



## Miocene stratigraphy and vertebrate paleontology along the western side of Cerros Cadena de los Zanjones (East Pisco Basin, Peru)

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### ABSTRACT

The Miocene Pisco Formation (East Pisco Basin, Peru) is renowned for its abundant, well-preserved fossils of marine vertebrates, representing one of the most spectacular and complete records of Neogene marine vertebrates worldwide. Here, we present a geological map at 1:10,000 scale investigating the spatial and temporal distribution of fossil vertebrates at Cerros Cadena de los Zanjones, in the Ica River Valley. Stratigraphic and paleontological analyses reveal the widespread occurrence of marine vertebrate remains in the Tortonian (10.0–8.6 Ma) P1 and Tortonian – Messinian (8.4–6.9 Ma) P2 sequences. These include 91 specimens preserved as bony elements, including cetaceans (both Odontoceti and Mysticeti), seals (Pinnipedia) and bony fishes (Osteichthyes). Elasmobranchs, including Carcharhiniformes, Lamniformes and Myliobatiformes, are represented by some 300 teeth. The P1-P2 passage is marked by faunal novelties such as the first appearance of seals. Overall, the assemblage taxonomically resembles that of the nearby, well-investigated site of Cerro Colorado.

### ARTICLE HISTORY

Received 20 December 2024  
Revised 18 February 2025  
Accepted 20 February 2025

### KEYWORDS

Facies analysis; structural analysis; paleontological heritage; Pisco formation; Tortonian; Messinian

## 1. Introduction

The Pisco Formation of southern coastal Peru is a well known stratigraphic unit that owes its celebrity to its extraordinary fossil content, offering profound insights into the Miocene evolution of marine ecosystems (e.g. Bianucci & Collareta, 2022; Bosio et al., 2021; Lambert et al., 2010). Indeed, the Pisco Formation cropping out in the Ica River Valley is home to an abundant and scientifically significant fossil fauna that includes marine vertebrates such as whales, dolphins, porpoises, seals, seabirds, marine turtles, crocodiles, and bony and cartilaginous fishes, all reflecting thriving ancient ecosystems (e.g. Bianucci et al., 2016a, 2016b, 2024; Collareta et al., 2021b; Lambert et al., 2010; Stucchi et al., 2015). This wealth of fossils makes the Pisco Formation invaluable for different studies in a variety of topics concerning the evolutionary paleoecology of the marine biosphere, thereby offering useful insights for the reconstruction of the evolutionary and ecological dynamics of the Neogene marine faunas of the southeastern Pacific Ocean (Collareta et al., 2021b). Detailed

sedimentological, taphonomic and geochemical studies have also revealed complex depositional and early diagenetic histories, which played a critical role in the often-exceptional preservation of fossils (Bosio et al., 2021; Gariboldi et al., 2015; Gioncada et al., 2016, 2018). Such discoveries further underscore the importance of the Pisco Formation as a paleontological hotspot and a natural archive of ancient marine life, highlighting the importance of preserving this unique paleontological heritage.

Here, we present a 1:10,000-scale geological map (Main Map) covering an area of approximately 37 km<sup>2</sup> along the western side of Cerros Cadena de los Zanjones, a new fossil-bearing locality of the Pisco Formation. This work builds upon earlier geological surveys (Di Celma et al., 2016a, b, 2022), and integrates new biostratigraphic and structural data, providing the groundwork for more detailed paleontological investigations and interpretations. The marine fossil vertebrates identified within these strata are systematically documented on the geological map and along two measured sections,

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Supplemental map for this article is available online at <https://doi.org/10.1080/17445647.2025.2472779>.

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illustrating their horizontal and vertical distribution in this area.

## 2. Geological and stratigraphic setting

The study area is located along the South American convergent margin, which is primarily characterized by erosional rather than accretional processes (Clift & Vannucchi, 2004; Noda, 2016). The forearc basin system of the Peruvian region is notably segmented across the margin and further divided by the Outer Shelf High, a northwest-trending structural high consisting of the Precambrian-Paleozoic basement. This configuration leads to the development of an inner and an outer set of elongated basins running parallel to the trench (Kulm et al., 1982; Thornburg & Kulm, 1981). The subsidence and uplift history within these forearc basins reflect the complex interaction between the subducting Nazca Plate and the overriding South American Plate along the Peruvian convergent margin (Herbozo et al., 2020; Viveen & Schlunegger, 2018; von Huene & Suess, 1988).

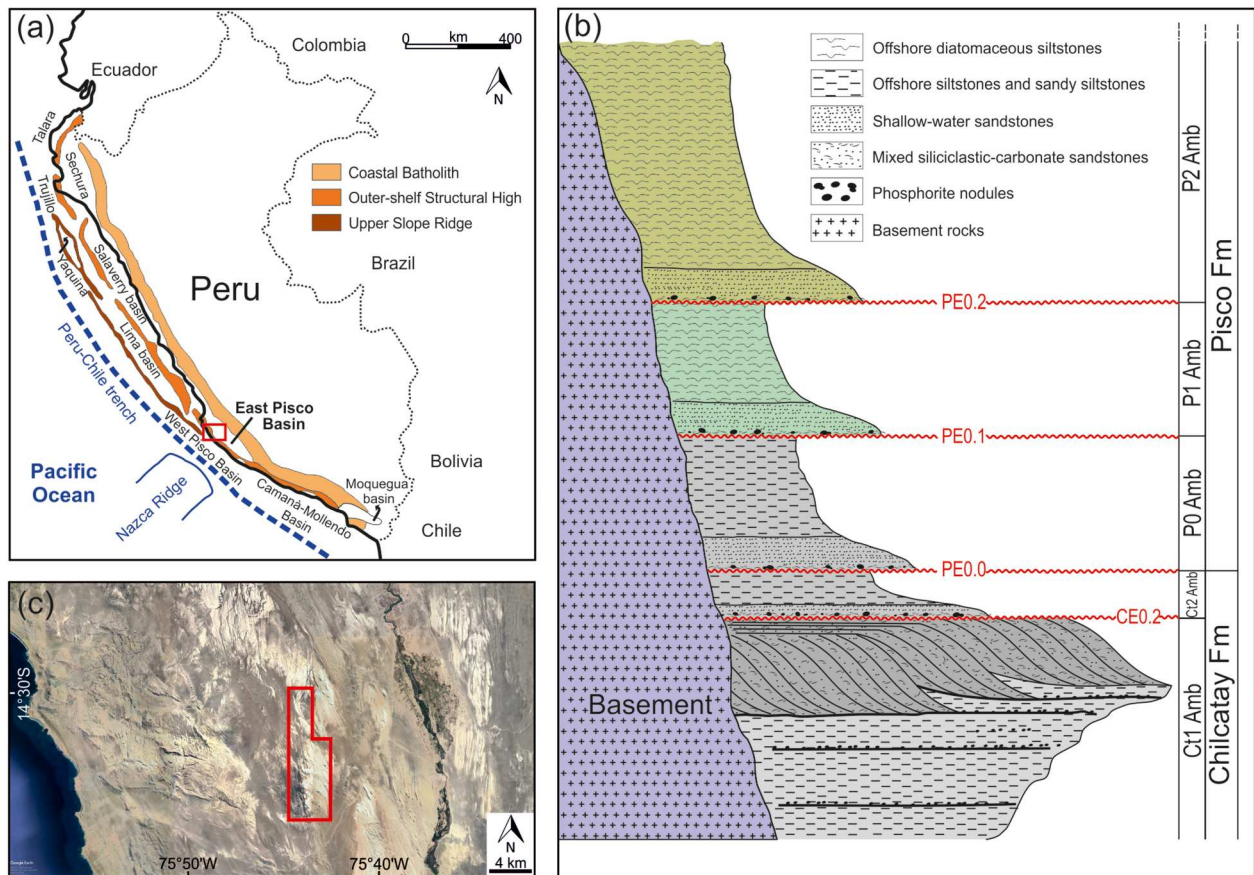
The forearc region of Peru is located landward of where the aseismic Nazca Ridge collides with the continental margin (Ciattoni et al., 2025 and references therein) and consists of the onshore East Pisco Basin (EPB) and the offshore West Pisco Basin (WPB) (Figure 1a). These basins are separated from each other by the Coastal Cordillera structural high, which represents the landward extension of the Outer Shelf High (Romero et al., 2013).

