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Theropod trampled bedding plane with laboring trackways from the Upper Cretaceous Abdrant Nuru fossil site, Mongolia

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Abstract. The Hayashibara Museum of Natural Sciences-Mongolian Paleontological Center Joint Paleontological Expedition team has excavated a bedding plane trampled by theropod dinosaurs from Abdrant Nuru fossil site, Gobi desert, Mongolia. 14 trackways consisting of 84 footprints have been discovered on a single exposure of the bedding plane. The depth of the trackways varies from extremely deep to shallow, proving sequential imprinting during the drying and hardening process of the substrate. Deep footprints and elongated footprints are not useful for ichnotaxonomy, but they are useful for studying the laborious locomotion of the trackmakers on soft substrate.

Introduction

On September 5th of 1996, Hayashibara Museum of Natural Sciences-Mongolian Paleontological Center Joint Paleontological Expedition team (abbreviated as HMNS-MPC-JPE) discovered several dinosaur footprints at Ereelzh sub-locality in the south-eastern part of Abdrant Nuru fossil site, 140km northwest of Dalanzadgad, South Gobi Aimag, Mongolia (Watabe and Suzuki, 2000a). In August 1997, HMNS-MPC JPE performed ichnological fieldwork of the site (Watabe and Suzuki, 2000b). In the course of the work, a bedding plane of hard white sandstone trampled with well preserved theropod footprints was exposed and mapped. The GPS coordinate of the bedding plane is 44˚31´24´´ N, 103˚09´18´´ E (Figure 1). It is in the northern part of Ereelzh sub-locality. In July 1998, the expedition team made a latex mold of the eastern part of the bedding plane about 5 m^2. High-resolution photographs were also taken during the fieldwork (Suzuki and Watabe, 2000). Watabe (2004) presented a detailed topographical map of the area. The results of the research were briefly reported in Ishigaki (1999), Ishigaki et al. (2008, 2009). The purpose of this paper is to describe footprints and trackways imprinted on the bedding plane, to estimate the trackmaker and to discuss the occurrence of the footprints.

Geological setting of the bedding plane

Geographic position of Abdrant Nuru and the bedding plane are presented in Figure 1. I redrew the topographic map of Ereelzh sublocality in Abdrant Nuru from Watabe (2004). Sochava (1975) first reported the vertebrate fossil site of Abdrant Nuru with a brief geological description. Then Watabe and Suzuki (2000a and b) and Watabe (2004) reported geology of the site briefly. Watabe (2004) also presented a topographical map of whole site. Watabe et al. (2010) present revised geological description of the site. According to their report, total thickness of the geologic section of the whole fossil site of Abdrant Nuru is about 80 m, and divided into two parts; “the upper part” which crops out Toosgot sublocality, and “the lower part” which crops out Ereelzh sublocalilty. Total thickness of “the lower part” is about 30m. It consists of alternation of sandstone and mudstone. The bedding plane in this paper belongs to upper part of “the lower part.” The sedimentary environment of “the lower part” of Abdrant Nuru fossil site is fluvial. The age of the site is unknown. However dinosaur remains possibly attributable to pinacosaur suggest the beds are of Djadokhta age.

The exposed bedding plane extends about 15 m long toward east-west direction, and 6 m wide toward north-south direction in maximum width. A photograph and a sketch of the whole bedding plane are presented in Figures 2, 3, and 4. Structurally, the bedding plane is almost flat. The bedding plane consists of white fine sandstone. This sedimentary unit is 2cm thick and overlain by red colored massive mudstone beds. Current ripple marks which ridges extend 170˚–350˚ are recognized on this bedding plane. The length from ridge to ridge is 4.3 cm on average. The dominant paleocurrent direction based on current ripples is toward the east. Three small faults are recognized on this plane (F. 1, 2, and 3 in Figure 4-2). These faults are low angle thrust faults. Fault 1 strikes 80˚ and thrusts up to southward about 16 cm in its maximum gap. It contin-

