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Dwarf mammoth footprints from the Pleistocene of Gonnesa (southwestern Sardinia, Italy)

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ABSTRACT - Tetrapod footprints have been reported in different types of environments, and are a suitable tool for palaeoenvironmental reconstructions. Previously, mammal footprints were reported in the Plio-Pleistocene fossil record of Sardinia (Italy), and were assigned to different endemic ruminants (Cervidae and Bovidae). In this work, we report the first occurrence of proboscidean footprints in the Italian fossil record. The ichnofossils are assigned to Proboscipeda panfamilia *McNeil, Hills, Tolman & Kooyman, 2007. The studied footprints are preserved in highly consolidated aeolian deposits from the Pleistocene of Funtana Morimenta (Gonnesa, southwestern Sardinia, Italy). The recovered ichnofossils are represented by isolated manus-pes couples preserved as hyporeliefs and/or epireliefs. Furthermore, other footprints were observed in situ. The footprints' shape and size indicate that the track-maker is likely to be the Sardinian dwarf mammoth* Mammuthus lamarmorai *(Major, 1883). The Sardinian record may represent a unique example of dwarf mammoth footprints in the western Mediterranean Basin. Furthermore, a synthetic summary of the knowledge of the proboscidean ichnofossil record is also provided.*

RIASSUNTO - [Impronte di mammut nano dal Pleistocene di Gonnesa (Sardegna sud-occidentale, Italia)] *- Le impronte fossili di tetrapodi, note in diversi tipi di ambienti, possono fornire un utile contributo nelle ricostruzioni paleoambientali. In tempi relativamente recenti, impronte riferibili a ruminanti (Cervidae e Bovidae) sono state segnalate nel Plio-Pleistocene della Sardegna (Italia). Impronte e piste lasciate da proboscidati sono note in diverse località del mondo e vengono generalmente incluse nell'icnogenere* Proboscipeda*, istituito da Panin & Avram nel 1962 per indicare tracce di forma ovoidale riferibili a Deinotheriidae rinvenute nei depositi miocenici della Romania.*

Nel presente lavoro vengono descritte le prime impronte di proboscidati segnalate nel record fossile italiano. Le impronte, riferibili all'icnospecie Proboscipeda panfamilia *McNeil, Hills, Tolman & Kooyman, 2007, sono state ritrovate nei depositi eolici (s.l.) di Funtana Morimenta (Gonnesa, Sud-Ovest Sardegna, Italia). Gli icnofossili, attualmente conservati nel "Museo Sardo di Geologia e Paleontologia D. Lovisato" (Cagliari) e nel "Museo dei Palaeoambienti Sulcitani - E.A. Martel" (Carbonia), sono rappresentati da coppie di manus-pes preservate come iporilievi e/o epirilievi. Altre impronte sono state localizzate in situ. La forma e le dimensioni delle impronte suggeriscono che il track-maker possa essere identificato nella specie nana di mammut* Mammuthus lamarmorai *(Major, 1883), i cui resti olotipici sono stati ritrovati nella medesima successione eolica (s.l.). Gli icnofossili sardi potrebbero rappresentare l'unico esempio di impronte riferibili a mammut nani nel bacino del Mediterraneo occidentale.*

INTRODUCTION

Fossil tetrapod tracks and trackways, and related deformation structures can represent a considerable source of sedimentological, biomechanical, palaecological and palaeogeographical information. Furthermore, in the last few years our knowledge of vertebrate tracks in Pliocene-Quaternary beaches, dunes, washover fans, and related environments considerably increased due to new data (e.g., Lewis & Titheridge, 1978; Fornós & Pons-Moyà, 1982; Loope, 1986; Lea, 1996; Fornós et al., 2002; McNeil et al., 2005; Fanelli et al., 2007; McDonald et al., 2007; McNeil et al., 2007; Buynevich, 2015). In particular, proboscidean footprints may provide useful palaeobiogeographical and palaeoecological information: Milàn et al. (2007) indeed recently described the possible latest record of proboscidean activity known in Europe on the basis of footprints found in Rhodes (Greece). Similarly, Bibi et al. (2012) reported early complex social structure in Miocene Proboscidea through the careful analysis of a huge tracksite in the United Arab Emirates.

