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ALAIN FAUQUEX

3D-Drohnen-Kartierung und Analyse der Lommiswiler Dinosaurier-Fährtenplatte

Zusammenfassung

Während Drohnen in der Industrie bereits weit verbreitet sind, um schwer zugängliche Gebiete zu vermessen, wurde ihr Einsatz in der Paläontologie erst kürzlich eingeführt. Dieses Projekt zielt darauf ab, den Einsatz von Drohnen als Vermessungsinstrument für schwerzugängliche Dinosaurierfährten zu untersuchen. Zu diesem Zweck wurde die Lommiswiler Dinosaurierfährtenplatte mit Hilfe von *Drohnen-Photogrammetrie* 3D-kartografiert und anschliessend ausgewertet. Diese Fundstelle hat sich in der Vergangenheit aufgrund ihrer grossen Fläche, Neigung und starker Steinschlagaktivität als besonders schwierig zu untersuchen erwiesen.

Durch den Einsatz der *Drohnen-Photogrammetrie* war es erstmals möglich, das gesamthaft 9500 m^2 grosse Gelände des mittleren und östlichen Lommiswiler Steinbruchs vollständig zu kartieren. Die Zahl der identifizierten Dinosaurierfussabdrücke konnte von 450 auf 806 und die Anzahl Fährtenwege von 7 auf 9 erhöht werden. Alle Fährten wurden sowohl mit digitalen Höhenmodellen als auch mit Übersichtskarten dokumentiert.

Eine spurentragende Schicht, die mehrere Meter unterhalb der Hauptplatte liegt, wurde zum ersten Mal kartiert. Obwohl bisher angenommen wurde, dass diese ausschliesslich sogenannte «Unterspuren» trägt, deutet eine im Rahmen dieser Arbeit durchgeführte Analyse der Umgebung des Fährtenbettes darauf hin, dass es sich bei diesen um «eigentliche Spuren» handelt, die zu einem früheren Zeitpunkt als die bisher bekannten Spuren erzeugt wurden.

Die Morphologie der Fährten und die Grösse der Fussabdrücke legen nahe, dass die Fährtenleger zu einem der grössten bisher entdeckten Sauropoden Spezies gehörten. Durch die Vermessung der Fährten konnte eine Hüfthöhe von circa 3,3 m bis 6,4 m berechnet werden. Durch den Vergleich der Spuren mit dem *Ichnospezies Breviparopus taghbaloutensis*, kann eine Fährtenlegerlänge von 33 m bis 37 m und eine Körpermasse von 62 t geschätzt werden. Es scheint zwei Gruppen von verschieden grossen Fährtenlegern gegeben zu haben, die sich in einem lockeren Verbund bewegten.

Diese Studie zeigt, dass die Drohnen-Photogrammetrie ein äusserst effektives und kosteneffizientes Werkzeug zur Kartierung und Analyse von grossen, schwer zugänglichen Dinosaurierfährten ist, welches die Erstellung genauer 3D-Modelle und eine unvoreingenommene Datenerfassung und Analyse ermöglicht.

Die vorliegende Arbeit wurde als Maturitätsarbeit 2020/21 an der Aargauischen Maturitätsschule für Erwachsene (AME) in englischer Sprache verfasst und wird deshalb nachfolgend in ihrer Originalsprache abgedruckt. Sie ist in ungekürzter Version auf Anfrage beim Autor erhältlich.

3D Drone Mapping and Analysis of the Lommiswil Dinosaur Tracksite

Abstract
While drones are already widely employed in industry to survey expansive areas, their application has only recently been introduced to the field of paleontology. This project aims to explore the use of consumer-grade drones as a surveying tool for difficult-to-access dinosaur tracksites. This was done by 3D mapping and subsequently analyzing the Lommiswil dinosaur tracksite using *drone photogrammetry*. In the past, this site has proven to be particularly difficult to examine due to its large area, stark inclination, and heavy rockfall activity.

By utilizing *drone photogrammetry*, it was possible to fully map the middle and eastern section of the 9500 m^2 tracksite for the first time. The number of identified footprints was increased from 450 to 806. Two new trackways were described, increasing their number from the previously reported seven to nine. All trackways were documented with digital elevation models as well as outline maps.

A track-bearing stratum several meters below the main tracksite was 3D mapped for the first time. Although previously thought to exclusively bear under tracks, an analysis of the track bed's surroundings suggests that the impressions are true tracks.

Trackway morphology and footprint size suggest that the trackmakers of the main tracksite belonged to one of the largest species of sauropod yet discovered. By measuring the trackway parameters of all nine trackways, it was possible to calculate

the trackmakers' hip heights to be between 3.3 m and 6.4 m. By comparing the tracks with the ichnospecies *Breviparopus taghbaloutensis*, a trackmaker length of 33 m to 37 m and a body mass of 62 t can be estimated. There seem to have been two size groups of trackmakers that walked in a loosely connected group.

This study demonstrates that drone photogrammetry is a highly effective and cost-efficient tool for mapping and analyzing large-scale and difficult-to-access dinosaur tracksites. It enables the creation of accurate 3D models of the tracks and their surroundings and facilitates their comprehensive and objective analysis.

The present article was initially written as a Matura thesis 2020/21 at the Aargauische Maturitätsschule für Erwachsene (AME). The unshortened version is available upon request from the author.

Contents

1. Introduction

In the fossil record, the preservation of dinosaur remains occurs typically in either of two ways: direct preservation of body fossils or indirect preservation of traces left behind by the animal (THULBORN, 1990). While skeletal remains provide essential information about dinosaur anatomy, trace fossils play a crucial role in understanding biomechanical processes such as locomotion and shed light on their social behavior, including herding and nesting. Among the various forms of trace fossils, foot imprints stand out as some of the most common. These imprints were formed as dinosaurs walked upon soft, malleable substrates such as wet sediments. Over time, sediment deposits or algal growth acted as protective layers, preventing erosion of the imprints. The gradual accumulation of sediments eventually led to the transformation of the substrate into sedimentary rock through compaction and cementation (THULBORN, 1990).

At the Lommiswil tracksite, all tracks are of sauropodian origin, as documented in multiple studies (MEYER, 1990; MEYER 1993; MEYER & THÜRING, 2003). These dinosaurs featured long necks and tails, small heads, and robust pillar-like legs.

The tracks they left behind often exhibit distinct features: notably, triangular to round-shaped hindfoot imprints (known as pes imprints) and the smaller halfmoon-shaped front foot imprints (known as manus imprints). Often, each stride's manus and pes imprint are grouped in pairs of two (THULBORN, 1990; LOCKELEY & MEYER, 2000) (See Figure 1).

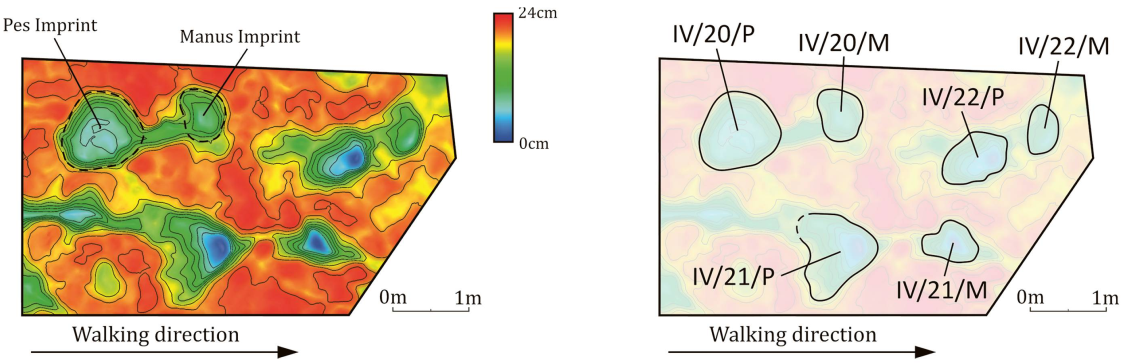

Figure 1: Left: Segment of the digital elevation model of track IV, depicting the imprints from IV/20/P to IV/22/M. Contour lines have spacing of 2 cm. Right: Same trackway segment, overlain with imprint labels and outline map.

In recent years, the market for commercial drones, such as quadcopters, has expanded significantly (INSIDER, 2022). While the cost of these unpiloted aerial vehicles (UAVs) has drastically decreased, their performance has significantly improved. High-capacity batteries, smart collision avoidance sensors, and high-resolution cameras make drones ideal for the survey of large, hard-to-access areas (EISENBEISS, 2009). *Ground-based photogrammetry* (using handheld cameras) has been standard practice in mapping tracksites for several years (FALKINGHAM, *et al.* 2018; MARTY, *et al.* 2012). *UAV-photogrammetry*, however, has only been introduced to the field on a broader level relatively recently (PETTI, *et al.* 2018).

This project aims to investigate the use of consumer-grade drones as a surveying tool for difficult-to-access dinosaur tracksites. This was done by mapping the Lommiswil dinosaur tracksite using the process of *drone photogrammetry*, where photos of the site taken from different directions are combined to generate three-dimensional models. These models were subsequently used to analyze the site scientifically, which provided a number of new insights about the trackmaker. All models were published on the internet and can be downloaded for free, which preserves them for coming generations, as heavy erosion threatens to destroy the site.

In addition to being subject to intense rockfall activity, the Lommiswil tracksite is starkly inclined (45°–50°) and therefore impossible to enter without climbing gear. Historically, the site had to be mapped using a labor-intensive and expensive method involving the application of black color over the imprints followed by aerial photography via helicopter (MEYER, 1993). This was extraordinarily costly and time-consuming, but the only feasible way to map the location at the time. In contrast, by utilizing a drone, it was now possible to 3D map the entire tracksite in mere hours and at a fraction of the cost. All trackways were thoroughly measured and analyzed using several different computer programs.

2. Study Site

2.1. Geographic Setting

The tracksite is situated inside the «Steingrueben» quarry near the northeastern end of the folded Jura, approximately 5.5 km north of Solothurn. While officially falling within the administrative boundaries of Oberdorf's municipality, it is often referred to as being in Lommiswil (MEYER, 1990; MEYER, 1993; MEYER & THÜRING, 2003), due to its proximity to the town of Lommiswil. It lies on the southeastwards dipping face of the Hasenmatt, a mountain peak of the Weissenstein chain. It can be accessed from the «im Holz» train station in Lommiswil via a 20-minute walk (Coordinates of the site: 47°14′11" N, 7°28′33" E).

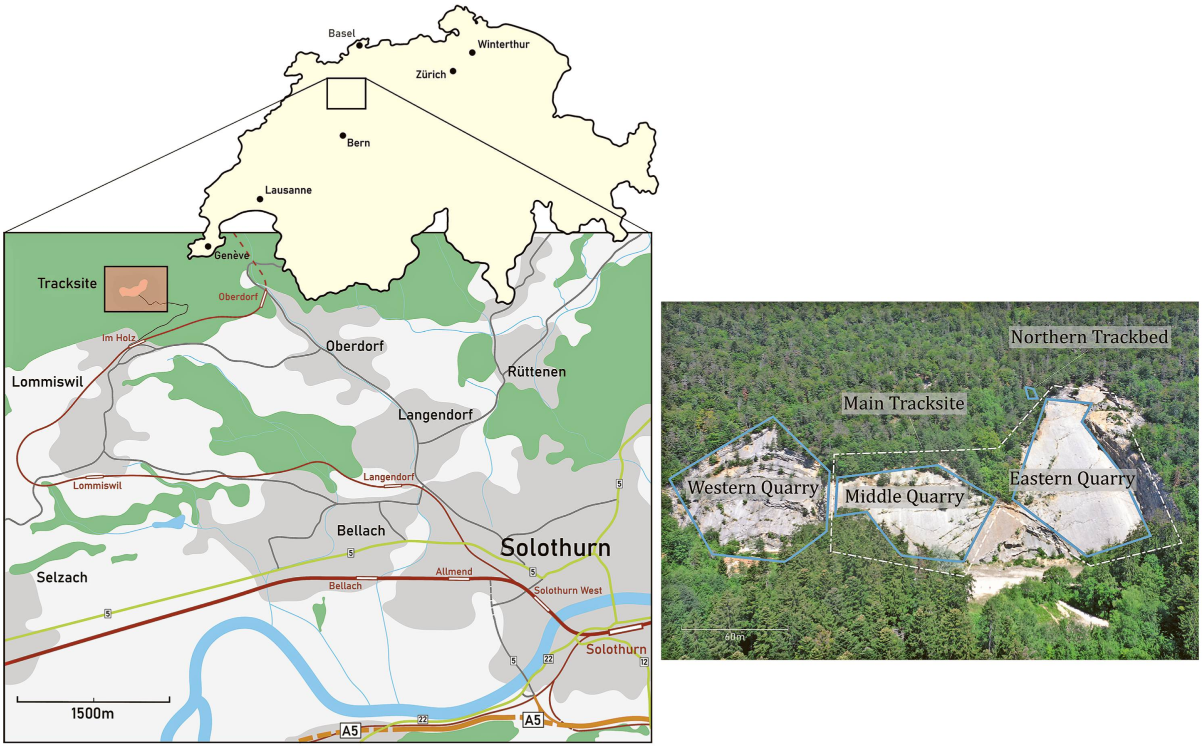

Figure 2: Location map of the tracksite. Tracksite is located around 1.2 km north of the town of Lommiswil, Canton of Solothurn, Switzerland.

In previous studies, solely the tracks of the easternmost part of the quarry were mapped (MEYER, 1990; MEYER 1993), which rendered the need for names for the other quarry sections unnecessary. However, given that a larger area of the quarry was now surveyed, the introduction of names for the different quarry sections was required. In this study, the three quarry sections are referred to as western, middle and eastern quarry. The main tracksite is made up of the middle and eastern quarry. A rock slab bearing several dinosaur imprints is located right above the eastern quarry and referred to as northern trackbed (See Figure 2).

