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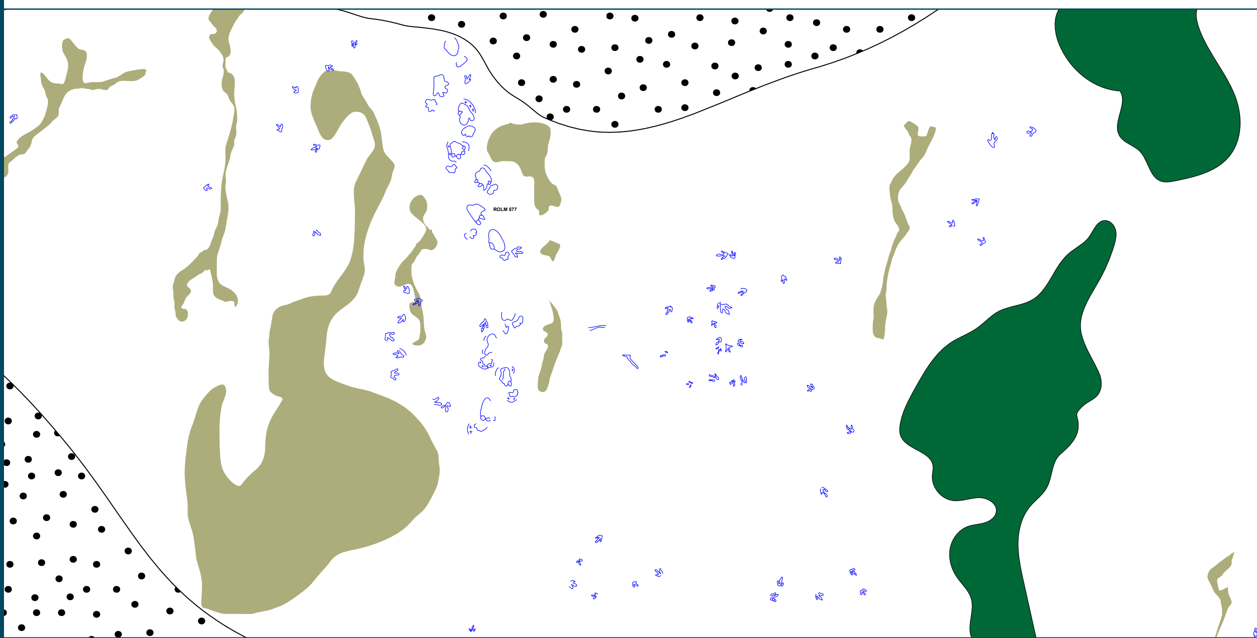

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Geothematic map of the Lavini di Marco tracksite (Lower Jurassic, NE Italy, Southern Alps)

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Cover
Above: detail of the geothematic map of the Lavini di Marco ichnosite.
Below: panoramic view of the "hinge" area, with trackway ROLM 26 appearing to ascend diagonally along the fold slope (Photo courtesy of F.M. Petti).

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ABSTRACT

A new ichnological study was carried out on the dinosaur tracks from the Lavini di Marco ichnosite (Trentino-Alto Adige/Südtirol, NE Italy), on the framework of a joint project between the Sapienza University of Rome and the MUSE - Sciences Museum of Trento, with the cooperation of the Geological Survey and the Fire Department of the Autonomous Province of Trento. The project consisted of a new analysis, made possible through modern digital technologies, of the Lower Jurassic tracks attributed to theropod and sauropod dinosaurs. Additionally, it included the realization of a geothematic map of the entire site, representing the objective of this contribution. Two different approaches were used during the ichnological mapping: i) traditional methods and ii) aerial- and close-range photogrammetry. Aerial photogrammetry was performed using two distinct drones, obtaining orthophotos and orthoplanes of the tracks-bearing horizons, to produce a detailed geothematic map. Close-range photogrammetry led to the production of more than seventy 3D color-coded models of the best-preserved dinosaur footprints. The map was produced in digital vector format with different levels of knowledge. The final geothematic map represents a complete multilayer documentation that will be useful for future work of conservation, dissemination, and valorization of the tracksite.

Keywords: Hettangian, dinosaur footprints, aerial photogrammetry, drones, geothematic map, Italy.

INTRODUCTION

The Lavini di Marco ichnosite is located in Trentino-Alto Adige/Südtirol (NE Italy), about 30 km south of Trento, in the southern sector of the Adige Valley (i.e., Lagarina Valley; central-eastern Southern Alps; Fig. 1). It was discovered in 1989 by Luciano Chemini, being the subject of several studies (Leonardi and Lanzinger, 1992; Leonardi and Avanzini, 1994; Avanzini et al., 1997; Leonardi and Mietto, 2000; Avanzini et al., 2001b, 2003; Piubelli et al., 2005; Avanzini et al., 2006; Piubelli, 2006; Avanzini and Petti, 2008). After its discovery, several other dinosaur tracksites have been found in Lower Jurassic deposits of the Southern Alps sector (Mietto and Roghi, 1994; Avanzini, 1997; Leonardi and Mietto, 2000; Mietto et al., 2000; Avanzini, 2001; Avanzini et al., 2001a, 2001c, 2007b, 2008; Avanzini and Petti, 2008; Petti et al., 2008; Petti et al., 2011a, 2011b; Belvedere et al., 2017).

The track-bearing horizons from the Lavini di Marco are exposed due to various landslide events that occurred in prehistorical and historical times between 21.200±100 and 800±200 years B.P. (Martin et al., 2014). Landslide bodies, arranged on a WNW dipping monoclinal surface (Piubelli et al., 2005), were already described in the 14th century by Dante Alighieri in his Divine Comedy, being the first to provide a geological interpretation of these landslides induced by seismic causes or by erosion at the base of the slopes (Romano, 2016).

The Lavini di Marco dinosaur ichnoassemblage consists of hundreds of tridactyl footprints, produced by small- to large-sized theropods, and dozens of quadrupedal narrow-gauge trackways, attributed to medium-sized sauropodomorphs (Leonardi and Lanzinger, 1992; Leonardi and Avanzini, 1994; Avanzini et al., 1997, 2003, 2006; Leonardi and

