Memoir of the Fukui Prefectural Dinosaur Museum (2002) 1: 7-18

A NEW TECHNIQUE TO ILLUSTRATE AND ANALYZE DINOSAUR AND BIRD FOOTPRINTS USING 3-D DIGITIZER

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ABSTRACT

Footprint morphology is a fundamental and important subject for the classification and paleoecology of the ichnotaxa. Different methods have been applied and produced highly various results of illustrations of the same specimen. Most commonly, ichnofossils have been drawn by professional artists because photographs often lose tiny features of important characteristics. However, the drawn illustration can be very subjective, and notoriously different due to the artists.

In order to draw more objective illustrations, we used the non-contact three-dimensional digitizer (VIVID700) and the software (3D-Rugle). Considering the results by applying this method to several dinosaur and bird footprints from China and Japan, it is confirmed that the applied method is more advanced in reproduction than photographs and in resolution than moiré pictures. The drawn outlines were, in some cases, significantly different from the outlines of the same specimens previously illustrated by artists. Because the method produces digitized 3-D images, it is also advanced in terms of applying numerical analysis. We also evaluated bias of this method due to color of specimens and brightness of shooting locations. White and whitish color of specimens and sunlight stronger than 500 lx cause noises by scattered reflection of laser. For avoiding them and obtaining reproductive results, making darker-colored copies and shading the sunlight are recommended. This method is very successful to get images representing the outlines, sectional profiles and depth of footprints, although it remains problems in judging surface clacks and in analyzing flat footprints.

Key words: paleoichnology, dinosaur footprints, bird footprints, three-dimensional, 3-D image, footprint morphology

荒川洋平・東　洋一・狩野彰宏・谷尻豊寿・宮本隆実 (2002) 恐竜及び鳥類足印化石の三次元形状入力機を用いた新しい描画・解析法．福井県立恐竜博物館紀要 1: 7-18.

従来の足印表現法は主観的要素が多かったため，筆者らは非接触三次元形状入力機と画像解析ソフトウェアを導入した．中国産と日本産の恐竜及び鳥類足印化石に適用した結果，足印形態をより客観的に表現し，得られた足印画像から数値データを得ることが可能となった．今回の手法はレーザー光を用いることから，標本の色や形状入力時の明るさによる三次元データの違いについても検証を行った．標本が白色の場合や太陽光などの強い光線を受ける場合には，足印表面上でレーザー光の多重反射が生じ，正常な結果が得られない可能性があるが，強い光線を遮ったり，標本の色をより黒色にしたりすることによって，正しい計測結果を得ることができる．また，足印表面上の割れ目の判断や，凹凸の少ない足印の解析には，肉眼観察と組み合わせて三次元データを取り扱うことが望ましい．本手法は足印の輪郭描画や断面形態の解析，深さの計測に対して非常に有効であることが明らかとなった．

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INTRODUCTION

We consider that the most important problem of paleoichnology is the method of description, nevertheless few studies have addressed to the methodology. Paleoichnologists commonly face difficulty to determine the shape of the vertebrate footprints. Outline of the same single footprint often differs depending on who illustrate it, although it is a basic character to study the taxonomy and paleoecology of the vertebrate ichnospecies. Ambiguity in illustration causes further problems. This problem is one of the subjects of this study, and to solve this, we use an objective method for illustrating and measuring dinosaur and bird footprints. Although an objective method using a moiré picture has been created (e.g., Ishigaki and Fujisaki, 1989), the result was not very successful. By using a non-contact three-dimensional digitizer, the present method is much more advanced than the previous methods in getting higher resolution. We can measure details of footprint configuration easily by equipment (VIVID700: Minolta Co., Ltd.) and software (3D-Rugle: Medic Engineering Inc.). Moreover, as this equipment is portable, we can record three-dimensional data in the fields. Furthermore, this technique produces the digitized results that can be used for numerical analyses.

In the last two decades, a large number of dinosaur and other terrestrial vertebrate remains have been found in the Hokuriku area, Central Japan. The Mesozoic terrestrial vertebrate-bearing formations in the Hokuriku area belong to the Tetori Group, of Middle Jurassic to Early Cretaceous in age. Especially, many dinosaur footprints are discovered from the Tetori Group. We use them as study material together with a Chinese specimen. This will be the pioneer study using the non-contact three-dimensional digitizer for the dinosaur and bird footprints in Japan, and we make some comments on problems in applying this objective method.

TERMS AND DEFINITIONS

It would be useful for readers to list and define the paleoichnological terms used in this study.

Cast (*convex hyporelief* and *negative footprint*): fillings in a mould. "*Cast*" also means a copy of an original specimen, but in this paper, we call them as "copy"

Mould (*concave epirelief*, *positive footprint*, *mold* and *hollow*): a hollow on the uppermost surface of substrata. *Original print* is the same meaning of *mould*, but in order to avoid confusing the term "original specimen", this paper does not use *original print*.

Total divarication: the angle between digit axes of II and IV.

STUDIED FOOTPRINTS

For three-dimensional morphological analysis, the well-preserved specimens were selected. They are a theropod footprint from China, two theropod footprints and a bird footprint from Japan.

Chinese Specimen

Theropod footprint (Chinese Liaoning Theropod: CLT)

The specimen (Fig. 1A) was collected from the Early Cretaceous of Chaoyang district, Liaoning Province, People's Republic of China. It is the holotype of *Jeholosauripus s-satoi* (IGPS. Coll. Cat. No. 61677: Tohoku University, Sendai, Japan), reported by Yabe et al. (1940a, b) and Shikama (1942). According to the careful study by Zhen et al. (1989), *Jeholosauripus* is considered a junior synonym of *Grallator*, a theropod ichnogenus. The used material is a copy (mould) of the holotype deposited at Toyama Science Museum.

Japanese Specimens

Small theropod footprint (Japanese Toyama Theropod: JTT)

The first dinosaur footprint from Toyama Prefecture was yielded from the Early Cretaceous Tetori Group of Ohyama Town in 1990 (Goto, 1993). In 1994, many footprints from the same group were found at Ohyama Town, and researched (e.g., Matsukawa et al., 1997). The studied material from Ohyama Town was found in August 2001 by the Toyama Dinosaur Research Group. It is an original specimen and its copy of small theropod footprint, exposed on a sandstone layer in the site (Fig. 1B; Toyama Dinosaur Research Group, 2002).

