Electronic Supplementary Material for

Repeated mass strandings of Miocene marine mammals from Atacama Region of Chile point to sudden death at sea

Nicholas D. Pyenson, Carolina S. Gutstein, James F. Parham, Jacobus P. Le Roux, Catalina Carreño Chavarria, Holly Little, Adam Metallo, Vincent Rossi, Ana M. Valenzuela-Toro, Jorge Velez-Juarbe, Cara M. Santelli, David Rubilar Rogers, Mario A. Cozzuol and Mario E. Suárez

*To whom correspondence should be addressed. E-mail: pyensonn@si.edu

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1. Supplementary figures

Figure S1. Light and SEM characterization of sediment from Cerro Ballena. A, light microscopy and B, high magnification image of A, showing angular grains of quartz, pyroxene, and feldspar, along with interstitial weathering products (e.g., clays) and Fe oxide minerals (orange). Siliceous diatom frustules or other definitive algal cell fragments are absent. C, Quartz sand grain with a surface cavity filled with micro- and nano-sized mineral grains. D, higher magnification imaging of minerals in e, identified as apatite spheres (Ap), Fe oxides (Fe), clays, and other weathering products as determined by EDS analysis (data not shown). E, thin-section of concretion showing sand grains encrusted in Fe-oxide minerals and other weathering products (e.g., clays). F, higher magnification image showing nanocrystalline Fe oxide- and clay-rich encrustations in E.
Figure S2. Dense 3D extraction from 359 source images of “La Familia” (MPC 665, 666, 667). A, 50 million pixel point cloud datasets. B, uncalibrated digital elevation maps of 3D points. C, fully color textured 3D surface model.
Figure S3. Phocidae from Cerro Ballena. A-B, *Acrophoca*, left scapula in lateral view and C-D, left femur in anterior view. E-F, new phocid morphotype, left humerus in lateral view. Abbreviations: Dc, deltopectoral crest; Gc, glenoid cavity; Gt, greater trochanter; Hf, head of femur; Is, infraspinous fossa of the scapula; Le, lateral epicondyle; Me, medial epicondyle; Ps, patellar surface; Ss, scapular spine; Sus, supraspinous fossa of the scapula. Scale bars equal 3 cm.
Figure S4. A fossil balaenopterid from Cerro Ballena, MPC 658. A, in the field 2011, ventral surface facing stratigraphic down. B-C, partially prepared skull, with associated skeletal material and features of the vertex highlighted in 2012. Abbreviations: Apmx, ascending process of the maxilla; Hum, humerus; Na, nasal aperture; Nas, nasals; Pa, parietal; So, supraoccipital; Tym, tympanic bulla. Scale bar equals 10 cm.
Figure S5. Physeteroidea from Cerro Ballena. A-C, three lower teeth from MPC 691, exhibiting rugose enamel caps. D, MPC 705, a right periotic.
Figure S6. *Odobenocetops* (SGO.PV. 21610) material from Cerro Ballena. A, distal left and B, right tusks. Other skeletal remains include a partial cranium and incomplete postcrania.
Figure S7. *Thalassocnus natans* from Cerro Ballena. A-B, mandible in lateral views, C-D, in medial views, and E-F, in occlusal view. G-H, femur in anterior views, I-J, femur posterior view, and K-L, distal view. Abbreviations: a.m1, alveolus for lower molar 1; a.m2, alveolus for lower molar 2; a.m3, alveolus for lower molar 3; cc, coronoid canal; fc, fovea capitis; gt, greater trochanter; h, head; lc, lateral condyle; le, lateral epicondyle; lt, lesser trochanter; mc, medial condyle; me, medial epicondyle; n, neck; pr, parasagittal ridge; ps, patellar surface; tf, trochanteric fossa; tt, third trochanter. Diagonal lines represent broken surfaces.
Figure S8. Rose diagram plots of rorqual skeleton by bone-bearing level (BL1-4) at Cerro Ballena. A-D, dominant modes of orientation (long axis of the body) in teal, red lines denote mean orientations, with 95% confidence intervals. Zero degrees represents true north.
Figure S9. Shark teeth from Cerro Ballena, all assigned to *Carcharodon hastalis*. A, MPC 641, an upper lateral tooth. B, MPC 642, an upper anterior tooth. C, MPC 643, an upper anterior tooth.
Figure S10. Invertebrate trace fossils from Cerro Ballena. A-B, *Ophiomorpha* burrows, whose pellets have been partially removed by erosion. C, long and straight vertical tubes, superficially resembling *Skolithos*. Pen length approximately 10 cm. D, *Psilonichnus*. E, *Thalassinoides*. 
Figure S11. A) Frilly structures below ripple marks at Cerro Ballena (see figure 2a), which are similar to B and C), interpreted as algal structures in the literature (from Mayall and Wright [main text Ref. 47]).
2. Supplementary Methods

A. Estimating sedimentation rates at Cerro Ballena

In the absence of any absolute dates, our estimations for sedimentation rates within the Bahía Inglesa Formation at Cerro Ballena are limited to comparisons with actualistic work on tidal flats. Morton and Holmes ([1], p. 519) reported an average sedimentation rate from 0.13 to 0.96 mm/yr and average 0.57 mm/yr for tidal flats similar to those inferred for the depositional environment at Cerro Ballena. Assuming a similar sedimentation rate of this order, it implies a period of roughly 16,000 yr for the deposition of a 9 m succession at Cerro Ballena. If the average sedimentation rate was slightly higher, around 1 mm/yr, Cerro Ballena might consist of ~10,000 yr of deposition. The general rise in sea-level suggested by the stratigraphy and age correlation with transgressive beds further to the south makes large-scale regressive erosion of the succession at Cerro Ballena very unlikely, so that a more or less constant sedimentation rate can be assumed.

B. Supplementary notes on the stratigraphy and sedimentology

Areal extent. Godoy et al. [2] provided the basis for estimating the areal extent of the Bahía Inglesa Formation at Cerro Ballena. The areal outcrop of this unit in the area of the Pan-Amerian Highway indicates as much 2 km² of the Bahía Inglesa Formation is deposited in the area to the west and east of the roadcut at Cerro Ballena.

Subdivisions of the Bahía Inglesa Formation. Walsh & Suárez [3] and Walsh & Martill [4] are the only authors to have proposed formal subdivisions to the Bahia Inglesa Formation. However, the stratigraphic section presented in both those papers (it is the same graphic) does not lineate the stratigraphic relationships among the different proposed members across a wide geographic area that is separated by multiple faults.
Our group’s extensive fieldwork in this same area, since 2009, has sought to clarify the relationships of these fault-bounded sections, but we have failed to identify all three members consistently, at any one locality. More critically, the section of Bahía Inglesa Formation where Cerro Ballena is located is too far north to be correlated to any of the localities or recognized members in the stratigraphic columns of these papers.

*No evidence for tsunami deposits.* In terms of concentration mechanism for marine vertebrate carcasses at Cerro Ballena, we propose that they were delivered to south-facing embayment, protected from normal wave action by basement rocks and a barrier bar to the west (figure 1b). We also infer the presence of an estuary south of the supratidal flat, due to the occurrence here of tsunami backflow deposits, consisting of large blocks ripped up from the substrate [4,5]. Tsunamis and their backflows are commonly accentuated along coastal inlets [6]. The fossiliferous succession at Cerro Ballena shows no evidence of high-energy events, however, so that these deposits are not chronologically related.

### C. Further notes on the geologic age

At Cerro Ballena, there were two biostratigraphically useful vertebrate fossils that co-occur in the Mio-Pliocene Pisco Formation of Peru: aquatic sloths (*Thalassocnus*) and sharks (*Carcharodon*). The type specimen of *Thalassocnus natans* was originally reported from the Sud-Sacaco Horizon (SAS [West] sensu [7]) at the Sud-Sacaco locality of the Pisco Formation in the Sacaco Basin of southern Peru. However, the source horizon for the type specimen was subsequently corrected in a follow-up publication [8] indicating that *T. natans* originates from the stratigraphically older Montemar Horizon (MTM). Recently, fossil mollusc samples from MTM yielded $^{87}\text{Sr}/^{86}\text{Sr}$ dates of 8.70–6.45 Ma, with a mean date of 7.30 Ma [9]. These dates are
broadly congruent with coarser biostratigraphic estimates that were previously presented for the age of the MTM horizon [8].

A recent revision of the taxonomy of fossil *Carcharodon* from Peru indicated that *Carcharodon hastalis* from the Pisco Formation in the Sacaco Basin was part of a chronospecies distributed in the El Jahuay (ELJ) horizon, whereas *C. hubbelli* and *C. carcharias* were recovered from stratigraphically younger units [9]. Although previous K-Ar dating of the Alto Grande tuff bed in the ELJ horizon yielded an age of 9.5 Ma, recent strontium dating from shell layers overlying this tuff bed produced an age range of 9.03–6.51 Ma, with a mean of 7.46 Ma. Thus, the strontium age ranges for ELJ are slightly older, on average, than those for the MTM horizon.

This age correlates with a strontium date of 6.8 Ma obtained from Unit 5 of Achurra [10], which consists of fine-grained sandstones and shales hosting fossiliferous phosphate beds, previously described by [3,4], among others.

**D. Capturing, processing and rendering 3D digital datasets**

A large set of digital data was collected on-site from Cerro Ballena from 2010-2012. However, three-dimensional (3D) datasets were collected only during the second field campaign, in November 2011. Three-dimensional digitization is a relatively new discipline in visual information that broadly covers a variety of nascent approaches to capturing, rendering, archiving and visualizing information from physical environments in three dimensions. Three-dimensional digitization can also involve the synthesis of datasets from two-dimensional (2D) information, such as photography. Fossilized tissues provide ideal surface textures for image capture, but the application of 3D digitization approaches for paleontological studies is relatively new.
At Cerro Ballena, 3D digitization complemented the acquisition of traditional documentation using 2D images using the following approaches: we used an articulated laser arm scanner for collecting high resolution 3D data (±0.041 mm volumetric accuracy using the Faro Edge Arm scanner); medium range laser scanners (using the Faro Focus); and photogrammetric and computer vision (using a Canon 5D with multiple lenses). It is worth noting that the functional resolution of the Faro Edge Arm depends on the surface quality of the object (i.e., dark or shiny objects tend to produce noise). Photogrammetry accuracy and resolution also varies based on camera resolution, surface detail and distance from the subject. Because of the logistical challenges in providing a stationary base and calibration, we restricted use of the Faro Edge Arm scanner to collect data on the most complete and well-articulated fossil rorqual (MPC 677; see figure 3). By late November 2011, only a fraction of the fossil marine mammal skeletons that were exposed during road excavation remained for collecting 3D data. For these remaining skeletons (MPC 665, 666, 667, 675, 678, 684, 685; see figure 4), we collected a variety of 2D and 3D as time constraints allowed. We collected 2D images of these remaining skeletons for photogrammetric 3D reconstruction.