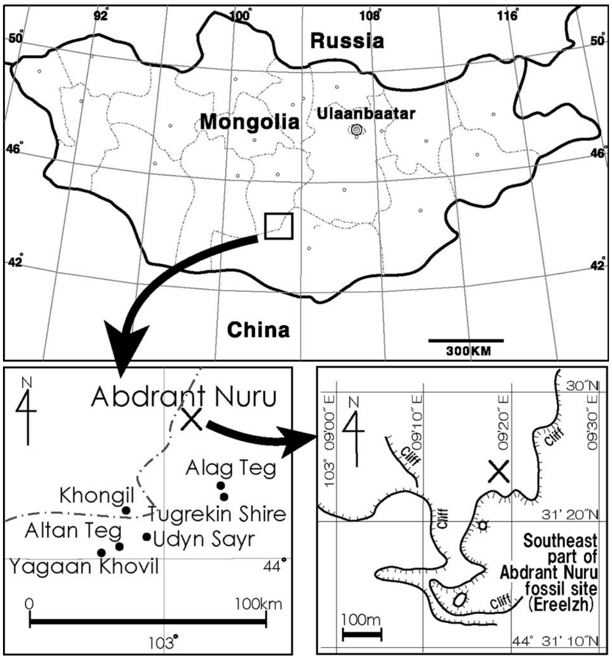

Figure 1. Locality map of Abdrant Nuru fossil site from the Gobi Desert, Mongolia. Site map of Ereelzh sublocality is redrawn after Watabe (2004).

Figure 2. Overview photograph of the bedding plane.

ues 2.5 m. Fault 2 strikes 55˚ and thrusts up to southward about 10 cm in its maximum gap. It continues 2 m. Fault 3 strikes 70˚ and thrusts up to southward about 13 cm in its maximum gap. It continues 5 m.

Ichnological Description

14 trackways consisting of 84 footprints and 3 isolated single footprints have been discovered on the bedding plane. They are all tridactyl or tetradactyl footprints imprinted by bi-pedal trackmakers. Table 1 presents measurement data of each trackway and the well-preserved footprints. Here I describe them.

Trackways A and B

I describe these two trackways together, because they are morphologically very similar. However, their footprint size and stride are slightly different. The footprints forming these trackways are tetradactyl, middle sized (26-30 cm in length) and footprint length (abbreviated as FL) is longer than footprint width (abbreviated as FW) (Figure 5-1a and b). Digit III is the longest. Digit I is short and imprinted lateral-behind of the footprint. Digit I impression is not always preserved. In well preserved imprints, all four digits have claw marks at the tapered termination. The tip of claw mark of digit III slightly rotates inward. Digital pad impressions are not well-preserved. Interdigital angle between II-IV is wide (around 80˚). Footprints are imprinted deeply. The average depth is 5.5 cm in the trackway A and 7 cm in the trackway B. Deformation of the digital impressions is common as a result of deep imprinting. The proximal part of digit III impression is particularly altered by the soft substrate. Digital width of this part often becomes narrow. Sometimes, it disappeared completely making the distal part of digit III isolated from other parts of the footprint. In front of the several footprints, scratch marks of the tip of digit III are preserved on the bedding plane. The rear portion of the footprints are always associated with a metapodial impression, and often elongated with a metatarsal impression. The rear termination of the footprints is often tapered.

Both the trackways A and B continue about 13 m. Footprints' axes are almost parallel to the trackway midline. Average pace angulation of the trackways A and B are 149˚ and 155˚ respectively (Figures 4 and 6-1). These values are the smallest among the trackways preserved on the bedding plane.

Trackway G

Footprints are tetradactyl, middle-large sized (38 cm in average length). FL is larger than FW (Figure 5-2a and b). They are imprinted very deeply. Their morphological characteristics are similar to the footprints of trackways A and B, except for their larger size. The average depth is 6.7 cm. The trackway G continues about 10 m. Footprints' axes are almost parallel to the trackway midline. Average pace angulation is 166˚, which is remarkably larger than those of the trackways A and B (Figures 4 and 6-3).

Trackway F

The footprints in this trackway are extremely deep. Footprints are tetradactyl and their FL is longer than FW. Digit III is the longest. Digit I is short and imprinted lateral-behind of the footprint. The values of interdigital angle between II-IV are around 90–100˚ which are very wide. Average depth of the footprints is 9.5 cm which is the deepest among the footprints preserved on this bedding plane. The true print is deformed and elongated in antero-posterior direction (Figure 5-3a and b). In the anterior part of a footprint, the impression of digit III is exaggerated laterally and elongated strongly to frontward. Displacement rims surround the withdrawal tip of digit III of the true print.