Access to the northern trackbed is possible via a hiking path leading to the upper part of the eastern quarry. No drone photogrammetry was carried out on the western quarry section.

2.2. Geology

The Steingrueben quarry is composed of limestone layers that slope southeastward, ranging in thickness from 0.1 m to 5 m. The Solothurn Turtle Limestone, the main trackbed, and all other layers exposed by the quarry below the trackbed belong to the Reuchennette formation. Along the quarry's eastern margin, above the Solothurn Turtle Limestone, one can observe thinly stratified layers, which mark the lower boundary of the Twannbach formation (MEYER, 1993). The Reuchenette formation around Solothurn is around 40 meters thick and is underlain by the Balstahl formation. It is comprised predominantly of white limestone formed from microscopic calcareous particles (micrite) (MEYER, 1993).

Using the index fossils *Aulacostephanus (pararaseina) quenstedti* and *Gravesia polypleura*, found at the top of the Reuchenette formation (MEYER, 1993) and *Orthosphinctes (Lithacosphinctes) evolutus*, found at its base (GYGI, 1986), it was possible to date the formation's origin to the Jurassic, more specifically the Kimmeridgian. (Approximately 157.3–152.1 million years ago (WALKER *et al.*, 2018)).

Fossils of gastropods, *Dasycladaceans* (green algae), and benthic foraminifera can be found throughout the entire formation (MEYER, 1993). Several sauropod tracks, as well as mud cracks, can be found along the main slab exposed by the quarry. Along the entire surface of the western part of the eastern trackside, one can observe *Thalassinoides* (burrows of crustaceans preserved as trace fossils), while in the eastern part, they are limited to the inside of sauropod tracks (MEYER, 1993). A number of faint sauropod foot imprints can be found on an exposed rock slab below the main tracksite in the northern part of the quarry.

2.3. Paleoenvironment

Fossilized remains of *stromatolithes* and *dasycladaceans* found in the sedimentary layers above and below the tracksite (MEYER, 1993), along with sea turtles, sharks, and crocodilians found in the strata directly above the track-bearing plate close to the site (MEYER, 1994), indicate a tropical, shallow, lagoonal environment. The tracksite was located atop the so-called «Jura platform», a carbonate

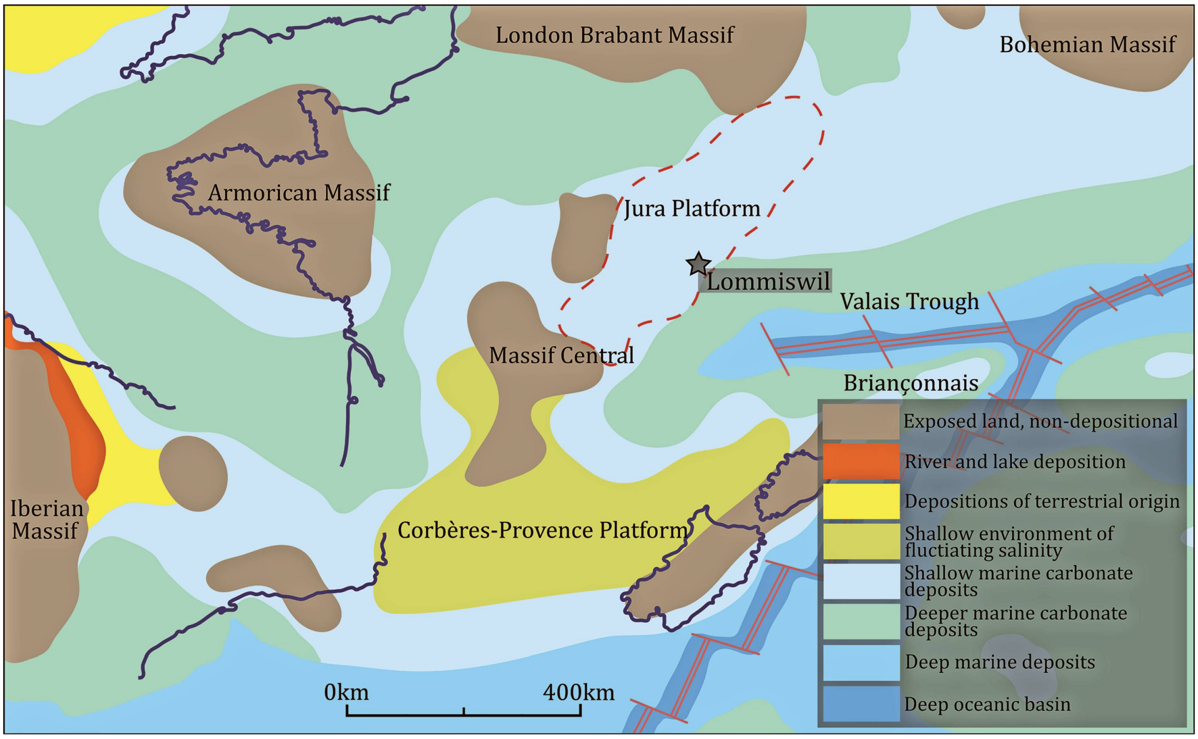

Figure 3: Map of the depositional areas of the northern margin of the Tethys Ocean (modified after THIERRY, 2000).

elevation of the Tethyan seafloor. Stratigraphic analyses have revealed that the earth generally experienced a rising sea level during the Jurassic period (BILAL, 2017). However, it has been established that sea level fluctuations (MEYER & MARTY, 2014), have resulted in multiple drops of the global sea level (JANK *et al.*, 2006). A number of these drops have evidently exposed portions of the platform (DIEDRICH, 2011). In the past, it was thought that the platform merely emerged from the ocean locally, resulting in the formation of islands. However, the recent discovery of land plants, very large dinosaurs in several different strata, as well as freshwater bodies suggest the Jura Platform has, on several occasions, formed a landmass of substantial extent, possibly even a land bridge between the Central and the London Brabant massif (MEYER & MARTY, 2014; DIEDRICH. 2011) as indicated in Figure 3. Several smaller dinosaur tracksites, located in the same stratigraphic layer as the Lommiswil tracksite (MEYER, 1993; MEYER & HAUSER, 1994) were found in the vicinity of Lommiswil, suggesting the presence of a hundreds of square kilometers large «mega tracksite» in the region (MEYER, 1993; MEYER & THÜRING, 2003).

2.4. Trackmaker

Track fossils, referred to as ichnites, can be distinguished by their morphology. Ichnites originating from the same species of animal are grouped into so-called ichnospecies.

Meyer has noted (MEYER, 1993), that the trace fossils found at the Lommiswil tracksite resemble the ichnospecies *Breviparopus taghbaloutensis*, which was found in deposits of the early Cretaceous in the Moroccan High Atlas. Some footprints found in Morocco exhibit a medially directed thumb-claw, implying that the trackmaker could have been of the Brachiosaur genus. However, recent investigations indicate that the Moroccan tracks could also have been produced by a very large member of the *Diplodocus* genus (MOLINA-PÉREZ & LARRAMENDI, 2020). The Moroccan pes imprints have a length of around 1 m and manus width of around 50 cm (RODGERS & WILSON, 2005). Estimations for the trackmaker responsible for the Moroccan tracks suggest a length ranging between 33 m and 37 m, with a minimum mass of 62 tons, positioning it among the largest dinosaurs ever discovered (MOLINA-PÉREZ & LARRAMENDI, 2020).

While sharing similarities with *Breviparopus taghbaloutensis*, there is not enough evidence to place the Lommiswil tracks in this ichnospecies beyond any reasonable doubt (MEYER, 1993). This is mainly owed to the tracks' poor preservation state. It is therefore not possible to say for certain what genus the Sauropods of Lommiswil belonged to. Nevertheless, estimates of the body size and mass of the Moroccan trackmaker can still roughly be transferred to the one of Lommiswil.

3. Methods

3.1. Traditional Means of Dinosaur Track Documentation

As highlighted by Thulborn (THULBORN, 1990), number, size, shape, and distribution of the footprints are the most important parameters for the documentation of dinosaur tracksites. A hand sketch of the site on graph paper, including the compass bearing of at least one of the tracks, is advised. In cases where there is an abundance of imprints or the tracksite can only be observed from a distance, the site should be photographed as a whole. To document large tracksites, researchers historically had to capture photographs from helicopters (MEYER, 1993), blimps (BREITHAUPT & MATTHEWS, 2001), or elevated vantage points (MILNER *et al.*, 2012) for this task. To ensure scientific accuracy, it is important to avoid photographing only «selected» or «representative» imprints of the site, as this brings about the loss of scientific data and can bias one's perception of the site. Each photograph should contain an object of known scale and an object of deeper three-dimensional extent that casts a shadow, indicating the prevailing lighting conditions' direction and intensity. Lockley and Meyer (LOCKELEY & MEYER, 2000) stress, that the acquired data should be used to draw a detailed map of the tracksite. This is often done by creating an outline map (BELVEDERE, 2008; MEYER *et al.*, 2018; MEYER, 1993). They also suggest the use of photogrammetry. For small outcrops of a tracksite, this can be done using a hand-held camera (REMONDINO *et al.*, 2010).

3.2. Drone Photogrammetry

Photogrammetry, or more specifically stereophotogrammetry, is the process of deriving 3D information of an object through a sequence of images taken of the object from different directions (EISENBEISS, 2009). Today, this is done primarily by computers utilizing sophisticated algorithms (SCHÖNBERGER, 2018).

Fast data acquisition, real color models, and the wide variety of how the processed data can be used and manipulated are definite advantages of photogrammetry over traditional surveying tools. However, one of the most decisive benefits of photogrammetry is, that it can be conducted on virtually any scale. It is applied anywhere from analyzing the shape of objects only a few nanometers across (GONTARD *et al.*, 2016) (using electron microscopes) to entire forests (PEARSE *et al.*, 2018) (using satellite imagery). The photogrammetry in this study was conducted using a commercial drone, which acts as an ideal intermediary between aerial and close-range photogrammetry. The drone's integrated high-resolution camera enables rapid mapping of an extensive area while the built-in collision avoidance system allows it to approach the tracks to less than one meter, if needed. The geotags saved in the metadata of the images enables the accurate scaling of the 3D-model to real-life dimensions (AGISOFT, 2020).

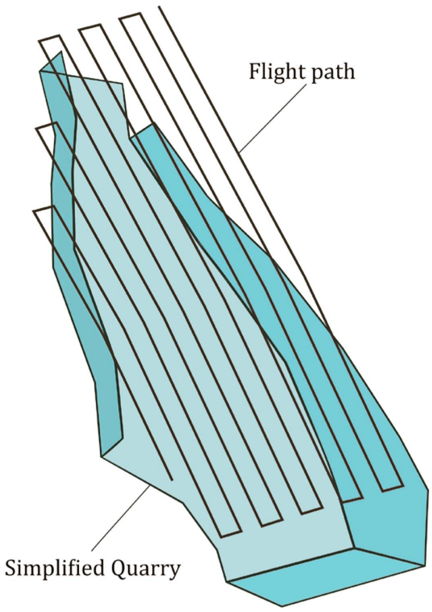

Figure 4: Grid pattern flight path with simplified eastern part of the quarry. The distance between drone and track bed was maintained at approximately 20 m. The distance between grid lines was kept at around 8 m. Images were taken approximately every 10 m along the flight path.

The images of the main tracksite were captured in a grid pattern parallel to the primary trackbed (See Figure 4). The distance between the drone and track bed was maintained at approximately 20 meters. The distance between grid lines was kept at around 8 meters. Images were taken approximately every 10 meters along the flight path.

The quadcopter drone employed in this study was DJI's «Mavic Pro 2». The photogrammetric models were generated using «Agisoft Metashape» and measurements were taken in Leica Geosystem's «3D-Reshaper». Transformations to the generated point cloud and 3D model were performed in the open-source software «CloudCompare». The open-source software «Inkscape» was used to generate vectorized outline maps.

Further information on the exact workflow, an analysis of different photogrammetry software options, an extensive experimental investigation into the expected geometric accuracy of the 3D model, as well as calculations justifying the flight path are provided in the Matura thesis upon which this article is based (FAUQUEX, 2021).

3.3. Illustrating Tracks

In outline maps, the imprint silhouettes of tracksites are depicted schematically. Some conditions in the field (lighting, accessibility, etc.) can severely diminish the quality of the outline map, if it is drawn on-site. Therefore, photographs are typically utilized to create outline maps away from the site. However, this introduces various other problems, like the lack of depth perception or scale. In any case, footprint margins are often rounded due to erosion, making it difficult to define borders to morphological features of the print in the first place. Also, given the potential for different interpretation of a footprint's morphology, there is always an element of subjectivity.

To address these difficulties, the outline maps in this project were faintly underlaid with a digital elevation model (DEM) of the track. The DEM contains depth information and is scaled to real-word dimensions using GPS-measurements of the drone. This method of data presentation enables the reader to compare the author's interpretation of the track morphology with empirical data in the background. Following the suggestions in FALKINGHAM *et al.*, 2017, all outline maps were juxtaposed with corresponding sections of the trackways in real color and a digital elevation model with contour lines.

The inner boundary of the footprint, which roughly corresponds to the track maker's foot anatomy, was outlined using a thick, continuous line. In instances where outlines are less certain, dashed lines were used.

3.4. Labelling Tracks

In outline maps, Roman numerals were used to indicate which track an imprint is part of, while Arabic numerals mark which manus-pes pair along the track it corresponds to. M and P indicate whether the manus or pes of the trackmaker made the print. The presumed walking direction is indicated with an arrow. For a grouping to be acknowledged as a track, it was required to contain a minimum of three consecutive footprints and display at least one walking direction indicator.

