9-2014

Sedimentology of Marine Vertebrate Burial in the Miocene Pisco Fm., Peru

Monte A. Fleming

LOMA LINDA UNIVERSITY
School of Medicine
in conjunction with the
Faculty of Graduate Studies

Sedimentology of Marine Vertebrate Burial in the Miocene Pisco Fm., Peru

by

Monte A. Fleming

A Thesis submitted in partial satisfaction of
the requirements for the degree
Master of Science in Geology

September 2014

Each person whose signature appears below certifies that this thesis in his/her opinion is adequate, in scope and quality, as a thesis for the degree Master of Science.

____, Chairperson
Kevin E. Nick, Associate Professor of Geology

____
Leonard Brand, Professor of Biology and Paleontology

____
Raúl Esperante, Adjunct Assistant Professor of Geology

ACKNOWLEDGEMENTS

I would like to thank my advisor, Dr. Kevin Nick, for allowing me to undertake a project that was a little unusual for our group of Pisco Basin researchers, and for the time, mentoring, and support he provided. I would like to thank my committee members, Dr. Leonard Brand and Dr. Raúl Esperante, for the time and resources they have dedicated to this project—their input has greatly improved the final product. I would like to thank Orlando Poma for his help with fieldwork and interpretations of the outcrops, and Mario Urbina for locating some of the specimens and lending his paleontological expertise. I would like to thank Geoscience Research Institute for the funding they provided to send us to Peru, and Loma Linda University for financial support and access to laboratory equipment. I also owe many thanks to family and friends who have provided me with financial support and equipment necessary for my studies.

Finally, I owe my greatest debt of gratitude to our Creator, in whom are hid all the treasures of wisdom and knowledge, and without whom the pursuit of knowledge would be meaningless.

CONTENTS

Appendices

FIGURES

Figures Page

TABLES

ABBREVIATIONS

HCS	Hummocky Cross-Stratification
SCS	Swaley Cross-Stratification
XRD	X-ray Diffraction
SEM	Scanning Electron Microscope

ABSTRACT OF THE THESIS

Sedimentology of Marine Vertebrate Burial
in the Miocene Pisco Formation, Peru

by

Monte A. Fleming

Master of Science, Graduate Program in Geology
Loma Linda University, September 2014
Dr. Kevin E. Nick, Chairperson

The Miocene Pisco Basin of Peru is known for abundant, well-preserved marine vertebrate fossils (Esperante et al. 2000). Cetacean fossils are particularly abundant—so much so that we were able to locate 10 outcrops containing specimens in cross section, which allowed us to do detailed sedimentological studies of the beds surrounding the whales. We discovered that six of the 10 specimens were buried in channels; the details of the other four burials are too disparate to meaningfully group together in categories. Chapters 3, 4, and 5 describe and discuss the six specimens found in channels, while Appendix A contains descriptions and discussions of the other four locations.

The dominant sedimentary structure associated with all of the whales is hummocky cross-stratification, which forms during waning storms and implies substantial sediment accumulation during the event, whether by sediment input from the coast or other source, or by resuspension and redeposition of sediment (Dumas and Arnott 2006). The whales are encased in siltstone, made up primarily of varying ratios of siliciclastic material, diatoms, and volcanic ash. All of the material was acted upon by storm processes, as evidenced by the sedimentary structures, and even the beds of pure ash are ripple laminated or hummocky.

Taphonomic work done on Pisco fossils shows that they were buried rapidly (Esperante et al. 1999, 2008; Brand et al. 2004). Severe storms, the depositional environments indicated by the data we acquired, provide a mechanism to explain rapid rates of deposition and substantiate the findings of the taphonomic studies.

CHAPTER ONE

INTRODUCTION

Fossil Preservation and the Depositional Environment of the Pisco Basin

Thousands of well-preserved marine vertebrate fossils are present in the Pisco Formation (Esperante et al. 2000, Brand et al. 2004). Modern whale carcasses and skeletons are quickly scavenged and eroded (Allison et al. 1991, Smith and Baco 2003, Esperante 2005), so an explanation for the preservation of the fossils in the Miocene Pisco Formation is of historical interest. How the animals died, and how they were buried and preserved is a highly relevant question for understanding the processes and history of sedimentation in the Pisco Basin. These questions also relate to other fossil beds exhibiting high concentrations of well-preserved fossils, because we are generally missing precise modern depositional analogues to understand their formation and preservation.

According to taphonomic work done in the Pisco Formation, the exquisite preservation of many of the specimens suggests that they were buried rapidly (Esperante et al. 1999, Brand et al. 2004). Specifics of the depositional processes, however, have not been sufficiently investigated in relation to the sedimentary features present. It has been noted in the Upper Eocene Fayum Depression of Egypt that whales have been deposited in low-energy environments (Abdel-Fattah et al. 2010). In the Lower Pliocene Huelva Sands Formation in Spain, where the whales are less well preserved than many of the Pisco specimens, the sediments are highly bioturbated, which may indicate a lower-energy environment as well (Esperante et al. 2009). In contrast, many of the whales in the Pisco Formation are associated with higher-energy depositional environments (Carvajal 2002, Esperante 2008). As is typical of ancient shelf deposits (Myrow and Southard 1996, Plint 2010), the Pisco sediments are dominated by erosional and depositional events related to storms.

Many of the storm deposits in the Pisco Formation are silt-dominated; such deposits are particularly abundant in the upper units of the Pisco Formation. The silt grains in these deposits can be brought onto the shelf by sediment transport from the coast, and the deposits can extend considerable distances out onto the shelf. Sand-size particles are also transported on the shelf by currents and storm processes, but not distributed as widely as finer-grained sediments (Plint 2010). It should be noted, however, that in the Pisco Formation, sandstone units can extend for kilometers—the orientation of the sandstone units relative to the paleo-coastline has not yet been determined.

Hummocky and swaley cross-stratification, key indicators of storm deposition, are the dominant sedimentary structures in the beds associated with the whales in this study. Investigations of hurricane deposits off of the coast of the Gulf of Mexico (Forristall et al. 1977, Evans et al. 2011, Goff et al. 2010) and winter storm deposits off of the coast of Sable Island near Nova Scotia (Amos et al. 1996), as well as some creative flume experiments (Dumas and Arnott 2006) have shown that beds of pebbles (both lags and cross-bedded deposits), hummocky cross-stratification (HCS), swaley cross-stratification (SCS), and ripple cross-lamination are common sedimentary structures resulting from severe storms.

According to flume experiments performed by Dumas and Arnott, HCS is the result of oscillatory wave motion, and may have a small unidirectional component. If the unidirectional component becomes too strong, however, HCS is destroyed. HCS is more easily created in fine sediments, such as the silt surrounding all but two of these whales, and may also be more easily created in low-density sediments, such as the diatoms and porous ash that make up a large portion of the rocks in these outcrops. When the sediment load is large and the rate of deposition is high, hummocks tend to be preserved, but when the sediment load is less and the rate of deposition is less, the hummocks tend to be eroded away, and the swales are preferentially preserved (Dumas and Arnott, 2006).

Sediment Sources and Rates of Deposition

While it has been noted in the literature that paleodepositional environments for many shelves are dominated by tempestites (Myrow and Southard 1996), models for large vertebrate burial and exceptional preservation for these organisms in Pisco shelf settings have not been proposed. Sediment types and rates of sedimentation are critical factors in developing a model for burial of marine vertebrates in the Pisco Formation. The typical sedimentary components of the Upper Pisco Formation are listed below:

Volcanic Ash

A prominent component of the diatomaceous units of the Upper Pisco Formation is volcanic material, primarily volcanic ash (O'Hare et al. 2012). The plentiful tuffs have benefited our research in two ways—they provide time markers that can be used to correlate different outcrops, and some of them contain biotite, which is useful for dating.

Diatoms

Other important components of the upper units of the Pisco Formation are microfossils, most notably diatoms (Marty, 1989). Though pure diatomite was only found in channel drapes in this study, diatoms make up a large percentage of the sediment surrounding the whales in some of the cross sections. One possible mechanism for the deposition of large quantities of diatoms is advection during storms. Apart from advection, observed modern diatom accumulation rates are quite slow.

Modern diatom depositional rates vary tremendously from one ecosystem to another. Off of Southern California, the rate is about 40-73 cm/k.y. (Allison et al. 1991). Lateral advection can play a significant role in some environments, however, such as in the fjords in British Columbia (Sancetta 1989) and a New England bay (Wells and Shanks 1987), where the measured rates of diatom deposition are 10 cm/yr. Diatom mats can be a source of rapid diatom deposition (400 mats in what may have been a few days in the eastern equatorial Pacific ocean) (Kemp et al. 1995), but in the Pisco Formation, diatom mats—tangled masses of diatoms that live, die, and sink to the bottom as a group—represent only a small part of the total diatom deposition (Esperante et al. 1999).

Sources of nutrients such as upwelling, storms, and volcanic events could have been important factors in diatom reproduction and subsequent deposition in the Pisco Basin. In the Pacific Ocean, iron enrichment studies increased diatom production by 85-fold (Behrenfeld et al. 1996). It is possible that frequent volcanic eruptions created just such an environment, though a study done in the Monterey Formation did not find any correlation between volcanic events and diatom production (Ingle 1981). It should be noted, however, that the Monterey Formation does not contain the quantity of volcanic material that the Pisco Formation contains. Typically, explosive volcanism occurs in silicic magmas that contain little iron, but despite this, the tuff beds in the upper units of the Pisco Formation may contain more iron than the beds surrounding them based on magnetic susceptibility readings (O'Hare *et al.* 2012).

Coastal Weathering and Siliciclastic Input

Two studies, one on the Gulf of Papua off of the south coast of New Guinea (Muhammad 2009), and another on the Waiapu River Delta on the northern island of New Zealand (Kniskern 2007), serve as good indicators of the range of processes at work at the interfaces between river mouths and shelves. The Waiapu River carries a heavy sediment load, and as a result, cores taken from the river delta show current-dominated structures. Biogenic structures dominate the sediments in the Gulf of Papua, however, due to the much lower rate of sediment deposition.

The Ica River and other rivers run off of the Andes and pass through the Pisco basin, and in the past, similar drainages could have contributed siliciclastic material to the basin. The siliciclastic input from these rivers would have been much greater during the storms recorded in the sedimentary structures of the Pisco Basin rocks.

Biogenic Structures and Rates of Deposition

Degree of Bioturbation

The presence or absence of a community of organisms living at the sediment/water interface at the time the whale touched the bottom, or after the whale touched the bottom, is another indicator of depositional and paleoenvironmental conditions, and may help interpret the timing of depositional events and breaks in deposition. A change in the form or density of biogenic structures close to the whale may indicate that the whale's decomposition influenced the benthic community, whereas no change may indicate the contrary (Smith et al. 1998). Bioturbation overwrites sedimentary structures, so if a given sedimentary structure has been preserved, it is because it has been placed out of reach of burrowing organisms, either by toxicity of the water, further sediment deposition, or a cohesive mat of microorganisms such as diatoms.

A modern example where rapid deposition is the main factor inhibiting benthic organisms from modifying sediments is in the Waiapu River Delta. At that location, pulsed event beds—flood deposits commonly 10-20 cm thick—are frequent enough to hinder the establishment of benthic communities (Kniskern 2007).

Geologic Setting

The Pisco Formation is a shallow-marine deposit near the central coast of Peru consisting of sandstones, siltstones, tuff beds, and a few mudstones. While the precise age of the lowest Pisco Formation sediments is not known, the sediments range in age from Miocene to Pliocene (León et al. 2008, Dunbar and Baker 1988) (Figure 1).

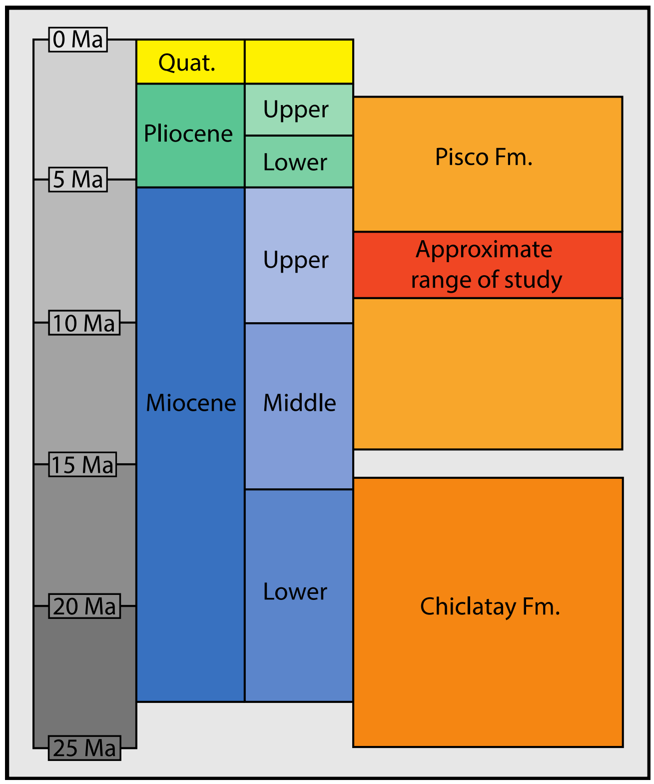


Figure 1. Stratigraphy of Pisco Basin, based on DeVries (1998). Range of this study confined by dated tuffs; dates of the bottom of the Pisco Formation are probably older than DeVries' estimate (Nick, K. Personal communication, June 6, 2014, not yet published).

The Pisco Basin consists of a pair of forearc basins containing the Pisco and other formations. The East Pisco Basin was probably a bay isolated from the Pacific Ocean by coastal mountains, and may have had only limited access to the open ocean at times during its depositional history (Dunbar et al. 1990) (Figure 2).

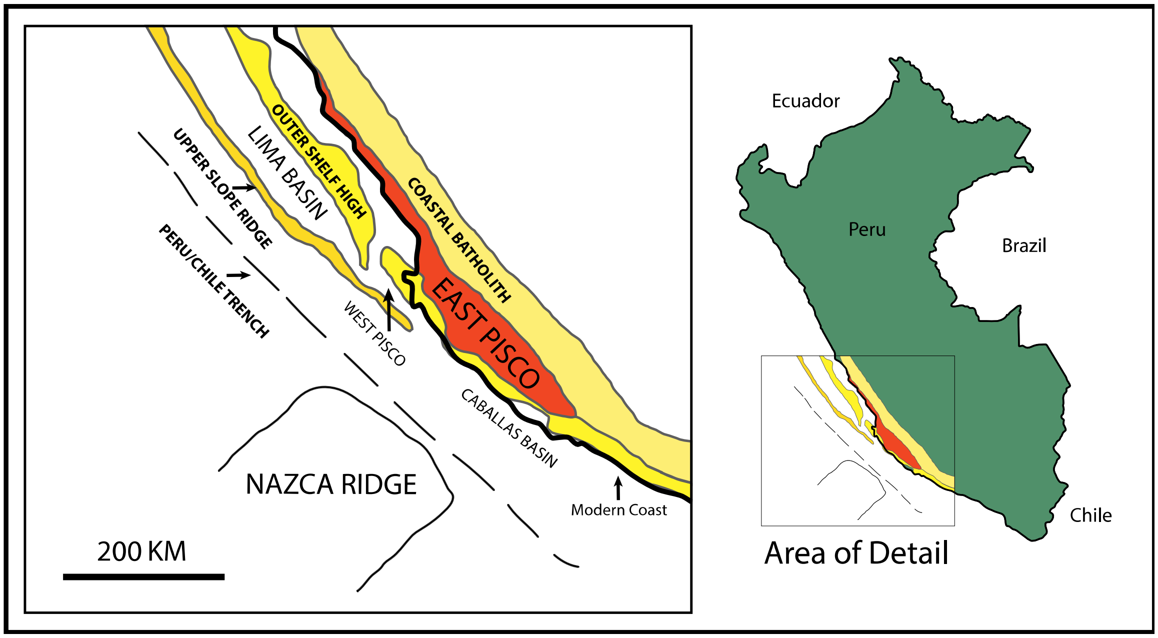


Figure 2. Diagram of Pisco Basin, based on Dunbar et al. (1990), which was based on Travis et al. (1976) and Thornburg and Klum (1981).

The siliciclastic portion of the Pisco sediments has been derived primarily from the surrounding mountains; the two other most important constituents of the sediments are volcanic ash and diatoms. The East Pisco Basin is noted for abundant and varied marine mammal fossils, most notably cetaceans (De Muizon and DeVries 1985; Esperante et al. 2000, 2002, 2008; Brand et al. 2004; Lambert et at. 2010).

Objective

This study takes advantage of the opportunity offered by the fossil whales in cross section in cliff faces to study the sedimentological features preserved around the whales. These cross sections provide us with an excellent view of the stratigraphic relationships of the sedimentary structures to the fossils and allow us to interpret processes and depositional environments.

The objective of this study is to propose a local depositional model for the sediments that encased the whales, incorporating the knowledge gleaned from the previous taphonomic work in the basin.

CHAPTER TWO

METHODOLOGY

In 2011 and 2012, we located several large vertebrate fossils in cross section (Figure 3). Criteria for including sites in the study were the presence of a large, articulated marine mammal fossil in a well-exposed, sufficiently vertical outcrop.

