Dinosaur footprints from the top of Mt. Pelmo: new data for Early Jurassic palaeogeography of the Dolomites (NE Italy)

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INTRODUCTION

Dinosaur footprints from the Early Jurassic of the Southern Alps of Italy have been studied since the early 1990s (Lanziger & Leonardi, 1992; Leonardi & Avanzini, 1994). Most of the documented trampled surfaces come from megatracksites located north of the Valsugana Fault. This fault system is a major alpine tectonic lineament that separates the classical successions of the Calcari Grigi Group in the Italian Prealps from those located in the Dolomites. Moreover, the discovery of the Pelmo tracks considerably expands the documented area of movement of Early Jurassic terrestrial vertebrates in the northern part of the Trento Platform, extending the size of the Early Jurassic megatracksites of the Southern Alps.

KEY WORDS - Dinosaur tracks, Palaeogeography, Early Jurassic, Calcari Grigi Group, Southern Alps.

ABSTRACT - Dinosaur footprints from the Lower Jurassic of northeastern Italy are well known and, since the first discoveries in the early 1990s, many sites have been described. Tracks are mostly found in the peritidal limestones of the Calcari Grigi Group, deposited on the Trento carbonate platform, now cropping out in the Southern Alps. In 2011, a group of speleologists discovered a new tracksite in the Lower Jurassic Calcari Grigi Group exposed almost at the top of Mt. Pelmo (Dolomites), 3037 m above sea level. Footprints are generally poorly preserved, but it proved possible to recognise some tridactyl footprints with theropodian features (i.e., elongated digit III and narrow interdigital angle) and some possible quadruped tracks whose configuration resembles that of a sauropodomorph trackmaker. Careful examination of the depressions excludes their inorganic origin (chemical weathering). Despite the poor quality of the traces, the Pelmo site is significant because it is the most easterly site ever found on the Trento Platform and the only one which is located north of the Valsugana Fault. This fault system is a major alpine tectonic lineament that separates the classical successions of the Calcari Grigi Group in the Italian Prealps from those located in the Dolomites. Moreover, the discovery of the Pelmo tracks considerably expands the documented area of movement of Early Jurassic terrestrial vertebrates in the northern part of the Trento Platform, extending the size of the Early Jurassic megatracksites of the Southern Alps.


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reported so far. Indeed, the Lower Jurassic carbonates in that area are less well investigated for three main reasons: 1) the relative scarcity of outcrops with respect to the south-western Southern Alps; 2) the chronostratigraphic uncertainties of the stratigraphic succession as compared to the classical sequence described to the south of the Valsugana Fault; 3) the lesser abundance of widely exposed surfaces of Lower Jurassic carbonates. These latter are instead found abundant in the surroundings of the Adige Valley, and often host the major tracksites (e.g., Lavini di Marco, nearby the town of Rovereto).

In 2011, during a speleological expedition made by the team La Venta Esplorazioni Geografiche, who were exploring caves located in the central Dolomites on the north-eastern flank of Mt. Pelmo (Veneto, Italy) (Fig. 1), several hollows were discovered that were afterwards interpreted as possible dinosaur footprints (Mietto et al., 2012).

A second prospection was carried out in 2014, and was dedicated to clean and enlarge the extent of the exposed trampled surface and to characterize the traces. This survey confirmed the Early Jurassic age of the site and the presence, although very weathered, of dinosaur tracks and allowed the identification of more footprints, recognizing the Mt. Pelmo site as the highest tracksite in Italy (3037 m a.s.l.). Mt. Pelmo was already known in the ichnological literature for being the first Italian site with dinosaur footprints, but they were recorded in the uppermost Carnian-Norian (Late Triassic) Dolomia Principale formation on a rockslide boulder almost at the base of the mountain (Mietto, 1985).

Here we report the description and interpretation of some footprints with theropod morphological characteristics and of others with uncertain affinity whose configuration resembles that of a sauropod(omorph) trackmaker. The study of the Mt. Pelmo tracksite, which represents the first Early Jurassic tracksite discovered north of the Valsugana Fault, contributes to a better knowledge of the palaeogeography of the area and of the distribution of Early Jurassic terrestrial vertebrates in the northern part of the Trento Platform.

GEOLOGICAL SETTING

The bio-chronostratigraphy of the Calcari Grigi Group is based on benthic foraminifera faunas (Bosellini
& Broglio Loriga, 1971; Fugagnoli & Broglio Loriga, 1998; Fugagnoli, 2004; Romano et al., 2005), calibrated through ammonoids in Morocco (Septfontaine, 1985), on very rare ammonite findings (Sarti & Ferrari, 1999) and on Sr and C isotope stratigraphy (Woodfine et al., 2008; Franceschi et al., 2014b). Four main formations are recognized (Avanzini et al., 2007; Avanzini & Petti, 2008): the Monte Zugna Formation (Hettangian-Sinemurian), the Loppio Oolitic Limestone (Middle to Upper Sinemurian), the Rotzo Formation (Sinemurian-Pliensbachian) and the Massone Oolitic Limestone (Upper Pliensbachian).