3.5. Dimensional Measurements

Dimensional measurements of all trackways and the imprints within them were conducted once the photogrammetric 3D model of the site had been generated (See Figure 5). When assessing the length or width of an imprint, the inner outline of the track, which most closely represents the shape of the trackmaker's foot, was considered to be the margins of the print. The pes length [P_L] was measured along the long symmetry-axis of the imprint, while the pes width [P_W] was mea-

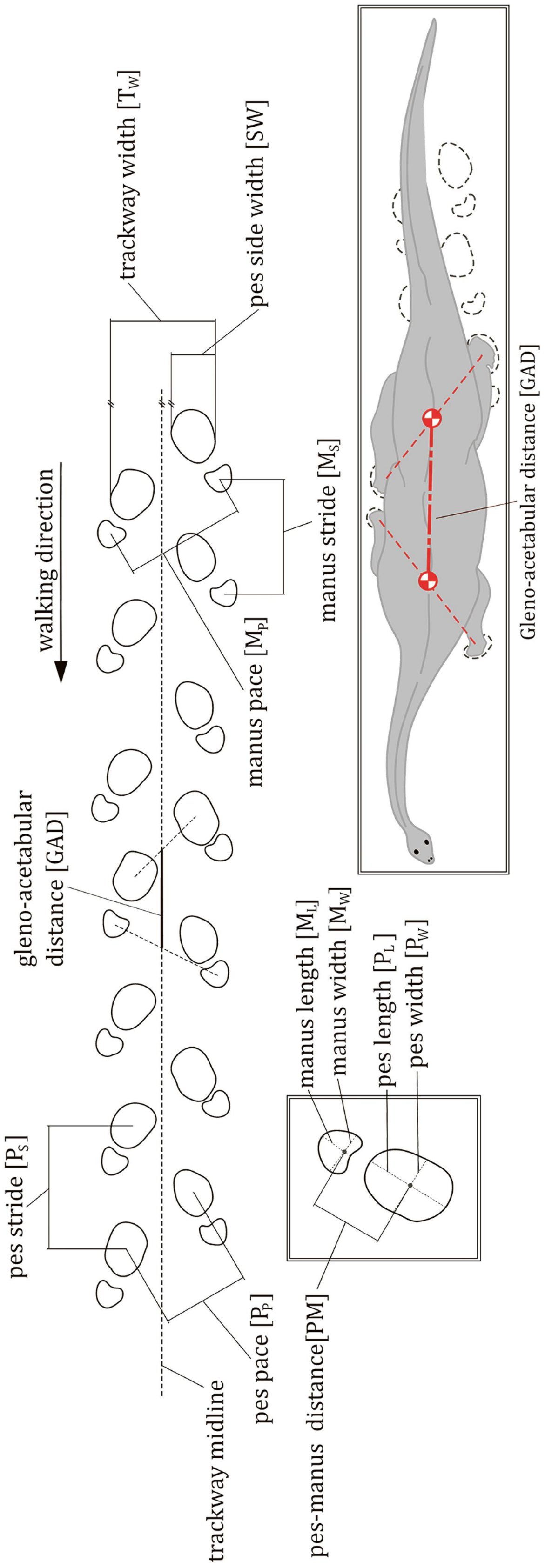

Figure 5: Schematic depiction of the taken dimensional measurements (Dinosaur schematic from DIEDRICH, 2011).

sured approximately perpendicularly to it. Correspondingly, the manus length [M_L] and width [M_W] were determined. The distance between the intersections of length and width line of manus and pes was measured as the pes-manus distance [PM]. Defined by the distance parallel to the walking direction between two consecutive imprints of the same foot (THULBORN, 1990), the stride length measurement was taken for pes [P_S] and manus [MS] respectively. The pace measurement for pes [P_P] and manus [M_P] was also determined in accordance with its definition as the distance between two successive pes/manus prints (THULBORN, 1990). The trackway width [T_W] represents the maximal distance between the outer margins of two successive pes imprints perpendicularly to the walking direction (THULBORN. 1990). The pes side width [SW] represents the width of the pes imprint perpendicularly to the walking direction (ROMANO *et al.*, 2007). Lastly, the gleno-acetabular distance [GAD] represents the distance between the middle points of two connecting lines of two successive pes and manus imprints (BELVEDERE, 2008). Given that this measurement roughly corresponds to the distance between the pivot points of the trackmaker's shoulders and hips, it can be utilized as an estimator for the trackmaker's torso length.

3.6. Trackmaker Parameters

Trackway ratio

The trackway ratio [TR] is defined as (ROMANO *et al.*, 2007):

$$TR = \frac{100 \times SW}{T_W}$$

and is a measure for the «width» of a sauropod's stance.

Hip height

It is contested how to most accurately estimate sauropodian hip heights from their track dimensions. Both Alexander's and Thulborn's methods are widely used in track studies.

$h_{al} \approx 4 \times P_L$ (ALEXANDER, 1976)

$h_{th} \approx 5.9 \times P_L$ (THULBORN, 1990)

In this project, the hip heights estimated through these formulas are juxtaposed but are left uncommented.

Gait

The gait G of a sauropod is defined as the ratio between pes stride length and the estimated hip height of the dinosaur: $G = \frac{P_S}{h}$. The resulting value indicates the mode of the sauropods locomotion (THULBORN, 1990):

$$G < 2.0 \rightarrow Walking$$
$$2.0 \leq G < 2.9 \rightarrow Trotting$$
$$2.9 \leq G \rightarrow Running$$

Speed

The speed of locomotion v of sauropods can be calculated using equations proposed by Alexander (ALEXANDER, 1976) (for $G<2.0$) and Thulborn (THULBORN & WADE, 1984) (for $G\geq2.9$). For gaits between 2.0 and 2.9, the mean of both estimates should be used (THULBORN & WADE, 1984). It is important to note, however, that the values derived from these equations are mere approximations and serve only as a means of comparison among multiple individuals walking in a group.

$$G < 2.0\ (Walking) \rightarrow v \approx 0.25 g^{0.5} P_S^{1.67} h^{-1.17}$$

$$2.0 \leq G < 2.9\ (Trotting) \rightarrow v \approx \frac{0.25 g^{0.5} P_S^{1.67} h^{-1.17} + \left(gh\left(\frac{P_S}{1.8h}\right)^{2.56}\right)^{0.5}}{2}$$

$$2.9 \leq G\ (Running) \rightarrow v \approx \left(gh\left(\frac{P_S}{1.8h}\right)^{2.56}\right)^{0.5},$$

where h is the hip height, P_S is the pes stride, and g the standard acceleration.

4. Results

4.1. The Main Tracksite

Track Morphology

All prints of the tracksite occur as impressions (negative or concave epireliefs) and do not display displacement rims around their outer margins. The tracks' stratigraphic occurrence and shape make it apparent that they are true tracks (MEYER, 1993), meaning that the exposed sedimentary layer that is preserved was in direct contact with the foot (MILÀN & BROMLEY, 2008). The imprints of the site occur in the form of two morphotypes, differing in their preservation state:

Pronounced foot imprints

These tracks are up to 30 cm deep and their imprint walls are starkly inclined towards a flat base. They transition to the trackbed via a comparatively sharp and defined boundary. In the eastern quarry, pes imprints are often preserved in a triangular shape, while in the middle quarry their outline is more irregular. Manus imprints are either D-shaped or elliptical (with their outline being more wide than long). With a typical depth of around 15 cm, manus imprints are generally shallower than their pes counterparts. No claw impressions were observed.

Weakly pronounced foot imprints

With a depth generally not greater than 10 cm and a very gentle transition from imprint to track bed, it was often difficult to identify these impressions as footprints. Although some imprints appear to be roughly arranged in a trackway pattern, most of them are distributed seemingly at random. These prints' poor preservation state made it impossible to identify a walking direction for the presumed trackways.

Sometimes, trackways of pronounced morphology transition to weak pronunciation and vice versa (See Figure 6).

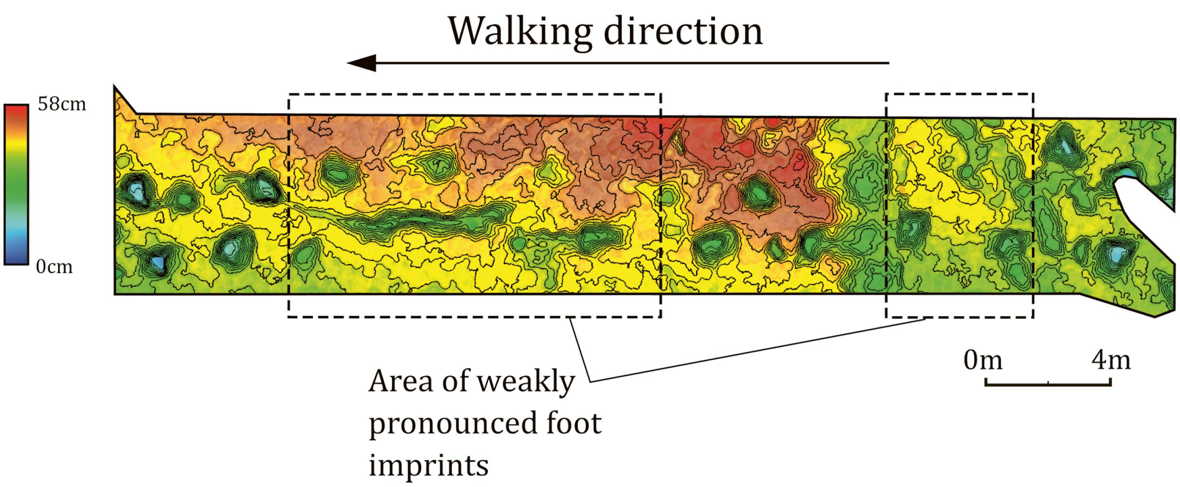

Figure 6: Digital elevation model of a temporary transition from heavily pronounced to weakly pronounced tracks in trackway III.

4.2. Trackway Structure

In total, nine 20 m to 75 m long trackways were identified with certainty. They contain several turns and display slight meandering of the walking direction (See Figure 7). Trackway II depicts a sharp 180° turn.

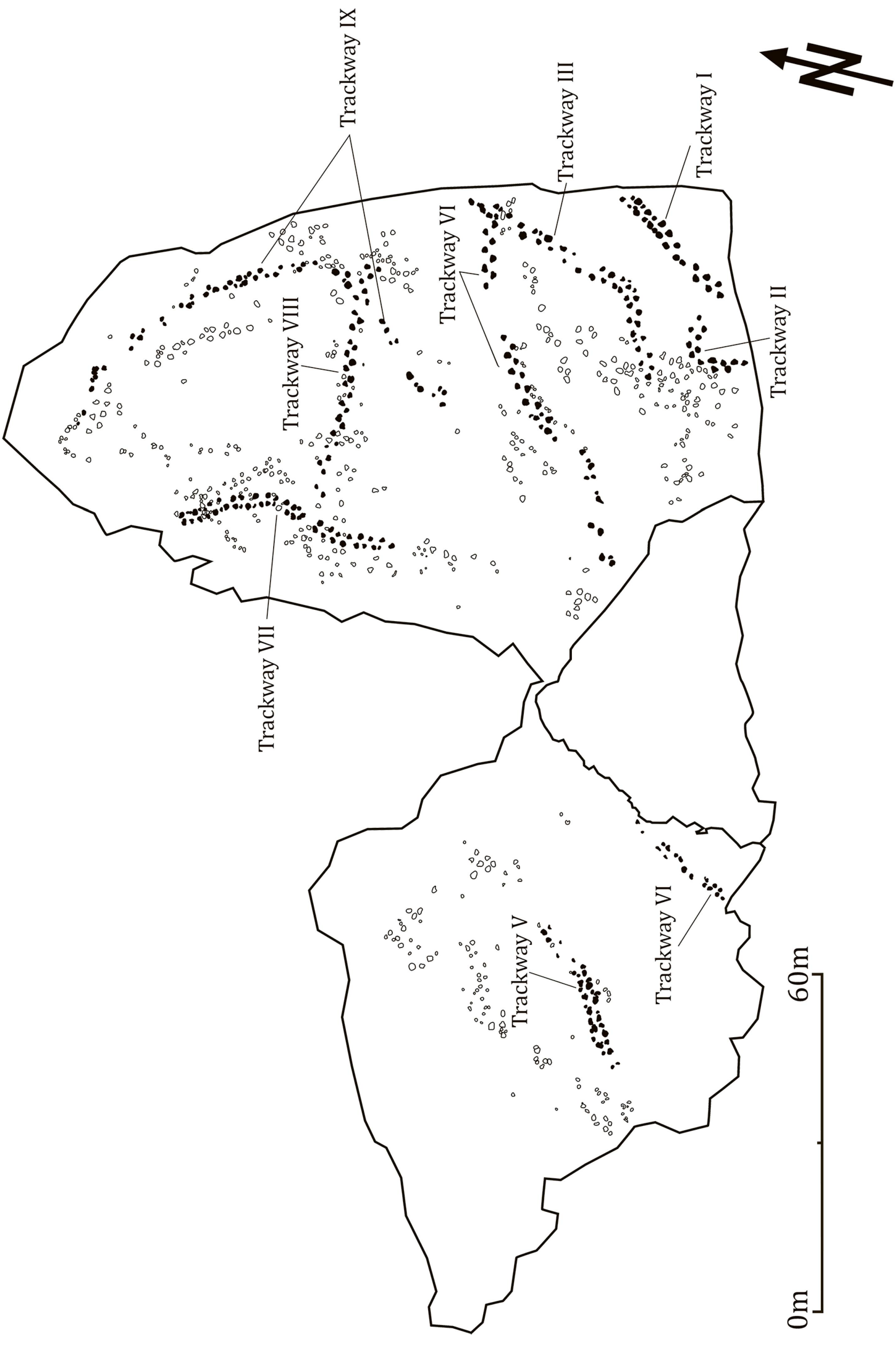

Figure 7: Outline map of the main tracksite.