Generally, the goal for this latter effort was to maximize physical, photographic coverage of the specimens’ topography of the resultant 3D point cloud dataset. Photogrammetry often deals with varying datasets and varying image quality, but it was the most efficient approach, given the scope of fossil material to capture and under the pressing time constraints during the November 2011 work at Cerro Ballena. URC Ventures (Redmond, Washington) also created orthogonal renderings from 3D point cloud data of fossil rorqual skeletons from Cerro Ballena using a similar workflow, as illustrated in figure S2. The resultant 3D point cloud datasets provided sub-cm accuracy, and full resolution texture mapped imagery. Both 3D polygon and 3D point
cloud datasets are amenable to 3D printing, at scales dependent on printer resolution and envelope size.

3D rendered surface models for 7 different fossil rorquals from Cerro Ballena used high dynamic range (HDR) imaging (figure 4). HDR images of the 3D rendered models were created on the final, rendered TIFF files with multiple bracketed exposures combined into an HDR image and then tone mapped for both print and online publication using Oloneo PhotoEngine. Full resolution versions of the images, along with high-resolution versions of figure 4, are freely available for download at http://cerroballena.si.edu. Please see this website for additional digital imagery and time-lapse videos documenting our efforts at Cerro Ballena.

E. SEM and EDS analysis of sediment and bone samples from Cerro Ballena

In 2012, we collected bone and sediment samples from each bone-bearing level at Cerro Ballena by covering freshly excavated surfaces in optically clear resin (Epo-Tek 301, from Epoxy Technology in Billerica, Massachusetts). Embedded samples were then cut and thin-sectioned for scanning electron microscopy and electron spectroscopy at the Department of Mineral Sciences at the National Museum of Natural History, in Washington D.C. We used an FEI Nova NanoSEM 600 under low vacuum with the gaseous analytical detector (GAD) for imaging and an energy dispersive X-ray spectroscopy detector (EDS; ThermoFisher) for geochemical analysis. Samples were either placed directly on carbon-tape or imbedded in epoxy and thin-sectioned, and left uncoated for SEM and EDS characterization (figure S1). Light microscopy was performed using an Olympus BX51 microscope with a Chameleon digital video camera.

In all samples, we observed localized areas enriched in nano- to micro-particulate iron oxide minerals between grains of pyroxene, quartz, feldspar, clays and
other minerals, as well as coating bone fragments. We further observed abundant apatite spherules, typically 5-10 µm in diameter with several larger (up to 20 µm) diameter spherules, in several samples. Although this size range is close to that of dinoflagellate cysts or cyanobacteria, the biogenicity of these spherules cannot be definitively confirmed. Fossilized algal diatom frustules or other microbial cells were not observed in any of the unaltered and thin-sectioned samples from each bone-bearing level. Alternate biogenic explanations for these spherules include their origin as phosphatized invertebrate pellets [11] or small colloidal spheres delivered from possible guano-rich seabird nesting areas [12] on rocky prominences to the west of Cerro Ballena.

While the dinoflagellate fossil record extends back in geologic time to Mesozoic era, the antiquity of HAB taxa is obscure. For example, we do not know of any fossil record for toxic diatoms. For dinoflagellate taxa linked to HABs, the sole study on a molecular phylogeny with fossil calibration [13] yields a late Paleogene to early Neogene divergence time for dinoflagellates in the Alexanderia tamarense complex, which includes HAB species. While this timeframe is clearly consistent with the findings of our study, we hesitate to link these results to our study, given the difficulty in assigning a specific HAB taxon as a casual agent at Cerro Ballena.
3. Supplementary Tables

Table S1. Reconstructed total lengths (TL) of fossil rorquals from Cerro Ballena.

Measurements used to reconstruct body size include skull bizygomatic width (BIZYG), skull condylobasal length (CBL), mandible chord length (Ch), and occipital condyle breadth (OCB).

| Specimen   | BL level | TL (m) | Proxy | Reference and notes |
|------------|----------|--------|-------|---------------------|
| MPC 660    | BL1      | 3.85   | Ch    | [14]                |
| MPC 665    | BL1      | 5.16   | Ch    | [14]                |
| MPC 669    | BL1      | 7.13   | Ch    | [14]                |
| MPC 667    | BL1      | 7.93   | Ch    | [14]                |
| MPC 666    | BL1      | 8.71   | Ch    | [14]                |
| MPC 673    | BL1      | 8.73   | BIZYG | [14]                |
| MPC 662    | BL1      | 8.95   | Ch    | [14]                |
| MPC 653    | BL1      | 10.45  | Ch    | [14]                |
| MPC 658    | BL1      | 10.82  | CBL (=Ch) | [14] |
| MPC 682    | BL2      | 3.11   | Ch    | [14]                |
| MPC 677    | BL2      | 6.65   | TL    | [14]; TL present, but calculated from mandible |
| MPC 675    | BL2      | 6.75   | BIZYG | [15]                |
| MPC 672    | BL2      | 7.79   | Ch    | [14]                |
| MPC 650    | BL2      | 8.10   | OCB   | [15]                |
| MPC 678    | BL2      | 8.45   | Ch    | [14]                |
| MPC 676    | BL2      | 11.18  | Ch    | [14]                |
| MPC 684    | BL3      | 6.92   | Ch    | [14]                |
| MPC 688    | BL3      | 8.34   | Ch    | [14]                |
| MPC 679    | BL4      | 6.72   | Ch    | [14]                |
| MPC 685    | BL4      | 7.86   | Ch    | [14]                |
| MPC 687    | BL4      | 11.29  | Ch    | [14]                |
Table S2. Frequency of articulation stages, by bone-bearing level (BL) of all marine vertebrates specimens at Cerro Ballena. Counts reflect number of individual specimens (NISP). Abbreviation: MNI, minimum number of individuals. See Section B in Supplementary Text, for more details on scores and stages.

| BL level | Stage 1 | Stage 2 | Stage 3 | Notes |
|----------|---------|---------|---------|-------|
| BL-4     | 1       | 2       | 2       |       |
| BL-3     | 1       | 0       | 0       |       |
| BL-2     | 4       | 4       | 15      | 8 of 15 in Stage 3 are phocids, represented by MNI = 3 |
| BL-1     | 10      | 5       | 5       |       |

Table S3. Frequency of articulation stages, by bone-bearing level (BL), of individual balaenopterid specimens at Cerro Ballena. Counts reflect number of individual specimens (NISP). See Section B in Supplementary Text, for more details on scores and stages.

| BL level | Stage 1 | Stage 2 | Stage 3 |
|----------|---------|---------|---------|
| BL-4     | 1       | 2       | 0       |
| BL-3     | 1       | 0       | 0       |
| BL-2     | 4       | 2       | 4       |
| BL-1     | 10      | 4       | 1       |

Table S4. Descriptive statistics for rose diagrams of rorqual skeleton orientation (long axis of the body). Data arranged by bone-bearing level (BL) at Cerro Ballena. Note that none of the correlation values are significant. See Section B in Supplementary Text, for more details on scores and stages.

|        | BL1     | BL2     | BL3     | BL4     |
|--------|---------|---------|---------|---------|
| Mean angle | 118.80  | 47.10   | 123.80  | 86.50   |
| Directionality | 0.43    | 0.50    | 0.84    | 0.84    |
| \( p \)-value | 0.06    | 0.14    | 0.12    | 0.12    |
| Chi\(^2\) | 6.07    | 3.00    | 3.67    | 3.67    |
| \( n \) | 15      | 8       | 3       | 3       |
Table S5. Average of scatter of cetacean carcasses at Cerro Ballena, by bone-bearing level (BL), measured from quarry maps. Counts reflect number of individual specimens (NISP). See Section C, on taphonomy and thereafter, for more details on scores and stages.

| BL level | Scatter (m) | NISP |
|----------|-------------|------|
| BL-4     | 2.77        | 3    |
| BL-3     | 2.21        | 3    |
| BL-2     | 2.80        | 8    |
| BL-1     | 3.45        | 14   |

Table S6. Average of scatter of only balaenopterid carcasses at Cerro Ballena, by bone-bearing level (BL), measured from quarry maps. Counts reflect number of individual specimens (NISP). See Section B in Supplementary Text, for more details on scores and stages.

| BL level | Scatter (m) | NISP |
|----------|-------------|------|
| BL-4     | 2.77        | 3    |
| BL-3     | 2.21        | 3    |
| BL-2     | 2.80        | 7    |
| BL-1     | 3.54        | 13   |
Table S7. Counts of minimum number of individual (MNI) for fossil marine vertebrates at Cerro Ballena, by bone-bearing level (BL), measured from quarry maps. A) Balaenopteridae; B) Delphinoidea; C) Physeteroidea; D) *Odobenocetops* sp.; E) *Acrophoca* sp.; F) Phocidae n. gen.; G) *Thalassocnus natans*; H) *Carcharodon hastalis*; I) Istiophoridae; J) Xiphiidae. See Section B in Supplementary Text, for more details on scores and stages.

| BL level | A | B | C | D | E | F | G | H | I | Sum |
|----------|---|---|---|---|---|---|---|---|---|-----|
| BL-4     | 3 | 0 | 0 | 0 | 0 | 0 | 1 | 0 | 0 | 4   |
| BL-3     | 3 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 3   |
| BL-2     | 10| 0 | 1 | 0 | 2 | 1 | 0 | 1 | 2 | 17  |
| BL-1     | 15| 1 | 0 | 1 | 0 | 0 | 1 | 0 | 0 | 18  |
| Totals   | 31| 1 | 1 | 1 | 2 | 1 | 1 | 2 | 2 | 42  |
Table S8. Frequency of bone abrasion stages, by bone-bearing level (BL) of all marine vertebrates specimens at Cerro Ballena. Counts reflect number of individual specimens (NISP). See Section B in Supplementary Text, for more details on scores and stages.