It is difficult to estimate the mean size and reconstruct the original morphology of these deformed true prints. In this case, the original morphology of the footprint could be estimated from the underprint just below the true print. Excavation of footprint F1 revealed that an underprint was preserved in the bedding plane which lies 2 cm beneath the bottom of true print (Figure 5-4a and b). FL and FW of this underprint are 27 cm and 21 cm respectively. In underprint, the digits II, III and IV have claw marks at the tapered termination. The digit I is not recognized in this underprint. Impressions of digital pads are not preserved. Interdigital angle between digits II-VI is 57˚ which is much smaller than the values of true prints. If this underprint of F1 footprint represent the original morphology, the footprints forming the trackway F are originally middle sized (around 27 cm in FL).

The trackway continues about 6 m. Footprints' axes are almost parallel to the trackway midline. Average pace angulation is 163˚ (Figures 4 and 6-2).

Trackway J

The footprints forming this trackway are tridactyl, middle-large sized (37 cm in average length) and their FL is longer than FW. Overall outline is mediolaterally symmetrical (Figure 5-5a and b). Digit III is the longest and digit IV is longer than digit II. All three digits have claw marks at the distal termination. The tip of the claw mark of digit III rotates slightly inward. Digital pad impressions are observed in well preserved footprints which have 2-3-3 formula. Interdigital angle between II-IV is around 40˚. The footprints are shallow. They are less than 3 cm in depth. There is a possibility that they are not true prints. The rear of the footprints is round.

The trackway continues about 8m. Stride length is the largest among the trackways preserved on this bedding plane. Footprints' axes are almost parallel to the trackway midline. Average pace angulation is 170˚ (Figures 4 and 6-4).

Trackway N

The footprints forming this trackway are tridactyl, middle sized (25 cm in average length) and their FL is longer than FW. Digit III is the longest and digit IV is longer than digit II. Three digits are slender with digital pad impressions which have 2-3-3 formula. All three digits have claw marks at the tapered termination. The tip of the claw mark of digit III slightly rotated inward. The rear of the footprints is round (Figure 5-6a and b).

The trackway continues only 2 m. Footprints' axes are almost parallel to the trackway midline. Pace angulation is 169˚ in average (Figure 4).

Trackways C, D, E, H, I, K, L, M, and footprints a, b, c

The footprints forming these trackways are tridactyl, small to middle sized (12-26 cm in length) with larger FL than FW (Figure 4). Digit III is the longest. Digits have claw marks at the tapered termination. Digital pad impressions are rarely preserved. Footprints are shallow with depth of less than 2 cm. Most of them are poorly preserved footprints on which it is inadequate to carry out morphological analysis.

Discussion

Ichnotaxonomy and trackmakers

The morphology of these footprints such as tridactyl and tetradactyl forms, sharp claw marks, larger FL than FW is typical characteristics for theropod dinosaur footprints. These footprints are attributed to those imprinted by various-sized theropods. The footprints of the trackway J is morphologically *Eubrontes*-type (Lull, 1953). As *Eubrontes* is established as Trias-Jurassic taxa, I am cautious for attribution. Thus I use the name with "-type" for describing the outline morphology of footprints. Identification and comparison of well-preserved footprints on this bedding plane to ever described ichnospecies is the subject for future study.

Taphonomical interpretation

Extremely deep imprints of the trackway F, deep imprints of the trackways A, B and G, and normal depth imprints of the trackway N all have clear outlines. These trackways apparently disturbed the sedimentary structure (ripple marks) on the substrate bed. They are deformed to varying degrees by post- imprinting deformation of the substrate bed. However they preserve primary structures such as sharp claw marks, scratch marks of claws, clear hallux impressions and displacement rims. They are regarded as true prints based on those characteristics.

Other trackways and isolated footprints are rather shallow, and not clearly preserved. Thus it is difficult to identify whether these footprints are true prints or underprints.