Theropod Footprint (Japanese Fukui Theropod: JFT)

In the Tetori Group distributed in the northwestern part of Katsuyama City (Fukui Prefecture), dinosaur footprints have been found in the Kitadani Formation consisting of mainly alternating beds of thick sandstone and shale interbedded with tuff layers. This studied footprint (FPDM-V137: Fukui Prefectural Dinosaur Museum) is well-defined mould (Fig. 1C), and impressed on the substrate with minimal disturbance.

Bird Footprint (Japanese Fukui Bird: JFB)

The Tetori Group is exposed in the upper reaches of the Kuzuryu River, the easternmost part of Fukui Prefecture. The dinosaur and bird footprints have been found from the upper part of the Itoshiro and the lower part of the Akaiwa Subgroups at six localities in this region (Azuma et al., 1992). The studied footprint (Fig. 1D) was found in a sandstone slab (Fig. 1E: FPDM-V43) from the uppermost part of the Itoshiro Subgroup. It is the holotype of *Aquatilavipes izumiensis* described by Azuma et al. (in this volume). The locality is situated in Izumi Village, and called as Nochino site.

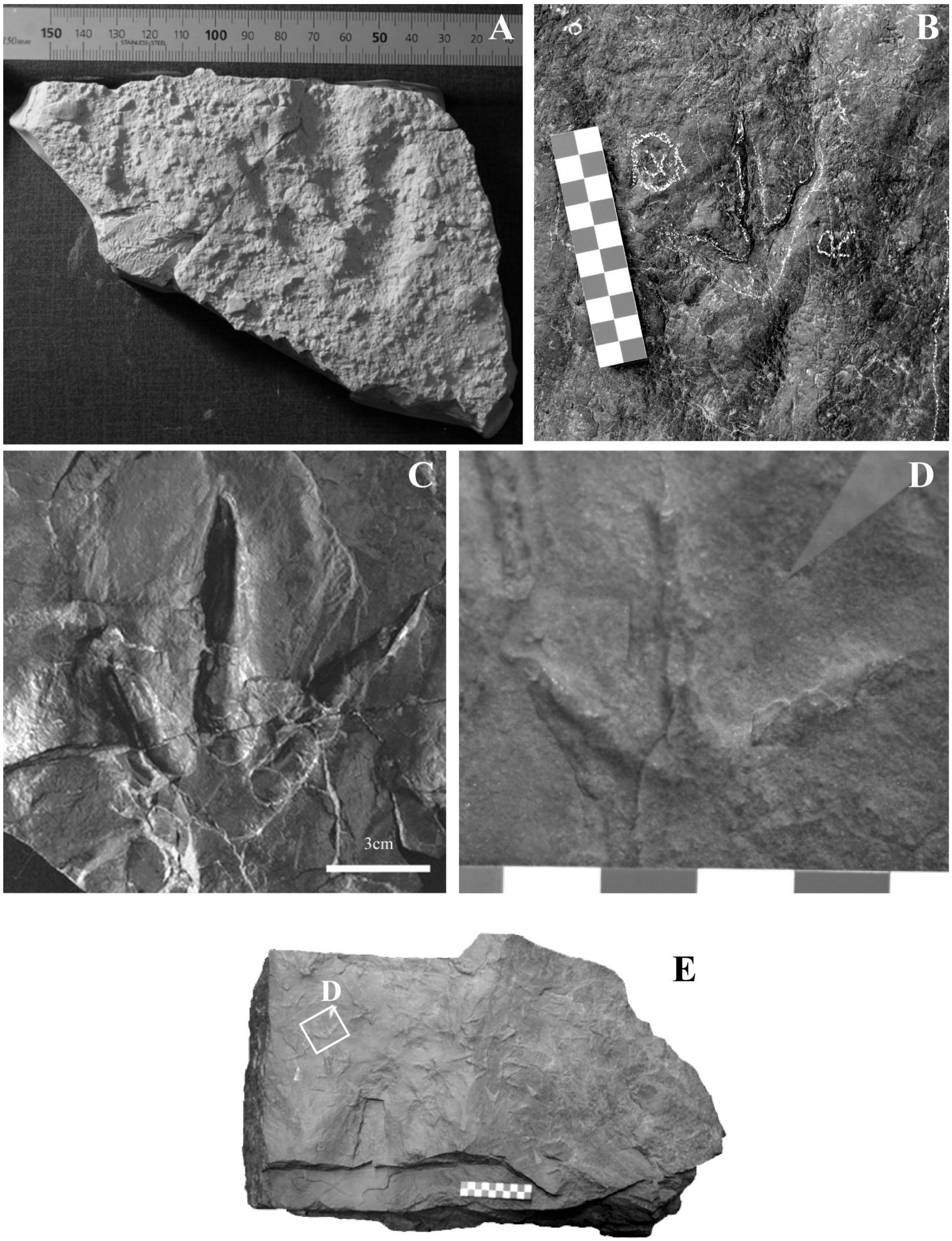

FIGURE 1. **A**, a copy (mould) of *Grallator s-satoi* found from Liaoning Province, China (CLT); **B**, natural mould of the small theropod footprint from Ohyama Town, Toyama Prefecture (JTT). Scale equals 10 cm (Toyama Dinosaur Research Group, 2002); **C**, theropod footprint (mould) from Katsuyama City, Fukui Prefecture (JFT); **D**, holotype (cast) of *Aquatilavipes izumiensis* from Izumi Village, Fukui Prefecture (JFB). Scale equals 1 cm interval; **E**, slab of JFB. Scale equals 10 cm.