The Monte Zugna Formation in the Adige Valley area hosts important dinosaur track sites, particularly in its middle peritidal portion. In one case, the abundance of tracks led to the institution of a megatracksite (Avanzini et al., 2006).

The lithostratigraphic characters and the scarcity of fossil markers in the Calcari Grigi Group in the Dolomites make difficult the recognition of the classical units: the classical Calcari Grigi Group units are not clearly identifiable, hence, most recent geological maps (Neri et al., 2007) refer only to the Calcari Grigi sensu lato. The differences with respect to the classical succession led to informally referring to this part of the Early Jurassic carbonate platform as the “northern Trento Platform” (Zempolich, 1993). Masetti & Bottoni (1978) document the presence of an important hiatus at the top of the Calcari Grigi Group in the northern Trento Platform, testified by the absence of the Pliensbachian units. These are locally replaced by the crinoidal grainstones of the Fanes Encrinite (Masetti et al., 2006; Neri et al., 2007). Elsewhere the Rosso Ammonitico Veronese directly overlies the unconformity.

The Calcare Grigi succession is rather homogeneous and can be subdivided in an upper and a lower portion. The lower part is characterized by shallowing up peritidal cycles, 50 to 70 cm thick and is referred to as the Monte Zugna Formation. It is in this lower portion that the Pelmo tracksite is located (Fig. 2). In the upper portion, layers become thinner and marly interlayers are present. Characteristic of the upper portion of the Rotzo Formation is the presence of thick-shelled large bivalves that can be referred to as the “Lithiotis Fauna”, typical of the upper portion of the Rotzo Formation, and whose diffusion is considered synchronous at the scale of the Trento Platform and referred to as the Protodactyloceras davoel-Amaltheus margaritatus ammonoid zones (Franceschi et al., 2014b).

METHODS

The tracksite is situated on the north-eastern shoulder of Mt. Pelmo, on a rocky platform which is accessible only by climbing or by helicopter transportation. In 2014, given the short time available and the effort...
spent in cleaning and enlarging the surface, tracks and trackways were only rapidly studied in the field. However, the entire surface, as well as each trackway and track, was photographed with a DSLR camera (Canon 70D); a Canon 18-135 mm STS lens or a wide-angle lens (Canon 10-18 mm STS) were used to take the pictures to generate photogrammetric 3D models. Agisoft Photoscan Pro (v.1.2.3, www.agisoft.com) was used to generate, orient, refine and scale the models (Fig. 3b) following the procedures detailed in Mallison & Wings (2014). The scaled mesh, exported Stanford PLY files, were then processed in CloudCompare (www.cloudcompare.com), where the meshes were accurately oriented through the generation of a plane intersecting the surface, to avoid imprecise alignment due to the roughness and irregularity of the surface and later measured. Rhinoceros (v. 5.12) was then used to create contour lines. The photos of the surface were taken holding a tripod over the head and using the wide-angle lens. A total of 144 photos were used to generate the model (Fig. 3a, Supplementary data 1: https://doi.org/10.6084/m9.figshare.3113824) which was then downscaled to 25 million faces to be easily used to generate contour maps and outline drawings of the site (Fig. 3b). Scaling was made using relatively short (from 10 to 50 cm) coded scale bars and two tape measures (> 10 m).

Due to the lack of time and the complex logistics, no casts were made on the site, but detailed 3D models of the site and the footprints, together with the raw photos used to generate them are made available as supplementary material, for future comparisons of these specimens to be made.

Fig. 3 - 3D models and outline drawings of main track site. a) Photogrammetric model of the surface. b) Schematic sketch of the trampled surface.
STUDIED MATERIAL