I estimate the sequences of formation of these imprints as follows. When the bedding plane had been exposed to the air or very close to the water surface level, the trackway F was imprinted while the substrate was still water-saturated (the first phase). Strongly deformed and extremely deep footprints of the trackway F indicate that the substrate was very soft. Then, the substrate dried gradu-

Figure 3. Photograph of the bedding plane. Scale bar is 1m. Footprints B8 and K1 (Figure 4-3) are exposed after the photograph is taken. Thus these footprints do not appear in this photograph.

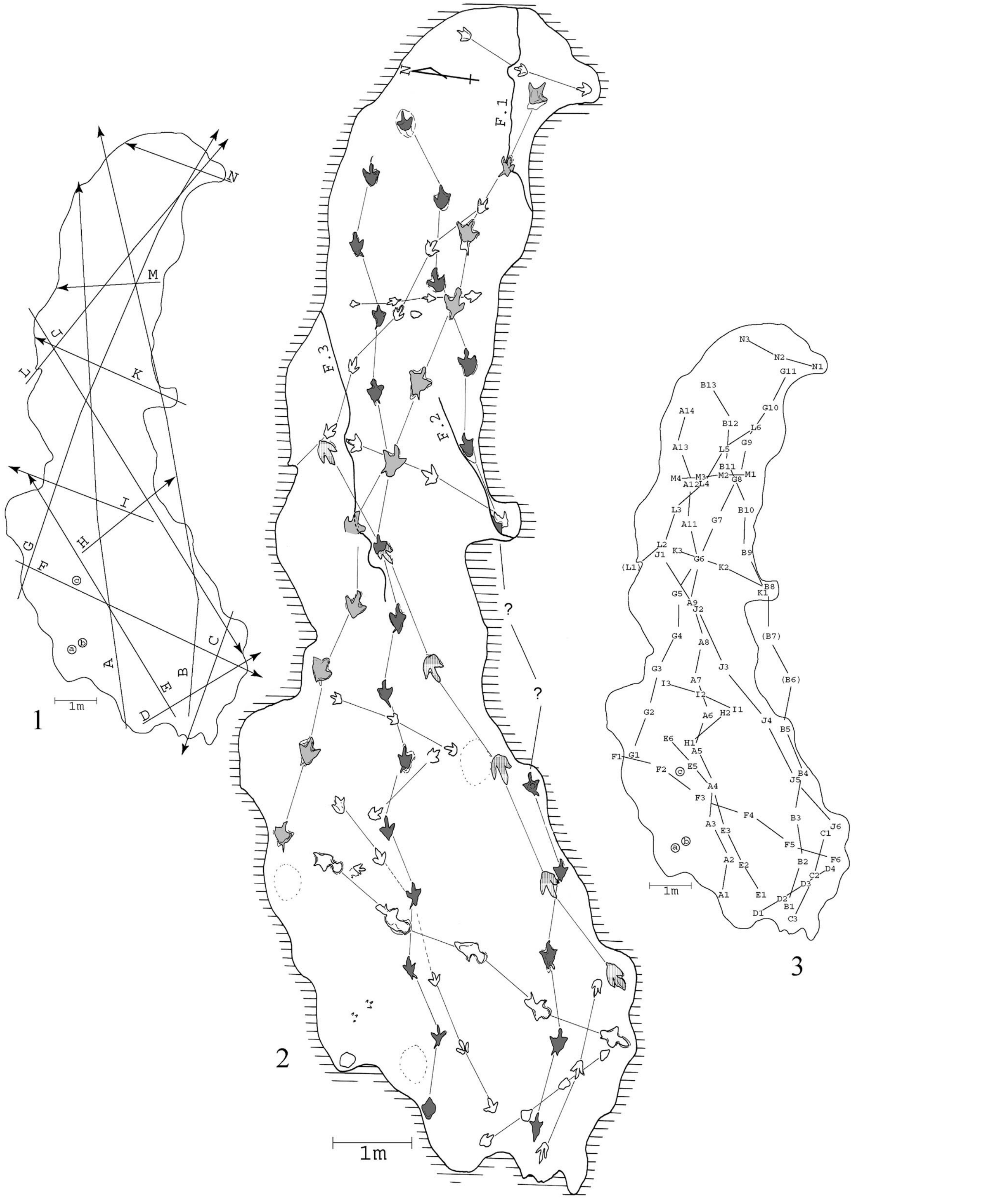

Figure 4. **1**, Distribution of trackways (A through N) and isolated footprints (a, b and c). Arrow denotes the direction of trackway. **2**, Sketch map of the bedding plane. Scale bar is 1 m. Thick solid lines denote small faults 1, 2 and 3 (labeled F.1, F.2 and F.3 in the sketch). **3**, Distribution map of each footprint.