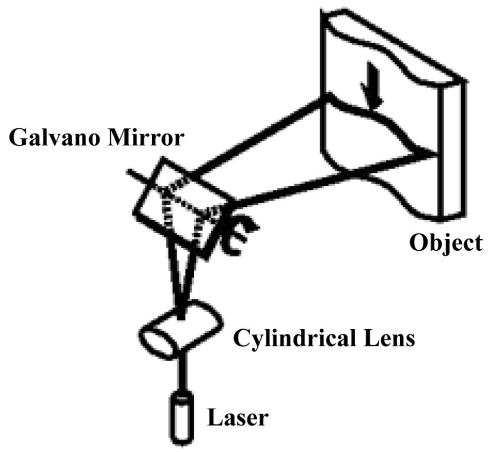

FIGURE 2. Measuring principle of VIVID700 (Minolta Co., Ltd., 1997).

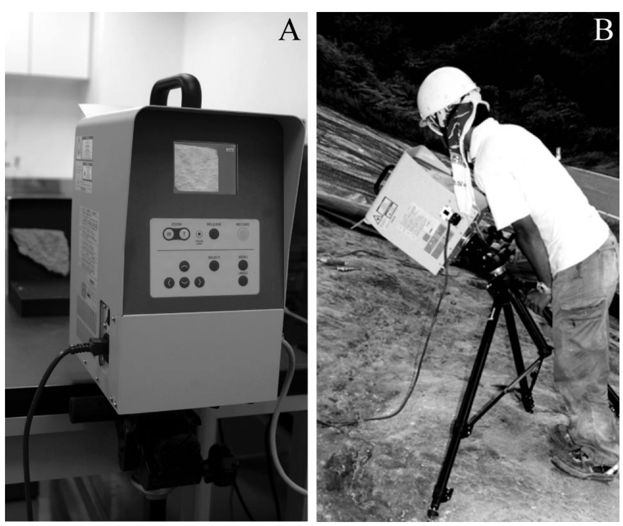

FIGURE 3. **A**, obtaining the 3-D data in the laboratory; **B**, in the field.

METHODOLOGY

Equipments and Software

In order to obtain objective numerical data of dinosaur and bird footprints, a non-contact three-dimensional digitizer (VIVID700: Minolta Co., Ltd.) was used. Measuring principle of VIVID700 is as follows: The VIVID 700 adopts the light-stripe method to emit a horizontal stripe light through a cylindrical lens to the object. The reflected light from the object is received by the CCD, and then converted by triangulation into range data. This process is repeated by scanning the stripe light vertically on the object surface using a galvano mirror, to obtain

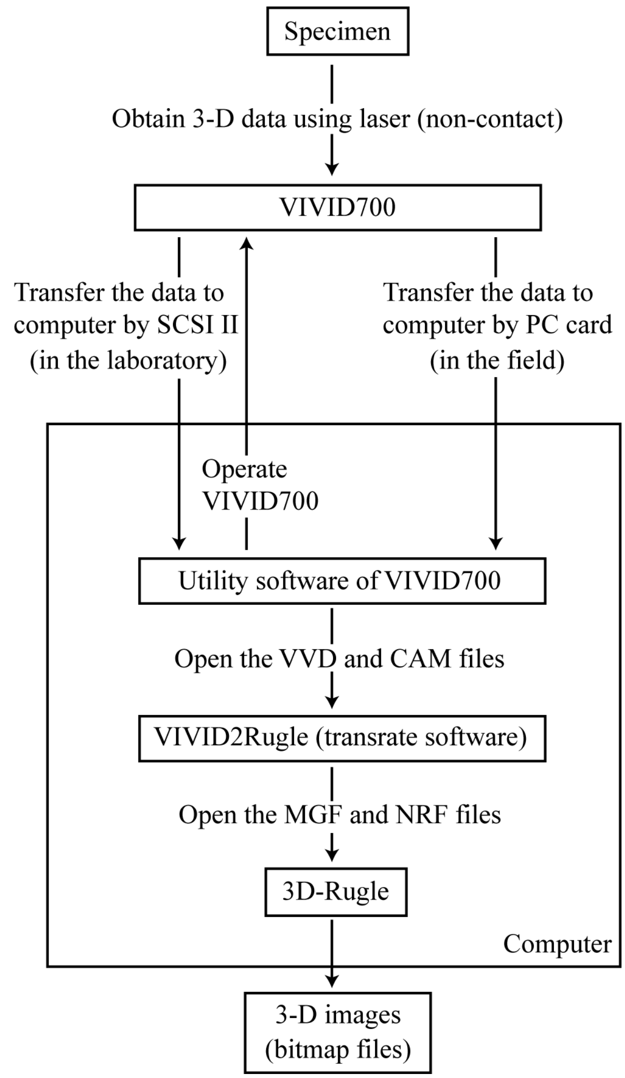

FIGURE 4. Flowchart to obtain 3-D images.

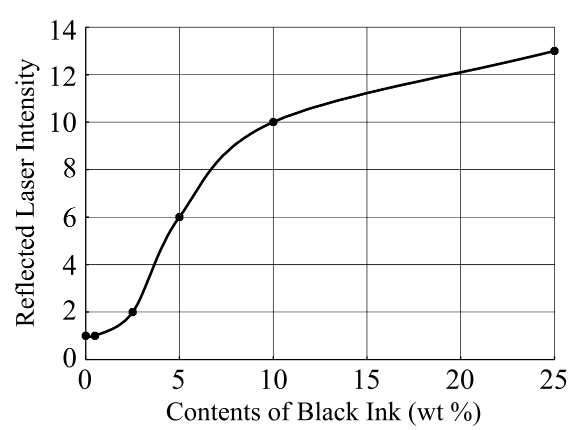

FIGURE 5. Correlation between reflected laser intensity and contents of black ink.

