprint or digit V of sixth left pes imprints) are pointed. The anterior portion of the metapodium area left a deeper imprint than the posterior portion, averaging 6 cm at the deepest point. The semicircular manus imprints are positioned right in front of the pes imprints. Most manus digits are not preserved in the imprints; however, some footprints show evidence of either three or four digits. The depth of the manus imprints is identical to the pes imprints. Pes imprints are turned outward relative to the trackway midline, while manus prints point inward (Fig. 10D). Mean stride length and pace angulations in the surveyed trackway are respectively 154 cm and 95 cm, which are smaller in most trackways at other localities. This parameter indicates that it was made by a small sauropod. Its SL/FL ratio is 4.8, which is less than average (Thulborn 1990). The mean height at hip ($\bar{h}$) of Baladeh's sauropods is 156 cm (Alexander 1976; Lockley et al. 1983 and Thulborn 1990).

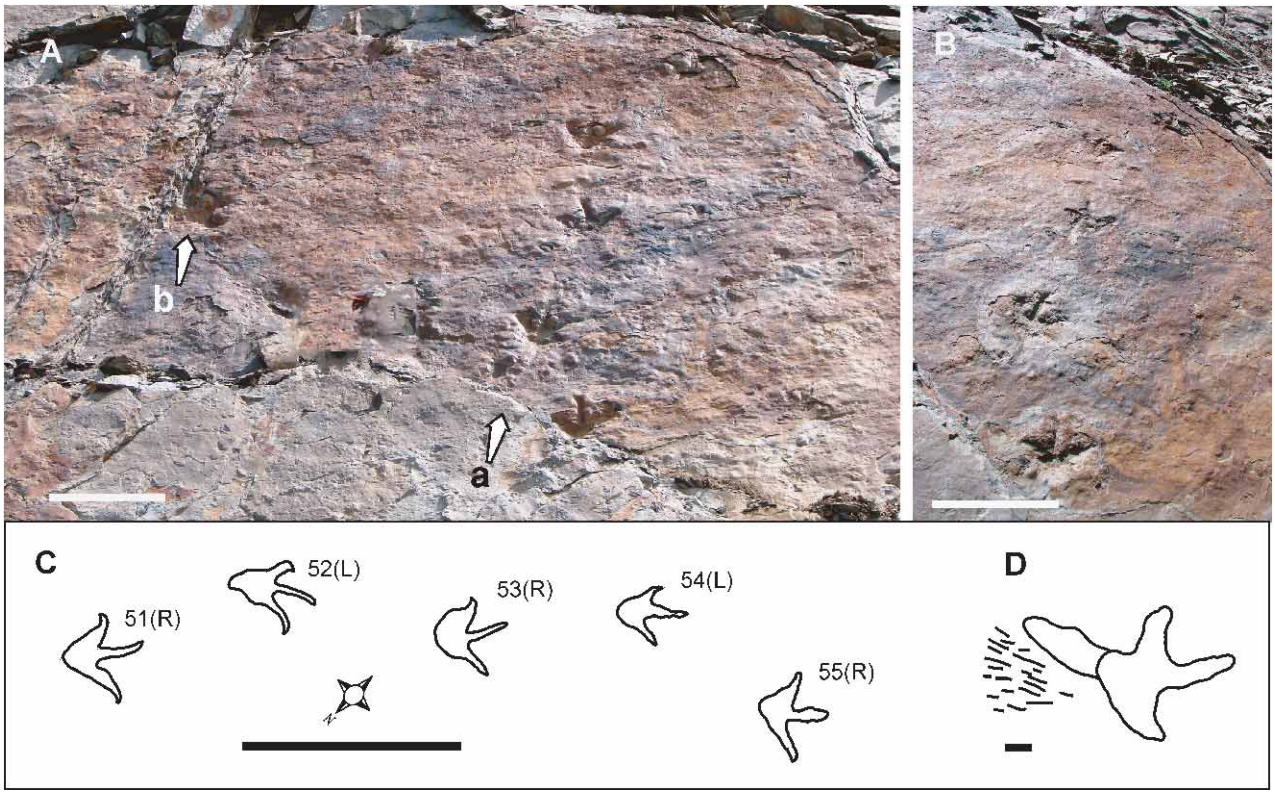


Fig. 9. Tridactyl bipedal theropod footprints of horizon five of the Royan section. **A** — dinosaur trackways, trackway (a) includes five footprints in the northeast to southwest direction and trackway (b) includes single trackway in south to north direction; **B** — the close up view of trackway (a); **C** — detail graph of footprints in trackway (a); **D** — graphed footprint of trackway (b) with slipped metapodium mark and deformed back imprints. **Abbreviations:** L — left, R — right. Scale bar of Fig. A–C equals 0.5 m and scale bar of Fig. D equals 5 cm.

Table 3: Geometry of measured dinosaur footprints of Bol-Yasel section. Dimensions are in cm and angles are in degrees. **Abbreviations:** F — frequency, FL — footprint length, FW — footprint width, L — layer, LBP — lower bedding plane, m — manus, P — pace, p — pes, PA — pace angulations, S — stride, T — trackway, TW — trackway width, UBP — upper bedding plane.

Horizon	L	T	F	S	P	PA	TW	FL	FW	Interdigital angles	
										II-III	III-IV
1	–	a	9	154	95	35	128	32 p 12 m	44 p 35 m	– –	– –
2	1	a	2	–	25	–	25	12	19	80	56
	2	a	3	61	31	165	9	9	8	56	46
		b	2	–	10	–	–	20	16	50	20
		c	1	–	–	–	–	22	20	50	23
		d	3	77	37	178	14	22	16	41	38
		e	3	87	44	160	18	11	12	32	44
		f	1	–	–	–	–	14	9	15	15
		g	1	–	–	–	–	9	11	65	45
	3	a	2	–	38	–	18	11	9	46	53
		b	2	–	70	–	17	18	17	60	53
		c	3	–	26	–	9	11	9	58	32
		d	1	–	–	–	–	23	14	30	38
		e	2	–	22	–	7	6	7	50	35
		f	2	–	64	–	23	14	16	55	40
		g	2	–	5	–	–	–	12	–	–
	4 LBP	a	1	–	–	–	–	15.7	13.2	60	35
		b	1	–	–	–	–	15.1	12.8	30	36
	4 UBP	a	1	–	–	–	–	20	20	50	55
		b	1	–	–	–	–	17.7	13	30	25
		c	1	–	–	–	–	–	–	–	–
		d	1	–	–	–	–	18	12	17	32
		e	1	–	–	–	–	12	6	30	–