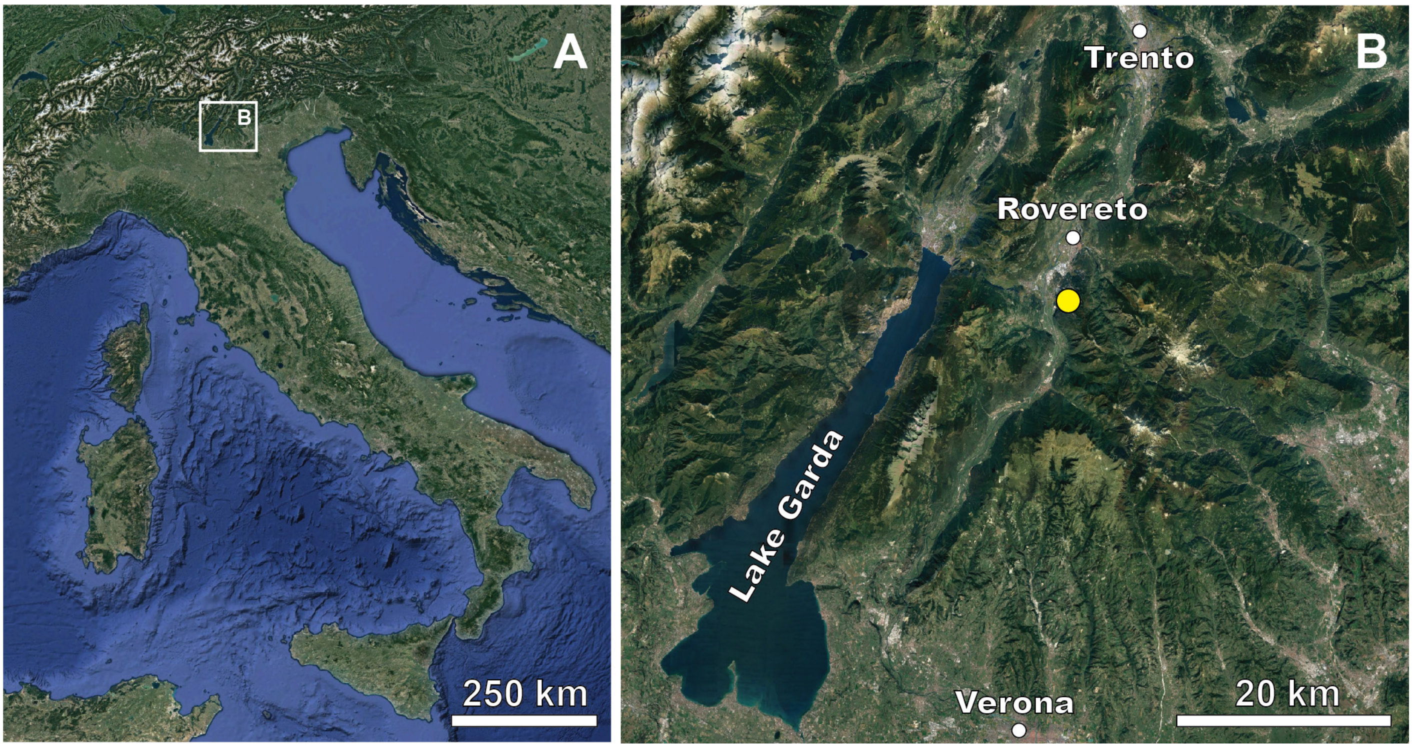

Fig. 1 - Location of the Lavini di Marco tracksite (Trentino-Alto Adige/Südtirol), modified from Google Earth Pro.

Mietto, 2000; Piubelli et al., 2005; Piubelli, 2006; Avanzini and Petti, 2008; Petti et al., 2020a). The discovery of small and elongated tridactyl footprints, assigned by Avanzini et al. (2001b) to the ichnogenus *Anomoepus*, suggested the possible occurrence of primitive ornithischians.
The present study aims to update the knowledge of the Lavini di Marco tracksite by presenting the georeferenced geothematic map of the area, obtained with innovative tools (i.e., drones; high-resolution digital photogrammetry).

GEOLOGICAL SETTING

The Lavini di Marco track-bearing surfaces crop out near Rovereto (Trentino-Alto Adige/Südtirol, NE Italy), on the western slope of Mt. Zugna (central-eastern Southern Alps). The trampled surfaces stratigraphically belong to the Calcari Grigi group (Hettangian-upper Pliensbachian; Avanzini et al., 2007a), exactly to the Monte Zugna formation (Bosellini and Broglio Loriga, 1971; Masetti et al., 1998, 2012; Avanzini et al., 2006; Fig. 4). The Calcari Grigi group was deposited within the Trento carbonate platform, a palaeogeographic domain characterized by shallow-water carbonate sedimentation throughout most of the Early Jurassic (Masetti et al., 1998, 2012; Avanzini et al., 2006).
The Monte Zugna fm is represented by light grey to whitish, micritic and oolitic-bioclastic limestones, often intensely bioturbated, divided into three members, from bottom to top: (a) “Lower Subtidal Cyclic Unit” (LSCU); (b) “Middle Peritidal Unit” (MPU); (c) “Upper Subtidal Unit” (USU; *sensu* Avanzini et al., 2007a). The Lavini di Marco tracksite belongs to the MPU, consisting of alternating stromatolitic and dolomitized layers, light grey peloidal mudstone, dark grey bioclastic wackestone, and reddish mudstone (Avanzini et al., 1997). Here, seven track-layers were recognized in a seven meters thick section (Avanzini et al., 2006; Avanzini and Petti, 2008). The occurrence of the dasycladacean alga *Palaeodasycladus mediterraneus* suggests a Hettangian age for the Lavini di Marco tracksite (Avanzini et al., 2006). The stratigraphic succession, WNW dipping, records a slope ranging from 20° to 50°.

PREVIOUS ICHNOLOGICAL ANALYSES

The Lavini di Marco ichnosite underwent systematic study through preliminary surveys and two major field campaigns in June 1992 and June 1993, under the direction of Giuseppe Leonardi and Paolo Mietto. This research was financially and logistically supported by the Museo Tridentino di Scienze Naturali di Trento (nowadays MUSE - Sciences Museum of Trento). During these campaigns, approximately 200 individual dinosaur tracks were cataloged, photographed, and classified, and some were molded. Subsequently, more footprints were discovered, and the total count reached about 800 individual tracks in this locality. The initial study of the Lavini di Marco tracksite resulted in a comprehensive collective volume publication (Leonardi and Mietto, 2000), coordinated by the two museums involved, and with the support of the National Research Council (CNR) and the Autonomous Province of Trento.
Numerous surveys of the site led to the identification of hundreds of dinosaur tracks belonging to both bipedal and quadrupedal dinosaurs, preserved as concave epirelief (*sensu* Leonardi, 1987). Initially, six tridactyl morphotypes were identified by Leonardi and Mietto (2000), attributed to small to medium-sized theropods. The authors compared the footprints from Lavini di Marco with the Triassic ichnogenus *Coelurosaurichnus*, the common Jurassic ichnogenera *Eubrontes* and *Grallator,* and the Cretaceous ichnotaxa *Bueckeburgichnus* and *Columbosauripus*, but they were not formally associated with specific ichnotaxa.
A later study by Piubelli (2006) reduced the number of morphotypes to four (LA1, LA2, LA3, LA4) based on morphological and morphometric analyses leading to the designation of a type specimen for each morphotype. Overall, in the analysis conducted by Piubelli et al. (2005) and Piubelli (2006) the recognized ichnotaxa are *Grallator* and *Kayentapus*, the latter representing the most common ichnotaxon in the Lavini di Marco site and usually referred to a theropod trackmaker close to *Dilophosaurus*. The distribution of the ichnotaxon reported from the Early Jurassic of Northern Europe (Gierliński, 1991; Gierliński and Alhberg, 1994) and North America (Welles, 1971), led Piubelli et al. (2005) to hypothesize a wide connection between Laurasia and Gondwana in the Early Jurassic represented by the Southern Alps sector. Piubelli et al. (2004) also reported a putative synapsid track from the Lavini di Marco ichnosite, ascribed to the ichnogenus *Brasilichnium* Leonardi, 1981.
A couple of tridactyl tracks with purported sub-parallel traces of metatarsal have been interpreted by Avanzini et al. (2001a) as a putative resting posture. The authors assigned the footprints to the ichnogenus *Anomoepus*, attributing them to a small ornithischian trackmaker, with affinities to tracks described from South Africa and Poland (Ellenberger, 1972; Olsen and Galton, 1984; Haubold, 1986; Gierliński, 1991; Gierliński and Pieńkowski, 1999). According to the authors, such attribution could suggest a Gondwanan origin for the Lavini di Marco trackmakers; however, recent re-analysis has allowed to re-interpret the traces of the metatarsals as the interference of separate tridactyl footprints rejecting the attribution to *Anomoepus* (Antonelli, 2018; Petti et al., 2020a).
Concerning quadrupedal footprints, Leonardi and Mietto (2000) identified several trackways since the first

studies, recognizing at least two morphotypes initially attributed to sauropod and ornithopod trackmakers. The 15 short segments of trackways, undoubtedly referable to sauropod producers, all narrow-gauge type and with *pes* print up to 52 cm, were compared by the authors to the ichnogenera *Breviparopus* and *Parabrontopodus*, with a putative trackmacker to be found within the Eusauropoda clade, in particular Cetiosauridae or Vulcanodontidae (Leonardi and Mietto, 2000). The authors also described five tracks interpreted as traces of a bipedal to semi-bipedal producers, referring them to possible ornithopod trackmakers; however, according to Sacco (2018) and Petti et al. (2020a) it is likely that these footprints all refer to sauropod dinosaurs, an alternative hypothesis proposed by Leonardi and Mietto (2000) themselves.