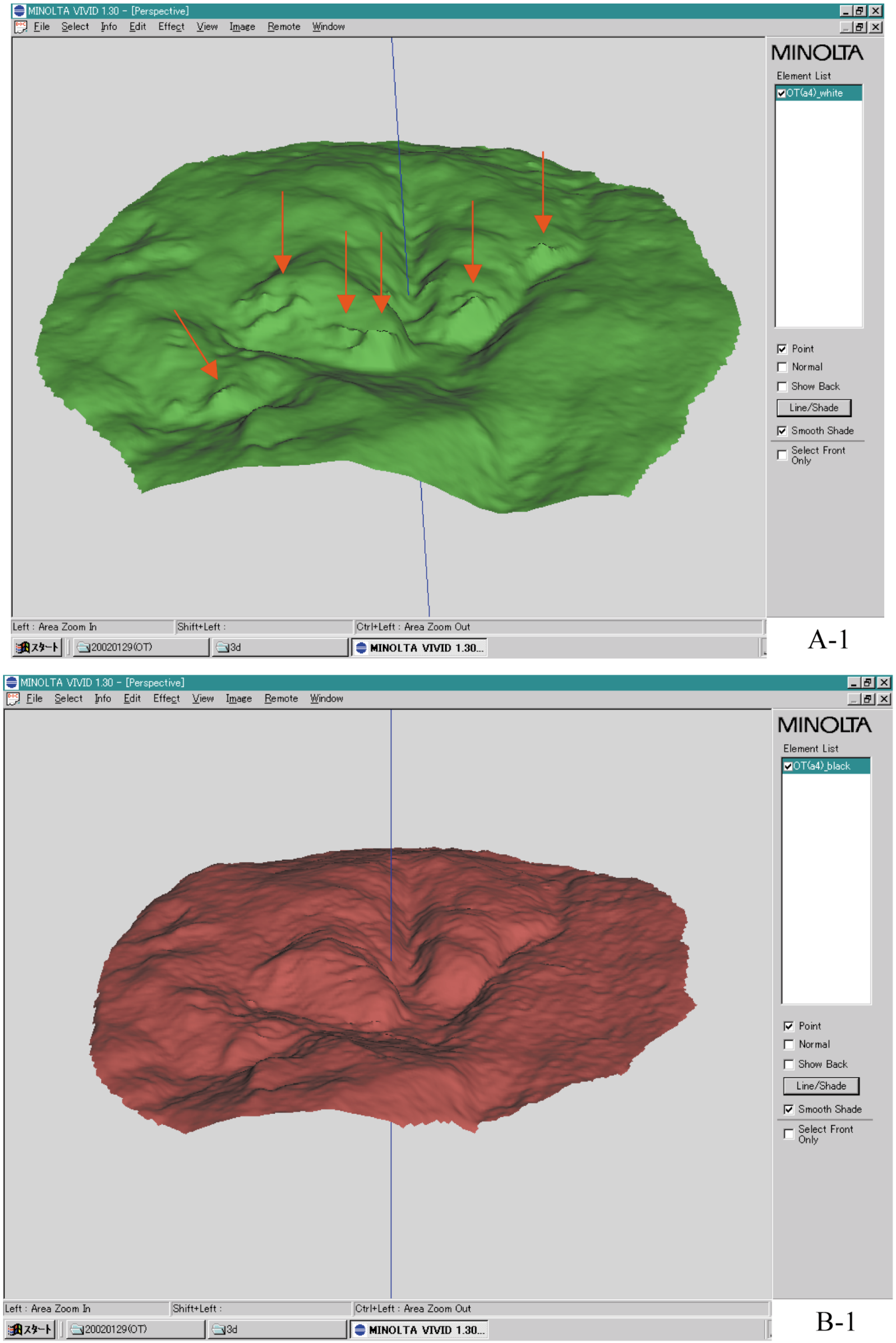

FIGURE 6. Differences of 3-D images between white (**A-1**) and gray (**B-1**) copy of JTT on utility software of VIVID700.