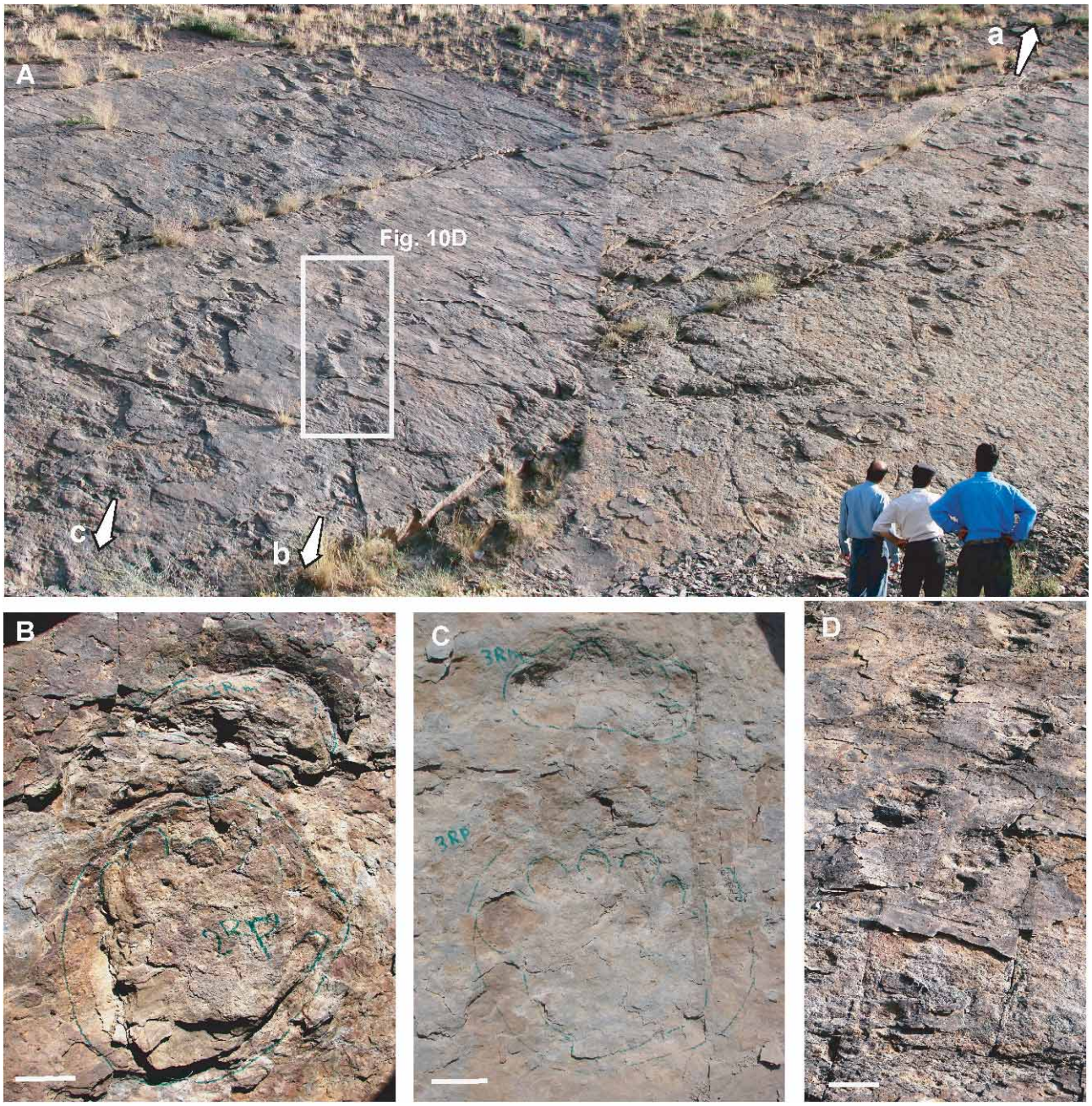


Fig. 10. Sauropod footprints of the Bol-Yasel section. **A** — three sauropod footprints from horizon one. Arrows show the number and direction of trackways, view is toward the northeast and the white rectangle represents the position of Fig. 10D; **B–C** — a close up view of some footprints from the trackway (a); **D** — part of trackway (b) in detail, note manus inward and pes outward orientations relative to midline of trackway. Scale bar of Fig. 10B–C equals 10 cm and Scale bar of Fig. 10D equals 0.5 m.

Horizon 2 — This uppermost horizon is located at 810–815 m. The dinosaur footprints were found on bedded layers of fining-upward sandstone containing shale intercalations bearing plant fossils. Some volcano-shaped reliefs were present on the upper bedding plains within the first layer of horizon two, infilled with sediments rich in coal and iron dioxide, likely the remains of tree stumps (Fig. 12A, B). This layer contains two large tridactyl footprints preserved as concave epireliefs that are part of a trackway within a trackway (Fig. 12C). The digits of the footprints in this trackway are curved, slender, and have pointed tips. The metapodium imprints are small and connected to the digits, and the posterior edge of each footprint is curved and shallow. Within the second layer, in a 1.5 square meter outcrop, 14 tridactyl tracks of a biped showing varying size and completeness were found (Fig. 13A). These footprints were arranged in seven trackways (A–G trackways in Fig. 13B), three of which were oriented west–east and the other three east–west, with one footprint oriented in a southwest–northeast direction (Fig. 13C). Long drag-marks, some straight and some curved, evidently extended

