



## Fossil marine vertebrates of Cerro Los Quesos: Distribution of cetaceans, seals, crocodiles, seabirds, sharks, and bony fish in a late Miocene locality of the Pisco Basin, Peru

Giovanni Bianucci, Claudio Di Celma, Alberto Collareta, Walter Landini, Klaas Post, Chiara Tinelli, Christian de Muizon, Giulia Bosio, Karen Gariboldi, Anna Gioncada, Elisa Malinverno, Gino Cantalamessa, Ali Altamirano-Sierra, Rodolfo Salas-Gismondi, Mario Urbina & Olivier Lambert

To cite this article: Giovanni Bianucci, Claudio Di Celma, Alberto Collareta, Walter Landini, Klaas Post, Chiara Tinelli, Christian de Muizon, Giulia Bosio, Karen Gariboldi, Anna Gioncada, Elisa Malinverno, Gino Cantalamessa, Ali Altamirano-Sierra, Rodolfo Salas-Gismondi, Mario Urbina & Olivier Lambert (2016) Fossil marine vertebrates of Cerro Los Quesos: Distribution of cetaceans, seals, crocodiles, seabirds, sharks, and bony fish in a late Miocene locality of the Pisco Basin, Peru, *Journal of Maps*, 12:5, 1037-1046, DOI: [10.1080/17445647.2015.1115785](https://doi.org/10.1080/17445647.2015.1115785)

To link to this article: <https://doi.org/10.1080/17445647.2015.1115785>



© 2016 Giovanni Bianucci



View supplementary material [↗](#)



Published online: 10 Jan 2016.



Submit your article to this journal [↗](#)



Article views: 292



View Crossmark data [↗](#)



Citing articles: 7 View citing articles [↗](#)



## SCIENCE

# Fossil marine vertebrates of Cerro Los Quesos: Distribution of cetaceans, seals, crocodiles, seabirds, sharks, and bony fish in a late Miocene locality of the Pisco Basin, Peru

Giovanni Bianucci<sup>a</sup>, Claudio Di Celma<sup>b</sup>, Alberto Collareta<sup>a,c</sup>, Walter Landini<sup>a</sup>, Klaas Post<sup>d</sup>, Chiara Tinelli<sup>a</sup>, Christian de Muizon<sup>e</sup>, Giulia Bosio<sup>f</sup>, Karen Gariboldi<sup>a,c</sup>, Anna Gioncada<sup>a</sup>, Elisa Malinverno<sup>f</sup>, Gino Cantalamessa<sup>b</sup>, Ali Altamirano-Sierra<sup>g</sup>, Rodolfo Salas-Gismondi<sup>g</sup>, Mario Urbina<sup>g</sup> and Olivier Lambert<sup>h</sup>

<sup>a</sup>Dipartimento di Scienze della Terra, Università di Pisa, Pisa, Italy; <sup>b</sup>Scuola di Scienze e Tecnologie, Università di Camerino, Camerino, Italy; <sup>c</sup>Dottorato Regionale in Scienze della Terra Pegaso, Pisa, Italy; <sup>d</sup>Natuurhistorisch Museum Rotterdam, Rotterdam, The Netherlands;

<sup>e</sup>Département Histoire de la Terre (CR2P - CNRS, MNHN, UPMC, Sorbonne Université) Muséum national d'Histoire naturelle, Paris, France;

<sup>f</sup>Dipartimento di Scienze dell'Ambiente e del Territorio e di Scienze della Terra, Università di Milano-Bicocca, Milan, Italy; <sup>g</sup>Departamento de Paleontología de Vertebrados, Museo de Historia Natural-UNMSM, Lima, Peru; <sup>h</sup>Institut royal des sciences naturelles de Belgique, Brussels, Belgium

## ABSTRACT

One-hundred and ninety-two fossil marine vertebrate specimens, preserved as bone elements cropping out at Cerro Los Quesos (Pisco Basin, Peru), are identified and reported on a 1:4,000 scale geological map and in the corresponding stratigraphic section. All the fossils originate from the Pisco Formation, which is dated in this area to the late Miocene (from 7.55 Ma to  $\geq 6.71$  Ma, based on  $^{40}\text{Ar}/^{39}\text{Ar}$  analyses of three volcanic ash layers along the section). Specimens are particularly concentrated near the top of the two main hills, where the geologically youngest portion of the examined section crops out. The impressive fossil assemblage includes cetaceans (91.6%), represented by mysticetes (balaenopteroids and cetotheriids) and odontocetes (phocoenids, physeteroids, and ziphiids, including the holotype of *Nazcacetus urbinai*). Seals, a crocodile, a seabird, bony fish, and sharks are also reported. Isolated large teeth of *Carcharocles* and *Cosmopolitodus* are common and, in several instances, associated to mysticete skeletons. Together with a similar work recently published for the other late Miocene locality of Cerro Colorado, this work represents a case study for the detailed inventory of the extraordinary paleontological heritage of the Pisco Basin. As such, it constitutes the basis for future taphonomic, paleoecological, and systematic studies, as well as for a much-needed conservation effort.

## ARTICLE HISTORY

Received 13 August 2015  
Revised 27 October 2015  
Accepted 30 October 2015

## KEYWORDS

Paleontological heritage;  
marine vertebrates; fossils;  
Miocene; Peru

## 1. Introduction

The lower portion of the Pisco Formation crops out in the desert area of Ocucaje (Ica Region), along the southern coast of Peru. This formation is famous for its fossil marine vertebrates: the quality of the preservation as well as the concentration of specimens places this unit as one of the very best for the study of the marine Neogene (Brand, Esperante, Chadwick, Poma, & Alomía, 2004, 2011; Bianucci et al., in press; Esperante, Brand, Nick, Poma, & Urbina, 2008, 2015). The fossil assemblage of the Pisco Formation is also highly diverse, including sharks and bony fish, marine turtles, crocodiles, seabirds, baleen and echolocating toothed whales, seals, and marine sloths (see Bianucci et al., in press and reference therein).