| BL level | Stage 0 | Stage 1 | Stage 2 | Stage 3 |
|----------|---------|---------|---------|---------|
| BL-4     | 0       | 2       | 1       | 1       |
| BL-3     | 0       | 1       | 0       | 0       |
| BL-2     | 0       | 8       | 7       | 3       |
| BL-1     | 0       | 6       | 5       | 0       |

Table S9. Frequency of bone abrasion stages, by bone-bearing level (BL), of individual balaenopterid specimens at Cerro Ballena. Counts reflect number of individual specimens (NISP). See Section B in Supplementary Text, for more details on scores and stages.

| BL level | Stage 0 | Stage 1 | Stage 2 | Stage 3 |
|----------|---------|---------|---------|---------|
| BL-4     | 0       | 1       | 1       | 0       |
| BL-3     | 0       | 1       | 0       | 0       |
| BL-2     | 0       | 4       | 1       | 0       |
| BL-1     | 0       | 5       | 2       | 0       |
Table S10. Frequency of weathering stages, by bone-bearing level (BL) of all marine vertebrates specimens at Cerro Ballena. Counts reflect number of individual specimens (NISP). See Section B in Supplementary Text, for more details on scores and stages.

| BL level | Stage 0 | Stage 1 | Stage 2 | Stage 3 |
|----------|---------|---------|---------|---------|
| BL-4     | 1       | 1       | 2       | 0       |
| BL-3     | 0       | 0       | 1       | 0       |
| BL-2     | 3       | 8       | 6       | 1       |
| BL-1     | 0       | 5       | 5       | 1       |

Table S11. Frequency of weathering stages, by bone-bearing level (BL), of individual balaenopterid specimens at Cerro Ballena. Counts reflect number of individual specimens (NISP). See Section B in Supplementary Text, on taphonomy and thereafter, for more details on scores and stages.

| BL level | Stage 0 | Stage 1 | Stage 2 | Stage 3 |
|----------|---------|---------|---------|---------|
| BL-4     | 0       | 0       | 2       | 0       |
| BL-3     | 0       | 0       | 1       | 0       |
| BL-2     | 1       | 0       | 4       | 0       |
| BL-1     | 0       | 4       | 2       | 1       |
Table S12. Reported and communicated densities for sites with complete, articulated cetacean skeletons. Values are maxima number of individual skeletons; see supplementary text for more details.

| Site             | Value | Notes                                | Sample area (km\(^2\)) | Density per km\(^2\) |
|------------------|-------|--------------------------------------|-------------------------|----------------------|
| Cerro Ballena    | 15    | BL-1, densest layer                  | 0.005                   | 3000                 |
| Pisco Formation  | 300   | Presumably between M25-26 in [68]    | 1                       | 300                  |
| Wadi Al-Hitan    | 70    | Maximum value; average of 14 per km\(^2\) | 200                     | 70                   |
4. Supplementary Text

A. Systematic Paleontology

**Institutional Abbreviations**

MPC, Museo Paleontológico de Caldera, Caldera, Chile; SGO.PV, Museo Nacional de Historia Natural, Santiago, Chile.

VERTEBRATA Lamarck, 1801

CHONDRICHTHYES Huxley, 1880

ELASMOBRANCHII Bonaparte, 1838

LAMNIFORMES Berg, 1958

LAMNIDAE Müller and Henle, 1838

*CARCHARODON* Smith in Müller and Henle, 1838

*CARCHARODON HASTALIS* (Agassiz, 1833)

Referred specimens

MPC 641-643.

Description

MPC 641, an upper lateral tooth. B, MPC 642, an upper anterior tooth. C, MPC 643, an upper anterior tooth. All teeth have smooth mesial and distal edges. The roots are poorly preserved, with MPC 642 and MPC 643 being the most complete. MPC 641, an upper lateral tooth. B, MPC 642, an upper anterior tooth. C, MPC 643, an upper anterior tooth. The anterior teeth (MPC 642, 643) are broad and symmetrical. Although the roots are poorly preserved in the upper teeth, they are flat and seem to have been nearly triangular in outline. The roots of the lower anterior teeth differ in being more
markedly lobed. MPC 641 represents an anterior lateral tooth because it is asymmetrical, being slightly inclined posteriorly.

**Remarks**

The relative position of the teeth was determined based on comparisons with described composite and complete dentitions of related taxa [9,16]. Based on the overall dimensions of the teeth, along with the lack of serrations, we conclude that they belong to *C. hastalis*, a cosmopolitan taxon that has been previously reported from the Bahía Inglesa Formation [17]. A recent review clarified existing discrepancies regarding the age of the different species in this genus, with *C. hastalis* now regarded as a late Miocene species [18].

VERTEBRATA Lamarck, 1801
OSTEICHTHYES Huxley, 1880
ACTINOPTERYGII Klein, 1885
TELEOSTEI Müller, 1846
PERCIFORMES Bleeker, 1859
SCOMBROIDEI Bleeker, 1859
ISTIOPHORIDAE Rafinesque, 1810
ISTIOPHORIDAE gen. et sp. indet.

**Referred material**

MPC 702, nearly complete vertebra and fragment of rostrum.

**Description**

The centrum is anteroposteriorly elongated and has an hourglass shape in lateral view. Both the anterior and posterior surfaces of the centrum are concave (amphicoelous). The neural spine is incompletely preserved, and its anterior end is
obscured by sediment. Posteriorly, the spine is high and long, reaching about 35 mm beyond the posterior surface of the centrum. The rostrum is incomplete, missing its proximal and distal ends, and partially covered by sediment throughout, therefore we cannot discount the presence of denticles on its dorsal and ventral surfaces. In cross section, the rostrum is slightly dorsoventrally flattened, indicating that it might be part of the distal end. Two nutrient canals are present in cross section. A central chamber is absent and a midline suture is present.

**Remarks**

Several morphological features of MPC 702, such as the long and high neural spine and the presence of two nutrient canals, the absence of central chamber and the evident middle suture of the rostrum, are diagnostic of Istiophoridae [19-21]. Previous reports of Istiophoridae from Bahía Inglesa Formation are fragmentary and included cranial and postcranial materials collected from other localities, such as Mina Fosforita, located southeast of Cerro Ballena [22]. Istiophorids are known from late Miocene deposits along the Pacific coast of North America [23-26], although the incompleteness of the Cerro Ballena material precludes us from further comparisons with these other records. Extant billfishes are found in oceanic waters (at least 100 m deep [20]). The presence of istiophorids in the shallow water deposits of Cerro Ballena indicates that this specimen was transported there peri- or postmortem.

**SCOMBROIDEI** Bleeker, 1859

**XIPHIIDAE** Rafinesque, 1810

**XIPHIIDAE** gen. et sp. indet.

**Referred material**

MPC 701, incomplete vertebra.
**Description**

The centrum is relatively square and hourglass shape in lateral view. Both anterior and caudal surfaces of the body are concave. Although both neural and hemal spines are broken, their bases indicate that these are narrow and predominantly dorsally extended. The base of the anterior and posterior neural zygapophyses is expanded and dorsally directed.

**Remarks**

The relatively square shape of the centrum, the narrow and extended neural and hemal spines, and the presence of prominent and dorsally directed anterior and posterior neural zygapophyses are all characteristic of the family Xiphiidae [20]. This is the first record of this taxon from the Bahía Inglesa Formation.

VERTEBRATA Lamarck, 1801
MAMMALIA Linnaeus, 1758
EUTHERIA (Huxley, 1880)
CARNIVORA Bowdich, 1821.
PINNIPEDIA Illiger, 1811
PHOCIDAE Gray, 1821
ACROPHOCA Muizon, 1981

*ACROPHOCA SP.*

Figure S3a-d

**Referred specimens**

SGO.PV 21563, left scapula; SGO.PV 21565, left femur; SGO.PV 21564, left tibia; SGO.PV 21566, left astragalus; SGO.PV 21567, indeterminate rib; SGO.PV 21568, left metacarpus 1; MPC 692, five thoracic vertebrae and indeterminate ribs.
Description

Scapula. SGO.PV 21563 (figure S3a,b) is an incomplete left scapula that preserves the glenoid cavity, proximal end of the scapular spine, the base of the acromion process and the proximal section of the supraspinatus and infraspinatus fossae. The glenoid cavity is mediolaterally flattened. The scapular spine is broken. The acromion process is incomplete but the width of the base shows that it was poorly developed. The infraspinatus fossa is deep and has approximately the same size of the supraspinatus fossa.

Femur. SGO.PV 21565 (figure S3c,d) consists of a left femur that is anteroposteriorly flattened and lacks a lesser trochanter. The greater trochanter is incomplete in its proximal section, although it is slightly smaller than the head. The trochanteric fossa is very shallow. The pectineus muscle insertion is faint and located distal to the head of the femur. The head is complete, but partially damaged at the level of the fovea for the teres femoris ligament, which is reduced. The distal section of the medial condyle is incomplete. The lateral condyle is incomplete but its base is rounded in shape. In anterior view, the caudal region of the shaft is partially covered with sediment, but is possible to see a shallow concavity, principally in the lateral half.

Tibia. SGO.PV 21564 is an incomplete left tibia without proximal and distal ends. The tibia is straight, slightly lateralized in the proximal third. The fossa for m. tibialis anterior is deep and reaches the end of the first third. The fossa of m. tibialis posterior is deep and proximodistally elongated.

Astragalus. SGO.PV 21566 is an incomplete left astragalus with sustentacular and ectal facets, broadly separated by a wide interarticular medial sulcus immediately anterior to the caudal process. The ectal facet is incomplete in its caudal end. The calcaneal process of the astragalus is mostly broken, but its incomplete base indicates
the presence of this process. The navicular facet is preserved and the sustentacular facet is short.

**Rib.** SGO.PV 21567 is an incomplete rib. It is assigned to *Acrophoca* by its association with other material identified to this genus.