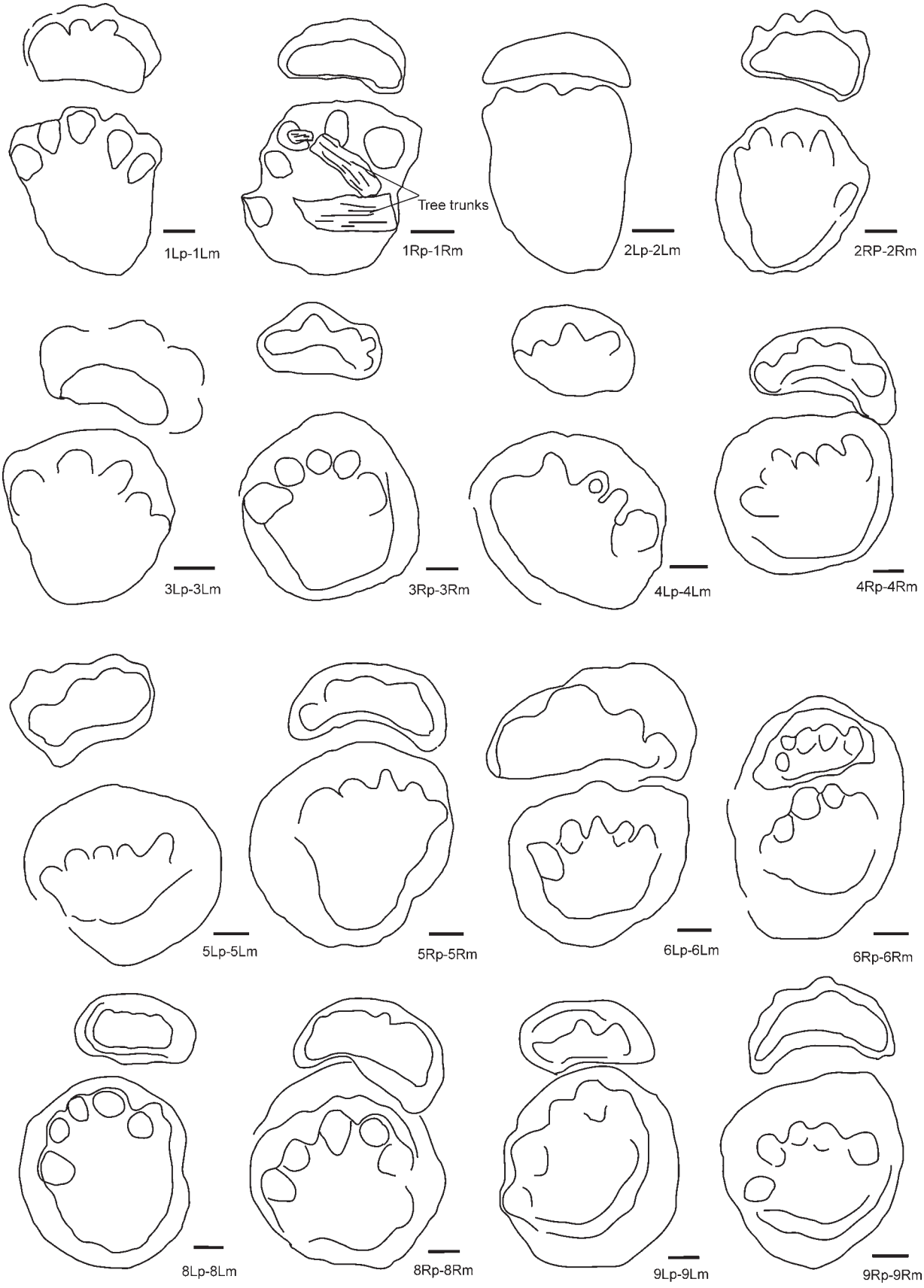


Fig. 11. Graphed figures of sauropod pes and manus footprints in the furthest right trackway of horizon 1 in the Bol-Yasel section, trackway (a) in Fig. 10. **Abbreviations:** L — left, m — manus, p — pes, R — right. Scale bar equals 10 cm.