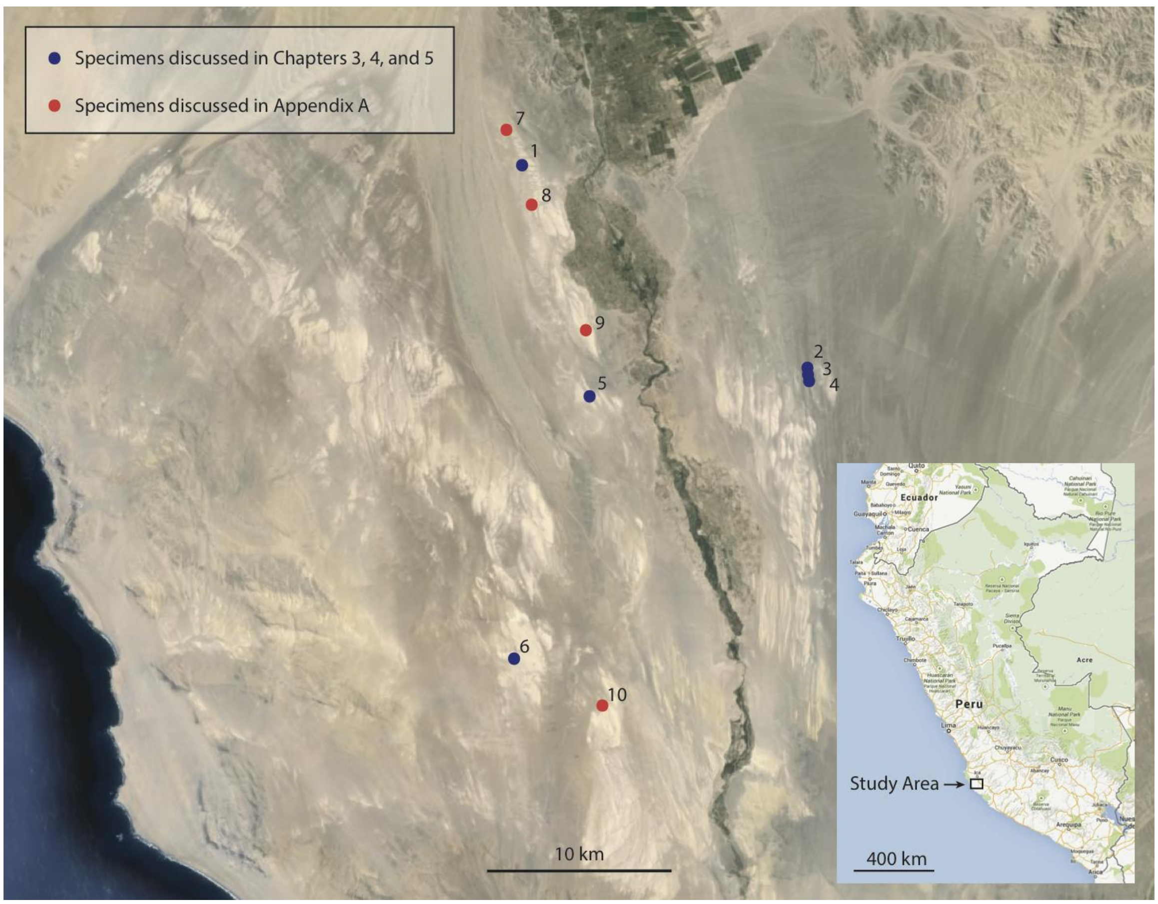


Figure 3. Location Map (Google Earth, 2014). Samples are from the east and west sides of the Ica River. Latitude/longitude coordinates are given in Table 1. Access is by a combination of 4x4 trails and walking.

In each of the outcrops we chose, the bedding was clearly visible. Each outcrop was also accessible on foot. These outcrops allowed us to clearly see the lateral and vertical sedimentary context of the cetacean's deposition. Table 1 shows a list of specimens and their locations.

Table 1. Locations of large marine mammals in cross section

Location	Coordinates
1: Cerro Ballena	14°19'32.27"S, 75°43'27.18"W
2: Antenna Whale 2	14°25'53.84"S, 75°34'36.33"W
3: Antenna Whale 3	14°25'56.00"S, 75°34'35.83"W
4: Antenna Whale 4	14°25'56.97"S, 75°34'35.69"W
5: Cerro Hueco la Zorra	14°26'46.34"S, 75°41'19.81"W
6: Cadena de Zanjones	14°34'31.50"S, 75°43'36.07"W
Appendix A Locations	
7: Cerro Ballena North	14°18'23.52"S, 75°43'57.40"W
8: Cerro Ballena South	14°20'48.28"S, 75°43'09.03"W
9: Cerro Blanco	14°24'44.74"S, 75°41'27.19"W
10: Amara	14°35'52.20"S, 75°40'58.18"W

We judged the articulation of the specimen based on the articulation of the exposed bones. We used the presence of a concretion as further evidence that the specimen was articulated, based on observations of dozens of specimens exposed on bedding planes in similar sediments. (It should be noted that some disarticulated specimens are in concretions, however.)

At each site, we described and recorded sedimentary and biogenic structures with photographs and drawings, and charted their relationships with each fossil. Then we took samples of the sedimentary rocks encasing the cetaceans' bones, the beds 1-2 meters above and below the cetaceans, and any tuffs within 1-2 meters of the fossils. We also identified the time horizon corresponding to burial of the cetacean, and checked for any evidence of bioturbation, or a change in depositional conditions at that horizon. We looked for any deformation of the sediments below the whale that might indicate that the whale sank into the sediment, or that when the whale struck the bottom, deformation of the sediment occurred.

Samples were analyzed using microscopy of thin sections, X-ray diffraction (XRD) and scanning electron microscope (SEM). Results from XRD are reported in weight percent and microscope estimates as volume percent. We determined the mineralogical content of the sediments and bones, and particularly noted any mineralogical or depositional difference between the beds above and below the bedding contact that was at the sediment/water interface when the whale was deposited. Because neither diatoms nor volcanic glass have enough crystalline structure to be differentiated by XRD, we used the SEM to determine the makeup of the amorphous content of the samples.

For the purposes of this study, channels are U- or V-shaped erosional surfaces that cut older beds and are overlain discordantly with younger sedimentary fill. Many of the channels in this study also had pebble lags at their bases, providing further evidence of high-energy flow capable of translocating or forming lags of larger clasts and eroding existing material.

Various techniques for enhancing the visibility of the sedimentary structures in the outcrops were investigated. Wetting with water or light oil was unsuccessful. Wetting with 90-weight oil did help visibility, but not enough to warrant the time required to cover the outcrop. Brushing and planing the surfaces proved to be the best approach. Removing the weathered surfaces was necessary, as the weathered surfaces tended to obscure the sedimentary structures.

CHAPTER THREE

RESULTS AND INTERPRETATIONS OF INDIVIDUAL SPECIMENS

Location 1: Cerro Ballena

At Cerro Ballena, erosion of the cliff face has sectioned a whale through its rib cage. The ribs and vertebrae present are close to articulated position, though fractured due to compaction. No macrobioerosion or abrasion is visible on the bones.

The whale is deposited on an erosional surface more than 3-m wide (which we have defined as a channel in the methodology section) (Figures 4 and 5) in a portion of the section about 4-m thick that is bounded by two tuff beds (Figure 6). Figure 4 shows an overview of the whale fossil in the outcrop, and Figure 5 is an overlay of how the depositional units are subdivided. This channel is draped by about 10 cm of diatom-rich sediment and a layer of diatomite about 2-cm thick (Unit 2), which continue over the whale (Figures 7 and 8). At this location, some other channels also contain diatomite drapes, but most swales do not. While the channel cuts several dm through multiple smaller structures, the swales with diatomite drapes are part of the hummocky and swaley cross-stratification.

There is no apparent change in the sedimentary structures between Units 1 and 3. The division between them is the erosional event that cut the channel and Unit 2, the channel drape. In the swaley bedding about 10 cm under the whale (part of Unit 1—see Figure 5), the swales are small-scale, with a wavelength of about 1-2 dm (Figure 9).

Symmetrical ripple marks occur immediately above the whale (part of Unit 3) (Figure 10). Large-scale hummocks and swales are also present at this location, on the order of 50 cm in width. The sedimentary structure dominating Units 1 and 3 is HCS.

The material of Units 1 and 3 is made up of primarily silt-size siliciclastics with abundant clay-size particles. The predominant minerals present are feldspars (49%) and quartz (13%). The amorphous constituent of the rocks (30% of the total) contains both volcanic glass and diatoms (Table 2, Sample E). Volcanic glass shards at this location are much more rounded than the volcanic glass shards at other locations in this study (Figure 11).

Many gypsum veins run through the outcrop. Some follow bedding planes, and others cut nearly vertically. Where these veins intersect mineral stains in the rocks, cross-cutting relationships can be determined. Two gypsum veins run on either side of the whale's concretion (Figures 4 and 5). One of these runs from the tuff below the whale to the tuff above it, and the other runs from the tuff below the whale and crosses the first vein above the whale. In the instances of intersection between coloration of the rocks and a gypsum vein, the cross-cutting relationship indicates that there was a permeability barrier in place prior to the arrival of the ions that stained the rocks (Figures 12, and 13).

The only bioturbation is above the fossil, at the base of a large swale (Figures 14 and 15).

HCS and SCS in silt-size sediments suggest suspension and deposition by oscillatory flow from storm-generated waves (Dumas and Arnott, 2006). Because we have observed coarser grain sizes in near-shore facies in other places in the Pisco Formation, silt-size and finer grains may suggest deeper water. A general lack of wave ripple reworking, except for an instance of ripple laminae, suggest a depth below fair weather wave base. The combination of grain size and sedimentary structures, therefore, suggests processes that occurred on the middle to upper shore face with deposition during waning storm events—waning, because in the more violent part of the storm, the currents are strong enough to keep the particles suspended.

Erosion of the channel probably also occurred during a storm or other high-energy event, as the erosion of silt-size grains requires more energy than the suspension of silt-size grains. Our three primary reasons for interpreting the structure in which this whale is buried as a channel are its erosional boundary, the preponderance of scour and fill structures in this area, and the size of this particular structure compared to the other scour and fill structures. The telltale pebble lag at the base of the channel is missing, but there weren't any coarse grains at this location at all. Because the channel is considerably wider than the whale and symmetrical around the whale, we propose that the channel was cut before the whale was emplaced rather than the carcass focusing currents to self-generate erosion.

The next event was a low-energy one—the deposition of the diatomite drape and about 10 cm of other beds of diatom-rich siltstone in the same plane as the diatomite drape, all labeled Unit 2. Deposition of this unit required fairly calm conditions, as diatoms are a low-density sediment.

The next recorded event—the deposition of the small, symmetrical climbing ripples—involves lower-energy oscillatory motion of the water.

Deposition of Unit 3 occurred under conditions similar to the deposition of Unit 1, as evidenced by the HCS and SCS. The slightly bioturbated, diatomite-draped swale in

Unit 3 is an interesting clue. It is isolated, but probably because it is a remnant of a slightly bioturbated surface that survived an erosional event.

The next event, judging by cross-cutting relationships, was the formation of permeability barriers. Following the formation of the permeability barriers, the concretion formed around the whale. Prior to this study, we had thought that the ubiquitous gypsum veins in the basin were precipitated a long time after the sediments were deposited. This assumption has not been discarded yet, but it has come under question. This whale provides one of the best studies of the interactions of the gypsum veins with the concretion ions. The interactions between the vertical gypsum veins and the whale's concretion show that there were permeability barriers in place before the movement of the concretion ions through the sediments on both sides of the whale (Figures 12 and 13).

Based on the observation that, at this interval, most of the articulated fossils in diatomaceous and/or tuffaceous sediments are encased in a concretion, while individual bones are not, it is likely that the ions that form the concretion minerals either came from the whale's flesh or were liberated by the reducing environment caused by the whale's decomposition. (By extension, concretions that do not contain fossils may be related to the deposition of organic matter.) In the case of this whale, it appears that a permeability barrier, possibly the gypsum that is now present, was in place before the whale completely decomposed. The primary mineral responsible for the staining is hematite, but the dominant concretion mineral is gypsum.

Assuming that the small, symmetrical climbing ripples (Figure 10) were deposited on a relatively flat bedding plane, the compaction of the whale and its surrounding sediments happened after the deposition of at least the bottom portion of Unit 3, based on the deformation in the bed in which these ripples are found. The diatomite drape and the laminae above it also drop in elevation as they pass over the whale, which is probably also due to differential compaction.

While it seems clear that a permeability barrier was present before the ions released by the decay permeated the sediments, the presence of channels with diatomite drapes and bioturbation makes it unlikely that this 4 m of sediment in which the whale was buried was the result of a single event, but rather the deposition of diatomaceous sediments interrupted by a series of storm events between two volcanic eruptions.

Location 1 Figures

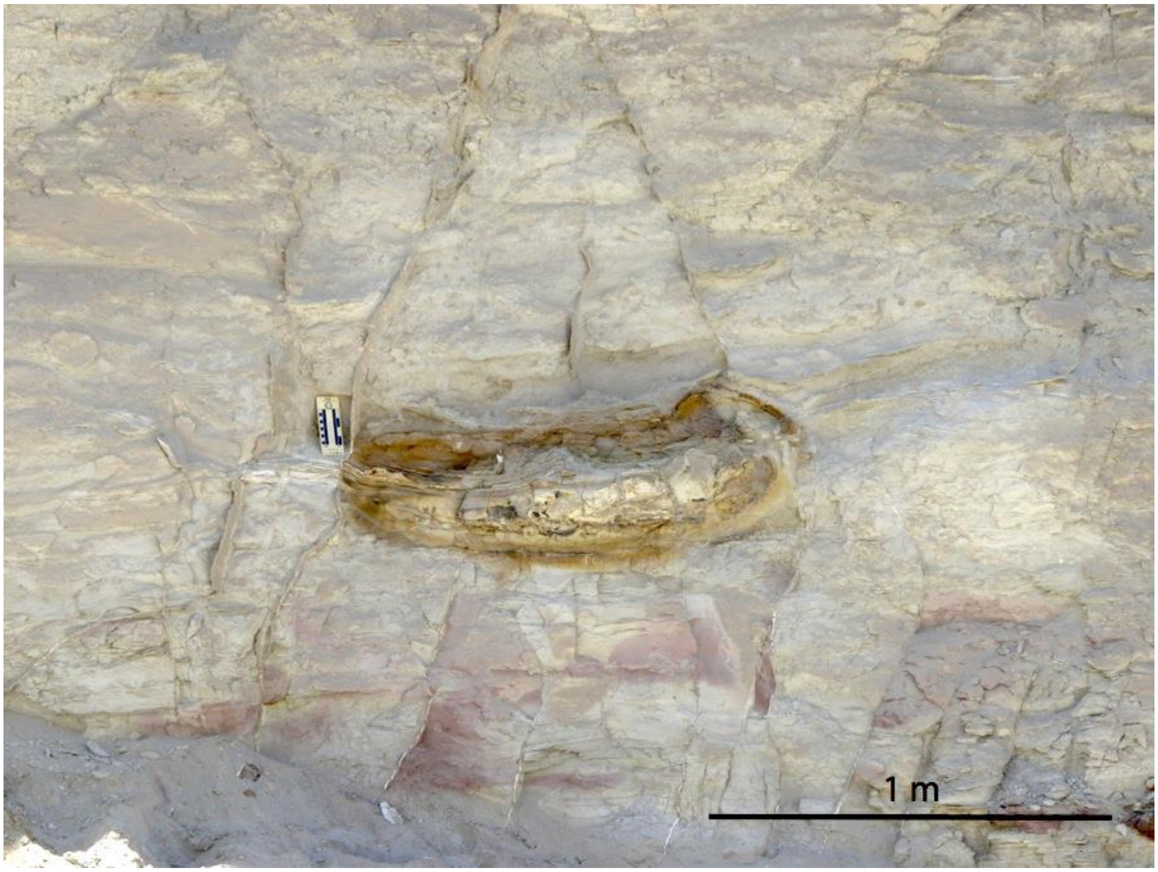


Figure 4. Cross section of Whale 1 at Cerro Ballena. HCS and SCS are present but not clear in the photo. As the dark red patches below the whale show, the truncation of the colored regions by gypsum veins is not unique to the whale's concretion.