**Metacarpus.** SGO.PV 21568 is a left metacarpus 1 with the distal section broken. The proximal section is rounded and smooth.

**Vertebrae and ribs.** MPC 692 corresponds to five articulated thoracic vertebrae associated with seven fragments of ribs. The vertebrae are almost complete and partially covered by sediment. The neural spine is low relative to the size of the centrum. The fovea costalis cranialis and caudalis are present in all specimens and it is relatively large. The accurate position of the vertebrae are uncertain because all caudal processes and transverse processes are incomplete, however they probably correspond to the posterior half of the thoracic sequence.

PINNIPEDIA Illiger, 1811

PHOCIDAE Gray, 1821

PHOCIDAE, nov. gen. et sp.

Figure S3e-f

**Referred specimens**

SGO.PV 21569, left humerus.

**Description**

SGO.PV 21569 is a left humerus that is small in size, short and robust, with fused epiphyses, a slightly porous surface with well-developed muscle insertions, which are indicative of physical maturity, even at its relatively small size. The deltopectoral crest is strongly developed, elongate, and it reaches two thirds of the length of the shaft.
and ends smoothly. The supinator ridge is poorly developed and the entepicondylar foramen is absent. The medial tuberosity is slightly higher than the head of the humerus.

**Remarks**

Until now, two phocids have been reported from late Miocene strata of the Bahía Inglesa Formation: *Piscophoca* and *Acrophoca*, which are medium to large sized phocids, respectively, previously described for the Pisco Formation of Peru. Based on the poorly developed acromion process and the relatively large size of the infraspinatus fossa of the scapula (figure S3a,b), the very shallow trochanteric fossa and the overall size of the femur (figure S3c,d), the relatively small size of the tibia (SGO.PV 21564), the relatively shorter sustentacular facet of the astragalus (SGO.PV 21566) and the overall large size of the vertebrae (MPC 692), these materials are assigned to the genus *Acrophoca* [22, 27, 28]. Due to the poor diagnostic potential of the rib (SGO.PV 21567) and metacarpus (SGO.PV 21568), it is not possible make a more precise identification, although they are assigned to *Acrophoca* because of their close physical association with other *Acrophoca* material from Cerro Ballena.

Moreover, the humerus (figure S3e,f) exhibits evidence of physical maturity, despite its relatively small size. Pending future studies on its body size and taxonomic identity, these findings nonetheless suggest a greater diversity of phocids during the late Neogene in the eastern South Pacific Ocean that previously reported.

Appendicular materials assigned to *Acrophoca* and the new morphotype were found forming an isolated cluster, while vertebrae (MPC 692) assigned to *Acrophoca* were found approximately 100 meters northeast from the rest of the phocid materials. Therefore, the preliminary minimum number of individuals (MNI) index of phocids from Cerro Ballena is three.
MAMMALIA Linnaeus, 1758
EUTHERIA Huxley, 1880
CETACEA Brisson, 1762
MYSTICETI Cope, 1891
BALAENOPTERIDAE Gray, 1864
BALAENOPTERIDAE, gen. et sp. indet.

Figure S4a-c

**Referred specimens**

A series of near-complete or complete specimens, MPC 645, 646, 650, 652, 653, 657, 658, 659, 660, 662, 663, 665, 666, 667, 669, 670, 671, 672, 673, 674, 675, 676, 677, 678, 679, 681, 682, 684, 685, 686, 687, 688.

**Description**

Balaenopteridae from Cerro Ballena are identified from at least 31 individuals (and likely more; see below). This collection of specimens includes an ontogenetic size range, from calves that are likely yearlings, immature and adult specimens, based on their reconstructed body sizes (see **Size estimation**, below). Generally, these skeletons are diagnosed as belonging to Balaenopteridae based on the following traits: mandibles bowed, with an elevated, laterally projecting coronoid process [29-31]; a posteriorly directed and hemispherically shaped articular condyle that is separated from a comparatively smaller, angular process by a pterygoid fovea [14]; and a relatively small, tubular bony aperture for the mandibular foramen [14]; a vertex that exposes ascending processes of the maxillae and premaxillae that together abut an anteriorly flattened termination of the supraoccipital shield [32-34]; and a vertex that is dorsally elevated, in a tabular, stepped fashion from the level of the supraorbital processes of the frontals [33,34].
Remarks

The fossil balaenopterids at Cerro Ballena exhibit several differences from existing, comparable taxa. Notably, the coronoid process of the mandible is somewhat triangular (e.g., MPC 665), and not spatulate as in extant *Balaenoptera* spp. Also, the postcoronoid fossa (sensu [34]) is reduced. Importantly, the cranial vertex of the fossil balaenopterids from Cerro Ballena, exemplified by MPC 658 (figure S4) shows features that are not shared by any described fossil or extant balaenopterid, although there are similarities with *Balaeonoptera siberi*. For example, the nasals in MPC 658 are 6 cm long, and 4 cm wide, with a sharp medial tapering that produces a triangular appearance unlike the comparatively thin and elongate nasals of *Parabalaenoptera*, *Archaeobalaenoptera*, “*Megaptera*” *hubachi*. The length and width of the nasals in *Balaeonoptera siberi* is proportionately similar to those in MPC 658, but the anterior margin *B. siberi* is even and does not taper medially. In MPC 658, the ascending processes of the maxillae have a rectilineal termination at the same level of the posterior margin of the nasals. The supraoccipital shield is relatively narrow, with a sharp anterior margin like *Parabalaenoptera*, but unlike *Archaeobalaenoptera*. Lastly, the anterior margin of the parietal, near the intertemporal constriction along the medial cranial surfaces of the temporal fossa, forms an acute triangular projection much like “*Megaptera*” *hubachi* [34]. Given the extensive amount of comparative material still unprepared, including skulls with intact tympanoperiotics, we think it is conservative to restrict the assignment of material from Cerro Ballena to the taxonomic level of Balaenopteridae. It is entirely possible that Cerro Ballena preserves multiple species of Balaenopteridae, given that extant rorquals live in sympatric assemblages [35] and occasionally strand in multispecies death assemblages [36]. It also possible that non-balaenopterid mysticetes are preserved in field jackets, awaiting preparation, but we
have not observed any evidence to suggest the presence of mysticete lineages other than rorquals at Cerro Ballena.

**Size estimation**

We reconstructed the body size (i.e., total length) of individual fossil Balaenopteridae specimens in the Cerro Ballena assemblage using several different proxy measurements. Body size proxies identified by [15] provide the basis for estimating total length (TL), a standard measurement in cetology, from specific skull measurements for a diverse range of cetaceans. Besides skull proxies, the significantly strong allometry between skull length and mandible length in mysticetes provides an additional proxy for estimating TL. Here, we used the latter (specifically, chord length of the mandible) to estimate body size in rorquals from Cerro Ballena (table S1). For some specimens that lacked mandibles (e.g., MPC 673), we used skull proxies; conversely, for MPC 658 we used condylobasal length of the skull instead of mandible length to estimate size. MPC 650 possesses an occipital condyle breadth (OCB) the same size as *Parabalaenoptera bauliensis*, an approximately contemporaneous balaenopterid species from the late Miocene of California and we used the best estimate for its TL reported by [15].

CETACEA Brisson, 1762

ODONTOCETI Flower, 1865

PHYSETEROIDEA Gray, 1821

PHYSETEROIDEA, gen. et sp. indet.

Figure S5a-d

**Referred specimens**
MPC 691, an associated collection of partial skull fragments and 26 upper and lower teeth; and MPC 705, an isolated left periotic.

**Description**

MPC 691 consists of an incomplete skull of unknown elements because it is not fully prepared. However, in the field, the skull was associated with 26 teeth that were distributed in an area ~2 m² near the skull. Five of these teeth were prepared in 2012, and we identified four lower teeth and one upper tooth from this sample (see [37] for criteria). Teeth range from 85-110 mm in straight-line length, with crown heights between 15-24 mm, and crown base diameters between 12-16 mm. The crowns of some of these teeth are broken because of tooth wear, but they all show tooth enamel with a rugose surface that is not constricted at the base of the crown, and a long, tubular, gibbous root with an open pulp cavity.

MPC 705 is a left periotic approximately 40 cm in anteroposterior length, measured following the terminology of [37]. The articular surface of its posterior process is expanded, concave and very lightly fluted. The pars cochlearis is relatively large, compared to the body of the periotic, and there is notable peak medial to the fenestra rotunda. The lateral tuberosity is angular and extends laterally from the parabullary ridge (sensu [38]). The anterior process exhibits a large accessory ossicle, and a bifid anterior termination, with a prominent ventrolateral angle (or apex, sensu [39]). Viewed laterally, the overall body of the periotic displays a marked L-shape.

**Remarks**

Based entirely on the crown and root morphology of the dentition, material belonging to MPC 691 is diagnostic to Physeteroidea, to the exclusion of other odontocetes. Living physeteroids (Physeteridae + Kogiidae) have tooth crowns that are entirely free of enamel [39-41]. The dentition of MPC 691 is similar to described fossil
physetertoid teeth that fall in the morphotype of *Scaldicetus* spp. that has been identified globally in Miocene-Pleistocene marine deposits [39-41]. Recently described fossil physetertoids that are phylogenetically placed outside of crown Physeteroidea show the widespread occurrence of this tooth morphotype with different cranial morphologies, such as *Zygophyseter* [39], and *Acrophyseter* [41].

MPC 705 is an isolated element recovered during on-site dry sieving of quarry material in 2012. It is possible that MPC 705 belongs to the same individual as MPC 691, although it was recovered >10 meters away, in loose sediment towards the end of excavation efforts. We do not find this proximity especially compelling for individual association, especially in comparison with the density of associated skeletal material from Cerro Ballena across horizons BL1-4. The overall morphology of MPC 705 is broadly congruent with periotic morphology described for stem physeteroids [40] and the presence and partial fusion of an accessory ossicle of the tympanic bullae on the anterior process is a diagnostic trait for physeteroids (figure S5d). We suspect that this periotic likely represents a currently unidentified physeteroid, as it does not match existing taxa, and comparative studies examining extant and fossil physeteroid tympanoperiotics remain much needed.