The sedimentary fill of the EPB is organized into two megasequences, namely, megasequences P (Paleogene) and N (Neogene), both of which are bounded by significant unconformities that mark critical phases of the basin evolution (Di Celma et al., 2022). Megasequence N, which includes the Miocene Chilcatay and Pisco formations, lies above megasequence P and locally onlaps the eroded crystalline basement. Stratigraphic analyses of the Chilcatay and Pisco formations have identified several key internal stratigraphic surfaces, which permitted the recognition of high-frequency sequences within each formation (Di Celma et al., 2017) (Figure 1b). In particular, based on the presence of three widespread erosional surfaces, called PE0.0, PE0.1 and PE0.2 from oldest to youngest, the Pisco Formation can be subdivided into three main sequences designated as P0 (14.7–12.6 Ma), P1 (10.0–8.6 Ma) and P2 (8.4 to  $\geq 6.71$  Ma) (Bosio et al., 2020a, 2020b, 2022; Gariboldi et al., 2017; Malinverno et al., 2025). Based on sedimentological analysis, the Ct1 sequence mainly comprises conglomerates and bioclastic sandstones divided into three facies associations recording deposition in shoreface, offshore, and subaqueous delta settings. The Ct2 sequence comprises two facies associations, recording deposition in shoreface (sandstones) and offshore

(siltstones) settings (Di Celma et al., 2019). The overlying Pisco Formation is characterized by three transgression cycles (P0, P1 and P2), each comprising a shoreface (fine-grained sandstones and coarse siltstones) and an offshore (diatomaceous mudstones) setting (Di Celma et al., 2017).

## 3. Surveying methods

The study area is located along the western side of Cerros Cadena de los Zanjones (Figure 1c). Although the stratigraphy of the Pisco Formation is relatively straightforward at this site, the occurrence of a complex network of faults complicates the efforts to provide a detailed correlation of the faunas in laterally separated areas (Figure 2). Consequently, the study area required comprehensive geological and structural mapping to unravel its intricate and dispersed features. Fieldwork focused on documenting the faults, including analyses of their geometry, kinematics and dimensional attributes, as well as on quantifying fault displacements wherever feasible. These efforts were complemented by the interpretation of recently available high-resolution imagery (a few meters per pixel or less) from Google Earth, which provided valuable insights into the spatial arrangement and characteristics of the fault system (see Tewksbury et al., 2012 for methods for mapping bedrock structures in remote areas in Google Earth). The stratigraphy of the exposed succession was established through detailed sedimentological logging of two reference stratigraphic sections (Figure 2a, b), geological mapping at 1:10,000 scale and facies analysis. Two sedimentary sections, namely, CCZ (western side of Cerros Cadena de los Zanjones; base: 14°34'12.6"S, 75°43'44.8"W; top: 14°34'39.3"S, 75°43'10.2"W) and CLQw (further north, western side of Cerro los Quesos; base: 14°31'2.2"S, 75°43'11.1"W; top: 14°31'13.2"S, 75°44'33.7"W), measuring respectively 175 and 130 m (Figure 2), were measured using a high-precision Jacob's staff with rotatable laser pointer (see Patacci, 2016). Log descriptions included information such as bed thickness, lithology, estimation of grain size (using a comparator and a hand lens), type of sedimentary structures and bioturbation intensity. Age constraints for the exposed sedimentary succession allow for basin-wide correlations across vast tracts of inaccessible desert, and are provided by  $^{40}\text{Ar}/^{39}\text{Ar}$  radiometric dating of volcanic ash layers (Bosio et al., 2020b) and biostratigraphic analyses using diatoms based on 45 rock samples. These samples were collected along the two measured sections with a spacing of about 1–2 m and integrated with 14 additional samples collected at a previously unmapped site at the south-western end of the study area. As for the paleontological prospecting, each vertebrate specimen encountered in situ during the survey had its



**Figure 1.** Geological and stratigraphic framework. **(a)** Map of the major Cenozoic sedimentary basins along the Peruvian coast, with indication of the major structural highs, i.e. the Coastal Batholith, the Outer Shelf High and the Upper Slope Ridge. Redrawn and modified after Travis et al. (1976) and Thornburg and Kulm (1981). The red box indicates the study area in the East Pisco Basin. **(b)** Schematic stratigraphic column of the Chilcatay and Pisco formations, and their internal subdivision into high-frequency sequences. Modified after Di Celma et al. (2018a). The green-colored sequences are those cropping out at this locality. The vertical scale is only indicative of thickness of sediment packages between unconformity surfaces. **(c)** Satellite image showing the geographic location of the study area along the western side of the Ica River valley (outlined by a red frame).

geographic location recorded with a handheld GPS, while its stratigraphic position along the measured sections was determined with an accuracy of  $\pm 0.4$  to  $\pm 3$  meters. The horizontal and vertical distribution of all recorded fossils in the study area is presented in the Main Map, which reports two sections, namely CCZ (for specimens from the southern part of the study area) and CLQw (for those from the northern part thereof). Similar to previous studies in fossil-rich areas of the Ica Desert (Di Celma et al., 2018b, 2019; Bianucci et al., 2016a, b; Collareta et al., 2021a), we prospected the study area by providing taphonomic characterizations and preliminary taxonomic identifications directly in the field. Depending on the nature of the skeletal parts that were preserved or exposed in the field, more or less accurate systematic determinations could be made, based also on comparisons with several well-investigated specimens from other Upper Miocene localities of the Ica Desert (Bianucci & Collareta, 2022; Bianucci et al., 2010, 2016c, 2024; Collareta et al., 2015; de Muizon, 1981, 1988; Dewaele & de Muizon, 2024; Lambert & de Muizon, 2013, 2021; Landini et al., 2017a, b). Only a few

