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ORIGINAL ARTICLE

The Paimogo Dinosaur Egg Clutch Revisited: Using One of Portugal's Most Notable Fossils to Exhibit the Scientific Method

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Abstract

Found in the Upper Jurassic outcrops of Lourinhã, Portugal, and first published in 1997, the Paimogo dinosaur egg clutch is one of Portugal's most remarkable fossils, with over one hundred eggs preserved in association with embryonic bones, of the allosauroid theropod *Lourinhanosaurus*. However, many questions about it have remained unanswered, even until the present day. After its discovery, this extraordinary fossil became the keystone of a small local museum, greatly kick-starting regional tourism, while also holding the fossils in trust for future generations to study. More than 20 years later, continually sustained paleontological interest from the public has even given rise to both a highly successful dinosaur theme park in the region and an aspiring UNESCO Geopark. Recently, a multidisciplinary team of preparators, paleontologists, sedimentologists, mineralogists, and geochemists revisited an unopened jacket from the original excavation using an array of techniques to address various questions. Studies are ongoing, but the corpus of information obtained and the methodologies utilized to gather data have offered an opportunity to design an exhibit around the history of the Paimogo clutch, highlighting the scientific methods involved, and asserting the importance of preserving geological heritage for the future, when new tools will doubtlessly become available to provide yet another new look at old fossils. Here, we describe our analytical procedures and present an innovative exhibit designed to introduce to the public the latest advances on the research behind an iconic piece of Portuguese geoheritage, increasing its value both as a research item and as an educational resource.

Keywords Embryos · Jurassic · Science dissemination · Paleontological heritage · Aspiring Geoparque Oeste

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Introduction

Throughout modern history, the general public has upheld a significant interest in scientific knowledge, a curiosity which has been continually sustained by the scientific community through museums as natural history repositories for scientific exposition. The origins of natural history collections can be traced back to the sixteenth century, through the surge of intellectual attempts at understanding the natural world that took place within the Renaissance period, and with the first exhibit of a naturalistic collection attributed to the Neapolitan Ferrante Imparato, circa 1599 (Stendardo 2001). This dawn of specimen and artifact collecting also came with the need to explain and order it, and so the concept of "museum" was born as a response (Findlen 2012). Throughout the eighteenth century, museums essentially evolved from private cabinets of curiosity to the dedicated public buildings we know today. While early museums acted more like research hubs for lofty scientists, ideologies began

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to shift in the nineteenth century, when information began to be dispensed to the masses, who were encouraged to adopt a behavioral reverence for objects of study (Chicone and Kissel 2013). Even today, most natural history museums have been limited by this historical exhibition style, preserving that format in which the visitor observes natural pieces or scientific instruments from a distance, almost as though they are in an art exhibition (Black 2005). These exhibitions would have usually been accompanied by generally informative explanatory panels (which began to illustrate some essential aspects of the display), but it was not until the twentieth century that attentions began to shift more towards education, and museums began to realize that improving their displays (and not necessarily collections) was the best way to engage and educate the public, especially when it came to science and technology (Chicone and Kissel 2013; Rader and Cain 2014). By beginning to create a dialog between exhibits and their behind-the-scenes research, education was transformed.

Museums today are indeed less rigid than those of the past, and continue to evolve in their attitudes, becoming more welcoming and user-friendly (Black 2005). Modern exhibitions provide support for users by involving a guiding thread, or narrative, which helps the visitor to navigate the space of the exhibition, acquiring concepts and experiences along the visit (Rader and Cain 2014). In natural history museums, this narrative is normally related to general concepts, such as "evolution" or "ecological reconstructions of an ecosystem," and paleontology-specific exhibitions traditionally focus on the narrative of fossil discoveries and their study. These exhibitions are of special interest for the dissemination of the discipline, as they show the public how the real work of the paleontologist is performed, and is indeed a far cry from pop culture icon stereotypes, such as the paleontologists in films like *Jurassic Park* (Spielberg et al. 1993), or the tomb-robbing, treasure-hunting characters of Lara Croft or Indiana Jones.

In recent decades, in likely association with the greater economic and technological resources becoming available, the research world has witnessed a considerable advancement of scientific knowledge (Şener and Sarıdoğan 2011; Goos et al. 2019). At the same time, society has also experienced its own concurrent rise in scientific understanding, which has been evidenced in the increased demand for technical data and more detailed explanations relating to the work of researchers (Black 2005; Siune et al. 2009; Cooke et al. 2017). The general public is no longer satisfied by simple exhibitions with empty narratives, looking instead for extraordinary quantity and quality in the information that they receive from researchers. Equipping visitors with this deeper knowledge is not only a modern museum's responsibility, but also enables the public to better evaluate the critical issues of the current day (Chicone and Kissel 2013). Fortunately, this public demand has gone hand-in-hand with changes in museum infrastructure regarding outreach management, resulting in new resources and spaces being innovated and created by collaborative scientific and outreach entities. As a consequence, the scientific community and society as a whole have found increased points of intersection, not only through the improvement of classical museums, but also with activities such as geoparks and geotourism (Williams et al. 2020), allowing increased opportunity in a vast array of diverse ways to share, spread, and inspire with scientific knowledge.

One particular area of recently attempted innovation in scientific dissemination is where new out-of-the-box and often outdoor activities are linked to new outreach centers, where in places such as Geolodía, BGS Open Day, DINOpaseo por El Castellar, ExpoLourinhã, etc. (McMillan 2008; Alonso-Zarza et al. 2016; Cobos et al. 2020), geologists and scientists are able to share their time and hands-on experience through field trips and conferences with enthusiastic members of the public, establishing a kind of paleontological tourism, which not only can be an economic and social boon to a region, but also preserves scientifically valuable sites and specimens (Antczak 2020). These popular activities allow for reaching visitors personally in a quick and easy form, and successfully resolve any of their questions thanks to this platform of direct interaction. Unfortunately, the scarce time availability and compensation of researchers to be able to develop these activities often enough, the specificity of weather conditions, and the discriminatory nature of participant mobility can sometimes hinder the absolute achievement of outreach goals, and for most nonparticipants, the information transmission deficit prevails.

Despite these subsequent attempts at advancement, transmitting accurate information to the general public about the procedures and methodologies that scientists use in executing studies still proves to be one of the main challenges for scientists (Treise and Weigold 2002; Cooke et al. 2017). Gathering the details regarding the formation of original hypotheses and the laborious collection of supporting data is a process that remains largely unknown to the general public, since it is presented by scientists directly to scientific journals (Treise and Weigold 2002; Cooke et al. 2017). Unfortunately, this key information is withheld for being less sensational for general consumption, but in fact embodies the core of what we could call "the kitchen of scientific work." This information lapse then, in turn, demands a leap of faith on the part of the public to blindly accept the concluding data that the scientist offers as their sole understanding of the topic.

In the last 3 years, as a part of the XtalEggs Project, funded by the Portuguese Fundação para a Ciência e Tecnologia, our team has restudied one of the most iconic fossils of Portugal: the Paimogo dinosaur egg clutch, an assemblage of theropod dinosaur eggs and embryos dating back 152 million years Mateus et al. 1997). Readdressing a mostly unaltered jacket from the original excavation of 1993 provided an opportunity to gather additional information on the fossil site that was not possible to obtain from the original dig. Further studies and analyses carried out on the specimen have included preservation and conservation analysis and intervention, paleontological analysis (paleoology and taphonomy), sedimentological studies (with detailed lithology characterization, granulometric, and facies analysis), mineralogical analysis (X-ray diffraction), geochemical work (elemental and stable isotopic analysis), and paleomagnetism (ASM). Results from the different studies will be published in the coming years, but the objective of the present work is to describe all the data sampling strategies used in this iconic fossil specimen, and to present a new useful resource for outreach, which emerged from the conservation, study, and preparation for exhibition of the Paimogo dinosaur egg clutch. The purpose of the new exhibition showcase is twofold: first, to impart information about paleontological heritage in the area, and second, to successfully explain the scientific method to the public, highlighting the scientific and technical work behind the fossil, rather than paleontological piece itself. By adding elements of the scientific process to museum exhibits, and embedding details of the quest for understanding into our displays, we can heighten the understanding of and empower the visitor through increased scientific literacy. Through this new itinerant museum piece, we aspire to answer all of the questions that the visitor may potentially ask, and impart in them a sense of what, in many cases, were the same scientific questions that we too initially asked ourselves.

The History of Lourinhã Paleontology Within the Context of the Paimogo Dinosaur Egg Clutch

In the case of the Lourinhã region of western central Portugal, abundant dinosaur remains have been found in the area since the mid-1800s (Lapparent and Zbyszewski 1957). The first dinosaur discovery in Iberia was made by Carlos Ribeiro (1813–1882) on June 20, 1863, and actually took place in Porto das Barcas, in the municipality of Lourinhã: two theropod dinosaur teeth (Lapparent and Zbyszewski 1957), later ascribed to *Torvosaurus gurneyi* (Hendrickx and Mateus 2014). In the late 1940s and early 1950s, the Portuguese Geological Survey conducted a number of excavations that concluded with the seminal work by Lapparent and Zbyszewski in 1957 (Antunes and Mateus 2003). The local renaissance in paleontology that followed came by the hand and the efforts of amateur paleontologists congregated around a local nonprofit association, the Lourinhã Ethnology and Archeology Group (G.E.A.L.) that eventually erected a small local museum, the Lourinhã Museum (Fig. 1a–b), on July 15, 1984, managed by the G.E.A.L. At first, the main objective of the museum was more so to exhibit ethnographic and archeological heritage, but soon the paleontological material recovered from the area was so abundant that its value became more prominent in promoting the geological heritage of the region. Thus, paleontological interests began to peak, and the circle of regional fossil collectors began to broaden from amateurs to involving professional paleontologists of the University of Lisbon and the NOVA University of Lisbon, such as António Galopim de Carvalho and Miguel Telles Antunes. The latter would eventually go on to advise the first PhD thesis on Lourinhã's dinosaurs, defended in 2005, by Octávio Mateus (Mateus 2005).