**ODONTOCETI** Flower, 1865

**DELPHINOIDEA** Gray, 1821

**DELPHINOIDEA**, gen. et sp. indet.

**Referred specimens**

MPC 649, associated skeletal elements consisting of two incomplete vertebrae (a thoracic and lumbar vertebra), along with rib fragments, a partial scapula and an incomplete ulna, collected in 2011.
**Description**

MPC 649 was collected in 2011 from the main quarry and later prepared in 2012. MPC 649 consists of two vertebrae, in close association, that represent a mid-thoracic vertebra and a post-thoracic vertebra, both approximately 10 cm in dorsoventral height, from the base of the vertebral centrum to the preserved top of the neural spine. The thoracic vertebra was recovered in direct contact with a rib fragment and the articular end of an incomplete scapula. MPC 649 was also associated with fragmentary distal limb elements, including a possible ulna.

**Remarks**

Although most fragments of MPC 649 do not permit a more precise identification beyond Odontoceti, the overall morphology is broadly comparable to extant delphinids, and most closely shares a size range with adult individuals belonging to the genera *Stenella* or *Lagenorhynchus*. Overall, this material could be assigned to Delphinidae, but we argue that assignment of this material to Delphinoidea is more appropriate, pending future comparisons in more detail.

ODONTOCETI Flower, 1865

ODOBENOCETOPSIDAE Muizon, 1993

*ODOBENOCETOPS* Muizon, 1993

*ODOBENOCETOPS* sp.

Figure S6a,b

**Referred specimens**

SGO.PV. 21610, partial skull, right and left tusks, a second cervical vertebra and ribs.

**Description**
The specimen consists of a partial skull, including the occipital, right parietal, right squamosal (including the right glenoid fossa), posterior portions of the maxilla and the frontal (including a part of the right orbit), and incomplete parts of the basioccipital, right palatine, right pterygoid, and portions of both premaxillary tusks (figure S6a,b). These skeletal elements were all associated in an area of approximately 12 square meters.

The skull is characterized by a very conspicuous configuration of the dorsal bones of the braincase that are unique to *Odobenocetops*, to the exclusion of all other known cetaceans. The posterodorsal portion of the skull is elevated, but with a wide exposure of the parietals. The ascending processes of the maxillae are poorly delineated, and restricted to the medial portion of the braincase in dorsal view, leaving the temporal fossa opened dorsally, in contrast to other delphinidans. Other diagnostic characteristics of *Odobenocetops* include an anteroposteriorly oriented glenoid fossa, forming a wide channel with no posterior limit, and the preserved portion of the supraorbital process of the frontal that is anterolaterally oriented. No other extant or fossil cetacean exhibits these features [42, 43]. In dorsal view, the parietals are widely exposed between the supraoccipital crest and the maxilla. The skull is broken at the level of the orbit and nasal passage. The maxilla is present in the dorsal portion posteriorly to the nasal passage but the supraorbital process of the maxilla and frontal are not laterally expanded. Rather, the maxilla is restricted to the medial portion of the braincase and its anterolateral expansion is limited to the level of the postorbital processes of the frontal, which is also diagnostic of *Odobenocetops* [43]. The anteriormost portion of the skull is broken, but we can infer that the rostrum was short and dominated by the alveolus for the two tusks, as they do in all other known species of *Odobenocetops*. These fragments were found associated, only centimeters away from the skull. The tusks are asymmetric,
with the smaller ones less than a third of the length of the other. Based on other described material of *Odobenocetops*, we presume that the small tusk is left, and the larger one belongs to the right side. Both tusks do not have enamel, and instead exhibit smooth dentine as in *Odobenocetops*, not with sinistral spirals as in narwhals (*Monodon*). In ventral view, the palatine and pterygoid are deep and arched. The pterygoids are more massive than observed in other delphinidans. The maxillae is excluded from the bony palate and relegated to a small triangular area on the lateral side of the rostrum and an elongated strip on the dorsal face of the skull.

**Remarks**

The preserved portion of the skull of SGO.PV. 21610 is very similar to *Odobenocetops peruvianus* and *O. leptodon* [42, 43]. We assign this specimen to *Odobenocetops* sp., based on the following list of traits: the presence of differently sized tusks with smooth and straight dentine; a vaulted palate; the shape and orientation of frontal in the orbit and the restriction to the medial portion of the braincase of the ascending process of the maxilla; an anterolateral frontal postorbital process; and an open, laterally facing glenoid fossa. The putative taxonomic differences between the two species of *O. leptodon* and *O. peruvianus* are primarily restricted to the rostral region, which is not preserved in the Cerro Ballena specimen. Previously, *Odobenocetops* was reported exclusively from two Pliocene age localities of the Pisco Formation in Peru. This new material is thus the most southerly and oldest record of this genus.

MAMMALIA Linnaeus, 1758

EUTHERIA Huxley, 1880

XENARTHRA Cope, 1889
Referred specimens

MPC 644, right femur; MPC 704, posterior part of left horizontal ramus of edentulous mandible.

Description

MPC 644 is an incompletely preserved mandible. It consists of a horizontal ramus broken anterior of the m1 and complete posteriorly to level of coronoid canal (figure S7a-f). The ventral border of the horizontal ramus is convex below the toothrow, about 39 mm high at the level of m2, becoming shallowly concave posteriorly. The coronoid canal is oval, and it opens anterolaterally, located on lateral surface of the base of the coronoid process at about the level of the toothrow. The alveolus for m1 is incomplete; the alveolus for m2 is about 11.5 mm long by 13 mm wide; and m3 alveolus is about 12 mm long by 11 mm wide. The area posterior to m3 is raised, rugose, and triangular.

The femoral shaft of MPC 704 is anteroposteriorly flattened and curved posteriorly (figure S7g-j). The femoral head is oriented dorsomedially relative to long axis of shaft; the fovea capitis forms a triangular indentation on the posteroomedial surface of the femoral head. The neck of the femoral head is short. The greater trochanter of the femur does not rise above head, its dorsolateral surface wide and
rugose, the trochanteric fossa is elongated and deep, opening medially. The prominent parasagittal ridge descends distally from anterior surface of greater trochanter to about the level of lesser trochanter. The third trochanter is continuous with the lateral surface of the greater trochanter, it is rugose and extends farther laterally than the greater trochanter and overhangs the anterior surface of shaft. Finally, the surface of the lesser trochanter is rugose. The distal end of the femur is wider than its proximal end. Its patellar surface is continuous with both condyles, although the medial edge is more prominent. The medial and lateral epicondylar ridges of the femur are present. The surface of the medial epicondyle is rugose and rounded in outline, while the lateral epicondyle is smoother. The lateral condyle is subrectangular in outline with a mediolaterally flat surface.

**Remarks**

The mandible (MPC 704) is very similar to those of others species of *Thalassocnus* [7, 8], and it is referred to *T. natans* tentatively, by association in the same horizon with the femur (MPC 644), which is more diagnostic. Specifically, MPC 644 exhibits a third trochanter that is continuous with the greater trochanter, and the shape and location of the fovea capitis, along with patellar surfaces continuous with the condyles, are all features diagnostic of *Thalassocnus natans* [7, 8]. Previous reports of *Thalassocnus* from the Bahía Inglesa Formation included only a partial mandible that shared similarities with *T. antiquus* and *T. natans*, indicating a late Miocene age at least for part of the formation [17]. Additional undescribed material from the Bahía Inglesa Formation housed at the MPC from a locality southwest of Cerro Ballena, includes cranial and postcranial material referable to *T. natans*. Examination and comparison of these with MPC 644 confirmed that the material can be confidently referred to *Thalassocnus natans*, thus extending the geographic range of this species. The age of *T.
natans was originally regarded as earliest Pliocene [7], however, it was subsequently determined that the type came from the Montemar Horizon of the Pisco Formation in Sacaco, Peru, which has been dated to about 7.3 Ma [8, 9]. The presence of material referable to T. natans therefore suggests a late Miocene age for the Bahía Inglesa Formation.

B. Taphonomic data from Cerro Ballena

Although cetaceans have figured prominently in taphonomic studies for decades, few studies have investigated the actualistic taphonomy of marine mammals in a quantitative or operational manner. For example, Schäfer [44] described a pathway for the drift, decay and final burial of cetacean carcasses in a nearshore environment, based on observations of small odontocetes in the North Sea. Allison et al. [45] provided a primary account of the fate of cetacean carcasses on the seafloor at bathymetric depths, but this depositional setting is distal from Cerro Ballena’s paleoenvironment. In the absence of longitudinal studies of the decay and decomposition of marine mammal carcasses in nearshore environments, we have applied taphonomic scoring schemes that have previously been used to elucidate taphonomic histories in a variety of environments, including marine ones.

Skeletal articulation

Scoring the degree of skeletal articulation in vertebrate remains has served as an indicator of different taphonomic signatures that can be attributed to specific postmortem decay pathways [46]. These signatures can be complex, and they can reflect the control of different factors related to ontogeny, taxonomy and habitat preference. The degree of skeletal articulation is fundamentally an estimated, qualitative score that can vary in scope and comparability across many different vertebrate clades. For
example, articulation scores for African bovids will differ from those for North Pacific Ocean odontocetes based on fundamental differences related to the divergent bauplans between terrestrial ungulates and obligate aquatic cetaceans [47]. Neither Schäfer [44] nor Allison et al. [45] provided comparative descriptions for taphonomic scoring of cetacean articulation, but Schäfer [44] implied that such taphonomic processes also operated on other marine vertebrates, such as pinnipeds.

Here we adopted a simple, three-stage categorization to capture the range of taphonomy exhibited by the marine vertebrates at Cerro Ballena, which included highly articulated balaenopterids, non-balaenopterid marine mammals, including phocids, thalassocnines and odontocetes, comprised by either isolated, individual elements or associated, but disarticulated skeletons (tables S2-3). Our scoring scheme covered three clear categories:

- **Articulation Stage 1** - Articulated, either completely or mostly, including axial and appendicular articulations.
- **Articulation Stage 2** - Disarticulated, but associated, where all the elements are articulated sections, or separated but clearly associated, and thus belonging to the same individual.
- **Articulation Stage 3** - Isolated, separated elements, with no implied association, although an association cannot be excluded.

These latter three categories are congruent with other taphonomic studies of marine vertebrates [48]. Specifically, this three-stage categorization is a heuristic focused on marine mammals, although we recognize that future studies may resolve more precise categorization for specific taxa (e.g., fossil cetaceans from Cerro Ballena).