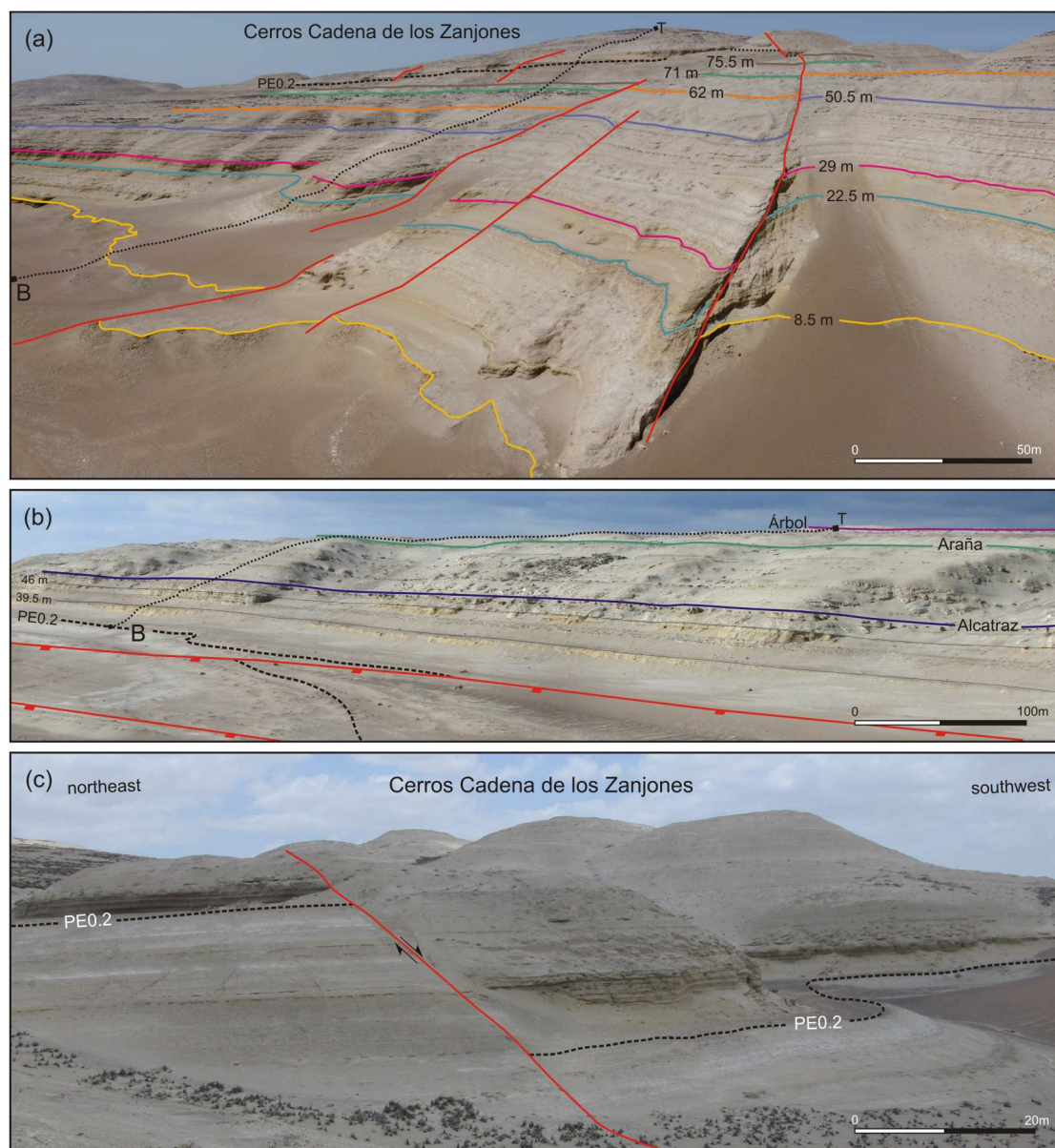
noteworthy specimens were collected for storage at the Museo de Historia Natural de la Universidad Nacional Mayor de San Marcos (MUSM) in Lima. As for the elasmobranchs (sharks and rays), only the teeth with precise GPS coordinates were consistently plotted on the map and included in the stratigraphic column. Similar to what was done for the marine tetrapods, the taxonomic identification of the elasmobranch finds was supported by comparisons with well-studied coeval materials from other outcrops of the Pisco Formation (Landini et al., 2017a).

## 4. Stratigraphic and structural overview

### 4.1. Stratigraphy and age

In the study area, only the Upper Miocene P1 and P2 sequences of the Pisco Formation are exposed. Sequence bounding unconformities are omission surfaces commonly demarcated by a *Glossifungites* ichnofacies and are interpreted as composite discontinuities that formed during a phase of relative sea-level fall to be subsequently modified during the onset of





**Figure 2.** Panoramic views showing the locations of the two measured sections and field examples of small-displacement normal faults (depicted as solid red lines) dissecting the studied succession. Numbers indicate the stratigraphic height (in meters) along the individual measured sections. **(a)** Oblique aerial view of the western side of Cerros Cadena de los Zanjones, showing the position of the CCZ measured section (B, base:  $14^{\circ}34'12.6''\text{S}$ ,  $75^{\circ}43'44.8''\text{W}$ ; T, top:  $14^{\circ}34'39.3''\text{S}$ ,  $75^{\circ}43'10.2''\text{W}$ ) and examples of small-displacement normal faults offsetting some of the main marker beds (colored lines). View is toward the southeast. **(b)** View of the western side of Cerro Los Quesos showing the position of the CLQw measured section, at the northern end of the study area (base:  $14^{\circ}31'2.2''\text{S}$ ,  $75^{\circ}43'11.1''\text{W}$ ; T, top:  $14^{\circ}31'13.2''\text{S}$ ,  $75^{\circ}44'33.7''\text{W}$ ). Names of main marker beds as in Di Celma et al. (2016a). View is toward the northeast. **(c)** Decameter-scale normal fault surface (colored as red) cutting through the PE0.2 unconformity (black dashed lines) at Cerros Cadena de los Zanjones.