More specifically, the Ocucaje area is characterized by the presence of several hills (named ‘cerros’) where an exceptional concentration of fossil vertebrates is observed: the best known are Cerro la Bruja (Lambert & Muizon, 2013; Lambert, Bianucci, & Beatty, 2014a), Cerro Ballena (Brand et al., 2004),

and Cerro Colorado (Bianucci, Lambert, & Post, 2010; Collareta et al., 2015; Lambert, Bianucci, & Post, 2010a, Lambert et al. 2010b, 2015a; Parham & Pyenson, 2010). Another equally important but less known fossiliferous locality of this area is Cerro Los Quesos, the type locality of the fossil beaked whale *Nazcacetus urbinai* Lambert, Bianucci, & Post, 2009.

Although a preliminary study of Cerro Los Quesos was undertaken by Esperante, Brand, Chadwick, and Poma (2015), as for other fossiliferous localities in the Ocucaje area, these authors focused their attention only on baleen whales; surprisingly, in Cerro Los Quesos they identified 42 mysticetes and only 2 pinnipeds among the other vertebrates.

With a methodology and objectives similar to those of a recently published work on the Cerro Colorado locality (Bianucci et al., in press), this study presents the first complete census of the fossil vertebrates found at Cerro Los Quesos. All specimens are reported on a geological map and a precise stratigraphical position is given for each fossil found.

## 2. Geological and stratigraphic setting

The southern portion of the forearc Pisco Basin is a 180 × 30 km elongated sedimentary basin originating from the subduction of the Nazca plate underneath the South America plates in southern Peru (e.g. Barazangi & Isacks, 1979; Cahill & Isacks, 1992; Pilger, 1981). The tertiary collision between these plates deformed the leading edge of the South American Plate and developed a composite transform-convergent margin characterized by normal and strike-slip faults that formed extensional/pull apart basins along the western margin of Peru (e.g. León, Aleman, Torres, Rosell, & De La Cruz, 2008; Thornburg & Kulm, 1981; Zúñiga-Rivero, Klein, Hay-Roe, & Álvarez-Calderon, 2010). The (East) Pisco Basin is the onshore sector of one of these basins and its fill comprises, from oldest to youngest, the Eocene Paracas Group, the late Oligocene-middle Miocene Chilcatay Formation, and the middle Miocene-Pliocene Pisco Formation (DeVries, 1998; Dunbar, Marty, & Baker, 1990). These units are bounded by regional angular unconformities recording discrete periods of subaerial exposure.

The layers of the Pisco Formation exposed at Cerro Los Quesos are at least in part younger than that of the layers farther north in Cerro Colorado (Di Celma, Malinverno, Gariboldi, et al., in press); they consist of sandstone, siltstone, and tuffaceous and diatomaceous mudstone that form a gently east-dipping monocline intensely dissected by almost-pure and oblique-slip normal faults (Rustichelli, Di Celma, Tondi, & Bianucci, 2016). Gariboldi et al. (2015) observed that a consistent number of vertebrate fossils, both from Cerro Colorado and Cerro Los Quesos, are included inside dolomitic nodules and/or have dolomite-filling bone cavities. Di Celma, Malinverno, Cantalamessa, et al. (in press) described the geology of the Cerro Los Quesos area and defined 6 informal members, designated by the letters A through F in ascending order, and 15 closely spaced marker beds allowing a higher-than-usual stratigraphic resolution and the precise stratigraphic placement of the vertebrate fossils. These marker beds were named (in ascending order) Alcatraz, Araña, Árbol, Ballena, Colibrí, Cóndor, Espiral, Estrella, Flor, Lagarto, Manos, Mono, Pájaro, Pelicano, and Perro after the geoglyphs found in the Nazca desert.

The area prospected for fossils in this study includes the main hills of Cerro Los Quesos but not all the surrounding areas investigated by Di Celma, Malinverno, Cantalamessa, et al. (in press), where the lower portion of the section crops out. Consequently, members A and B and the lowest three marker beds (Alcatraz, Araña, and Árbol) reported in Di Celma, Malinverno, Cantalamessa, et al. (in press) do not appear on the Main Map.

## 3. Chronostratigraphic framework

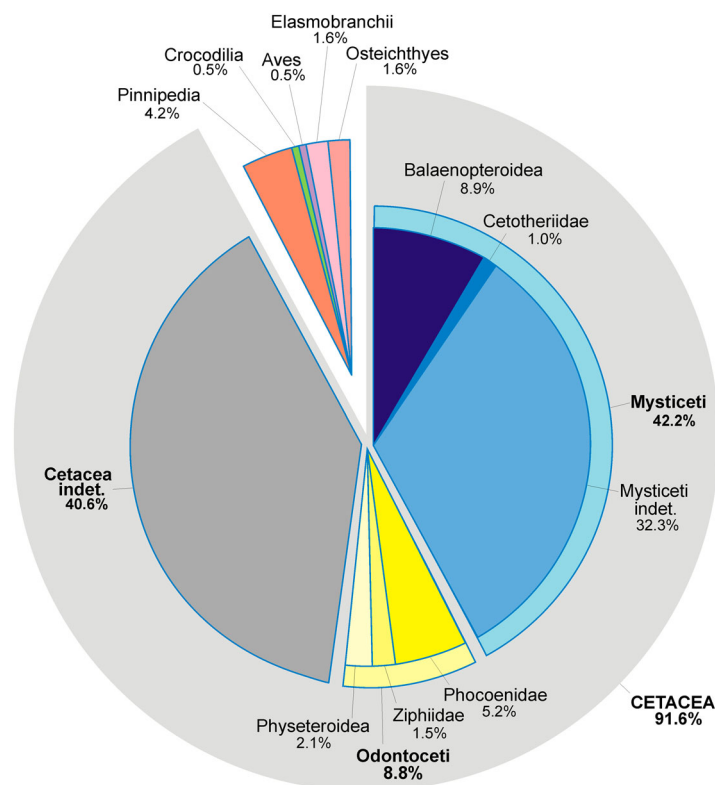
Radiometric ( $^{40}\text{Ar}/^{39}\text{Ar}$ ) dating of biotite from three volcanic ash layers of Cerro Los Quesos was published by Di Celma, Malinverno, Cantalamessa, et al. (in press). The stratigraphically lowest of the three dated tuffs, resting directly on top of the Ballena marker bed (31.4 m above the base of the section in Member C), gave an age of  $7.55 \pm 0.05$  Ma (all uncertainties are given at the 95% confidence level). The second dated volcanic ash layer is the Mono marker bed (142.3 m above the base of the section in the lower portion of Member F), which provided an age of  $6.93 \pm 0.09$  Ma. The stratigraphically higher tuff, exposed in the uppermost part of the Cerro Los Quesos section (193 m above the base), provided an age greater than or equal to  $6.71 \pm 0.02$  Ma. These ages are in agreement with those reported as ‘Kevin Nick, written communication, 2014’ by Esperante et al. (2015); these authors reported an Ar–Ar age from 7.73 to 7.11 Ma for Cerro Los Quesos, but they did not provide any information about the stratigraphical position of the dated ash layers.