**Carcass orientation**
Dorsal/ventral up. In modern cetacean strandings, the orientation of stranded carcasses is an obvious feature, although it has been inconsistently documented in stranding reports [49]. Generally, ventral up orientation of a cetacean carcass on a beach is a strong sign that the individual was dead at the time of deposition because a live-stranded individual would be oriented dorsal up because of its blowhole. Moreover, for Balaenopteridae, a ventral up orientation is consistent with taphonomic decay pathways for rorquals that signals postmortem transport because the ventral pouch [31] can accumulate gases during decomposition and act as flotation device. Other cetaceans likely have different decomposition pathways [47]. For all cetaceans, a possible confounding factor for dorsal/ventral up orientation might be redeposition or refloating of individuals over the course of prolonged exposure to tidal fluctuations (J. R. Geraci, pers. comm., 2012). Equally, it is possible that dorsal-up orientations are not entirely a reliable indicator that they were beachcast alive. For individual cetaceans that die suddenly nearshore (by ship-strike or toxin-related), carcasses can arrive on the beach dorsal-up, even after the rupture of the expanded, post-mortem ventral pouch cavity (J. R. Geraci, pers. comm., 2012). Schäfer [44] indicated that the integument of dead cetaceans can hold cetaceans together for a period of time even after the loss of decayed tissue.

Despite these caveats, there has been no systematic investigation into dorsal/ventral up carcass orientation in modern settings. Brand et al. [50] and Esperante et al. [51] scored fossil mysticetes from the Pisco Formation of Peru for such orientations, and we followed their scheme for scoring fossil balaenopterids from Cerro Ballena (table 2).

Compass orientation of long axis. Because of the abundance of large rorqual skeletons at Cerro Ballena, we also measured the orientation of the long axis of the
carcasses, relative to magnetic north. Unlike mysticete skeletons from the Pisco Formation of Peru [51], nearly all of the rorqual skeletons at Cerro Ballena had crania that were in articulation or nearly articulated with the postcranial skeleton. Using digitized quarry maps, we used Image J [52] to measure the angular orientation of the long axis of the skeletons (which were almost always identical to the orientation of the skull) with respect to magnetic north. We then used PAST [53] to calculate the statistical distribution of the data (table S4), with plot bins of 20° and Chi² bins of 4°, and visualized the plots using rose diagrams with mean orientations (figure S9).

**Skeletal scatter**

We also measured the extent of skeletal scatter in a direction orthogonal to the long axis of the body in rorqual skeletons from Cerro Ballena. As with the rose diagram analyses, we used Image J [52] to measure the maximum extent of skeletal scatter from the main body axis of digitized quarry maps. We conducted these analyses for all cetacean skeletons (including *Odobenocetops* and MPC 691, a physeteroid), and then an exclusively Balaenopteridae set (tables S5 and S6, respectively). The average skeletal scatter for both sets is 2.81 m and 2.83 m, respectively, which is a distance shorter than the total length of the adult rorquals in the assemblage.

**Measuring diversity**

In palaeoecological studies of the relative abundance at fossil sites where individual skeletons are easily discerned, measuring the minimum number of individuals (MNI) is a more informative metric than the minimum number of elements (MNE [54]), especially for discerning taphonomic history. At Cerro Ballena, discrete skeletal associations plotted on the quarry map excavation charts determined MNI (table S7). MNE, while perhaps revealing for skeletal completeness, cannot be
determined until all material has been fully prepared from field jackets. MNI values are reported in table S7.

**Bone modification**

Taphonomic studies have employed various schemes to score bone modification in an effort to describe alterations to bone surface and structure that are comparable across sites, time periods and taxonomic groups [55-58]. Ultimately, such comparisons provide the basis to structure inferences about processes that generate such taphonomic patterns, and discriminate between different taphonomic histories.

Most taphonomic studies incorporating bone modification scoring have focused on terrestrial ecosystems, including both modern and fossil ones [56, 57]. Studies employing such schemes for marine vertebrates are in clear minority, although some examples [58, 59] have demonstrated the value of such approaches.

For Cerro Ballena, our bone modification comparisons focused on categories that were clearly useful for discriminating taphonomic features of the skeletal material at this site. Some categories that have been useful in terrestrial settings, such as fracture patterns and trample marks, were not the focus of our investigation because their marine analogs were dubious. For bite marks, out of >40 associated individual specimens and >1000 skeletal elements that we have personally observed from Cerro Ballena, we observed potential traces of shark bites on a single specimen, MPC 682, although further study is required to exclude the possibility that this is a human-caused discovery mark.

**Abrasion stages.** Here we follow Fiorillo ([57], pp. 74-75) for fossil bone abrasion stages, paraphrased below:

- Abrasion Stage 0 - Angular, fresh bone, unabridged. All edges defined.
• Abrasion Stage 1 – Bone edges are subangular, showing slight abrasion. Some edges rounded and polished.

• Abrasion Stage 2 – Bone edges are subrounded, showing moderate abrasion. Osteological processes recognizable but not in their original state. Some bone surfaces may be polished.

• Abrasion Stage 3 – Bone edges are rounded, with sufficient removal of the surface to reveal mostly trabecular bone. Remnant may be a bone pebble.

As with bone weathering, we are explicitly transposing abrasion scores built for mammalian bone in terrestrial environments to marine ones, but see [58, 59] for examples of parallel use in marine environments. Here, we scored bone abrasion for all marine vertebrate fossils from Cerro Ballena (table S8), and then for an exclusively balaenopterid dataset (table S9).

Weathering Stages. Here we followed Fiorillo [57] for fossil bone weathering stages:

• Weathering Stage 0 - No sign of cracking or flaking

• Weathering Stage 1 - Parallel cracking, outermost only

• Weathering Stage 2 - Flaking and cracking, outermost only. Cracking penetrates.

• Weathering Stage 3 - Outermost gone, most cracks penetrate.

It is important to recognize that the original stages proposed [57] were based on taphonomic studies of modern mammal bone weathering in terrestrial environments. It is unclear whether taphonomic processes operating on bone in marine environments produce the same weathering patterns. There are a number of taphonomic studies investigating tetrapod and vertebrate bone in aquatic environments [55, 58, 59]. Our
results are reported in table S10 for all marine vertebrates and table S11 exclusively for balaenopterids from Cerro Ballena.

**D. Extant billfish mortalities**

The occurrence of billfish remains (Xiphiidae and Istiophoridae) suggests that these large predatory consumers are similarly susceptible to HABs. Billfish mortalities are most directly related to fisheries, although we note that references in both the harmful algal bloom literature [60] and the ichthyological literature [61] attribute some billfish mortalities to HABs. This linkage, however, is less clearly documented than the one for marine mammals and HABs.

**E. Mass strandings of baleen whales**

Mass stranding events for cetaceans are not uncommon, especially for socially gregarious species of toothed whales (odontocetes). Mass strandings for baleen whales (mysticetes) are rare, but they have been documented. Most publications summarizing the taxonomic coverage of mass strandings rarely identify specific mysticete mass strandings. Geraci et al. [36]’s description of the Cape Cod stranding of humpback whales (*Megaptera novaeangliae*) is a notable exception. For example, Mazzuca et al. [62] listed mysticete mass strandings instances that included, in addition to Geraci et al. [36]’s event, “4 minke whales (*Balaenoptera* [sic] *acutorostrata*), and 2 fin whales (*Balaenoptera* [sic] *physalus*).” L. Mazzuca (2012, personal correspondence) indicated that [63] was the source reference for the latter two taxonomic occurrences, but that this reference that was deleted from early manuscript drafts at editorial request to shorten text length. Nevertheless, Mead [63] indicates no mysticete mass strandings along the east coast of the United States up to that time.
Geraci et al. [36], interestingly, possibly qualifies as a multispecies rorqual mass stranding. As reported in their figure 1 and on p. 1897, two fin whales (*Balaenoptera physalus*) and three minke whales (*B. acutorostrata*) also stranded nearby during the same time period. One year later, in the same area, another humpback (*M. novaeangliae*) stranded with high concentrations of saxitoxins in the Atlantic mackerel from its stomach [36]. Putatively, we consider these incidental events, which occurred one year after the major mass stranding, to qualify as a multispecies mass stranding of rorquals.

**Other rorqual mass strandings**

Sergeant [64]’s comprehensive evaluation of mass strandings in odontocetes described only two separate “multiple” stranding events for mysticetes: 1) “about 12 specimens” of fin whales dead at St. George’s Bay, west coast of Newfoundland, Canada, in 1959, caught in the ice; and 2) “[at] least 12 rorquals, probably fin whales, caught in ice in northern Gulf of St. Lawrence and Strait of Belle Isle between March 8 and 28 or later observed dead,” likely in 1968, although the year is inferred from Figure 3 of Sergeant et al. ([65], p. 1905). Interestingly, the fifth occurrence reported on p. 1905 refers to death of a trapped individual adult fin whale described in Mowat [66]’s classic narrative *A Whale for the Killing*. Sergeant et al. [65] thus reported at least two documented cases of mass strandings in mysticetes, with anecdotal evidence for two other cases in the same area of Strait of Belle Isle between Newfoundland, Québec and Labrador, all likely involving fin whales. Sergeant et al. [65] inferred that the causes for the vast majority of these mortalities was by asphyxiation from ice floes, which at the time formed on northwest coast of Newfoundland between February-March and lasted until April. This death mechanism is poorly elucidated, although sufficient anecdotes
exist surrounding the dangers of ice-traps for cetaceans for these reports to be considered valid.

R. L. Brownell, Jr., in a section contribution to [67], listed the known “die-offs” of baleen whales, besides the instance of humpbacks at Cape Cod. This list included several events. First, Vidal & Gallo-Reynoso [68] reported a multispecies mass stranding event in the northern Gulf of California in early 1995 that consisted of three fin, two minke, one Bryde’s (B. edeni), and two unidentified (probably fin) whales, as well as 51 California sea lions (Zalophus californianus). The cause was not identified. Second, Braulik et al. [69] reported four Bryde’s whales in the Persian Gulf, near Salakh, Qeshm Province, Iran in 2007. No cause was identified. Third, [70] and [71] both reported >40 individuals humpbacks from 2008-2010 in the state of Western Australia. Although strandings occurred over the course of several months, they covered a range of coastline >1000 km. Currently, no common cause has been identified.

