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A Pompeii-like preservation for *Dosinia ponderosa* (Gray, 1838): two volcanic ash casts from the East Pisco Basin (Miocene, Peru)

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KEY WORDS - Taphonomy, tephra, fossil-diagenesis, carbonate dissolution, distal ashfall, pyroclastics.

ABSTRACT - In the East Pisco Basin, in Peru, a highly unusual example of Pompeii-like preservation has been discovered. At the locality of Cerros la Mama y la Hija, along the western side of the lower Ica River Valley, south of Ocucaje, two bivalve specimens were found preserved as volcanic ash casts. As is the case for most fossil invertebrates from the Pisco Formation, the original carbonate shell is not preserved, but these specimens are nonetheless exquisitely preserved, even featuring taxonomically informative characters of the shell exterior that allow for their assignment to the locally common species Dosinia ponderosa *(Gray, 1838). Both casts are mainly constituted by fine-grained volcanic glass shards and biotite crystals. The high abundance of glass shards and the absence of non-volcaniclastic material such as biogenic or terrigenous particles indicates that the casts are the product of primary deposition of a volcanic ash layer on the seafloor. These specimens testify to an intriguing taphonomic history that features burial underneath a distal volcanic ashfall. During the Late Miocene, pyroclastic ashfalls coming from the Central Andes were indeed frequent in the East Pisco Basin, allowing this exceptional type of fossil preservation.*

INTRODUCTION

The Peruvian East Pisco Basin is globally known for its paleontological content. The Miocene Pisco Formation (Fm) hosts one of the major marine vertebrate Fossil-Lagerstätte of the Cenozoic Era, which includes fossil cetaceans, pinnipeds, fishes, seabirds and marine reptiles (e.g., Lambert et al., 2010; Esperante et al., 2015; Bosio et al., 2021b; Collareta et al., 2021; Bianucci & Collareta, 2022; Bianucci et al., 2023). Abundant and diversified fossil assemblages of marine invertebrates, comprising mollusks, acorn barnacles, cirratulids, echinids, brachyuran decapods, rare bryozoans, and benthic foraminifera are also found in this basin (e.g., Lisson, 1925; Rivera, 1957; Alleman, 1978; DeVries, 1988; DeVries & Frassinetti, 2003; Coletti et al., 2019a, b; Collareta et al., 2019, 2023; Villaseca et al., 2020; Bosio et al., 2021a; Kočí et al., 2021; Sanfilippo et al., 2021).

In the Pisco Fm, paleontologists can find a variety of fossil preservation styles. Vertebrate remains are found partially or totally enclosed in dolomite nodules or, more frequently, they are characterized by extensive bone phosphatization. Therefore, there are two main mineralization processes which allow bone fossilization: the dolomite precipitation and the apatite dissolution-recrystallization (Gariboldi et al., 2015; Gioncada et al., 2018a; Bosio et al., 2021b, c). Different preservation modes are also recognized for fossil invertebrates in the three depositional sequences of the Pisco Fm (Di Celma et al., 2017). In particular, in the Middle Miocene strata, fossil preservation consists of calcite internal molds, with both pristine and recrystallized calcite shells (Di Celma et al., 2017; Bosio et al., 2020b). In the Upper Miocene units, fossil invertebrates are usually preserved as dolomite internal, external and compound molds, and/or as gypsum/anhydrite molds, recrystallized shells or casts. In these strata, the original mineralogy of the carbonate shells is not preserved (Di Celma et al., 2017; Gioncada et al., 2018b; Bosio et al., 2021a; Kočí et al., 2021; Sanfilippo et al., 2021).

Here, a highly unusual preservation style is reported for the first time in the East Pisco Basin for fossil invertebrates. Two fossil specimens of *Dosinia ponderosa* (Gray, 1838) were found preserved as casts of volcaniclastic material in a surrounding sandy sediment. These volcanic ash casts represent the only reported find of this type of preservation in the Peruvian fossil record and one of the few cases in the world.

GEOLOGICAL AND PALEONTOLOGICAL FRAMEWORK

Tectonic and stratigraphic setting

On the South American plate, a NW-SE series of Cenozoic marine basins runs along the Peruvian coast (Thornburg & Kulm, 1981). Among these forearc basins, the East Pisco Basin mainly extends between the towns of Pisco in the north and Nazca in the south and is mostly exposed onshore (Fig. 1). Sediment deposition in this marine basin has been active from the Eocene to the Pliocene, when the most recent exhumation of the marine sediments started following the subduction of the Nazca Ridge (Hsu, 1992). These sediments are organized in the following formations, from the oldest to the youngest: the Caballas Fm, the Paracas Fm, the Otuma Fm, the Chilcatay Fm and the Pisco Fm (Dunbar et al., 1990; DeVries, 2017; DeVries et al., 2017; DeVries & Jud, 2018; Di Celma et al., 2022). Along the western side of the Ica River Valley, south of the village of Ocucaje, the Pisco Fm is Middle to Late Miocene in age and comprises three depositional sequences, namely P0, P1 and P2 in stratigraphic ascending order, bounded by stratigraphic unconformities, PE0.0, PE0.1 and PE0.2, respectively (Di