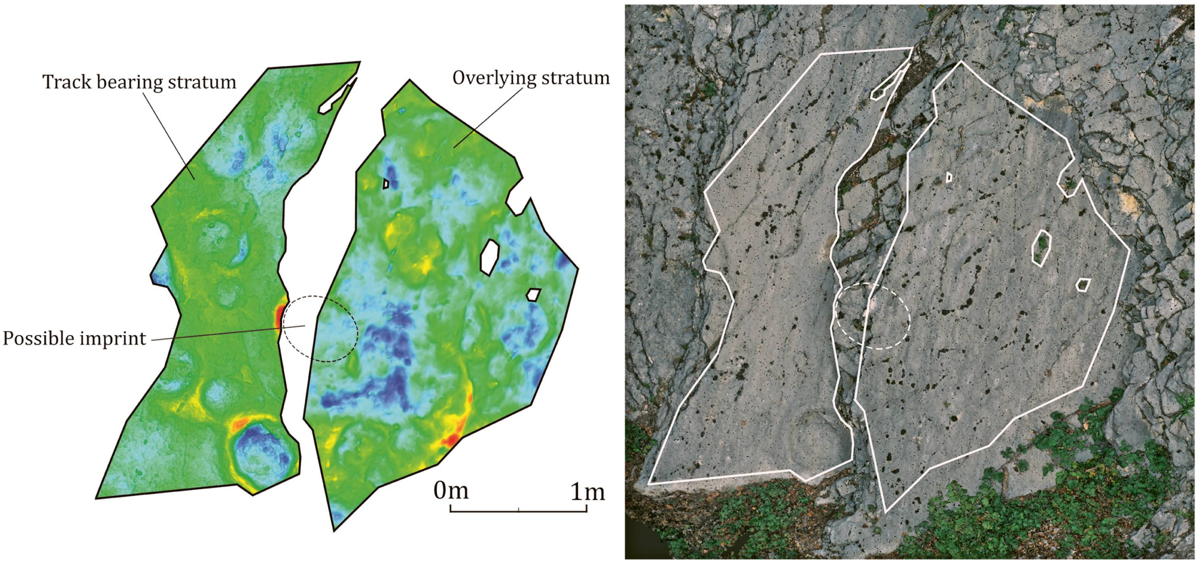

Figure 8: Digital elevation model and real-color image of the northern trackbed

4.3. Ichnology of the Lommiswil Tracksite

Northern Trackbed

The Author first noticed the northern trackbed on a hike along a trail leading to the eastern quarry's top. Since then, it has become apparent, that these imprints have already been discovered by a student of Prof. Christian Meyer several years earlier (STRANSKY, 2006), but were thought to be underprints (meaning they were indirectly formed due to the substantial pressure exerted by the trackmakers of the main track site, causing deformation across multiple strata). Both pes and manus imprints are circularly to elliptically shaped and display a displacement rim. Pes and manus imprints can clearly be distinguished. A foot print appears to have been covered by the superincumbent stratum, with only parts of the displacement rim exposed (See Figure 8). The superincumbent stratum does not display any deformation, indicating the imprints of the northern trackbed are actually true prints.

Trackway Mapping and Measurements

In previous works, only the eastern quarry's imprints were mapped (MEYER, 1990; MEYER, 1993). While a trackway in the middle quarry was reported on (referred to as Trackway V in this study), no surveys were undertaken. In this study, it was possible to map both the eastern and middle quarry for the first time. The initial count of 450 imprints reported previously (MEYER & THÜRING, 2003) has been expanded to 806, owing to the quarry's expansion and the more modern method used to map the site. A new trackway in the middle section of the quarry was identified (Trackway VI).
Displayed below (Figure 9–22) are the outline maps of the identified trackways. They are juxtaposed with their corresponding real-color image and digital elevation model. Contour lines are spaced at intervals of 5 cm.

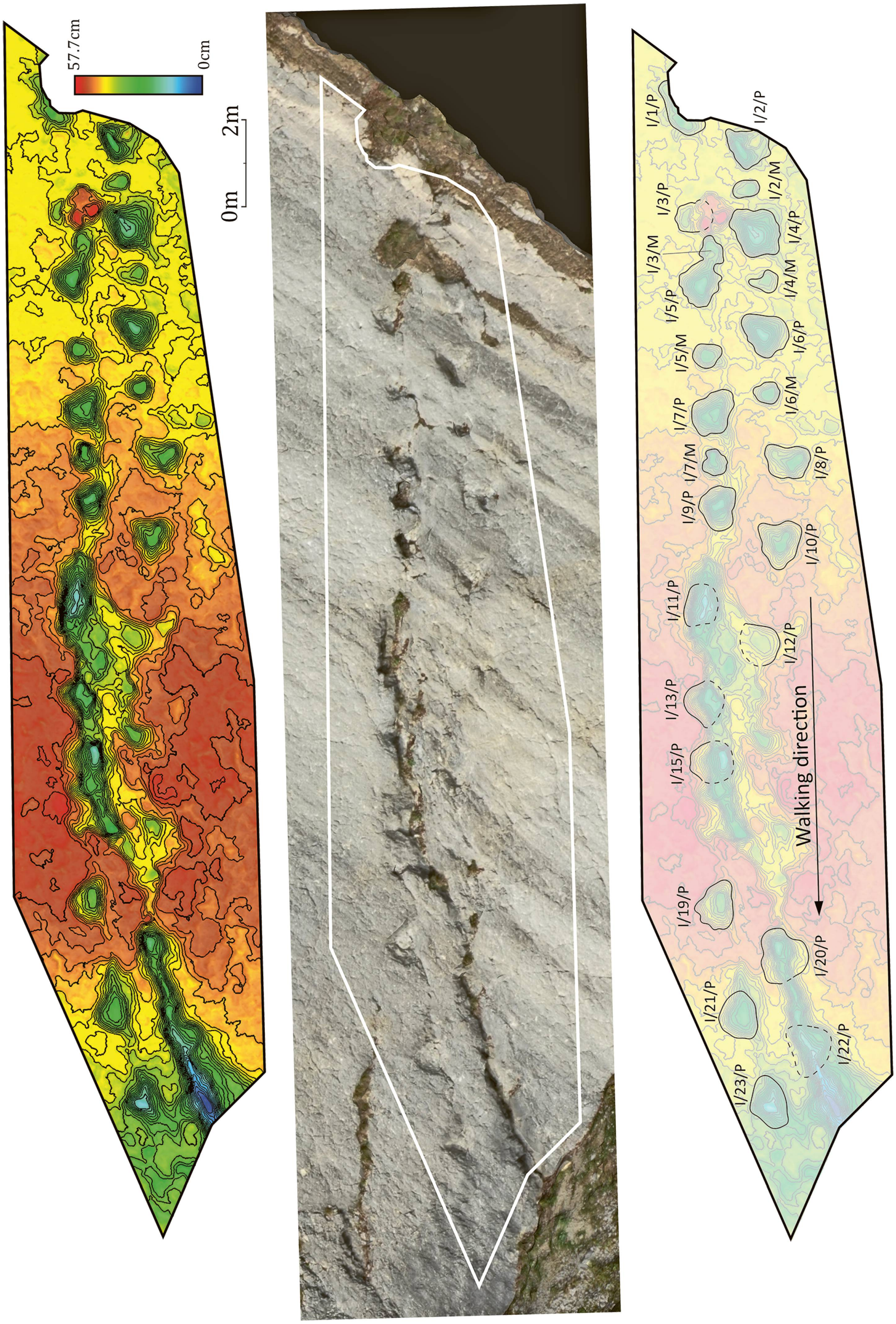

Figure 9: Digital elevation model, real-color model, as well as the outline map of trackway I.

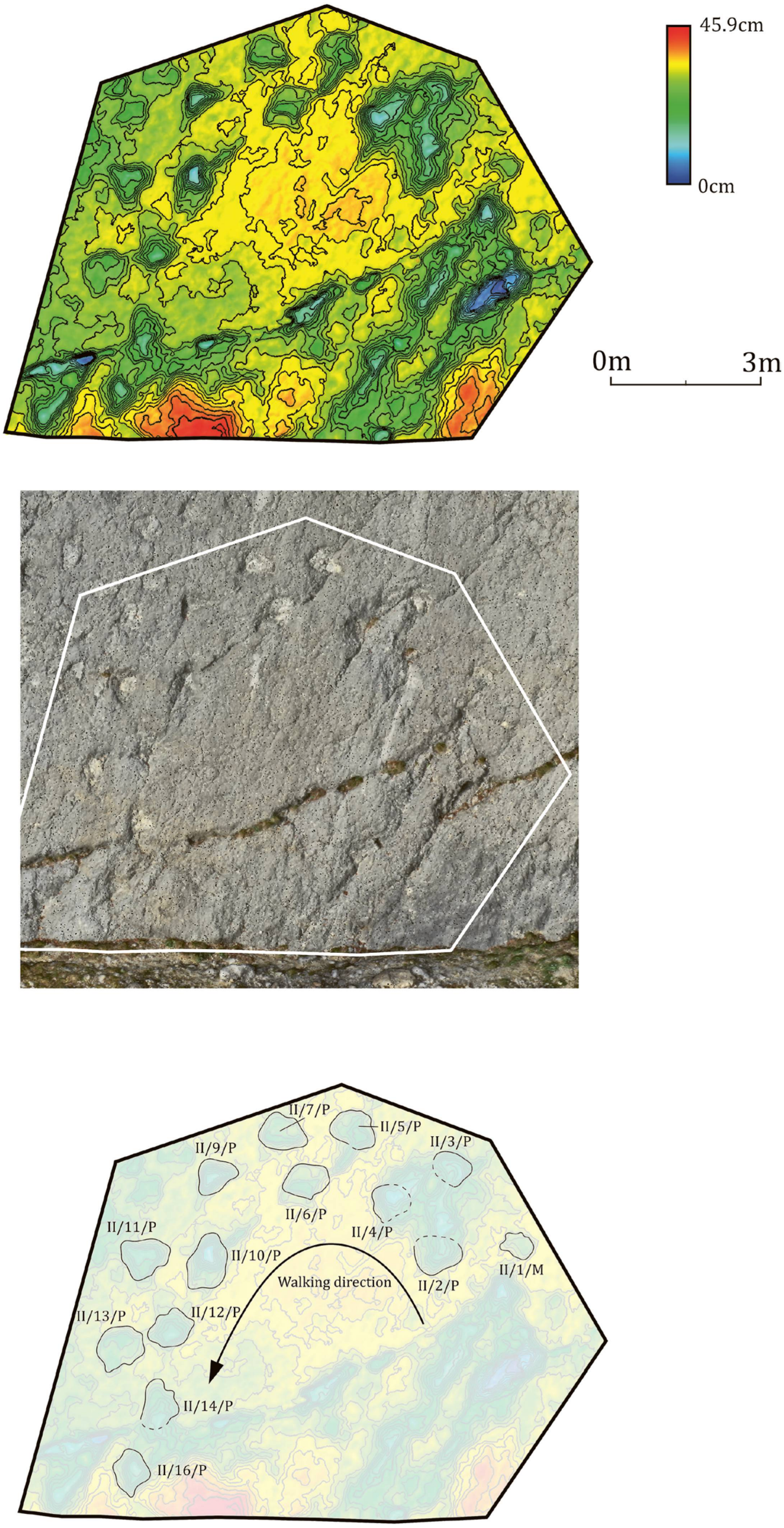

Figure 10: Digital elevation model, real-color model, as well as the outline map of trackway II.

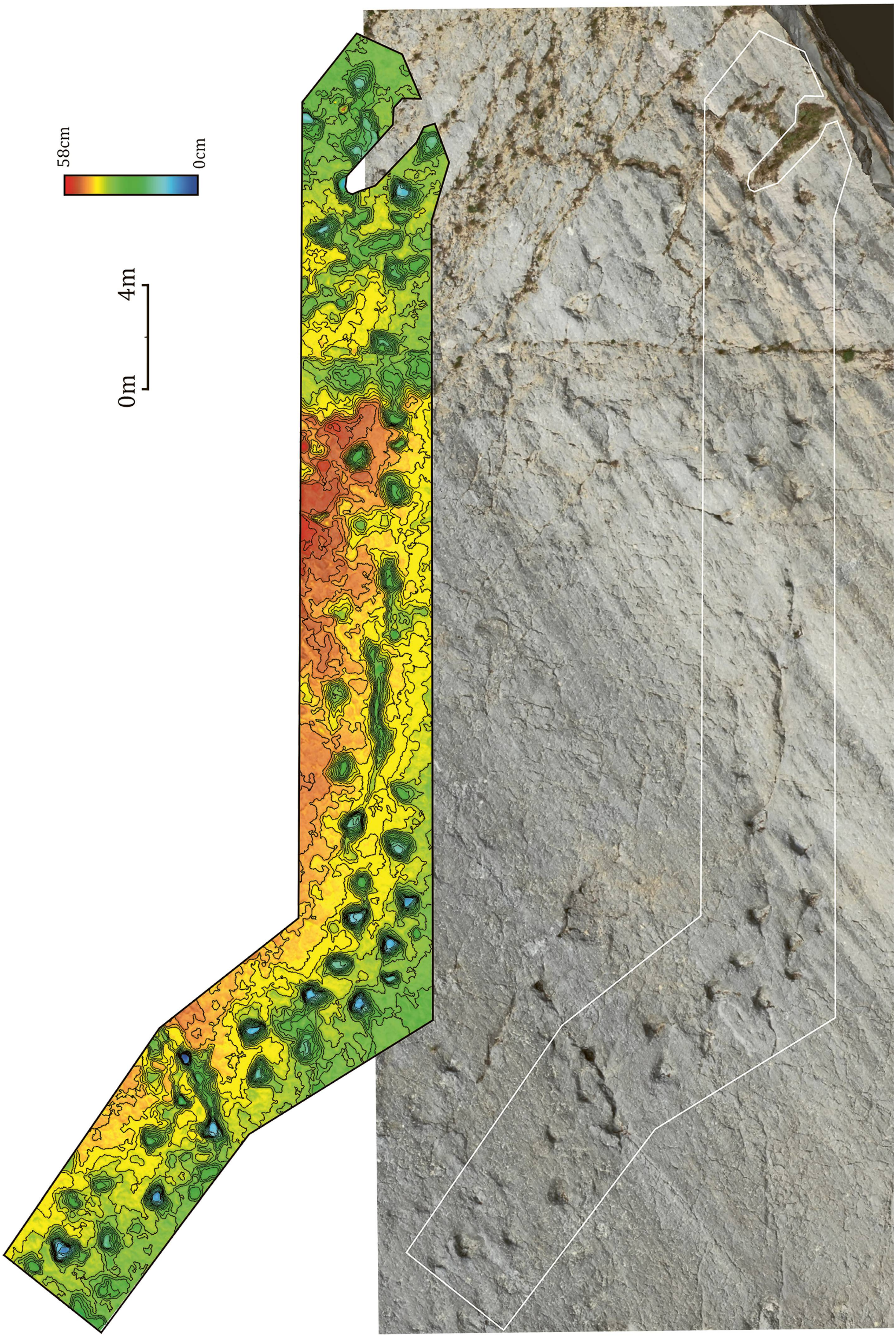

Figure 11: Digital elevation model, as well as real-color model of trackway III.