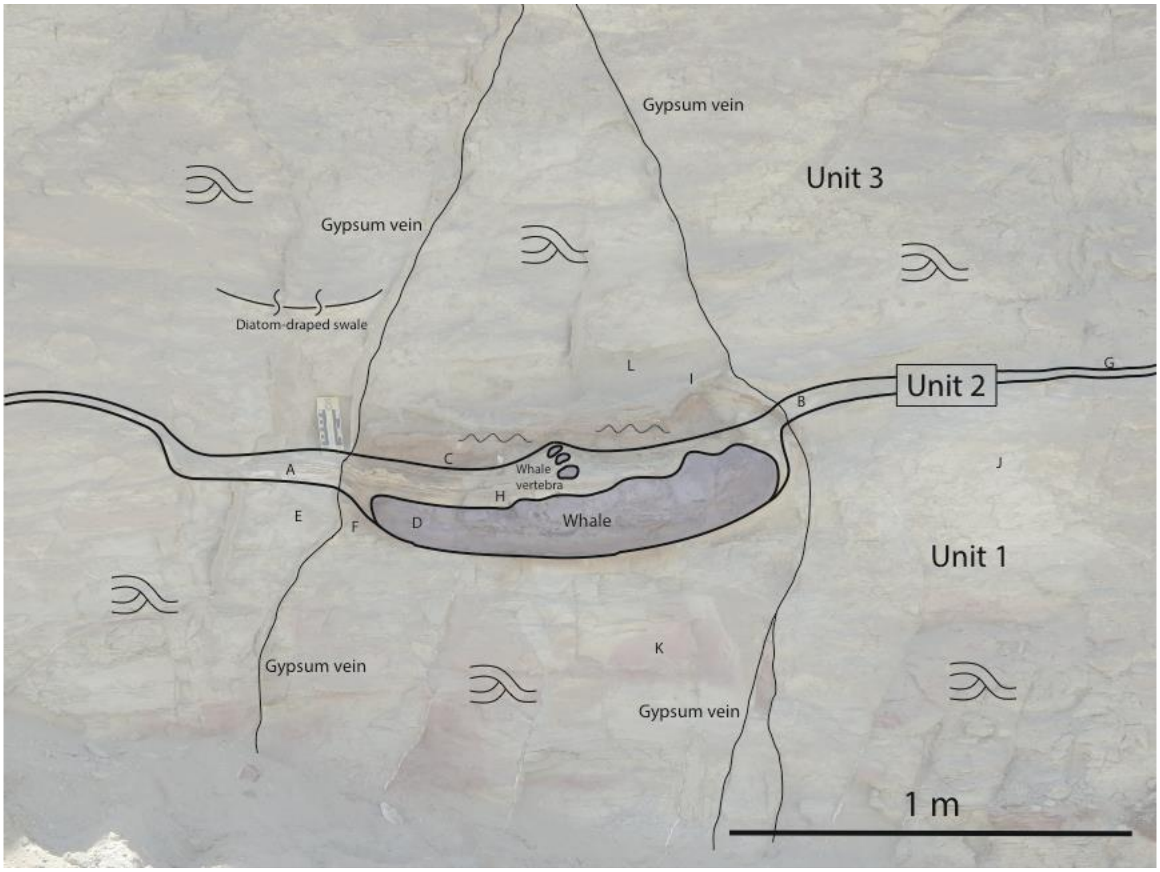
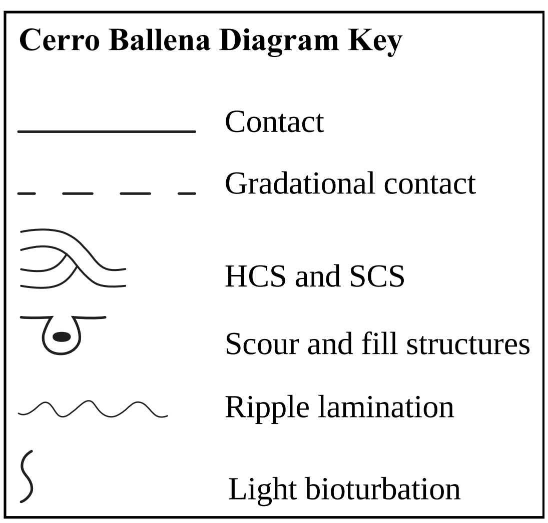


Figure 5. Interpretative overlay of Figure 4. Letters A-L indicate the sampling locations within the area of the diagram.



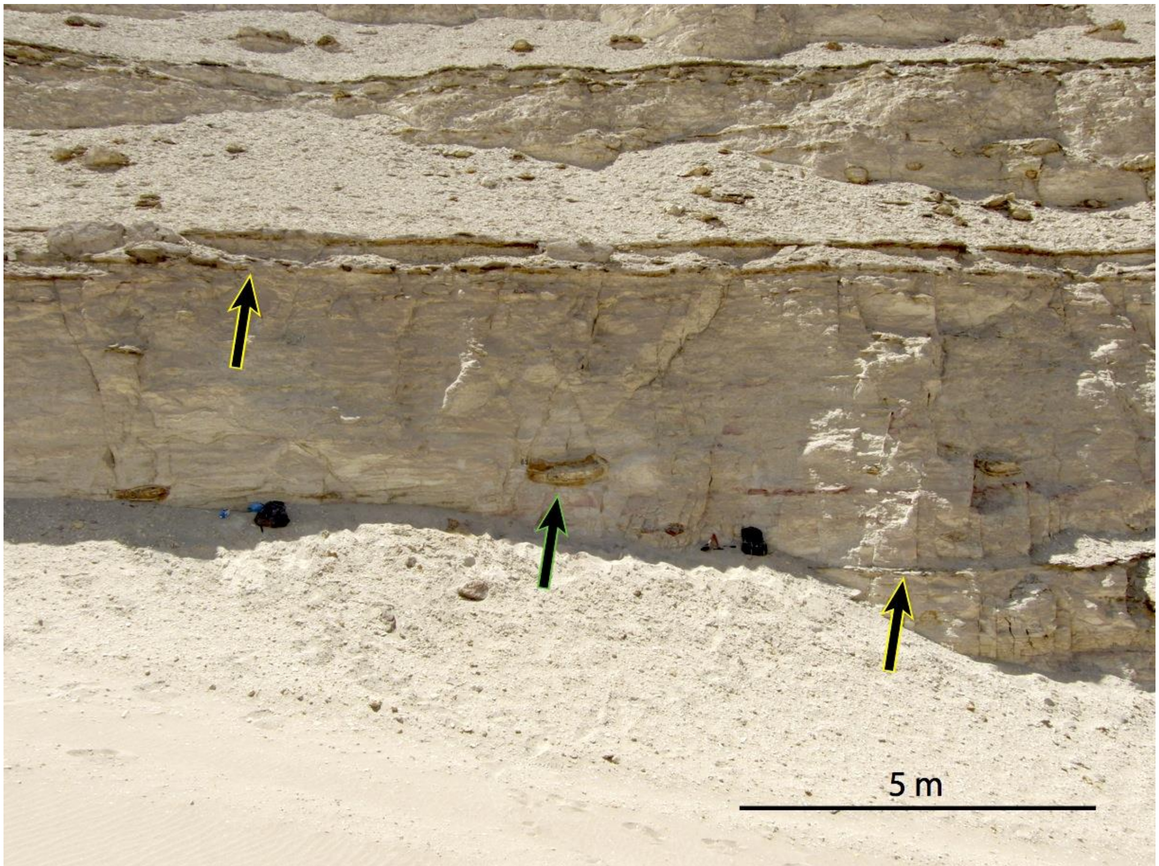


Figure 6. Yellow-bordered arrows indicate the two tuff beds that bound the packet of sediment in which the whale is buried. The whale is marked with a green-bordered arrow.

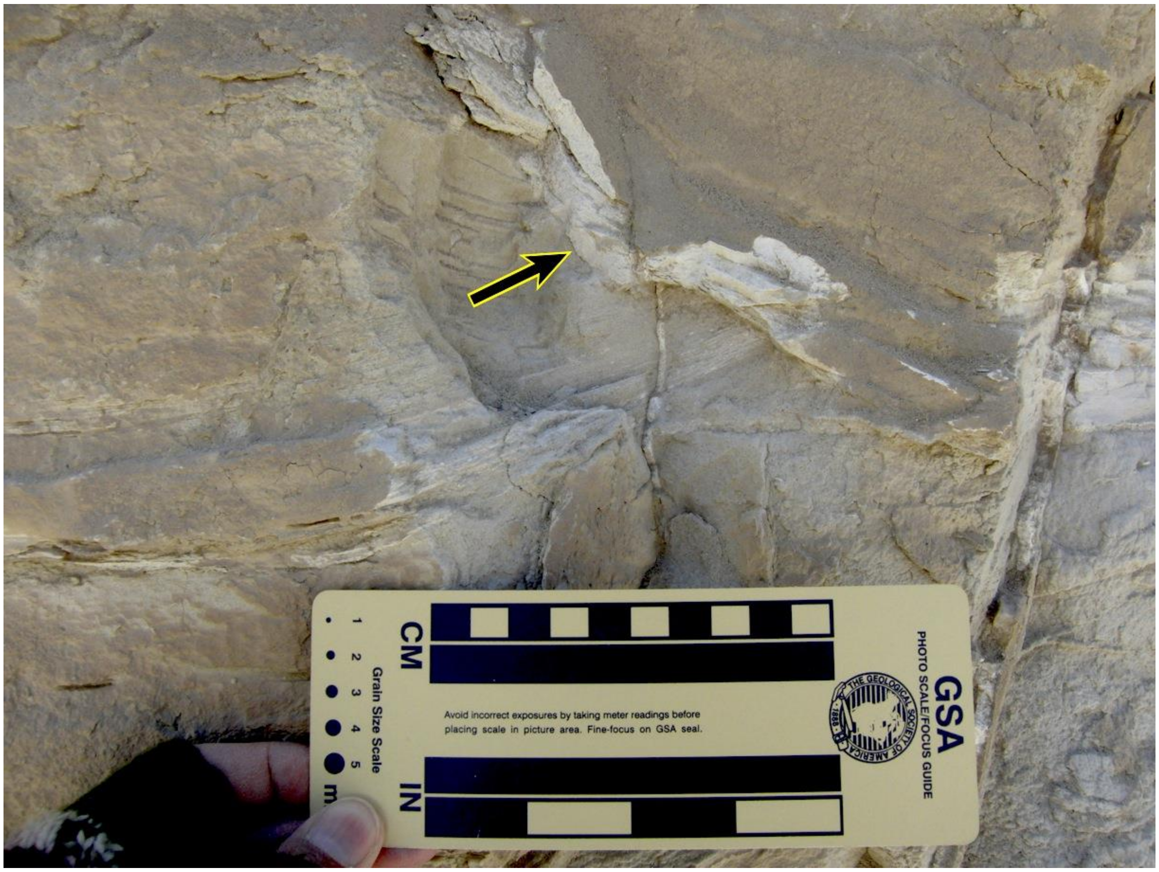


Figure 7. The white bed marked with an arrow is a diatomite drape in whale’s channel.

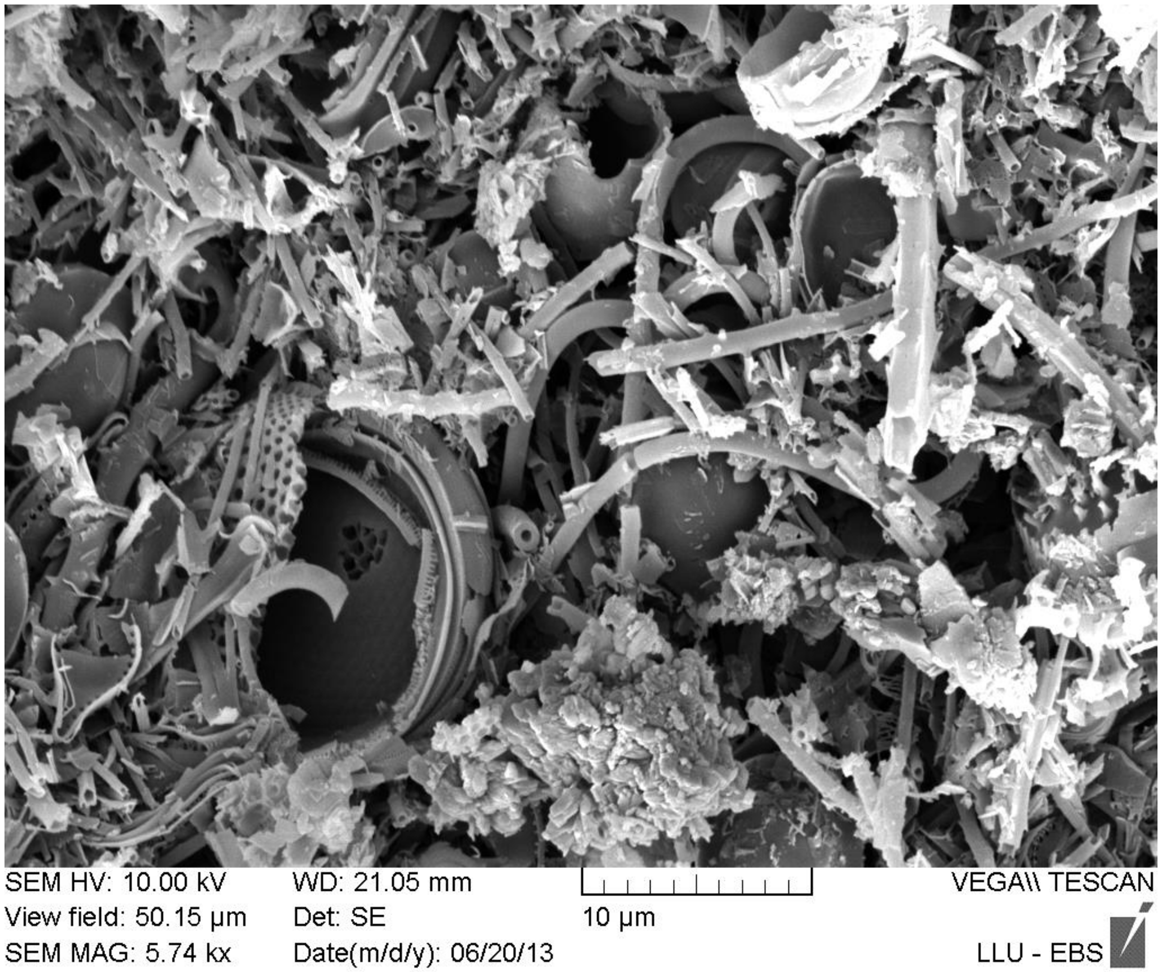


Figure 8. Diatoms from the diatomite drape in whale's channel. These drapes, and some features that might have been mat fragments, were the only instances of pure diatomite found in this study.

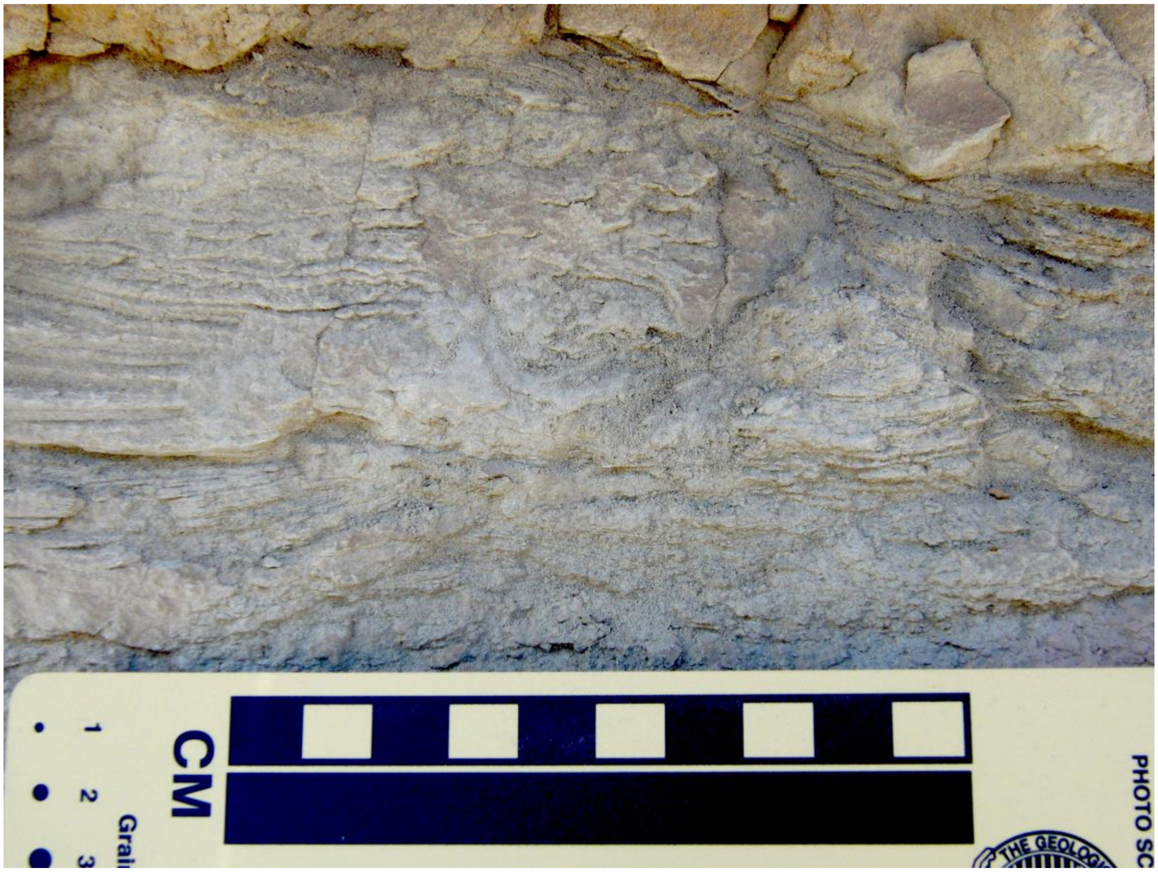


Figure 9. Convoluted swaley bedding about 10 cm under whale

Figure 10. Small-scale in-phase climbing ripples over the whale

Table 2. XRD analysis of selected rock samples from all sites. Except for those marked "tuff" or "drape," the samples chosen were representative of the rock encasing the specimen. Figures are given in weight percent.