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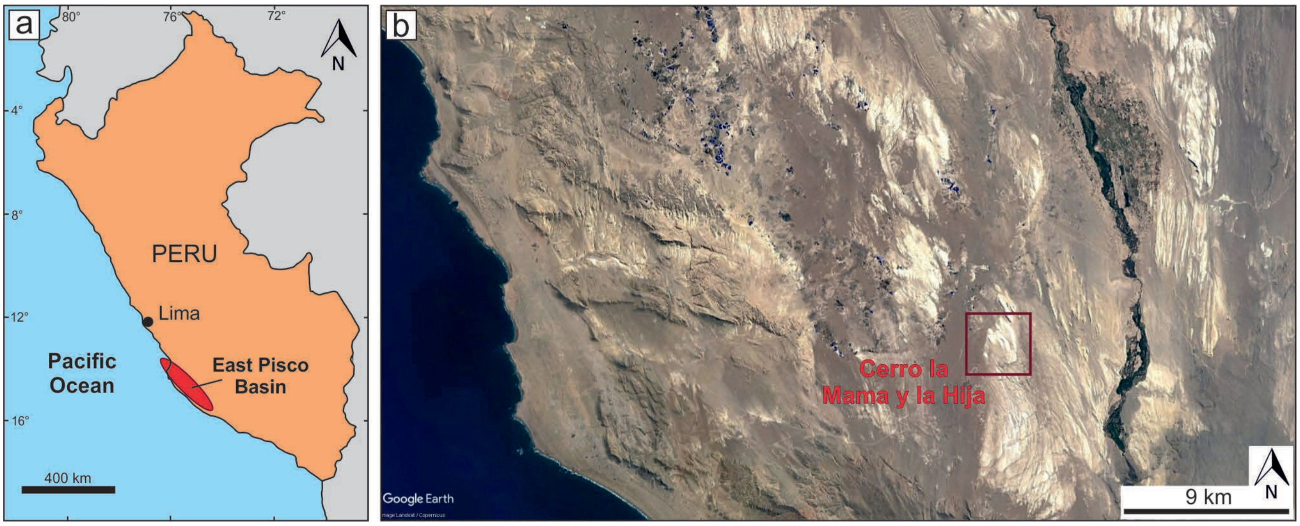

Fig. 1 - (color online) Geographic context. a) Geographic location of the East Pisco Basin along the Peruvian coast. b) Satellite image of the locality of Cerros la Mama y la Hija (Ica Desert, Peru). Based on Google Earth image.

Celma et al., 2017). Each stratigraphic unit is composed of sandstones at the base and siltstones or diatomaceous siltstones at the top, representing a transgressive cycle (Di Celma et al., 2017). The P0 sequence is dated between 14.7 and 12.6 Ma (Bosio et al., 2020b, 2022), the P1 sequence between 9.5 and 8.6 Ma, and the P2 sequence between 8.4 and ≥ 6.71 Ma (Bosio et al., 2020c). All the stratigraphic units record long-lasting, explosive volcanic activity. Numerous volcanic ash layers are found within the marine sediments, testifying to pyroclastic fallout in the area, coming from both the Western and Eastern Cordillera (Bosio et al., 2019, 2020a, b).

Invertebrate paleontology

In the East Pisco Basin, fossil invertebrates can be found throughout the sedimentary succession, from the middle Eocene Los Choros Member of the Paracas Fm to the Upper Miocene strata of the Pisco Fm, with a very wide range of fossil preservation types. Since the 1980s, much attention has been given to fossil mollusk assemblages from the East Pisco Basin, including descriptions of new species (e.g., Muizon & DeVries, 1985; DeVries, 1988, 1997, 2001, 2007, 2016, 2019; DeVries & Frassinetti, 2003; DeVries et al., 2006; Bosio et al., 2021a; Sanfilippo et al., 2021). The Pisco Fm hosts abundant molluscan remains, usually concentrated in mollusk-rich layers with low biodiversity and high dominance (Bosio et al., 2021a) and rarely associated with vertebrate remains (Bosio et al., 2021b).

Along the western side of the Ica River Valley, in the P0 sequence, the Middle Miocene molluscan fauna suggests warm-water conditions, as also indicated by the vertebrate fauna (DeVries & Frassinetti, 2003; Bosio et al., 2020b; Collareta et al., 2021). An important invertebrate faunal change occurred through the PE0.1 unconformity due the appearance of new species that show affinities with the Miocene Panamic fauna rather than with that of the Lower to Middle Miocene Navidad Fm of Chile, suggesting cooler conditions (DeVries & Frassinetti, 2003; Nielsen & Glodny, 2009; Di Celma et al., 2017). Regarding bivalves, specimens of *Dosinia ponderosa* are found in all the three depositional sequences of the Pisco Fm (Di Celma et al., 2017). Today, this species is typical of intertidal zones down to depths of 60 m (Coan & Valentich-Scott, 2012), suggesting a shallow-water marine paleoenvironment at the locality of Cerros la Mama y la Hija during the Late Miocene. Even if the molluscan fauna of the Upper Miocene Pisco Fm suggests cooler conditions than Lower and Middle Miocene fauna, showing affinities with the Panamic fauna (DeVries & Frassinetti, 2003; Di Celma et al., 2017), *Dosinia ponderosa* is usually associated with warm waters and its disappearance from the southern Peruvian coast could be attributed to the onset of Pleistocene cooling (DeVries, 1986; DeVries & Frassinetti, 2003) and/or to the upwelling conditions due to the strengthening of the Humboldt Current that started in the Late Miocene and continued until today (Amiot et al., 2008; Bosio et al., 2020b; Collareta et al., 2021; Kiel et al., 2023).