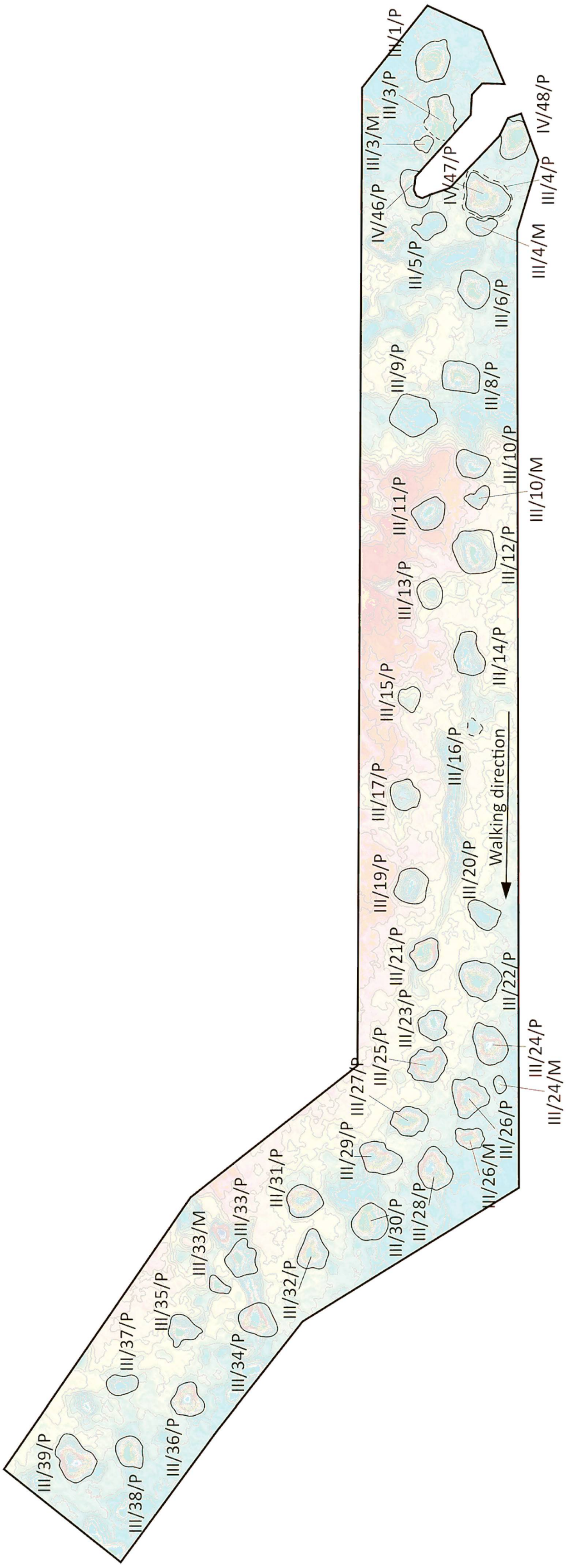

Figure 12: Outline map of trackway III.

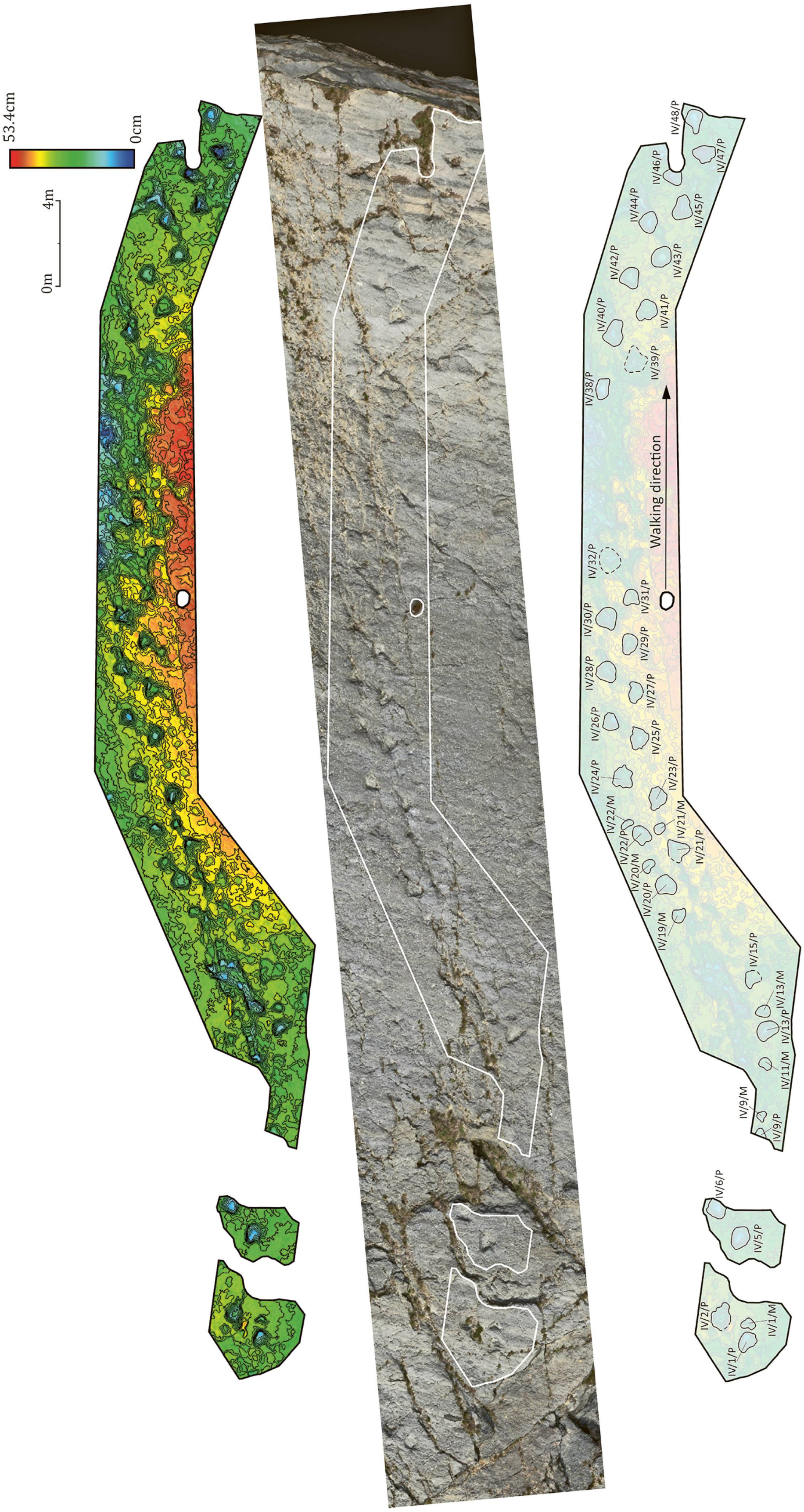

Figure 13: Digital elevation model, real-color model, as well as the outline map of trackway IV.

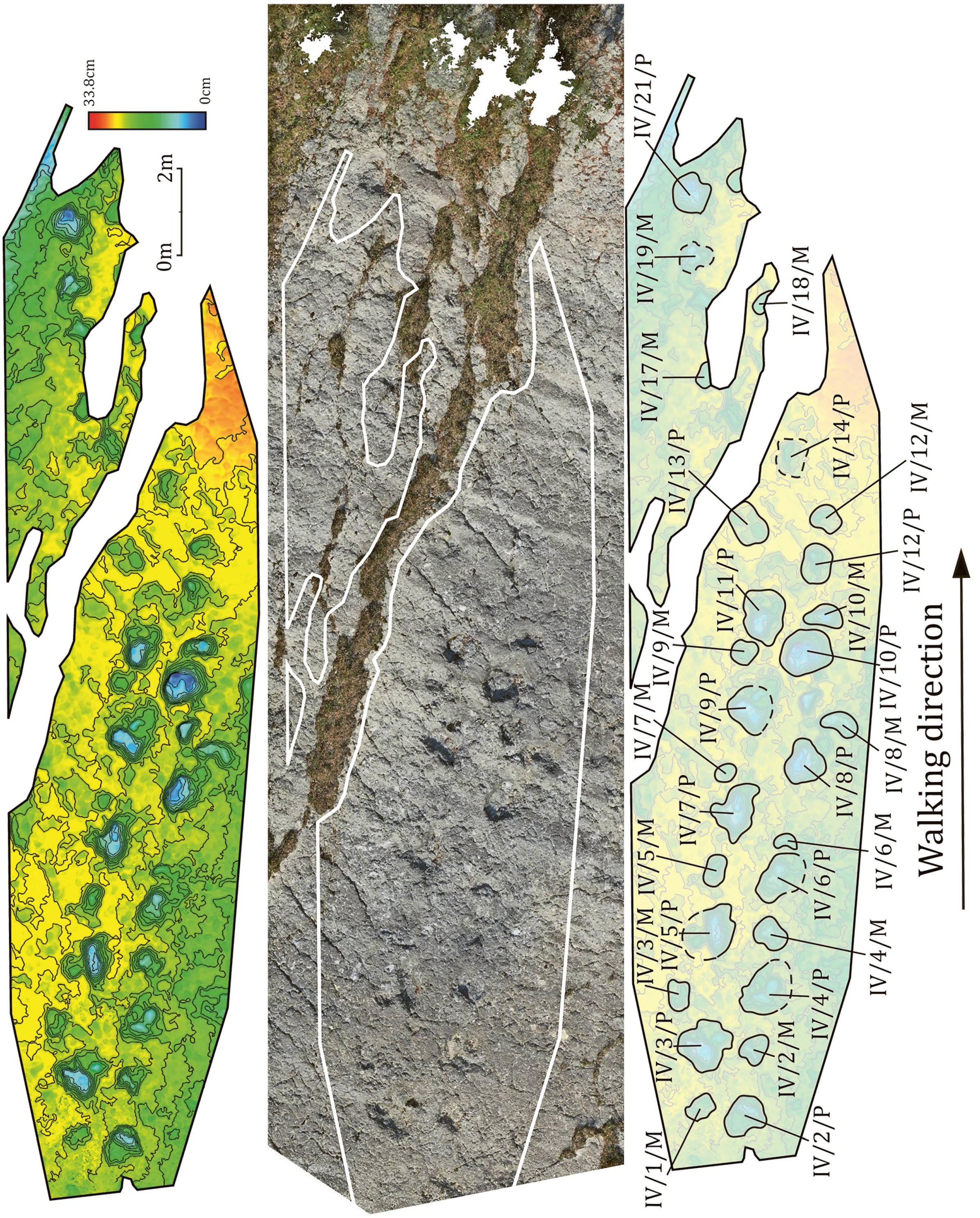

Figure 14: Digital elevation model, real-color model, as well as the outline map of trackway V.