A new analysis of the quadrupedal tracks from the Lavini ichnosite by Avanzini et al. (2003) led to the description and establishment of the new ichnotaxon *Lavinipes cheminii*. According to the authors, it is characterized by narrow-gauge trackways, with a pentadactyl U-shaped *manus* (wider than long) and a longer-than-wide tetradactyl *pes*. The authors stressed similarities with the ichnotaxa *Pseudotetrasauropus* and *Otozoum*, although reporting differences in the number and morphology of the digits and the type of gait. Based on all traits, according to Avanzini et al. (2003) the most plausible putative trackmaker for the new ichnotaxon *Lavinipes cheminii* should be sought among primitive sauropods, with greater affinity to the basal Eusauropoda.

In 2018, a new project started for the study of the Lavini di Marco ichnosite carried out by MUSE, Sapienza University of Rome and the Autonomous Province of Trento. After an initial survey that led to the recognition of over 700 tridactyl footprints and numerous quadruped tracks, the project consisted of the study of the abundant ichnological material, both through traditional ichnological techniques and through detailed 3D digital models, combining close-range and aerial photogrammetry. The result, in addition to a new detailed study of the traces, is the realization of the first detailed geothematic map of the ichnosite, the subject of this contribution. Differently, the abundant ichnological material referable to theropod and sauropod dinosaurs, reanalyzed through the use of new digital technologies, is currently under review and will be presented shortly in manuscripts in preparation.

MATERIALS AND METHODS

An area of more than 25,000 m^2 was estimated for the track-bearing surfaces, within an overall surface of 600,000 m^2. The trampled area was subdivided into five main sectors (Fig. 2), ranging from 15,000 to 500 m^2 and characterized by a high degree of trampling (*sensu* Lockley, 1991), named as follows: i) “Strada Forestale”; ii) “Colatoio Chemini”; iii) “Piega”; iv) “Colatoi Inferiori”; v) “Laste Alte”.

The work plan consisted of four steps (Fig. 3): i) cleaning of the surface; ii) ichnological survey, supported by using close-range photogrammetry; iii) aerial photogrammetric survey of each sector; iv) graphical digitization and georeferencing of the ichnological data obtained by aerial-based photogrammetry.

The track-bearing horizon was carefully cleaned, to remove debris from each footprint and surrounding surface. A manual cleaning allowed to remove of the debris without impacting the extremely weak and fractured trampled surface.

Morphological interpretative sketches of each track were subsequently drawn in the field with colored chalks, to highlight: i) in each track, the outline and the anatomical characters of the trackmaker autopods; ii) the substrate deformations due to dinosaur trampling; iii) the extramorphologies of the footprints, when subjected to mud collapse or displacement. Seven different track-bearing layers were identified (Avanzini et al., 1997; Leonardi and Mietto, 2000), and several sectors are likely characterized by undertracks (the deformed layer beneath the true track; Milàn and Bromley, 2006).

More than 700 tridactyl footprints, some of which arranged in short bipedal trackways, and nine quadrupedal narrow-gauge trackways were identified. The main ichnological parameters were measured following the methods proposed by Leonardi (1987) and Thulborn (1990).

A subsequent step consisted in the realization of high-resolution photogrammetric 3D digital models, both via close-range photogrammetric and through the use of drones. High-resolution digital photogrammetry is a measurement technique that returns metric information about an object (shape, position, and size) through the acquisition and analysis of a pair of stereometric frames. If an object is recorded in at least two images from different angles, the different positions of the object in the images allow a stereoscopic view of it, by deriving 3D information in the overlapping areas of the images captured. Its widespread use is due to its reduced time of data acquisition, extremely high resolution, and limited costs, as well as the possibility to study areas difficult to access and share and quickly access data (e.g., Citton et al., 2017; Romilio et al., 2017; Petti et al., 2018; Cónsole-Gonella et al., 2021; Romano et al., 2022a).

Aerial photogrammetry is based on the acquisition of high-resolution aerial orthophotos. It uses wide-angle images and georeferenced ground points to recreate the geometry and topography of a selected area into a three-dimensional digital model, where the measurements are recorded in a geospatial data file. The resolution and the scale of the model substantially depend on the focal width of the camera

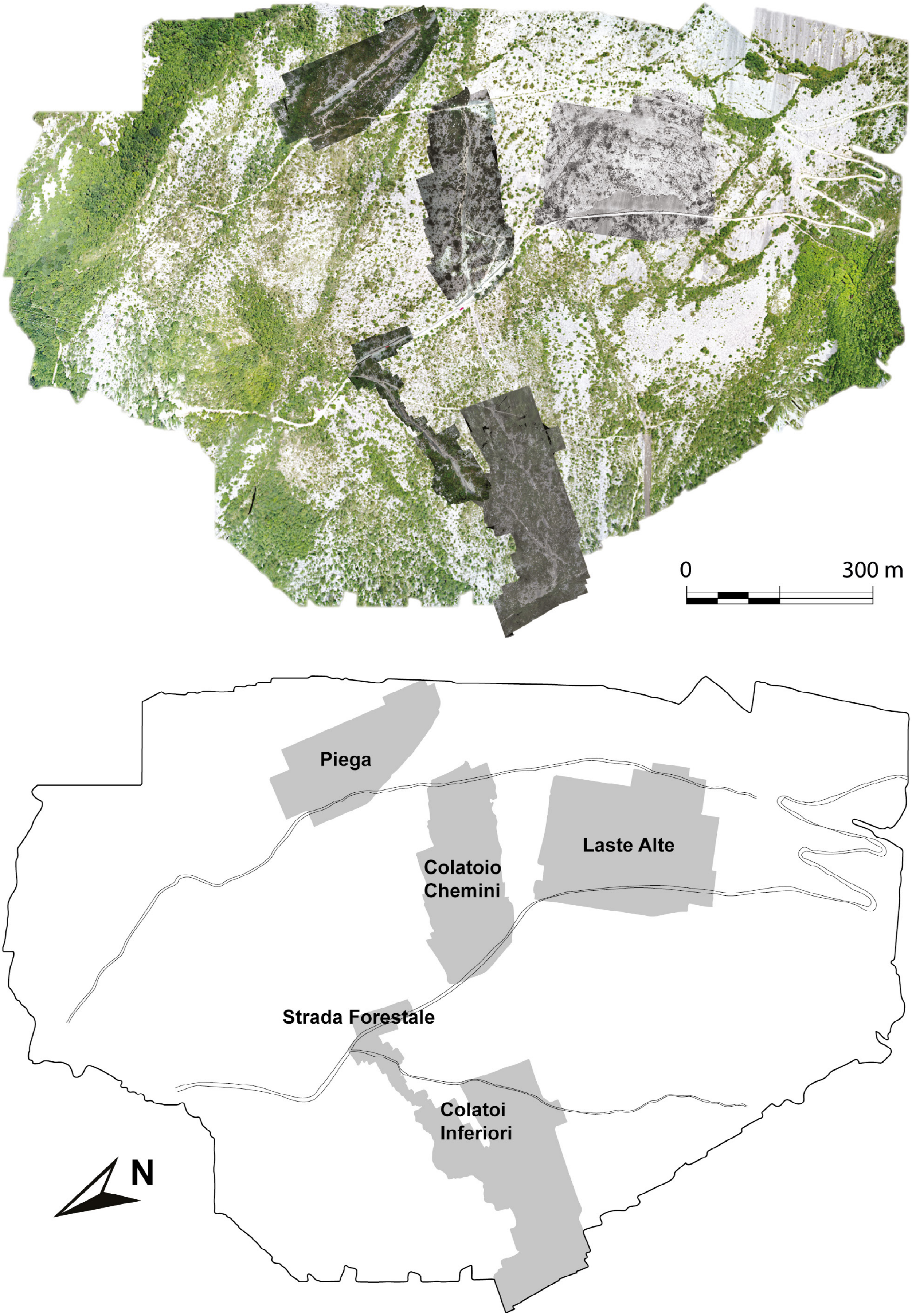

Fig. 2 - Orthophoto of the whole area of the Lavini di Marco, with superimposed the high-resolution orthophotos of the five main dinoturbated sectors.