McNeil et al. (2005) described mammoth tracks and trackways, produced by *Mammuthus primigenius* (Blumenbach, 1799) in the Late Pleistocene aeolian sediments of St. Mary Reservoir (southwestern Alberta, Canada). Consequently, a new ichnospecies (*Proboscipeda panfamilia* McNeil, Hillis, Tolman & Kooyman, 2007) was established within the ichnogenus *Proboscipeda*, proposed by Pain & Avram (1962), to include oval traces produced by Miocene proboscideans. Recently, the ichnotaxon *Proboscipeda panfamilia* was reported for the first time in Pleistocene deposits of Europe (Carvhalo, 2009). In the present work, we describe tracks assignable to the same ichnotaxon from the fossil record of Italy. Previously, the only large mammal ichnofossils known in the Cenozoic of Sardinia have been attributed to Pliocene-Quaternary endemic ruminants (Fanelli et al., 2007; Kotsakis et al., 2008). The tracks of ruminants, observed in several distinct localities of Sardinia, were mainly produced by the Pliocene-Pleistocene bovids of the *Nesogoral* group (Kotsakis et al., 2008), especially by the Upper Pleistocene megacerine deer *Praemegaceros cazioti* (Depéret, 1897) (Fanelli et al., 2008). Generally, these tracks have been assigned to the ichnogenus *Bifidipes* Demathieu, Ginsburg, Guérin & Truc, 1984, and were

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produced in sandy substrates of eolianites, coastal and temporary shallow pond deposits.

Recently, new evidence of large mammal footprints found in the Quaternary deposits of the Gonnesa area (Funtana Morimenta and Porto Paglia) was reported for the first time (Zoboli & Pillola, 2015). These new data are represented by dog and proboscidean footprints, attributed to *Canipeda* Vialov, 1983 and *Proboscipeda* Panin & Avran, 1962, respectively.

GEOLOGICAL CONTEXT AND AGE OF THE FOOTPRINTS

The mammoth footprint site is located near the Funtana Morimenta spring, 0.5 km S-W of the Gonnesa village (Fig. 1) and consists of a 150 m long and up to 10 m high Quaternary aeolian sandstone cliff, showing deer and rare mammoth footprint impressions with clear deformations of the underlying laminae (Figs 2-3). Well-exposed large scale cross and low angle planar stratifications are visible along the natural exposures and in a small quarry located in the northern sector of the outcrops (Fig. 2a). Associated deer tracks assigned to *Bifidipes* isp. occur above and below the proboscidean manus-pes impressions (Figs 2a-b), and in both bedding plane and cross-section. The apparently larger size of some deer footprints, compared to those previously described by Fanelli et al. (2008), could be related to the different conditions of the trampling surface at the time of their production, such as grain size and water content; alternatively, they could be related to the most primitive and larger deer, belonging to the genus *Praemegaceros* (Van der Made & Palombo, 2006).