transgression (Di Celma et al., 2017, 2018a). Each sequence is characterized by a coarse-grained basal portion, representing deposition in distal lower shoreface to inner shelf settings, which progressively grades upward into finer-grained, offshore sediments. Usually, the base of each sequence consists of a thin conglomerate layer comprised of well-rounded, pebble-sized phosphate nodules, mollusk shells, sporadic polished vertebrate bones and teeth, and subangular to rounded crystalline cobbles and boulders (Bosio et al., 2024). Overlying this lag, a package of massive orange sandstones and coarse

siltstones characterizes the first meters of the measured sections. These sandstones are often moderately to highly bioturbated and exhibit local sedimentary structures such as unidirectional cross-lamination, swaley cross-stratification and wave ripples. These structures indicate deposition in a shoreface setting strongly influenced by storms (Chiocci & Clifton, 1991; Leckie & Walker, 1982; Myrow, 1992). The overlying, fine-grained sediments are made up of finely laminated, gray to white diatomites or diatomaceous siltstones rich in planktic and benthic diatoms, reflecting a low-energy, highly productive,

offshore marine environment (Gariboldi et al., 2023). Associated lithologies include thin layers of fine – to medium-grained sandstone, dolomitized mudstone beds (Malinverno et al., 2023), and andesitic to rhyolitic, metaluminous to peraluminous volcanic ash layers (Bosio et al., 2019). These fine-grained ashes represent the distal, crystal-depleted falls of large explosive eruptions, dispersed from the eruption column or from a co-ignimbrite ash-cloud (Fisher & Schmincke, 1984) following the volcanic activity in the Eastern and Western Cordillera of the Central Andes (Bosio et al., 2020c). They allow for the  $^{40}\text{Ar}/^{39}\text{Ar}$  dating and tephrostratigraphic correlation of sections several kilometers apart, thus greatly increasing the chronostratigraphic detail.

At Cerros Cadena de los Zanjones, the lower portion of the P1 sequence is exposed along the CCZ section. It is dated to the Tortonian thanks to two ash layers, namely, ZANJ-T6 (3 m above the base of the section, hereinafter abs) and LA(16) (8 m abs), which provide radiometric ages of  $9.46 \pm 0.05$  Ma and  $9.00 \pm 0.02$  Ma, respectively (Bosio et al., 2020b). Along the CLQw section, an ash layer at the base of P1 gives an age of  $9.31 \pm 0.01$  Ma (ANF-T1) (Bosio et al., 2020b). This age framework is further supported by diatom biostratigraphy. Specifically, the co-occurrence of the diatom marker species *Lithodesmium reynoldsii* and *Denticulopsis praekatayamae* from 15–66 m abs along the CCZ section constrains this interval between 9.6 Ma (First Occurrence, hereinafter FO, of *D. praekatayamae*) and 9.0 Ma (Last Occurrence, hereinafter LO, of *L. reynoldsii*) (ranges of taxa according to Lazarus et al., 2014). The lowest few meters of the succession, known by samples from the southwestern edge of Cerros Cadena de los Zanjones, include *Denticulopsis vulgaris* but lack both *D. praekatayamae* and *L. reynoldsii*, and as such, are probably slightly older than 10 My, as reported for the basal layers of the P1 sequence at Cerro Tiza (Malinverno et al., 2025). The top of P1 has been dated through the ZANJ-T3 tephra (92 m abs, CCZ section) that yields an age of  $8.60 \pm 0.11$  Ma, whereas the LO of *D. praekatayamae* (8.6 Ma) is locally recognized 83 m abs (Bosio et al., 2020b). The base of the overlying P2 sequence is dated to  $8.39 \pm 0.03$  Ma in the CLQw section thanks to the  $^{40}\text{Ar}/^{39}\text{Ar}$  dating of the ash layer ANF-T4 (Bosio et al., 2020b). In the study area, the age of the P2 strata has been estimated based on the radiometric dating of ZANJ-T28 (161 m abs, CCZ section), which provides an age of  $7.62 \pm 0.11$  Ma, 14 m below the top of the measured section (Bosio et al., 2020b). Furthermore, the occurrence of *Fragilariopsis pliocena* between 122–163 m along the CCZ section constrains this interval between 8.0 and 6.9 Ma (corresponding to the FO and LO of *F. pliocena*, respectively), whereas

the FO of *Fragilariopsis reinholdii* (7.7 Ma) is recognized ca. 73 m abs along the CLQw section.