At present, paleontological research is regularly developed in Portugal through a partnership with the NOVA University of Lisbon [Universidade Nova de Lisboa], and also independently organized with the collaboration of paleontologists worldwide. By association, the Lourinhã Museum has now grown to become a notable institution in paleontology at a global level, and has continually highlighted paleontology as a significant new economic resource for the area. Even now, the Lourinhã region continues to opt for the further promotion of geotourism and paleontology, with the most recent examples of this being the building of a dinosaur theme park, the Dinoparque de Lourinhã, in 2017 (Fig. 1c–d), and the Aspiring Geoparque Oeste, an initiative for a new Geopark in the area.

To give more context on the fossil specimen in focus, one of the most famous pieces of the Lourinhã Museum is the "Paimogo clutch." In 1993, two members and co-founders of the G.E.A.L, Isabel Mateus and Horácio Mateus, were carrying out an archeological survey in the surroundings of the Paimogo Fort, located at the NNW of Lourinhã, where Neolithic and Bronze Age human remains were known to be found (Silva 2012). During a survey performed on April 3, 1993, Isabel found some dinosaur eggshells and bones on the ground surface. Dinosaur eggs and eggshells had been previously reported in the area, including complete eggs in Peralta (Dantes et al. 1992), a few kilometers south, so they were able to correctly evaluate the importance of the findings. The forthcoming excavations took place in 1994 (Fig. 2a–b), 1995, and 1996, with primary participation from Octávio Mateus, Vasco Ribeiro, and the late Horácio Mateus (1950–2013). Paleontologists Pedro Dantas and later Miguel Telles Antunes had an ephemeral but important presence throughout the excavations as well.

During the 3 years of the excavation, the G.E.A.L. recovered five large blocks, encased in polyurethane jackets, and several other smaller blocks from the fossiliferous bed (Fig. 2c–f). The results were an exceptional accumulation of eggs and embryonic bones of theropod dinosaurs (Mateus

Fig. 1 **a** The historic building of the Lourinhã Museum, located in the downtown, and divided into ethnography, archeology, and paleontology exhibitions. **b** The ML's permanent and temporary exhibitions of Portuguese paleontological heritage. **c** The Dinoparque de Lourinhã, where temporary exhibitions and a permanent paleontological laboratory are located. **d** Life-sized models of dinosaur species in the outdoor exhibition of the Dinoparque de Lourinhã

et al. 1997, 1998). Altogether, the assemblage comprises more than 100 closely grouped eggs within 32 m^2 in the top of the Praia da Amoreira-Porto Novo member (Lourinhã Fm.), corresponding to the upper Kimmeridgian (Cunha et al. 2004). Dinosaur embryos are extremely rare in the fossil record, with only three reported instances of pre-Cretaceous dinosaur embryos (Argentina, Upper Triassic (Cerda et al. 2014), South Africa, Lower Jurassic (Reisz et al. 2005), and China, Lower Jurassic (Reisz et al. 2013)). Nowadays, the "Paimogo clutch" still represents the most numerous egg accumulations, and the embryonic bones still represent one of the oldest records of theropod perinatals worldwide.

The discovery was announced to the scientific community and to the public in 1997 (Mateus et al. 1997, 1998), resulting in vast worldwide media coverage (even considered one of the Top 100 Science Stories of 1997 by *Discover* magazine (Gibbons 1998)) and a significant impact on the local community, which quickly sparked interests and intentions of building a new, improved museum that could host this new sensational collection. The goal took 20 years to achieve, by way of the Dinoparque de Lourinhã, a joint effort between a private for-profit corporation, the public municipality, and a nonprofit association.

The individual fossil blocks followed different courses of study over time, with each path depending on the destiny and finality of each block. Several replicas of the smaller blocks were made for exhibit throughout the different activities of the Lourinhã Museum, whereas the original fossils themselves have remained stored since the 1990s. Regarding the five bigger blocks, the largest one (75 × 78 × 20 cm), which contains the biggest number of eggs, was prepared and installed in the permanent exhibition of the Museu da Lourinhã (ML; Fig. 2c), where it remained until its recent move to an exhibition at the Dinoparque de Lourinhã (DPL), which currently houses a part of the G.E.A.L collections. A second smaller block (55 × 43 × 20 cm), containing 14 eggs, was prepared for an itinerant exhibition, and then encased in a wooden container which acts both as a transport crate and showcase (Fig. 2d). This specimen has been one of the key pieces of a traveling exhibition on Portuguese dinosaurs that has travelled to several places in Portugal and throughout larger Europe. Currently, the block is in storage at the Lourinhã Museum. The three other blocks also remained in storage at the museum in their original polyurethane jackets.

The first studies on these specimens were carried out by the amateur members of the G.E.A.L. (Mateus et al. 1997,

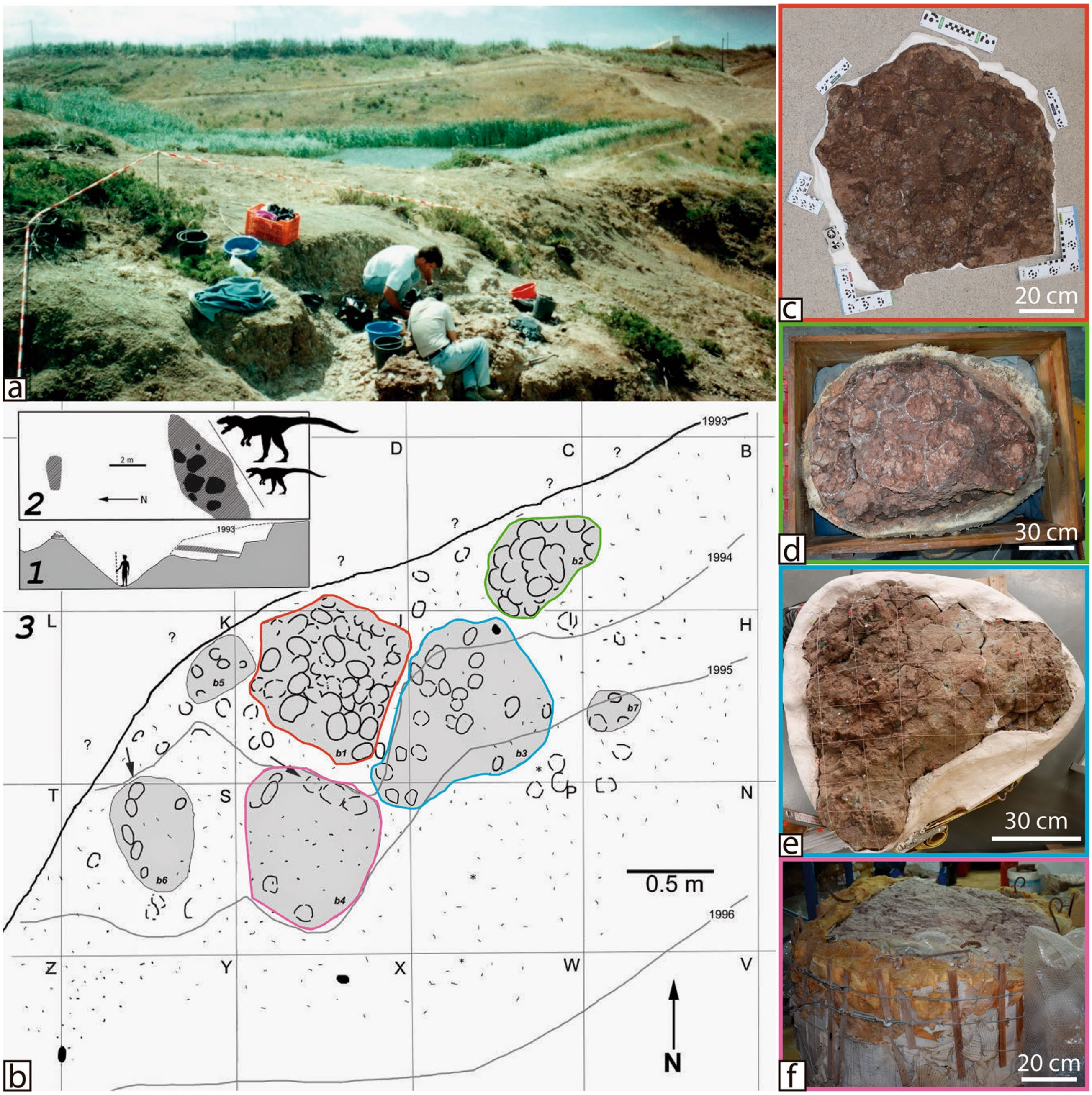

Fig. 2 **a** Members of the G.E.A.L. working on collecting the Paimogo clutch during the first excavation campaign of 1994 (photo by OM). **b** A sketch of the Paimogo paleontological site drawn by Vasco Ribeiro (note the distribution of the eggs, the position of the blocks, and the block excavation margins). **c** Fossil block that had been in the permanent exhibition in the Lourinhã Museum previously, and now at the Dinoparque de Lourinhã. **d** Small fossil block and its wooden case for itinerant exhibition. **e** Surface of the fossil block ML 565-B (the focus of this work), during an intermediate preparatory stage. **f** Original jacket and storage conditions of one the fossil blocks in the Lourinhã Museum's storage facility

1998), under the supervision of internationally recognized paleontologists, namely Prof. Philippe Taquet and Prof. Miguel Telles Antunes. These authors characterized the paleontological site as a large egg accumulation comprising 80–100 *Preprismatoolithus* oosp. eggs, some of them containing embryonic remains of a theropod, which can be attributed to the allosauroid *Lourinhanosaurus* (Mateus et al. 2001). Because no nesting traces were recognized at the time, they were interpreted as clutches. The eggs were buried in a massive mudstone facies, with no appreciable differences below or above the egg horizon, avoiding the recognition of sedimentary structures. Based on the large number of eggs and considering mass estimations made for an adult female *Lourinhanosaurus*, a series of hypotheses were formulated about the origin of this egg concentration: (i) several clutches were laid by several females during different times; (ii) a sedimentary reworking occurred of eggs that accumulated together in a single place; (iii) several females were laying together under the care of one male; and (iv) several females laid their eggs together and each female looked after her own.