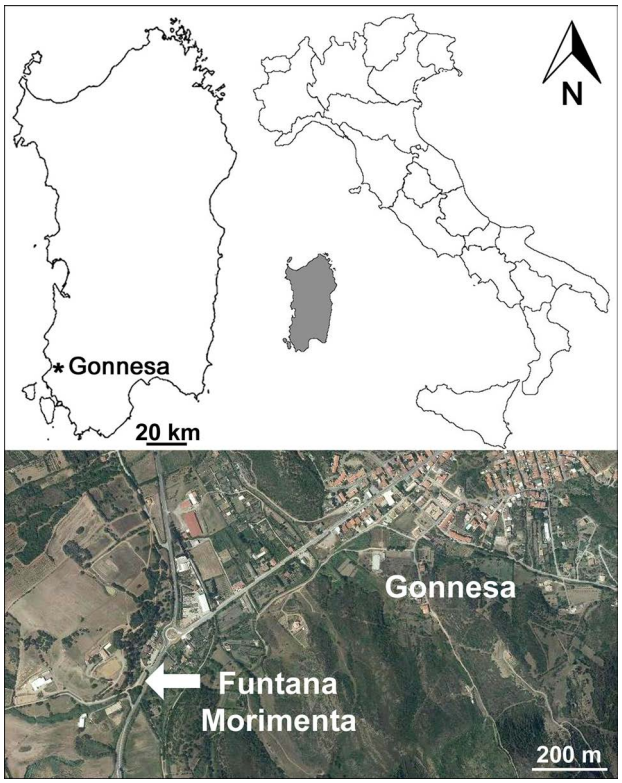

Fig. 1 - (Color online) Location map of Funtana Morimenta (Gonnesa, Sardinia, Italy).

The aeolian deposits of Funtana Morimenta have been mentioned since the beginning of the 19th century (Lamarmora, 1826); however, they only became relevant due to the discovery of a small proboscidean skeleton at the end of the same century (Acconci, 1881). During the Quaternary, the western coasts of Sardinia were characterised by important aeolian processes, generating extensive dune systems. These deposits are generally associated with palaeosols, alluvial and fluvial deposits (e.g., Maxia & Pecorini, 1968; Orrù & Ulzega, 1986; Andreucci et al., 2010; Pascucci et al., 2010). The age of the Sardinian coastal aeolian deposits was recently questioned and is still a matter of debate. Orrù & Ulzega (1986) recognized two different generations of dunes along the coast. The oldest aeolian deposits ("Funtana Morimenta Formation", FMF) were assigned to the Middle Pleistocene and the most recent ones to an undefined Upper Pleistocene. The local geological context indicates that the FMF is older than MIS 5e, due to the relationships observed in the Funtanamare shoreline (Gonnesa) (Ulzega & Orrù, 1986). In fact, in the Gonnesa Gulf, along the Plage 'e Mesu beach (Punta 'e S'Arena), a Tyrrhenian conglomerate (MIS substage 5e) lies on the erosional surface, cutting the aeolianites of the FMF. The second aeolian complex crops out in the valley of Riu Crabiola. It is well-cemented, and the cross bedding is well recognizable. It was attributed to the post-Tyrrhenian by Orrù & Ulzega (1986).

The geological settings of a number of sedimentary successions along the western Sardinian coast show that aeolian deposits occur both below and above Tyrrhenian deposits, bearing "warm-guests" mollusks, including *Persististrombus latus* (Gmelin, 1791) and *Chelyconus ermineus testudinarius* (Bruguière, 1792) (MIS 5e) (e.g., Pecorini, 1954; Comaschi Caria, 1968; Carboni & Lecca, 1985; Kindler et al., 1997; Andreucci et al., 2006; Lecca & Carboni, 2007; Pascucci et al., 2010).

The strong controversy between specialists on the Sardinian Quaternary stratigraphy concerns the use of the Optically Stimulated Luminescence (OSL) data due to both the scantiness of reliable isotopic data, and the highly precise biostratigraphic constraints of coastal deposits (e.g., Andreucci et al., 2010; Catto, 2010; Coltorti et al., 2010). A preliminary sampling of the Funtana Morimenta outcrop suggests an age not older than 130 Ka for the richest footprint levels (unpublished data). Until new data are reported, we prefer to assign an undefined Middle-Late Pleistocene age to the fossil footprint site of Funtana Morimenta.

MATERIALS AND METHODS

The collected specimens are stored at the "Museo Sardo di Geologia e Paleontologia D. Lovisato" (acronym MDLCA) of the University of Cagliari (Sardinia, Italy) (MDLCA 23636, MDLCA 23637) and in the "Museo dei Palaeoambienti Sulcitani - E. A. Martel" (acronym MPC) of Carbonia (Sardinia, Italy) (MPC - A, MPC - B). The recovered ichnofossils are represented by isolated manus-pes couples preserved as convex hyporeliefs or concave epireliefs. In addition, a dozen single and manus-pes couples have been observed in transverse sections in the field.