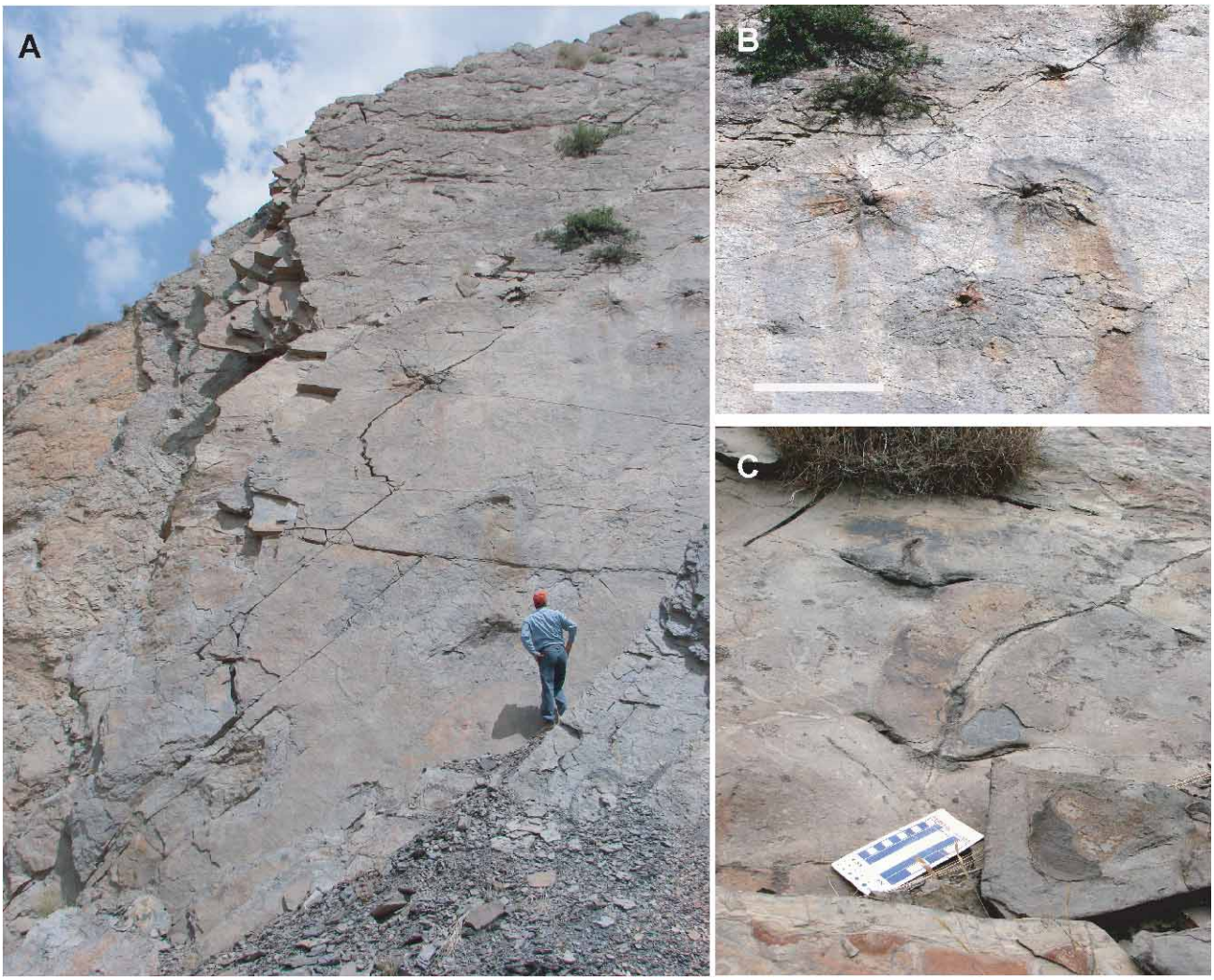


Fig. 12. The sandstone succession of horizon 2 in the north Yasel village (section c of Fig. 1). **A** — volcano-shaped tree pillar remains on the upper bedding planes; **B** — close up view of the upper right corner of Fig. 12A that shows three volcano-shaped mounds as tree pillar remains; **C** — tridactyl bipedal dinosaur trackway of layer one. Scale bar equals 1 m in B and 10 cm (upper scale) in C.

from the tips of the digits of the A_3 and E_1 footprints (Fig. 13B). These footprints clearly indicate a digitigrade posture of the pes. A variety of sizes are present due to preservation differences and perhaps due to variation in the age of the dinosaurs. These footprints show $\bar{h}$ values ranging from 30–116 cm (mean 73.4 cm).

The third layer of this horizon contains both complete and incomplete tridactyl bipedal imprints, which is located 0.5 m above the second layer (Fig. 13D). There are 17 footprints preserved as concave epireliefs constituting 10 trackways (Fig. 13E, and F), which are mostly oriented northwest–southeast and that have a displacement rim around the digits or metapodium that indicates a high plasticity of substrates at the time of footprint formation.

The fourth layer of horizon two in the Bol-Yasel section contains large tridactyl tracks found in a 0.5×0.5 m slab. These footprints were preserved as concave epirelief in the upper bedding plane and either concave epirelief or convex hyporelief in the middle laminated bedding planes. The skin of the metapodium pads has been preserved in these imprints (Fig. 14). Two large footprints showing wide digits and no pad imprints were found in the lower bedding plane. V-shaped wrinkles cover the digit's imprint surface forming a central longitudinal furrow (Fig. 14A,B). Eight footprints preserved as concave epireliefs and convex hyporeliefs, respectively, were found in the mid surface of the slab, two of them didactyl and the others tridactyl like the aforementioned footprints of the lower bedding plane (Fig. 14C,D). These imprints are also wrinkled and include visible striations from crosscutting wrinkles, reticulating the surface (Fig. 14E). These footprints have distinctive metapodium marks and wide digits with rounded tips and small angles between them and made by ornithopod dinosaurs. The $\bar{h}$ value is 80 cm in these samples.

Discussion

Theropod footprints are the most common type found in the Baladeh area. The north and west-bound theropod trackways of Baladeh are morphologically comparable to *Schizograllator*