MATERIAL AND METHODS

Study area and sample collection

The P1 sequence of the Pisco Fm displays a maximum thickness in its southern outcrops, at the locality Cerros la Mama y la Hija (14°36’ S; 75°41’ W) (Figs 1b, 2). Here, the P1 strata consist of sandstones at the base, and the rest of the succession is composed of diatomaceous siltstones alternating with dolomite nodules and volcanic ash layers (Fig. 2a). At the top, a stratigraphic unconformity separates the P1 sequence from the overlying P2 sequence, starting with a lag of authigenic nodules and sandstones (Fig. 2a). At this locality, many fossil vertebrates have been discovered, such as the mysticete specimen shown in Fig. 2c (Esperante & Poma, 2015; Collareta et al., 2021), and several volcanic ash layers have been studied and collected (Fig. 2d). The two mollusk specimens that are studied herein were collected at the base of the hill: MUSM-INV308 from the northern side of these hills

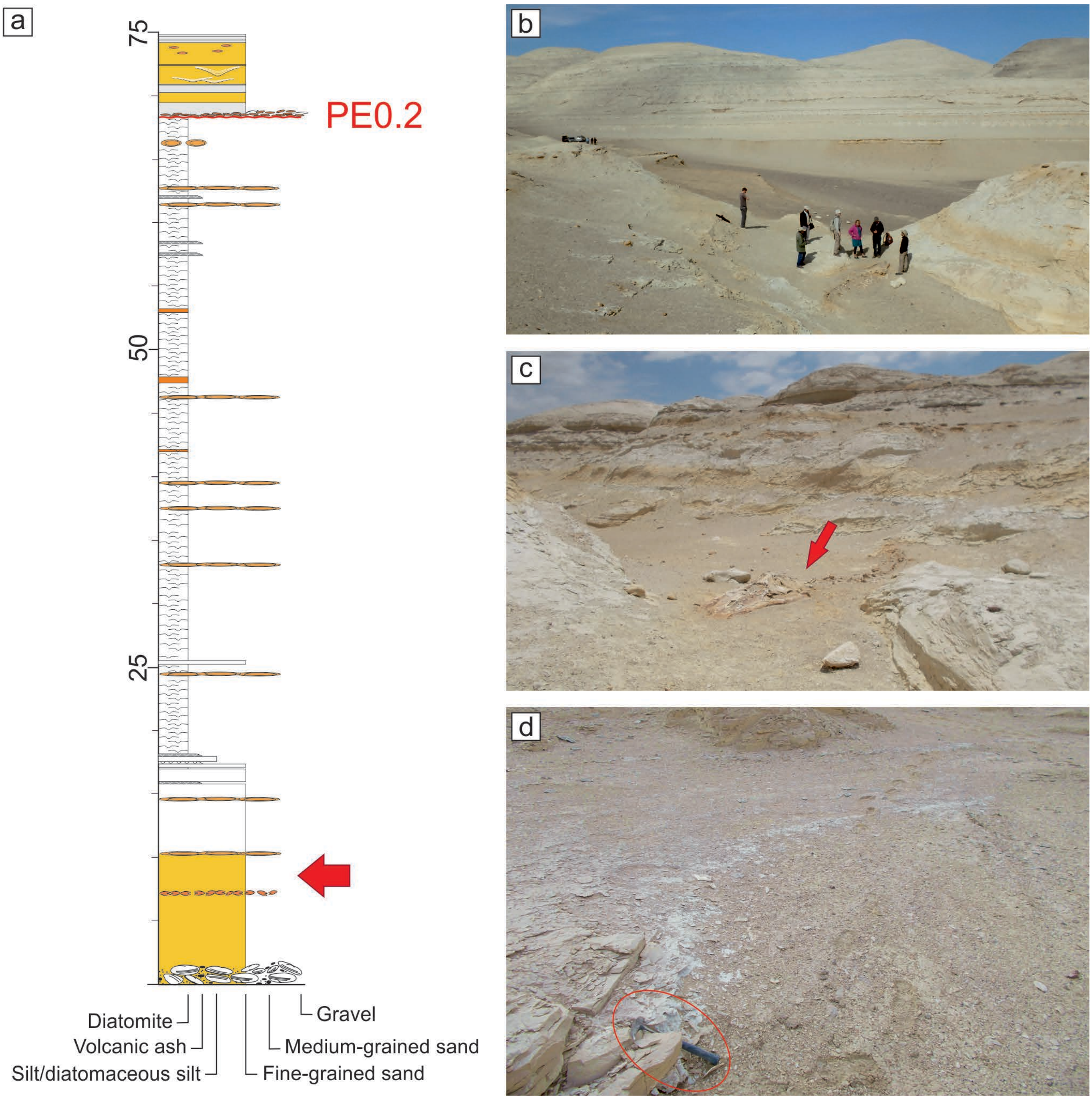

Fig. 2 - (color online) Stratigraphy and field photos. a) Measured stratigraphic section at the locality of Cerros la Mama y la Hija. The red arrow indicates the layer of the collected bivalve samples. b) Sandstones and diatomites of the Pisco succession cropping out at the locality of Cerros la Mama y la Hija. Note that sandstones are the orange sediments in the lower part of the photo, whereas the diatomaceous silstones are whitish in color and exposed at the top of the succession. c) Fossil specimen of a mysticete (red arrow) in the sediments of the P1 sequence at the locality of Cerros la Mama y la Hija. d) A volcanic ash layer (whitish layer) in the sedimentary succession of the P1 sequence at the locality of Cerros la Mama y la Hija. The red circle spotlights the hammer in the left corner.

during fieldwork in June 2017, not in situ (14°35’56.5” S; 75°40’58.4” W), and MUSM-INV309, in situ, from the southern side of the hills during fieldwork in September 2021 (14°36’37.8” S; 75°40’41.4” W). The two specimens were described and deposited in the invertebrate paleontology collection at the Museo de Historia Natural de la Universidad Nacional Mayor de San Marcos (MUSM, Lima, Peru).

Laboratory analyses