Biostratigraphic analyses based on diatoms substantially agree with the radiometric ages (Di Celma, Malinverno, Cantalamessa, et al., in press). Indeed, the interval from 117.5 m to 141.3 m above the base of the section (end of Member E and base of Member F) is characterized by the co-occurrence of *Nitzschia porteri* and *Nitzschia miocenica*. The first has its last occurrence at 7.1 Ma (ages for tropical planktonic diatoms in the equatorial Pacific; Barron, 2003), whereas the latter has its first occurrence at 7.35 Ma (low-latitude diatom zonation of Barron, 1985), therefore biostratigraphically constraining this part of the section between 7.35 and 7.1 Ma (base of the *N. miocenica* zone in the low-latitude diatom zonation of Barron, 1985).

In conclusion, both radiometric dating and diatom analyses converge to indicate a late Miocene age (late Tortonian–early Messinian) for the portion of the Pisco Formation exposed in the study area, which is significantly younger than previously thought (Lambert et al., 2009).

## 4. Study area and methods

From 2006 and during seven successive field campaigns, an area of approximately 4 km<sup>2</sup> was investigated in detail at Cerro Los Quesos, Ica Region, southern coast of Peru. The methods used in the field to collect global positioning system (GPS) receiver coordinates and to establish a preliminary identification of the fossil specimens discovered are the same as in a previous work in Cerro Colorado (see Bianucci et al., in press for details). As for the latter locality, a few highly significant specimens were collected and



**Figure 1.** Quantitative composition of the fossil vertebrate assemblage from the Pisco Formation at Cerro Los Quesos, based on systematic surface prospecting. Isolated teeth of Elasmobranchii are not considered.

deposited in the Museo de Historia Natural de la Universidad Nacional Mayor de San Marcos (MUSM) in Lima for preparation, study, and curation.

All fossil vertebrate specimens discovered were reported on a 1:4,000 scale geological map; they were positioned along the newly described sequence of distinctive marker beds and with a stratigraphic accuracy from  $\pm 0.4$  to  $\pm 3$  m in a measured stratigraphic section (Di Celma, Malinverno, Cantalamessa, et al., in press) providing a framework for the spatial and temporal distribution of all data, observations, samples, and specimens collected or examined *in situ* in the course of this long-term project.

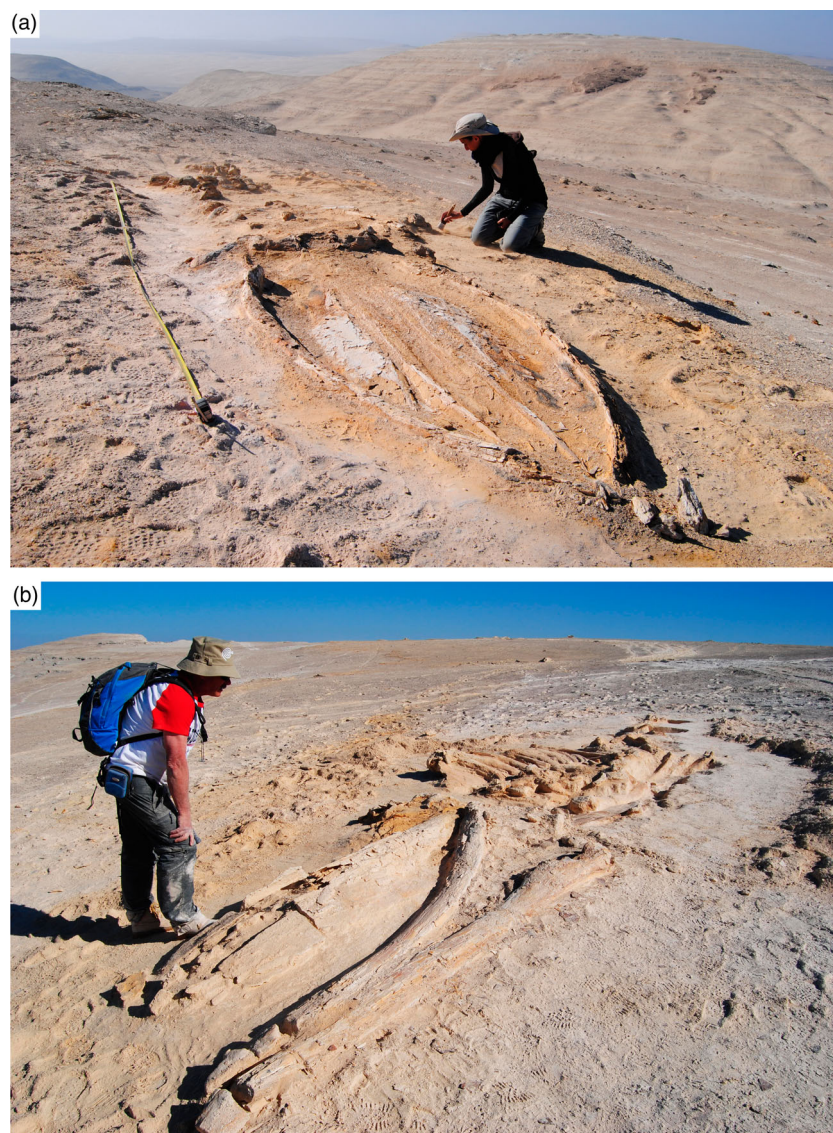
Isolated shark teeth belonging to the genera *Carcharinus*, *Carcharocles*, and *Cosmopolitodus*, in several cases strictly associated with other fossil vertebrate skeletons, were reported on the map and along the stratigraphic column as well. However, as already pointed out by Bianucci et al. (in press), it should be noted that different from other bony remains, isolated shark teeth generally do not record the death of the animal, as one shark can lose several thousand teeth in a lifetime. In addition, the concentration of exposed large shark teeth was observed to decrease significantly over the course of our subsequent field campaigns, due to their continuous looting.