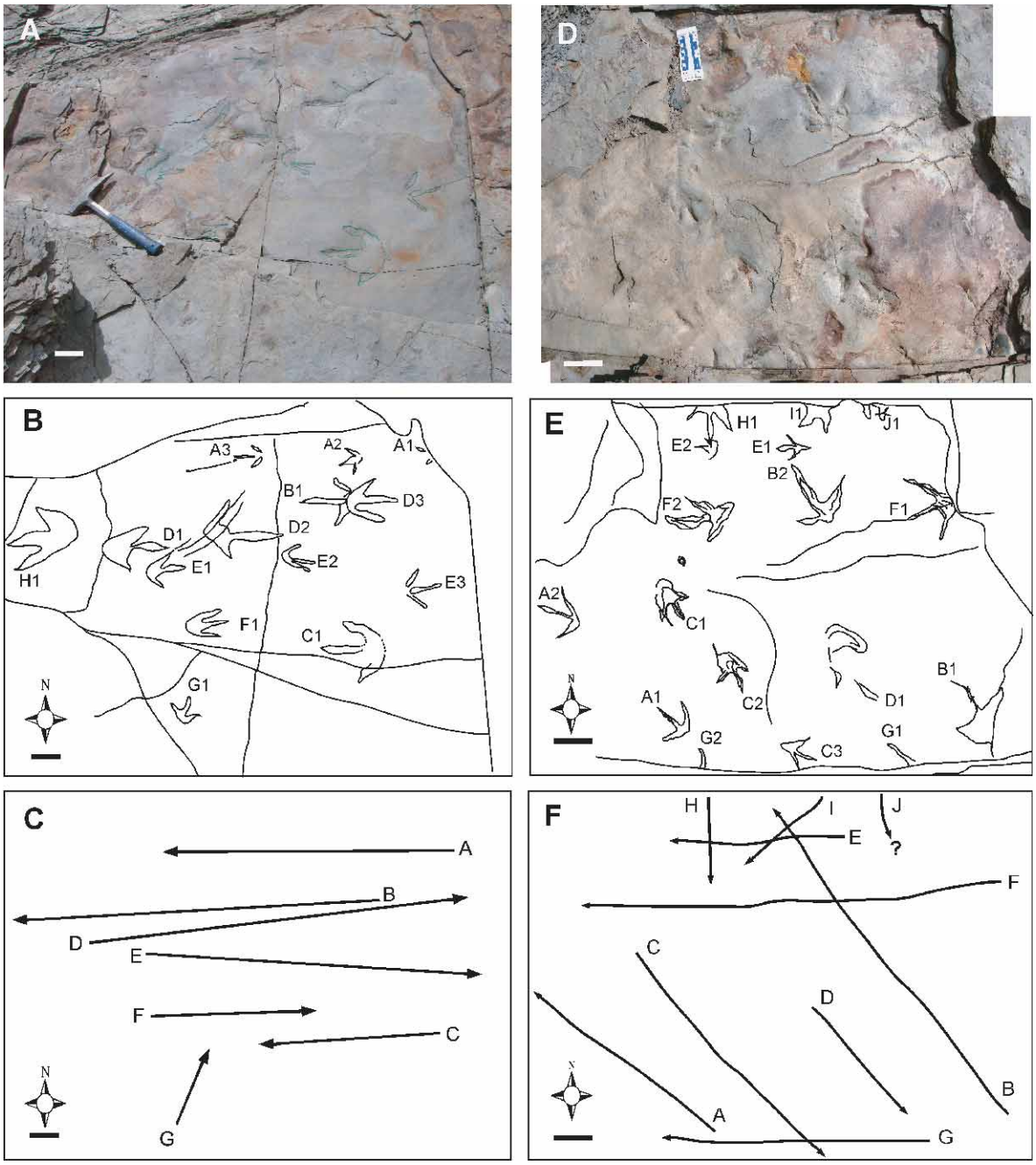


Fig. 13. Tridactyl bipedal theropod footprints of layer two (A) and layer three (D) in horizon 2 of the Bol-Yasel section and their graphed figures (B and E) with trackway directions (C and F). Scale bar equals 10 cm.

otariensis (Matsukawa et al. 2005; Lockley et al. 2007), in digit shape, divarication angle and footprint length is greater than width. *Schizograllator otariensis* have been reported from Jurassic sediments in Japan, also (Matsukawa et al. 2005). Although these footprints are the same size, the Baladeh theropod trackways do not show a clear imprint of the pads of digits. Matsukawa et al. (2005) reported some footprints that are similar to Baladeh samples and are Valanginian–Baremian in age, but they are larger in digit III. *Talmontopus tersi,* reported from the Hettangian of France, has wider digits than the Baladeh theropod footprints (Haubold 1986). The footprints found in the Baladeh area are different from *Grallator*, because the Baladeh samples have small size and lack of digit pads. They are also distinct from *Wildeichnus casamiquela,* which was reported from Lower Jurassic sediments of Morocco (Gierliński et al. 2009a), and from Lower and Upper Jurassic sediments of Poland (Gierliński 2007; Gierliński et al. 2009b), because of their larger size, lack of tips on digits, and digits that connect to sole imprints without a change in relief. However, if size is not used as the main taxonomic diagnostic factor for *Wildeichnus*, the theropod footprints of the second horizon of Bol-Yasel section

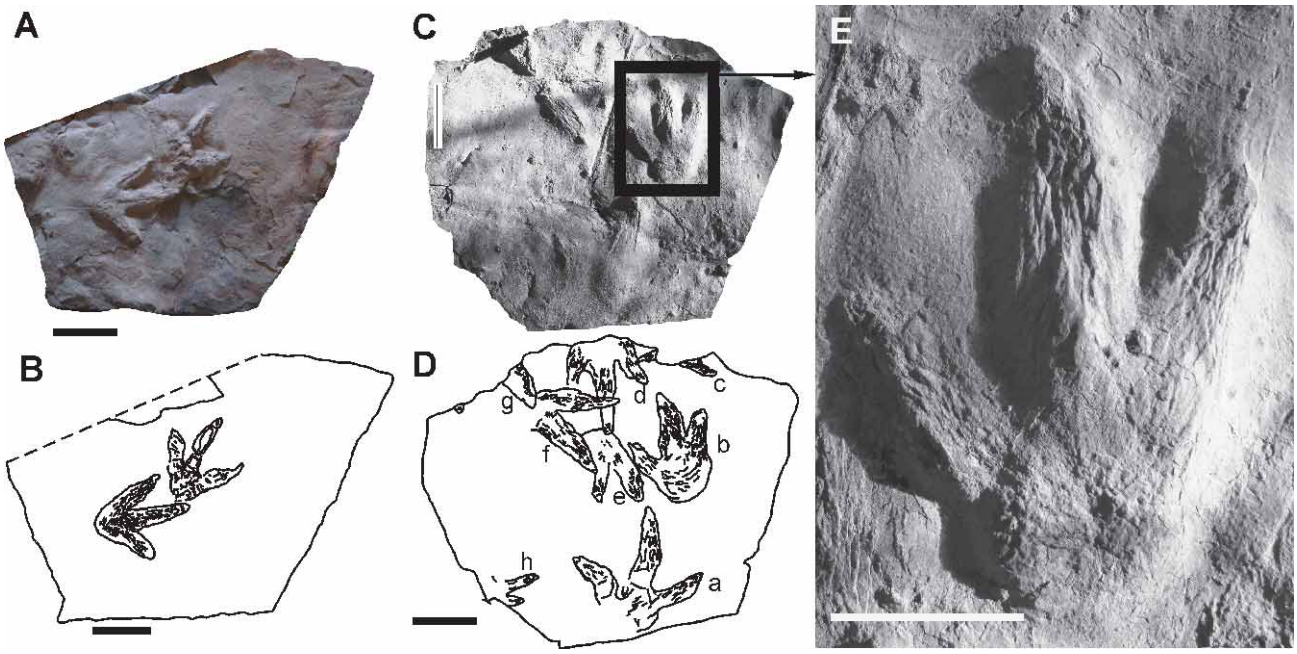


Fig. 14. Dinosaur footprints on slabs from the fourth layer of horizon 2 at the Bol-Yasel section. **A** — convex hyporelief preserved in lower bedding plane; **B** — skin imprint on metapodium marks in the graphed footprint of Fig. 14A; **C** — didactyl and tridactyl footprints in the middle part of the studied slab; **D** — graphed footprint of Fig. 4C; **E** — one tridactyl footprint in detail shows wrinkles arrangements. Scale bar equals 10 cm.

are attributable to it. Finally, theropod footprints of the fourth horizon of Royan are dimensionally identical to *Iranosauripus zerabensis*, but they differ in digit forms as *Iranosauripus zerabensis* have strongly straight digits with sharp tips.