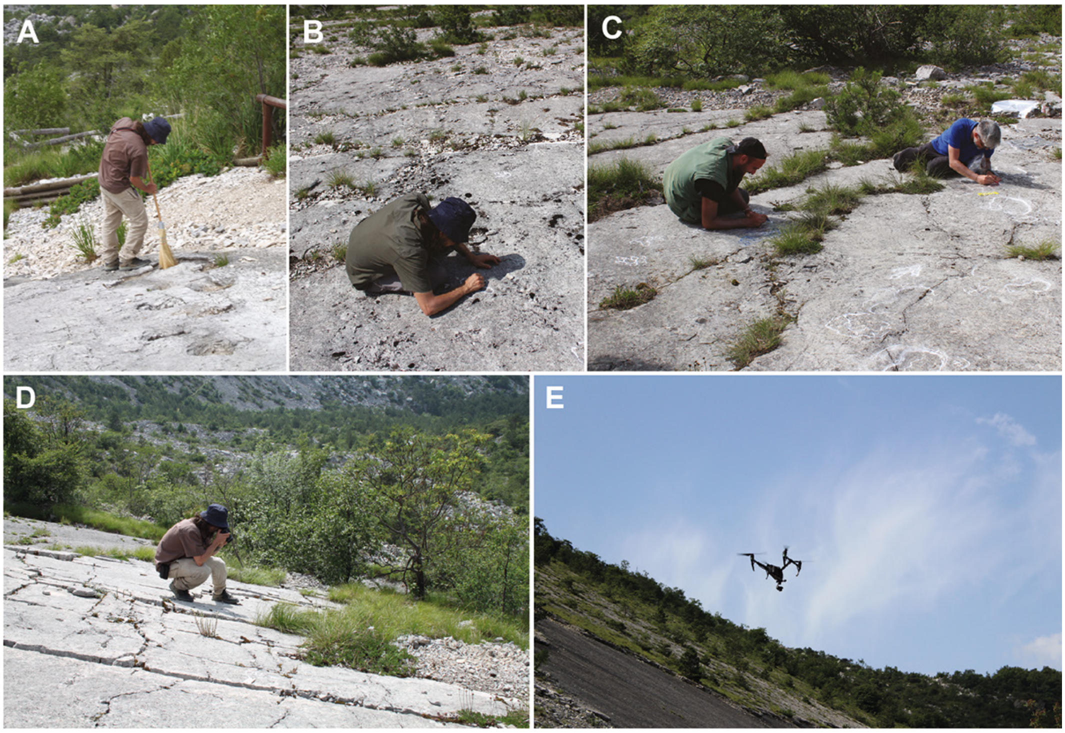

Fig. 3 - Ichnological mapping at the Lavini di Marco ichnosite. A) cleaning of the track-bearing surface; B, C) interpretative drawings of the dinosaur footprints; D) close-range photogrammetry; E) drone photogrammetry.

lens and the height (and thus the distance from the object) from which the aerial photos are acquired (Matthews, 2008). The use of UASs (Unmanned Aerial Systems; i.e., drones) for data acquisition greatly improved the quality of the aerial photogrammetry, formerly performed with helicopters, gliders, airships, or hot air balloons, on which digital cameras were installed (e.g., Breithaupt et al., 2004; Romilio et al., 2017). This new approach is recently finding numerous applications in the geological and paleontological field, from the 3D reconstruction of large skeletons mounted in museum structures to the reconstructions and mapping of outcrops, and 3D detailed mapping of whole tracksites (e.g., Citton et al., 2017; Romilio et al., 2017; Petti et al., 2018, 2022; Xing et al., 2018, 2020; Filipov et al., 2020; Giordan et al., 2020; Cónsole-Gonella et al., 2021; Honarmand and Shahriari, 2021; Papadopoulou et al., 2021; Thomas et al., 2021; Peace and Jess, 2022; Romano et al., 2022a, 2022b, 2023; Soncco et al., 2022).

Close-range photogrammetry was carried out on the best-preserved tracks and trackways, to gain more accurate morphological information and anatomical details about the trackmaker autopods. For data acquisition, each track was photographed turning 360° around it, with four different vertical points of view with respect to the surface horizon (i.e., 10°, 30°, 60°, and 90°), attempting to maintain a 1 m distance from the footprint. For each selected track about 40 photos were taken, using the digital single-lens reflex camera Canon EOS 1300D, equipped with an 18.0 Megapixel CMOS (APS-C) image sensor and EF-S 18-55 mm lens. For each analyzed specimen, the processing of the images was carried out on Agisoft Photoscan ® Professional v. 1.4.5, according to the workflow proposed by Mallison and Wings (2014), to obtain a dense point cloud. The latter was exported as a .txt file in Golden Software Surfer ® 16 to produce a grid file and, finally, a 3D color-coded (i.e., DEM) contour map.

Twenty-four GCPs (Ground Control Points, i.e., markers used as strongholds for georeferencing) were placed on the surface before the aerial survey, and their spatial position was recorded via GPS, effectively defining and covering the whole area of the Lavini di Marco tracksite. Two different drones were used to perform the aerial photogrammetric survey: the quadcopters DJI Inspire 2 and DJI Mavic Pro. DJI Inspire 2 is equipped with a digital camera ZENMUSE X4S (FC6510) with 1" 20 Mpx Exmor R CMOS sensor. DJI Mavic Pro is equipped with a digital camera FC220, with 1/2.3" 12.7 Mpx CMOS sensor. Both drones have a medium flight duration of up to 27 minutes. Nine overflights were carried out, with flight height between 15 m and 30 m, and 2389 photos were taken to complete the aerial survey, in time-lapse mode (photographic shot every 5 seconds). Overall, 865 images were taken on the "Laste Alte" sector, 368 on the "Colatoio Chemini", 752 on the "Colatoi Inferiori", 83 on the "Strada Forestale", 170 on the "Piega". Additionally, 151 images were captured with a flight height of 30 m to cover the whole area, thus obtaining the base orthophoto of the Lavini di Marco site, on which the detailed orthophotos of the main sectors were overlapped. The detail of the aerial survey is evidenced by the Ground Sampling Distance (GSD), comprised between 0.22 and 0.81 cm/pixel. The processing of digital images was made using Pix4Dmapper Pro v. 4.2.27, following the same workflow used for the