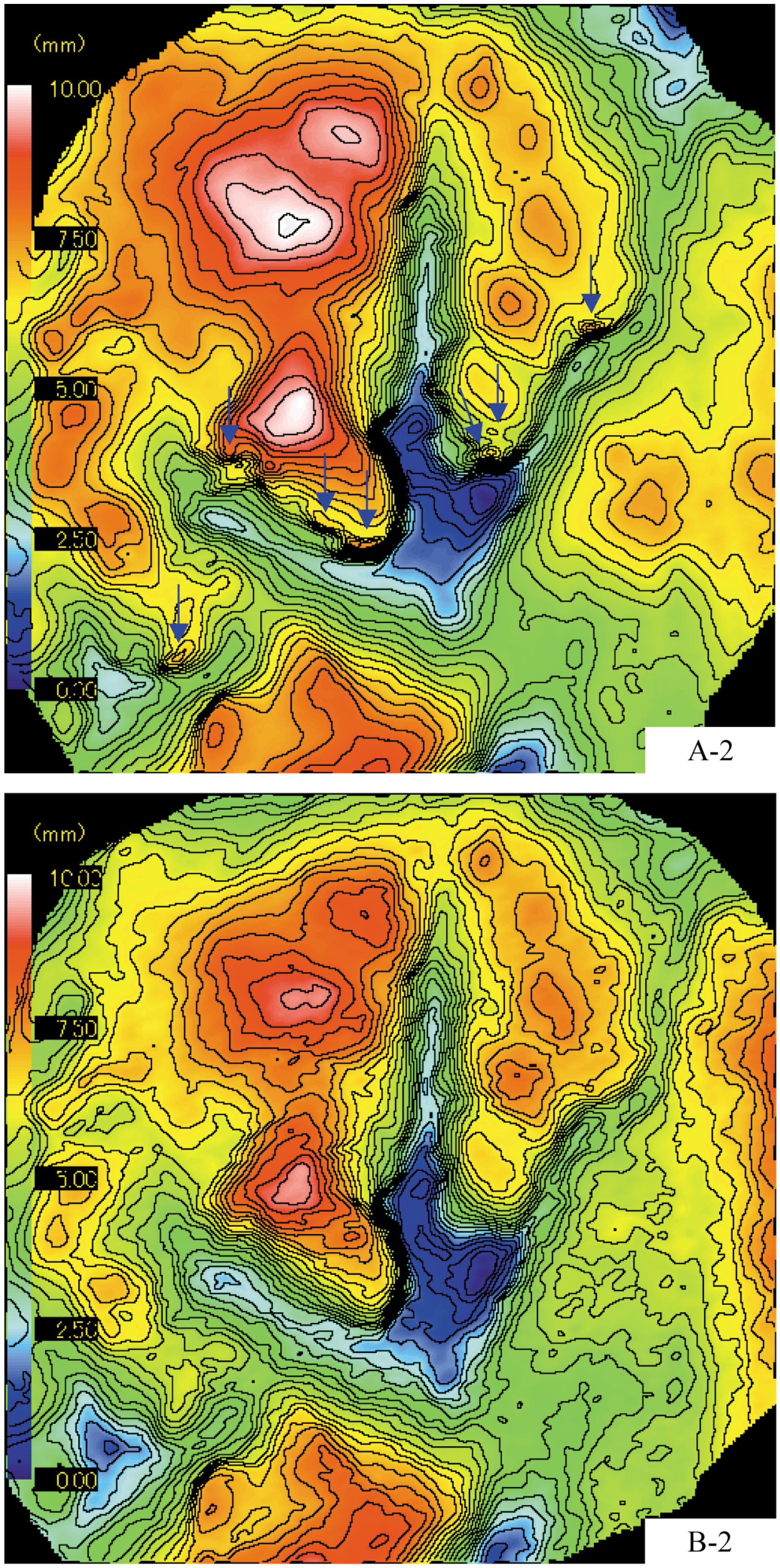

FIGURE 7. Differences of topographic images between white (**A-2**) and gray (**B-2**) copy of JTT on 3D-Rugle.

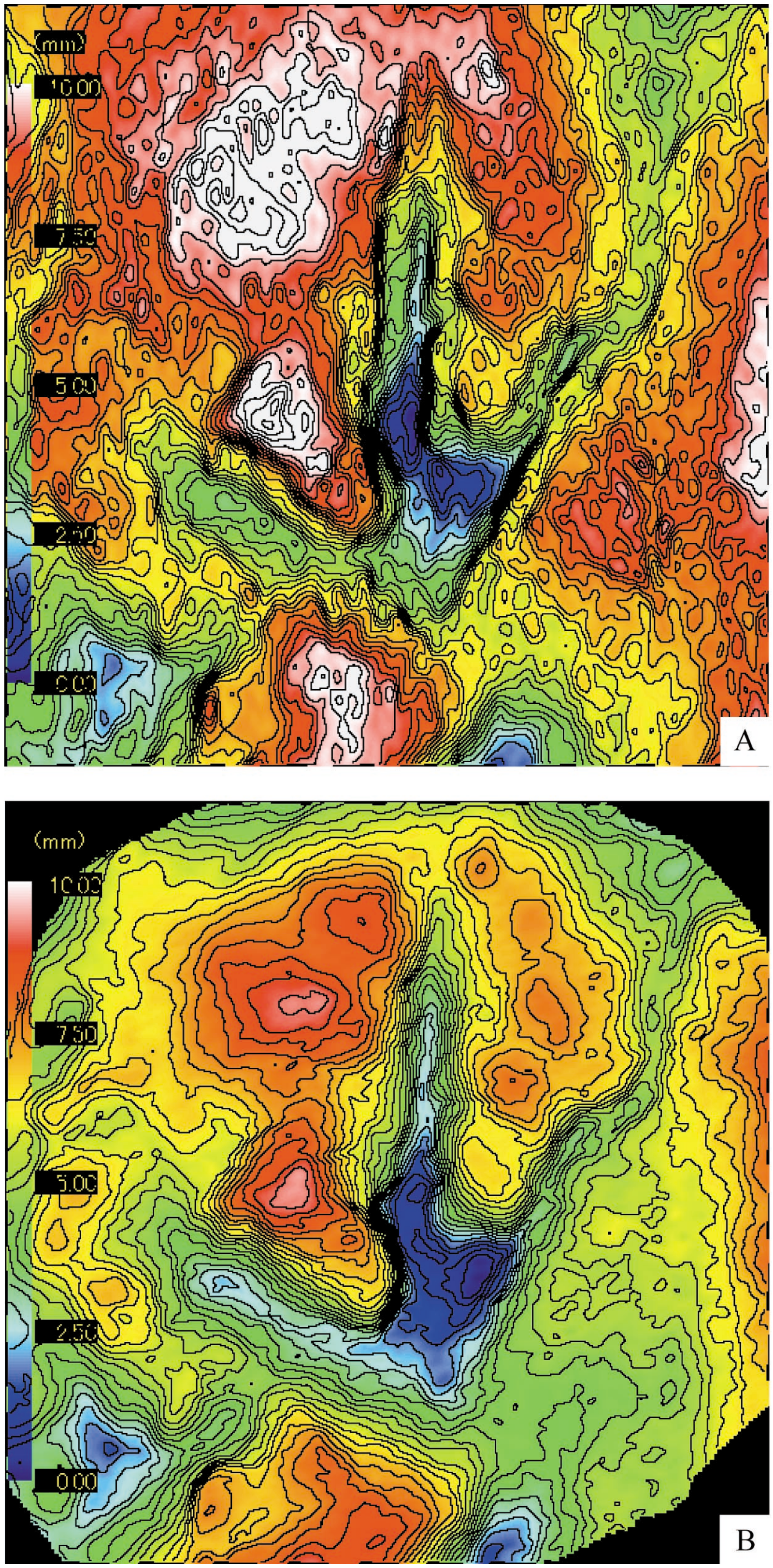

FIGURE 8. Differences of topographic images (JTT) caused by brightness. The image **A** represents a footprint in outcrop and the **B** was obtained from the plaster pigmented with black ink.