The two studied specimens were described in the laboratory and measured with a standard analog caliper. Two smear slides were prepared from the unconsolidated material forming the casts for investigating the composition of the two bivalve specimens. A small amount of sediment composing the mold was collected from the specimens with a wet toothpick and rubbed on the microscope slide with a drop of distilled water. Slides were positioned on an electric burner at ca. 50°C and dried. They were then covered with a cover glass using a Norland Optical Adhesive and exposed under a UV lamp. The two smear slides were analyzed through an Optika B-500POL optical microscope under transmitted light.

RESULTS

At Cerros la Mama y la Hija, specimen MUSM-INV309 was found in an indurated layer within the sandstones at the base of the succession (Figs 2a, 3a-c). This specimen was preserved in situ but not in life position, with the posterior part pointing to the stratigraphic bottom (Fig. 3a-c). The other specimen, MUSM-INV308, was found ex situ, on the desert floor, far from the outcrop (Fig. 3d). Both the specimens are white-colored fossil casts of uncemented and scarcely consolidated volcanic material consisting of fine-grained glass shards and biotite crystals observable through a hand lens. They are surrounded by a coarser-grained brownish sediment with the grain size of medium sand. The casts are partially eroded or display abrasion marks due to recent wind action. Except for these slightly eroded parts, the fossils are exquisitely preserved, retaining the original shell morphology. The casts of the shells are subcircular in shape, moderately inflated, equivalve and slightly inequilateral (Fig. 4). The lunula is not well-preserved or is covered by sediment, whereas the escutcheon is obscure (Fig. 4). The umbos are pointing anteriorly, indicating that the shell is prosogyrate (Fig. 4). They exhibit an evident sculpture of commarginal ribs with very narrow interspaces (Fig. 4). The MUSM-INV308 specimen measures 7.22 cm in height, 7.62 cm in length, and 3.20 cm in width; the L/H ratio is 1.05. The MUSM-INV309 specimen measures 7.19 cm in height, 7.82 cm in length, and 2.90 cm in width; the L/H ratio is 1.09. Both the casts have a small portion lacking in length. By comparing shell characteristics and measurements with published data about the tropical West American molluscan fauna (Coan & Valentich-Scott, 2012) and the Pisco Fm molluscan fauna (DeVries, 1986; DeVries & Frassinetti, 2003; Bosio et al., 2021a), the casts are attributed to the species *Dosinia ponderosa* (Gray, 1838). The values of height, length and width and the L/H ratios perfectly overlap those reported by Bosio et al. (2021a) for internal dolomite molds preserved in the P1 strata.