Subsequently, Cunha et al. (2004) focused only on the hypothesis that multiple females (up to six) laid eggs simultaneously in a restricted area, and then left the eggs in non-actively incubated clutches. These authors avoided the sedimentary reworking hypothesis, instead explaining the egg accumulation as theropods' colonies during low water discharge (indicating no evidence that the nest was dug or the eggs buried), and discarded the idea of the existence of a true nest structure. These authors also noted that the eggs had probably been laid on a flat surface, and been moderately dragged by an overflow, despite the Antunes et al.'s (1998) conclusion that the high-water vapor conductance found to be necessary would require either a complete burial or plant covering of the eggs to avoid dehydration.

During the last 3 years, we decided to address the open questions on the biological and geological conditions in which the "Paimogo clutch" was formed, from a holistic point of view. After reanalyzing all the available data, we selected the largest remaining block for preparation and semi-destructive sampling. A multiproxy study was carried out, both in the block itself and in the original outcrop of Paimogo, in order to answer a series of scientific questions (Fig. 3). It was during this process of data collection that the team realized that these key questions that we were trying to answer were, in essence, more elaborated versions of those raised by the several thousands of visitors that had admired the "Paimogo clutch" during the last 25 years. We also realized that a significant value of the specimen lies not only in the fact that we were able to answer more of these questions, but also in being able to show the public the principles and methods of the modern techniques being used to gather that information.

The New Approach to the "Paimogo Clutch": a Summary of the Vast Array of Scientific Methodologies Used

Fossil Preparation: Deploying a Strategy for Safe Handling and Long-Term Preservation

Fossil preparation is the process of readying and physically stabilizing fossils for research and exhibition, and has a lasting impact on how fossils can be studied and interpreted (Wylie 2009). This transformative process is applied to rough, field-wrapped specimens, in order to properly expose their hidden features and address their long-term preservation needs in the stable environment of a laboratory, where absent factors such as weather conditions and narrow time constraints allow for controlled, deliberate conservation work. Preparation work usually involves several degrees of cleaning, consolidation, and repair (e.g., Brown et al. 2009; Horie 2010; Davidson and Brown 2012), although the techniques and materials used can vary dramatically, depending on the fragility of the fossils and the composition of their surrounding matrix. Preparation treatments are therefore individually tailored to address the needs of each individual fossil collection scenario (as in the case of the Paimogo clutch), and ideally are always minimally invasive and reversible, in order to preserve fossil specimens for the future, in as original a state as possible.

Because of the time period in which it was excavated (and the limited resources available at the moment of extraction), coupled with the suboptimal storage conditions that the Paimogo clutch (specimen number ML 565-B; Fig. 2e) withstood over the years, a number of conservation challenges readily presented themselves upon assessment of the block. The original field jacket that had been created for the block had been made using a hodgepodge of materials

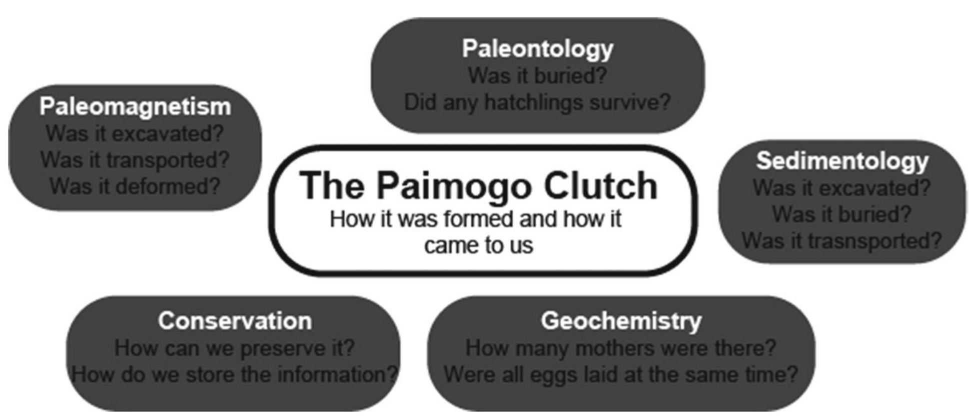

Fig. 3 A conceptual diagram of the synthesis of the open questions and hypotheses that the studied fossil block should answer in its current reevaluation

utilized to create rigidity (focusing more on stable transport than long-term archivability), producing a field jacket that incorporated foreign elements into a surrounding polyurethane foam encasement, including items such as street signs, ropes, composite lumber scraps, metal shrapnel, cardboard advertising, etc. These objects were largely of unknown compositions. The deteriorating surrounding foam, identified as expansive polyurethane (although the exact composition was not able to be analyzed), had significantly degraded during storage and was now pulverized, and thus, potentially harmful and even carcinogenic upon inhalation. Therefore, the entire original support structure required removal and replacement. However, before this could be addressed, it was deemed priority to address the stabilization and preparation of the fossil itself, so that it would be able to withstand the disturbance and potential trauma of breaking apart its 20+-year-old encasing structure. Therefore, a multilayer "working jacket" (Fig. 4a) was created with burlap and plaster over the entire field jacket, in order to completely encase the foam and foreign objects, assuring safe working conditions meanwhile for the preparator.

The block had been partially prepared in the early years following its excavation; however, scant record remained of who exactly had worked on it, what exactly had been done, and with what materials. It was evident that a number of glues had been used on the block, all in varying states of deterioration. Superficial examination of the glue remains allowed some identification of them as cyanoacrylates, used for labelling the eggs, and an elastic residue that was probably a white wood glue, used for filling cracks and larger fractures. Additional adhesives of unknown nature had been applied over the few exposed eggs. Therefore, it was deemed that solvents would be used only sparingly overall, and that a mechanical means of removal of the failing adhesives would be largely relied on. When necessary, acetone-drenched gauze and cotton rounds were sparingly used as a poulticing method to soften known adhesives, and metal dental tools, tweezers, scalpels, and wooden dowels were used for further adhesive removal. Consolidation with Paraloid B-72 in acetone (of varying concentrations) and infills of polyethylene glycol were only used on the block for fracture abatement and stabilization purposes, and no new glues or protective coatings were used on the eggs or eggshells themselves.

A 15 cm × 15 cm grid was created on the nest surface using round corded elastic and kept in place with nails inserted into the field jacket. This grid not only assisted in orienting the preparator and facilitating communication about certain areas of the specimen, but also created numerical quadrants for assigning loose eggshells and sediments to their original locations. The objectives to clean and further expose individual egg shapes, while also performing a fine-level surface cleaning of the eggshells themselves, were done by basic hand tools. Preparation and cleaning were

Fig. 4 **a** Fossil block appearance and temporary working jacket used for stabilizing the block during the mechanical preparation process. **b** Second stage of preparation in which the old jacket is removed. **c** Final appearance of the block after the new jacket application (note the treatment of the surface, holes, and cracks)

carried out quadrant by quadrant, primarily using wooden dowels so as to minimize any potential damage to the eggshells, and also using a variety of metal dental tools and soft-bristled brushes. Although marks from a pneumatic micro-hammer could be observed on the specimen from some prior treatment, this tool was deemed too violent to be used again in terms of auxiliary vibrations and subsequent airflow currents over the egg nest block. Despite the eggshells adhering somewhat naturally to their surrounding matrix, this relationship could quickly be compromised by any such power tools.

Once the egg nest block had fully undergone surface preparation and consolidation, the preparator (AF) supervised and helped perform all of the sampling for the different analytical techniques that were applied to the fossil, addressing any damage to the specimen (mostly, eggshell breakage) in the precise moment that it occurred. The field jacket was systematically opened on its sides, with test holes first created to assess the overall stability of the matrix, and then by a methodical removal of the rest of the old jacket (Fig. 4b). Portions of the old jacket were detached from the nest block beginning in areas of least visible stress, and continued on section by section, until finally exposing bare matrix. Consolidation with a 20% concentration of Paraloid B-72 in acetone and infills of polyethylene glycol were applied to abate any uncovered side fractures in the block, and any instabilities were infilled immediately as they were seen. After sedimentological samples were taken, gauze soaked in Paraloid B-72 was then applied to the external side surfaces of the nest block. Once dry, a fresh jacket was constructed, covering the sides of the block in several layers of burlap and plaster and plugging the holes created by the sedimentological sampling with plugs of burlap soaked in plaster as well (Fig. 4c). The visible dry hole plugs were sanded for esthetics for future exhibition purposes, even offering the future possibility of being painted, should exhibit curators deem a more discreet look preferable. Additional remedial preparation of the block was performed after all of the analytical procedures described where fully carried out, to ensure the stabilization of the block and to prepare it both for archive and exhibition.

The underside of the egg nest was a problematic area for preparation due to a thick slab of composite wood spanning the entire base, which was also encapsulated in a thick layer of polyurethane foam and a latticework of steel rebar, which made removal impossible without lifting and compromising the integrity of the entire egg nest block. Throughout preparation, the possibility of flipping the egg nest to remove this substantial base and prepare the egg nest from the opposite side was discussed. Although flipping the jacket was outside of the scope of this particular project, significant interest remains in potentially flipping the jacket for a future intervention. Therefore, for the time being, the entire foam base was encapsulated in several layers of burlap and plaster to deter further deterioration and provide for safe handling, and a distinct seam was left in the burlap, where the new nest jacket met the old jacket remnant base, in order to facilitate any future removal of the old base, while leaving the new jacket sides intact and supporting the block.

Photogrammetry and GIS to Map 3D Data: Digitally Archiving Information for the Future

In order to have detailed spatial control of the sampling, and to aid with restitution of possible damage caused by the aggressive sampling methods that were to be carried out, a digital replica of ML 565-B was generated using one form of computational photography, photogrammetry. Important recent evolutions have been registered for those aspects of scientific research that involve digital imaging of cultural (and natural) heritage, most of them brought together under the broader term of computational photography (Miles 2020). Computational photography can be simply defined as a set of methods and techniques that gathers the knowledge provided by a series of digital photographs, in order to create a new representation of reality that offers additional information than that provided by the source photographs on their own.