	Sample	Aragonite	Calcite	Clays	Feldspars	Gypsum	Halite	Jarosite	Quartz	Amorphous
Location 1: Cerro Ballena	E	0.0	2.5	0.0	49.4	5.1	0.0	0.0	12.7	30.4
Location 1: Cerro Ballena drape	A	0.0	0.0	0.0	13.0	6.0	0.0	14.0	7.0	61.0
Locations 2, 3, and 4: Antenna	EE	0.0	0.0	0.0	35.1	0.0	0.0	0.0	18.9	45.9
Location 5: Cerro Hueco la Zorra	J	0.0	0.0	0.0	25.7	0.0	0.0	0.0	8.1	66.2
Location 5: Cerro Hueco la Zorra tuff	F	0.0	0.0	0.0	1.4	0.0	1.4	0.0	0.0	97.1
Location 7: Cerro Ballena N	2A	10.4	0.0	0.0	28.4	26.9	0.0	0.0	13.4	20.9
Location 8: Cerro Ballena S	K	0.0	0.0	46.5	16.9	0.0	4.2	0.0	7.0	25.4
Location 9: Cerro Blanco	K2	0.0	0.0	27.5	29.0	0.0	0.0	0.0	7.2	36.2
Location 9: Cerro Blanco tuff	C	0.0	0.0	0.0	36.0	0.0	0.0	0.0	0.0	64.0
Location 10: Cerro Yesera de Amara	A2	0.0	0.0	14.9	44.6	0.0	2.7	0.0	18.9	18.9

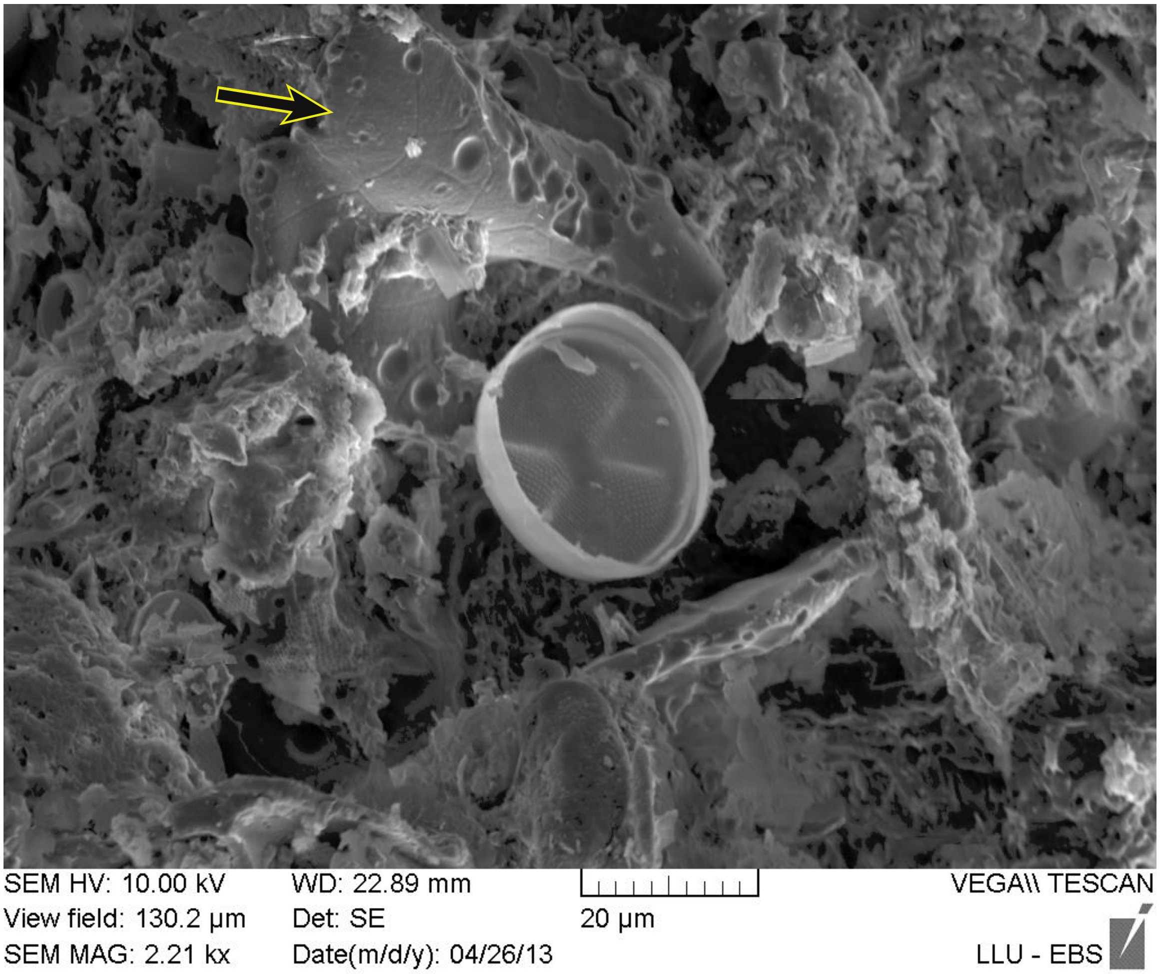


Figure 11. SEM image of volcanic glass and diatom frustules from sediment surrounding whale. The volcanic glass (marked by arrow) is more rounded here than at many of the other locations.

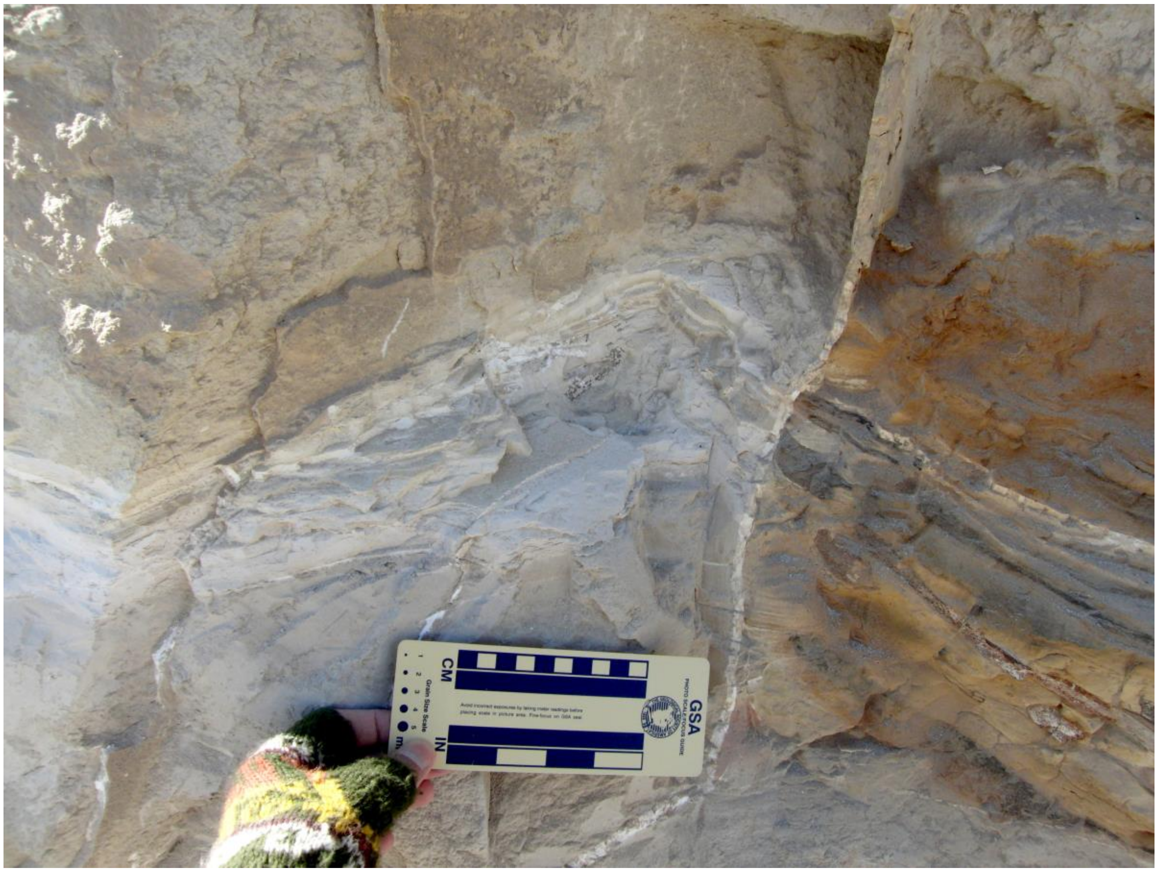


Figure 12. Permeability barrier on the left side of the concretion. Both the orange stain (iron oxides) and the black stain (manganese oxides) have been blocked on this side of the whale. While the iron might have come from the whale carcass, the manganese probably came from the seawater.

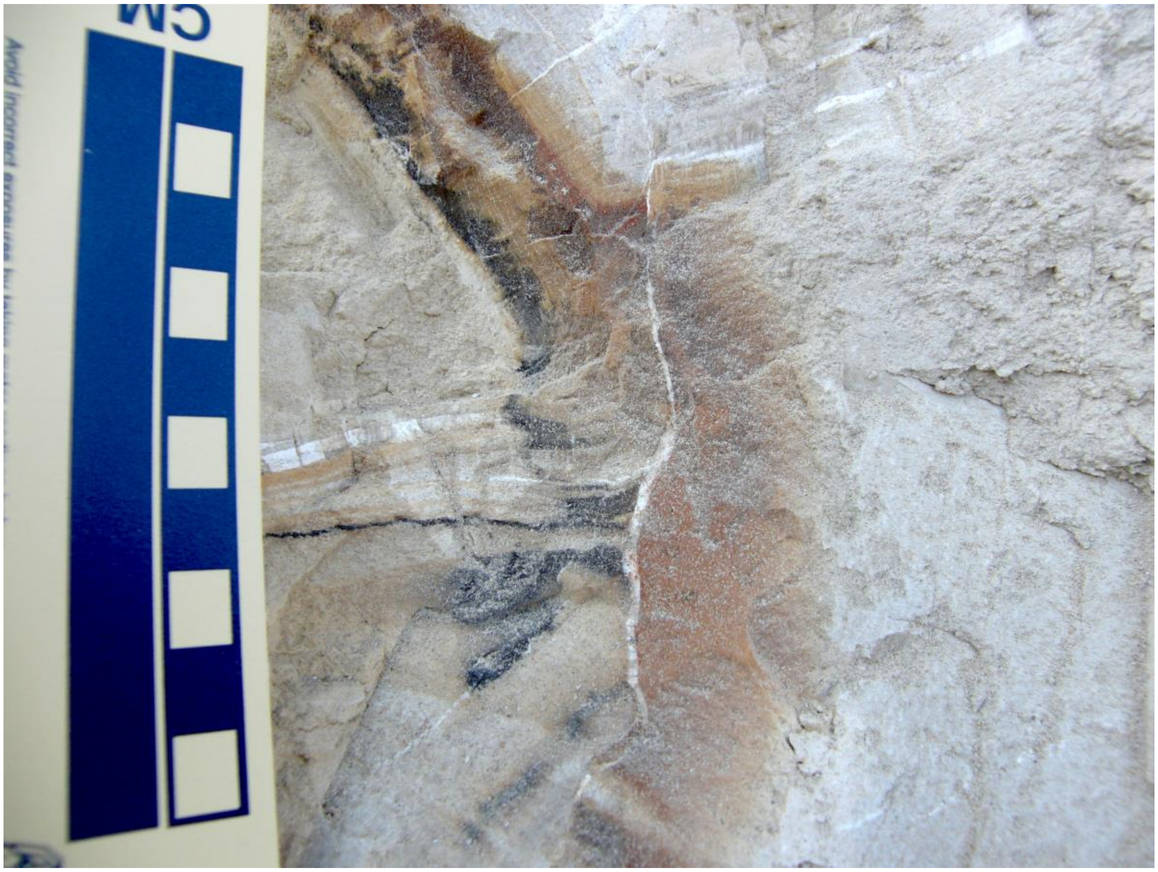


Figure 13. Permeability barrier on the right side of the concretion

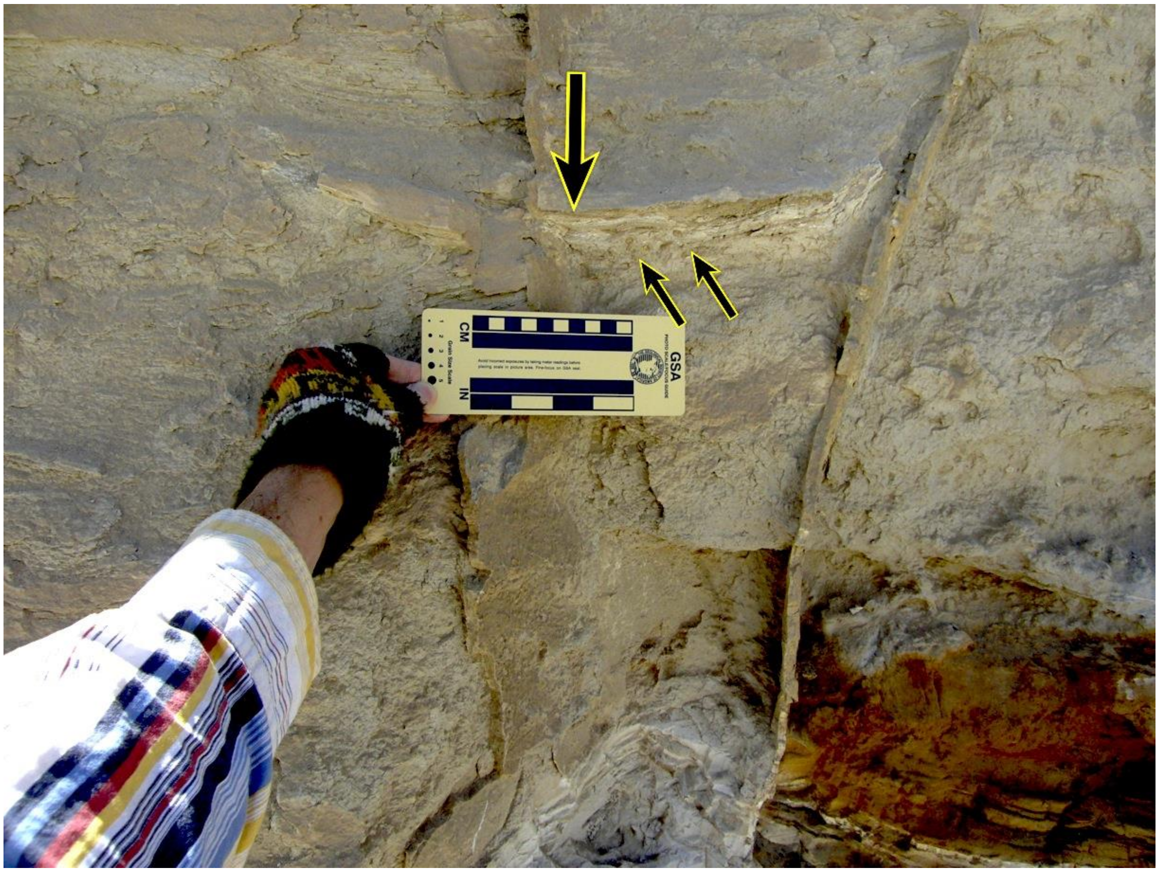


Figure 14. Diatomite-draped swale just above whale (marked with large arrow), with a few burrows (two are marked with small arrows)

Figure 15. Burrows in diatomite-draped swale

Locations 2, 3, and 4: Antenna

At the location called Antenna, we found five whales very close to the same stratigraphic horizon. Only three of these met the criteria for inclusion in this study and are discussed here. They are numbered 2, 3, and 4, going north to south along the outcrop.

For Whale 2, spatial relationships between exposed bones suggest complete articulation (Figure 16). Only the tail of Whale 3 is present, so the state of articulation cannot be stated with certainty (Figure 17). Whale 4 is somewhat unique in the study, because the rostrum and one dentary are encased in a concretion, but the other dentary is not (Figure 18). It appears that the rostrum and the right dentary are in articulated position, but the left dentary disarticulated and ended up on the right side of the skull (Figure 19). No abrasion or macrobioerosion was evident on any of the bones at the Antenna location.

Whale 2 is buried in a wide, shallow channel (Figures 20 and 21). There are two more channels below the one in which the whale is buried, and the lowest channel contains a lag of coarse sandstone (Figure 22). Whale 3 is buried in a similar wide, shallow channel (Figure 17). Whale 4's channel is deeper and contains a lag of coarse material (Figure 23).

HCS is prevalent in all the beds within a few meters of the whales, both below and above them. There is no apparent difference in the widths or amplitudes of the sedimentary structures below and above the whales. Many swales and hummocks are more than a meter long at this location. As such, the wavelengths of HCS and SCS surrounding these whales are the largest such bedforms surrounding any of the whales in this study (Figure 24).

There is soft-sediment deformation at this location (we noticed it primarily below the whales), including fluid escape structures and recumbent folds (Figure 25). Very little to no soft-sediment deformation is present at the other locations. This is also the only location where we encountered deformation immediately under the whale (Figure 26). The U-shaped structure over Whale 4 shows evidence of deformation, and is similar to the similar U-shaped structures over many of the other whales (Figure 27).

The sedimentary units below and above these whales are primarily composed of amorphous and siliciclastic material (Table 2, Sample EE). The bulk of the amorphous material is diatoms (Figure 28). Material surrounding the whales is essentially homogenous; one exception is the lens of siliciclastic pebble conglomerate under Whale 4 (Figure 23). There are many isolated grains of coarse sand throughout the siltstone at this outcrop.

No bioturbation or change in composition is visible at the paleo-sediment-water interface that marks the time the whales were deposited (Figures 18 and 24).

As is the case with Whale 1, the grain size of the sediments at the Antenna outcrop suggests deposition on the lower to middle shoreface. A lack of diatomaceous beds and wave ripples and the abundance of HCS and SCS present throughout all the units suggeests deposition on a storm-dominated shelf during waning storms, perhaps at a shallower depth than for Whale 1.