**Non-rorqual mysticete mass strandings**

In the North Pacific Ocean, non-rorqual mysticete mass strandings include mass strandings of gray whales in Baja California, primarily attributed to periodic losses in resource availability [68]. In the South Atlantic Ocean, unusual mortalities of juvenile Southern right whales (Eubalaena australis) have also been reported [67]. However, taphonomic pathways guiding the deposition of carcasses for both of the aforementioned species of mysticetes will likely be different from the sequence of decay for rorquals, given the differences in fat content and distribution in the bodies of gray and right whales, and the lack of a ventral throat pouch in either taxon.

**Unusual mortality events archived by NOAA**
Since 1991, the NOAA of the United States has archived stranding events that have occurred within the surveillance program of the US Marine Mammal Stranding Network. To date, two out of 56 unusual mortality events (UMEs) since 1991 are recorded as multispecies marine mammal mass strandings, and both of these events were biotoxin-related (see http://www.nmfs.noaa.gov/pr/health/mmume/)

Fossil record of cetacean mass strandings

There are equivocal reports of cetacean mass strandings from Holocene deposits [72] and no putative mass strandings known from the fossil record [73] meet the criteria observed for the assemblages documented at Cerro Ballena.

F. Density of cetacean skeletons at other sites in the world

We compared the density of fossil balaenopterid skeletons preserved at Cerro Ballena with those from productive and abundant fossil marine mammals localities elsewhere in the world. We excluded fossil sites that preserve condensed, time-averaged assemblages such as bonebeds [55, 59]. These exclusions are notable because material from these units figured prominently in systematic description of new fossil marine mammal taxa. The middle Miocene Sharktooth Hill bonebed, for example, likely preserves hundreds of thousands individual fossil marine mammals, including cetaceans and pinnipeds, but the unit is a time-averaged deposit that accumulated during a depositional hiatus, encompasses 700 k yr, and preserves mostly disarticulated and disassociated skeletal remains [59]. Equally, the early-middle Miocene Antwerp Sands, in Belgium, preserves a comparable richness of marine mammal taxa, with several species of odontocetes, mysticetes and pinnipeds. Although this formation has yielded some associated skeletons, there is a high density of similarly isolated, disarticulated parts [74]. Collections from the Antwerp Sands were made during 19th and early 20th
century fort excavations at Kessel, and detailed stratigraphic studies of the original, productive marine mammal-bearing units was never accomplished. Other reported Mio-Pliocene localities with dense accumulations of marine vertebrate material, which likely represent attritional deposits on hiatal surfaces, include the San Diego Formation in California [75] and other parts of the Bahía Inglesa Formation (localities southwest of Cerro Ballena [76]).

Specifically, we limited the comparisons to non-bonebed localities with moderate to high stratigraphic control (i.e., reported provenance from a stratigraphic profile), yielding two known areas: 1) the middle-late Miocene Pisco Formation, in the Pisco Basin of southern Peru; and 2) the Eocene Birket Qarun Formation and the Gehannam Formation of Wadi Al-Hitan, northern Egypt. Data from these two sites are described below, and reported in table S12:

**Pisco Formation**

The Pisco Basin, and in particular the Miocene-Pliocene Pisco Formation, has produced a wealth of fossil marine vertebrates including penguins, pinnipeds, marine sloths, and cetaceans [50]. Numerous balaenopteroid skeletons have been reported from putatively middle-late Miocene strata of the Pisco Formation, near the localities of Cerro Blanco and Cerro Ballena, in the Pisco Basin just south of Ocucaje. Brand et al. ([50], p. 166) reported that "the whales occur in large numbers, 30–300 individuals per square kilometer of surface exposure (N = 180).” Brand et al. [77] provided supplemental precision about the stratigraphic source for these data, and this figure implies that the maximum density of mysticete skeletons from this sequence derives from between units M25 and M26.

**Wadi Al-Hitan**
Currently a UNESCO World Heritage Site, Wadi Al-Hitan of the Egyptian desert has produced a rich diversity of marine mammals, including early cetaceans (mostly basilosaurids) and early sea cows (dugongids). Peters et al. [78] reported "1,400 complete or partial vertebrate skeletons from an area of ~200 km²." Gingerich [79] and Peters et al. [78] indicated that the highest density of marine mammals skeletons originate from the Birket Qarun Formation, near or below the Pr-2 SB of Priabonian stage. Peters et al. [79] stated 20.6 vertebrates sites per km (along strike) at Pr-2 SB. P. D. Gingerich (2012, personal correspondence) indicated that, assuming approximately half of the reported area (200 km²) consists of cetacean-bearing rocks from the Birket Qarun or Gehannam formations, 1400 skeletons or partial skeletons would produce an average estimate of 14 cetaceans per square kilometer. This average differs substantially in spatial heterogeneity, and there are unpublished data supporting as many as ~70 whales per km² in both the Birket Qarun and Gehannam formations (P. D. Gingerich, 2012, personal correspondence).
G. Personal correspondence

J. R. Geraci

On Wed, Dec 19, 2012 at 2:06 PM, JOSEPH GERACI <jrgeraci2@verizon.net> wrote:
Hello, Nick. I am interested in your fascinating account. I think we are going to find HABs behind many of our mysterious strandings, but going back as far as you are is absolutely over the top. To answer your questions: In my experience, there has been no particular orientation of carcasses after a mass stranding, mostly, I suppose, because by the time we get there, original orientation has been confounded by successive tides and wave action. In our study of a 1977 mass stranding of 130 long-finned pilot whales on Sable Island, Nova Scotia, we found "the carcasses were randomly oriented, but in general were parallel to the shoreline." Small cetaceans tend to roll around in the wave wash, the tail, being relatively lighter, is left lower on the beach, more "orthogonally" oriented. (I am going to forward this email to Greg Early for his input; he has considerable experience and may have recorded data).

I agree that a live-stranded rorqual is, almost by definition, dorsal side up, at least enough to breathe. Those that come ashore dead and decomposing are almost always belly up until they hit the beach, where they may keep that orientation or begin to roll around. If I found a reasonably close-spaced cluster belly-up on the shore, I would be suspicious that they had been drifting at sea for varying amounts of time until driven ashore all in a sweep by a favorable wind. (common in my experience with smaller cetaceans). A cluster could be shaped, I suppose, by carcasses already drifting nearshore in a spring high tide that rapidly receded, leaving them deposited on the beach. We see that kind of thing in mass strandings of smaller cetaceans, but maybe a long-shot in your case.

Other than those you list, I know of no other reports of mass stranded mysticetes. F.G. Wood, who was with the Navy at the time, spoke to me of one such occurrence (no details) that I do not believe was a published
account. With respect to the humpbacks on Cape Cod, had we happened on the event two or three weeks later, with no witnesses to guide our thinking, and without examining the carcasses, might we have called it a mass stranding? Sure.

Now I'm going to search through my unread June issue of Smithsonian magazine.

Good luck, let me know what you find, and happy holidays.

Joe

Joseph R. Geraci, VMD, PhD
38166 Hunts End Place
Leesburg, VA 20175
tel (540)338-2071; cell (860)271-1814
jrgeraci2@verizon.net<mailto:jrgeraci2@verizon.net>
Hi Nick,

Thanks for the inquiring...Sorry, this went to junk mail and I'm just finding it now.

What is it you want to know? In looking at that paper (I wrote it a long time ago!)--I see that there should be a citation after the mention of fin/minke whales (darn it!). I believe in one of my earlier drafts the details were there for the fin and minke whales, just as the humpbacks' info is there, but I think the reviewers pushed me to shorten. I think in the revision of excluding unnecessary details (as it had nothing to do with the Hawaii stranding paper I was writing), somehow the citation was removed. I believe all of those mysticete strandings referred to were in the same paper (Mead 1979), but I don't have that paper handy at the moment to reference and I looked online but couldn't find an electronic copy of it. Here is the citation. Let me know if I can help further. Ref below:

Mead, James G. 1979. An Analysis of Cetacean Strandings along the Eastern Coast of the United States. In: Geraci, J. B. and St. Aubin, D. J., Biology of Marine Mammals: Insights through Strandings. pp.54-68.
Mead, J.G. 1979 --An analysis of cetacean strandings along the eastern coast of the United States. In: Biology of Marine mammals; insights through strandings pp. 54-68. Mar Mamm Comm: Washington, DC.

-Lori

Re: Quick question about density of whales at Wadi Al-Hitan
Philip Gingerich [gingeric@umich.edu]
Sent: Wednesday, November 28, 2012 2:15 PM
To: Pyenson, Nicholas

One area with this density is in the Birket Qarun Formation, but there is an area in the Gehannam Formation that has whales of this abundance too.

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PHILIP D. GINGERICH--Professor of Geology, Biology, and Anthropology
Curator, Museum of Paleontology, University of Michigan
1514 Ruthven Museums, 1109 Geddes Ave., Ann Arbor, MI 48109-1079
gingeric@umich.edu * Phone: 734-764-0490 * Fax: 734-936-1380
http://www-personal.umich.edu/~gingeric/

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E-mail is not read daily and not secure: do not use for urgent or sensitive issues.

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P. D. Gingerich
From: Philip Gingerich [gingeric@umich.edu]
Sent: Wednesday, November 28, 2012 1:53 PM
To: Pyenson, Nicholas
Subject: Re: Quick question about density of whales at Wadi Al-Hitan

Dear Nick -- The density of whales in Wadi Hitan is a tough question. Yes, the 20.6 vertebrates sites per km in Peters et al. was along strike when mapping a long marker bed trace.