A detailed taphonomic and paleoecological analysis is beyond the aims of the present work, which constitutes a starting point for further investigations and comparisons among studied localities.

## 5. Overall composition of the vertebrate assemblage

A total of 192 marine vertebrate specimens preserved as bony elements were recorded in the assemblage of Cerro Los Quesos. Cetacean remains dominate the assemblage (91.6% of the specimens), with a predominance of mysticetes (42.2%), more than four times less odontocetes (8.8%), and a relatively large number of more fragmentary specimens noted as Cetacea indet. (40.6%) due to their fragmentary state and/or to the partial burial-covering diagnostic features (Figures 1–3).

Among mysticetes, balaenopteroids are by far the most common clade at Cerro Los Quesos, with many specimens corresponding to at least partly articulated skeletons; two to three species are tentatively identified, characterized by distinct size ranges: the largest one exhibits a skull about 3 m long and an estimated body length of about 15 m; the smallest species has a skull length and estimated body length of 1.6 and 8 m, respectively; and an intermediate group of specimens, with a skull about 2.5 m long and an estimated body length of 12–13 m, could either belong to the largest species or to a third species. Although balaenopteroids represent only 8.9% of the entire vertebrate assemblage of Cerro Los Quesos, most of the indeterminate mysticete remains and most of the indeterminate cetacean remains (together representing 72.9% of the vertebrate assemblage) correspond to large-size cetaceans that more likely belong to Balaenopteroidea. Mysticetes are



**Figure 2.** Fossil vertebrates from the Pisco Formation at Cerro Los Quesos. (a) Partially articulated skeleton of a medium-size balaenopteroid mysticete. (b) Disarticulated skeleton of large-size balaenopteroid mysticete.

also represented by at least two small cetotheriid skeletons sharing similarities with *Piscobalaena nana* (Pilleri & Siber, 1989) from the latest Miocene of the Pisco Formation, in the Sacaco area (southern part of the Pisco Basin; see Bouetel & Muizon, 2006).

The odontocete assemblage consists of phocoenids (5.2%), physeteroids (2.1%), and ziphiids (1.5%). Phocoenids are represented by 10 more or less fragmentary specimens, including several abraded skulls (two of which were collected). Three of these remains show affinities with, and can tentatively be referred to, *Lomacetus ginsburgi* (Muizon, 1986), originally described from the Aguada de Lomas Level (AGL) of Sacaco area (late Miocene of the Pisco Formation; Ehret et al., 2012; Lambert & Muizon, 2013; Muizon, 1988). Physeteroids include two skulls with associated mandibles and teeth sharing similarities with (but not referable to) *Acrophyseter deionodon* (Lambert, Bianucci, & de Muizon, 2008) from Sud-Sacaco (latest Miocene, Pisco Formation). The best preserved skull was

collected and prepared and is now under study. Another skull collected belongs to a kogiid and displays some affinities with *Scaphokogia cochlearis* (Muizon, 1988) also from the AGL level of Aguada de Lomas. All ziphiid remains were collected; they are represented by one skull with associated mandibles and cervical vertebrae, described by Lambert et al. (2009) as the holotype of *N. urbinai*, and by two other specimens (an incomplete skull and mandible and a rostrum with associated mandibles), now under study, belonging to two distinct undescribed new genera and species.

Non-cetacean marine vertebrates are represented by eight partial pinniped skeletons (4.2%, family Phocidae), one partial disarticulated skeleton of a marine crocodylian (0.5%) with osetoderms very similar to those of *Piscogavialis jugaliperforatus* (Kraus, 1988) from Sud-Sacaco, one fragmentary postcranial skeleton of a *Phalacrocorax*-like seabird (0.5%), a few bones belonging to three bony fish specimens (1.6%), and



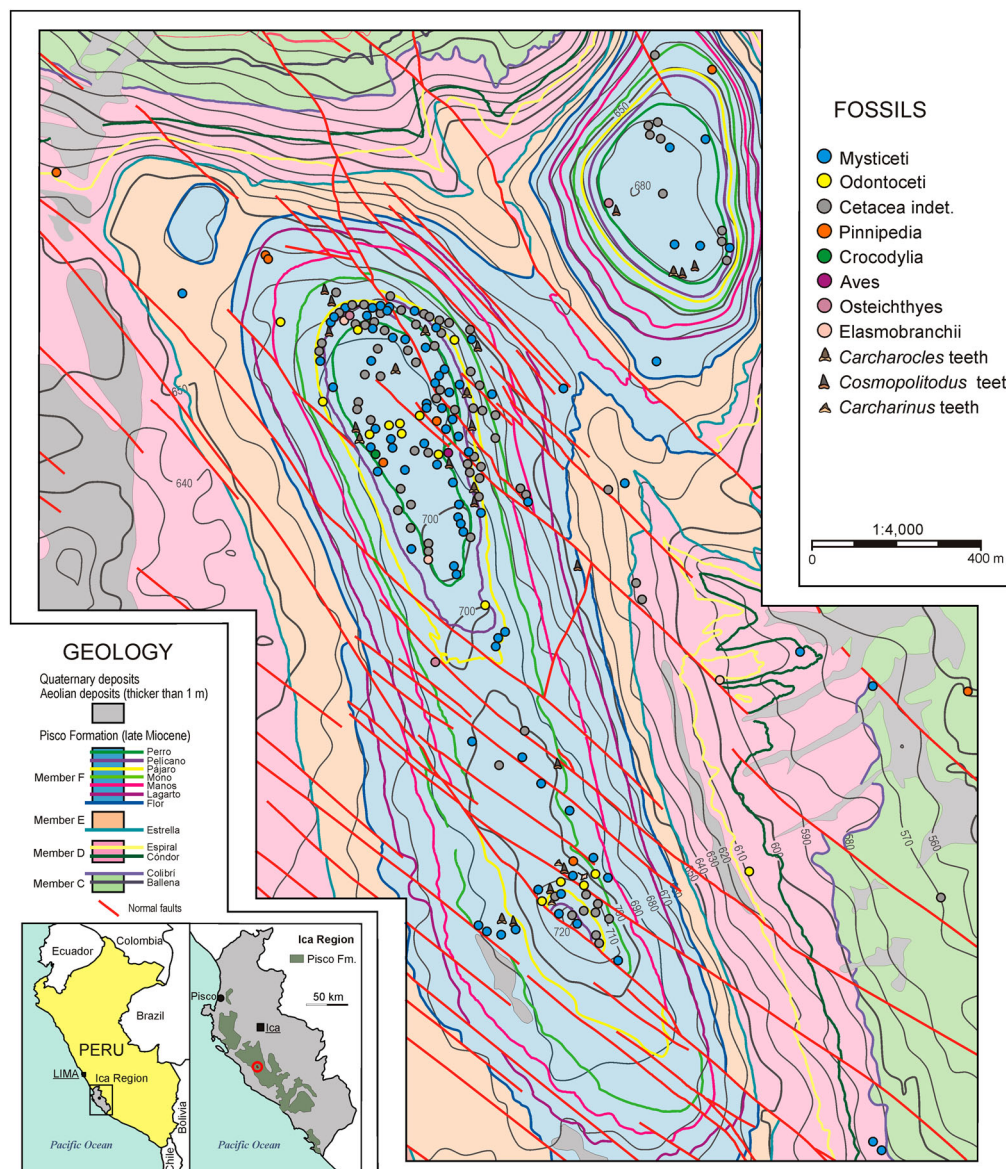
**Figure 3.** Fossil vertebrates from the Pisco Formation at Cerro Los Quesos. (a) Articulated skeleton of a large-size balaenopteroid mysticete inside a dolomitic nodule. (b) Partial articulated skeleton of a small-size balaenopteroid mysticete. (c) Portion of articulated skeleton of *Piscobalaena*-like cetotheriid mysticete. (d) Abraded skull of a *Lomacetus ginsburgi*-like phocoenid odontocete. (e) Several associated shark teeth belonging to the same individual of *C. hastalis*.