At first, ornithopods appeared as small forms such as those of the Fabrosauridae and Heterodontosauridae families of the Late Triassic to Middle Jurassic. However, true ornithopods achieved great abundance in the Cretaceous Period with the emergence of better known families such as Iguanodontidae. Ornithopod footprints were found in two horizons in the Baladeh area: the third horizon of the Royan and the latest layer in horizon two of the Bol-Yasel section. A single footprint in horizon three of the Royan section in northern Baladeh was likely made by a small ornithopod, as shown by its broad digit imprints with rounded tips and its symmetry about its elongated, slightly hollow metapodium mark. The size of this footprint can give us information about the age of the ornithopod that left it (Cotton et al. 1998). Ten closely-spaced footprints in the fourth layer of horizon two of the Bol-Yasel section are ornithopod footprints as well. They have broad digits with predominantly rounded tips and distinctive sole marks. Most of these footprints exhibit skin imprints on the plantar surface. Skin imprints are well known from dinosaur footprints (e.g. Avanzini et al. 2001; Klein & Haubold 2007). The specimens examined here show an organized orientation to the wrinkles, which are oblique to the midline of digits (e.g. left footprint of Fig. 14B), and reach each other as rhomboidal from the central part of the metapodium. These footprints could be classified as belonging to *Atreipus milefordensis* (Bock 1952), but this ichnospecies essentially established for the *Grallator*-like footprints includes tridactyl manus impressions (Olsen & Brird 1986). One of the footprints from layer 4 of the second horizon of Bol-Yasel section shows claw imprint (Fig. 14Db), like the *Therangospodus* isp. (Gierliński et al. 2009a: fig. 3D), but these footprints are attributed to theropods (Lockley et al. 1998). These footprints differ from *Eubrontes giganteus* (Hitchcock, 1845) because of a lack of claw and pad imprints (Olsen & Baird 1986; Olsen et al. 1998). Ornithopod footprints of the west Baladeh resemble *Jiayinosorupus johnsoni* (Dong et al., 2003) that belong to tracks without manus and tail traces (Xing et al. 2009). They are the same as the broadly tridactyl foot and possessed wide and thick digits, but webbing is not found in the Baladeh footprints, as in the ornithopod track from the Upper Cretaceous Zhutian Formation of China (Xing et al. 2009: fig. 2D). Two distinctive didactyl footprints belong to *Velociraptorichnus sichuanensis* and have been reported from Poland (Gierliński 2007) and East Asia (Lockley et al. 2007).

Most sauropod dinosaurs range in size from about 1 to more than 35 m but with broadly similar skeletal structure. Sauropodomorpha includes the first huge terrestrial herbivores at and before the Triassic–Early Jurassic boundary, while sauropods gain dominance in the Early Jurassic. These dinosaurs are quadrupedal and produced the largest dinosaur footprints known (Lockley et al. 2007). The sauropod manus and pes morphology is variable in either digit pads or size and position of claws (Allain et al. 2004; Milàn et al. 2005). Most sauropod footprints have been found as large, rounded or ellipsoid hollows, and digit imprints are visible in well-preserved samples. Sauropod footprints of the Baladeh show five digits in the pes and up to five digit imprints in the manus in well-preserved footprints. Early–Middle Jurassic

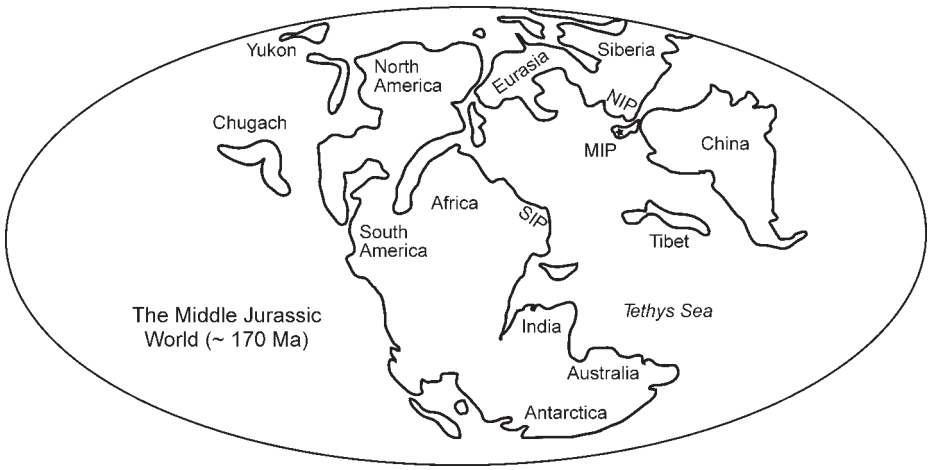


Fig. 15. Paleogeographical location of the Middle Iran Plateau including the Alborz-central Iran and Sanandaj–Sirjan zones during Middle Jurassic time (Modified after Golonka & Ford 2000). **Abbreviations:** MIP — Middle Iran Plateau, NIP — North Iran Plateau, SIP — South Iran Plateau.

sauropods include the Vulcanodontidae, Cetiosauridae and Barapasauridae families. Since the Dansirit Formation of western Baladeh is Early Jurassic in age, *Vulcanodon* and *Tazoudasaurus* are also candidates as track-makers. There are numerous studies on sauropod footprints (e.g. Wright 2005) and the Baladeh sauropod footprints are identical to those reported from China or from Lesotho, identified as *Pseudotetrasauropus* (Haubold 1986). *Pseudotetrasauropus* is a problematic name, which was revised by Lockley et al. (2006). The shape and outlines of the sauropod footprints in the Baladeh area, however, are similar to Eosauropus that reported by (Klein & Lucas 2010; Xing et al., in print).

When compared with other Early to Middle Jurassic dinosaur footprints, the Baladeh footprints most closely resemble reported footprints from eastern Asia (Lockley et al. 2002; Matsukawa et al. 2005; Wright 2005; Lockley et al. 2007) in both morphology and complex footprints. This is consistent with the paleogeographical reconstructions of the area, which show that the Middle Iran Plateau was near China and the territories of central Eurasia in the Early to Middle Jurassic, after its separation from Gondwana in the Carnian (Fig. 15).