Since the grain size of the poorly consolidated volcaniclastic material is below 2 mm, the bivalve casts are composed of ash (White & Houghton, 2006). Under the optical microscope, ca. 90-95% of the components are volcanic glass shards, whereas the remaining 5-10% is composed of biotite crystals (Fig. 5). Glass shards are mainly highly vesiculated and stretched (Fig. 5). Since the extraneous particles (i.e., biogenic material, rock fragments, iron oxides, clays) represent less than 5%,

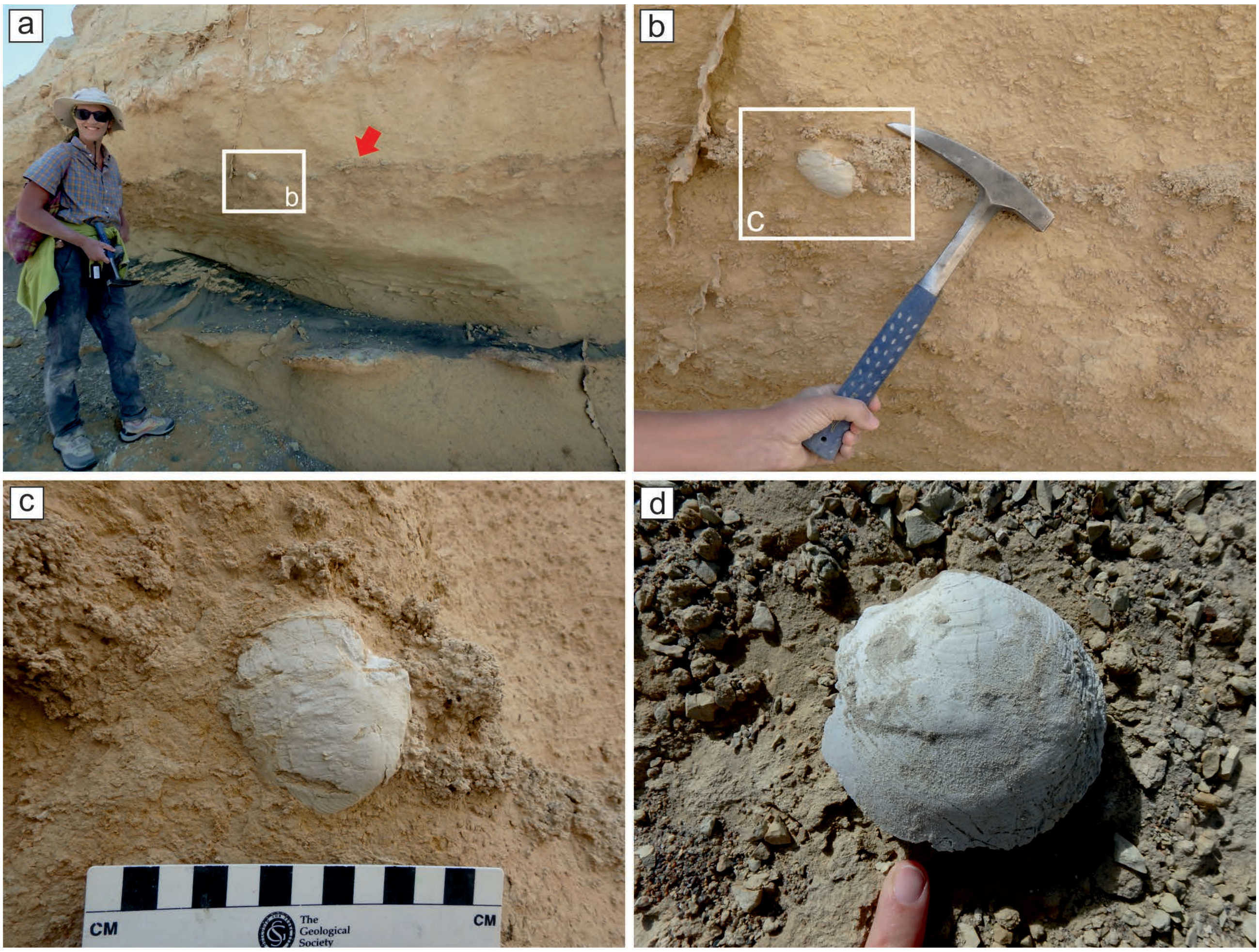

Fig. 3 - (color online) Field photos of the bivalve specimens. a) Field photo of the P1 sandstones cropping out at Cerros la Mama y la Hija where one of the samples was collected in situ. The red arrow indicates the layer of the collected MUSM-INV309 specimen. b) Close-up of the boxed area in Fig. 3a showing the layer with the bivalve MUSM-INV309. c) Close-up of Fig. 3b showing MUSM-INV309 specimen. d) MUSM-INV308 specimen found not in situ at the base of the sandstones of the P1 sequence cropping out at Cerros la Mama y la Hija.

Fig. 4 - (color online) MUSM-INV308 specimen. Fossil cast of *Dosinia ponderosa* (Gray, 1838) from Cerros la Mama y la Hija, Peru. From upper left clockwise: left valve, right valve and dorsal view. Height: 7.22 cm; length: 7.62 cm; width: 3.20 cm. Scale bar corresponds to 2 cm.

the casts' components represent the product of primary deposition of a volcanic ash layer, excluding a reworking (see Griggs et al., 2014; Bosio et al., 2019).

DISCUSSION

Fossil conservation in volcanic ash

There are not many cases of fossils preserved in volcanic ash, but these are usually exquisitely preserved (see Lockley, 1990). It is worth mentioning the archeological site of Pompeii and its external molds formed within the body of pyroclastic materials (e.g., Giacomelli et al., 2003; Deem, 2005). Today, studies on recent ashfall deposits have been carried out to understand taphonomic processes in these particular settings (e.g., Hayward et al., 1989; Heikoop et al., 1996b; Lokier, 2021; Maguire, 2022).