three partial skeletons with associated teeth of sharks (1.6%, two belonging to *Cosmopolitodus hastalis* and one to *Carcharinus leucas*). Isolated teeth of *Carcharocles megalodon* and *C. hastalis* are common. Teeth of *C. leucas* and of the ray *Myliobatis* sp. were found around a large balaenopteroid skeleton during its excavation.

## 6. Fossil distribution

For what concerns the spatial and vertical distribution of fossils, the most striking observation is the concentration of fossil vertebrates at the top of the two hills, where the geologically youngest portion of Member F crops out (Figure 4). Indeed, analyzing the fossil

distribution along about 200 m of section, it appears that 178 specimens (92.7% of the total) are inside Member F. Within the latter, 166 specimens (86.5% of the total) are concentrated in an interval of 40 m of sediments (140–180 m from the base of the examined section). Inside these 40 m of the section there are more than 10 peaks of concentration and in some cases the corresponding fossils appear in the field very close to each other and with similar orientations of skeletons. These peaks could represent single catastrophic-like episodes of deposition. Although only two large peaks and a third smaller peak are observable in the simplified large-scale section (Figure 5), this pattern is especially conspicuous in the detailed



**Figure 4.** Map of the investigated area of Cerro Los Quesos showing the whole fossil vertebrate distribution.

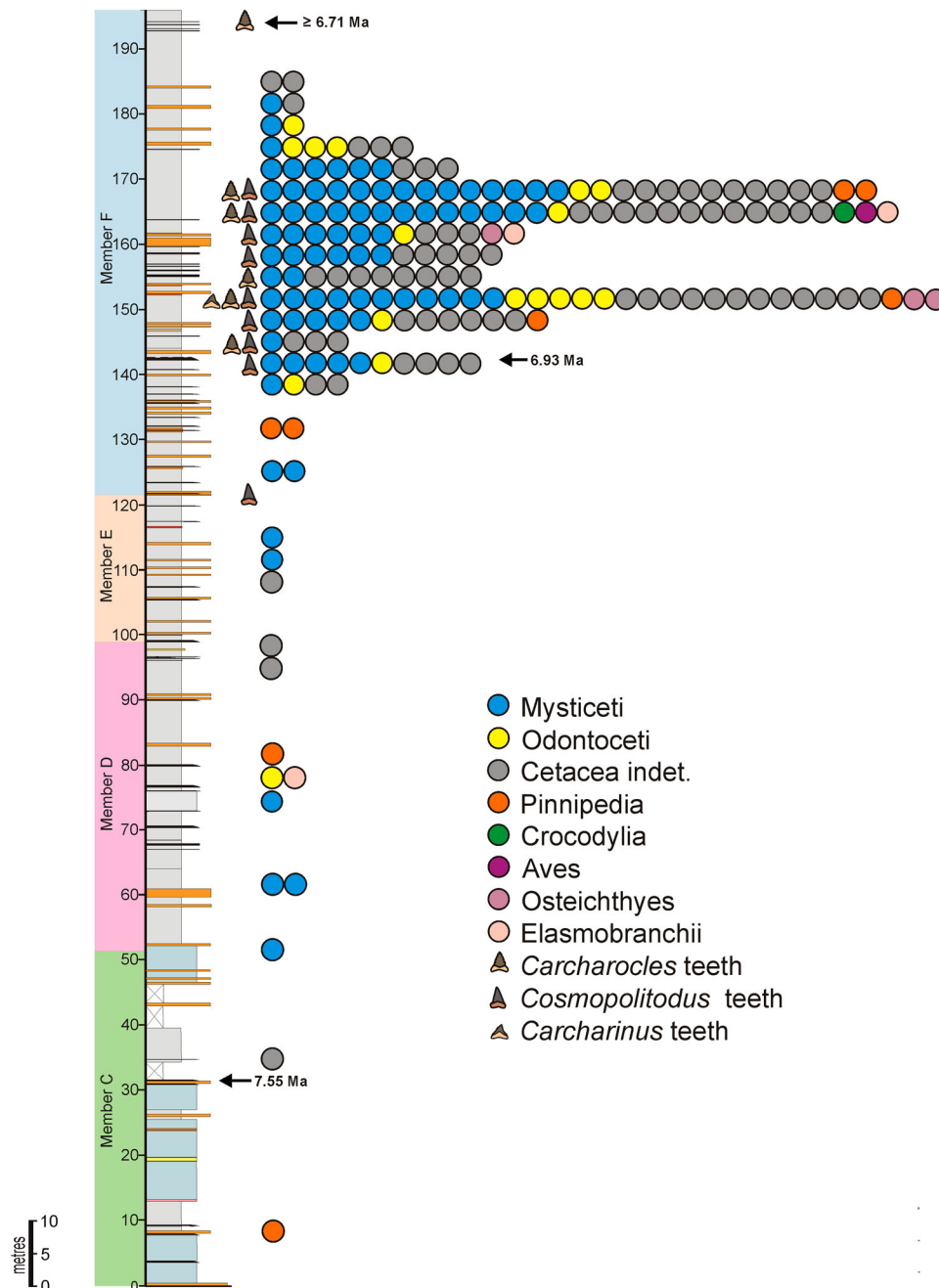
small-scale section included on the [Main Map](#). Isolated teeth of *C. megalodon* and *C. hastalis* are also common in this 40 m part of the section, with several cases associated to mysticete skeletons.