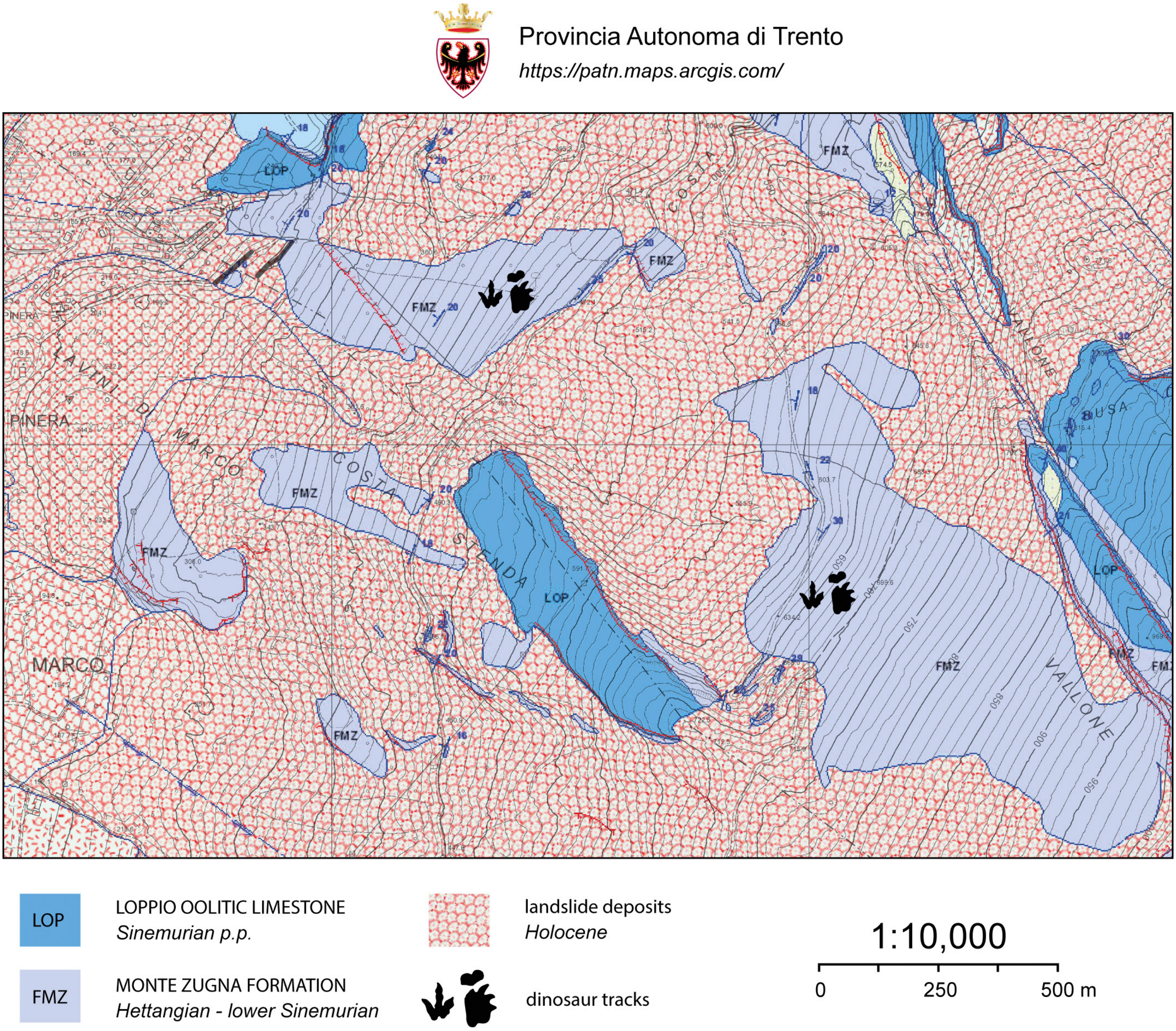

Fig. 4 - Geological setting of the Lavini di Marco locality and surrounding area (http://patn.maps.arcgis.com).

close-range photogrammetry. The obtained products are represented by orthophotomosaics and orthoplanes (i.e., horizontal planes on which an orthorectification is carried out, consisting of a projective transformation of a sloped object) of the whole ichnosite, as well as more detailed orthophotos focused on the areas with a higher degree of trampling. The final map was produced in digital vector format and edited in ©Adobe Illustrator.

MAP DESCRIPTION

The map of the Lavini di Marco tracksite was realized evidencing five different levels of knowledge, represented by dinosaur tracks, vegetation, debris, fractures, and anthropic infrastructures (i.e., forest roads, scenic trails, and watchtowers), to generate a comprehensive product. The scale map is 1:500 (i.e., 1 cm = 5 m). Its relevance consists in the accuracy of the information provided. It is thus possible: i) to get an overview of the whole tracksite, distinguishing the areas covered by the landslide debris or by plants, from those where the track-bearing surfaces are best exposed; ii) to detect the areas with a high degree of trampling, appreciating the richness of the tridactyl ichnoassemblage and the numerous quadrupedal trackways.

The "Strada Forestale" sector can be accessed from the entrance of the paleontological trail. After a few hundred meters, eight tridactyl footprints are visible on the left side of the path, evidenced by an information board. The analysis

started with the already known and well-preserved tridactyl tracks ROLM 198-1 and ROLM 198-2 (Fig. 5A-D) and led to the discovery of the other specimens. Proceeding on the trail, approximately 200 m after the crossroad with the "Colatoio Chemini", on the right a dozen of tridactyl tracks occur, including the well-preserved and large-sized ROLM 137 (Fig. 5E-F). Finally, proceeding southwardly for about 300 m, another quadrupedal trackway, and numerous tridactyl tracks are observable on the left.
The "Colatoio Chemini" consists of a preferred corridor for the runoff water, about 200 m long and 6 m wide, eastwardly rising almost perpendicular to the "Strada Forestale". It is bordered by a path along which the presence of wooden towers allows a panoramic view of the area. In this sector, named after Luciano Chemini discovery, the most famous dinosaur tracks are preserved (Fig. 6). Almost five trackways were referred to sauropods, whereas only one trackway and some isolated specimens were attributed to theropods (Leonardi and Mietto, 2000). The main issues in this area are represented by the progressive weathering of the track-bearing surface and the poor degree of footprint preservation. The former is evidenced by the discontinuity of the track-layer, which, due to runoff waters, was subjected to numerous detachments and landslides during the last decade. As a result, entire portions of the dinoturbated horizons were lost, leading to the exhumation of the underlying layers, on which undertracks are sometimes visible. On the western side of the "Strada Forestale", the "Colatoio Chemini" continues, revealing the occurrence of another isolated quadrupedal trackway.
Rising from the path bordering the "Colatoio Chemini" and proceeding to the left, the sector called "Piega" crops out; it is represented by an almost vertical wall, where at least three trackways occur, two attributed to sauropods and one, poorly preserved, to a theropod (Leonardi and Mietto, 2000). Among them, the trackway ROLM 26 is perhaps the most famous and spectacular trackway of the ichnosite (Fig. 7A-B), as it seems produced by a "rock-climbing dinosaur", although the surface actually represents the hinge of a fold (Leonardi and Mietto, 2000). A few meters north of the ROLM 26, the ROLM 28 trackway, attributed to a sauropod, is crossed by the ROLM 59, referred to a theropod. Proceeding on the scenic path between the "Colatoio Chemini" and the "Piega" sectors, it is worth mentioning the occurrence of the largest tridactyl track of the Lavini di Marco tracksite, the ROLM 219, produced by a large-sized theropod (Fig. 7C-D).
The "Colatoi Inferiori" can be reached from a crossroad located on the "Strada Forestale" trail (a few meters before the "Colatoio Chemini"). This sector ramifies downstream from "S.F.", representing the lower part of the tracksite. The Y-shaped configuration has led to the individual arms being conventionally known as "sauropod colander" and "theropod colander": in this area, about a hundred theropod footprints and two sauropod trackways are indeed preserved.
The "Laste Alte" is the least accessible area of the entire ichnosite, due to the slope and slippery surface, which is also not equipped for visitors: it is located south of the "Colatoio Chemini", enclosed between the scenic trail and the "Strada Forestale" path. It turns out to be the richest sector in footprints, some of which extraordinarily preserved. Most of the studies in this sector have been concentrated in the last 20 years (e.g., Avanzini et al., 2003; Piubelli, 2006). The ichnological analysis of this sector led Avanzini et al. (2003) to establish the new ichnotaxon *Lavinipes cheminii*, typified by the quadrupedal trackway ROLM 577

