Fossil whale preservation implies high diatom accumulation rate in the Miocene–Pliocene Pisco Formation of Peru

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ABSTRACT

Diatomaceous deposits in the Miocene–Pliocene Pisco Formation contain abundant whales preserved in pristine condition (bones articulated or at least closely associated), in some cases including preserved baleen. The well-preserved whales indicate rapid burial. The 346 whales within ~1.5 km^2 of surveyed surface were not buried as an event, but were distributed uninterrupted through an 80-m-thick sedimentary section. The diatomaceous sediment lacks repeating primary laminations, but instead is mostly massive, with irregular laminations and speckles. There is no evidence for bioturbation by invertebrates in the whale-bearing sediment. Current depositional models do not account for the volume of diatomaceous sediments or the taphonomic features of the whales. These taphonomic and sedimentary features suggest that rapid burial due to high diatom accumulation, in part by lateral advection into protected, shallow embayments, is responsible for the superb preservation of these whales, leading to a higher upper limit on phytoplankton accumulation rates than previously documented.

Keywords: taphonomy, diatoms, Pisco Formation, Miocene, Pliocene, Cetacea, sedimentation rates.

INTRODUCTION

The Miocene–Pliocene Pisco Formation, ~350 km south of Lima, Peru, is a diatomaceous, tuffaceous deposit 200–1000 m thick that was deposited in shallow bays over a span of 10–12 m.y., as calibrated by K-Ar (De Muizon and DeVries, 1985; Dunbar et al., 1990). It also contains abundant whales and other vertebrates. If the sedimentation rate was relatively constant over 10–12 m.y. during deposition of the Pisco Formation, the diatomaceous sediment accumulated at <10 cm/k.y., which is consistent with other accumulation rates reported here. If these average rates of accumulation pertained through the fossiliferous portions of the diatomaceous sediment, however, it would have taken thousands of years to bury an individual whale. However, the whales are too well preserved for such slow burial processes. Our research addressed the relationship between the depositional rate and the preservation of the whales.

Diatoms in modern oceans sink slowly after death while their organic tissue decays and most of their siliceous frustules dissolve. In general, only an estimated 2%–3% of frustules enter the geologic record without dissolving (Heath, 1974; Tréguer et al., 1995; Abrantes, 2000), but this preservation rate is as high as 24% in Antarctica (Tréguer et al., 1995).

In modern ocean basins, diatomite accumulation rates are low, e.g., 40–73 cm/k.y. off southern California (~20% biogenic) (Allison et al., 1991). However, in the fjords of British Columbia, the accumulation rate of diatoms and clay laminae is 250–500 cm/k.y. to several tens of meters per thousand years (Sancetta, 1989), and involves lateral advection. In a shallow bay on the New England coast, marine snow accumulated, largely by lateral advection, at a mean rate of 10 cm/yr, or 100 m/k.y. (Wells and Shanks, 1987).

Published accumulation rates for ancient diatomites are also generally low: 2–16 cm/k.y. in the Pliocene–Quaternary off the coast of Peru (Kemp, 1990) and 118–260 cm/k.y. during the late Pleistocene–Holocene in the Gulf of California (on the basis of ^{14}C dates; partly nonbiogenic sediment) (Schrader et al., 1980). Fine diatomaceous laminations in the Miocene Monterey Formation accumulated at 19–80 cm/k.y. (Pisciotto and Garrison, 1981; Chang and Grimm, 1999). Miocene–Pliocene laminated deposits from the eastern equatorial Pacific accumulated at >10 cm/k.y. (Kemp and Baldauf, 1993). Parts of these latter deposits were evidently deposited much more rapidly, because the deposit contains sets of as many as 400 diatom mats estimated to have accumulated in days by rapid sinking (Kemp et al., 1995).

GEOLOGIC SETTING

The lower half of the studied sections at Cerro Blanco is mostly sandstone with some diatomaceous units. Whale specimens are mostly in the upper part of this section, in an 80-m-thick diatomaceous and tuffaceous mudstone (Esperante et al., 2002). The study section contains abundant scour-and-fill sedimentary structures that indicate active bottom currents, including tidal currents. Indicators of storm deposits, such as hummocky cross-bedding, indicate that the sediments were deposited above storm wave base. There are no varves or other cyclical laminations, but randomly located individual white laminations and speckles consist primarily of diatoms (5%–10% clay), whereas the surrounding massive grayish diatomite (Figs. 1E, 1F) has a higher clay content. The randomly spaced laminations are intact, indicating that the whale-bearing diatomaceous sediment is undisturbed by any bioturbation. As some whale skeletons settled onto the surface, the underlying sediment was scoured out, and new diatomaceous units filled these scours (Fig. 1E).