Close-range digital photogrammetry has become one of the most important image-based survey techniques, especially in the metric documentation of context research (Yilmaz et al. 2007), since it provides rapid, non-contact, and highly accurate recording outputs in many potential forms: orthophotomosaics, digital surface models, interactive 3D models, etc. Recent progress in digital imaging, computer hardware and software has allowed for significant developments towards fast and accurate 3D photogrammetric digitization, making use of the "structure from motion" (SfM) algorithms, based on subsequent digital photographs taken with a shifted location of the camera (Mallison and Wings 2014).

The photographic documentation of the Paimogo specimen was done following the rules established by the International Committee for Architectural Photogrammetry, the so called 3X3 rules of photogrammetric documentation (Waldhäusl and Ogleby 1994). A series of overlapping (more than 66%) high-resolution nadiral and oblique photographs were collected in a grid pattern over the nests, using a DSLR camera with a fixed 28-mm lens, manual exposure and low ISO for greater image quality (Fig. 5a). The processing of the 168 high-resolution photographs was performed using Agisoft Metashape 1.6, a licensed professional photogrammetry software package. As a rule, the SfM algorithm requires digital images taken from different perspective points but with a high degree of overlap, in configurations adapted to the surfaces being documented (Micheletti et al. 2015). For most of the surfaces of interest, the required ideal overlap was achieved, with very few areas of missing data (only the hard-to-photograph deepest grooves or lowest overhangs).

For this project, a specially coded target scale was used, with georeferencing being done using local coordinates. The resulting dense point cloud contains over 52 million points, allowing for the extraction of a high-resolution

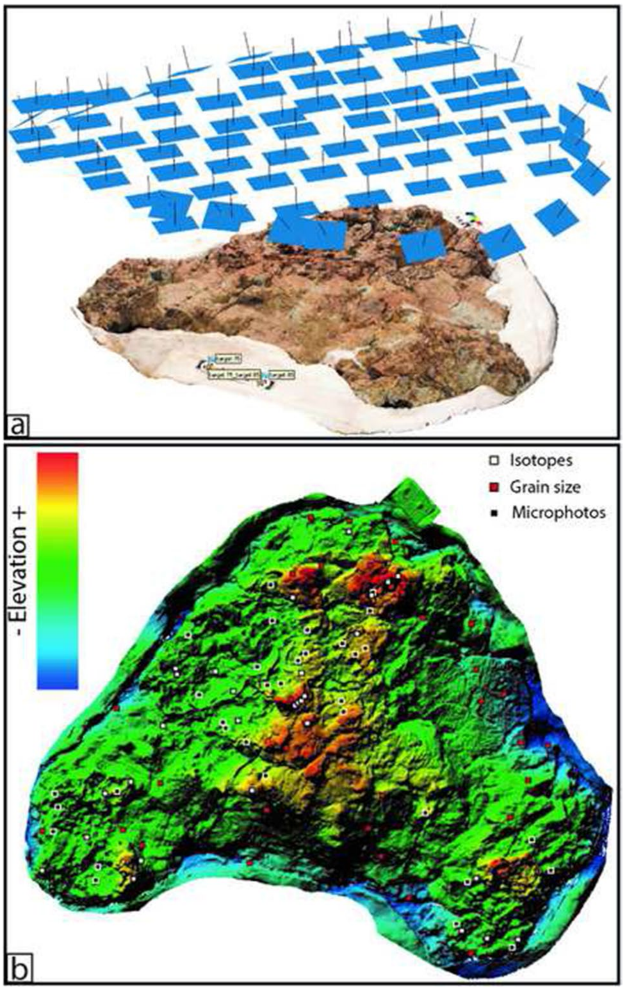

Fig. 5 **a** Using photogrammetry to record sampling locations and track physical preparation interventions. **b** Creating digital elevation models from scans

digital elevation model (DEM), of 0.198-mm per pixel and with an extraordinary coverage of 25.6 points for each square mm, thus offering a much-improved visualization of the variations encountered in the nest structure (Fig. 5b). The obtained products, the DEM and the orthophotomosaic, were exported into GeoTIFF format, to be further used as datasets within Global Mapper 19, a GIS software solution. These high-resolution outputs were used to pinpoint and track each sampling location in accurate 3D local coordinates, thus providing us with a useful base map for any current and future analysis. The resulting 3D model of the nest is also a complete and accurate record of the features identified and an important record of the specimen's current state of preservation. In this respect, the 3D model will also be used as a baseline recording, to allow further monitoring of degradations over time, by comparing subsequent 3D point clouds, collected at set intervals (Díaz-Martínez et al 2018). Through the use of online platforms, it can also be disseminated virtually within the scientific community (and to the general public), for further interpretation and research, diminishing the risk posed to such valuable but fragile specimens such as these by any further manual handling.

Paleontological Fossil Sampling: "Cracking" the Fossil Eggs

Profiting from the availability of newly prepared exposed eggs, we checked the previous interpretations of the paleoological affinity of the eggshell, confirming the attribution of the eggshell to the oogenus *Preprismatoolithus* and the allosauroid affinity of the embryos. New thin sections were prepared, and eggshells from different eggs were collected for scanning electron microscope analysis. In addition, two samples were selected and prepared for an electron backscattered diffraction (EBSD) study. EBSD enables measurement of crystallography orientation with spatial control, with a resolution below the micron (Prior et al. 1999). The automatization of this process allows to elaborate high-resolution maps that characterize different crystallographic properties, such as crystal orientation, misorientation between grains, crystal size, and mineralogy. The samples need careful preparation, including high-quality mechanical polishing with diamond and alumina and chemo-mechanical polishing with colloidal silica, which can be difficult in eggshells (Moreno-Azanza et al. 2013, 2016; Choi et al. 2019). This study allowed to identify possible recrystallizations that may alter the eggshell structure (Moreno-Azanza et al. 2016) and to infer eggshell growth mechanisms (Moreno-Azanza et al. 2013; Choi et al. 2018).

Taphonomic analysis of the eggs was carried out using a digital polarizing microscope (Dino-lite AM7013MZT). All individual eggs were checked for several bioestratinomic features, namely the degree of the reabsorption of the mammillae, the presence of erosion or abrasion marks in the outer surface, and the presence of a secondary calcite layer in the outer surface.

Embryonic material from the "Paimogo clutch" is currently under study. Techniques being applied include micro-CT scanning of eggs and embryos and synchrotron radiation micro-CT imaging. A single new skeletal element, an undetermined distal part of a long bone, was also recovered during the preparation of the jacket.

Sediment Sampling: Understanding the Rocks

Sedimentary rocks are compounded by clasts or grains of different sizes, with the amount of each size represented being controlled by the energy of their transport and deposition (Brookfield 2004). In a broad sense, the grain size of siliciclastic sediments reflects the hydraulic energy of the environment: coarser sediments are transported and deposited by faster flowing currents than finer sediments (Tucker 2003). The particles in a flow are transported in three modes, traction (rolling always in contact with the surface), saltation (jumping like a ballistic movement), and suspension (floating inside the water mass), which have been studied in some detail from a theoretical and mathematical viewpoint (Visher 1969; Allen 1982). This fact enables classification of the sediments on the basis of their grain population statistics, which is useful in interpretation (e.g., median, mean, sorting, and skewness) of the former flow (Syvitski 1991; Selley 2000; Brookfield 2004). According to Syvitski (1991), depositional processes and environments control the shape of the central portion of the sediment grain-size distribution, as given by the standard deviation (SD). In this way, we can represent the sediment characteristics as a graph that provides a specific "portrait" of each kind of deposit (Fig. 6).

Grain-size analyses provide quantitative information when a comparison of the character of sediments deposited in a known environment is required (Nichols 2009). Curves with the same statistical distribution (mean and standard deviation) are characteristic of the same sedimentary processes (Syvitski 1991). Beyond simple summaries, it is useful to compare sediments and attempt to explain the differences as a consequence of distinct sedimentary events (McLane 1995). The joint representation of grain-sized curves should indicate a grouping of the sediments deposited under the same energy conditions and differing groups related with small variations in the flux of energy during sedimentary events (Fig. 6).

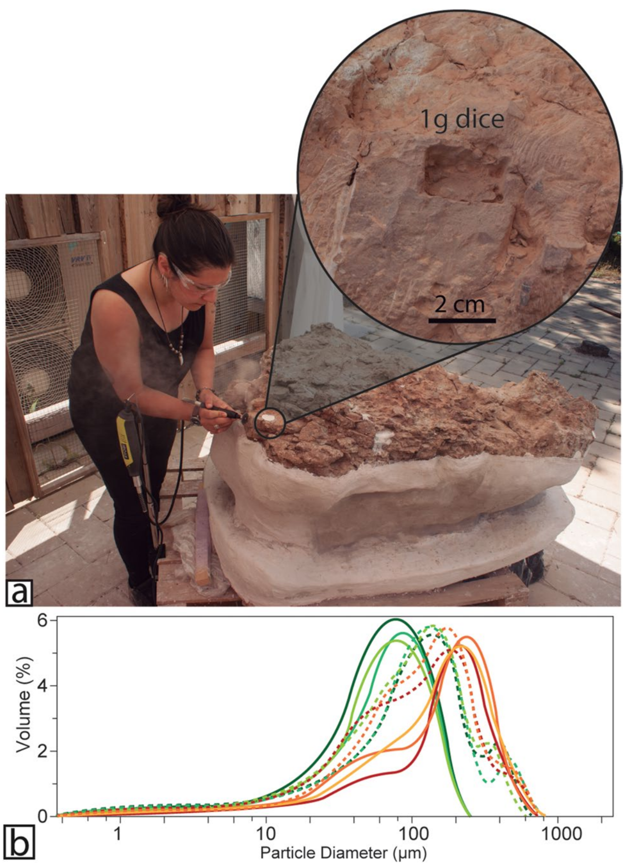

Fig. 6 **a** Samples being taken of the grain-size particles using an electric saw to obtain standard specimens (magnification shows a detail of the damage sustained before final surface preparation). **b** Plotted different grain-size analyses showing the different transport styles and energy of the flows

The grain size of conglomerates and breccias (coarser grain-sized rocks) can be measured accurately in the field with a tape measure, and sands and silts (medium-sized sediments) can be studied adequately with a sieve-pipette or optical microscope, whereas fine silts and muds (finer materials) can only be analyzed with laser diffractometry. Laser grain-size analysis consists of measuring the angle of the diffracted light when a particle cuts a ray, with the angle increasing with decreasing particle size (Syvitski 1991; Beuselinck et al. 1998). The sediments have to be disaggregated in a liquid to isolate the individual grains and be put into a test tube. While the liquid flows through the glass cell, a laser targets the sample, diffracting in an angle that can be correlated with grain size.