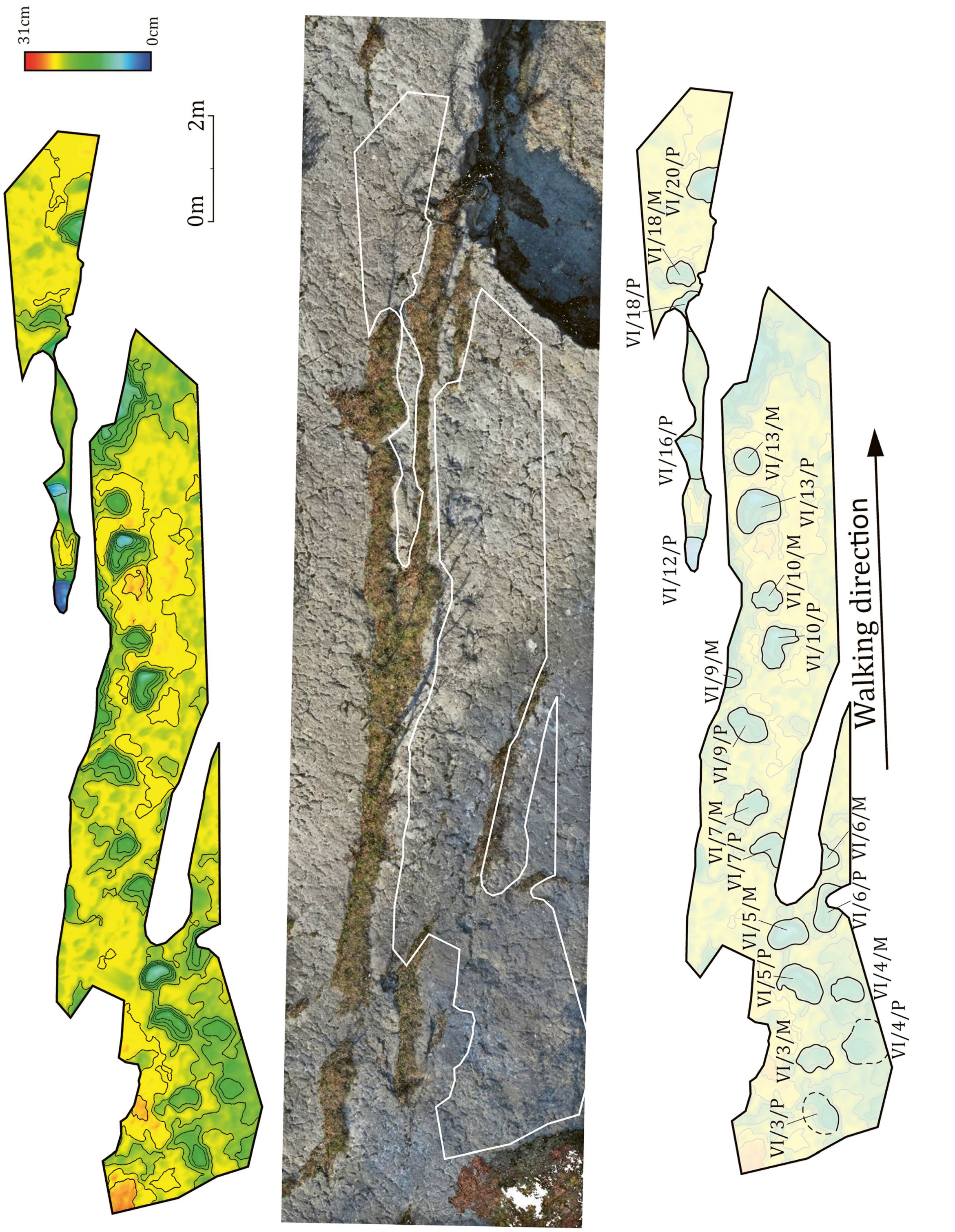

Figure 15: Digital elevation model, real-color model, as well as the outline map of trackway VI.

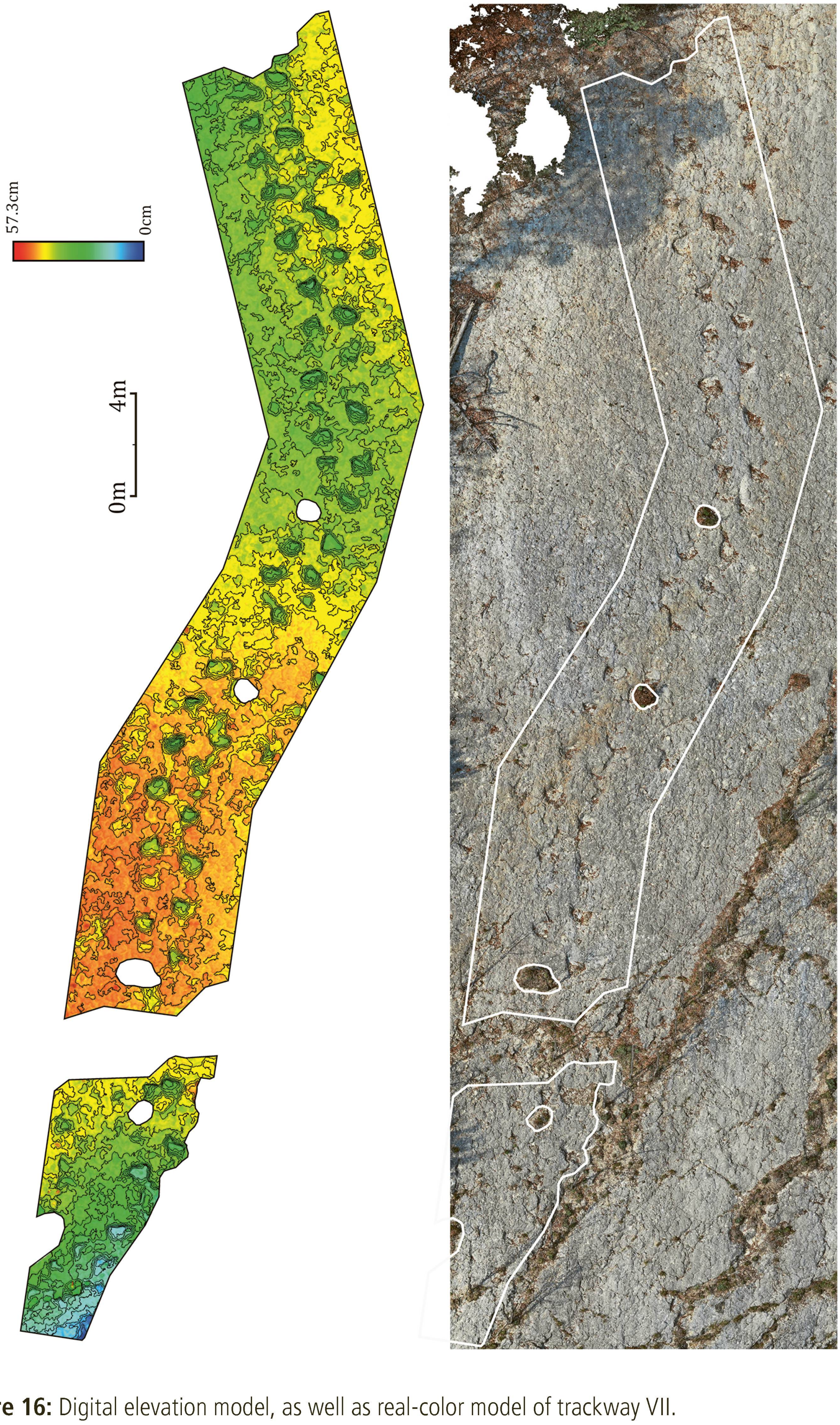

Figure 16: Digital elevation model, as well as real-color model of trackway VII.

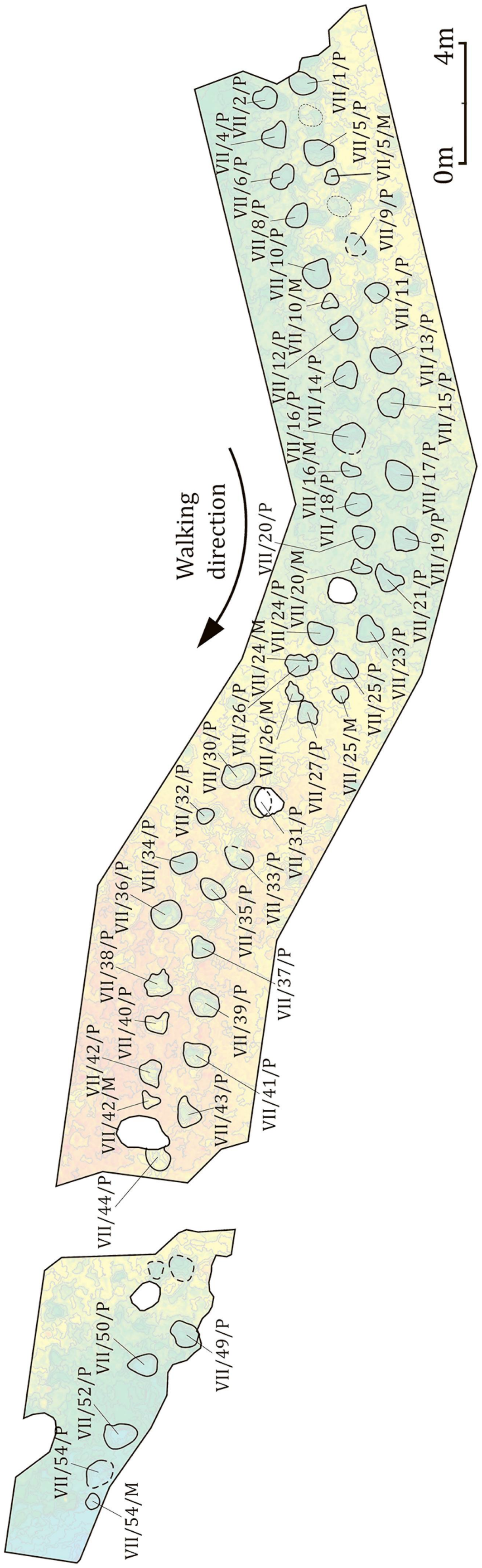

Figure 17: Outline map of trackway VII.

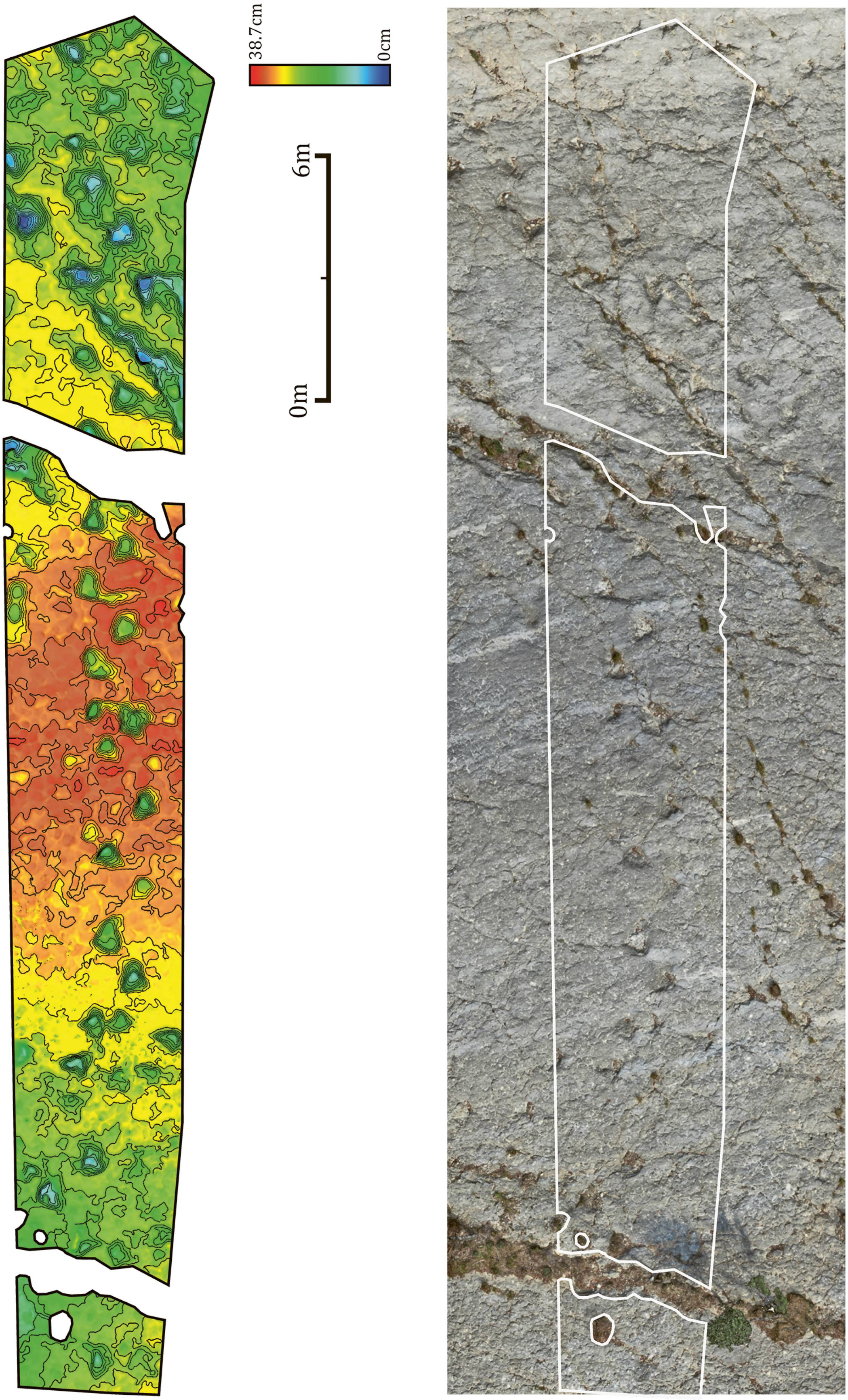

Figure 18: Digital elevation model, as well as real-color model of trackway VIII.