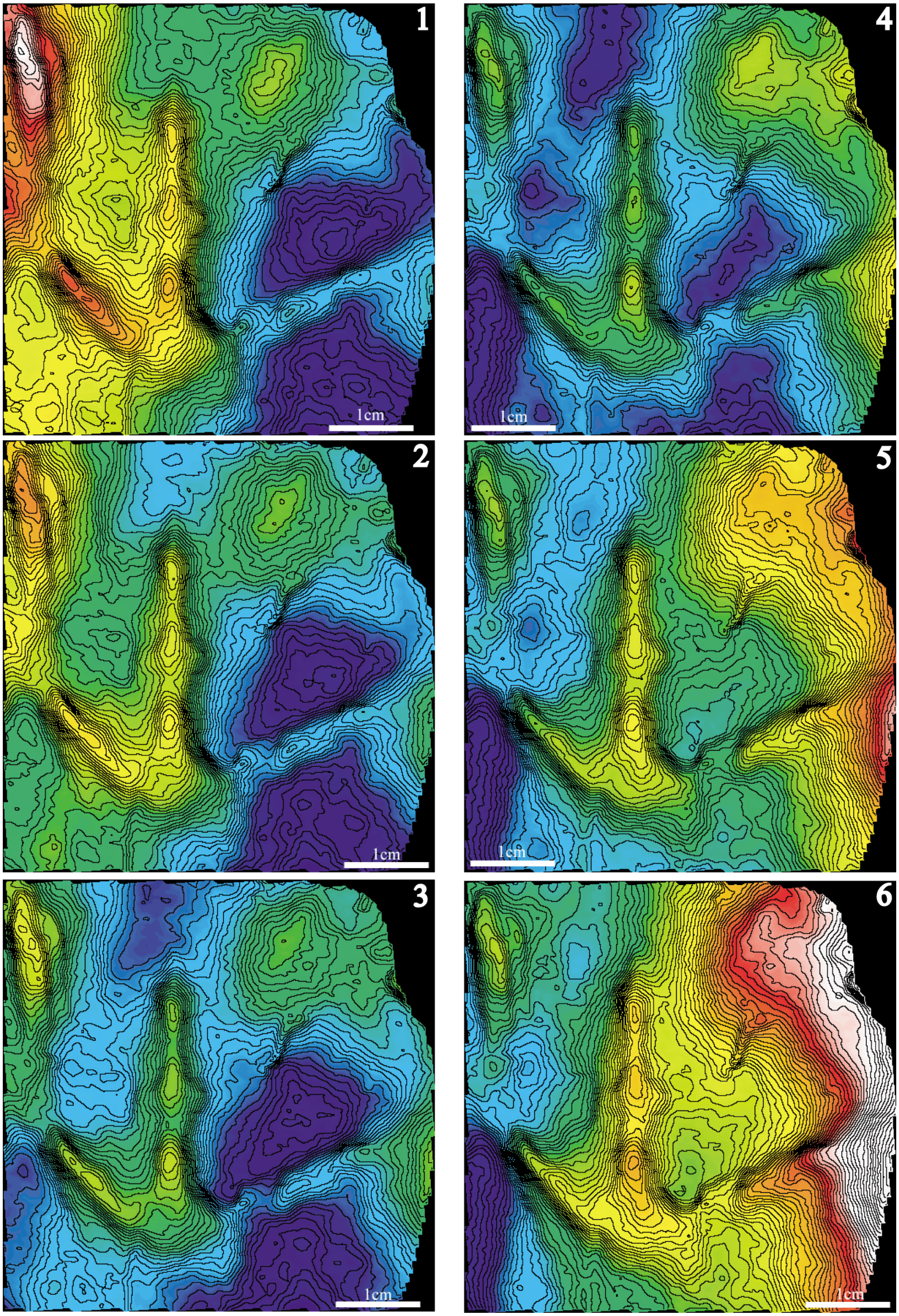

FIGURE 9. Several views of JFB. Contour interval of each image equals 0.1 mm.

a 3-D image data of the object (Minolta Co., Ltd., 1997; Figs. 2, 3A, B). Scanning time of VIVID700 is 0.6 second. The available distance between the digitizer and a specimen is 600-2,500 mm. Accuracy of this digitizer is about ±2-4 % (Isao Kiyofuji, personal communication).

Illustrations are drawn, by using two kinds of software (VIVID2Rugle and 3D-Rugle: Medic Engineering Inc.). The flowchart to obtain 3D images is shown in Fig. 4.

There are two methods of operating: on-line mode and stand-alone mode. In the laboratory (on-line mode), interface between VIVID700 and computer (OS: Windows NT) is SCSI II, and operated by utility software of VIVID700. In the field (stand-alone mode), obtained data is saved in memory card (PC card). Saved data is CAM format, 1.1MB per a file (or one shot). Saved data can transfer to computer by PC card or connection of SCSI II.

Files should be changed to MGF and NRF to be opened by means of 3D-Rugle. DXF or STL files are also available. Data in 3D-Rugle produces various types of illustrations of footprints even as sectional profiles. Moreover, it is able to measure some morphological characters including length, distance, angle, surface-square and volume (OS: Windows 98, Me, NT and 2000). The resolution of the images of this study is much better in comparison with previous studies such as moiré photo.

Technical Aspect

There are some technical problems in procedures of collecting data. To obtain accurate data, disturbance against stable reflection of the emitted laser should be avoided. Degree of the disturbance is due to color of the material and intensity of sunlight. Fig. 5 represents correlation between the reflected laser intensity and object color. X-axis indicates weight percents of black ink of the mixture (water, black ink (POSTER COLOR: Sakura Color Products Corp.) and plaster of Paris) to form a copy, and Y-axis shows intensity of laser reflected from the colored plaster of Paris. It is concluded that darker color gets stronger laser intensity. This is due to the physical property of laser. Figs. 6 and 7 represent differences between white and gray copies in 3-D images of the same footprints. A-1 and A-2 are images from white copy, and B-1 and B-2 are from gray. The 3-D images from the white copy show some noisy spots (arrowed) that are due to scattered reflection of laser. Mixture with 5 % black ink to gypsum is able to avoid the problem (Dr. Sohmura, personal communication) and is recommended. Mixture with 5 % black ink produce laser intensity level 6 (Fig. 5). We follow the Sohmura's technique because of the experiments of this study show whereas copies containing 0 to 3 % black ink show in 3-D images, and produces laser intensity levels 1 to 3. If the laser intensity level is less than 3, it is recommended to make a copy by mixing with 5 % black ink.

Sunlight (or illumination) also affects the three-dimensional data. Recommended level for VIVID700 is less than 500 lx (nearly equal to the standard illumination of laboratory). We tried to obtain three-dimensional data in the fields (Arakawa, 2001). The image A is made of data obtained from outcrop before sunrise and B from copy of JTT (Fig. 8). The image B shows smoother contour than the image A showing noises as closed circles of contour lines. This noises in image A are probably caused by sunlight, and sunlight is more influential than the specimen color in the field (Mitsutaka Nakao, personal communication). Because ranges of wavelength of laser and sunlight are partly overlapped, VIVID700 catches noises of 3-D data even under the sunlight of a cloudy day. To avoid these noises, VIVID700 and an outcrop should be covered by blackout curtain.