Off the top of my head, if we use the 1400 number of skeletons or partial skeletons from 200 km2, and assume that half of the area is Birket Qarun or Gehannam formation with whales, then we get an estimate of about 14 per square kilometer. These aren't all whales, but then we haven't found all of the whales on the surface in each square kilometer either. Something on the order of 14 archaeocetes per square kilometer would be about the right average. These are then unevenly distributed so there are areas with five times this number per square kilometer and other areas with 1/5 this number. When I am able to finish my mapping I will be able to give more precise estimates, but in the meantime I hope this helps! Philip

PHILIP D. GINGERICH--Professor of Geology, Biology, and Anthropology
5. Supplementary Equations

Calculation of water depth at Cerro Ballena

The general paleoenvironment in the Bahía Inglesa Formation at Cerro Ballena is interpreted as a tidal/supratidal flat because of the fine grain-sizes and trace fossils (figure 2), with occasional storm events that temporarily increased the water depth. There is no direct evidence that the lower levels were deposited in deeper water, as the absence of wave ripples could be due to a lack of algal mats covering and protecting them from wind action.

To calculate the average water depth at Cerro Ballena, we needed to assess the three factors, at any particular site, that determine the wave climate and depth to which they will affect the bottom: wind velocity; duration; and fetch, the last being the distance that the wind blows over an open stretch of water. The east-west orientation of the preserved ripples indicates that the waves propagated from the south, which under present climatic conditions occurs mainly during storms. The distance from the whale site to the nearest basement outcrops (figure 1b) in that direction was measured between 4.94 and 7.46 km on Google Earth. Assuming that this Paleozoic outcrop formed the southern shore of the bay and tidal flat during the time that this uppermost portion of the Bahía Inglesa Formation was deposited, the wind fetch would have been about 6250 m. A major storm, here assumed to have had a sustained 20 m s\(^{-1}\) wind speed (72 km per hour), requires a fetch of about 600 km and a duration of 32 hours for the waves to become fully developed [80]. However, it is unlikely that such conditions would have lasted for more than 12 hours. Fetch- and time-limited waves can thus be calculated under these conditions using the following steps and assuming “normal conditions” where the air and water temperatures are 20º and 23ºC, respectively [80]:

First, the fully developed deepwater wave height \(H_o\) is calculated, given by
\[ H_{at} = \frac{2C_1 \rho_a U_a^2}{9g \rho_w} = \frac{(2)(863.042)(1.186)(20^2)}{(9)(9.81)(1023.94)} = 9.06 \text{ m} \quad \text{(Eq. 1)} \]

where \( C_1 \) is a proportionality constant having a value of 863.042 under “normal” air/water temperature conditions, \( \rho_a \) and \( \rho_w \) are the air and water densities at 20° and 23°C, respectively, \( U_a \) is the sustained wind speed, and \( g \) is the acceleration due to gravity.

The fetch- and time-limited wave height \( (H_{FTL}) \) at the whale site would be given by

\[ H_{FTL} = 863.042 \left( \frac{\rho_a}{\rho_w} \right) \left( \frac{2U_a^2}{9g} \right) \left( \frac{F_a}{F_{aF}} \right) \left( \frac{T_a}{T_{aF}} \right)^{\frac{1}{3}} \quad \text{(Eq. 2)} \]

\[ H_{FTL} = 863.042 \left( \frac{1.1864}{1023.94} \right) \left( \frac{(2)(20^2)}{(9)(9.81)} \right) \left( \frac{6250}{605400} \right) \left( \frac{43200}{115600} \right)^{\frac{1}{3}} = 0.44 \text{ m} \]

where \( F_a \) and \( T_a \) are the actual wind fetch and duration and \( F_{aF} \) and \( T_{aF} \) are the fetch and duration required for fully developed wave conditions, respectively [80].

The fetch- and duration-limited wave period \( T_{FTL} \) at the whale site is calculated by

\[ T_{FTL} = \left( \frac{18\pi^2 H_{aF}}{g} \right)^{\frac{1}{5}} \left( \frac{F_a}{F_{aF}} \right)^{\frac{2}{5}} \left( \frac{T_a}{T_{aF}} \right)^{\frac{2}{5}} = \left( \frac{(18)(\pi^2)(9.06)}{9.81} \right)^{\frac{1}{5}} \left( \frac{6250}{605400} \right)^{\frac{2}{5}} \left( \frac{43200}{115600} \right)^{\frac{2}{5}} = 1.19 \text{ s} \quad \text{(Eq. 3)} \]

whereas the fetch- and time-limited wavelength is found by

\[ L_{FTL} = 3 \sqrt{\frac{H_{FTL} g T_{FTL}^2}{2}} = 3 \sqrt{\frac{(0.44)(9.81)(1.19)^2}{2}} = 5.24 \text{ m.} \quad \text{(Eq. 4)} \]
As this is a fraction of the fully developed wavelength of 256 m, the waves would still be developing towards the deepwater breaking limit, so that the median crest diameter \( [81] \) at the water surface at the depth of ripple formation \((MCD_w)\) would be

\[
\frac{L_{FTL}}{6} = 0.87 \text{ m}.
\]

Entrainment of bottom sediments, which is necessary for ripple formation, requires that the maximum wave crest and trough boundary velocity \((U_{bmax})\) must exceed the critical boundary velocity. This is calculated by \([82]\):

\[
U_{bmax} = \frac{H_{FTL} g T_{FTL} L_{FTL}}{8 MCD_w^2 \cosh \left( \frac{\pi d}{MCD_w} \right)}.
\]  (Eq. 5)

In this equation every parameter can be calculated, except the water depth \(d\), which can be found by iteration of \(d\) until \(U_{bmax}\) coincides with the critical boundary velocity \(U_{bcrit}\). The latter is determined as follows \([83,84]\) where units in this case are in cm, g and s, with the final answer converted to m s\(^{-1}\).

\[
U_{bcrit} = 2\pi \left[ 1 + 5 \left( \frac{T_R}{T} \right)^2 \right]^{-\frac{1}{4}} = 2\pi (0.8773) \left[ 1 + 5 \left( \frac{1.3728}{1.19} \right)^2 \right]^{-\frac{1}{4}} = 3.314 \text{ cm s}^{-1} = 0.033 \text{ m s}^{-1}
\]  (Eq. 6)

where \(J\) and \(T_R\) are coefficients derived from \(s^*\), a scaled dimensionless immersed sediment weight given by

\[
s^* = \frac{D \sqrt{gD (\rho_s - \rho_w)}}{4 \left( \frac{\mu}{\rho_w} \right)} = \frac{0.000625 \sqrt{(981)(0.000625)(2.65 - 1.0239)}}{4 \left( \frac{0.00985}{1.0239} \right)} = 0.0162
\]  (Eq. 7)

\(\rho_s\) being the density of the sediment grains (taken as that of quartz, i.e. 2.65 g cm\(^{-3}\)), \(D\) is the mean grain size (0.00625 cm), and \(\mu\) the kinematic viscosity of sea water with a salinity of 3.5% at 23°C (0.00985 g cm\(^{-1}\) s\(^{-1}\)).
\[ J = 2.53s^{0.92} \frac{\mu}{\rho_w D} = (2.53)(0.0162)^{0.92} \left( \frac{0.00985}{1.0239}(0.000625) \right) = 0.8773 \quad \text{(Eq. 8)} \]

and

\[ T_R = 159s^{-1.3} D^{2} = (159)(0.0162)^{-1.3}(0.000625)^{2} = 1.3728 \quad \text{(Eq. 9)} \]

In Eq. (5), the wavelength at the depth of sediment entrainment \( \lambda_w \) is required. This is calculated by first finding the wave breaking depth \( d_b \) and height \( H_b \), which are obtained by the iteration of two equations [85]:

\[ H_w = H_o \left[ a \exp\left( \frac{H_o}{L_o} b \right) \right] = \frac{2U_o^2}{9g} \left[ a \exp\left( \frac{1}{9\pi} b \right) \right] \quad \text{(Eq. 10)} \]

where \( H_o \) and \( L_o \) are the deepwater wave height and length (in this case \( H_{FTL} \) and \( L_{FTL} \)), whereas \( a \) and \( b \) are coefficients given by \( a = 0.5875 \left( \frac{d}{L_o} \right)^{-0.18} \) when \( \frac{d}{L_o} \leq 0.0844 \);

\[ a = 0.9672 \left( \frac{d}{L_o} \right)^2 - 0.5013 \frac{d}{L_o} + 0.9521 \text{ when } 0.0844 < \frac{d}{L_o} \leq 0.6; \quad a = 1 \text{ when } \frac{d}{L_o} > 0.6; \]

and \( b = 0.0042 \left( \frac{d}{L_o} \right)^{-2.3211} \). Iteration shows that \( d_b = 0.5183 \text{ m and } H_b = 0.43 \text{ m: } \frac{d}{L_o} = \frac{0.5183}{5.24} = 0.0989, a = 0.9672(0.0989)^2 - 0.5013(0.0989) + 0.9521 = 0.912, \) and

\[ b = 0.0042(0.0989)^{-2.3211} = 0.9026. \] Therefore:

\[ H_w = H_o \left[ a \exp\left( \frac{H_o}{L_o} b \right) \right] = \frac{2U_o^2}{9g} \left[ a \exp\left( \frac{1}{9\pi} b \right) \right] = 0.44 \left[ 0.912 \exp\left( \frac{0.44}{5.24} \right) \right] = 0.43 \text{ m.} \]

From \( H_b \) and \( db \) the breaker length \( L_b \) is obtained by [86]:
whereas the wavelength $L_w$ at the depth of sediment entrainment is given by [86]:

$$L_w = T\sqrt{g(0.5H_b + d_b)} = 1.19\sqrt{(9.81)(0.5)(0.43) + 0.52} = 3.19 \text{ m} \quad \text{(Eq. 11)}$$

This is found by iterating the water depth $d$ until $U_{b\text{max}}$ coincides with $U_{b\text{crit}}$, (at 0.033 m s$^{-1}$) thus giving the water depth in which the wave ripples could have formed. In this case it turns out to be 1.47 m:

$$U_{b\text{max}} = \frac{H_{FTL}gT_{FTL}L_{FTL}}{8MCD_w^2 \cosh\left(\frac{\pi d}{MCD_w}\right)} = \frac{(0.44)(9.81)(1.19)(3.93)}{(8)(0.87)^2 \cosh\left(\frac{\pi(1.47)}{0.87}\right)} = 0.033 \text{ m s}^{-1}.$$ 

If a supratidal flat environment is assumed, it is possible that vertebrate carcasses entered the area during a storm surge (which might have coincided with a spring high tide), and were left stranded in very shallow water when the surge subsided or the tide ran out.
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