In this study, considering the dimensions and the homogeneous lithology of the Paimogo outcrop, the grain-size distribution allows to differentiate several stratigraphic levels as either belonging to the same sedimentary episode or not. Since most of the blocks and field outcrops show unclear sedimentary limits, establishing a nesting structure or a sedimentary accumulation of eggs is very complex. Thus, we used grain-size analyses in order to better characterize the energy and timing of the sedimentation. The sampling was based on small broken, scraped, and cut rock fragments (1 g in weight) which were extracted using hammers, chisels, and rotatory saws (Fig. 6). The protocol was focused on obtaining several samples of different heights and spatial positions, resulting in a total of 41 samples that cover 7 vertical profiles with 5 samples on average per profile. The particle size distribution of samples was determined using a Beckman Coulter LS 13 32,085 laser diffraction particle size analyzer in the IPE-CSIC laboratory.

Geochemical and Mineralogy Sampling: the Signature of Life and Fossilization

Despite an apparent fragility, dinosaur eggshells are composed of ca. 95% $CaCO_3$, accounting for a high preservation potential of these materials. The chemical signature in non-altered calcium carbonate eggshell thus offers useful paleoenvironmental and paleobiological information. In the last decades, geochemical analysis of dinosaur eggshells has seen significant advances due to higher technical capability allied with increased scientific and public interest in this rare and exciting paleoenvironmental archive (Cojan et al. 2003; Bojar et al. 2005, 2010; Montanari et al. 2013; Riera et al. 2013; Amiot et al. 2017; Graf et al. 2018; Montanari 2018; He et al. 2019).

Among the most widely used geochemical proxies in eggshell research, carbon and oxygen isotopic compositions have successfully informed on ingested organic materials (e.g., vegetation types, diet), drinking water (temperature, evaporation) and atmospheric carbon dioxide content (Zhao and Yan 2000; Kim et al. 2009; Montanari et al. 2013; Riera et al. 2013; Amiot et al. 2017). Complementarily, because trace elements are essential nutrients for vertebrates, the relative abundance of major and trace elements in eggshells can also be used to reconstruct main food and water sources, further used as proxies for dinosaur extinction, paleoenvironment, and paleoclimate (Weidong et al. 1996; Montanari et al. 2013). Other factors influencing the isotopic characteristics of shells, such as body temperature and species-specific vital isotopic fractionation, must also be considered.

From above, it is clear that dinosaur eggshells encompass an undeniable potential. But to ensure that only the best-preserved materials are used during paleoenvironmental research, diagenetic alteration over time has to be confidently ruled out. Ideally, geochemical signals obtained from eggshells should be compared to samples taken from other neighboring materials, namely, encasing matrix, carbonate nodules, and/or later diagenetic cements (veinlet infill). This is because non-biogenic carbonates, just as pedogenic carbonates, record the environmental conditions during their formation (Kim et al. 2009; Riera et al. 2013) and encasing matrix is highly prone to diagenetic alteration. Therefore, these alternative materials can be used to perform contrast comparisons of geochemical signatures.

In the case of the Paimogo dinosaur egg clutch, powder samples were drilled using a hand drill with 1-mm diamond drill bits (Fig. 7). The outer layer of the selected eggshells was discarded, and drilling was visually controlled to minimize contamination from other sources (matrix, glue coating, dust). Analyzed materials included eggshell material from each identified egg, making sure inter- and intra-egg variability was tested, as well as encasing terrigenous matrix and carbonate nodules. Stable isotope composition (carbon and oxygen) and elemental concentrations of Ca, Mg, Sr, Fe, and Mn (mass spectrometry and ICP-AES, respectively) were analyzed. Diagenetic influence was accessed via geochemical screening. Overall, eggshell samples were plotted within a very narrow range of values when compared to other types of samples showing a clear diagenetic signature. This suggests a high preservation of the eggshell materials. Carbonate nodule values coincide with widely reported ranges from other studies, showing considerably different values when compared to eggshell samples. A closer overview revealed only a slight degree of alteration for a small number of eggshell samples, with conspicuous higher Mn and Fe abundance. These were discarded and only best-preserved samples were considered for further paleoenvironmental interpretations.

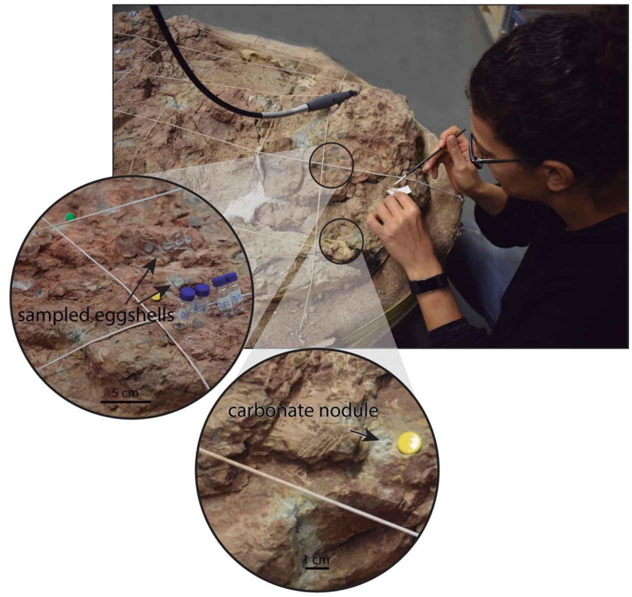

Fig. 7 **a** The sampling technique performed on several portions of shell belonging to the same egg, used to establish intra-egg geochemical variability (magnification shows the drilling site on several portions of eggshell belonging to the same egg). **b** The sampled carbonate nodule (note the distinctive gray coloration)

The study of both facies and clay mineralogy in sedimentary successions is of great interest in allowing paleoclimatic and paleoenvironmental conditions to be inferred (Velde 1995; Thiry 2000). In Mesozoic and Cenozoic sequences of continental materials, which include paleosol developments, the variations in clay mineral assemblages have been widely used as paleoclimatic and paleoenvironmental proxies (Do Campo et al. 2010, 2018; Bauluz et al. 2014; and references therein). Notably, paleosols are formed in direct contact with the atmosphere, and thus the clay minerals that formed during that development can be correlated with climatic and paleoenvironmental factors such as temperature, water availability during pedogenesis, and vegetation cover, which controls chemical weathering (Varela et al. 2018). Vertisols are a specific type of paleosol characterized by the presence of expansive clay minerals, and have been reported to have a role in the post-sedimentary modification of nesting grounds (Jackson et al. 2013), so a clay mineral study is key to characterize any egg accumulation.

In this work, 28 small clay-rock samples (1 g) were taken along the grid of ML656-B. We used X-ray diffraction and optical and electron microscopy to undertake a mineralogical and textural characterization of the clay-rich matrix: (i) to characterize sedimentary (in situ vs. detrital) and diagenetic minerals; (ii) to establish the variation of in situ clay mineral assemblages and the paleoenvironmental conditions under which they were formed; (iii) to characterize the formation conditions, in particular temperature/humidity; and (iv) to rule out the presence of expansive clay minerals that may have altered the original distribution of the eggs within the assemblage.

Magnetic Susceptibility Study: Revealing the Hidden Signal

The anisotropy of magnetic susceptibility (AMS) is a physical property of rocks which is based on characterizing the intrinsic magnetic susceptibility and degree of preferred orientation of the individual magnetic minerals (Chadima et al. 2006). The magnetic minerals can be classified into three main groups (Tarling and Hrouda 1993), depending on their behavior under an external magnetic field, as diamagnetic (negative susceptibility), paramagnetic (positive susceptibility), and ferromagnetic (higher positive susceptibility and remnant magnetization after withdrawing an external field). The ASM technique is based on the measurement of the directional variations of susceptibility in a standard volume of rock when a weak magnetic field ($\leq 1\eta T$) is applied in different directions (Rees et al. 1982; Rochette et al. 1992; Borradaile and Henry 1997; Cifelli et al. 2009). Thus, we can express this physical parameter as an ellipsoid whose principal axes represent the three principal susceptibilities' axes, resulting from the sum of the whole of the magnetic minerals in a rock ($K1_{(max)} \geq K2_{(int)} \geq K3_{(min)}$; Baas et al. 2007). Thus, the magnitude ellipsoid represents the magnetic grain's preferred orientation in the sample and the strength of the preferred alignment (Park et al. 2013).

AMS determines susceptibility distribution, which can be used as a nearly nondestructive method to determine sedimentary grain orientation (Fig. 8a–b), since only small drillings are needed to extract rock samples. This technique allows us to discriminate any sedimentary reworking or deformational processes which may affect the sediments. When deposition occurs in standing water, the magnetic fabric is planar, characterized by gravity-induced settling with minimum susceptibility axes of magnetic grains oriented perpendicular to the depositional plane, within which maximum and intermediate susceptibility axes are uniformly dispersed. The magnetic fabric of sediments deposited under the action of flowing water is typified by a current-oriented magnetic foliation plane (Ellwood and Whitney 1980; Lowrie and Hirt 1987; Schwehr et al. 2007; Pueyo-Anchuela et al. 2012; Novak et al. 2014; Felletti et al. 2016, see Fig. 8b). Syndepositional or early post-depositional soft-sediment deformation (load cast, clastic dykes, slump, etc.) and the modifying effect of organisms (footprints, burrowing, etc.) are usually considered to be shaping processes of primary fabrics, although it is important to realize that these processes may significantly alter the original sedimentary fabric, resulting in oriented or disrupted fabrics (Hiscott and Middleton 1980).