Ashfalls allow the exquisite preservation of fossil traces (e.g., Hay & Leakey, 1982; Baales et al., 2002; Mietto et al., 2003; Nelson et al., 2008; Marriott et al., 2009) and both mineralized and non-mineralized bodies by instantaneously blanketing entire forests and terrestrial plant remains - the "Pompeii effect" (e.g., Wagner, 1989; Scott, 1990; Hayward & Hayward, 1995; Goetcheus & Birks, 2001; Pfefferkorn & Wang, 2007; Opluštil et al., 2009; DiMichele & Falcon-Lang, 2011; Rößler et al., 2012; Locatelli, 2014; Góis-Marques et al., 2019; Wick, 2023) - as well vertebrate fauna in both continental (e.g., Hay, 1986; Famoso & Pagnac, 2011; Antoine et al., 2012; Iurino et al., 2014; Jiang et al., 2014) and marine (Bosio et al., 2021b) settings, and benthic communities on the seafloor (e.g., Heikoop et al., 1996a; Droser et al., 2006; Maguire et al., 2016). One of the most renown examples of the lattermost case is the Ediacaran fauna, which is characterized by different types of preservation, all sharing the rapid burial by event beds, such as instantaneous deposit of volcanic ash on the seafloor to form an "Ediacaran Pompeii" (Seilacher, 1992; Narbonne, 2005; Droser et al., 2006; Hofmann et al., 2008). The predominant type of preservation is a "conception-style preservation", which consists of epireliefs (positive reliefs) such as casts of ash molds on a surface overlain by a volcanic ash bed (Narbonne, 2005; Bamforth et al., 2008). Fossil preservation turns out to be exceptional also in other volcanic settings such as maar lakes (e.g., Kovács et al., 2020; Grandi et al., 2023)

The extraordinary preservation in volcaniclastic material is due to the rapid burial below a thick and heavy load of ashfall and the early diagenesis of labile minerals, which allows a rapid cementation in the volcanic ash that contribute to preserving organisms (Heikoop et al., 1996a; Narbonne, 2005; Opluštil et al., 2009; DiMichele & Falcon-Lang, 2011). The instantaneous burial rapidly isolates the organisms from the destructive effects of subsequent hydraulic disturbance, scavenging, bioerosion