Apparently absent in the first 35 m of the examined section, the remaining fossil vertebrates are more or less uniformly distributed in the lower strata forming Members C, D, and E.

Two parameters may contribute to the non-homogeneous vertical distribution of the fossil vertebrates across the mapped area. Although a non-homogenous vertical distribution of fossils in the strata seems to be a predominant factor, the resulting distribution is also impacted by recent morphological changes in the landscape. Indeed, smaller portions of horizontally deposited skeletons are exposed along a steep slope, contrasting with less inclined outcropping surfaces. Furthermore, specimens on slopes are subject to greater erosion rates with respect to specimens on the top of the hill.

Interestingly, with the exception of a pinniped skeleton found near the base of the exposed section, all the fossils of Cerro Los Quesos were deposited during an interval time of not more than 0.84 million years, as they are all included in a 161.6 m thick interval between a lower and an upper ash layer that provided a radiometric dating of 7.55 and  $\geq 6.71$  Ma, respectively ([Di Celma, Malinverno, Cantalamessa, et al., in press](#)). Moreover, only not more than 0.22 million years separate the two uppermost ash layers (in Member F, dated to 6.93 and  $\geq 6.71$  Ma, respectively by [Di Celma, Malinverno, Cantalamessa, et al., in press](#)), for a 50.7 m thick interval.

When analyzing separately the vertical and horizontal distribution of each identified taxon, no substantial differences are observed; where fossils are abundant mysticetes remain common, whereas pinnipeds (phocids) are represented by only a few remains distributed along the whole exposed section. Two exceptions are represented by birds and crocodilians, which are both



**Figure 5.** Stratigraphic distribution of fossil vertebrates at Cerro Los Quesos.

represented by a single specimen located in the part of the section corresponding to the highest peak of fossil abundance.

## 7. Conclusions

As for the recently published paper about Cerro Colorado (the type locality of the giant raptorial sperm whale *Livyatan melvillei*), this work provides a combined quantitative and qualitative evaluation of the distribution of marine vertebrates in a fossil-rich late Miocene (late Tortonian–early Messinian) Pisco Formation locality.

The combination of a detailed geological and stratigraphic study with the prospection and mapping of fossil vertebrates allowed positioning of all the fossils

on a geological map and along the related stratigraphic section. This is the best way to provide a precise overview of the spatial and stratigraphic distribution of the 192 specimens discovered. More specifically, most of the fossils are concentrated near the top of the two hills, where proportionally larger surfaces of outcrops are available: 166 specimens (86.5%) originate from the interval between 140 and 180 m above the base of the Cerro Los Quesos section.

Based on the systematic field determination of the mapped specimens, important information on the composition of the fossil assemblage is obtained. The Cerro Los Quesos assemblage is dominated by cetaceans (91.7% of the specimens), with 42.2% of the total represented by mysticetes, 8.8% by odontocetes, and 40.6% by indeterminate cetaceans (with a

majority of the latter probably being balaenopteroid mysticetes).

Because of the possible occurrence of the phocoenid *Lomacetus ginsburgi* and the kogiid *S. cochlearis*, two species only collected so far in the AGL level, a correlation of the Cerro Los Quesos beds with those of the AGL level at Aguada de Lomas (a locality of the Sacaco area 150 km SE to Cerro los Quesos) is tentatively suggested. As a matter of fact, the time range provided by the radiometric dating at Cerro Los Quesos (7.55–6.71 Ma) approximately matches the rough estimation (7.5–7 Ma) proposed by Muizon (1988) for the AGL level at Aguada de Lomas (see also Ehret et al., 2012; Lambert & Muizon, 2013).

Similar to the work done in Cerro Colorado, this study provides a vast amount of data to be used in different studies: (1) reconstruction of the ecological structure of the vertebrate assemblage at Cerro Los Quesos; (2) observation of faunal changes across the section and tentative correlation with sedimentological changes (more specifically the deposition of diatomites and volcanic ash layers); (3) taphonomic analysis of the exceptional conservation of this fossil assemblage (including multiple fully articulated large mysticete skeletons); (4) systematic and phylogenetic studies of significant specimens belonging to new taxa (specimens of cetaceans and sharks have been collected and are currently under preparation), in a stratigraphic, sedimentologic, and faunal framework markedly more precise than in earlier work.

In addition, this work represents the second step of a long-term and multidisciplinary project undertaking (1) the production of similar maps of fossil vertebrates from other localities of the Pisco Formation, and (2) from localities of the older and seemingly fossiliferous Chilcatay Formation (e.g. Ullujaya, see Bianucci, Urbina, & Lambert, 2014; Lambert, Bianucci, & Urbina, 2014b; Lambert, de Muizon, & Bianucci, 2015b), as well as (3) attempts to correlate stratigraphically distant localities and to compare their marine vertebrate content and changes through time.

Finally, the results of this work together with future studies in other localities should be added to data gathered from Cerro Colorado in a general database for the paleontological content of Pisco Basin fossiliferous localities. Such a database will be made available to the community for various future projects (involving research, mining, construction, recreation, and tourist activities in the Pisco Basin area), with the general aim of preserving and valuing this exceptional Peruvian heritage.