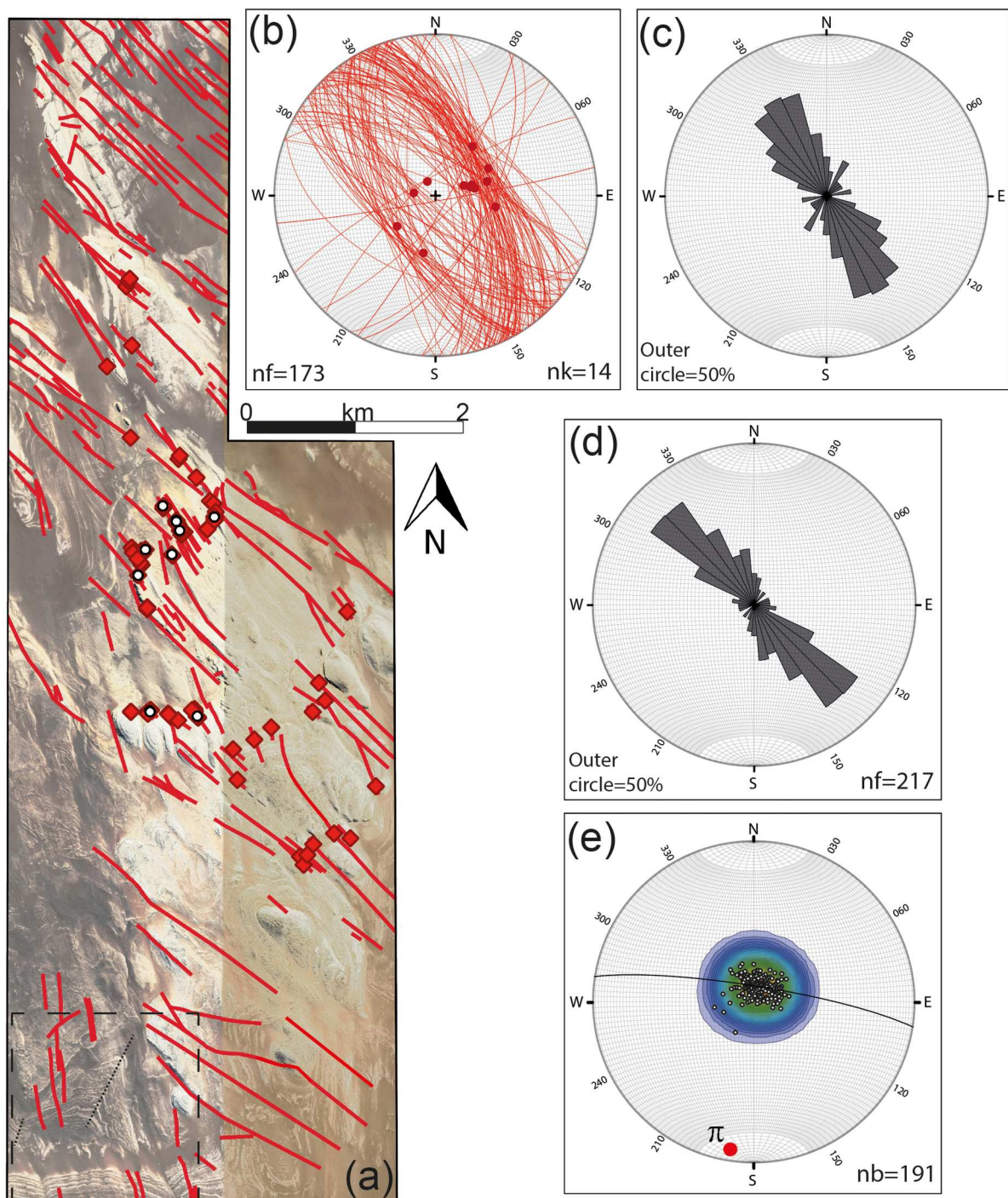
#### 4.2. Structural framework

A detailed field-based structural analysis was conducted to characterize the numerous faults that cut through the stratigraphic succession exposed in the study area (Figure 3a). These faults display variable normal offsets, ranging from decimeter – to several meter-scale, with maximum displacements up to ~50 m in the northern part of the study area. Two main orientations are observed, namely, a set of NW – SE-striking faults, and a subordinate set of NNE – SSW-striking faults. A comparison of our field data with satellite-derived lineament orientations (Figure 3a) reveals consistent primary trends in both datasets, with dominant strikes in the range of N130–150°. The secondary fault set, striking roughly N30°, was identified by means of field observations and is less prominent in satellite data. That said, the fault sets identified in the study area are generally consistent with those outlined by Viveen and Schlunegger (2018) based on the interpretation of satellite imagery and field-based structural mapping, which led those authors to recognizing three main sets of large-scale faults and lineaments within the EPB, striking approximately N160°, N120° and N30°, respectively (Figure 3c-d).

Fault planes are planar, with dip angles ranging between 65–75°, and fault lengths vary from a few hundred meters to a maximum of 4 km (mean: 500 m; median: 400 m). Through a detailed field survey, 173 fault attitude measurements and associated kinematic indicators, such as slickenlines and slickenfibers, were collected along fault planes (Figure 3b, c). These data indicate that extensional dip-slip faulting dominates both fault sets. Constraining the timing of these structures is challenging, with field evidence suggesting that they postdate the deposition of P2. On the other hand, some of the normal faults appear to control thickness variations within the Pisco Formation, thus suggesting a Miocene, syn-sedimentary extensional activity.

In the central and northern portions of the study area, the Pisco Formation strata generally dip at low angles (5–10°). In the southern portion, the lower strata of the P1 sequence are involved in a gentle anticline-syncline fold pair. These gently south-plunging folds are characterized by interlimb angles of approximately 165°. Within the area outlined by the dotted square in Figure 3a, 191 bedding attitudes were recorded. Structural analysis was undertaken using Stereonet v.11 software (Allmendinger et al., 2012; Cardozo & Allmendinger, 2013), including the elaboration of stereonet plots and best-fit great-circles ( $\pi$  diagrams) of bedding pole distributions (Figure 3e). The results indicate a sub-horizontal fold axis plunging 8° toward N189° (Figure 3a). These folds appear





**Figure 3.** Structural map of the study area. **(a)** Map view from Google Earth, showing the study area (outlined by the black perimeter line; see Figure 1). Red lines represent fault traces identified through satellite image analysis. Red squares indicate field measurements of fault attitudes, while white circles mark locations of kinematic indicators. The dashed box outlines the area where the structural analysis of bedding attitudes was performed (panel 3e). Dotted lines represent the axial trace of folds. **(b)** Lower-hemisphere, equal-area projection of fault planes (great circles) measured in the field. Red dots represent kinematic data recorded from striae and/or mineral fibers on fault surfaces within the studied succession. **(c)** Rose diagram, showing strike frequency of faults identified by means of satellite imagery interpretation. **(d)** Rose diagram showing strike frequency of faults surveyed in the field. **(e)** Lower-hemisphere, equal-area projection of bedding poles within the dashed area in panel 3a. The plot includes a best-fit great circle approximating the distribution of bedding poles, concentration contour lines, and the associated  $\pi$  statistical fold axis. Stereographic projections and rose diagrams were created using the Stereonet v.11 software (Richard W. Allmendinger). nf = number of fault data used; nk = number of kinematic indicators; nb = number of bedding attitudes.

to record a minor phase of mild shortening intercalated within the extensional tectonic regime that was dominant throughout the Neogene evolution of the East Pisco Basin. The timing of the deformation

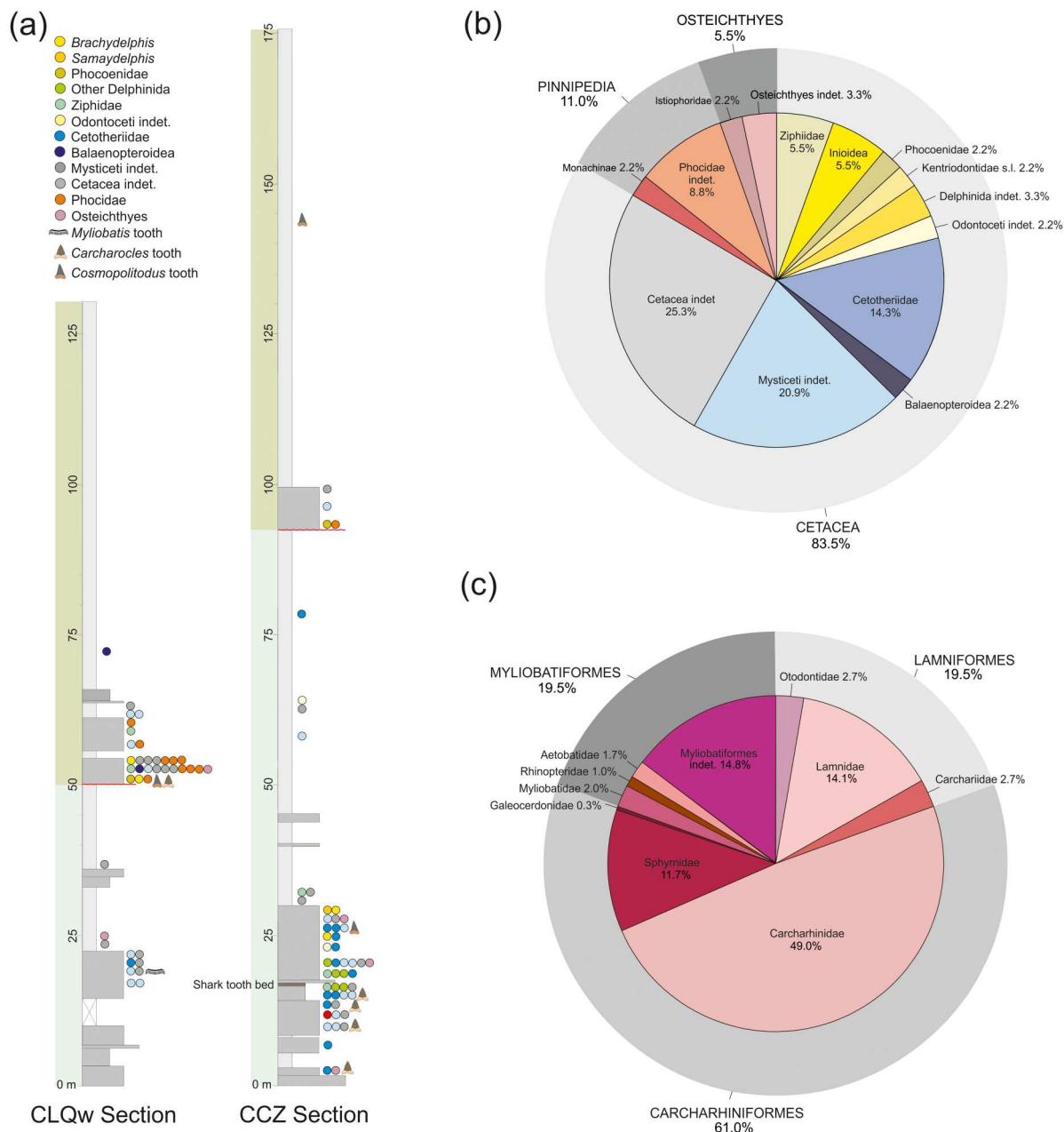
unraveled by this study refines previous basin analysis interpretations that overlooked the occurrence of such punctuated shortening events during basin evolution (e.g. Di Celma et al., 2022).