Conclusions

The Shirindasht and Dansirit Formations of the Shemshak Group in the central Alborz Mountains of northern Iran provided numerous footprints of theropod, ornithopod and sauropod dinosaurs in the northern and western parts of the town of Baladeh. These footprints are described here for the first time, organized by the two major areas in which they were found, the Royan and Bol-Yasel sections. There are four horizons within the Royan section in northern Baladeh that include theropod footprints and one horizon that provided possible ornithopod footprints. The theropod footprints from this section themselves are classifiable into three classes based on their sizes: (1) the smallest theropod footprint is 6 cm in length and was found in the second horizon of the Royan section; (2) medium-sized theropod footprints include footprints found in the fourth horizon, which are 11–15 cm in length and abundant. The mean dimensions of these footprints are similar to coelurosaurian footprints; (3) large theropod footprints found in the first and fifth horizons of the Royan section are 16–20 cm in length. These footprints are morphologically similar to the footprints from horizon 4.

The dinosaur trackways of the fourth horizon of Royan include more than 160 footprints, and are arranged in west–east or south–north orientations within sixteen trackways. The Dansirit Formation contains theropod, possible ornithopod and sauropod dinosaur footprints in two horizons in western Baladeh. Sauropod footprints are arranged in three trackways and are described from Iran for the first time. The second horizon of the Dansirit Formation contains several theropod and possible ornithopod footprints. The size variation of the theropod footprints can be attributed to different preservation of the footprints in soft sediments. The possible ornithopod footprints have wide toes with rounded tips and small angles between the toes and skin imprint. Paleogeographical data show that the Middle Iranian Plateau was originally near China and Central Asia during the Early to Middle Jurassic period, making the similarities between dinosaur footprints from these areas and those found near Baladeh consistent with what we might expect.

Acknowledgments: This manuscript resulted from a research project of the Research Affairs Office of the University of Zanjan (RAOUZ) with Grant No. 1388-8848. We thank the manager of RAOUZ for his support. Reviewers Spencer G. Lucas (NM Museum of Natural History), Hendrik Klein (Saurierwelt Paläontologisches Museum), Anne Schulp (Naturalis Biodiversity Center), Ricardo N. Melchor (Universidad Nacional de La Pampa), Martin Kundrát (Uppsala Universitet) and Majid Mirzaei Ataabadi (University of Zanjan) made constructive suggestions for improvement of the manuscript. We thank Patrick Druckenmiller (University of Alaska Museum) and Eva Chorvátová (Slovak Academy of Sciences) for their courtesy and useful comments. The authors would like to thank Miss Meg O'Connor for her help.

References

Abbassi N. 2006: New Early Jurassic dinosaur footprints from Shemshak Formation, Harzavil Village, western Alborz, north Iran. *J. Geosci.* 62, 31–40 (in Persian).

Aghanabati A. 1998: Jurassic stratigraphy of Iran. *Geol. Sur. Iran Publ. Tehran,* Iran, 1–746 (in Persian).

Alexander R.McN. 1976: Estimates of speeds of dinosaurs. *Nature* 261, 129–130.

Allain R., Aquesbi N., Dejax J., Meyer C., Monbaron M., Montenat C., Richir P., Rochdy M., Russell D. & Taquet P. 2004: A basal sauropod dinosaur from the Early Jurassic of Morocco. *C.R. Palevol* 3, 199–208.

Assereto R. 1966: The Jurassic Shemshak Formation in Central Alborz (Iran). *Riv. Ital. Paleont. Stratigr.* 72, 1133–1182.

Avanzini M., Leonardi G., Tomasoni R. & Campolongo M. 2001: Enigmatic dinosaur trackways from the Lower Jurassic (Pliensbachian) of the Sarca valley, Northeast Italy. *Ichnos* 8, 235–242.

Avnimelech M.A. 1966: Dinosaur tracks in Judean Hills. *Proc. Israel Aca. Sci. Huma., Sec. Sci.* 1, 1–19.

Bock W. 1952: Triassic reptilian tracks and trends of locomotive evolution. *J. Paleontology* 26, 395–433.

Cotton W., Cotton J.E. & Hunt A.P. 1998: Evidence for social behavior in ornithopod dinosaurs from the Dakota Group of Northeastern New Mexico, USA. *Ichnos* 6, 141–149.

Dong Z.M., Zhou Z.L. & Wu S.Y. 2003: Note on a hadrosaur footprints from Heilongjiang River area of China. *Vertebrata PalAsiatica* 41, 324–326.

Fürsich F.T., Hautmann M., Senowbari-Daryan B. & Seyed-Emami K. 2005: The Upper Triassic Nayband and Darkuh Formations of east-central Iran: stratigraphy, facies patterns and biota of extensional basins on an accreted terrane. *Beringeria* 35, 53–133.

Fürsich F.T., Wilmsen M., Seyed-Emami K. & Majidifard M.R. 2009: Lithostratigraphy of the Upper Triassic-Middle Jurassic Shemshak Group of Northern Iran. In: Brunet M.F., Wilmsen M. & Granath J.W. (Eds.): South Caspian to Central Iran Basins. *Geol. Soc. London, Spec. Publ.* 312, 129–160.

Ghasemi M. & Saeedi A. 1993: Geological quadrangle map of Baladeh, 1:100,000. *Geol. Sur. Iran,* Tehran. Sheet number 6362.

Gierliński G.D. 2007: New dinosaur tracks in the Triassic, Jurassic and Cretaceous of Poland. In: Huerta P.H. & Fernández-Baldor F.T. (Eds.): Actas de las IV Jornadas Internacionales sobre Paleontología de Dinosaurios y su Entorno. Salas de los Infantes, Burgos, Spain, 13–15 September 2007. *Publica Colectivo Arqueológico y Paleontológico de Salas*, Burgos, Spain, 75–90.

Gierliński G.D., Menducki P., Janiszewska K., Wicik I. & Boczarowski A. 2009a: A preliminary report on dinosaur track assemblages from the Middle Jurassic of the Imilchil area, Morocco. *Geol. Quart.* 53, 477–482.