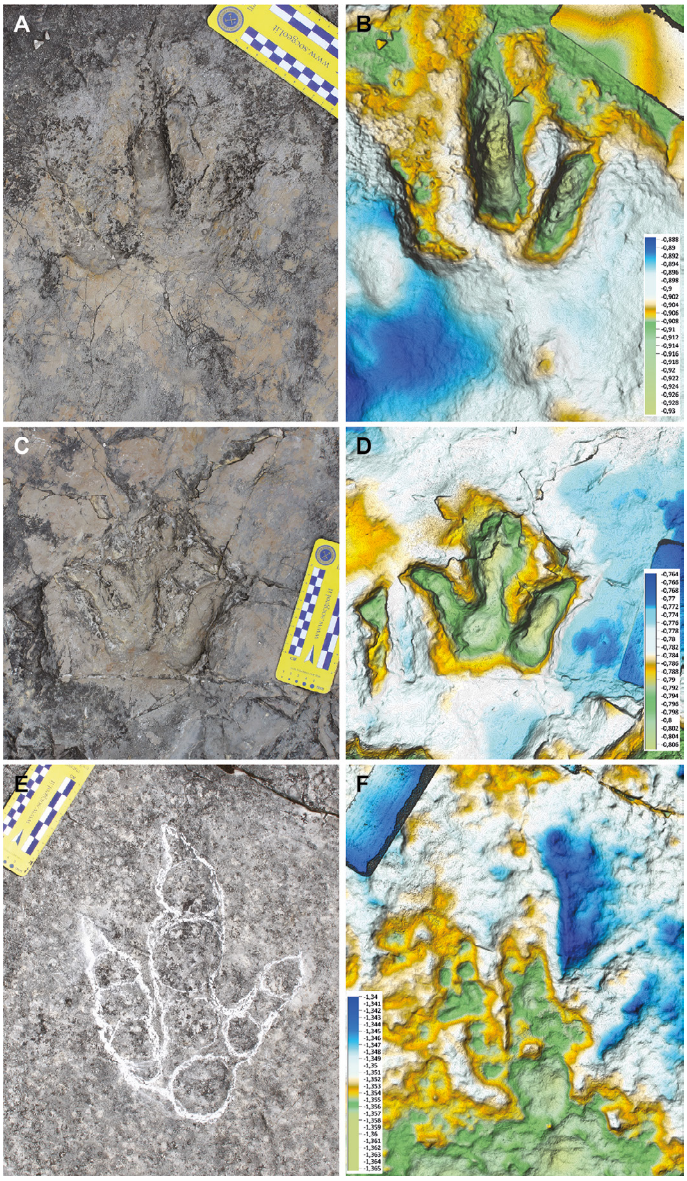

Fig. 5 - The tridactyl tracks ROLM 198-1, ROLM 198-2 and ROLM 137, occurring on the surfaces around the "Strada Forestale" sector: A, C, E) footprint *in situ*; B, D, F) DEM with contour lines (depth scale in m).

Fig. 6 - The "Colatoio Chemini". On the left, a panoramic view from the bottom of the sector; on the right, the trackways ROLM 9 (foreground) and ROLM 11 (background).

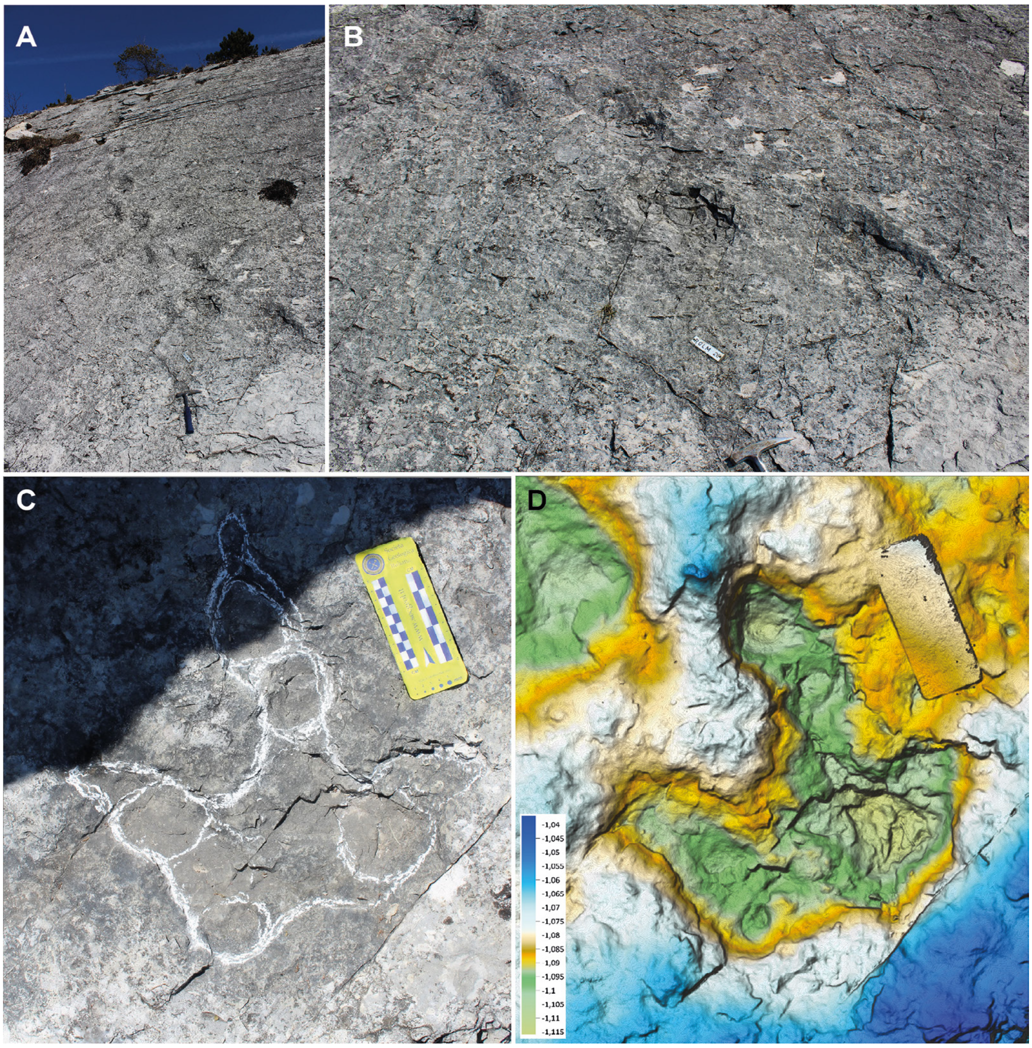

Fig. 7 - The most representative dinosaur tracks occurring in the "Piega" sector and its bordering path: A) the trackway ROLM 26 (geological hammer for scale); B) close-up of the first steps of the same trackway; C) ROLM 219, the largest tridactyl tracks of the Lavini di Marco ichnosite, and its DEM with contour lines in (D). Depth scale in m.

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(Figs. 8-9). The latter is a narrow-gauge quadrupedal or semi-bipedal trackway, with *manus* and *pes* inward and outward oriented with respect to the midline. Both fore- and hindlimb impressions are tetradactyl, as evidenced by DEMs. The study carried out in 2018 also led to assign to *Lavinipes cheminii* the trackways ROLM 11 and ROLM 26, preserved on the "Colatoio Chemini" and "Piega" sectors, respectively (Sacco, 2018).

However, the sector of "Laste Alte" is clearly theropod-dominated (Fig. 9), revealing four smaller areas with a very high degree of trampling. It is worth noting the abundance of very small-sized tridactyl tracks (no longer than 10 cm) in the southernmost of these areas.

As already stressed above, the results of the ichnological analysis of both quadrupedal trackways and tridactyl tracks will be discussed in forthcoming papers.

All the analyzed dinosaur tracks from the Lavini di Marco ichnosite are represented in blue in the geothematic map, and for the most important specimens (both trackways and isolated footprints) the acronym is provided.

DISCUSSIONS

The last two decades have witnessed substantial development in photogrammetry, stemming from pioneering work in the field of paleontology (Breithaupt and Matthews, 2001; Breithaupt et al., 2001). With the introduction of new open-source software and progressively reduced processing times, this digitalization technique is becoming the new standard in many paleontological studies.

Photogrammetry, in fact, has been extensively applied in paleontology, enabling the easy manipulation and digital study of specimens that would be otherwise either fragile or extremely heavy. Its applications range from the reconstruction of skeletons in museum structures (e.g., Fau et al., 2016; Romano et al., 2018, 2022a, 2023, 2024; Rubidge et al., 2019; Van den Brandt et al., 2024), body mass studies in fossil tetrapods (e.g., Gunga et al., 1999, 2008; Bates et al., 2015; Brassey et al., 2015; Basu et al., 2016; Brassey, 2016; Reolid et al., 2021; Romano and Rubidge, 2021; Romano et al., 2021a, 2021b, 2022b, 2023; Hart et al., 2022), locomotion and biomechanics (e.g., Hutchinson et al., 2005; Gatesy et al., 2009; Mallison, 2010; Bates and Schachner, 2012; Reiss and Mallison, 2014; Otero et al., 2017, 2019; Sellers et al., 2017; Bishop et al., 2018; Klinkhamer et al., 2018a, 2018b; Díez Díaz et al., 2020; Vidal et al., 2021), ichnology (e.g., Petti et al., 2008, 2018, 2020b, 2022; Mallison and Wings, 2014; Matthews et al., 2016; Citton et al., 2015; 2019; 2020; Antonelli et al., 2023a, 2023b), fossil invertebrates (e.g., Polonkai et al., 2017; Peterman et al., 2020) and feeding modes (Hernesniemi et al., 2011; Young et al., 2012; Cuff and Rayfield, 2015; Lautenschlager et al., 2016; Konietzko-Meier et al., 2018).