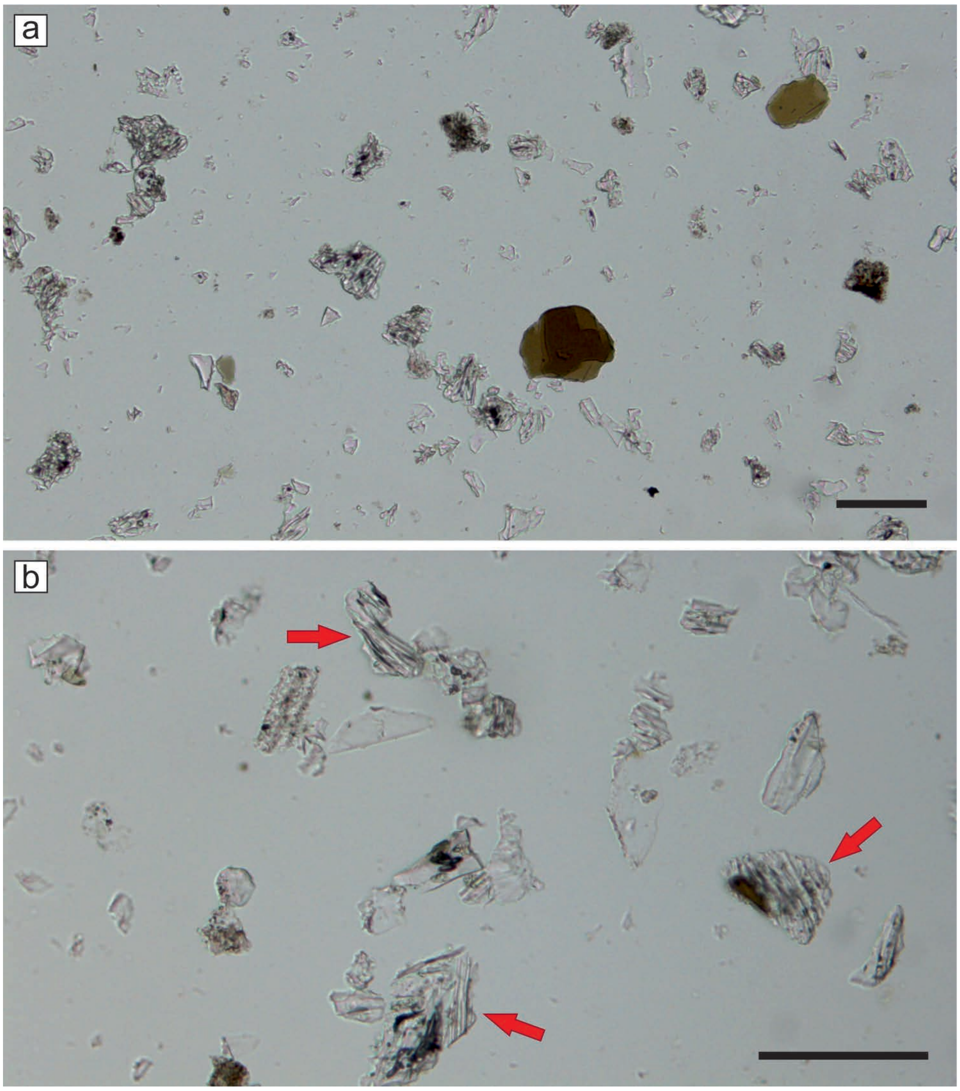

Fig. 5 - (color online) Photomicrographs. a) Highly vesiculated volcanic glass shards (transparent) and biotite crystals (brown color) forming the bivalve casts observed under the optical microscope. b) Detail of the highly vesiculated and stretched volcanic glass shards (red arrows). Scale bars equals 100 μm.

and bioturbation (Heikoop et al., 1996a). Droser et al. (2006) assert that organisms already lying on the substrate are cast with precision, while those transported by the ashfalls are less well molded. The preservation potential for organism details could be also limited by the crystal size of the volcanic grains (Narbonne & Gehling, 2003) and the temperature of the volcanic material (Iurino et al., 2014). In fact, the fine-grained material favors the formation of external molds and the low temperature phreatomagmatic deposits preserve detailed paleontological information that are normally lacking in the fossil record (Iurino et al., 2014). The variety of preservation includes cellular permineralization, also defined "petrification" for plants, adpressions, epireliefs, casts and molds (Rößler, 2021). In some cases, volcanic ash deposits preserved fossils in carbonate concretions (Orr et al., 2000; Briggs et al., 2008).

A taphonomic enigma

The two volcanic casts of *Dosinia ponderosa* (Gray, 1838) discovered at the locality of Cerros Mama y la Hija tell an intriguing taphonomic story. The exact order of the processes which brought about the formation of ash casts within a sandy sediment remains an enigma.

Dosinia ponderosa is a mobile infaunal suspension feeder, with a compressed shell shape and vertical life position (Di Celma et al., 2002). This species lives in substrates of fine sand to coarse silt characterized by low to high energy (Baqueir, 1979) in a nearshore zone shallower than 60 m (Coan & Valentich-Scott, 2012). During the Late Miocene, *Dosinia ponderosa* specimens lived in the shallow waters of the East Pisco Basin within a sandy sediment with sedimentological features attributable at ca. 5-10 m of depth (see Sanfilippo et al., 2021 for an analog from the basal sandstones of P2). After death, infaunal mollusks tend to stay buried within the sediment, while epifaunal mollusks tend to remain exposed on the sediment-water interface (Lazo, 2004). Therefore, infaunal bivalves such as *Dosinia ponderosa* have a possibly higher fossilization potential and time averaging than the epifaunal bivalves (Lazo, 2004). Because we found the in situ specimen not in life position, both Pisco specimens would have been slightly rotated by bioturbation or exposed on the seafloor by a storm event without being disarticulated (Fig. 6). On the seafloor, they were soon covered either by a sandy sediment or by a centimeters-thick volcanic ash layer erupted by volcanic centers in the near Central Andes (Bosio et al., 2020a) (Fig. 6). This rapid burial probably prevented the disarticulation of the shells.

In the first hypothesis (see Fig. 6 left), sand surrounding the bivalves started to consolidate, allowing the formation of an external mold in the sediment. At the boundary between the sulphate reduction and methanogenesis zones, pH variations may occur during early diagenesis (Meister et al., 2007, 2011; Xu et al., 2019). A decrease of pH would explain the dissolution of the aragonitic shell, aragonite being unstable and easily dissolved (Cherns et al., 2011). After these processes, two empty external molds remain in the consolidated sediment. Then, an event such as a storm removed the first few centimeters of lesser consolidated sediments, and a small aperture opened at the top of the cavities. Immediately, a volcanic ashfall covered the seafloor filling the cavities. In shallow water settings, volcanic deposits have a very low preservation potential due to the presence of syndepositional disturbances, such as the action of marine currents and storm waves (Carey, 1997; Griggs et al., 2014; Bosio et al., 2019). In this case, a winnowing event occurred, removing the ash layer and leaving intact the two filled cavities on the sediment surface. After winnowing, the two casts were buried in newly deposited sandy sediment and stayed fossilized until the recent exhumation.