## Software

The geological map was compiled by scanning hand drafts as black and white TIF files, and then digitizing the linework using the Corel Draw X3 graphics

package. By using the GIS Data processing application Global Mapper 12, contour lines for the topographic base map were generated from digital elevation models (DEMs) based on the Shuttle Radar Topography Mission 26 (SRTM) as released by the United States Geological Survey (SRTM3 USGS version 2.1). Positions of fossil specimens were superimposed on the outcrop pattern of distinctive marker bed horizons by using Global Mapper 12 to convert a Google Earth kmz file containing their position into Corel Draw.

## Acknowledgements

We would like to thank W. Aguirre, E. Díaz, J. Tejada, N. Valencia, and R. Varas-Malca for their kind and endless help in the field and at the MUSM, and T. DeVries for valuable comments about various general aspects of the geology and stratigraphy of the Pisco Formation. We also wish to thank J. Reumer (Natuurhistorisch Museum Rotterdam, NMR) for his participation in the fieldtrip in 2008. C. Brochu, P.D. Gingerich, and M. Murad-al-shaikh reviewed the manuscript and provided constructive comments.

## Disclosure statement

No potential conflict of interest was reported by the authors.

## Funding

This research was supported by a grant of the Italian Ministero dell'Istruzione dell'Università e della Ricerca (PRIN Project 2012YJSBMK), by the University of Pisa (PRA\_2015\_0028) and by a National Geographic Society Committee for Research Exploration grants (9410–13) to G. Bianucci.

## References

- Barazangi, M., & Isacks, B. L. (1979). Subduction of the Nazca plate beneath Peru: Evidence from spatial distribution of earthquakes. *Geophysical Journal of the Royal Astronomical Society*, 57, 537–555. doi:10.1111/j.1365-246X.1979.tb06778.x
- Barron, J. A. (1985). Miocene to Holocene planktic diatoms. In H. M. Bolli, J. B. Saunders, & K. P. Perch-Nielsen (Eds.), *Plankton stratigraphy* (pp. 763–809). Cambridge: Cambridge Univ. Press.
- Barron, J. A. (2003). Planktonic marine diatom record of the Past 18 M.Y.: Appearances and extinctions in the Pacific and Southern Oceans. *Diatom Research*, 18, 203–224. doi:10.1080/0269249X.2003.9705588
- Bianucci, G., Di Celma, C., Landini, W., Post, K., Tinelli, C., de Muizon, C., ... Lambert, O. (in press). Distribution of fossil marine vertebrates in Cerro Colorado, the type locality of the giant raptorial sperm whale *Livyatan melvillei* (Miocene, Pisco Formation Peru). *Journal of Maps*, doi:10.1080/1744567.2015.1048315
- Bianucci, G., Lambert, O., & Post, K. (2010). High concentration of long-snouted beaked whales (genus