## 5. Vertebrate paleontology of the study area

Fossil vertebrate remains from the study area have been categorized into either bony or dental elements (see the Main Map). Ninety-one marine vertebrate specimens preserved as bony elements were recorded from the Pisco strata exposed at the study site (Figure 4a). Cetaceans dominate this assemblage, being represented by 76 specimens (corresponding to about 83.5% of the total number) (Figure 4b). Of all the cetacean specimens identifiable at the suborder level, 53

are represented by complete to strongly incomplete skeletons, 34 (37.3%) belong to Mysticeti (baleen-bearing whales) and 21 (20.9%) to Odontoceti (echo-locating toothed whales).

Among mysticetes, 13 specimens (14.3%) are identified as members of the extinct family Cetotheriidae, including an exquisitely preserved juvenile skull (Figure 5). Most of these large cetotheriids appear to be referred to an as-yet undescribed, large-bodied, *Piscobalaena*-like taxon whose skeletons are commonly encountered throughout the P1 sequence, e.g. at



**Figure 4.** Stratigraphic distribution and taxonomic composition of the fossil vertebrate assemblage from Cerros Cadena de los Zanjones. **(a)** Stratigraphic distribution of marine vertebrate fossil specimens for which precise GPS coordinates are known along the two simplified sedimentary sections (CCZ and CLQw). The green bands represent P1 and P2 sequences; the red line corresponds to the sequence boundary; the horizontal axis represent the grain size distribution. **(b)** Taxonomic composition of the fossil marine vertebrate assemblage from the P1 and P2 strata, based on the systematic surface prospecting of 91 specimens preserved as bony elements. **(c)** Taxonomic composition of the fossil elasmobranch assemblage from the P1 and P2 strata, based on systematic surface prospecting and collection of some 300 dental elements.





**Figure 5.** Field photographs of mysticete specimens from the study area. **(a)** Excavation of a cranium and mandibles of a juvenile of Cetotheriidae indet. (CCZ52). **(b)** Articulated cranium and mandibles of Cetotheriidae indet. (CCZ13) preserved dorsal side-up.

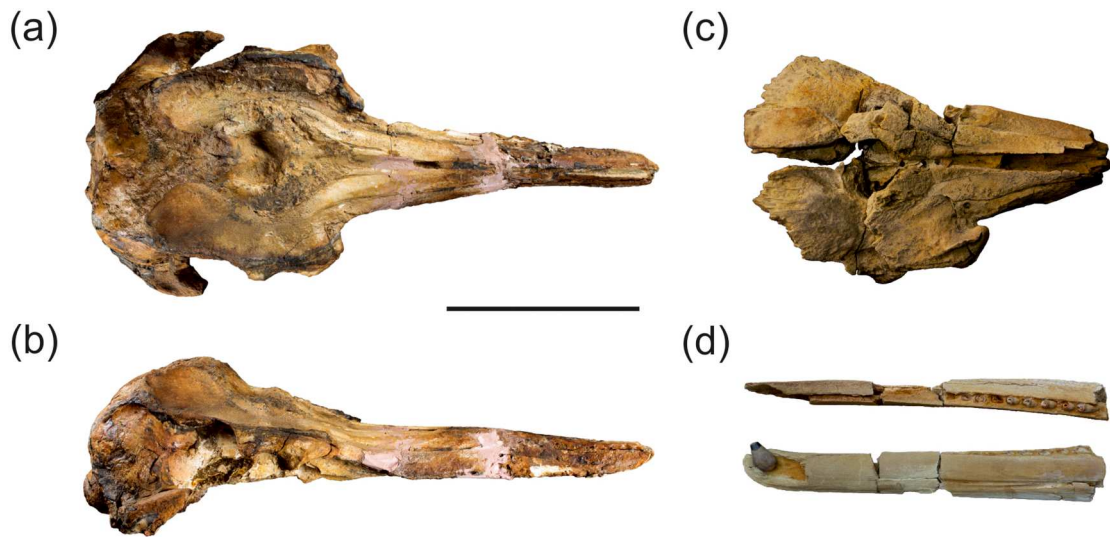
Cerro Colorado (Bianucci et al., 2016b; Bianucci & Collareta, 2022). Two large mysticete specimens (2.2%) belong to the superfamily Balaenopteroidea, all the remaining records being identified as Mysticeti indet.