We've interpreted the structures into which the whales were deposited as channels, based on their shape, the cutting of older laminations, the presence of pebble lags (Figure 23) and their scale (Figures 17, 18, and 20). While there is no pebble lag under the first whale, two channels lie immediately under the channel in which the whale is buried, and the lowermost channel does contain a lag (Figure 22).

Based on the scale of the HCS and SCS compared to the scale of the channels, the lack of channel drapes, the absence of bioturbation, the preponderance of fluid-escape structures above and below the whale fossils, and the deformation of the beds above Whale 4, it does not appear that there was a hiatus in the storm process between the depositions of the beds above and below the channels in which the whales are found. Such hiatuses cannot be ruled out, however, as they can be overwritten by subsequent storm events. One question that is pertinent to the discussion of how many events are recorded at this outcrop is whether or not the amount of sediment present could have been suspended in the water column. The advection studies (Sancetta 1989, Wells and Shanks 1987) may be informative here—where diatom deposition has happened in horizons that contain sedimentary structures that indicate transport and reworking, we should consider advection as a possibility.

The question of whether or not the Pisco Formation contains a record of any mass kills is a frequent one, and the burial of five whales in the same stratigraphic interval may be evidence of just such a mass kill. The scale of the HCS at this location was greater than at any other location, and the violence of the depositional environment implied by such large-scale HCS may be linked to the large number of specimens found. There are pebbles and sand grains interspersed through the siltstone here as well, which again suggest a high-energy depositional environment.

Regarding Whale 4, the whale in the study with the greatest degree of disarticulation, the disarticulated dentary is very close to the rest of the skull (Figure 19). One possibility is that decay of the organism had taken place prior to burial, but some connective tissue was still in place and kept the dentary from separating completely from the whale in the turbulent burial conditions. Deformation in the bedding over Whale 4 suggests that the sediments above the whale were in place prior to the decomposition and compaction of the whale.

Location 2, 3, and 4 Figures

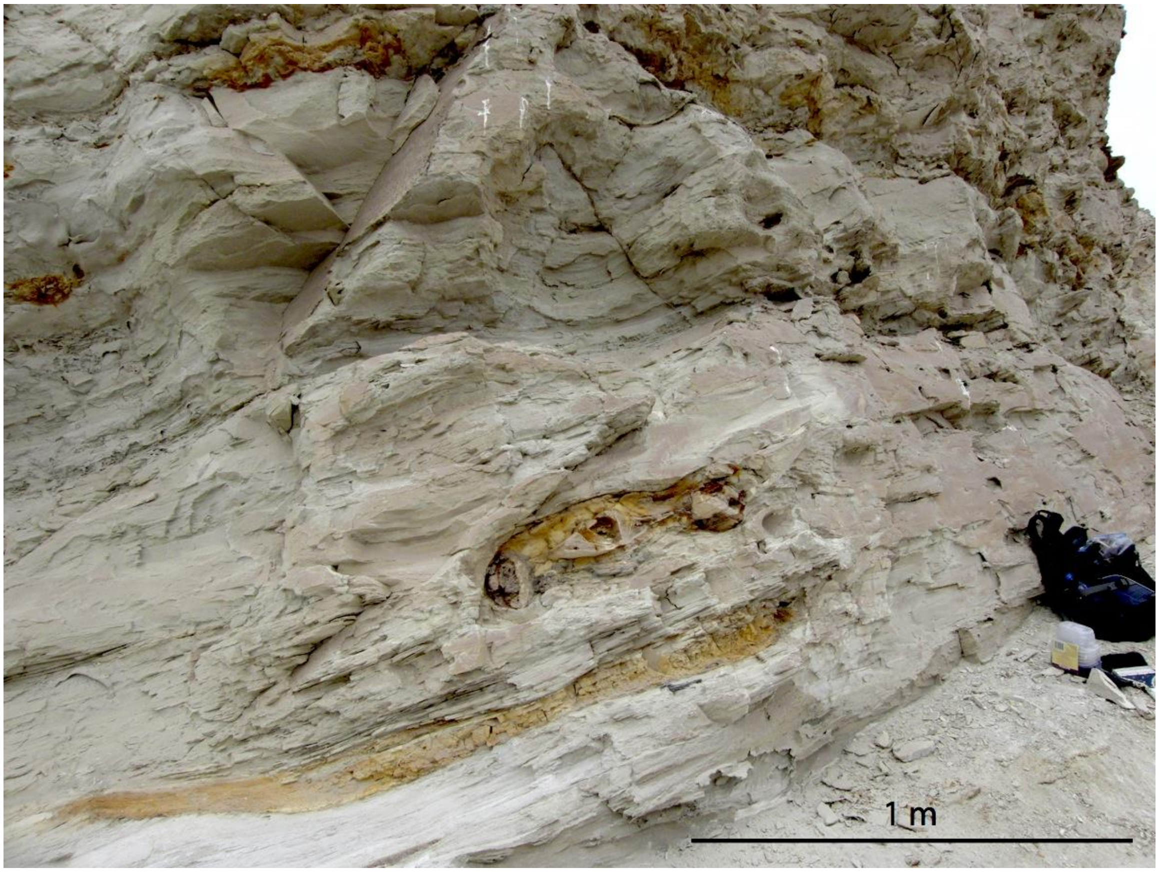


Figure 16. Whale 2. The gently sloping left wall of the whale's channel is faintly visible in this picture. The concretion's channel is clear. Both channels are much wider than they are deep. The bedding dips into the outcrop a few degrees due to tectonic forces. The whale's bones are in articulated position. The cross section is approximately halfway through the whale's head. The whale is in ventral position, with its rostrum pointing into the outcrop. There is large-scale, low-amplitude SCS below concretion, smaller-scale HCS between concretion and whale, and large-scale HCS above the whale.

Figure 17. Whale 3. Panorama of the entire channel. Channel is marked with dotted line. Scale is 1 m.

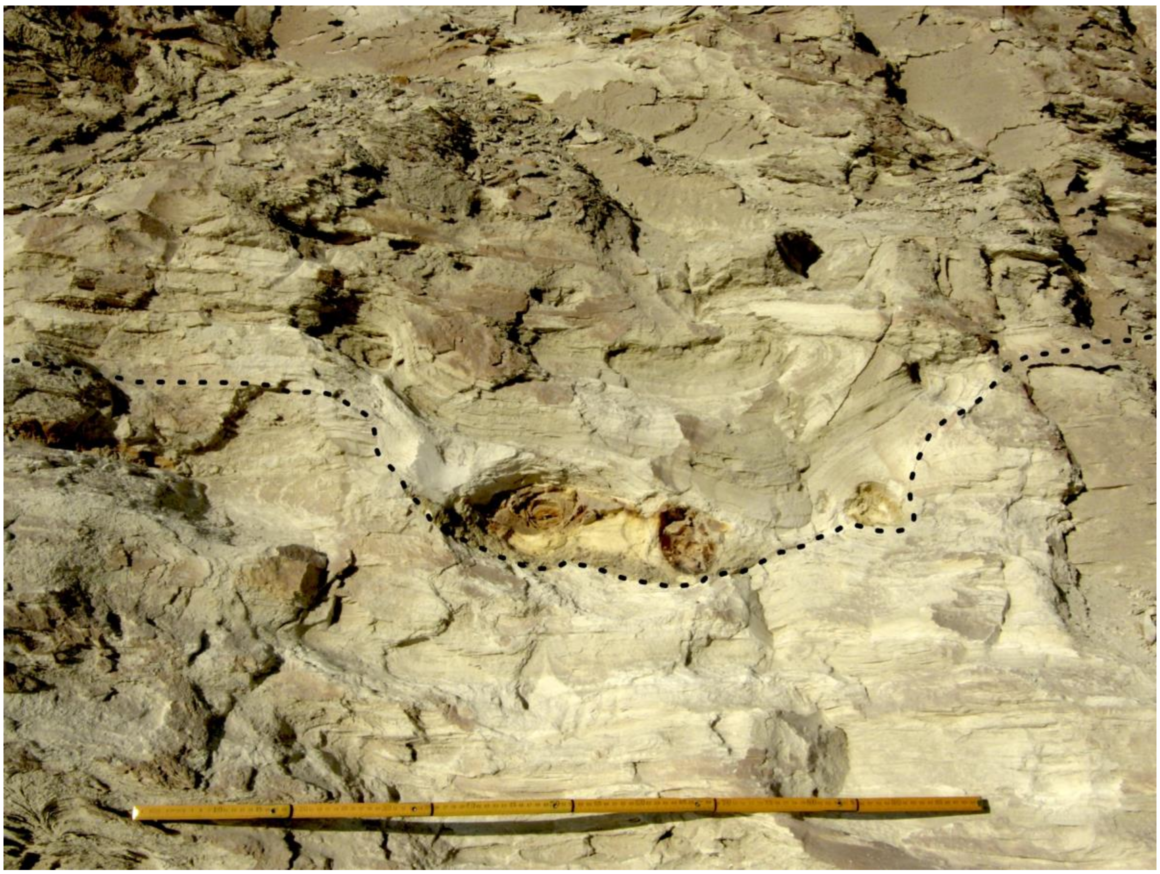


Figure 18. Whale 4. The rostrum and one dentary are visible in the concretion. The other dentary is visible further to the right and a little higher, about 15 cm away from the first dentary. The channel is marked with dotted line. Notice the U-shaped structure 30 cm above the whale.

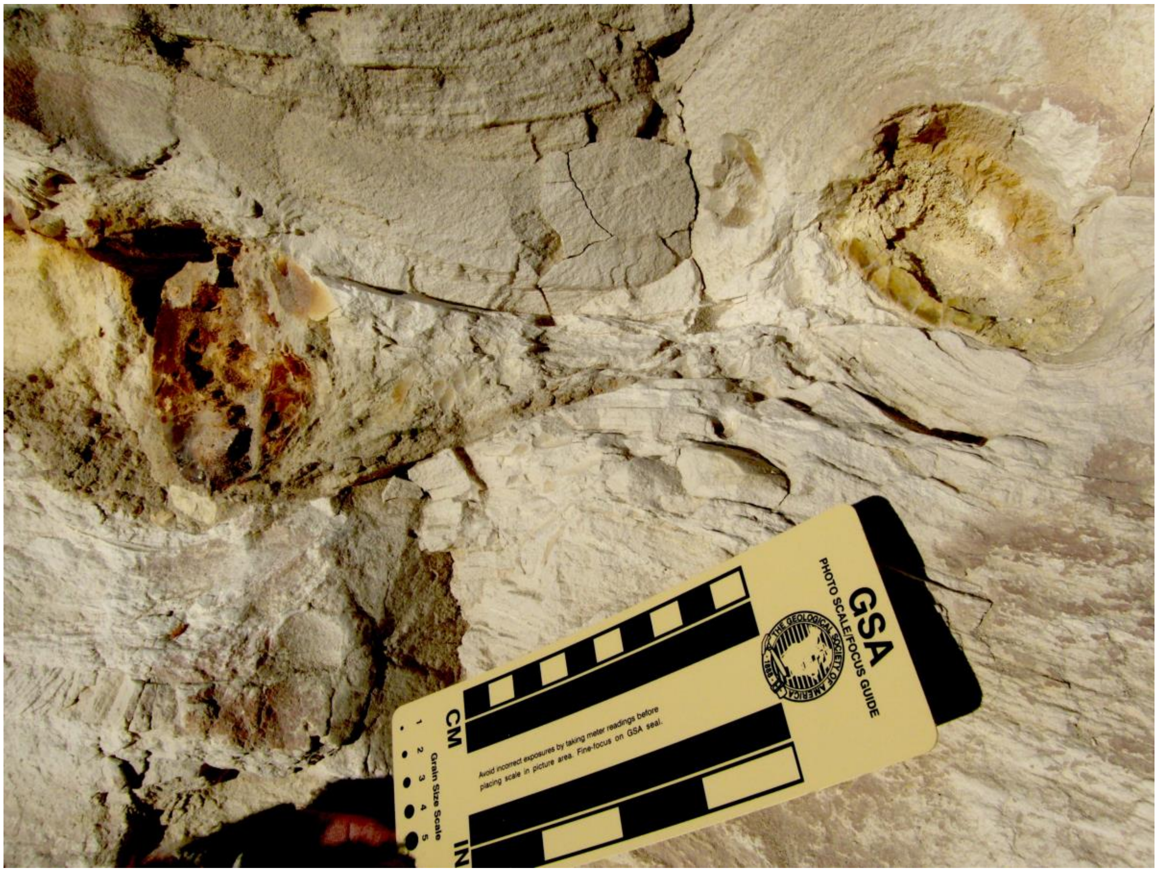


Figure 19. Whale 4. The erosional surface at the base of the channel can be seen clearly about 7 cm above the scale. Both dentaries are visible, and the difference in preservation between the dentaries can be seen. The whale's right dentary (on the right) is much softer and is not surrounded by a concretion. The left dentary and the rostrum were more thoroughly mineralized and are much harder, and are surrounded by a small concretion. This may be evidence that they were still surrounded by some flesh when the whale was buried, but that the right dentary was not. The right dentary seems to have been pressed down into soft sediment. The left dentary may not have been pushed down much, because of the coarse lag below it. The coarse bed is normally graded. Light sedimentary structures are visible in the rock surrounding and between the bones. Staining by concretion-forming ions is minimal.

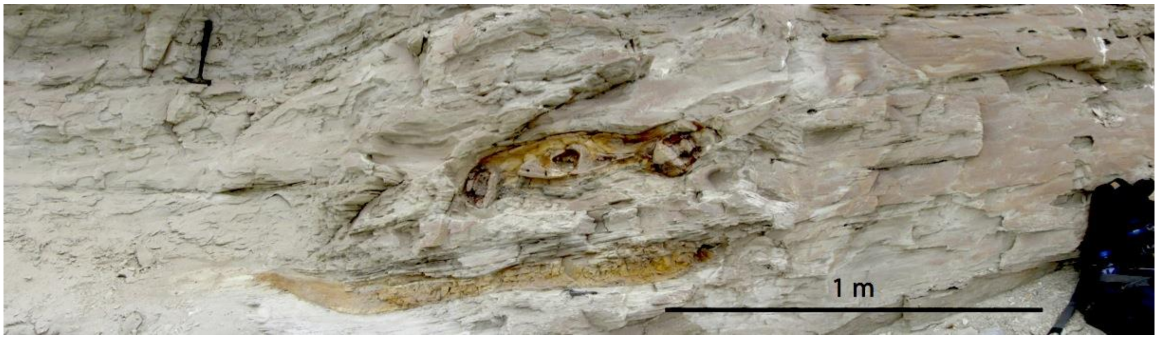


Figure 20. Cross section of Whale 2 at the Antenna location. The dip of the bedding at this outcrop is a few degrees off of horizontal. The whale is in the middle of the panorama, and the rostrum and dentaries are visible. See Figure 24 for a close-up of the right side of this channel, showing a clear erosional surface.

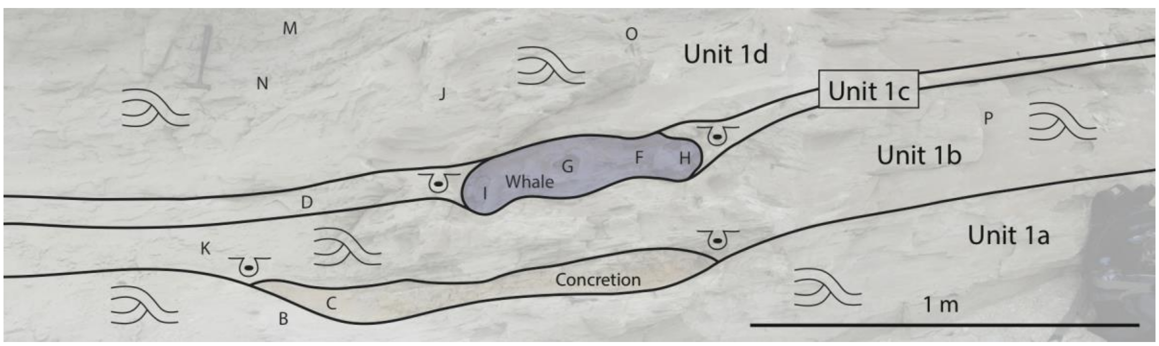


Figure 21. Interpretative overlay of Figure 20. Unit 1c was deposited with the whale. Letters B-P indicate the sampling locations within the area of the diagram.

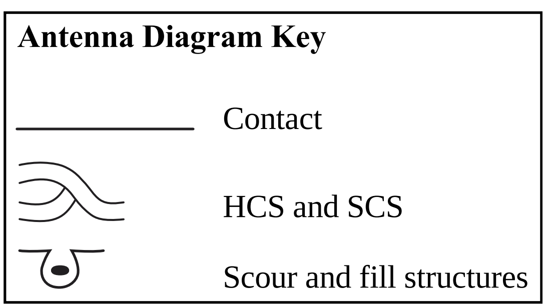


Figure 22. Channel with a coarse sandstone lag at the base. This structure is located a little below the large channel with concretion cements shown in Figures 20 and 21. The steep right boundary of the channel, marked by the dotted line and the arrow, implies scour by moving particles.

Figure 23. Whale 4. Pebble and sand bed at the base of the channel. The clasts tend to be well rounded, but poorly sorted.

Figure 24. Whale 2, right side of channel. The channel has been cut into the laminae of Unit 1b. There is no change in sediment texture, nor is there a change in the sedimentary structures below and above the channel boundary. The channel boundary is marked with a dotted line, and the swale is marked with an arrow.

Figure 25. Recumbent folds. This structure is located above and to the right of the hammer, below and to the left of Whale 2.