In the second scenario (see Fig. 6 right), during burial by the primary deposition of a volcanic ash, the two specimens were filled by the ash. Due to the fine grain size of the ash, winnowing occurred, but the articulated bivalves preserved the compact and stiff ash inside the shell. After the winnowing, the filled shells were buried again by sandy sediment deposited on the seafloor. After a long time, the surrounding sediment started to cement and an external mold of the shells formed. During diagenesis, fluids enriched in silica, probably due to the highly siliceous environment (e.g., volcanic ash, terrigenous sediments, overlying diatomaceous silts) dissolved aragonite of the shells and remobilized the fine-grained ash inside the internal casts, which took on the form of the external mold of the shells. In fact, the release of dissolved silica and cations such as $Fe^{2+/3+}$, Mn^{4+}, and Ba^{2+} from volcanic glass shards in marine sediments is always accompanied by a strong decrease in alkalinity and pH in the surrounding waters (Kutterolf et al., 2006).

A difficulty with the first scenario is that an unusual series of synchronized processes needed to have occurred. The problem with the second scenario is that in the last process, where the shell dissolved and ash adapted to the external molds, a diminishment of volume should have occurred (and this is not observed).

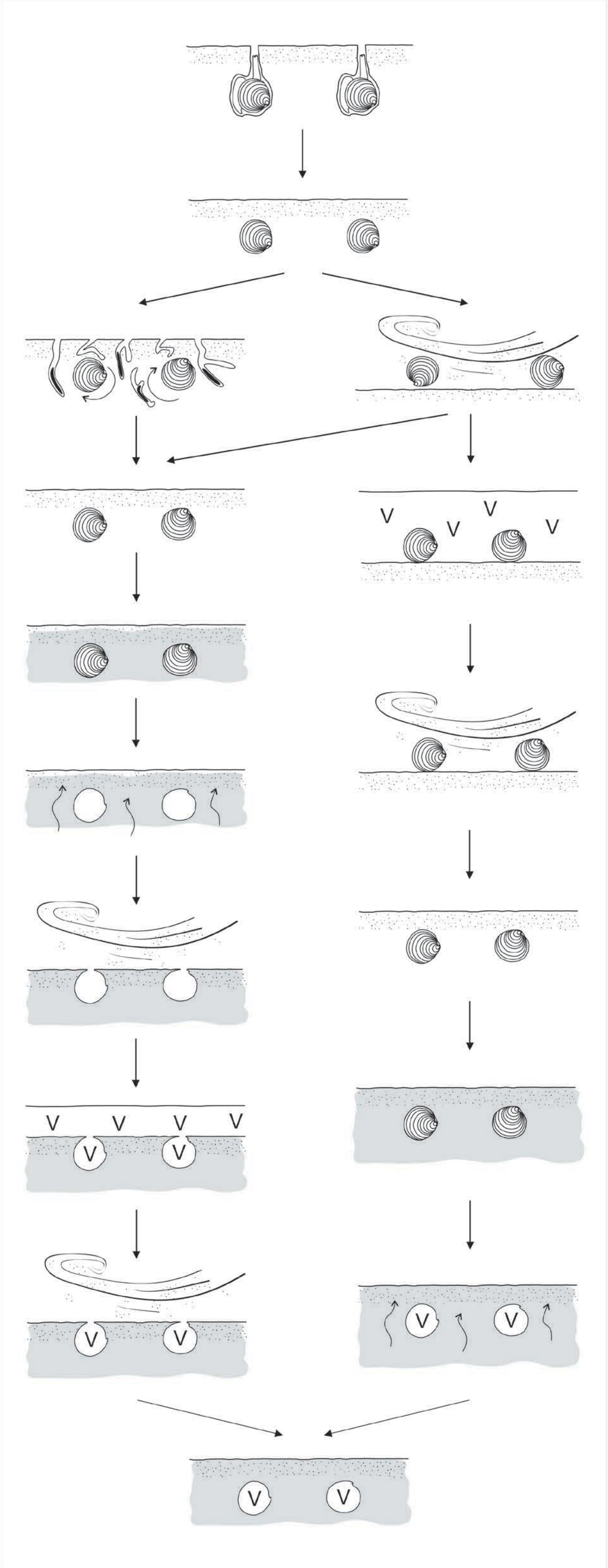

Fig. 6 - Schematic reconstruction of the taphonomic history of *Dosinia ponderosa* (Gray, 1838) in the Pisco Formation. On the left, the first scenario, on the right, the second scenario (see Discussion for the explanation of the processes). The gray halo is the consolidated sediment, the thin arrows represent the circulating diagenetic fluids, the "V" symbol indicates the volcanic ash.

CONCLUSIONS

Casts of two bivalve specimens collected at the locality of Cerros la Mama y la Hija in the East Pisco Basin (Peru) exhibit exquisitely preserved features of the species *Dosinia ponderosa* (Gray, 1838) thanks to the fine-grained volcaniclastic material of which they are composed. Analyses of the volcanic composition, mainly consisting of glass shards and biotite crystals, suggest that these mollusks or their molds experienced a "Pompeii-effect", i.e., a rapid burial caused by the primary deposition of a volcanic ash layer. The succession of taphonomic processes leading to the formation of these casts remains unclear, but two main alternatives are hypothesized herein. In both cases, it was the strong explosive volcanic activity affecting the East Pisco Basin during the Late Miocene that allowed this peculiar preservation style in a shallow-water marine setting.

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