Though relatively uncommon, the odontocetes are seemingly more diverse, being represented by different members of Delphinida (the largest toothed whale clade, including many forms of dolphins, porpoises and kin, accounting for 14 specimens, or 13.2%) as well as of Ziphiidae (beaked whales, numbering five, or 5.5%). Specifically, delphinidans include (i) the pontoporiid *Brachydelphis mazeasi* (Figure 6c), a relative of the present-day franciscana (*Pontoporia blainvillei*), and the putative pontoporiid *Samaydelphis chacaltanae* (Figure 6a,b), both of which belong in

the superfamily Inioidea (totaling five specimens, or 6.5%) (Figure 4b); (ii) an as-yet undescribed kentriodontid-like basal delphinidan (two specimens, or 2.2%); and (iii) at least two porpoise-like taxa (two specimens, or 2.2%), including an unambiguous member of Phocoenidae. Ziphiids are represented by fragmentary remains (Figure 6d) comprising a total of five specimens (5.5%), including one that may represent *Messapicetus* and two that have previously been assigned to Ziphiidae genus and sp. indet. 1 (Bianucci et al., 2016a, 2024).

Besides cetaceans, the marine vertebrate assemblage is also rich in seals (Pinnipedia, Phocidae) and bony fishes (Osteichthyes). The former group comprises ten specimens (11.0%) and include two skeletons (2.2%) referred to the monk seal subfamily





**Figure 6.** Photographs of odontocete specimens from the study area. **(a,b)** Cranium of *Samadelphe chalcitanae* (MUSM 3903 = CCZ60) in (a) dorsal and (b) lateral views. **(c)** Fragmentary cranium in dorsal view of *Brachydelphis mazeasi* (CCZ25). **(d)** Symphyseal fragment of left mandible and associated apical tooth of Ziphiidae genus and sp. indet. 1 in dorsal (top) and lateral (bottom) views (MUSM 4966 = CLQC37). Scale bar equals 10 cm.

Monachinae, whereas the latter accounts for five specimens (5.5%) and includes two istiophorid billfishes (2.2%) (Figure 4b).

Most of the aforementioned specimens (63.7%) come from P1 (Figure 4a). Finds are much more common in the sandy lower portions of both sequences (75.8%) rather than in the diatomaceous portions thereof. Just a few skeletons exhibit a high degree of completeness and articulation (Figure 7a), whereas most other specimens for which exhaustive taphonomic data are available are poorly articulated and incomplete, belonging to classes 0–1 of Bosio et al. (2021). The latter also include isolated crania, mandibles, and limb bones, evoking the trend of progressive dismembering of carcasses during flotation as explained by Bosio et al. (2021). Twenty-three cetacean specimens, some four-fifths of which are mysticetes, are found embedded into more or less developed dolomite nodules (Figure 7b–d), which commonly form around large, articulated skeletons after the rapid burial of the carcass (Bosio et al., 2021). Ventrally-disposed skeletons appear to be much more common than the dorsally-disposed ones (Figure 7), with a ratio of about 4:1 based on the available data, which evokes the refloating of the carcasses after death (Bosio et al., 2021). As few as two specimens were found with associated shark teeth, and just one features shark tooth marks (Figure 7e). Seven specimens were found with associated mollusks, primarily the bivalve *Dosinia* and the gastropod *Turritella* (Figure 7d), which are possibly derived from the shell beds in which the cetacean carcasses sank on.

Elasmobranchs (shark and rays) are represented by some 300 teeth that mostly come from a single

diatomite horizon running through P1 some 17 m above the base of the CCZ section (Figure 4a, Figure 8). Among these, there are representatives of Carcharhiniformes (requiem sharks, including Carcharhinidae, Sphyrnidae and Galeocerdonidae, accounting for 61.0% of the teeth), Lamniformes (mackerel sharks, including Lamnidae, Carcharhiidae and Otodontidae, accounting for 19.5% of the teeth) and Myliobatiformes (eagle and cownose rays, including Myliobatidae, Rhinopteridae and Aetobatidae, accounting for 19.5% of the teeth) (Figure 4c). The extant copper shark, *Carcharhinus brachyurus*, is by far the most common elasmobranch species.

The marine mammal assemblage recorded at the study site mostly resembles that from the well-investigated locality of Cerro Colorado, ca. 30 km further northwest, where P1 and P2 are also exposed (Bianucci et al., 2016b; Bosio et al., 2021; Collareta et al., 2021b). Similarities between the two fossil faunas include the shared presence of (i) an as-yet undescribed cetotheriid species for which paleoecological inferences were drawn by Collareta et al. (2015); (ii) the inioid delphinids *B. mazeasi* and *S. chalcitanae* (Lambert et al., 2021); and, possibly, (iii) the beaked whale *Messapicetus* (Bianucci et al., 2010). All these forms but *B. mazeasi* are limited to P1. Faunal similarities between the study site and Cerro Colorado also include the abundance of teeth referred to *C. brachyurus* from the P1 strata (Landini et al., 2017a, 2017b). The high concentration of vertebrate finds observed within the lowermost 30 m of the CCZ section (Main Map) may correspond to a similar accumulation of fossils observed in the P1 strata at Cerro Colorado (Bianucci et al., 2016b; their Figure 4).