Gierliński G.D., Niedźwiedzki G. & Nowacki P. 2009b: Small theropod and ornithopod footprints in the Late Jurassic of Poland. *Acta Geol. Pol.* 59, 221–234.

Golonka J. & Ford D. 2000: Pangean (Late Carboniferous–Middle Jurassic) paleoenvironment and lithofacies. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 161, 1–34.

Haubold H. 1986: Archosaur footprints at the terrestrial Triassic–Jurassic transition. In: Padian K. (Ed.): The beginning of the age of dinosaurs faunal change across the Triassic–Jurassic Boundary. *Cambridge University Press*, Cambridge, 189–201.

Kellner A.W.A., Vecchia F.M.D., Mirzaei Ataabadi M., Silva H.D.P. & Khosravi E. 2012: Review of the dinosaur record from Iran with the description of new material. *Riv. Ital. Paleont. Stratigr.* 118, 261–275.

Klein H. & Haubold H. 2007: Archosaur footprints — potential for biochronology of Triassic continental sequences. In: Lucas S.G. & Spielmann J.A. (Eds.): The global Triassic. *New Mexico Mus. Nat. Hist. Sci. Bull.*, USA 41, 120–130.

Lapparent A.F. de & Davoudzadeh M. 1972: Jurassic dinosaur footprints of the Kerman area central Iran. *Geol. Sur. Iran, Report Number* 26, 5–22.

Lapparent A.F. de & Nowgol Sadat M.A.A. 1975: Une trace de pas de dinosaur dans le Lias de l'Elborz, en Iran. *Consequences de cette decouverte. C.R. Hebdomadaires des Séances Acad. Sci., Sér. D., Sci. Nat.* 280, 161–163.

Lockley M.G. 1991: Tracking dinosaurs, a new look at an ancient world. *Cambridge University Press*, Cambridge, 1–238.

Lockley M.G., Young B.H. & Carpenter K. 1983: Hadrosaur locomotion and herding behavior: evidence from footprints in the Mesaverde Formation, Grand Mesa Coal Field, Colorado. *Mountain Geol.* 20, 5–14.

Lockley M.G., Meyer C.A. & Moratalla J.J. 1998: *Therangospodus*: trackway evidence for the wide spread distribution of a Late Jurassic theropod with well-padded feet. In: Perez-Moreno B.P., Holtz Jr. T., Sanz J.L. & Moratalla J. (Eds.): Aspects of Theropod paleobiology. *Gaia* 15, 339–353.

Lockley M.G., Lucas S.G. & Hunt A.P. 2006: Evazoum and the renaming of northern hemisphere "Pseudotetrasauropus": Implication for tetrapod ichnotaxonomy at the Triassic–Jurassic boundary. In: Harris J.D., Lucas S.G., Spielmann J.A., Lockley M.G., Milner A.R.C. & Kirkland J.I. (Eds.): The Triassic–Jurassic Terrestrial Transition. *New Mexico Mus. Nat. Hist. Sci. Bull.*, USA 37, 199–206.

Lockley M.G., Lires J., García-Ramos J.C. & Pinuela L. 2007: Shrinking the world's largest dinosaur tracks: observations on the ichnotaxonomy of *Gigantosauropus asturiensis* and *Hispanosauropus hauboldi* from the Upper Jurassic of Asturias, Spain. *Ichnos* 14, 247–255.

Matsukawa M., Shibata K., Kukihara R., Koarai K. & Lockley M.G. 2005: Review of Japanese dinosaur track localities: implications for ichnotaxonomy, paleogeography and stratigraphic correlation. *Ichnos* 12, 201–222.

Milàn J., Christiansen P. & Mateus O. 2005: A three-dimensionally preserved sauropod manus impression from the Upper Jurassic of Portugal: implications for sauropod manus shape and locomotor mechanics. *Darmstädter Beitr. Naturgeschichte, Heft* 14, 47–52.

Olsen P.E. & Baird D. 1986: The ichnogenus *Atreipus* and its significance for Triassic biostratigraphy. In: Padian K. (Ed.): The beginning of the age of dinosaurs, faunal change across the Triassic–Jurassic Boundary. *Cambridge University Press*, Cambridge, 61–87.

Olsen P.E., Smith J.B. & McDonald N.G. 1998: Type material of the type species of the classic theropod footprint genera *Eubrontes*, *Anchisauripus* and *Grallator* (Early Jurassic, Hartford and Deerfield basins, Connecticut and Massachusetts, U.S.A.). *J. Verte. Paleont.* 18, 586–601.

Stöcklin J. 1974: Northern Iran: Alborz Mountains. In: Spencer A.M. (Ed.): Mesozoic–Cenozoic orogenic belts: Data for orogenic studies. *Geol. Soc. London, Spec. Publ.* 4, 213–214.

Thulborn T. 1990: Dinosaur Tracks. *Chapman and Hall Publications*, London, 1–409.

Vaez Javadi F. & Abbassi N. 2012: Study of plant macrofossils from Baladeh area (Central Alborz), dating and biostratigraphy. *J. Stratigr. Sed. Res., Isfahan Univ. J. Press*, Isfahan, Iran 28, 37–64 (in Persian).

Wilmsen M., Fürsich F.T., Seyed-Emami K., Majidifard M.R. & Taheri J. 2009: The Cimmerian Orogeny, in northern Iran: tectono-stratigraphic evidence from the foreland. *Terra Nova* 21, 211–218.

Wright J.L. 2005: The importance of sauropod tracks. In: Rogers K.A.C. & Wilson J.A. (Eds.): The Sauropods, evolution and paleobiology. *University of California Press*, Berkeley and Los Angeles, California, 252–280.

Xing L.D., Jerald H.D., Dong Z.M., Lin Y.L., Chen W., Guo S.B. & Ji Q. 2009: Ornithopod (Dinosauria: Ornithischia) tracks from the Upper Cretaceous Zhutian Formation in the Nonxiong basin, Guangdong, China and general observations on large Chinese ornithopod footprints. *Geol. Bull. China* 28, 829–843.

Xing L., Peng G., Marty D., Ye Y., Klein H., Li J., Gierliński G.D. & Shu C. (in print): An unusual trackway of a possibly bipedal archosaur from the Late Triassic of the Sichuan Basin, China. *Acta Palaeont. Pol.*