Fig. 2 - (Color online) Sandstone cross-sections showing a series of mammoth (big arrows) and deer (small arrows) footprints and relative deformation of the underlying strata. a) General view. b-c) Details of the deformed strata.

The most fragile specimens were consolidated using Paraloid B-72. Photographs of the specimens were performed using a Nikon D5000 digital camera. Comparison was made using literature data and plaster casts of the holotype of the dwarf Sardinian mammoth stored in the "Museo Sardo di Geologia e Paleontologia D. Lovisato" (Cagliari) and at the "Museo dei Palaeoambienti Sulcitani - E. A. Martel" (Carbonia). All measurements are reported in centimeters.

Fig. 3 - (Color online) Sandstone cross-section showing a mammoth footprint (MDLCA 23636, MDLCA 23637) before its recovery and relative deformation of the underlying strata.

SYSTEMATIC ICHNOLOGY

Ichnogenus *Proboscipeda* Panin & Avram, 1962
Type Ichnospecies *Proboscipeda enigmatica* Panin & Avram, 1962

Ichnospecies *Proboscipeda panfamilia* McNeil, Hills, Tolman & Kooyman, 2007
(Figs 4-6)

Description - Unfortunately, the nature of the sediment, mainly constituted by well-cemented coarse sandstone, did not allow the impression and preservation of detailed morphological features. In fact, the free-digit impressions are not preserved in all specimens. The specimens MDLCA 23636 and MDLCA 23637 (Figs 4-5) are represented by an isolated manus-pes couple preserved in convex hyporelief (Fig. 4a), and by a corresponding part of concave epirelief (Fig. 4b). The manus imprint is proximally deformed by the subsequently overlapped pes impression (Fig. 5). The estimated size