METHODS

The locations of all fossils (N = 346) and marker beds were determined with high-precision Global Positioning System equipment, and the taphonomic condition of each specimen was documented. A section was measured and described, and sediment samples were analyzed with X-ray diffraction (Mineral Lab, Lakewood, Colorado, USA), X-ray fluorescence (XRAL Laboratories, Don Mills, Ontario, Canada), study of thin sections (sections made by Spectrum Petrographics, Winston, Oregon), and scanning electron microscope (SEM) study of diatomaceous sediment. Identification of diatoms was by Winsborough Consulting Labs. Whales on the surface have been affected to varying degrees by modern erosion. We counted an occurrence of a skull and/or postcranial elements including vertebrae and ribs in approximately articulated position as a complete whale (N = 180). Many or most of those labeled as partial whales (N = 166) were probably originally complete, but there has been too much erosional damage to verify that likelihood.

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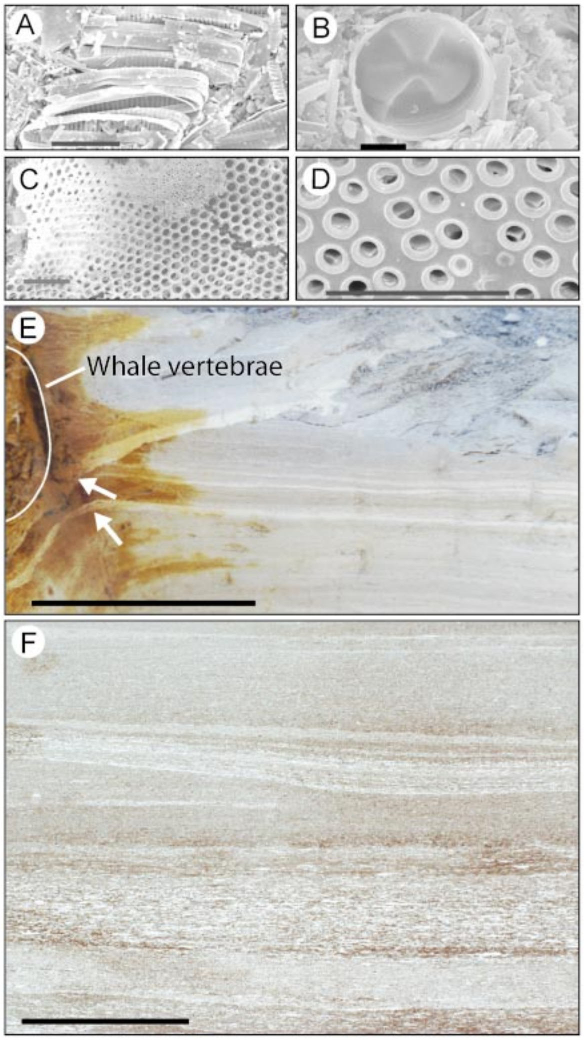

Figure 1. Diatoms and diatomite associated with fossil whales. A–D: Scanning electron microscope images of diatoms, showing complete diatoms and fragments without evidence of dissolution. E: Cross section through diatomite adjacent to whale vertebral column. Two arrows indicate corner of excavated trench. Left of arrows trench wall is nearly perpendicular to plane of photograph. Lowest white lamination is entirely horizontal, and apparent downward bend results from change in perspective at corner of excavation. Sediment was scoured from under whale carcass, and thickest white diatom lamination was first sediment to fill scour. This lamination, which to left of arrow is horizontal, was traceable along entire whale skeleton, and surrounded at least portions of ribs. Lamination seems to represent settling out of diatoms during slack tide, after scouring of depression under whale carcass. F: Cross section through diatomite, with laminations and speckled beds of diatoms and fragments of diatom mats. Scale bars: A–D = 10 μm; E = 10 cm; F = 2 cm.