Figure 26. Whale 2. The sedimentary structures to the left of the dentary have been overwritten by soft-sediment deformation, which is probably the result of fluid escape. The fluid escape could have happened upon the whale's deposition or during post-depositional compaction of the sediments around the whale. Each of the whale's dentaries has been pushed several cm down into the sediments.

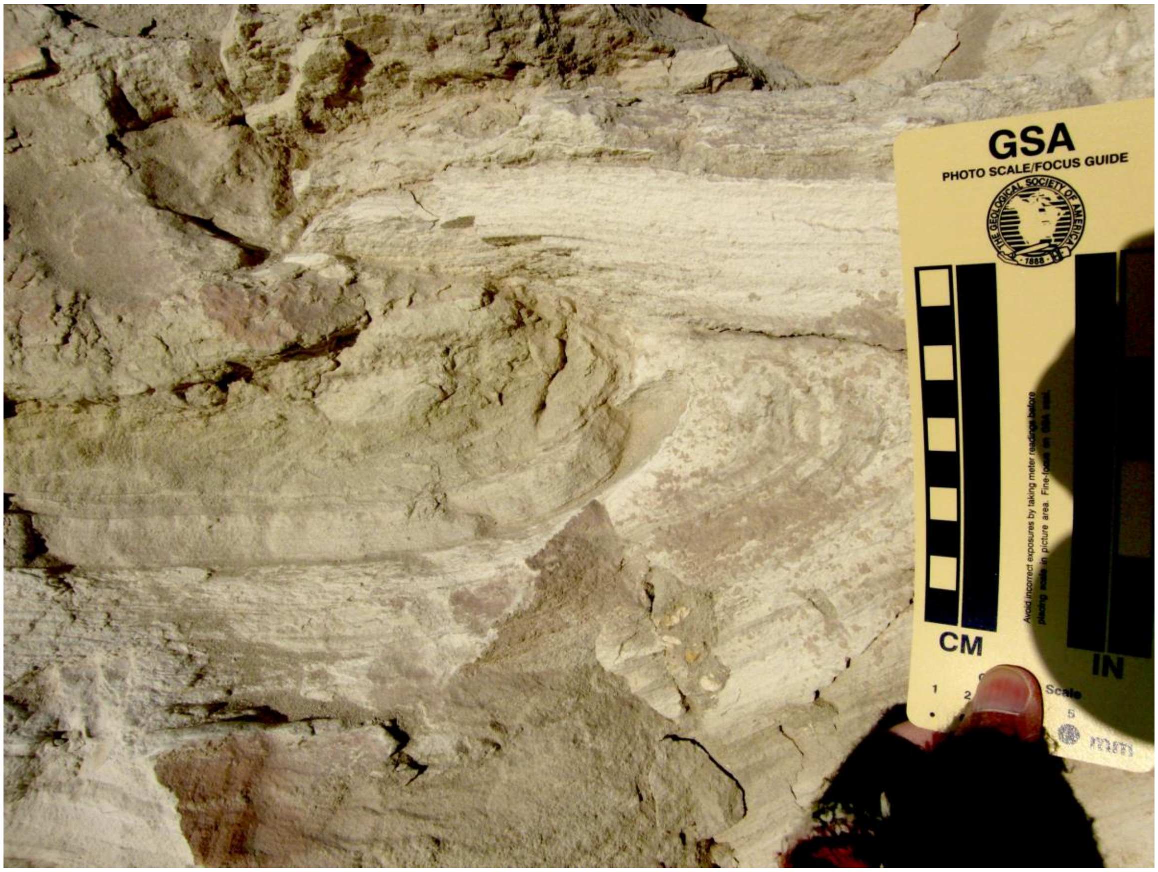


Figure 27. Sediment deformation above Whale 4, probably resulting from differential compaction of the whale and sediments.

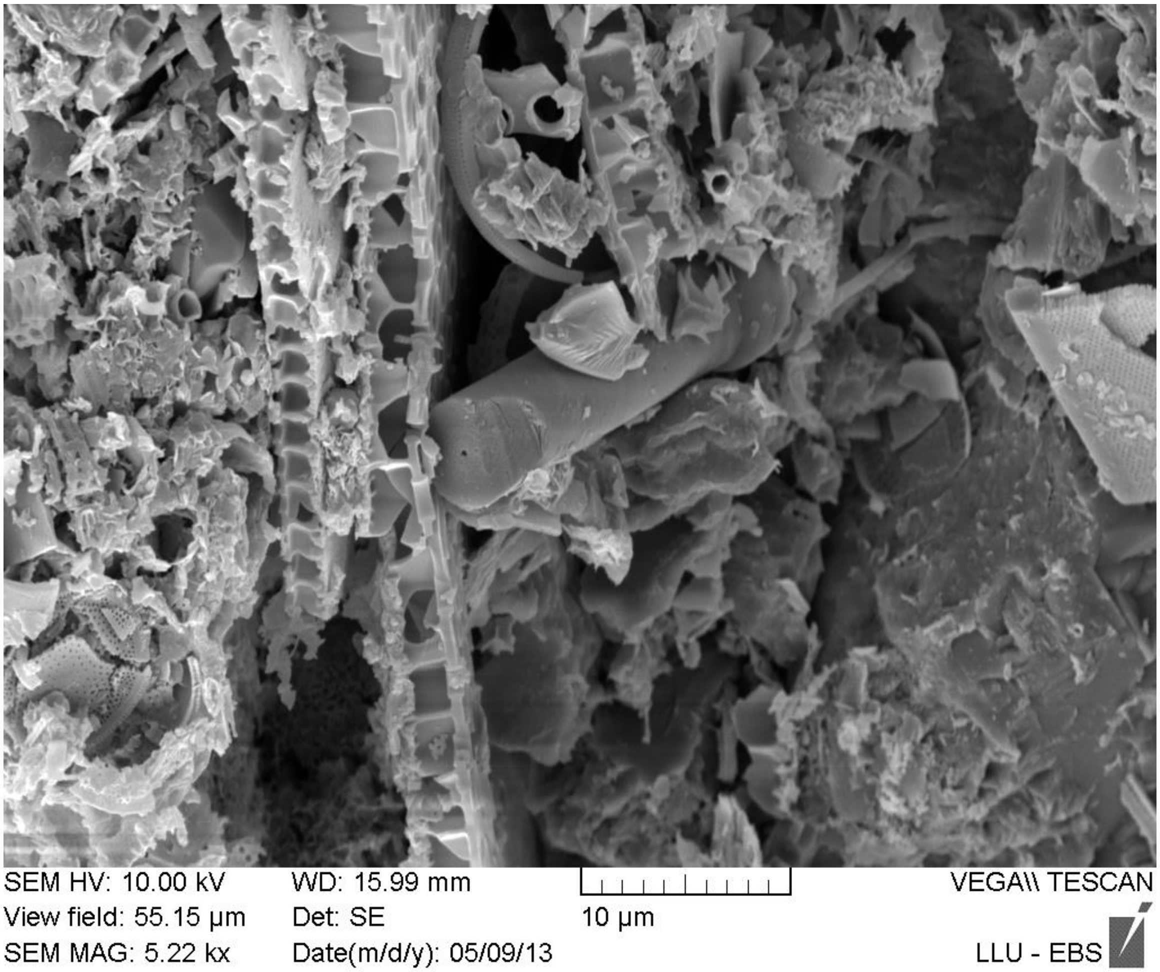


Figure 28. SEM image of diatomaceous sediment around Whale 4.

Location 5: Cerro Hueco la Zorra

The pygmy whale skeleton at Cerro Hueco la Zorra is completely articulated, including its phalanges. It is encased in concretion cement, and none of its bones show evidence of macrobioeriosion or abrasion (Figure 29). For reference, Figure 30 shows the locations of the other figures on the outcrop. As is the case at the other outcrops, the concretion around the skeleton is predominantly made up of gypsum, and the primary cement in the porous fossilized bones is gypsum (Appendix C, Figure 67).

There are no fewer than five channels or scours in the section of the outcrop that was cleared for this study (Figures 31 and 32). The skeleton rests in the largest channel at the outcrop, which was cut into Unit 3 and has a lens of coarse sand and pebbles at its base (Figure 33). The other channels or scours were cut into Unit 1. Contacts between the units are erosional.

All of the units consist of varying mixtures of tuffaceous material and siliciclastic material, though Unit 1 contains more siliciclastic material than the other units. Unit 2 is made up of almost pure volcanic glass (Table 2, Sample F; Figure 34). At the base of the tuff, the XRD measured 99% amorphous material, and at the top of the tuff, close to the contact between Units 2 and 3, the measurement was 97% amorphous material. In Unit 3, at the level of the whale, the volcanic glass content drops to about 66%; the rest is mostly feldspars (26%) and quartz (8%) (Table 2, Sample J). The predominant grain size in all units is silt.

The dominant sedimentary structure in all units is HCS (Figure 35). The wavelengths of the hummocks and swales in this outcrop vary from about 1 dm to nearly a meter (Figures 36 and 37). There is a U-shaped structure in the material of Unit 4 that filled the channel, which we also found at several other locations (Figure 38). The U-shape might be partially due to the angle at which the surface of the outcrop cuts the laminae of the sediments filling the channels (this would indicate cross-bedded laminae). Another factor may be differential compaction of the whale and surrounding sediments, resulting in the U-shape over the whale. As the laminae tend follow the boundary of the channel, however, the biggest factor in the formation of the U-shape appears to be the way the sediment infilling took place. We did not find any bioturbation at this outcrop at all.

As is the case at the Cerro Ballena outcrop and the Antenna outcrops, the grain size of the sediments at the Cerro Hueco la Zorra outcrop suggests deposition on the lower to middle shoreface, and the HCS and SCS present throughout all the units indicate deposition on a storm-dominated shelf during waning storms.

While the Antenna outcrops (Whales 2-4) appear to be the result of one big storm, the bedding and sediments present at this outcrop indicate a more diverse sequence of events.

Unit 1 was deposited by a more energetic storm, based on the large-scale hummocks present (Figure 37). The sediments of Unit 1 are highly siliciclastic, which probably indicates significant coastal runoff. The deep scours in Unit 1 are actually erosionally-modified swales, likely indicating that at the time of the deposition of Unit 2, the sediment-water interface was covered with large hummocks or swales.

Unit 2 is a remarkably pure bed of volcanic ash. There are a few biotite crystals, mostly concentrated toward the base of the bed. Very little material in the ash is not amorphous.. A very small percentage of the amorphous material is diatoms. The bed is friable, to the extent that one can scoop out the material with one's fingers with a little effort. The bed contains large-scale HCS. One explanation for the presence of HCS in the pure ash of Unit 2 is that the ash fell during a storm and overwhelmed the depositional environment. Another explanation is that the siliciclastics arrived later than the ash, because they were brought in by runoff from the surrounding mountains.

Units 2 and 3 may both contain ash from the same source, and the distinction between Units 2 and 3 may simply be that Unit 3 contains siliciclastic material that has been mixed in with the ash by a storm event. Unit 3 contains a very large quantity of volcanic ash, as the unit itself is many meters thick, and the amorphous content of the unit is about 66% (Table 2, Sample F).

We've interpreted the structure into which the whale was deposited as a channel, based on the erosional boundary of the structure and the pebble lag at the bottom of it (Figures 29 and 33). The sand and pebbles are localized below the whale, probably indicating that this was an active channel, transporting and concentrating debris.

The filling of the pores in the bone with gypsum, and the possible partial mineralization of the bone with gypsum observed at this outcrop is the dominant mode of preservation in the specimens we studied.

Location 5 Figures

Figure 29. Whale 5—pygmy whale at Cerro Hueco la Zorra. The left boundary of the channel is marked by the dotted line. The beds that filled the channel continue to the left. The whale appears to have been deposited on the lee slope of one of the cross beds that filled the channel. Scale is 1 m.

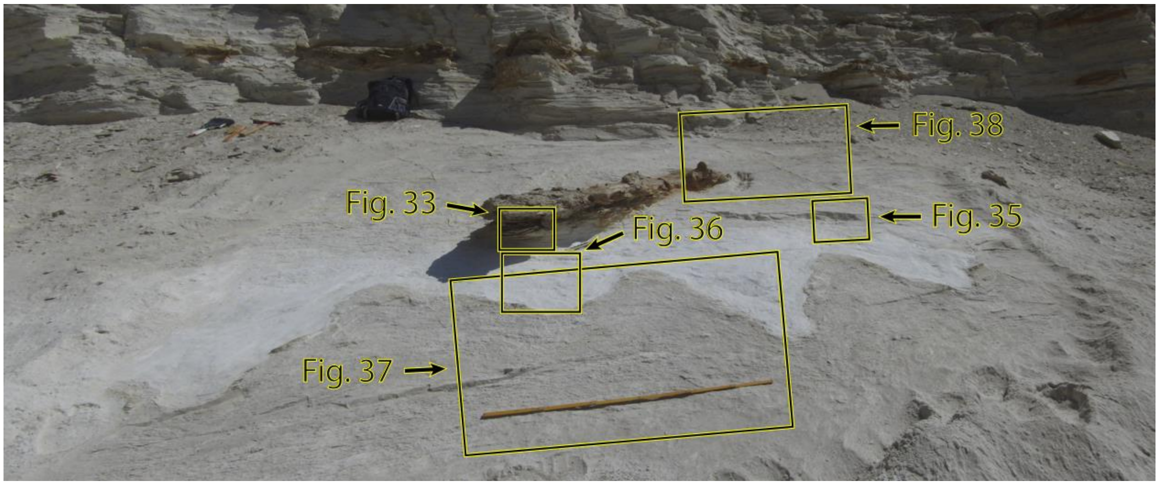


Figure 30. Boxes indicate locations of other figures. Scale is 1 m.

Figure 31. Pygmy whale and surrounding sed rock in cross section at Cerro Hueco la Zorra. Contact between Units 1 and 2 is very irregular, and not due to the surface of the outcrop. It is exaggerated by the angle of the outcrop surface, however, which dips at approximately 30°. (The angle of the photo mostly corrects for the exaggeration.) Scale is 1 m.

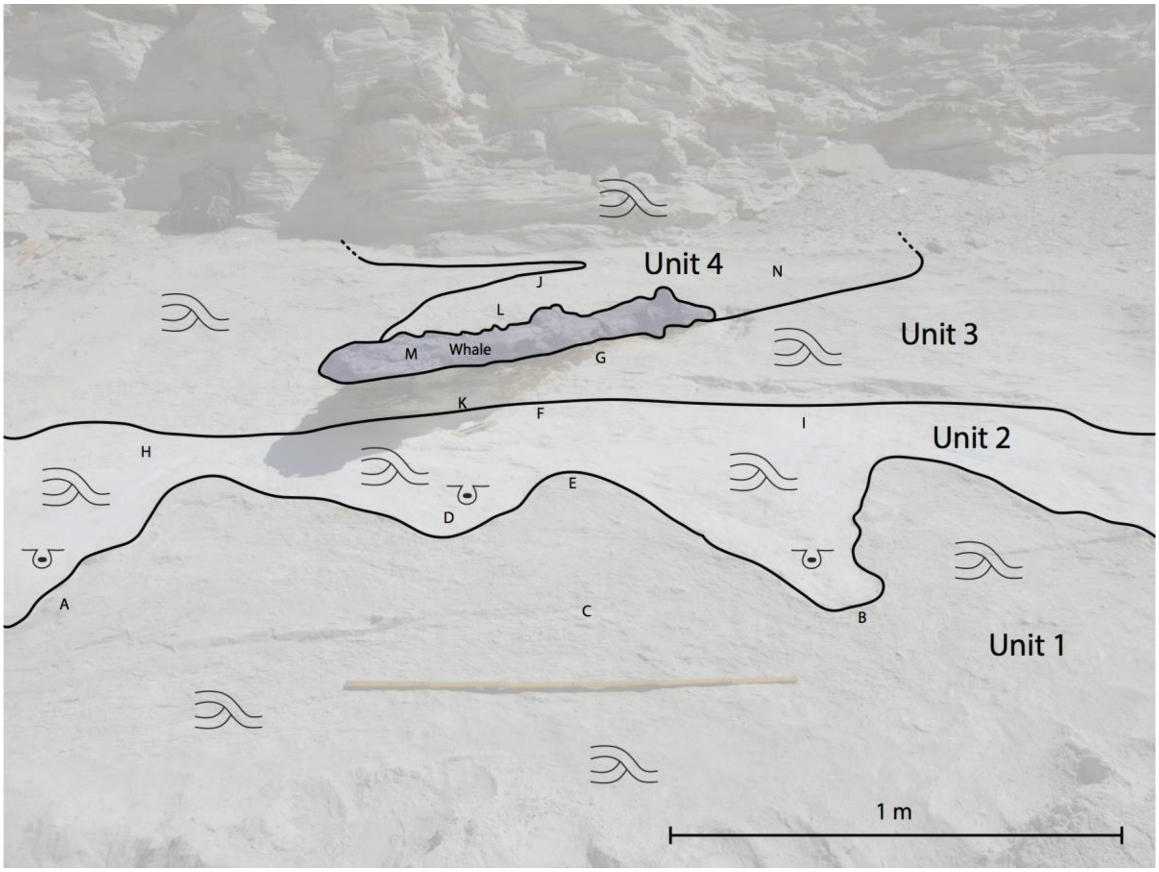


Figure 32. Interpretative overly of Figure 31. Letters A-N indicate the sampling locations within the area of the diagram.