Another difficult issue is setting the base plane (X-Y zero surface) of the three-dimensional data on a computer. In this study, position of the base plane is decided using the following procedures: (1) seeking the position to obtain the best view of footprint shape; (2) confined by showing several views of the three-dimensional image. Figure 9 represents the several views of JFB. From image 1 to 6 show the variation of contour and color. These images indicate to be turned on the vertical axis. Among these images, image 2 seems to be the best to show the morphology, because it clearly indicates the distal end of digit IV; and (3) arrangement of Z value using the function of 3D-Rugle. First, distal end of digit III corresponds to posterior end of sole, and then the tip of digit II to tip of digit IV.

If surface morphology of footprints is not clear, it is difficult to draw the outlines. In this case, the outline cannot be drawn by this technique alone, and it should be done by referring the outline by traditional technique (artificial drawing).

This technique has limitation in resolution. Because the distance between two neighboring laser spots is millimeters, finer structures are not recorded in the data.

Comparison with Other Methods

Photographs are very objective and there is no restriction of scale of footprint. The problem is that intensity and direction of light are able to change the image of photographs. When it is cloudy or noon, the shading of photographs is not enough to show accurate three-dimensional image.

Moiré topography (moiré picture) is suitable for three-dimensional representation of dinosaur and bird footprints such as surface morphology and dactyly. Ishigaki and Fujisaki (1989) succeeded in representing the three-dimensional plot of a footprint measured by the automatic computer analysis system and proposing to take moiré pictures during fieldwork. Goto et al. (1996) tried to digitize the dinosaur footprint to topography using computer system. However their pictures (or topographies) did not represent enough resolution to understand the surface morphology in detail. The images of this study are advanced, also in terms of showing colorful and smooth contours. Farlow and Lockley (1993) and Graham et al. (1995)

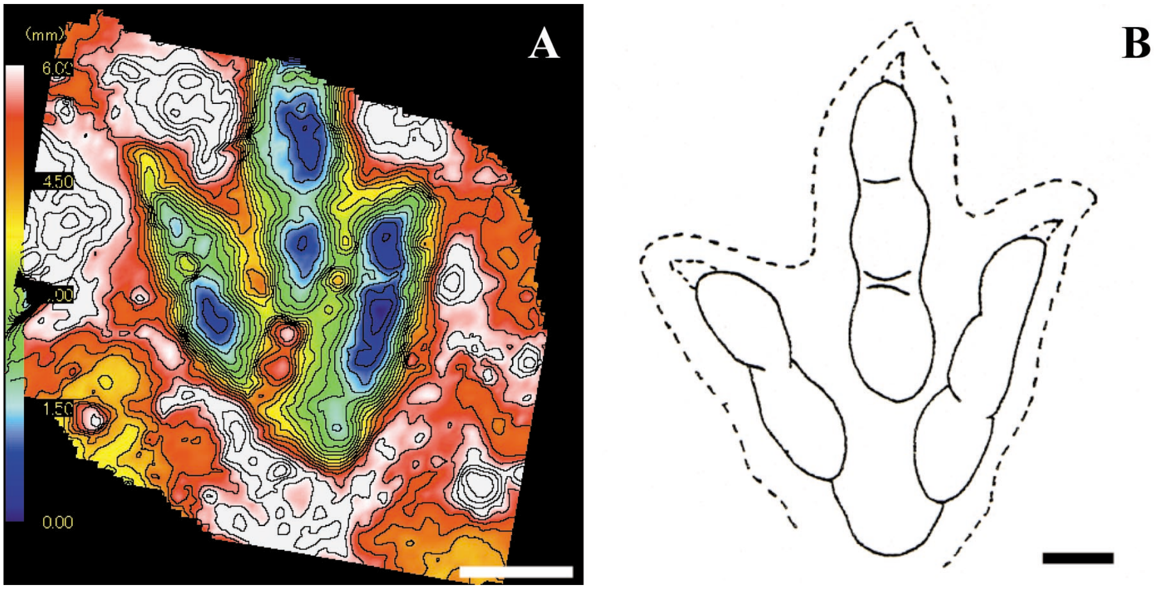

FIGURE 10. **A**, result of CLT. Contour interval equals 0.4 mm; **B**, outline of *Grallator s-satoi* (Shikama, 1942; Zhen et al., 1989). Scale of both images equals 2 cm.

also showed digitized topographic images of dinosaur and mammal footprints, but their technique is slightly different from this study. They used the contact three-dimensional digitizer (3SPACE ISOTRAK) to collect the 3-D data, and succeeded to gain enough resolution to discuss the morphology. However, their method is limited in sized of analyzed specimens and measures mostly through using copies of footprints.

Numerical analysis can be performed much easily in 3-D images using VIVID700 and 3D-Rugle. Not only two-dimensional characters such as footprint length, footprint width and total divarication, but the method of this study can also measure depth of footprints. Furthermore, measurement of angle can be highly objective because of the deepest pads (hollow) are selected automatically.