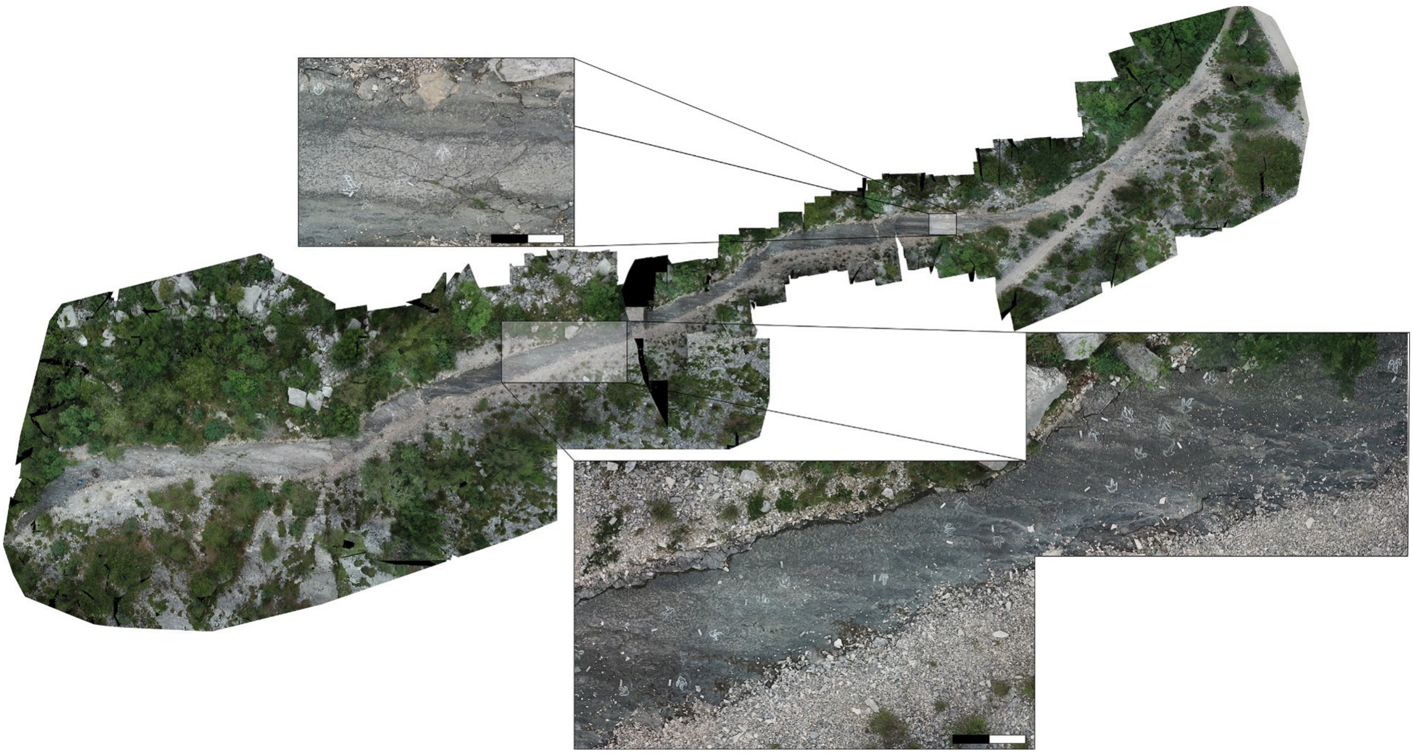

Fig. 8 - Orthophoto of the "Colatoi Inferiori" with a close-up of the main dinoturbated sectors.

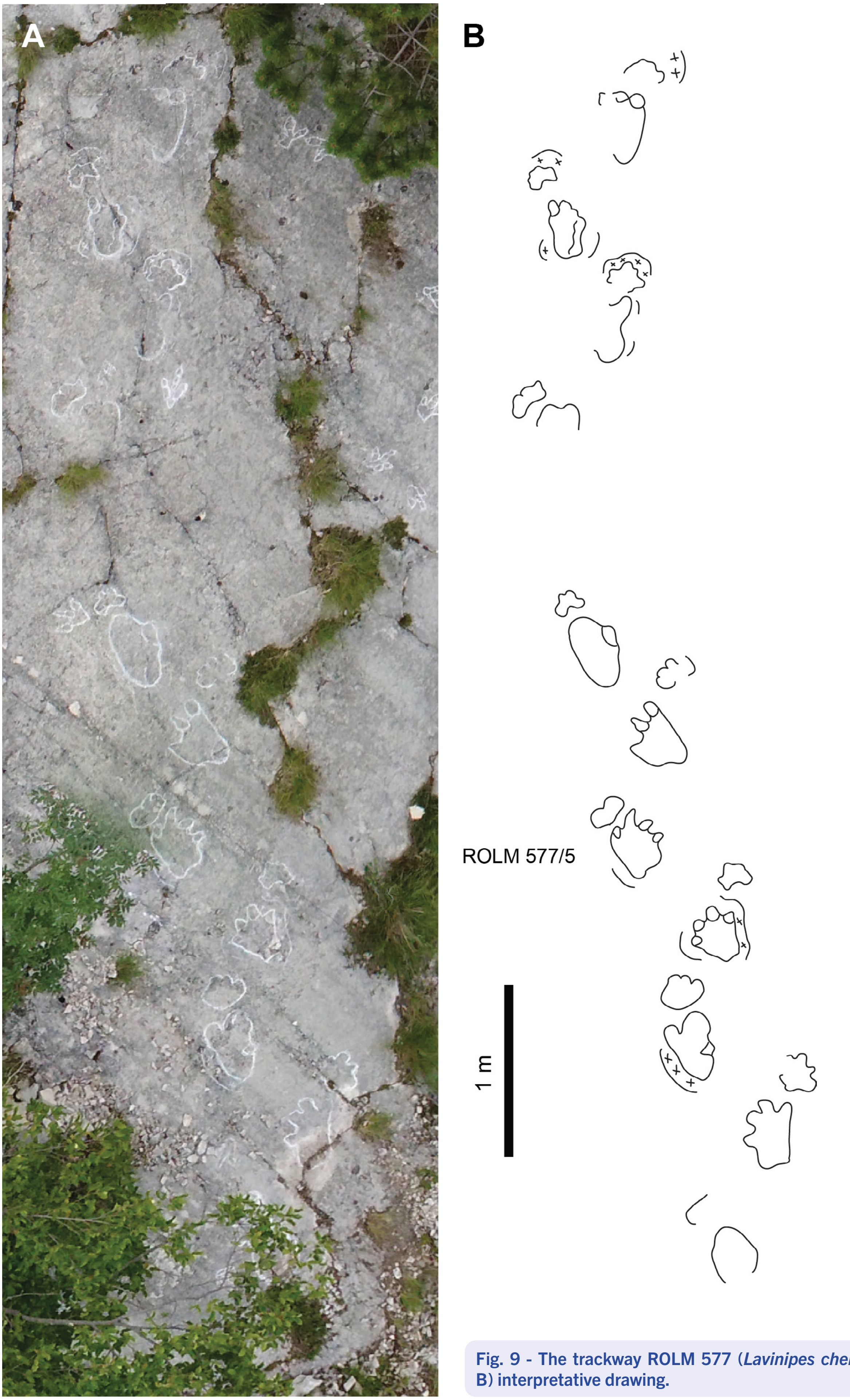

Fig. 9 - The trackway ROLM 577 (*Lavinipes cheminii*). A) orthophoto; B) interpretative drawing.