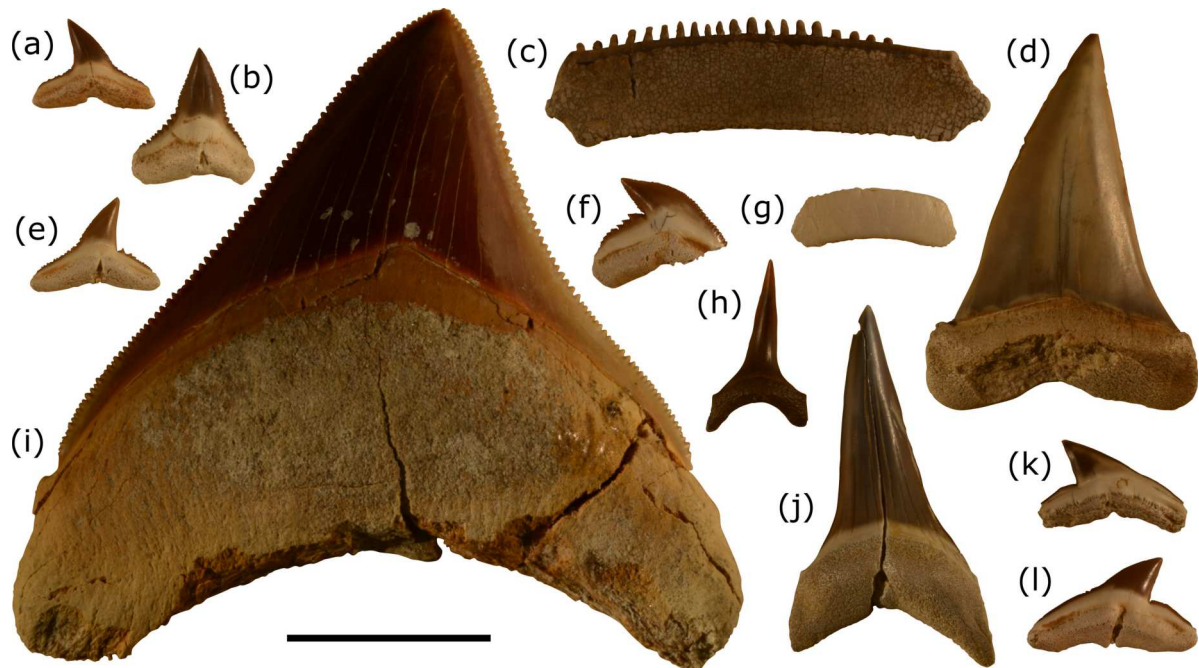


**Figure 7.** Field photographs exhibiting the main taphonomic features of the fossil marine vertebrates. **(a)** Complete and almost fully articulated skeleton of Cetotheriidae indet. including cranium, articulated mandibles, vertebral column (the thoracics are partially disarticulated) and left scapula, preserved in ventral disposition within a partially developed dolomite nodule (CCZ10). **(b)** Partially eroded cranium of Cetotheriidae indet., preserved in dorsal disposition within a nodule; the postcrania may have been destroyed by erosion (CCZ23). **(c)** Skull, mandible, teeth, and ear bones of Kentriodontidae s.l. n. sp. preserved in ventral disposition and within a nodule (CCZ3). **(d)** Vertebra of Phocidae indet. within a partial nodule with associated internal molds of *Turritella* and other gastropods (CLQC25). **(e)** Rib of Mysticeti indet. displaying shark tooth marks (CLQC11).

At the study site, the P1-P2 passage is marked by the sudden appearance of seals and porpoises (Phocoenidae). This renewed fauna corresponds to the ‘CLB vertebrate level’ recognized by [de Muizon and DeVries \(1985\)](#) at the locality of Cerro La Bruja, ca. 10 km further northeast ([Dewaele & de Muizon,](#)

[2024](#)). A faunal turnover is also indicated by the disappearance of the large-bodied cetotheriid species that is very common in the P1 strata, whereas the pontoporiid *Brachydelphis* is found on both sides of the PE0.2 unconformity, as observed in other localities of the East Pisco Basin ([Bianucci & Collareta, 2022](#); [Lambert](#)





**Figure 8.** Teeth of Elasmobranchii (sharks and rays) from Cerro Cadena de los Zanjones. (a,e) *Carcharhinus brachyurus*; (b) *Carcharhinus cf. leucas*; (c,g) *Myliobatis* sp. (the largest specimen corresponds to CLQC28); (d,j) *Cosmopolitodus hastalis*; (f) *Galeocerdo aduncus*; (h) *Carcharias* sp.; (i) *Carcharocles megalodon* (specimen CCZ20); (k,l) *Sphyrna* sp. Specimens in panels (c) and (g) are shown in occlusal view; all other specimens are shown in lingual view. Scale bar equals 2 cm.

& de Muizon, 2013). Based on their relatively low stratigraphic position at the base of P2, the phocoenid fossils from the study site (among which is a well-diagnostic periotic) may be the oldest of the whole basin.

## 6. Concluding remarks

This study provides a comprehensive overview of the Miocene marine vertebrate paleontology and stratigraphy at the locality of Cerros Cadena de los Zanjones, in the Ica River Valley, East Pisco Basin, Peru. In this work, we present a 1:10,000-scale geological map that reports the spatial and temporal distribution of fossil marine vertebrates in the nearby of Cerros Cadena de los Zanjones. Here, the Upper Miocene strata of the Pisco Formation are exposed, including the Tortonian P1 sequence and the Tortonian – Messinian P2 sequence. New and previously published tephrochronological and biostratigraphic dating enabled precise age constraints, shedding light on the temporal span of the fossil assemblage. The Pisco strata exposed in the study area are dated between 9.5–8.6 Ma (P1 sequence) and between 8.4–6.9 Ma (P2). Fossil vertebrates are mostly found in the sandy lower portions of both sequences. They consist of cetaceans, pinnipeds, and bony and cartilaginous fishes. The preservation of the cetacean skeletons, which are often poorly articulated and disposed belly-up, strongly suggests a post-mortem phase of refloating for most carcasses. The taxonomic composition of the vertebrate assemblage resembles that

from the celebrated, nearby locality of Cerro Colorado. A remarkable feature of this assemblage is the abrupt appearance of seals and porpoises and the disappearance of a large-bodied cetotheriid at the P1-P2 boundary. This fossil assemblage conforms to that of the ‘CLB vertebrate level’ reported by previous workers from Cerro La Bruja, providing further evidence of significant faunal novelties during the Late Miocene. In summary, the data presented herein expand our understanding of the Miocene marine ecosystem of the East Pisco Basin, thus offering new insights into the biodiversity and preservation patterns of marine vertebrates along the southeastern Pacific coasts. Furthermore, this work provides a valuable database for future research while contributing to the valorization and conservation of the exceptional paleontological heritage of the Ica Desert.

## Software

The geological map was compiled by scanning hand drafts as black and white TIF files, and then digitizing the line art using the Corel Draw X3 graphics package. The topographic base used for the Main Map was created using the GIS Data processing application Global Mapper 12 to generate contour lines for the 1:10,000 scale topographic base map. The process relied on a digital elevation model (DEM) derived from the Shuttle Radar Topography Mission 26 (SRTM), specifically the SRTM3 dataset provided by the United States Geological Survey (USGS version 2.1). Field data collection was carried out using FieldMOVE (Petroleum

Experts Limited), a digital mapping application designed for geological fieldwork. This tool enables the accurate geolocation of observations and sample positions as well as the measurement of small-scale features directly on digital maps, thus facilitating the efficient gathering and documentation of extensive datasets while enabling real-time visualization of data during fieldwork.

## Acknowledgments

Our gratitude goes to Stefania Malagù, Anna Gioncada, Klaas Post, Christian de Muizon, Felix G. Marx, Marco Merella, Karen Gariboldi, Chiara Tinelli, Thomas J. DeVries, Rodolfo Salas-Gismondi, César Chacaltana, Niels Valencia, Walter Aguirre, Ali Altamirano-Sierra, Manuel Laime-Molina, Eusebio Diaz and Joan Chauca-Luyo, for their support in the field and in the lab as well as for many fruitful discussions on the geology and paleontology of the Pisco strata. We are also grateful to Mike Shand, Jose Cuitiño, Alfredo Zurita, the Associate Editor Jasper Knight and the Editor-in-Chief Mike J. Smith for fruitful and helpful comments and suggestions on this work.

## Disclosure statement

No potential conflict of interest was reported by the author(s).

## Funding

We acknowledge financial support by the European Union – NextGenerationEU, Mission 4, Component 2 CUP I53D23002070 006. Project Title: BIOVERTICES (BIOdiversity of VERTEbrates In the CEEnozoic Sea). This project is also supported by the Università di Pisa under the ProArcheo 2024 Call for co-funding of Archaeological and Geo-paleontological Research.

## Data availability statement

The data that support the findings of this study are available from the authors upon reasonable request.

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