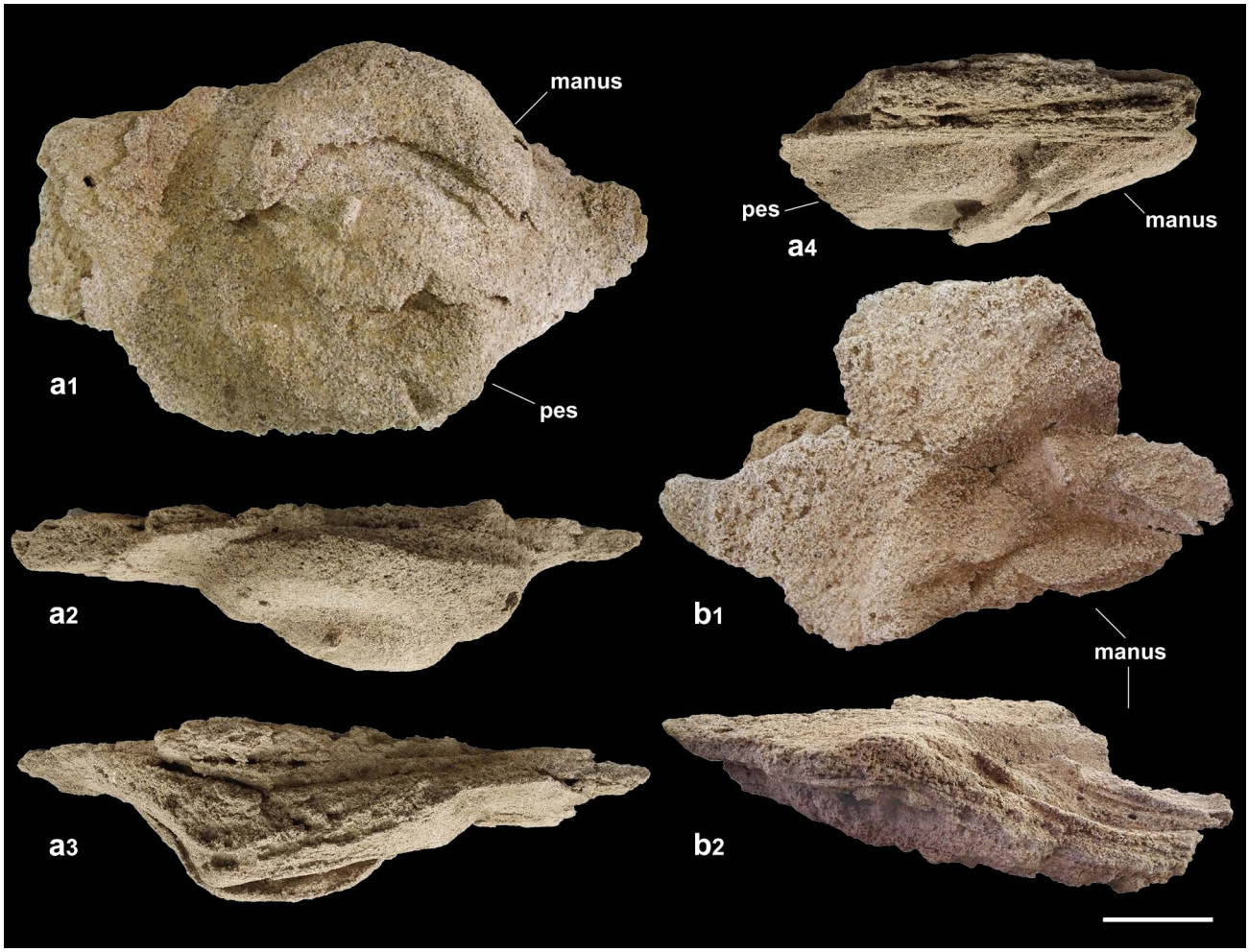

Fig. 4 - (Color online) *Proboscipeda panfamilia* McNeil, Hills, Tolman & Kooyman, 2007 of Funtana Morimenta (Gonnesa). a) MDLCA 23636, manus-pes hyporelief in inferior (a1), anterior (a2), posterior (a3), and lateral (a4) views. b) MDLCA 23637, part of epirelief in superior (b1), and lateral (b2) views. Scale bar corresponds to 10 cm.

of the manus imprint is 20.0 and 25.0 in length and width, respectively. The incomplete epirelief shows the underlying laminae deformation (undertrack). MPC - A (Fig. 6a) is an isolated block with hyporeliefs of manus and pes impressions. Moreover, the convex hyporeliefs clearly represent the deformed volume of sediment and not the original footprint fillings. Even in this case, the pes imprint partially oversteps the posterior part of the manus imprint. MPC - B (Fig. 6b) is represented by an incomplete manus-pes set preserved as a concave epirelief.

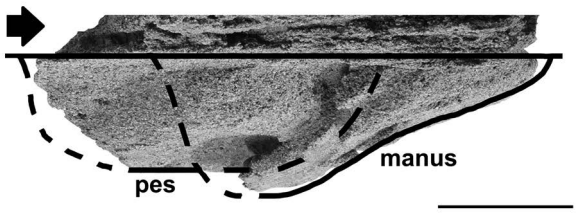

Fig. 5 - Superimposed interpretive drawing of MDLCA 23636 in lateral view. It is possible to note the deformed volume of the manus impression by the overlapped pes. The arrow indicates the walking direction. Scale bar corresponds to 10 cm.

The pes impression oversteps the manus impression as in the other two specimens. The estimated size of the restored footprints is approximately 20.0 x 25.0.

The putative track-maker - Given the size, ovoidal shape, age and occurrence of mammoth body fossils in the same aeolian (s.l.) deposits, the footprints of Gonnesa can be likely attributed to the dwarf Sardinian mammoth *Mammuthus lamarmorai* (Major, 1883). The holotype of this endemic taxon, represented by an incomplete skeleton, was indeed found in the same locality of Funtana Morimenta at the end of the 19th century (Acconci, 1881; Comaschi Caria, 1965). The Sardinian mammoth probably reached 140-160 cm in height and 500 kg in weight (Palombo et al., 2012) (Fig. 7).