DIATOMS

The diatoms are almost all of marine species, but freshwater diatoms in some samples suggest runoff from rivers. The most common diatoms in our samples are characteristic of elevated nutrient levels associated with blooms in areas with upwelling, including *Delphineis karstenii*, *Thalassionema nitzschioides*, and *Chaetoceros* resting spores (Schuette and Schrader, 1981). The latter is especially indicative of the final stages of a bloom (Sancetta, 1999).

If most diatoms dissolve before preservation in the sediment, one would find frustules in all stages of dissolution. Diatoms in the Pisco diatomaceous sediment are often broken, but SEM study indicated fine preservation, with no significant evidence of dissolution (Figs. 1A–1D). In the shallow-water Pisco Formation, the diatoms were probably buried too quickly for much dissolution to occur.

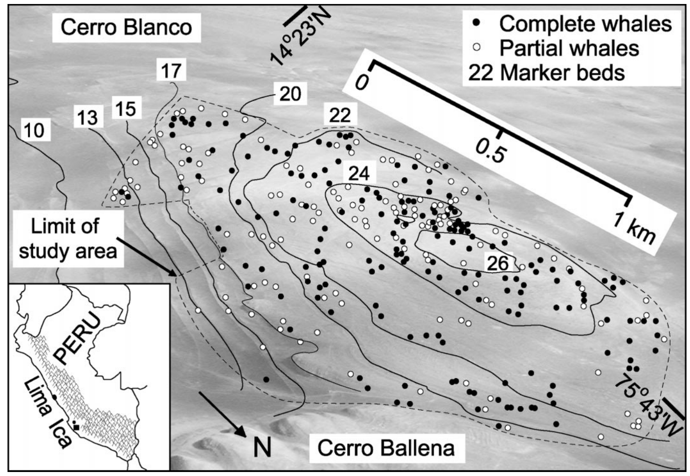

Figure 2. Map of fossil whales on Cerro Blanco, superimposed on aerial photograph. Numbers printed in white boxes are identification numbers for marker beds. Small black square in inset, below Ica, is location of study area.

VERTEBRATE TAPHONOMY

Vertebrate fossils in the Pisco Formation include sharks, fish, turtles, seals, porpoises, ground sloths, penguins, and whales (De Muizon and DeVries, 1985). In our study area, the only common fossils are shark teeth and whales, mostly baleen whales, cf. *Balaenoptera* (Balaenopteridae), 5–13 m long. The whales occur in large numbers, 30–300 individuals per square kilometer of surface exposure ($N = 180$) (Fig. 2), and are fully articulated (Fig. 3) to disarticulated but with skeletal elements still closely associated. In all cases the whale bones are well preserved; they show no evidence of corrosion, boring by invertebrates, or other postmortem damage. The most complete whale (WCBa 20) was fully articulated; the microscopic detail of its baleen was preserved (Figs. 3A, 3C–3E), and there is black, heavy-mineral replacement of the spinal cord and some intervertebral disks. There were no similar minerals in the surrounding sediment. These nonbony tissues were still present when the whale was completely buried. We also found baleen fossilized with three other whales in the study area reported here, and with 16 additional whales at other Pisco Formation localities.

Whales are not concentrated in specific stratigraphic levels, but are distributed throughout the diatomaceous sediment (Fig. 4). Their taphonomic condition is constant throughout this interval, indicating a fairly uniform paleoenvironment during the entire interval.

In modern oceans, whale carcasses on the ocean floor are rapidly colonized by large numbers of invertebrate scavengers that remove the flesh and begin to degrade the bone (Allison et al., 1991). They also bioturbate the adjoining sediment in search of organic compounds leached from the whale. This process strips a whale skeleton within a maximum of a few years. Sediment accumulating at a few centimeters per thousand years would deposit at maximum a few millimeters of diatomite during the time available to preserve even a reasonably complete whale skeleton. Preservation of nonmineralized tissue would not be a realistic possibility at this slow burial rate, and even bones are unlikely to be well preserved.