Cerro Hueco la Zorra Diagram Key

———	Contact
_ — — _	Gradational contact
	HCS and SCS
	Scour and fill structures

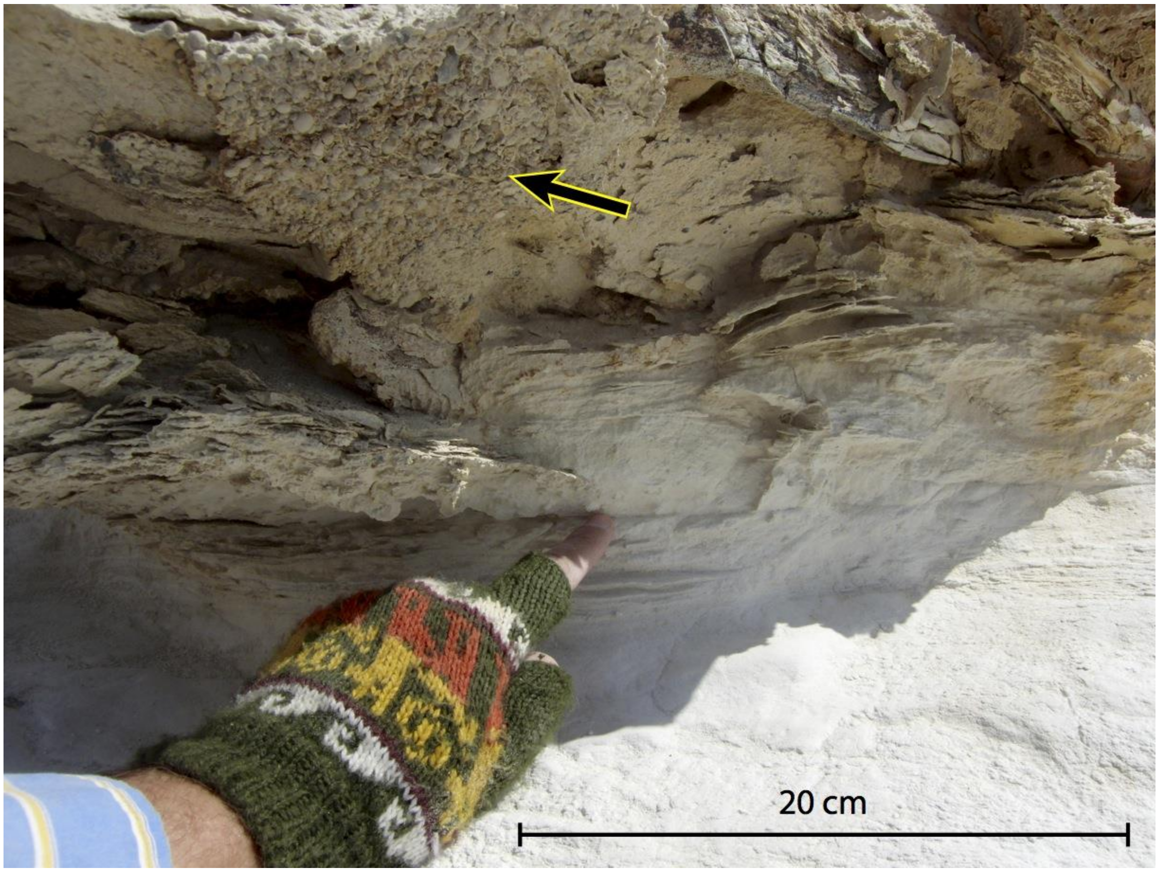


Figure 33. Pebble lag at base of channel, indicated by arrow. (Finger is pointing to a bed 5 cm under the whale.) Concretion-forming ions diffused through several cm of the sediments around the whale.

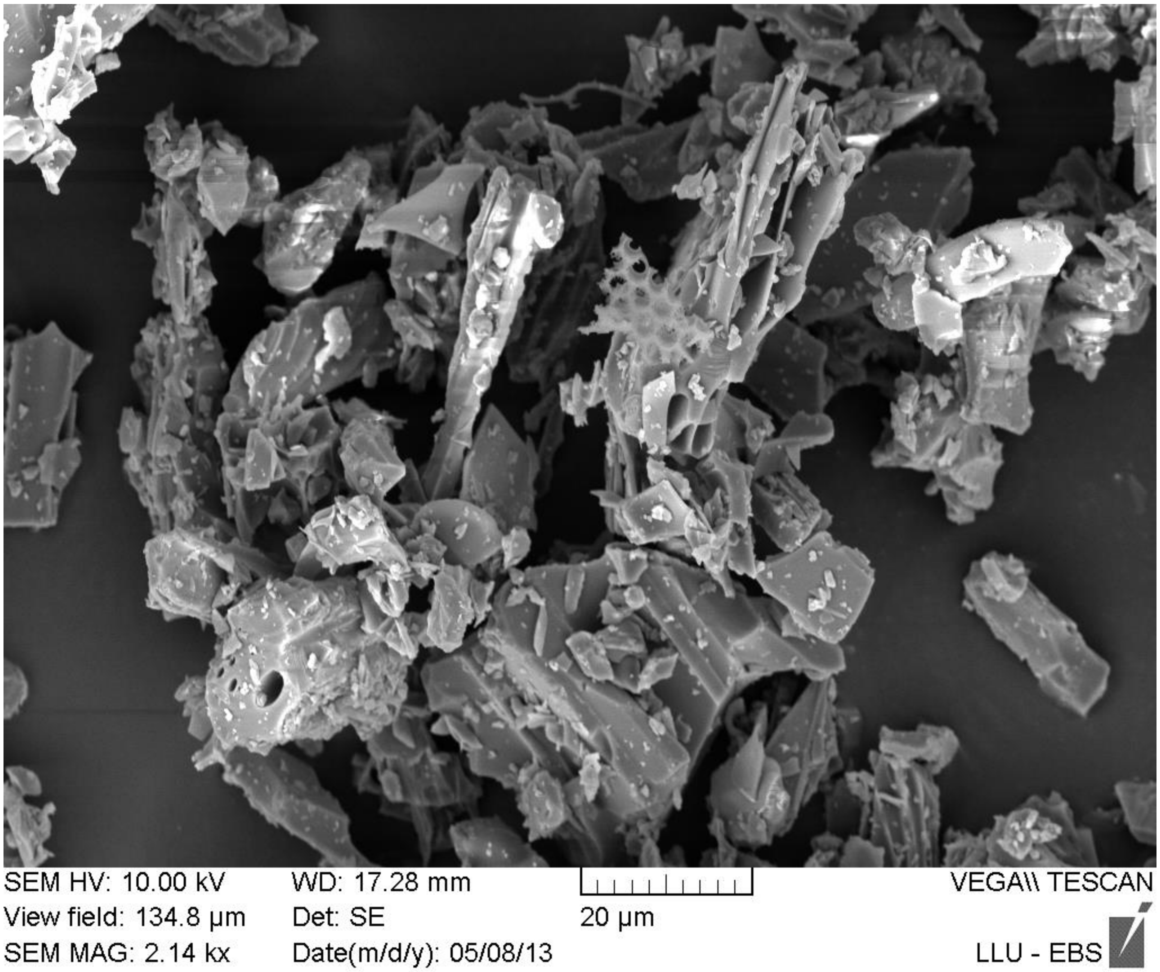


Figure 34. SEM image of tuff bed (Unit 2), showing that the amorphous material is almost entirely volcanic glass. Only a very small fraction of the bed consists of diatoms.

Figure 35. HCS in Units 2 and 3. Scale numbers are in cm. The thicker dotted line marks the contact between Units 2 and 3. Thinner dotted lines mark HCS.

Figure 36. Large swale, with a wavelength of about 60 cm, in tuff below whale (Unit 2). This tuff is almost pure volcanic glass, with a few diatoms and some biotite. The sedimentary structures imply some transport, but the glass is pristine and the biotites are intact, despite being fragile.

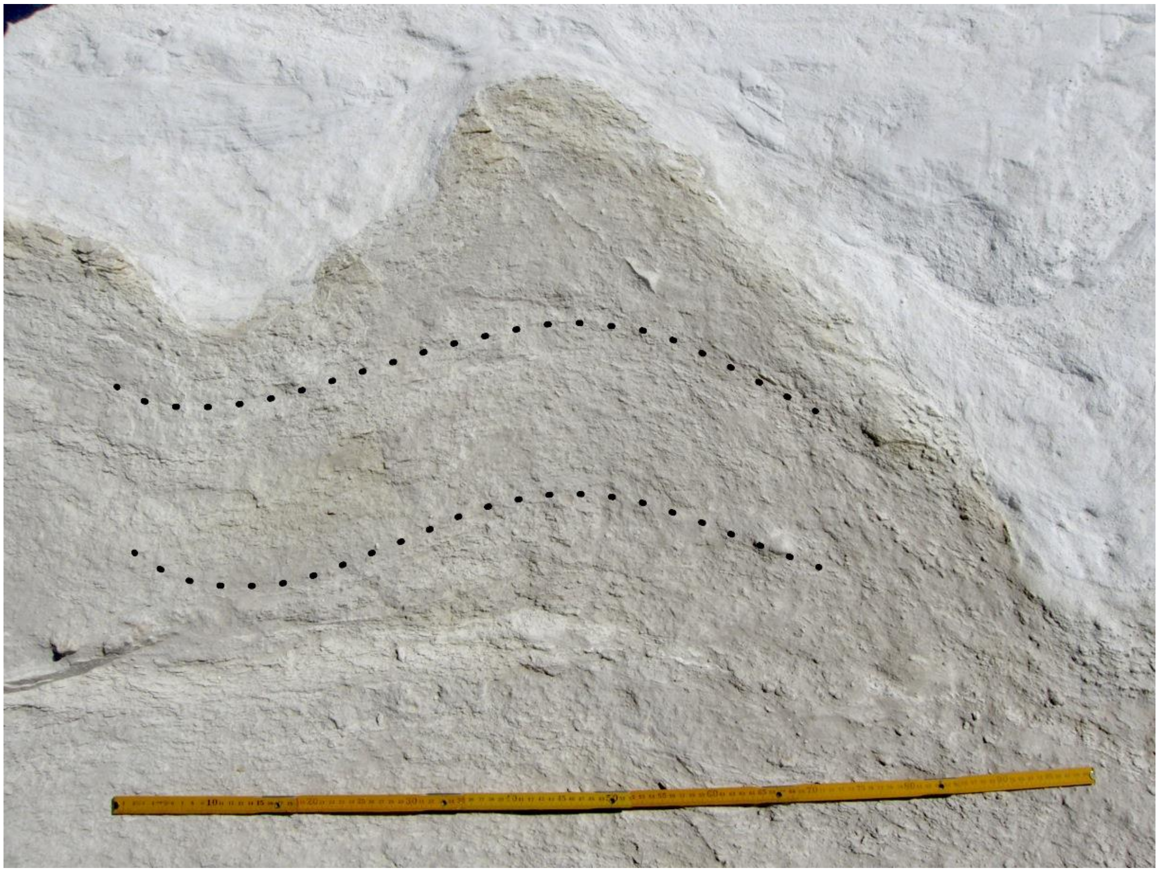


Figure 37. Large hummocks in Unit 1, marked with dotted lines. The erosional surface between Units 1 and 2 was partially controlled by the sedimentary structures in Unit 1. Scale is 1 m.

Figure 38. The top part of the channel. Large-scale HCS in material above channel, marked by arrow. The sides of the channel are marked with the thicker dotted line. The channel fill material has formed a large U-shape, marked by the thinner dotted line. To the left, the beds curve up out of the channel and join the other sediments. The beds filling the right side of the channel conform to the channel boundary. Sixty-eight cm of the 1-m stick can be seen in the picture.

Location 6: Cadena de los Zanjones

At Location 6, a fossil dolphin backbone, complete with preserved cartilage discs is present. Though there is not a large concretion around the vertebrae, this specimen has stained the surrounding sediments (Figure 39). The vertebrae that are visible are all articulated.

The dolphin fossil is preserved in a channel a little over a meter wide (Figures 40 and 41). Bedding in Units 1-6 is slightly sub-planar. All units at this outcrop consist of very fine sandstone with little diatomaceous or tuffaceous input, and the dominant sedimentary structures in all units are ripple cross-laminae, HCS, and SCS (Figure 41). There is a small amount of erosion between Units 1 and 2. All of the contacts appear gradational (as a result of bioturbation) with the exception of the contact between Units 3 and 4, which is the channel boundary. The beds of Unit 4, which fill the channel, pinch out towards the margins of the channel.

All the units and contacts are moderately bioturbated, and the predominant burrow orientation is vertical. The level of bioturbation at the channel boundary may be slightly lower than the level of bioturbation in the units above and below the channel boundary, but the bedding is not destroyed in any of the units (Figure 42).

The grain size at the Cadena de los Zanjones outcrop is larger than at any of the other outcrops with cetacean fossils in channels, probably indicating burial closer to shore. The dolphin skeleton is in a narrower, shallower channel than some of the larger whale skeletons (Figure 40). This channel is filled in a way that is typical of subaqueous, but not tidal environments, as the channel fill is symmetrical (Enos, et al. 2008). In tidal environments, channel fill tends to be asymmetrical.

Each of these units probably represents a single depositional event—likely a storm, based on the remnants of sedimentary structures present. The contacts below Units 2, 3, 5, and 6 are bioturbated, which indicates that the deposition of these units did not completely inhibit the functioning of the benthic community. There is one sharp contact, however. The channel boundary, below Unit 4, is not very bioturbated, and the best-preserved laminae are in Unit 4—the channel fill. This detail, in addition to the fact that a channel exists at this horizon, indicates that, in the events represented by Units 1-6, the erosional event that carved the channel was uniquely energetic and the deposition of Unit 4 was probably more rapid than the deposition of the other units. The presence of the dolphin, then, may be linked to the energetic event represented by the erosion of the top of Unit 3 and the deposition of Unit 4.

It is likely that the backbone present does represent an articulated specimen, based on the presence of the vertebral processes, the lack of lamina truncating against the processes, the presence of vertebral discs (Figure 39), and the stained sediments around the specimen. The dolphin is also encased in more permeable, coarser-grained rock, which may have been less conducive to concretion formation.

The moderately bioturbated sediments around the dolphin probably indicate slower deposition or a longer hiatus between depositional events than occurred during the burial of many of the other specimens. This specimen is the only one that is not buried in siltstone, but we have included it in the study because it matched the criteria for choosing specimens.

Location 6 Figures

Figure 39. Dolphin vertebral column, complete with preserved cartilaginous discs (indicated by the finger pointing) and processes

Figure 40. Dolphin skeleton at Cadena de Zanjones. Most of the sedimentary structures have been overwritten by bioturbation, but a few in Units 2 and 3 (shown in Figure 41) are marked with black lines.

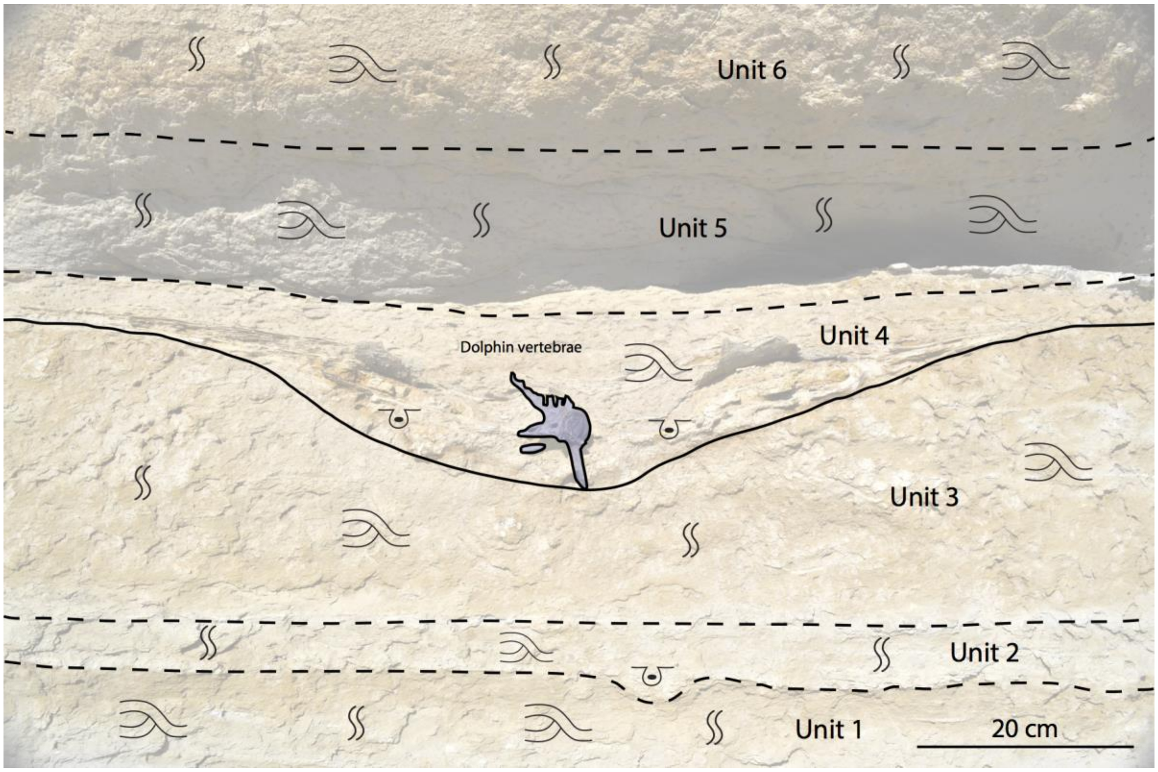


Figure 41. Interpretative overlay of Figure 40

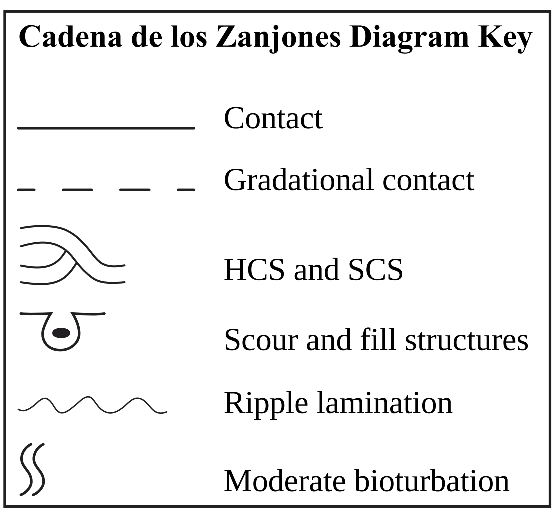


Figure 42. Backbone of dolphin in channel, marked by arrow. The cartilage disc can be seen, and the processes are partially preserved. Material filling the channel is bioturbated, but only partially. The material under the channel appears to be more completely bioturbated.