Table 1. Measurement data of trackways and footprints imprinted on the bedding plane.

Trackway code	Number of footprints in the trackway	Trackway direction (°)	Average footprint length (mm)	Average footprint width (mm)	FW/FL (%)	Average footprint depth (mm)	Digital Length of well preserved footprint (mm)				Interdigital angle of well preserved footprint (°)			Average pace length (mm)	Average pace angulation (°)
							I	II	III	IV	I-II	II-III	III-IV		
A	14	79	255	220	86	55	55	130	195	175	108	35	38	90	149
B	13	76	301	251	83	70	58	158	217	198	111	43	39	106	155
C	3	284	236	152	64	17	—	126	168	135	—	17	26	110	167
D	4	143	190	140	74	12	—	?	?	?	—	?	?	64	175
E	6	56	202	179	88	10	—	118	159	145	—	32	23	84	174
F	5	202	463	242	52	95	—	?	?	?	98	46	52	118	163
G	11	112	378	328	87	67	68	205	254	242	118	43	45	99	166
H	2	134	230	165	72	15	—	?	?	?	—	33	43	110	—
I	3	16	170	142	84	15	—	?	?	?	—	36	40	87	173
J	6	233	367	267	73	30	—	232	273	267	—	19	24	155	170
K	3	15	257	229	89	20	—	155	200	168	—	46	32	117	168
L	6	124	220	159	72	12	—	138	162	155	—	37	25	92	158
M	4	350	118	65	55	5	—	75	110	80	—	13	20	52	170
N	3	15	240	179	75	20	—	148	210	175	—	22	23	97	169
F1 (Underprint)	—	—	270	210	76	—	—	155	190	193	—	32	25	—	—