Fig. 8 **a** One side of the fossil block after AMS core sampling (details show the drilling techniques). **b** Image from the optical petrographic microscopy in which the ferro- and paramagnetic are oriented, forming a magnetic fabric

The mudstone lithology of the Paimogo clutch is ideal for these kinds of studies due to its great richness in phyllosilicates, which, in general, are paramagnetic and ferromagnetic minerals. Thus, we used an AMS analysis to perform a better characterization of the egg accumulation and distribution within the Paimogo clutch, through understanding the origin and history of the sediments. The block was sampled in order to analyze the spatial magnetic fabric variations that could be related with sedimentary or biological processes. To develop these kinds of studies, standard-sized specimens are necessary (rock cylinders of 2.2 cm in height and 2.5 cm in diameter), and the longest possible cores are always drilled. Then, the cores are cut in the laboratory to obtain the maximum number of standard specimens, allowing more measurements and more accurate data.

The sampling protocol was focused on drilling several oriented cores at different heights, resulting in a total of 81 cores, with 30 cores on average per side (Fig. 8a). The cores were obtained with an electric drill and a hollow cylindrical drill bit, 2.5 cm in diameter, which facilitates the subsequent laboratory procedures. The body of the drill bit is made of stainless steel with a diamond head and a water-cooling system, to avoid disturbances due to heating or foreign magnetic minerals while drilling (Fig. 8a). All the samples were oriented with two parameters, azimuth and immersion, which together with the axis of the sample enable the spatial reconstruction in the laboratory. For this, and to again avoid any disturbances due to strange magnetic minerals, an aluminum bronze sample guider (inclinometer with compass) was used to reference the samples (Fig. 8a). Finally, the magnetic susceptibility was measured with a KLY-3S susceptometer in the University of Zaragoza.

Results: Exhibit Design

Once the vastness of the applied scientific methodologies used was fully realized, it was immediately expounded upon by its great potential for public education and opportunity for the dissemination of collaborative science. Therefore, a strategy was made to showcase and best communicate all of the intricacies of the various processes to the general public in a dynamic way. Although all of the above methodologies have been previously applied to fossil specimens, some of them (AMS, extensive, semi-destructive egg-by-egg geochemical sampling) were used here for the first time on fossil eggs. Thus, the main novelty of this project was the more holistic approach to the specimen, showcasing paleontology as a discipline which lays in the intersection of geology and biology (among other sciences), and requiring the analytical inputs common to both disciplines. The Paimogo egg clutch represents a recognizable, iconic fossil, with an important link to the history of paleontology in Portugal, and the resulting newly prepared specimen also shows an objective esthetic value, standing as an exemplary museum piece worthy of exhibition. Therefore, it offered the opportunity to transfer new knowledge to the public, both showcasing the peculiarities and fossil history of the specimen itself and, perhaps more interestingly, the methods used to reveal that history.

As the exhibition of the Museu da Lourinhã is currently split between two exhibition venues—the ML itself, and the exhibition hall at the DPL—and furthermore, with the ongoing momentum of the Aspiring Geoparque Oeste project, portable exhibits are highly in need to demonstrate the geological heritage of the area within the limits of the future Geopark and outside that area as a marketing resource. Thus, the requirements of the exhibit were as follows: (i) a small, versatile, modular exhibition was preferred; (ii) the newly prepared specimen should be the central piece of the exhibition; (iii) it had to work both as a standalone exhibition and as a part of a larger exhibit, in coherence with other specimens of the same assemblage that are currently on exhibit at the DPL.

With these concepts in mind, an itinerant exhibition was designed with the narrative "how many questions can a fossil answer?". The exhibit comprises a showcase that contains the specimen itself (protected by glass) with four interpretative panels on its sides, and four double-sided movable surrounding walls that provide space for additional interpretative elements (Fig. 9). In its standard display mode, the exhibition is organized with the showcase in the middle, and the four panels facing each side of the showcase, with a 2.5-m gap in between. In this format, and assuming a 1.5-m space between the exhibition panels and the walls of the exhibition hall itself, the exhibition would occupy a total space of 100 m^2, which could alternately be reduced up to 60 m^2, if needed.

On the external face of each of the four moveable surrounding walls, general information about the Paimogo clutch and the exhibit is provided: one wall contains the title of the exhibit and a brief summary that acts as an invitation to enter the space, together with the exhibition credits; the second wall contains the history of the Paimogo clutch and gives context on the importance of the fossil; the third

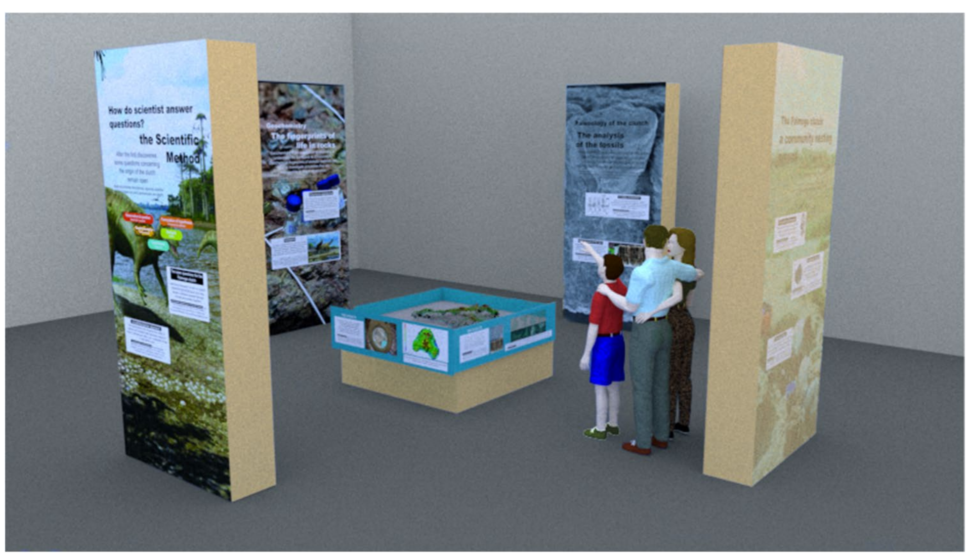

Fig. 9 A visualization of the new itinerant museum exhibition created to detail the vast array of scientific methodologies used in the current study, and elaborating the ongoing study history of the Paimogo dinosaur egg clutch

external wall introduces the fundamentals of the scientific method, and how hypotheses are tested; and the final wall includes assorted pictures and explanations of the general preparation procedure.

Once inside the exhibit space, each side of the central showcase corresponds to one of the surrounding interior sides of the exterior walls, both spatially and in content. Each interior side of the moveable surrounding walls introduces a scientific discipline and methodology, and the corresponding lateral panel of the showcase explains how this method was specifically used in the case of the Paimogo clutch and what we learned using that approach. These four sets of surrounding walls with their corresponding sides of the showcase describe: (i) the paleoology of the clutch, focusing on the eggs, eggshell, and embryos; (ii) the magnetic properties of minerals, focusing on AMS and describing the 3D spatial arrangement of the eggs; (iii) geochemistry, and the role of isotopes on inferring paleodiets, paleotemperatures, and motherhood of the eggs; (vi) the final preparation of the clutch, describing the last steps to leave the fossil preserved and archived, ready for its future storage and potential study going forward. Information is organized in this manner so that a visitor is not necessarily forced to experience the display in a specific order, but rather to encourage visitors to select for themselves the section that they are entering, and immerse themselves in the individual scientific methodologies without missing any information.

The walls and showcase of the exhibit are constructed with materials that make any necessary replacement of information easy, as the individual elements are all sized to fit the general design of the exhibits of the ML and the DPL and can endure extensive transport. The basic template for the exhibit was also built with the flexibility of potential further improvements to the exhibit in mind, including the possibility of adding interactive elements such as gamified displays and interactive screens. The 3D models created and made available through this study could also provide the potential opportunity to recreate the exhibition online, using the web pages of the institutions involved to allow for a virtual visit to this iconic specimen, or even have published models within the layout of an interactive webpage from well-established online visualization platforms, using customized embedding tools. These platforms offer further means for visualization to the public via mobile apps, including VR and AR, with powerful online tools for precise measurements and high-resolution screenshot exports, to mention just a few further options.

Providing digital content is particularly relevant during times of unforeseen museum closings, which highly impact in-person museum attendance. Online access would allow unobstructed museological interaction to a much wider, international audience, also accommodating difficult circumstances like those created by situations such as global pandemics (Pennisi 2020). These digital initiatives aim to potentially bring more visitors to the museum overall, at the same time as they increase its accessibility.

Conclusion

The Paimogo dinosaur egg clutch still remains one of the most important and iconic fossils of Portugal since its discovery, and keeps continually providing new valuable scientific information, even more than 20 years after its collection. There was a time where paleontological studies were merely descriptive, and the amount of information retrieved was considerable for such a superficial approach; however, as the range of tools available for modern paleontologists keeps growing exponentially, and new interdisciplinary methodologies develop, it becomes essential to bring new perspectives to scientific questions, old and new. Public curiosity and consumption often operate in tandem with these advances, and so new museographical resources must be innovated, to keep the museum visitor experience engaging, and also add new value to already-precious specimens. The new exhibition resource designed here accomplishes just this, taking a beloved Portuguese specimen, and representing it anew as an itinerant exhibit that introduces the new scientific methods used in paleontology, and presents paleontological research as the crossroads of multiple disciplines that it has become today.