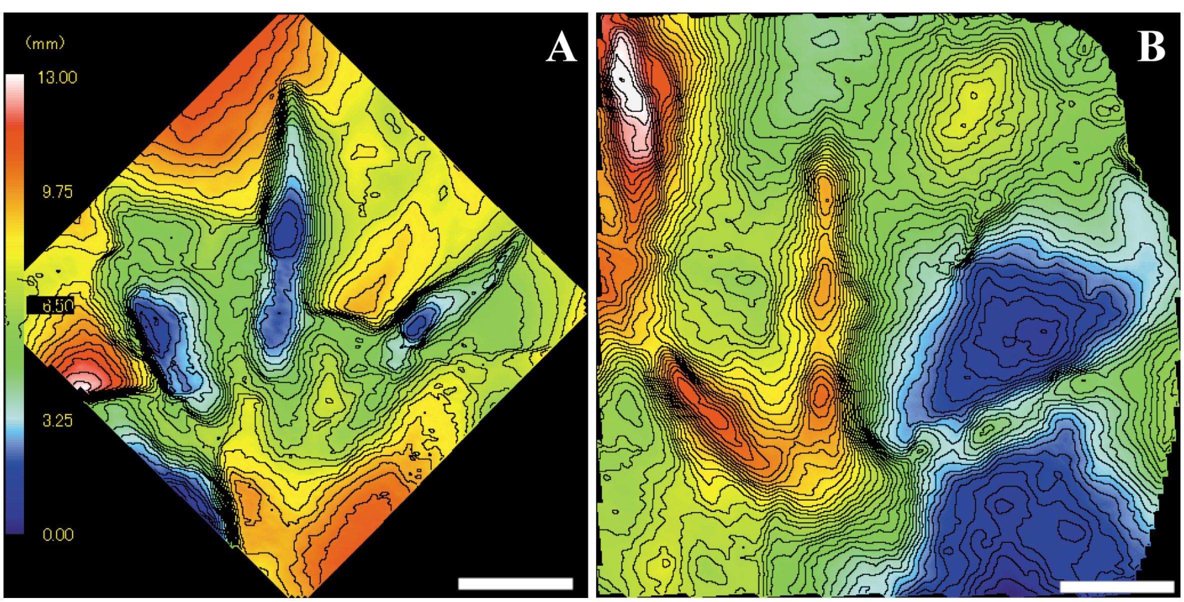

FIGURE 11. **A**, result of JFT. Scale equals 2.5 cm and contour interval equals 0.5 mm; **B**, result of JFB. Scale equals 1 cm and contour interval equals 0.1 mm.

RESULTS AND COMPARISON WITH PREVIOUS STUDIES

CLT (Figs. 1A, 10A, B)

In this study, interdigital angles of the footprint are 21.7º between digit II and III, and 9.4º between digit III and IV that makes the total divarication 30.1º. Depths of digits are 3.4 mm for digit II, 4.6 mm for digit III and 3.5 mm for digit IV. The maximum footprint depth (FD) of this image is 6.5 mm. According to Yabe et al. (1940a, b) and Shikama (1942), interdigital angles of the footprint are 20º between digit II and III, 10º between digit III and IV, and total divarication is 30º. These values are similar to the results of this study. However, previous measurements showed a larger value in FD 10-15 mm. Outline drawn in the previous studies (Fig. 10B) exhibits more slender digit than this study. But, both previous and this study show that two pads in digit II, two or three pads in digit III, and three or four pads in digit IV. The previous studies did not show hypex that was confirmed by 3-D image of this study. Metapodium was also differently recognized by 3-D image. The proximal end of digit IV is not clear, and we agreed with the previous outline of proximal end of digit IV.

JFT (Figs. 1C, 11A)

In this study, depths of digits are 5.5 mm for digit II, 4 mm for digit III and 4.1 mm for digit IV. Interdigital angles are 31.5º between digit II and III, and 41.9º between digit III and IV. Total divarication is 73.3º. According to the measurement using previous technique, the interdigital angles are 32.5º between digits II and III, and 37º between digits III and IV, and the total divarication is 71.5º. These numerical data are similar to the results of this study. Proximal ends of three digits are clear, but metapodium is unclear. Two cracks occur in the footprint. One crack is across the middle of the footprint, another one is along the digit IV. Digit IV looks longer than real due to the crack.

JFB (Figs. 1D, 11B)

Depths of digits are 1 mm for digit II, 0.9 mm for digit III and 0.6 mm for digit IV. Interdigital angles are 51.1º between digit II and III, and 61.2º between digit III and IV. Total divarication is 112.3º. Azuma et al. (in this volume) shows that the total divarication of this specimen is 111º. The result of this study is suitable for the previous study. This footprint is shallower in digit depth and wider in total divarication than other specimens (CLT and JFT).

CONCLUSIONS

1. The applied new technique using 3-D digitizer can provide the high-resolution objective images of the dinosaur and bird footprints.
2. It advances the previous method (e.g., moiré picture) in resolution of images, and in terms of performing numerical analyses.
3. As the equipments are portable, data can be obtained in field.
4. Noises of 3-D data due to the scattered reflection can be avoided, by selecting darker-colored specimens and reducing lightness under 500 lx.
5. The drawn outlines are significantly different from those of the same specimens by the previous studies.
6. Evaluation of footprint depth is reliable on the 3-D image.
7. If footprints are flat (e.g., the mould filled with the sediments), VIVID700 has difficulty in representing the characteristics in the 3-D image.
8. The technique is possible to be applied to another materials (e.g., another kinds of trace fossils, sedimentary structure).

ACKNOWLEDGMENTS

We wish to express our sincere gratitude to Dr. Hiroto Ichishima of the Fukui Prefectural Dinosaur Museum, whose valuable suggestions and critical comments greatly improved the manuscript. Thanks are also extended to Dr. Philip J. Currie of the Royal Tyrrell Museum of Palaeontology, Prof. Dong Zhiming of the Institute of Vertebrate Paleontology and Paleoanthropology, and Prof. Shuqin Zan of the Changchun University for advice of this study. We also wish to thank Dr. Masato Fujita of Board of Education of Ohyama Town, Toyama Prefecture and Mr. Yutaka Tanaka of Toyama Science Museum for providing the materials. We would like to thank Messrs. Isao Kiyofuji and Mitsutaka Nakao of Minolta Co., Ltd. and Dr. James O. Farlow of the Indiana-Purdue University at Fort Wayne for their kind advice on three-dimensional analysis. We also thank Associate Prof. Taiji Sohmura of the Osaka University for kind advice to make copy. We appreciate the kindness of the staff of the Fukui Prefectural Dinosaur Museum.

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* : in Japanese

** : in Japanese with English abstract

*** : in Japanese with English summary

＜地名・地層名＞

Akaiwa Subgroup…………赤岩亜層群
Fukui…………………………………福井
Itoshiro Subgroup………石徹白亜層群
Izumi…………………………………和泉
Katsuyama…………………………勝山
Kitadani Formation………………北谷層
Nochino……………………………後野
Ohyama……………………………大山
Sendai………………………………仙台
Tetori Group…………………手取層群
Toyama……………………………富山