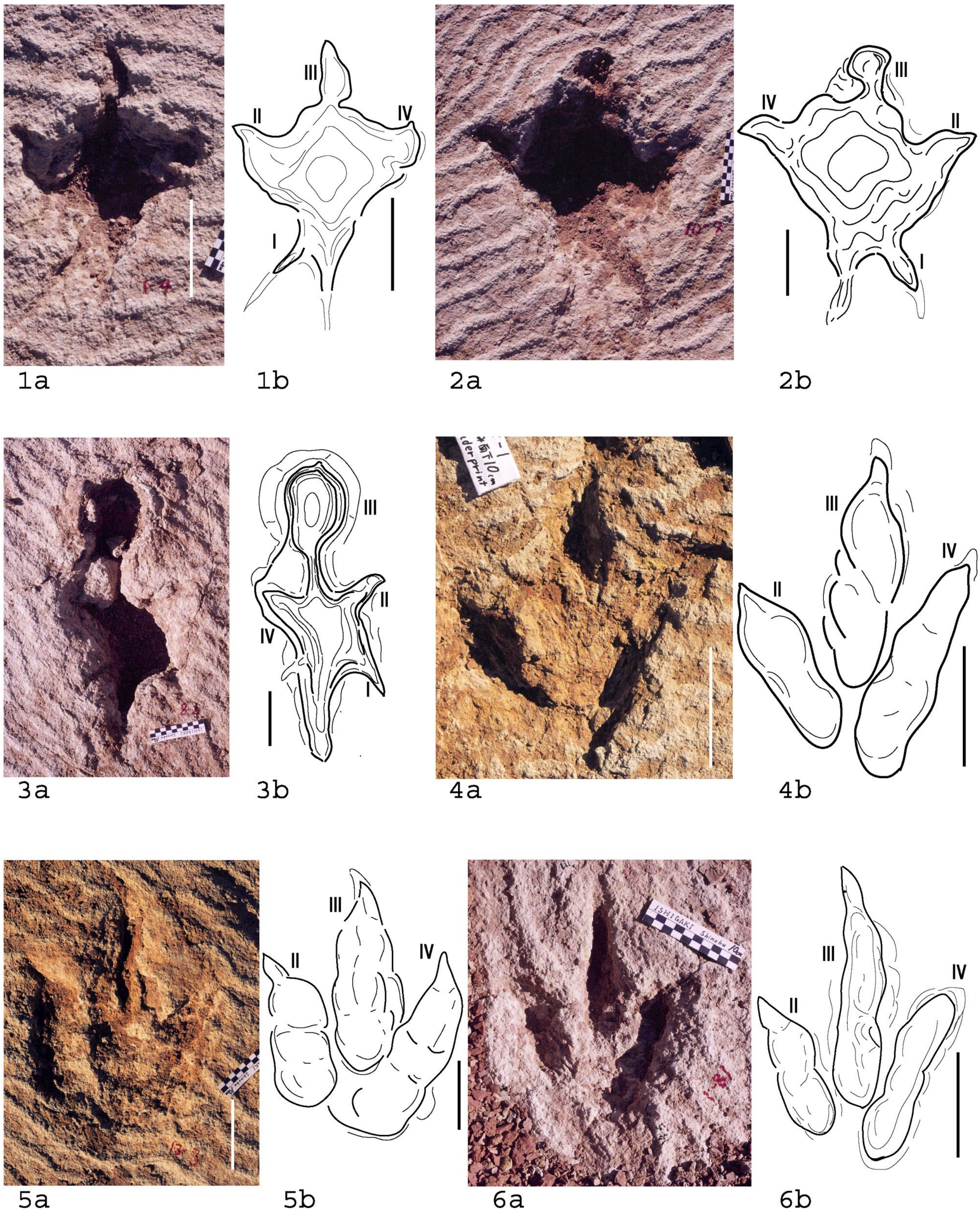

Figure 5. Photographs and drawings of footprints. **1**, Footprint A2 from trackway A: 1a, photo; 1b, schematic drawing. **2**, Footprint G9 from trackway G: 2a, photo; 2b, schematic drawing. **3**, Footprint F2 from trackway F: 3a, photo; 3b, schematic drawing. **4**, Underprint of footprint F1 from trackway F: 4a, photo; 4b, schematic drawing. **5**, Footprint J3 from trackway J: 5a, photo; 5b, schematic drawing. **6**, Footprint N1 from trackway N: 6a, photo; 6b, schematic drawing. Scale bar = 10 cm. Ruler in the photographs = 10 cm.