The holistic approach used here in the study of one mostly unaltered specimen from the original Paimogo egg assemblage, together with a new analysis of the original locality, has provided a large source of information that will be studied in the forthcoming years. The "Paimogo clutch" is a paradigmatic case of the importance of preserving unaltered, unprepared samples of every paleontological intervention, in order to save information that can be gathered later as the field develops further. With this in mind, an additional large specimen remains stored in the collections of the Museu da Lourinhã, to be revisited in the next decades and indubitably answer more questions to satisfy the evolving curiosity of many future publics.

The Museu da Lourinhã, and especially its paleontological collection, started as the initiative of amateur collectors to protect and catalog the astonishing paleontological heritage of a small locality. In the last 30 years, scientific knowledge emerging from the ML collections has exponentially grown, improving the exhibitions of both ML and PDL. Resources that educate the public on how this knowledge is acquired increase the didactic value of the exhibits and help to promote a more accurate role model of the paleontologists, outside of classical, less desirable stereotypes.

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References

Allen JRL (1982) Sedimentary structures: their character and physical basis. Elsevier, New York

Alonso-Zarza AM, Aurell M, Carcavilla L, Corral I, Crespo-Blanc A (2016) Geolodía! Geoscientist 2016:17–19

Amiot R, Wang X, Wang S, Lécuyer C, Mazin J-M, Mo J, Flandrois J-P, Fourel F, Wang X, Xu X, Zhang Z, Zhou Z (2017) δ^{18}O-derived incubation temperatures of oviraptorosaur eggs. Palaeontology 60:633–647

Antczak M (2020) Are fossils enough? Palaeontological tourism based on local dinosaur discoveries. Geogr Tour 8(2):15–27

Antunes MT, Mateus O (2003) Dinosaurs of Portugal. CR Palevol 2(1):77–95

Antunes MT, Taquet P, Ribeiro V (1998) Upper Jurassic dinosaur and crocodile eggs from Paimogo nesting site (Lourinhã-Portugal). Memórias Da Academia De Ciências De Lisboa 37:83–100

Baas JH, Hailwood EA, McCaffrey WD, Kay M, Jones R (2007) Directional petrological characterisation of deep-marine sandstones using grain fabric and permeability anisotropy: methodologies, theory, application and suggestions for integration. Earth-Science Review 82:101–142

Bauluz B, Yuste A, Mayayo MJ, Canudo JI (2014) Early kaolinization of detrital Weald facies in the Galve sub-basin (Central Iberian Chain, north-east Spain) and its relationship to palaeoclimate. Cretac Res 50:214–227

Beuselinck L, Govers G, Poesen J, Degraer G, Froyen F (1998) Grain-size analysis by laser diffractometry: comparison with the sieve-pipette method. CATENA 32:193–208

Black G (2005) The engaging museum: developing museums for visitor involvement. Taylor & Francis, London

Bojar A-V, Grigorescu D, Ottner F, Csiki-Sava Z (2005) Palaeoenvironmental interpretation of dinosaur- and mammal-bearing continental Maastrichtian deposits, Hateg basin, Romania. Geol Q 49:205–222

Bojar A-V, Csiki-Sava Z, Grigorescu D (2010) Stable isotope distribution in Maastrichtian vertebrates and paleosols from the Hateg Basin, South Carpathians. Palaeogeogr Palaeoclimatol Palaeoecol 293:329–342

Borradaile GJ, Henry B (1997) Tectonic applications of magnetic susceptibility and its anisotropy. Earth -Science Reviews 42:49–93

Brookfield ME (2004) Principles of stratigraphy. Blackwell Publishing Ltd, Oxford

Brown MA, Kane JF, Parker WG, (eds) (2009) Methods in preparation: proceedings of the first annual fossil preparation and collections symposium; April 2008; Petrified Forest. http://preparation.paleo.amnh.org/assets/FPCSvolume-Final.pdf

Cerda IA, Pol D, Chinsamy A (2014) Osteohistological insight into the early stages of growth in Mussaurus patagonicus (Dinosauria, Sauropodomorpha). Hist Biol 26(1):110–121

Chadima M, Pruner P, Šlechta S, Grygar T, Hirt AM (2006) Magnetic fabric variations in Mesozoic black shales, northern Siberia, Russia: possible paleomagnetic implications. Tectonophysics 418:145–162

Choi S, Han S, Kim N-H, Lee Y-N (2018) A comparative study of eggshells of Gekkota with morphological, chemical compositional and crystallographic approaches and its evolutionary implications. PLoS ONE 13(1–31):e0199496. https://doi.org/10.1371/journal.pone.0199496

Choi S, Han S, Lee Y-N (2019) Electron backscatter diffraction (EBSD) analysis of maniraptoran eggshells with important implications for microstructural and taphonomic interpretations. Palaeontology 62:777–803. https://doi.org/10.1111/pala.12427

Chicone SJ, Kissel RA (2013) Dinosaurs and dioramas: creating natural history exhibitions. Left Coast Press, Walnut Creek

Cifelli F, Mattei M, Chadima M, Lenser S, Hirt AM (2009) The magnetic fabric in “undeformed clays”: AMS and neutron texture analyses from the Rif Chain (Morocco). Tectonophysics 466:79–88

Cobos A, Alcalá L, Royo-Torres R (2020) The dinosaur route in El Castellar (Teruel, Spain): palaeontology as a factor of territorial development and scientific education in a sparsely inhabited area. Geoheritage 12:52. https://doi.org/10.1007/s12371-020-00474-3

Cojan I, Renard M, Emmanuel L (2003) Palaeoenvironmental reconstruction of dinosaur nesting sites based on a geochemical approach to eggshells and associated palaeosols (Maastrichtian, Provence Basin, France). Palaeogeogr Palaeoclimatol Palaeoecol 191:111–138

Cooke SJ, Gallagher AJ, Sopinka NM, Nguyen VM, Skubel RA, Hammerschlag N, Boon S, Young N, Danylchuk AJ (2017) Considerations for effective science communication. Facets 2(1):233–248

Cunha PP, Mateus O, Antunes MT (2004) The sedimentology of the Paimogo dinosaur nest site (Portugal, Upper Jurassic). In: Pena dos Reis R, Callapez P, Dinis P, eds. Abstracts Book: 23rd IAS Meeting of Sedimentology; 2004 September 15–17; Coimbra. Imprensa de Coimbra, Lda, Coimbra. p. 93

Dantes PM, Moratella JJ, Hirsch KF, Santos VF (1992) Mesozoic Reptile eggs from Portugal, new data. Second Georges Cuvier Symposium, Abstracts. Montbeliard, France

Davidson A, Brown GW (2012) Paraloid™ B-72: practical tips for the vertebrate fossil preparator. Collection Forum 26(1–2):99–119

Díaz-Martínez I, Citton P, de Valais S, García-Ortiz E (2018) La fotogrametría se convierte en una poderosa herramienta para la conservación y difusión del patrimonio paleontológico. Revista PH 94:20–22

Do Campo M, del Papa C, Nieto F, Hongn F, Petrinovic I (2010) Integrated analysis for constraining palaeoclimatic and volcanic influences on clay-mineral assemblages in orogenic basins (Palaeogene Andean foreland, Northwestern Argentina). Sed Geol 228:98–112

Do Campo M, Bauluz B, del Papa C, White T, Yuste A, Mayayo MJ (2018) Evidence of cyclic climatic changes recorded in clay mineral assemblages from a continental Paleocene-Eocene sequence, northwestern Argentina. Sediment Geol 368:44–57

Ellwood BB, Whitney JA (1980) Magnetic fabric of the Elberton granite, Northeast Georgia. J Geophys Res Solid Earth 85:1481–1486

Felletti F, Dall'Olio E, Muttoni G (2016) Determining flow directions in turbidites: an integrated sedimentological and magnetic fabric study of the Miocene Marnoso Arenacea Formation (northern Apennines, Italy). Sed Geol 335:197–215

Findlen P (2012) The museum: its classical etymology and Renaissance genealogy. In: Carbonell BM (ed) Museum studies: an anthology of contexts, 2nd edn. Blackwell Publishing, London, pp 23–45

Gibbons A (1998) Theropod in progress. Discover 19(1):50

Goos M, Arntz M, Zierahn U, Gregory T, Carretero Gómez S, González Vázquez I, Jonkers K. The impact of technological innovation on the future of work [Internet]. Seville: European Commission, 2019 March [cited 2021 January 9]. 48 p. Available from: https://ec.europa.eu/jrc/sites/jrcsh/files/jrc117212.pdf

Graf J, Tabor NJ, Ferguson K, Winkler DA, Lee Y-N, May S, Jacobs LL (2018) Diagenesis of dinosaur eggshell from the Gobi Desert, Mongolia. Palaeogeogr Palaeoclimatol Palaeoecol 494:65–74

He Q, Jiang Q, Xing L, Zhang S, Pang W, Hu H, Lu S, Yin Q (2019) Geochemical characteristics of newly discovered Elongatoolithidae eggs from the Upper Cretaceous of Jiangxi Province, southern China: palaeoenvironmental and palaeoclimatic inferences. Cretac Res 99:352–364

Hendrickx C, Mateus O (2014) Torvosaurus gurneyi n. sp., the largest terrestrial predator from Europe, and a proposed terminology of the maxilla anatomy in nonavian theropods. PLoS One 9(3):1–25. https://doi.org/10.1371/journal.pone.0088905

Hiscott RN, Middleton GV (1980) Fabric of coarse deep-water sandstones, Tourelle Formation, Quebec, Canada. J Sediment Petrol 50:703–722

Horie V (2010) Materials for conservation, second edition: organic consolidants, adhesives and coatings. Butterworth-Heinemann, London

Jackson FD, Schmitt JG, Oser SE (2013) Influence of vertisol development on sauropod egg taphonomy and distribution at the Auca Mahuevo locality, Patagonia, Argentina. Palaeogeogr Palaeoclimatol Palaeoecol 386:300–307. https://doi.org/10.1016/j.palaeo.2013.05.031