The antero-posterior and the mesial diameters of the manus and pes, based on the skeletal reconstruction of the holotype, are 17.0 x 21.0 (manus) and 20.0 x 17.0 (pes), respectively (Fig. 8). Surprisingly, the correspondence between the size of the footprints and the bone remains of manus/pes is remarkable, even though the volume of the fleshy portion is unknown and the exact outline of the manus/pes are not well-defined in the tracks (these, in fact, are influenced by the nature of the sediment). Additionally,

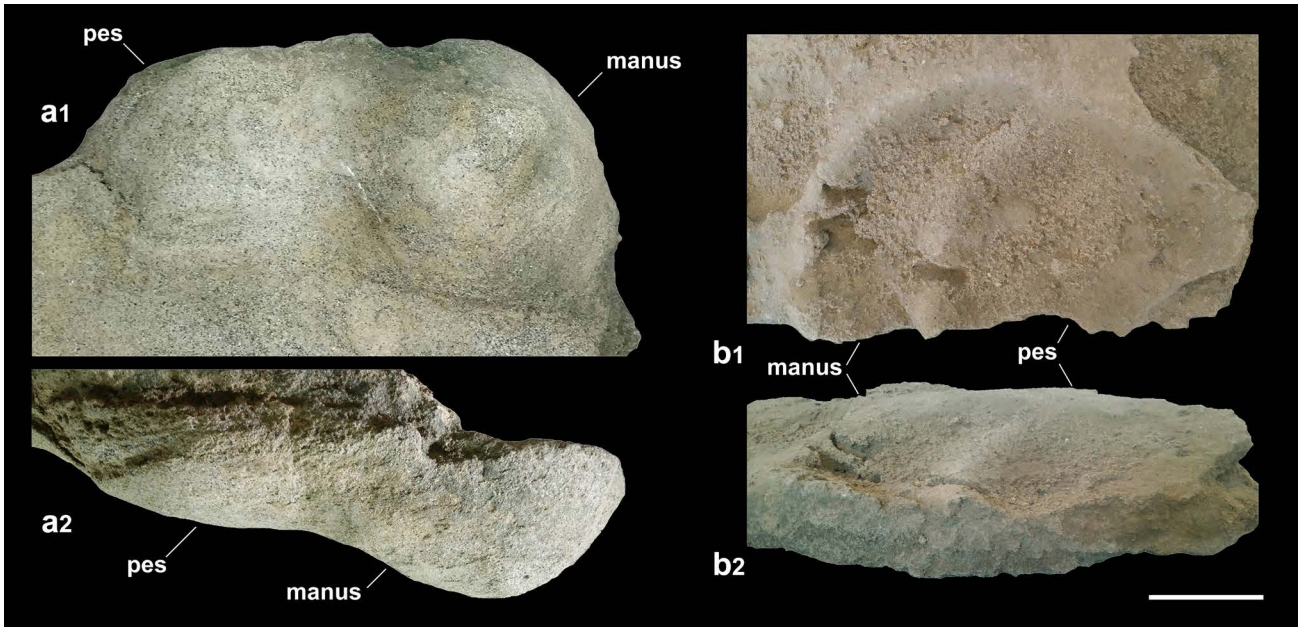

Fig. 6 - (Color online) *Proboscipeda panfamilia* McNeil, Hills, Tolman & Kooyman, 2007 of Funtana Morimenta (Gonnesa). a) MPC - A, manus-pes hyporelief in inferior (a1) and lateral (a2) views. b) MPC - B, incomplete epirelief of manus-pes couple in superior (b1) and lateral (b2) views. On the left, superimposed deer tracks are visible. Scale bar corresponds to 10 cm.

M. lamarmorai represents to date the only proboscidean species known in the Sardinian fossil record. The only other dwarf mammoth reported in the Mediterranean area is *Mammuthus creticus* (Bate, 1907) of Crete (Greece) (Poulakakis et al, 2006).