In contrast, whales of the Pisco Formation show no invertebrate

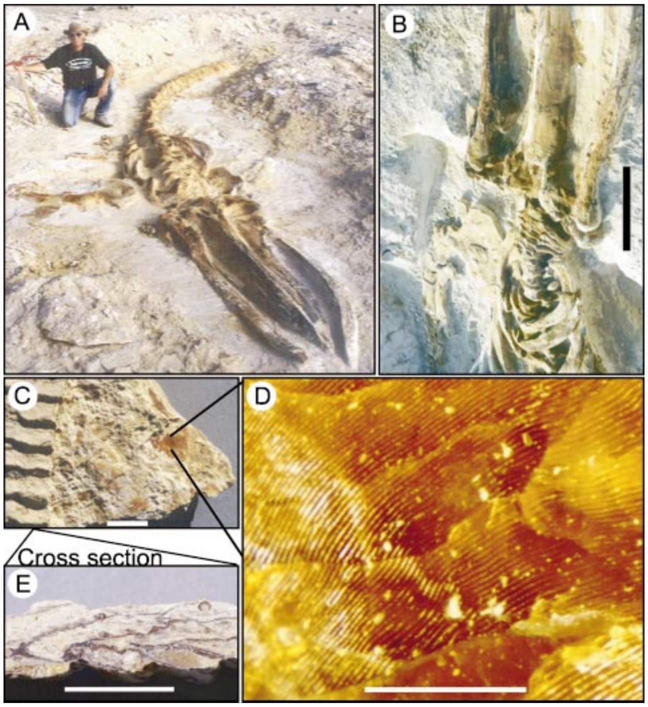

Figure 3. Two complete excavated whales, and details of baleen. A: Whale WCBa 20, ventral side up, 9.2 m long. B: Whale WCBa 32, ventral side up, 12 m long. C: Surface view of baleen from whale 20. Baleen had drifted from whale's mouth and was lying on top of its limb bones. Top part of right side of sample has been removed to expose reddish surface of well-preserved baleen sheet. D: Close-up surface view of baleen sheet. E: Cross section of baleen, showing sheets of baleen (dark lines) with whitish diatomite between. Of 11 whales excavated, all were complete or nearly complete, articulated or partially disarticulated but associated. Scale bars: B = 1 m; C and E = 1 cm; D = 0.5 mm.

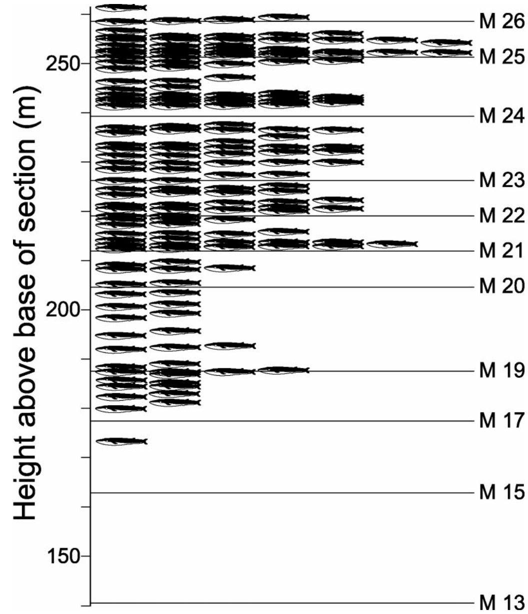

Figure 4. Stratigraphic distribution of whales in Cerro Blanco study area. Horizontal center line of each whale symbol designates precise stratigraphic position of one complete whale (N = 180) in relation to mapped marker beds (beds 13–26), as indicated in Figure 2.

colonization, bioturbation of surrounding sediment, or degradation of bones, and several specimens preserve textures of some nonbony tissues in fine detail. Thus, some set of unique conditions existed in coastal Peru to permit such unusual preservation.

DISCUSSION

Possible mechanisms for preserving the whales include three hypotheses: (1) anoxia, (2) a covering of diatom mats, and (3) rapid burial. The first mechanism, anoxia, would be expected to reduce disarticulation of the whales by inhibiting bioturbators and scavengers, but would require a noncirculating body of water. Sediments deposited in this environment would not contain sedimentary structures indicative of significant water currents. The second mechanism involves covering the whales with an extensive series of diatom mats with the tensile strength and impenetrability to inhibit bioturbators and scavengers, as postulated for equatorial Pacific Neogene deposits (Kemp and Baldauf, 1993; Kemp et al., 1995). Evidence for such mats should be visible in the sediments. The third mechanism, exclusion of bioturbators and invertebrate scavengers by rapid burial, would not require anoxia or extensive diatom mats, but could occur in tandem with one or both of them, or without them.