Footprint identification and weathering processes

Twenty probable footprints have been recognized on the exposed surface (Fig. 3, Supplementary data 1: https://doi.org/10.6084/m9.figshare.3113824), and attributed to three, possibly four trackways, based on correlation between dimensions, alignments, pace andmorphologies. However, the preservation of the tracks is generally poor and only a few cases provide morphological details. This is mainly due to the location of the site on the lateral side of a glacial cirque and to frost and solution weathering processes locally reworking the limestone formation. All the tracks occur as negative, usually very shallow, epireliefs (impressions) that were originally infilled with rock fragments. However, sporadically shallow displacement rims are present that make them distinctive from karstic depressions, like kamenitze (Perna & Sauro, 1978; Lundberg, 2013). Other morphological characters allow us to exclude a karstic origin of these depressions: 1) most of them have an uneven bottom which is uncommon in typically flat-floored solution pands due to karstification; it is also worth noting that, in most cases, it is not possible to correlate the uneven bottom with any fissure or fracture system on the surface, thus strengthening the non-karstic origin of the depressions; 2) the tracksite almost completely lacks other surface karst morphologies like karren or microkarren which are normally associated with karstic solution pans (Lundberg, 2012). Instead, frost weathering at this height in the Dolomites (3037 m a.s.l.) is expected to be the predominant weathering process (Panizza, 2009), and responsible for the bad preservation of the footprints, their secondary enlargement and infilling with angular centimetre-sized rock fragments (Walder & Hallet, 1986). Preservation grades are determined according to Belvedere & Farlow (2016).

Track description and interpretation

PelM.A1 - This footprint is located on the same surface but far from the main site, on the northern edge of the studied area (Fig. 4a, Supplementary data 2: https://doi.org/10.6084/m9.figshare.3113824). It is a shallow tridactyl track, with all three digits preserved, but no clear internal morphologies. These features give a preservation grade of 1.5. The footprint seems to be slightly longer than wide, although digit III is incomplete and the total length cannot be evaluated (approx. PL = 23 cm, PW = 20 cm), quite symmetrical (II’^III = 21.2°; III’^IV = 21.7°), and, although digits are tapering, no clear claw marks are present.

This footprint, despite the poor preservation and the lack of the distal digit III, is similar to the morphotype described in the Coste dell’Anglone site (Petti et al., 2011) and assigned to Kayentapus Welles, 1971. Despite the similarities, however, we prefer not to assign an ichnotaxonomical attribution for PelM.A1, which is therefore classified as an indeterminate theropod track.

PelM.B - The trackway is composed of five, possibly six footprints aligned along the same direction, and very likely left by a bipedal dinosaur. Most of the footprints are preserved merely as irregular depressions with no morphological details (grade 0). It is, however, possible to measure pace and stride, which are quite regular for the length of the trackway, supporting the hypothesis of a bipedal trackmaker. Only one track, PelM.B5 (Fig. 4b, Supplementary data 3: https://doi.org/10.6084/m9.figshare.3113824), despite some deformation in the depth due to secondary karst weathering, shows some better details (preservation grade 1); it is tridactyl, longer than wide (PL = 21.3 cm, PW = 14.4) and slightly asymmetric (II’^III = 17°, III’^IV = 20°). Digit III is the longest and is quite elongated. All digits, especially digit III, have tapering endings, probably due to claw marks and then highlighted by the weathering of the footprints, suggesting a theropod trackmaker. A possible impression of digit I and of the distal part of metatarsus may be present in the posterior part of the impression, but it is very difficult, even looking at the 3D models, to discriminate whether they are true morphological features or deformation due to the erosion of the footprint.

The elongated digit III and the narrow interdigital angles are features of the ichnotaxon Grallator Hitchcock, 1845, a theropod ichnogenus very common in the Early Jurassic. However, due to the preservation, it is impossible to reliably assign the PelM.B to any ichnotaxon and therefore we consider it an indeterminate theropod trackway. It is impossible to determine whether the trackmaker of PelM.B was different from that of PelM.A: the differences in the shape of the tracks (e.g., divarication angles differences) can be due either to real differences of the autopodia (i.e., different trackmaker) or to extramorphological factors, e.g., the softness of the substrate at the moment of the impression; the poor preservation of both tracks prevents discrimination between either of the two hypotheses.

PelM.C - Three small elliptical depressions were mapped. They have a longer axis of about 10 cm. The preservation is too poor to make any determination and even to discriminate if they are prints or only weathering structures. Some other depressions were mapped, but due to the preservation, and to the alignment with major cracks of the surface, it was impossible to determine if they were tracks or erosional structures.

PelM.D - The trackway is composed of six large impressions, elliptical or bell-shaped, longer than wide (average PL = 34 cm; PW = 20) and not very deep (Fig. 4c, Supplementary data 4: https://doi.org/10.6084/m9.figshare.3113824). In one case, on the external side of PelM.D1, it is possible to observe a smaller, elliptical (ML = 7.4 cm; MW = 8.3 cm) impression which has been interpreted as the forelimb print of a quadrupedal animal and highlights very marked heteropody. Unfortunately, the trackway lies on a large crack in the surface which is very rough and deteriorated and which led to a maximum quality value of 0.5, as no internal morphologies are preserved, but manus and pes prints are discernible. The incompleteness of the trackway (which is quite narrow) prevents the quantification of the trackway gauge both using the PTR (Romano et al., 2007) and WAP/PL ratio (Marty, 2008) methods.