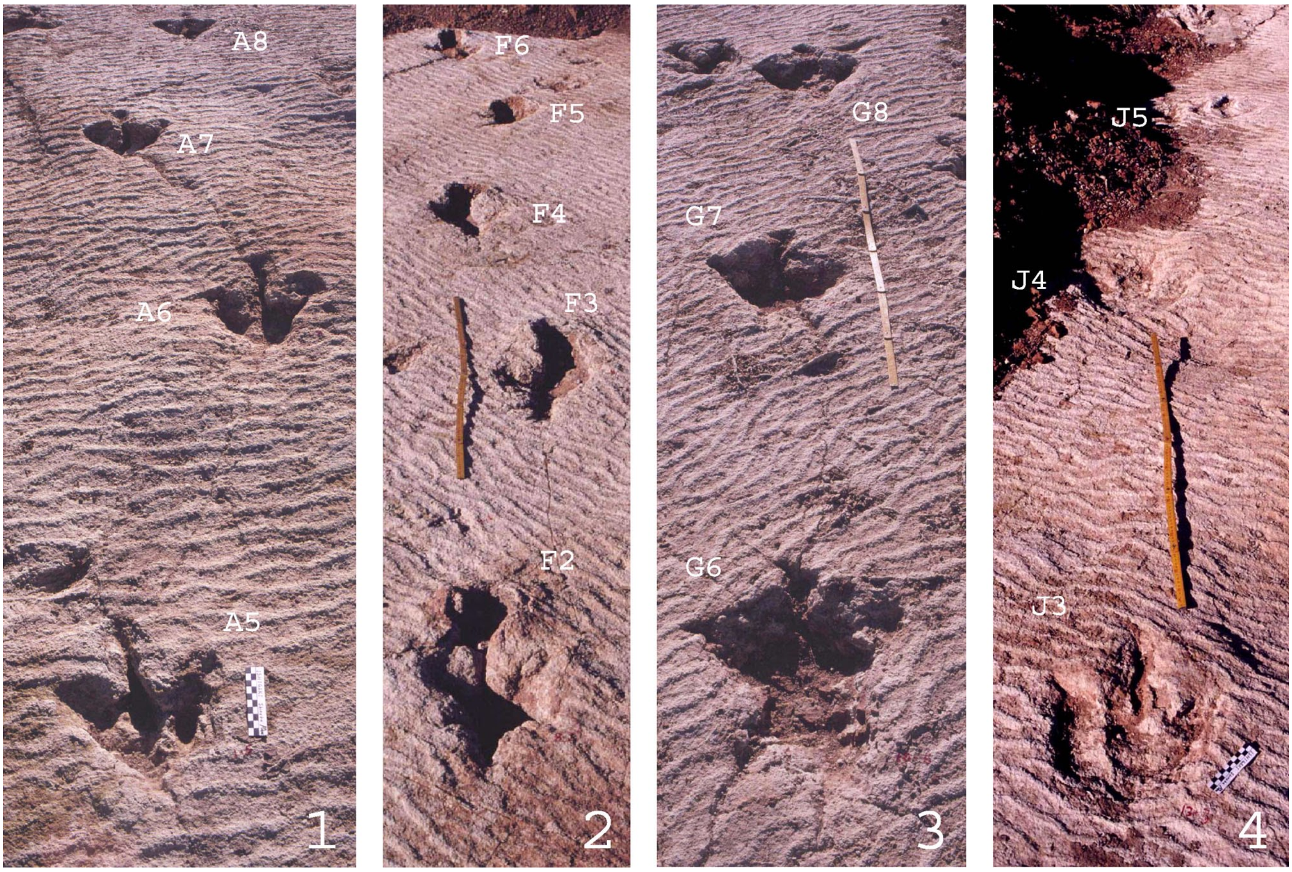

Figure 6. Photographs of trackways from oblique angle. **1**, Trackway A. **2**, Trackway F. **3**, Trackway G. **4**, Trackway J. Ruler in photograph 1 is 10 cm. Scale stick in photograph 2, 3 and 4 is 1 m.

ally. As the second phase, the trackways A, B and G, the second-deep trackways, were imprinted. In the third phase, the trackway N was imprinted on the same substrate. As other footprints are very shallow, there is no clear data for reconstruction of sequence of footprint formation.

Behavior of laborious locomotor

In the trackway F, the footprints are extremely deep and the withdrawal part of digit III is surrounded by displacement rims (Figure 5-3a and b). This fact tells that at the time of withdrawal of the hind-foot, the trackmaker pushed its foot strongly forward removing substrate aside. The trackmaker of the trackway F had to labor against the soft substrate to advance its body, pulling out the foot from soft and sticky substrate. The underprint of the footprint of trackway F (Figure 5-4a and b) is similar size as the footprints of trackways A and B. Thus, I interpret that if the trackmakers of the trackways A and B had walked in extremely soft substrate with laboring, the trackway would become like trackway F.

Parallel trackways

There are three groups of nearly-parallel trackways. They are Group 1 including the trackways A and B; Group 2 with the trackways H and L; and Group 3 consisting the trackways I, K and N. However, the stride, pace angulation, size, shape and depth of footprints in each group are differs from one another. It is too speculative to estimate the gregariousness of the trackmakers on available data at present.

Conclusion

Discovery of the well-preserved footprint and trackways bearing bedding plane is remarkable for investigating the taphonomical process of dinosaur footprints. Deep footprints are not useful for taxonomy, but they are useful for studying the laborious locomotion of the trackmaker on soft substrate. Behavior of theropod on such extraordinary environments shows evidence of characteristic functional movement that had not been preserved on bone fossils (e.g., mode of movement, position of pes on hind limbs when they move forward). Elongated footprints are also useful for investigating the posture of theropods. Ichnotaxonomical studies of well-preserved specimens are the task of future research. Currently, this bedding plane is covered for preservation. As a natural heritage of Mongolia, adequate conservation action on this tracksite should be done. It is for future research and education not only in Mongolia but also in the world.

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