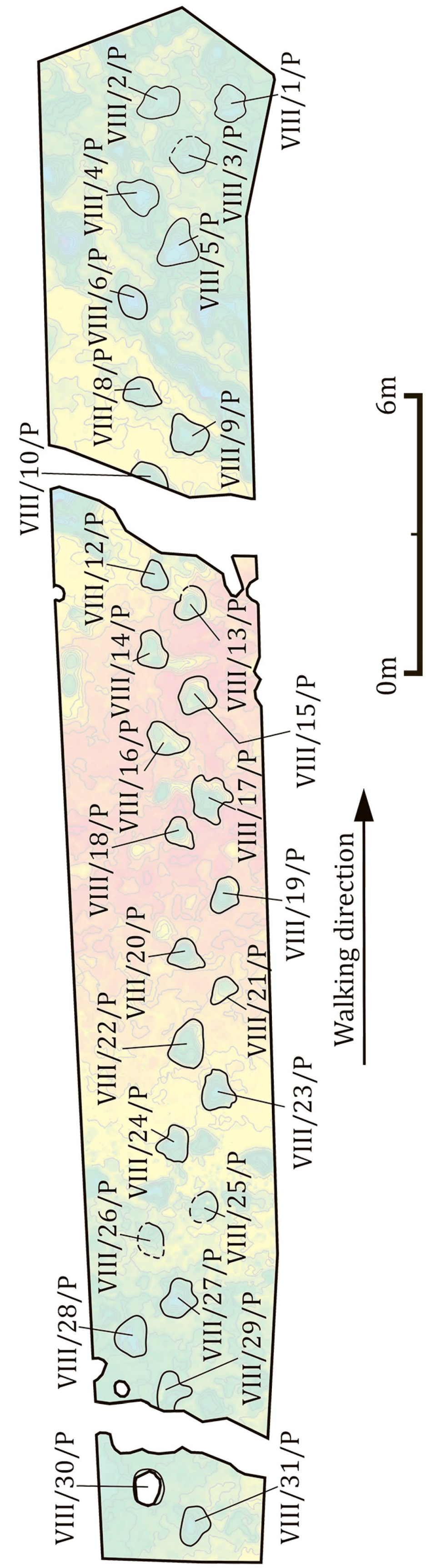

Figure 19: Outline map of trackway VIII.

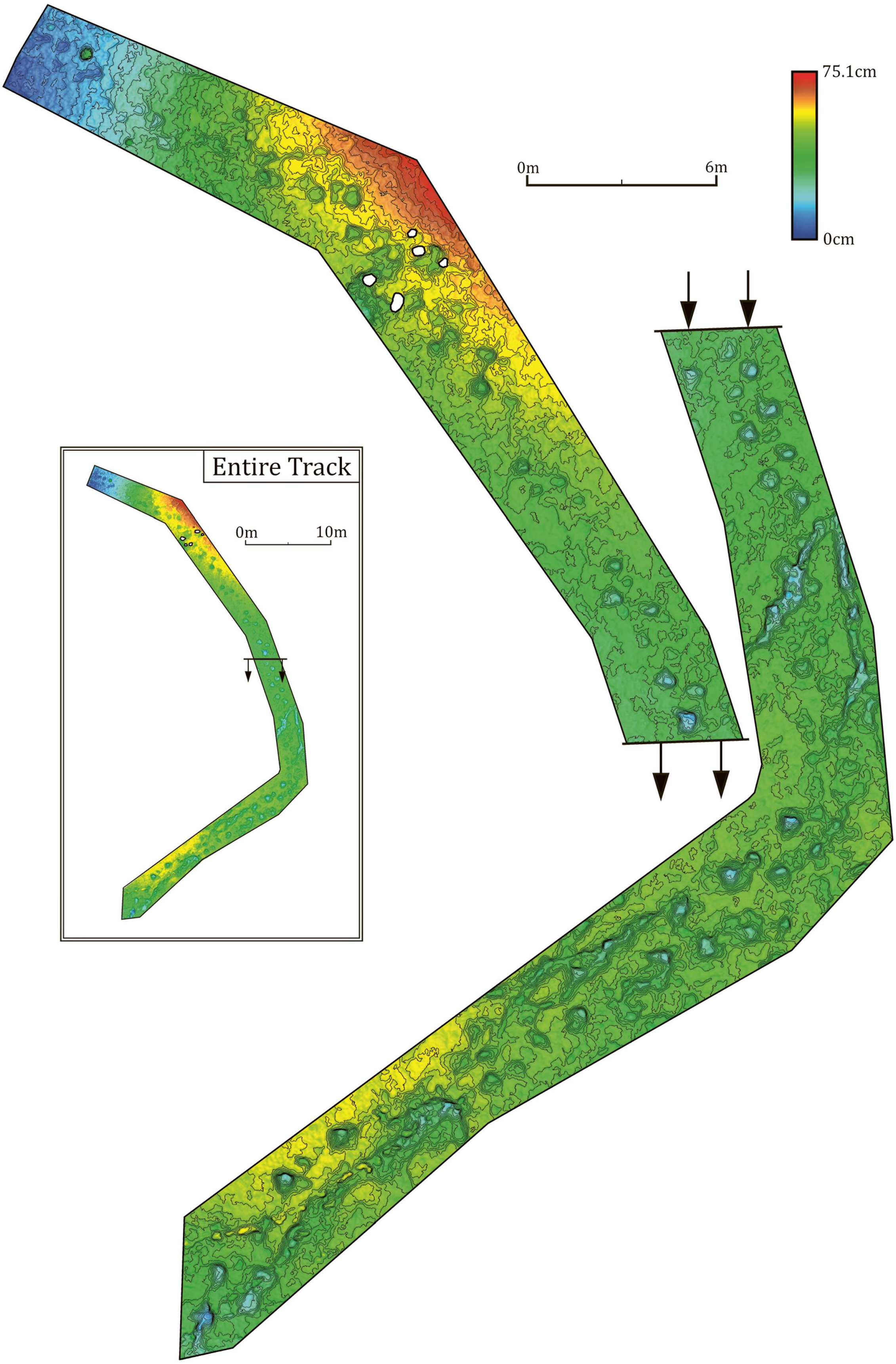

Figure 20: Digital elevation model of trackway IX.

Figure 21: Real-color model of trackway IX.

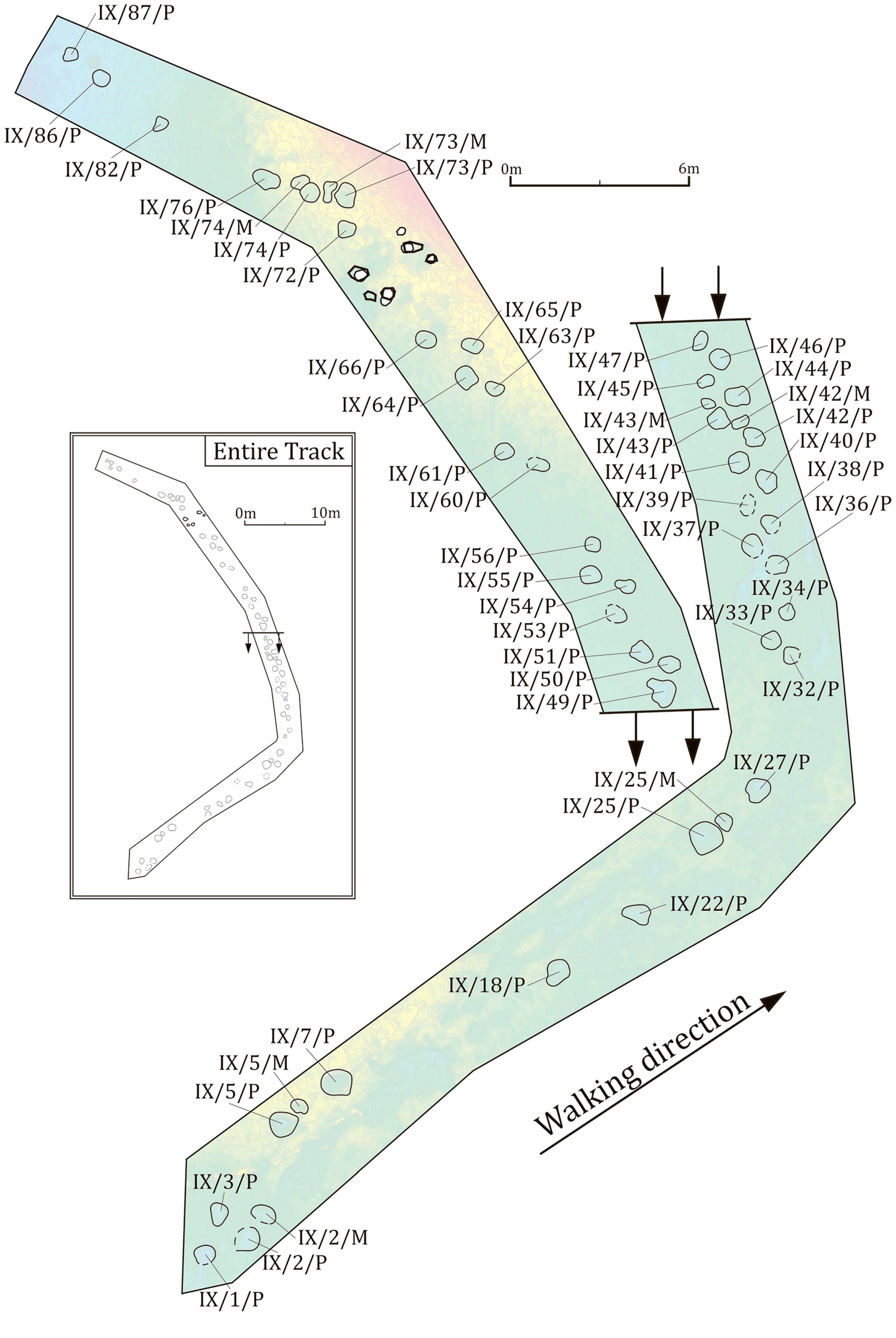

Figure 22: Outline map of trackway IX.

Name of Trackway	P_L [m]	P_W [m]	M_L [m]	M_W [m]	P_S [m]	M_S [m]	P_P [m]	M_P [m]	T_W [m]	SW [m]	PM [m]	GAD [m]
Trackway I	1.09±0.12 (9)	0.86±0.10 (9)	0.55±0.11 (6)	0.62±0.09 (5)	2.6±0.4 (9)	2.56±0.18 (4)	1.98±0.22 (11)	1.90±0.31 (5)	2.58±0.11 (14)	1.09±0.13 (11)	1.34±0.26 (5)	2.71±0.29 (3)
Trackway II	1.09±0.11 (6)	0.93±0.08 (6)	0.85 (1)	0.71 (1)	-	-	-	-	-	-	-	-
Trackway III	1.04±0.18 (25)	0.88±0.11 (25)	0.443±0.015 (4)	0.74±0.06 (4)	2.5±0.4 (18)	-	2.05±0.31 (19)	-	2.62±0.21 (15)	1.04±0.14 (14)	1.00 (1)	-
Trackway IV	1.06±0.17 (22)	0.93±0.13 (21)	0.49±0.04 (4)	0.70±0.03 (5)	2.83±0.23 (10)	-	1.93±0.09 (15)	-	2.35±0.14 (16)	1.03±0.10 (16)	1.03 (1)	-
Trackway V	1.05±0.14 (6)	0.90±0.12 (6)	0.58±0.07 (11)	0.73±0.05 (11)	2.78±0.5 (10)	2.76±0.2 (9)	2.07±0.13 (9)	2.42±0.2 (9)	2.61±0.18 (6)	1.13±0.18 (6)	1.39 (6)	2.81±0.16 (2)
Trackway VI	0.91±0.04 (5)	0.64±0.13 (4)	0.46±0.04 (7)	0.66±0.10 (7)	2.80±0.09 (5)	2.75±0.12 (5)	1.76±0.07 (6)	1.69±0.12 (4)	1.92±0.03 (5)	0.82±0.11 (6)	1.07±0.07 (7)	2.58±0.10 (2)
Trackway VII	0.89±0.17 (30)	0.71±0.09 (27)	0.44±0.04 (4)	0.56±0.10 (4)	1.9±0.4 (22)	1.22 (1)	1.68±0.20 (23)	1.59±0.06 (2)	2.34±0.18 (27)	0.94±0.08 (26)	1.04±0.11 (6)	1.78 (1)
Trackway VIII	0.84±0.08 (13)	0.75±0.11 (13)	-	-	2.59±0.21 (12)	-	1.75±0.22 (13)	-	1.95±0.14 (12)	0.87±0.09 (12)	-	-
Trackway IX	0.90±0.14 (11)	0.76±0.11 (11)	0.41±0.09 (5)	0.66±0.18 (5)	2.2±0.5 (7)	-	1.36±0.18 (8)	1.57 (1)	2.00±0.35 (10)	0.87±0.11 (10)	1.03±0.15 (5)	1.72 (1)

Table 1: Average values for the measured pes length (P_L), pes width (P_W), manus length (M_L), manus width (M_W), pes stride (P_S), manus stride (M_S), pes pace (P_P), manus pace (M_P), trackway width (T_W), pes side width (SW), pes-manus distance (PM), and gleno-acetabular distance (GAD) of the identified trackways (See Figure 5). The value inside the brackets represents sample size.

Name of Trackway	Hip Height [m] (Alexander)	Hip Height [m] (Thulborn)
Trackway I	4.3±0.5	6.4±0.7
Trackway II	4.4±0.4	6.4±0.6
Trackway III	4.2±0.7	6.1±1.1
Trackway IV	4.3±0.7	6.2±1.0
Trackway V	4.2±0.6	6.2±0.9
Trackway VI	3.6±0.1	5.4±0.2
Trackway VII	3.6±0.7	5.3±1.0
Trackway VIII	3.3±0.3	4.9±0.5
Trackway IX	3.6±0.6	5.3±0.8

Table 2: Hip heights calculated using Alexander's and Thulborn's method.

Measurement tables, containing all parameters that could clearly be measured can be found in the Matura thesis this article is based upon (FAUQUEX, 2021). In total, 836 dimensional measurements were taken. As stride, pace, and trackway width have been reported to greatly vary during turns (XING *et al.*, 2015), they were not measured in sections where the trackmaker changed direction. As one can assume that the variation in stride and pace also effects the measured GAD, it was also not measured in turns.

Using the averaged trackway dimensions, the trackmakers' hip height could be estimated. This was done using Alexander's (ALEXANDER, 1976) and Thulborn's (THULBORN, 1990) methods (See Table 2).