- Messapicetus*) from the Miocene of Peru. *Palaeontology*, 53, 1077–1098. doi:10.1111/j.1475-4983.2010.00995.x
- Bianucci, G., Urbina, M., & Lambert, O. (2014). A new record of *Notocetus vanbenedeni* (Squalodelphinidae, Odontoceti, Cetacea) from the early Miocene of Peru. *Comptes Rendus Palevol*, 14, 5–13. doi:10.1016/j.crpv.2014.08.003
- Bouetel, V., & de Muizon, C. (2006). The anatomy and relationships of *Piscobalaena nana* (Cetacea, Mysticeti), a Cetotheriidae s.s. from the early Pliocene of Peru. *Geodiversitas*, 28, 319–395.
- Brand, L. R., Esperante, R., Chadwick, A. V., Poma, O., & Alomía, M. (2004). Fossil whale preservation implies high diatom accumulation rate in the Miocene-Pliocene Pisco Formation of Peru. *Geology*, 32, 165–168. doi:10.1130/G20079.1
- Brand, L. R., Urbina, M., Chadwick, A., DeVries, J. T., & Esperante, R. (2011). A high resolution stratigraphic framework for the remarkable fossil cetacean assemblage of the Miocene/Pliocene Pisco Formation, Peru. *Journal of South American Earth Sciences*, 31, 414–425. doi:10.1016/j.jsames.2011.02.015
- Cahill, T., & Isacks, B. L. (1992). Seismicity and shape of the subducted Nazca plate. *Journal of Geophysical Research*, 97, 17503–17529. doi:10.1029/92JB00493
- Collareta, A., Landini, W., Lambert, O., Post, K., Tinelli, C., Di Celma, C., ... Bianucci, G. (2015). Piscivory in a Miocene Cetotheriidae: First record of fossilized stomach content for an extinct baleen-bearing whale. *The Science of Nature*, 102 (11–12), 70. doi:10.1007/s00114-015-1319-y
- DeVries, T. J. (1998). Oligocene deposition and Cenozoic sequence boundaries in the Pisco Basin (Peru). *Journal of South American Earth Sciences*, 11, 217–231. doi:10.1016/S0895-9811(98)00014-5
- Di Celma, C., Malinverno, E., Cantalamessa, G., Gioncada, A., Bosio, G., Villa, I. M., ... & Bianucci, G. Stratigraphic framework of the late Miocene Pisco Formation at Cerro Los Quesos (Ica Desert, Peru). *Journal of Maps*. doi: 10.1080/17445647.2015.1115783
- Di Celma, C., Malinverno, E., Gariboldi, K., Gioncada, A., Rustichelli, A., Pierantoni, P. P., ... Bianucci, G. (in press). Stratigraphic frame work of the late Miocene to Pliocene Pisco Formation at Cerro Colorado. *Journal of Maps*. doi:10.1080/1744567.2015.1047906
- Dunbar, R. B., Marty, R. C., & Baker, P. A. (1990). Cenozoic marine sedimentation in the Sechura and Pisco basins, Peru. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 77, 235–261. doi:10.1016/0031-0182(90)90179-B
- Ehret, D. J., McFadden, B. J., Jones, D. S., DeVries, T. J., Foster, D. A., & Sala Gismondi, R. (2012). Origin of the white shark *Carcharodon* (Lamniformes: Lamnidae) based on recalibration of the Upper Neogene Pisco Formation of Peru. *Palaeontology*, 55(6), 1139–1153. doi:10.1111/j.1475-4983.2012.01201.x
- Esperante, R., Brand, L. R., Chadwick, A. V., & Poma, O. (2015). Taphonomy and paleoenvironmental conditions of deposition of fossil whales in the diatomaceous sediments of the Miocene/Pliocene Pisco Formation, southern Peru—A new fossil-lagerstätte. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 417, 337–370. doi:10.1016/j.palaeo.2014.09.029
- Esperante, R., Brand, L. R., Nick, K. E., Poma, O., & Urbina, M. (2008). Exceptional occurrence of fossil baleen in shallow marine sediments of the Neogene Pisco Formation, Southern Peru. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 257, 344–360. doi:10.1016/j.palaeo.2007.11.001
- Gariboldi, K., Gioncada, A., Bosio, G., Malinverno, E., Di Celma, C., Tinelli, C., ... & Bianucci, G. (2015). The dolomite nodules enclosing fossil marine vertebrates in the East Pisco Basin, Peru: Field and petrographic insights into the Lagerstätte formation. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 438, 81–95. doi:10.1016/j.palaeo.2015.07.047
- Kraus, R. (1998). The cranium of *Piscogavialis jugaliperforatus* n. gen., n. sp. (Gavialidae, Crocodylia) from the Miocene of Peru. *Paläontologische Zeitschrift*, 72, 389–405. doi:10.1007/BF02988368
- Lambert, O., Bianucci, G., & Beatty, B. L. (2014a). Bony outgrowths on the jaws of an extinct sperm whale support macroraptorial feeding in several stem physteroids. *Naturwissenschaften*, 101, 517–521. doi:10.1007/s00114-014-1182-2
- Lambert, O., Bianucci, G., & de Muizon, C. (2008). A new stem-sperm whale (Cetacea, Odontoceti, Physterioidea) from the latest Miocene of Peru. *Comptes Rendus Palevol*, 7, 361–369. doi:10.1016/j.crpv.2008.06.002
- Lambert, O., Bianucci, G., & Post, K. (2009). A new beaked whale (Odontoceti, Ziphiidae) from the Middle Miocene of Peru. *Journal of Vertebrate Paleontology*, 29, 910–922. doi:10.1671/039.029.0304
- Lambert, O., Bianucci, G., & Post, K. (2010a). Tusk bearing beaked whales from the Miocene of Peru: Sexual dimorphism in fossil ziphiids? *Journal of Mammalogy*, 91, 19–26. doi:10.1644/08-MAMM-A-388R1.1
- Lambert, O., Bianucci, G., Post, K., Muizon, C. de Salas-Gismondi, R., Urbina, M., & Reumer, J. (2010b). The giant bite of a new raptorial sperm whale from the Miocene epoch of Peru. *Nature*, 466, 105–108. doi:10.1038/nature09067
- Lambert, O., Bianucci, G., & Urbina, M. (2014b). *Huariidelphis raimondii*, a new early Miocene Squalodelphinidae (Cetacea, odontoceti) from the Chilcatay Formation, Peru. *Journal of Vertebrate Paleontology*, 34, 987–1004. doi:10.1080/02724634.2014.858050
- Lambert, O., Collareta, A., Landini, W., Post, K., Ramassamy, B., Di Celma, C., ... Bianucci, G. (2015a). No deep diving: Evidence of predation on epipelagic fish for a stem beaked whale from the late Miocene of Peru. *Proceedings of the Royal Society B*, 282, 20151530. doi:10.1098/rspb.2015.1530
- Lambert, O., & de Muizon, C. (2013). A new long-snouted species of the Miocene pontoporiid dolphin *Brachydelphis* and a review of the Mio-Pliocene marine mammal levels in the Sacaco Basin, Peru. *Journal of Vertebrate Paleontology*, 33, 709–721. doi:10.1080/02724634.2013.743405
- Lambert, O., de Muizon, C., & Bianucci, G. (2015b). A new archaic homodont toothed whale (Mammalia, Cetacea, Odontoceti) from the early Miocene of Peru. *Geodiversitas*, 37, 79–108. doi:10.5252/g2015n1a4
- León, W., Aleman, A., Torres, V., Rosell, W., & De La Cruz, O. (2008). Estratigrafía, Sedimentología y evolución tectónica de la cuenca Pisco Oriental. *Boletín INGENMET, Serie D*, 27, 1–154, Lima, Peru.
- de Muizon, C. (1986). Un nouveau Phocoenidae (Odontoceti, Mammalia) du Miocene superieur de la Formation Pisco (Perou). *Comptes Rendus de l'Académie des Sciences, Série II*, 303(16), 1509–1512.
- de Muizon, C. (1988). Les Vertébrés fossiles de la Formation Pisco (Pérou). Troisième partie: Les Odontocètes (Cetacea, Mammalia) du Miocène. *Travaux de l'Institut Français d'Études Andines*, 42, 1–244.

- Parham, J. F., & Pyenson, N. D. (2010). New sea turtle from the Miocene of Peru and the iterative evolution of feeding ecomorphologies since the Cretaceous. *Journal of Paleontology*, 84, 231–247. doi:10.1666/09-077R.1
- Pilger, R. H. (1981). Plate reconstructions, aseismic ridges, and low-angle subduction beneath the Andes. *Geological Society of America Bulletin*, 92, 448–456. doi:10.1130/0016-7606(1981)92<448:PRARAL>2.0.CO;2
- Pilleri, G., & Siber, H. J. (1989). Neuer spattertiärer cetotherid (Cetacea, Mysticeti) aus der Pisco-Formation Perus. In G. Pilleri (Ed.), *Beiträge zur Palaontologie der Cetaceen Perus* (pp. 108–115). Berne: Hirnanatomisches Institut, Ostermundigen.
- Rustichelli, A., Di Celma, C., Tondi, E., & Bianucci, G. (2016). Deformation within the Pisco basin sedimentary record (southern Peru): Stratabound orthogonal vein sets and their impact on fault development. *Journal of South American Earth Sciences*, 65, 79–100. doi:10.1016/j.jsames.2015.11.002
- Thornburg, T. M., & Kulm, L. D. (1981). Sedimentary basins of the Peru continental margin: Structure, stratigraphy, and Cenozoic tectonics from 6°S to 16° latitude. *Geological Society of America, Memoir*, 154, 393–422.
- Zúñiga-Rivero, F. J., Klein, G. D., Hay-Roe, H., & Álvarez-Calderon, E. (2010). *The hydrocarbon potential of Peru*. BPZ Exploración & Producción S.R.L., Lima, Peru, 338 p.