DISCUSSION AND CONCLUSION

Large footprints and trackways of "normal sized" putative proboscideans have been described from different sites (e.g., Aramayo & Bianco, 1987; Remeika, 2001; Lucas et al., 2007; McNeil et al., 2007; Carvalho, 2009; Bibi et al, 2012; Aramayo et al., 2015). *Proboscipeda enigmatica* is the earliest name proposed for proboscidean tracks. This ichnotaxon was erected to describe tracks from a Miocene trampled surface of Romania (Panin & Avram, 1962). *P. enigmatica* has specific dimensions (14.0 to 17.0 cm in diameter and 42.0 to 52.0 cm in circumference), oval shape (longer than wide) and mostly lacking free digit impressions (Panin & Avram, 1962; McNeil et al., 2007). The authors attributed them to a deinothere, a fairly common Old World Miocene proboscidean. An isolated footprint of *Proboscipeda* was reported by Pèrez-Lorente et al. (1999) in the Upper Miocene of Spain. Abbassi et al. (2016) reported the oldest known proboscidean

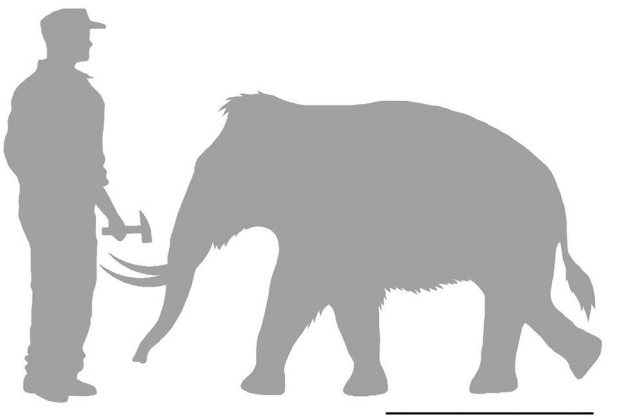

Fig. 7 - Estimated dimensions for the Sardinian dwarf mammoth track-maker *Mammuthus lamarmorai* (Major, 1883). Scale bar corresponds to 1 m.

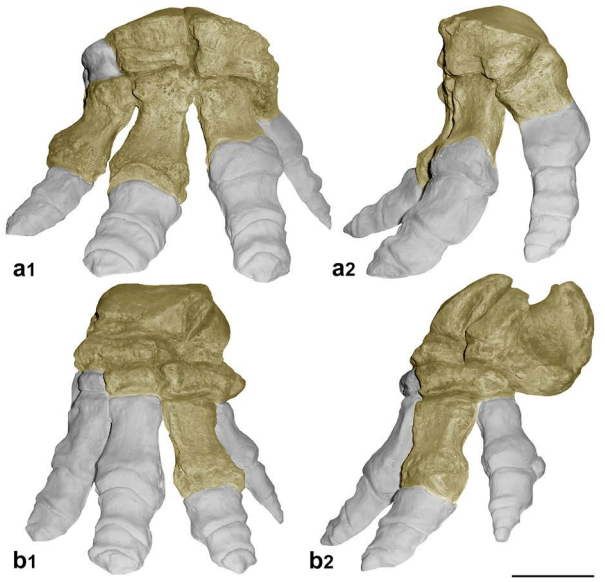

Fig. 8 - (Color online) *Mammuthus lamarmorai* (Major, 1883) from Funtana Morimenta (Gonnesa). Plaster cast of the right manus of the holotype in anterior (a1) and lateral (b2) views. Plaster cast of the left pes of the holotype in anterior (b1) and lateral (b2) views. "Museo Sardo di Geologia e Paleontologia D. Lovisato" (Cagliari, Sardinia). Scale bar corresponds to 5 cm.