The shallow water indicated by the Pisco Formation sedimentary deposits (Dunbar et al., 1990, and our data), with sedimentary structures indicating abundant tidal and storm current action, does not favor an anoxic environment. Pisco diatomite contains fragments of diatom mats (speckles and white laminae), but not extensive, continuous mats like those postulated to inhibit bioturbation and scavenger activity in equatorial Pacific Neogene deposits (Kemp and Baldauf, 1993; Kemp et al., 1995). The most viable explanation for whale preservation seems to be rapid burial, fast enough to cover whales 5–13 m long and ~50 cm thick within a few weeks or months, to account for whales with well-preserved bones and some soft tissues. Such burial requires diatom accumulation rates at least three to four orders of magnitude faster than is usual in the ocean today—centimeters per week or month, rather than centimeters per thousand years.

Several natural factors may have facilitated such rapid diatom accumulation in the Pisco Formation. Good preservation of the diatoms implies that phytoplankton aggregation processes inhibited dissolution (Logan et al., 1995), and the diatoms were preserved in the shallow bay.

There is evidence of natural sources of nutrient enrichment in the Pisco environment. Volcanic ash, common in the Pisco sedimentary deposits, and runoff from the continent could have contributed iron and other nutrients. The Peruvian coast is a site of ocean upwelling today and was in the Neogene (Kemp, 1990; Kemp and Baldauf, 1993), providing another important source of nutrient enrichment. These factors could have raised diatom reproduction at least an order of magnitude, as occurred in equatorial Pacific iron enrichment experiments (85-fold increase for diatoms) (Behrenfeld et al., 1996).

Deposition of the Pisco Formation was coincident in time with the abundant accumulation of diatomaceous sediment in the latest Miocene–early Pliocene (referred to as the biogenic bloom) in the Indian and Pacific Oceans related to significantly increased productivity from ''a fundamental change in global nutrient cycling'' (Dickens and Owen, 1999, p. 87). An abundant nutrient supply potentially produced frequent blooms, increasing sedimentary accumulation of diatom frustules in the Pisco Formation one or two orders of magnitude compared to most modern diatomite-accumulating environments.

The diatomaceous sediment that was scoured out from under at least some whales as they sank into the unconsolidated sediment (Fig. 1E) may have settled down on top of the carcass, creating an initial thin sediment cover. Sediment deformation under and beside another, smaller, excavated whale carcass indicated that it sank even farther into the soft sediment. These self-burial processes could have hastened carcass burial somewhat.

Lateral advection of resuspended diatoms was likely the most significant cause of high phytoplankton accumulation rates, as reported in modern shallow bays (Wells and Shanks, 1987). The Pisco Formation diatomaceous sedimentary deposits are not laminated, but are massive, and commonly contain local, small-scale diatomite horizons, and sedimentary structures indicating current action. Thus, it appears that the diatoms were not only gently settling out of the water column, but were also being advected and redeposited by currents resulting from tides and/or storms. A three-day storm along the Oregon coast formed a modern deposit of diatoms that was 10–15 cm thick and 32 km long (Campbell, 1954). Similar current action may have concentrated diatomaceous sediments in the shallow, protected bays of the Pisco Basin, assisting the rapid burial of whales. The excellent preservation of the whales implies the additive effect of such natural factors that resulted in very high diatom accumulation rates of centimeters to meters per year.

CONCLUSIONS

Anoxia or extensive diatom mats don't seem to be adequate explanations for the unusual whale preservation or the lack of invertebrate scavengers and lack of bioturbation. The evidence for shallow water and high energy do not favor anoxia, and the sediment contains evidence of broken-up mats, but not intact series of mats. Several lines of evidence seem to allow the possibility that the Pisco Formation diatomaceous sediment accumulated more rapidly than commonly occurs today. For example, Pisco Formation diatom frustules do not show evidence of dissolution, perhaps because, in the relatively shallow water, they accumulated too rapidly to dissolve. Sedimentary structures also indicate tidal current action and storms, which could have acted to concentrate diatoms in the shallow bays along the Peruvian coast. The well-preserved whale carcasses seem to require rapid burial, within weeks to months for any given whale, to account for their preservation and articulation, including fossilization of some nonbony tissues. This necessity of rapid burial indicates that, at times in the past, diatom accumulation rates were much higher than those typical in modern oceans. This rapid accumulation was most likely predominantly the result of lateral advection of phytoplankton by currents and/or storms into shallow bays. The volume of phytoplankton available for advection was enhanced by abundant blooms offshore, as most diatom species represent environments with deeper water than the bays in which they accumulated (B. Winsborough, 2003, personal commun.).

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