Kim C-B, Al-Aasm IS, Ghazban F, Chang H-W (2009) Stable isotopic composition of dinosaur eggshells and pedogenic carbonates in the upper Cretaceous Seonso Formation, South Korea: Paleoenvironmental and diagenetic implications. Cretac Res 30:93–99

Lapparent AF, Zbyszewski G (1957) Les dinosauriens du Portugal. Services Géologiques du Portugal, Mémoire n.2, Lisbon

Lowrie W, Hirt AM (1987) Anisotropy of magnetic susceptibility in the Scaglia Rossa pelagic limestone. Earth Planet Sci Lett 82:349–356

Mallison H, Wings O (2014) Photogrammetry in paleontology – a practical guide. J Paleontol Tech 12:1–31

Mateus O (2005) Dinossauros do Jurássico Superior de Portugal, com destaque para os saurísquios. Dissertation, Universidade Nova de Lisboa

Mateus O, Antunes MT, Taquet P (2001) Dinosaur ontogeny: the case of *Lourinhanosaurus* (Late Jurassic, Portugal). J Vertebr Paleontol 21(supplement to 3):78A

Mateus I, Mateus H, Antunes MT, Mateus O, Taquet P, Ribeiro V, Manuppella G (1997) Couvée, oeufs et embryons d'un Dinosaure Théropode du Jurassique superieur de Lourinhã (Portugal). C R Acad Sci Ser IIA Earth Planet Sci 325:71–78

Mateus I, Mateus H, Antunes MT, Mateus O, Taquet P, Ribeiro V, Manuppella G (1998) Upper Jurassic theropod dinosaur embryos from Lourinhã (Portugal). Memórias Da Academia De Ciências De Lisboa 37:101–109

McLane P (1995) Sedimentology. Oxford University Press, New York

McMillan AA (2008) The role of the British Geological Survey in the history of geoconservation. In: Burek CV, Prosser CD (eds) The History of Geoconservation, vol 300. Geological Society Special Publications, London, pp 103–112

Micheletti N, Chandler JH, Lane SN (2015) Structure from motion (SfM) photogrammetry. In: Cook SJ, Clarke LE, Nield JM (eds) Geomorphological Techniques, Online. British Society for Geomorphology, London, pp 1–12

Miles J (2020) Computational photography. In: López-Varela SL (ed) The encyclopedia of archaeological sciences. Wiley Online Library, pp 1–5

Montanari S (2018) Cracking the egg: the use of modern and fossil eggs for ecological, environmental and biological interpretation. R Soc Open Sci 5:1–14

Montanari S, Higgins P, Norell MA (2013) Dinosaur eggshell and tooth enamel geochemistry as an indicator of Mongolian Late Cretaceous paleoenvironments. Palaeogeogr Palaeoclimatol Palaeoecol 370:158–166

Moreno-Azanza M, Bauluz B, Canudo JI, Gasca JM, Torcida Fernández-Baldor F (2016) Combined use of electron and light microscopy techniques reveals false secondary shell units in Megaloolithidae Eggshells. PLoS ONE 11:1–17. https://doi.org/10.1371/journal.pone.0153026

Moreno-Azanza M, Mariani E, Bauluz B, Canudo JI (2013) Growth mechanisms in dinosaur eggshells: an insight from electron backscatter diffraction. J Vertebr Paleontol 33:121–130. https://doi.org/10.1080/02724634.2012.710284

Nichols G (2009) Sedimentology and Stratigraphy, 2nd edn. Wiley-Blackwell, New York

Novak B, Housen B, Kitamura Y, Kanamatsu T, Kawamura K (2014) Magnetic fabric analyses as a method for determining sediment transport and deposition in deep sea sediments. Mar Geol 356:19–30

Park ME, Cho H, Son M, Sohn YK (2013) Depositional processes, paleoflow patterns, and evolution of a Miocene gravelly fan-delta system in SE Korea a constrained by anisotropy of magnetic susceptibility analysis of interbedded mudrocks. Mar Pet Geol 48:206–223

Pennisi E (2020) Shuttered natural history museums fight for survival. Science 368(6495):1042–1043

Prior DJ, Boyle AP, Brenker F, Cheadle MC, Day A, Lopez G, Peruzzi L, Potts G, Reddy S, Spiess R, Timms NE, Trimby P, Wheeler J, Zetterstrom L (1999) The application of electron backscatter diffraction and orientation contrast imaging in the SEM to textural problems in rocks. Am Miner 84(11–12):1741–1759

Pueyo-Anchuela O, Ramajo JC, Gil-Imaz A, Meléndes G (2012) Analysis of anisotropy of magnetic susceptibility in iron-oolitic beds: a potential tool for paleocurrent identification. Int J Earth Sci (geologische Rundschau) 102:1131–1149

Rader KA, Cain VEM (2014) Life on display: revolutionizing U.S. museums of science and natural history in the twentieth century. University of Chicago Press, Chicago

Rees AI, Brown CM, Hailwood EA, Riddy PJ (1982) Magnetic fabric of bioturbated sediment from the northern Rockall Trough: Comparison with modern currents. Mar Geol 46:161–173

Reisz RR, Scott D, Sues HD, Evans DC, Raath MA (2005) Embryos of an Early Jurassic prosauropod dinosaur and their evolutionary significance. Science 309(5735):761–764

Reisz RR, Huang TD, Roberts EM, Peng S, Sullivan C, Stein K, LeBlanc ARH, Shieh D, Chang R, Chiang C, Yang C, Zhong S (2013)

Embryology of Early Jurassic dinosaur from China with evidence of preserved organic remains. Nature 496(7444):210–214
Riera V, Anadón P, Oms O, Estrada R, Maestro E (2013) Dinosaur eggshell isotope geochemistry as tools of palaeoenvironmental reconstruction for the Upper Cretaceous from the Tremp Formation (Southern Pyrenees). Sed Geol 294:356–370
Rochette P, Jackson M, Aubourg C (1992) Rock magnetism and the interpretation of anisotropy of magnetic susceptibility. Rev Geophys 30:209–226
Schwehr K, Driscoll N, Tauxe L (2007) Origin of continental margin morphology: Submarine-slide or downslope current-controlled bedforms, a rock magnetic approach. Mar Geol 240:19–41
Selley RC (2000) Applied sedimentology. Academic Press, London
Şener S, Sarıdoğan E (2011) The effects of science-technology-innovation on competitiveness and economic growth. In: Özşahin M, ed. The Proceedings of 7th International Strategic Management Conference: Procedia - Social and Behavioral Sciences: 2011 June 30-July 2; Elsevier, Paris. Available from: https://www.sciencedirect.com/science/article/pii/S1877042811016557
Silva AM (2012) Antropologia Funerária e Paleobiologia das Populações Portuguesas (Litorais) do Neolítico Final/Calcolítico. Dissertation, Universidade de Coimbra
Siune K, Marcus E, Calloni M, Felt U, Gorski A, Grunwald A, Rip A, de Semir W, Wyatt S. Challenging features of science in society, emerging trends and cutting-edge issues [Internet]. Brussels: MASiS Expert Group, European Commission, 2009 [cited 2021 January 9]. 75 p. Available from: https://ec.europa.eu/research/science-society/document_library/pdf_06/the-masis-report_en.pdf
Spielberg S, Crichton M, Koepp D (1993) Jurassic park [motion picture]. Spielberg S, director, Kennedy K, producer. 1 reel: 127 min, sound, color, 35mm. Universal Pictures, USA
Stendardo E (2001) Ferrante Imperato: collezionismo e studio della natura a Napoli tra Cinque e Seicento. Accademia Pontaniana, Napoli
Syvitski JPM (1991) Principles, methods, and application of particle size analysis. Cambridge University Press, New York
Tarling DH, Hrouda F (1993) The magnetic anisotropy of rocks. Chapman & Hall, London
Thiry M (2000) Palaeoclimatic interpretation of clay minerals in marine deposits: an outlook from the continental origin. Earth Sci Rev 49:201–221
Treise D, Weigold MF (2002) Advancing science communication: a survey of science communicators. Sci Commun 23(3):310–322
Tucker ME (2003) Sedimentary rocks in the field. Wiley & Sons Ltd, London
Varela AN, Raigemborn MS, Richiano S, White T, Poiré AG, Lizzoli G (2018) Late Cretaceous paleosols as paleoclimate proxies of high-latitude southern hemisphere: Mata Amarilla Formation, Patagonia, Argentina. Sed Geol 363:83–95
Velde B (1995) Origin and mineralogy of clays: clays and the environment. Springer-Verlag, Berlin
Visher GS (1969) Grain-size distributions and depositional processes. J Sediment Petrol 39:1074–1106
Waldhäusl P, Ogleby C (1994) 3x3-Rules for simple photogrammetric documentation of architecture. In: Proceedings of the Symposium of the ISPRS Commission V Close Range Techniques and Machine Vision; 1994 March 1–4; Melbourne. The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences. p. 426–429
Weidong Y, Mingqing W, Nansheng C, Junya N, Hongjun T, Arakel A (1996) Element geochemical characteristics of the Cretaceous dinosaur eggshell fossils and their implications for palaeoenvironment. Chin J Geochem 15:147–152
Williams MA, McHenry MT, Boothroyd A (2020) Geoconservation and geotourism: Challenges and unifying themes. Geoheritage 12:63. https://doi.org/10.1007/s12371-020-00492-1
Wylie C (2009) Preparation in action: Paleontological skill and the role of the fossil preparator. In: Brown MA, Kane JF, Parker WG, eds. Methods in Fossil Preparation: Proceedings of the First Annual Fossil Preparation and Collections Symposium; April 2008; Petrified Forest. p. 3–12
Yilmaz HM, Yakar M, Gulec SA, Dulgerler ON (2007) Importance of digital close-range photogrammetry in documentation of cultural heritage. J Cult Herit 8(4):428–433
Zhao Z, Yan Z (2000) Stable isotopic studies of dinosaur eggshells from the Nanxiong Basin, South China. Sci China, Ser D Earth Sci 43:84–92