tracks, assigned to *Proposcipeda enigmatica* and cf. *Probscipeda* isp., in the Late Eocene of Iran. *P. enigmatica* tracks from Iran are characterized by circular to oval manus-pes impressions (14.9 x 11.5 cm in diameter). Three digit impressions are preserved in the pes tracks (Abbassi et al., 2016). Scrivner & Bottjer (1986) assigned to *Proboscipeda* sp. some proboscidean trackways from the Miocene of southern California. In these tracks (re-described by Reynolds, 1999) digital impression are poorly preserved or absent, and their diameters are about 50.0 cm. The footprint-group name *Proboscipeda* is usually used to denote all Cenozoic huge mammals tracks (from Eocene to the present), diagnosing the group as very large (11.0 - 62.0 cm in diameter), ovoidal to circular depressions that may show digit impressions, and typically showing overstepping of manus and pes imprints in trackways. The ichnogenus *Stegomastodonichnium* Aramayo & Bianco (1987) from the Pleistocene of Argentina is considered to be a junior subjective synonym of *Proboscipeda* by Lucas et al. (2007). Remeika (2001) used the new name *Stegomastodonichnium garbanii* for the Pliocene proboscidean tracks of California, but this ichnospecies is also considered a nomen nudum (Lucas et al., 2007). Remeika (2006) also introduced the ichnogenus *Mammutichnium* for the Pliocene tracks of California, but Lucas et al. (2007), considered this name as a nomen nudum. A second ichnospecies of *Proboscipeda*, named *P. panfamilia*, was proposed by McNeil et al. (2007), for Pleistocene proboscidean tracks of southern Alberta (Canada). These tracks can be distinguished from the smaller *P. enigmatica* by their large size and more circular shape. *P. panfamilia* impressions range between 11.0 and 62.0 cm in diameter (including juvenile track-makers) and are characterized by bilateral symmetry and a nearly-circular outline. Well-preserved specimens may show the rounded outline of three or more digits. The hoof impressions in the pes tracks are usually clearly visible. Almost all the observed trackways show only the pes imprint. Occasionally, part of the manus impression can be observed, partially overstepped by the pes. *Mammuthus primigenius* (Blumenbach, 1799) is recognized as a suitable track-maker, being the most common postglacial proboscidean in southwestern Alberta. Lucas et al. (2007) described fossil footprints attributed to *Mammuthus columbi* (Falconer, 1857) and belonging to the Upper Pleistocene deposits of New Mexico, assigning them to *P. panfamilia*. Carvalho (2009) describes some stratigraphic horizons with mammal and bird footprints in the Pleistocene of Portugal and *P. panfamilia*, possibly related with *Elephas antiquus* Falconer & Cautley, 1847, was reported in Europe for the first time. Therefore, *P. panfamilia* was chosen to designate the occurrence of many different sized tracks, representing very young to old mammoths. Aramayo et al. (2015) describe *Proboscipeda australis* from the Late Pleistocene of Argentina. These footprints are circular to slightly oval in shape (length: 23.0 - 27.0 cm, width: 23.0 - 30.0 cm) with manus similar to the pes and slightly large, 3 to 5 digit impressions are commonly present in the distal margin of the sole or palm. *P. australis* is similar to *P. enigmatica* and *P. panfamilia* but differ for some morphological features: 1) in *P. australis* the largest dimension can be either the width or the length of the footprint (*P. panfamilia* footprints are always wider than long and *P. enigmatica* are longer than wide); 2) the palm/sole surface in *P. australis* is rough and cracked; 3) *P. australis* is smaller than the remaining ichnospecies and manus and pes can be distinguished considering the relative size and number of digit imprints (Aramayo et al., 2015).

Dwarf elephant footprints were previously reported in coastal areas of the SW part of the island of Rhodes, Greece (Milàn et al., 2007). Outside the Mediterranean region, other footprints likely produced by pygmy proboscideans were described by Matsukawa & Shibata (2015) in the Miocene of Japan and attributed to the small insular species *Stegolophodon pseudolatidens* (Yabe, 1950).

Considering shape and size, the Sardinian ichnofossils are assignable to the ichnotaxon *P. panfamilia*. The footprints described herein are consistent with the dimension of the plantar/palmar surfaces of the manus and pes of the holotype of *M. lamarmorai*, a dwarf mammoth found in the same locality. Excluding the remote possibility of a contemporary presence of large mammoths in the same insular context where the dwarf mammoth lived, it is parsimonious to attribute the footprints of Funtana Morimenta with the only proboscidean species known to date in the Sardinian fossil record. Unfortunately, the absence of available trackways at the site does not allow the acquisition of relevant data such as the gait and the body-size of the track-maker. In any case, the proboscidean footprints of Funtana Morimenta represent the first record of mammoth tracks of Italy and, if possible, the first attributable to a dwarf mammoth in the western Mediterranean Basin.

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