The trackway ratio was calculated and the hip heights resulting from Alexander's method were used to estimate the sauropod's gait and speed (See Table 3).
The point clouds generated from the Lommiswil tracksite were uploaded to https://doi.org/10.5281/zenodo.4421888. They are available for anyone to download for free.

Name of Trackway	Trackway Ratio [%]	Gait	Speed [m/s]
Trackway I	42±5	0.59±0.12	0.68±0.20
Trackway II	-	-	-
Trackway III	40±6	0.60±0.15	0.67±0.24
Trackway IV	44±5	0.67±0.12	0.82±0.19
Trackway V	43±8	0.66±0.15	0.82±0.19
Trackway VI	43±6	0.77±0.04	0.96±0.07
Trackway VII	40±5	0.52±0.15	0.52±0.15
Trackway VIII	45±5	0.77±0.10	0.93±0.19
Trackway IX	43±9	0.62±0.17	0.67±0.28

Table 3: Trackway parameters calculated using hip heights derived from Alexander's method. Trackway II consists entirely of a 180° turn. As stride values of sauropods vary greatly during turns (XING *et al.*, 2015), a gait and speed estimation was not possible for this trackmaker.

5. Analysis of the Tracksite

5.1. Main Tracksite

Using a drone, a photogrammetric model of the Lommiswil dinosaur tracksite was generated. It was the first full analysis of the site using this method and increased the number of identified foot impressions from 450 (MEYER & THÜRING, 2003) to 806. Two previously unmapped trackways (Trackway VI & Trackway VIII) were surveyed for the first time. Distinct pes/manus pairs can be observed on almost all trackways and strongly suggest that the tracks are of sauropodian origin.

The pes tracks of the eastern tracksite often exhibit a distinct triangular shape and a smooth surface, while the ones of the middle quarry are mostly irregularly shaped and rough. This could indicate that while the substrate might have been moldable on the eastern side, it either stuck to the foot or collapsed in the middle quarry.

5.2. Trackmaker Analysis

Size of Trackmakers

By analyzing the relationship between the trackmakers' pes width and length (See Figure 23), one can observe clustering of the mean values into two size groups. The larger group has pes lengths of around 1.05 m and pes widths of around 0.9 m. The smaller group has a pes length of around 0.9 m and a pes width of around 0.7 m. It must be noted, however, that despite the comparatively dense clustering of mean values into two groups, the errors of the measured lengths and widths remain relatively large compared to the distance between the supposed size clusters. It is hence possible, that all datapoints stem from a single size cluster centered at around the middle of the connection line between the supposed clusters.

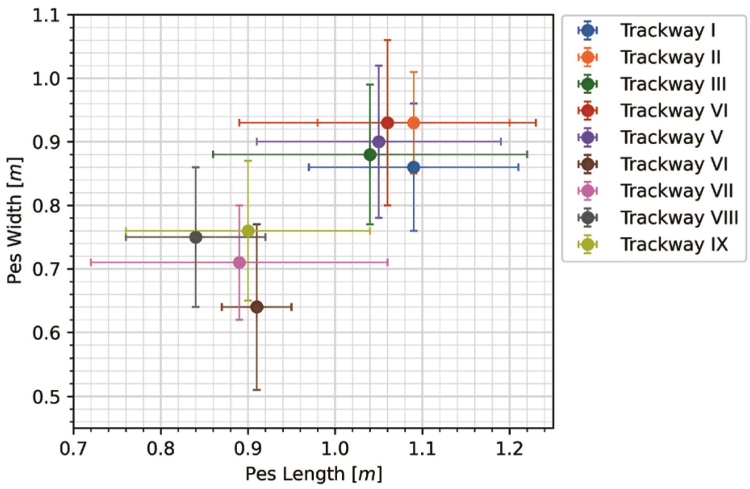

Figure 23: Scatter plot showing the relation between trackmaker pes widths and lengths. Distribution of the mean values, despite their relatively large error, seems to suggest that there are two size clusters of trackmakers.

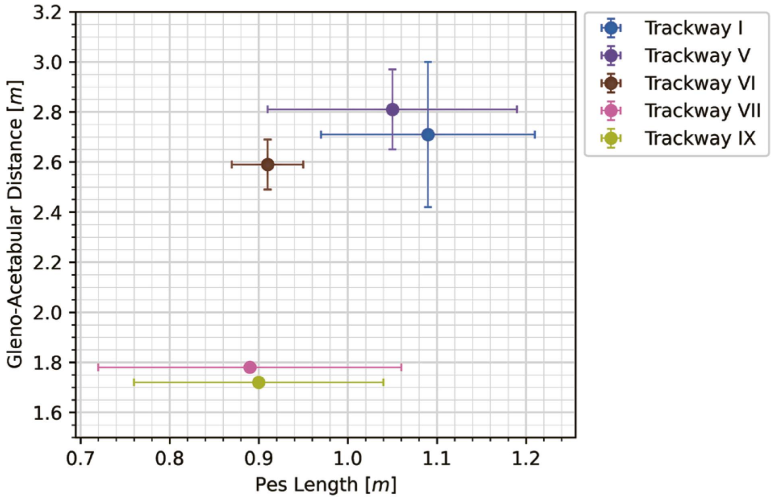

Figure 24: Scatter plot comparing pes length to gleno-acetabular distance (GAD) for the trackmakers where the GAD could be measured. While no error for the GAD of trackmaker VII and IX could be calculated (sample size 1), this data also appears to suggest two size clusters of trackmakers.

Provided that two consecutive pes and manus imprints are preserved and their center points can be approximated, the GAD of the trackmaker can be measured. Its accuracy is less reliant on good footprint preservation than the pes dimensions, which can vary substantially within poorly preserved trackways. A comparison between the GAD and pes length of the trackmakers is provided in Figure 24.

This plot also seems to imply the existence of two size clusters of trackmakers. The larger one has pes lengths of around 1.05 m and GADs of around 2.8 m. The smaller one has pes lengths of approximately 0.9 m and GADs of around 1.7 m. Since both pes length and GAD can be assumed to scale with the size of the animal, one can also assume that the members of the small and large clusters are the same in Figures 23 and 24. This is the case for trackmaker I, V, VII, and IX, while trackmaker VI appears to be in the smaller size group in the pes length-width comparison and in the larger size group in the pes length-GAD comparison.

The state of preservation for footprints in the middle quarry, specifically where trackway VI is situated, is generally inferior in comparison to those found in the eastern quarry. This could potentially be attributed to differing substrate properties in the two quarry sections. If the substrate in the middle quarry was more prone to collapse than the substrate in the eastern quarry, the imprints of Trackway VI might appear smaller than the actual size of the trackmaker's foot due to partial collapse of the imprint's sidewalls. Another factor contributing to the reduced size could be the erosion of the track-bearing surface. Notably, both proposed reasons for the decreased pes size leave the measured GAD unchanged. As a consequence, in this scenario, the GAD measurement is regarded as more reliable. It is suggested to be more likely, that individual VI was in the larger group of individuals.

The tracks of Lommiswil bear resemblances to the ichnospecies *Breviparopus taghbaloutensis*, (MEYER, 1993), which was initially found in the High Atlas of Morocco (RODGERS & WILSON, 2005). This ichnotaxon was estimated to have been produced by a trackmaker between 33 m and 37 m long and weighing at least 62 tons (MOLINA-PÉREZ & LARRAMENDI, 2020). The pes width and length was around 0.9 m, with the actual foot dimensions probably being slightly larger due to a partial collapse of the print sidewall. The pes imprint lengths of Lommiswil are up to 1.09 m long and 0.93 m wide. Therefore, we can reasonably assume that the trackmaker of Lommiswil was either around the same size or even larger than the one in Morocco.

Herding behavior

As can be seen in Figure 25, which displays the trackmakers' headings, the walking direction of the herd was not uniform, with only a weak north-eastern and south-western tendency. An analysis of the walking speeds (see Figure 26) shows that the trackmakers were walking at a speed between 0.04–1.1 m/s. Figure 27 displays the relation between the trackmakers' hip heights and gaits. In a close herd it would be expected, that smaller individuals have a higher gait than larger ones. While there appears to be a spread in gaits, there does not seem to be a correlation between trackmaker gait and body size.

Considering the varying walking directions, slow walking speeds, and lack of correspondence between gait and size of the trackmaker, it is suggested that the sauropods were walking as a loosely connected group at a slow pace.

5.3. Northern Trackbed

Several tracks on an approximately 5 m^2 large rock face, multiple stratigraphic layers below the main tracksite, were mapped for the first time.

The northern trackbed was previously thought to exclusively bear underprints. By creating a DEM of the trackbed and its surroundings, it was possible, however, to locate a displacement rim that could indicate the presence of an additional foot imprint right below the border of the overlying stratum. The absence of any deformation in this overlying stratum indicates that these tracks are true prints and not under prints. The existence of true tracks on different strata could be possible, as recent findings suggest multiple global sea-level fluctuations during the Jurassic period (JANK *et al.*, 2006), several of which exposed the Jura platform (MEYER & MARTY, 2014).

6. Conclusion

This study investigated the use of consumer-grade drones for the survey of large, difficult-to-access dinosaur tracksites, specifically focusing on the challenging Lommiswil tracksite. By employing drone photogrammetry, this project successfully documented previously unmapped sections of the site in 3D, identified a large number

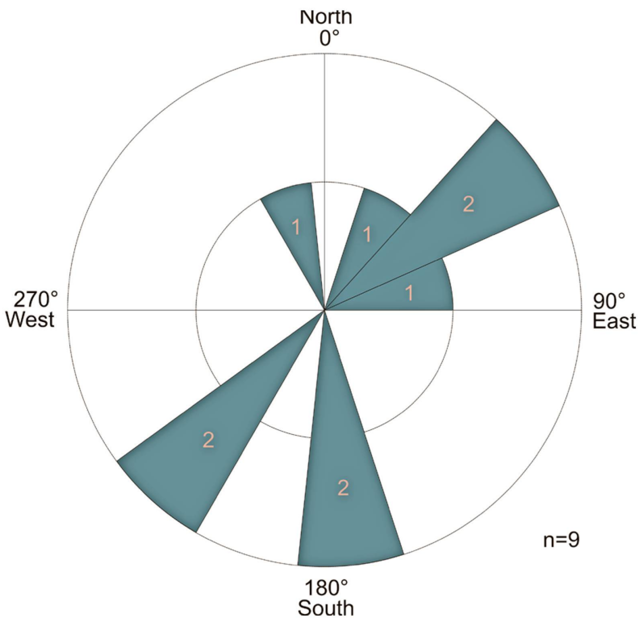

Figure 25: Rose diagram of the dinosaur's walking direction (at the end of the respective trackway).

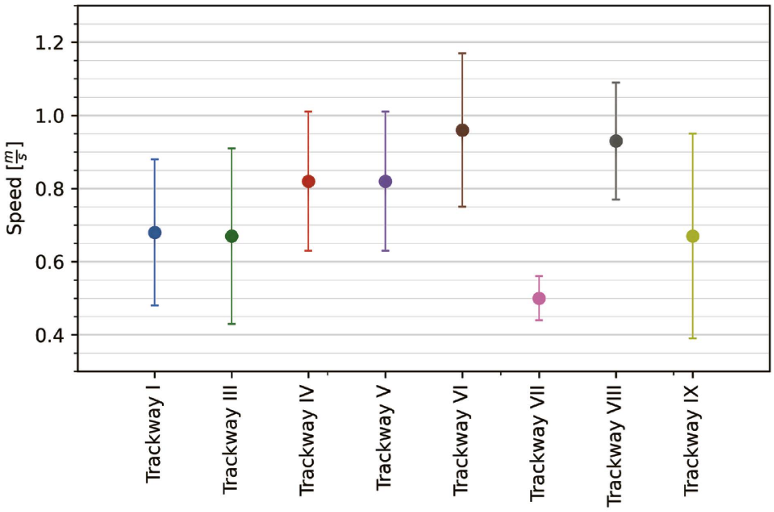

Figure 26: Calculated trackmaker walking speeds.

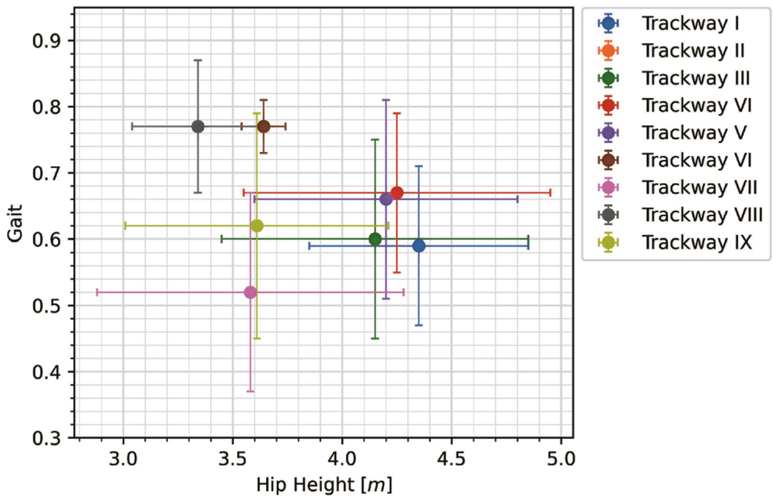

Figure 27: Scatter plot comparing the trackmakers' hip heights to their gaits.

of new imprints and described two new trackways. By analyzing their surroundings using photogrammetry, the tracks of a stratum below the main tracksite, which was previously thought to bear under prints, could be identified as actually bearing true prints. A large number of measurements were taken from the generated 3D model of the main tracksite, which enabled the calculation of various properties of the track maker, such as hip height and speed. The trackmakers seem to have been present in two size groups and walking in a loosely connected group. The study concludes that drone photogrammetry is a cost-efficient and precise method for mapping and analyzing expansive and difficult-to-access dinosaur tracksites.

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