Although poorly preserved theropods may appear as oval footprints, and despite the marked heteropody, these tracks are attributed to a sauropodomorph trackmaker based on the shape and the overall quadrupedal
configuration, however, seems to be more wide-gauge than in the studied specimens, and there are no other recognizable morphological remarks, e.g. the curved digits with distinct claw marks both in the pes and in the manus, or the entaxy of the pes. Moreover, *Tetrasauropus* has almost always been reported from the Late Triassic; there is only one occurrence in the Early Jurassic of this ichnotaxon (Milàn et al., 2008), but the poor preservation of the studied tracks prevents any reliable comparison. *Parabrontopodus* isp. tracks have been recorded at Mt. Finonchio, from the younger upper supratidal unit of the Monte Zugna Formation (Avanzini et al., 2008). These tracks have similar preservation, a marked heteropody and comparable morphology of the pes. Given the similarities with the Mt. Finonchio footprints, Pelm.D tracks could be assigned to *Parabrontopodus* isp., although *Parabrontopodus* Lockley et al., 1994 has become a wastebasket ichnotaxon, including any poorly preserved, elliptical quadrupedal track. For these reasons, we prefer not to assign Pelm.D to any ichnotaxon and classify it as footprints of uncertain affinity whose configuration resembles a sauropod(morph).

**CONCLUSIONS**

Despite the small size of the trampled surface and the poor preservation, the tracks of the Mt. Pelmo site depict at least three different ichnomorphotypes occurring on the same level, suggesting the presence of theropods and quadruped dinosaurs. The association of *Kayentapus*-like theropod tracks and sauropodomorph tracks (*Parabrontopodus* Lockley et al., 1994; *Lavinipes* Avanzini et al., 2003) is very common in the Early Jurassic of Southern Alps and can be easily linked to the other sites of the peritidal unit the Monte Zugna Formation. The same association, in fact, even if more complete and of better preservation, occurs in the famous Lavini di Marco site, and in many other coeval localities of north-eastern Italy (Avanzini & Petti, 2008). It is not possible to assign a precise age to the Pelmo tracksite. Since the stratigraphic level of their finding is ascribed to the middle peritidal unit the Monte Zugna Formation, the trampled surface can be broadly referred to the middle portion of the Sinemurian (e.g., Masetti et al., 2016).

The Mt. Pelmo tracksite finding is the first recorded north of the Valsugana Fault, in the so-called “northern Trento Platform” (Fig. 1), and considerably extends the northern limit of at least temporarily exposed lands that could be reached by dinosaurs. According to this hypothesis, supported by the ichnoassociation that the Pelmo tracksite could be attributed to deposits coeval to the middle peritidal unit of the Calcare Grigi Group, its finding expands the boundaries of the Calcare Grigi megatracksite (Avanzini et al., 2006). In terms of palaeogeography, this extension is likely considerably larger than the present recorded distance to the other tracksites located in the southern Trento Platform because of the tectonic shortening that occurred during Alpine orogenesis along the Valsugana Fault, which is estimated by Schönborn (1999) in some 22 km.

It is very likely that future investigations on the same surface or on other areas of the Mt. Pelmo outcrops of the

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Fig. 4 - 3D models and outline drawings of the best-preserved tracks. Grey lines indicate cracks on the surface. a) Pelm.A1 isolated tridactyl footprint. b) Pelm.B5, deep tridactyl track, possibly part of a trackway; it was the first track discovered during the speleological investigations. c) Pelm.D1 impressions of the manus and pes of a sauropodomorph.

configuration of the footprints. Sauropodomorph tracks are quite common in the coeval levels of the Monte Zugna Formation of the Trento Platform, and at the Lavini di Marco site, a new ichnotaxon was erected: *Lavinipes cheminii* Avanzini et al., 2003. The tracks of the Pelmo site, however, do not show the peculiar features of *Lavinipes*, such as the occurrence of clearly separated digit impressions, with a marked digit I, and the pentadactyl or semi-circular manus tracks.

A similar heteropody is also present in the ichnogenus *Tetrasauropus* Ellenberger, 1972 (amended by D’Orazi Porchetti & Nicosia, 2007). *Tetrasauropus* trackway
Calcari Grigi Group will provide more ichnological data, possibly higher quality as to allow proper comparisons and better constrain the age of the site. Mt. Pelmo tracksite has the potential to contribute to increasing the knowledge of the Early Jurassic terrestrial vertebrates in the northern part of the Trento Platform, extending the size of the Early Jurassic megatracksites of the Southern Alps.

SUPPLEMENTARY DATA ARCHIVING

All the Supplementary data of this work are available at the Figsshare https://doi.org/10.6084/m9.figshare.3113824.

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