The use of photogrammetry has proven to be extremely important, especially in the field of ichnology. The photogrammetric 3D modeling of footprints firstly allows for a more objective representation and communication of tetrapod tracks, as a drawing always reflects the interpretation of an author, and different authors may have varying sensitivities even when describing and interpreting the same object. Furthermore, high-resolution models, achieved using contour lines and false colors, enable a detailed study of the preserved morphologies of autopods. This serves as a supporting element in the search for the trackmaker, highlighting characteristics often not visible to the naked eye directly in the field. The analysis of differential depth in different portions of the footprint also allows for the reconstruction of the complex movement of the *autopodium* in the substrate. This analysis enables the examination of the axes of maximum load during a locomotor cycle, providing significant insights into the fields of biomechanics and locomotion (e.g., Citton et al., 2015; Hatala et al., 2016a, 2016b, 2016c; Romano et al., 2016, 2020; Marchetti et al., 2017; Lallensack et al., 2018; Mujal et al., 2020; McNutt et al., 2021).

The power of the photogrammetric method is exemplified by applications that have allowed the three-dimensional reconstruction of fossil sites that were lost. This has been achieved through the use of historical photos taken in the past during fieldwork when the method was not yet available (Falkingham et al., 2014; Lallensack et al., 2015).

Unmanned Aerial Systems (i.e., drones) significantly improved the quality of aerial photogrammetry with respect to the past tools (e.g., helicopters, gliders, and hot-air balloons with digital cameras on board; see Breithaupt et al., 2004; Romilio et al., 2017). The affordable costs, the simplicity of the georeferenced data acquisition, and the quick processing workflow allow the production of multiple results with great accuracy and less effort.

The digitalization in vector format of the track-bearing surfaces from high-resolution orthophotos permits reporting with higher detail the relative position of the dinosaur footprints, also allowing to avoid the use of acetate overlays to reproduce and measure whole trackways. Additionally, the chance to accurately check the orthophotos allows to add of numerous features useful to evaluate and plan the conservation of the track layers, such as vegetation, fractures, and possible landslide niches. The position of different trails and watchtowers provides the opportunity to plan a wider open-air museum itinerary, emphasizing the most interesting areas.

For all the above, also in the present case, close-range photogrammetry supported the ichnological analysis, allowing us to obtain more accurate information about the morphological features of the dinosaur tracks and thus enhance their ichnotaxomomic assignment. The great improvement provided by the drone survey and the geothematic map herein presented is due to the comprehensive knowledge obtained by using this tool at macro- and meso-scale. Indeed, photogrammetry proves particularly suitable for geological studies, enabling 3D representation at various scales, ranging from millimetric features to the reproduction of the entire geological site or context (Cipriani et al., 2016; Romano et al., 2019; Ziegler et al., 2020). Dinosaur tracks, fractures, vegetation cover, and debris are reported in detail, with a decimeter spatial accuracy, thus recording the ichnological record and providing useful information from a structural logistical, and conservational point of view. As a result, the Lavini di Marco map can represent essential support for the management, future dissemination, and outdoor musealization of this paleontological heritage, developing the prerequisites for sustainable geotourism, based on a long-term conservation plan.

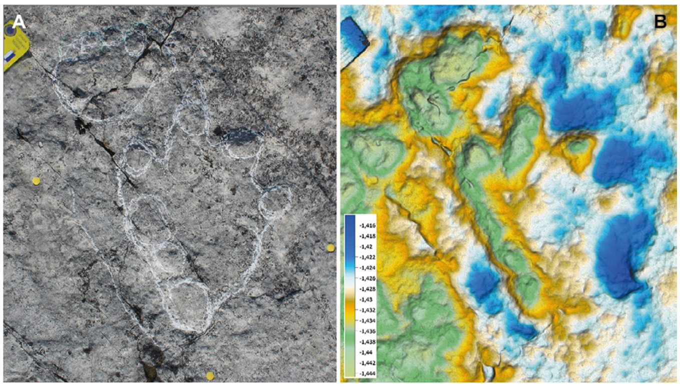

Fig. 10 - *Manus-pes* couple ROLM 577/5, holotype of *Lavinipes cheminii*: A) footprints in situ; B) DEM with contour lines (depth map in m).

Unlike body fossils, in the vast majority of cases, footprint specimens remain at the original discovery site, including specimens on which new ichnotaxa are established. All geosites are subject to various scales of natural evolution, involving weathering, erosion, and mechanical destruction of rock masses. These processes could lead the tracks to conditions significantly different from their original state of discovery and description (Ziegler et al., 2020). Moreover, in unfortunate cases, specimens can be vandalized, destroyed, or stolen, eliminating the comparative material for future studies. For these reasons, photogrammetry of entire sites and the deriving comprehensive geothematic map of detailed features prove to be indispensable tools for digitally preserving specimens, geological contexts, and outcrops, often of unique paleontological, paleoenvironmental, and paleobiogeographic importance.

Thus, also in the case of Lavini di Marco ichnosite, the geothematic map and the color-coded three-dimensional images may represent preliminary tools for the researchers

interested in the study of the tracksite or will permit to easily analyze the ichnoassemblage without the need to access the area. An expanding field in dissemination science, especially after the recent Covid-19 pandemic, is the development and implementation of Virtual Field Trips. These trips enable remote digital navigation of sites with varying degrees of knowledge, allowing interaction with the physical features of interest (Ziegler et al., 2020). In the context of democratizing science, virtual tours provide remote access to anyone interested, who may not have the economic means to visit the site in person. They also facilitate virtual excursions to rugged areas, making them accessible even for individuals with limited mobility. The tool can also be useful for teachers and instructors in the preparatory phase of an in-person field visit, with the idea that such tools should not replace active visits to natural sites but rather serve as additional support in the analysis and dissemination of content. In this regard, for the Lavini di Marco site, possible future interactive development could involve the installation of QR codes in specific areas of the ichnosite. By using a tablet or simply a personal smartphone, visitors could access numerous multimedia content, such as navigable 3D models of individual footprints or entire trackways, immersive reconstructions of the palaeoenvironment, and *in vivo* reconstructions of the dinosaurs that produced the tracks. This tool, in our opinion, should not replace the in-person visit to the site, which we consider crucial, but would provide a wealth of additional material essential for effective dissemination and popularization of science to as wide an audience as possible.
Likewise, the photogrammetric products (i.e., orthophotos and 3D models) will be useful for the protective operations and multi-temporal monitoring of this area, affected by weathering, landslides and massive fracturing events. The realization of this geothematic map is strategic for the ongoing project of valorizing the Lavini di Marco tracksite, one of the most internationally important ichnosites that can become truly touristically relevant when it is equipped with the necessary infrastructure, the right promotion and an innovative visit proposal.
The geothematic map herein presented describes one of the larger dinosaur tracksites in Europe, whose ichnological richness represents an important milestone for knowledge about the dinosaur evolution during the Early Jurassic.

CONCLUSIONS

The geothematic map of the Lavini di Marco ichnosite (Trentino-Alto Adige/Südtirol, NE Italy) represents the most comprehensive knowledge tool of the whole track-bearing area. It provides information about the rich ichnoassemblage, precisely reporting the position of the dinosaur tracks and trackways, and also describes other elements, such as vegetation, debris, fractures, forest roads, panoramic trails, and watchtowers.
The analysis of the whole tracksite was conducted combining traditional ichnological methods and technological tools, such as close-range and drone photogrammetry.
Close-range photogrammetry allowed to improve the interpretation of the dinosaur footprints, recognizing with higher accuracy their morphological details.
Drone photogrammetry led to producing numerous detailed and georeferenced orthophotos of the track-bearing area, aimed at digitizing in vector format dinosaur tracks and the other elements with a decimeter accuracy, thus mapping the ichnosite.
The products obtained with close-range and drone photogrammetry represent complete documentation that will be useful for future work of virtual and digital dissemination, valorization, conservation, and open-air musealization of the tracksite.

ELECTRONIC SUPPLEMENTARY MATERIAL

This article contains electronic supplementary material (Geothematic map of the Lavini di Marco tracksite).

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