CHAPTER FOUR

GENERAL DISCUSSION

The hummocky cross-stratification prevalent in the units below and above the whales at each outcrop indicates that the whales were buried during storms, and above storm wave base. It is likely that they were not buried too far above storm wave base, however, because closer to shore, unidirectional currents associated with the storms might inhibit the formation of HCS. HCS is the result of oscillatory wave motion, and, at least under the conditions of Dumas and Arnott's experiment, if there is a unidirectional current greater than 5 cm/s the hummocks become anisotropic, and if the current is greater than 10 cm/s, the hummocks are replaced by unidirectional dunes (Dumas and Arnott, 2006).

The channels, then, are a bit enigmatic, as they indicate just such a unidirectional current, presumably perpendicular to the coast. In general, there is no apparent change in the paleodepositional environment pre- and post-channel, and both the sediments below the channel and those above it show evidence of being deposited in a storm. In a sequence of events, then, the storm deposited hummocky cross-stratified material in oscillatory flow conditions, the oscillatory flow was interrupted by a unidirectional flow which carved the channel, the whales were deposited, and then oscillatory flow resumed.

If the unidirectional flow is confined, however, it could cut the channels without destroying the HCS, and the channels may indicate just such a confined flow. It persisted in the most energetic conditions we studied, and transported large clasts, as indicated by the pebble lags at the bases of many of the channels. One explanation for this current is that it may have been the result of a combination of denser, sediment-laden runoff from the coast and currents secondary to storm surges (Figure 43).

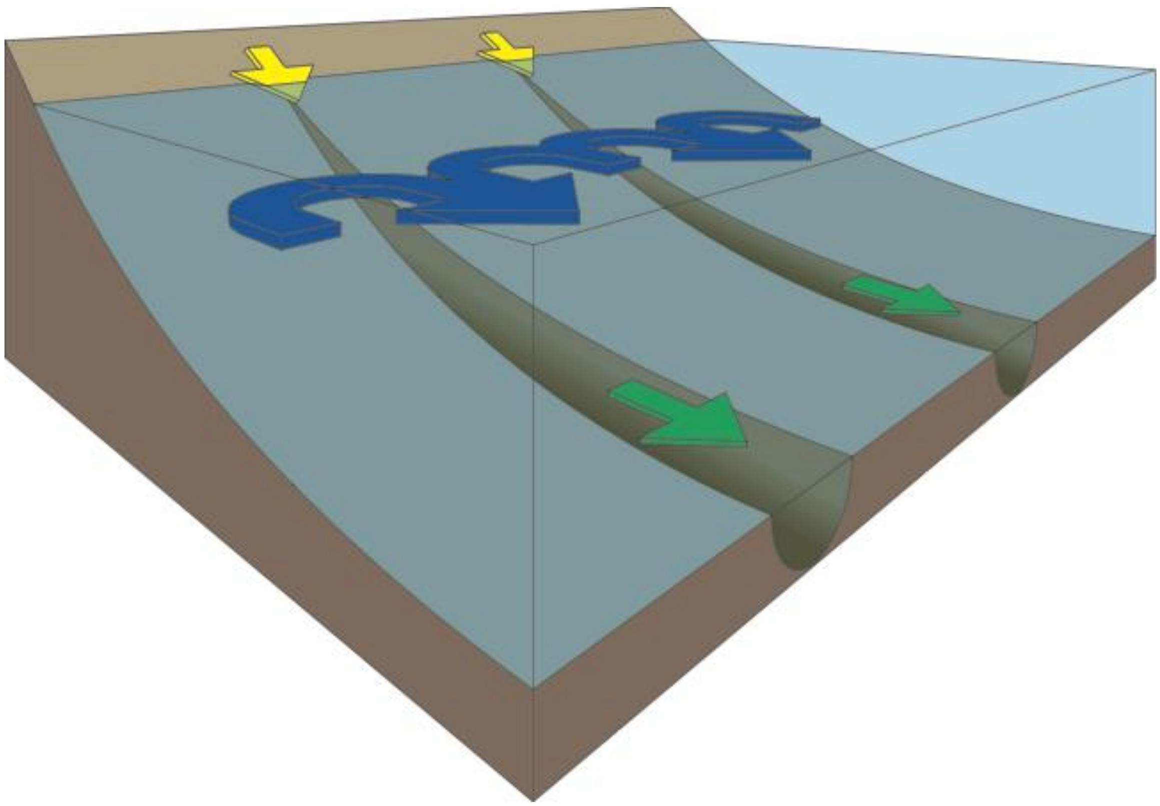


Figure 43. The current that eroded out the channels, indicated by the green arrows, could have come from two sources: sediment-laden runoff from the coast, indicated by the yellow arrows, and a rip current secondary to a storm surge, indicated by the blue arrows.

The four whales in cross section that were not in channels were also surrounded by HCS, but the wavelengths of the largest hummocks and swales were, without exception, much less than the wavelengths of the largest hummocks and swales surrounding the specimens reported on in chapters 3, 4, and 5 (Figure 44). It appears that where there is sufficient energy to create longer hummocks and swales, there is also sufficient energy to carve out channels.

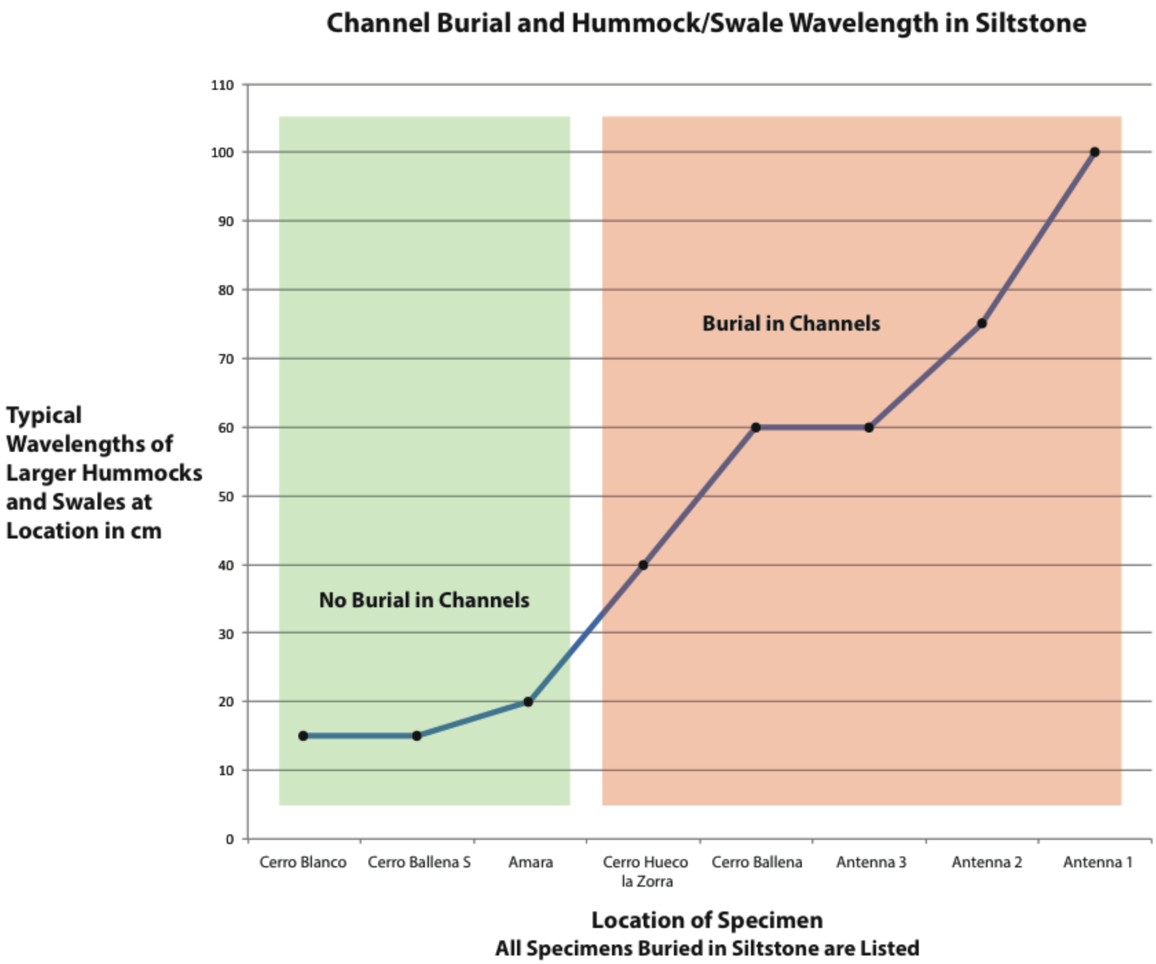


Figure 44. The specimens at Cerro Blanco, Cerro Ballena South, and Amara are buried in siltstone with smaller-scale hummocks and ripple marks and are not buried in channels. These three specimens are surrounded by the green box. The specimens at Cerro Hueco la Zorra, Cerro Ballena, and Antenna are buried in channels in siltstone. They are surrounded by the red box. The specimens at Cerro Ballena North and Cadena de los Zanjones are not included in this graph because they are buried in sandstone.

An unexpected line of evidence that we uncovered pointing to a high depositional rate is the presence of permeability barriers in the sediments surrounding the whale prior to the whale's complete decomposition. In a sequence of events, it is necessary that the sediment be in place prior to the formation of the permeability barrier. If the permeability barrier forms prior to decomposition of the whale, then the sediments were in place before the deposition of the whale. Gypsum is abundant in the Pisco Basin, and in all instances of ion diffusion being blocked by a permeability barrier, the barrier is now gypsum. Gypsum is very mobile, however, and may have precipitated in these places at a later date. What is certain is that there was a permeability barrier in place before the movement of the staining agents.

Over the course of this investigation, the necessity of a good outcrop became much more apparent. The channels in this study had erosional surfaces measuring two to five meters in lateral extent, and without a clear view of at least two meters at each outcrop, it would not have been clear that channels were present. A clear view of the vertical context of each whale was crucial as well, as some of the channels were about a meter deep, and many other features relevant to the interpretation of the depositional environments were found above and below each channel. While useful observations may be made during an excavation of a whale fossil, cross sections of fossils provide a much more complete context for interpreting depositional environments.

CHAPTER FIVE

CONCLUSIONS

Deposition in channels and modified swales appears to be a prominent mode of burial and preservation of articulated specimens in the Middle to Upper Pisco Formation, and many lines of evidence point to rapid deposition during storm events as the key to the preservation of the Pisco specimens.

It does not appear that currents associated with storms eroded the sediment around the already-present whales, as the pebble lags present are directly under the whales and the erosional boundaries of the channels extend far above the whales' fossils in some cases. What appears to be more likely is that the storm processes carved out the channels, and then brought the whale carcasses to the channel. Once in the channel, the currents were not sufficiently powerful to move the whales further.

While the channels could have provided a way to entomb the cetaceans more deeply, thereby increasing the probability of their preservation, the excellent preservation of the whales not buried in channels negates the necessity of a channel. The channel, however, may give us an interesting insight into the storm processes, as they may have been eroded out by sediment-laden water receding from the coast secondary to storm surges.

A key difference between the conditions that create HCS and those that create SCS is the rate of sediment accumulation. In the flume experiment mentioned previously, at a sediment accumulation rate of 4.2 mm/minute, hummocks were preserved, but at a sediment accumulation rate of 1 mm/minute, swales were preferentially preserved (Dumas and Arnott, 2006). Preservation of hummocks in all of these outcrops may, therefore, be yet another indicator of a high rate of deposition.

The general lack of bioturbation also suggests rapid deposition. There was no bioturbation closely associated with any of the whales buried in channels in siltstone. While bioturbation may be hindered by toxic or anoxic bottom conditions, the strong, oscillatory motion of the water, along with the relatively shallow, storm-dominated shelf conditions, preclude anoxia as a mechanism for inhibiting bioturbation. In such an environment, rapid deposition is the best explanation for a lack of bioturbation.

REFERENCES

Abdel-Fattah, Z. A., Gingras, M. K., Caldwell, M. W., and Pemberton, S. G. 2010. Sedimentary environments and depositional characteristics of the Middle to Upper Eocene whale-bearing succession in the Fayum Depression, Egypt. *Sedimentology*, 57(2): 446-476.

Allison, P. A., Smith C. R., Kukert, H., Deming J. W., and Bennett, B. A. 1991. Deep-water taphonomy of vertebrate carcasses: a whale skeleton in the bathyal Santa Catalina Basin. *Paleobiology*, 17(1): 78-89.

Amos, C. L., Li, M. Z., Choung, K. 1996. Storm-generated, hummocky stratification on the outer-Scotian Shelf. *Geo-Marine Letters*, 16(2): 85-94.

Behrenfeld, M. J., Bale, A. J., Kolber, Z. S., Aiken, J., and Falkowski, P. G. 1996. Confirmation of iron limitation of phytoplankton photosynthesis in the equatorial Pacific Ocean. *Nature*, 383: 508-511.

Brand, L. R., Esperante, R., Chadwick, A. V., Poma, O., and Alomia, M. 2004. Fossil whale preservation implies high diatom accumulation rate in the Miocene-Pliocene Pisco Formation of Peru. *Geology*, 32(2): 165-168.

Carvajal, C. 2002. *Sedimentology and Paleoenvironments of the Miocene/Pliocene Pisco Fm., Peru.* (Master's Thesis.) Loma Linda University.

De Muizon, C., and DeVries, T. J. 1985. Geology and paleontology of late Cenozoic marine deposits in Sacaco area (Peru). *Geologische Rundschau*, 74(3): 547-563.

DeVries, T.J., 1998. Oligocene deposition and Cenozoic sequence boundaries in the Pisco Basin (Peru). *Journal of South American Earth Sciences*, 11(3): 217-231.

Dumas, S. and Arnott, R. W. C. 2006. Origin of hummocky and swaley cross-stratification—the controlling influence of unidirectional current strength and aggradation rate. *Geology*, 34: 1073-1076.

Dunbar, R. B., Baker, P. A., ed. 1988. *Cenozoic geology of the Pisco Basin: a guidebook to accompany a regional IGCP 156 field workshop: "Genesis of Cenozoic phosphorites and associated organic-rich sediments: Peruvian continental margin."* Lima, Peru.

Dunbar, R., Marty, R., and Baker, P. 1990. Cenozoic marine sedimentation in the Sechura and Pisco basins, Peru. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 77(3-4): 235-261.

Enos, P., Jefferson, R. D., and Goetz, S. L. 2008. Channels Ran Through It—The Lawrence Formation at Lone Star Lake, Douglas County, Kansas. Kansas Geological Society, *Current Research in Earth Sciences*, 254, Part 1.

Esperante, R., Brand, L., Chadwick, A. V., and Poma O. 1999. Taphonomy of whales in the Miocene/Pliocene Pisco Formation, western Peru. Geological Society of America Annual Meeting, Abstracts with Programs, 31(7): A466.

Esperante, R., Brand, L., Chadwick, A. V., and DeLucchi, F. 2000. Fossil whales of the Miocene/Pliocene Pisco Formation, Peru: stratigraphy, distribution, and taphonomy. Geological Society of America Annual Meeting, Abstracts with Programs, 32(7): A499.

Esperante, R. 2002. *Taphonomy of Fossil Whales in Diatomaceous Sediments of the Neogene Pisco Formation, Peru.* (Doctoral dissertation.) Loma Linda University.

Esperante, R. 2005. How not to become a fossil—Taphonomy of modern whale falls, in: Martinell, J., Domènech, R., de Gibert, J.M., eds., 2nd International Meeting TAPHOS'05, 103-104.

Esperante, R., Brand, L., Nick, K.E., Poma, O., Urbina, M., 2008. Exceptional occurrence of fossil baleen in shallow marine sediments of the Neogene Pisco Formation, southern Peru. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 257: 344-360.

Esperante, R., Muñiz Guinea, F., and Nick, K. E. 2009. Taphonomy of a Mysticeti whale in the Lower Pliocene Huelva Sands Formation (Southern Spain). *Geologica Acta*, 7(4): 489-505.

Evans, C. A., Wilkinson, M. J., and Eppler, D. 2011. Hurricane Ike deposits on the Bolivar Peninsula, Galveston Bay, Texas. American Geophysical Union, Fall Meeting, abstract EP33A-0906.

Forristall, G. Z, Hamilton, R. C., and Cardone, V. J. 1977. Continental Shelf Currents in Tropical Storm Delia: Observations and Theory. *Journal of Physical Oceanography*, 7: 532–546.

Goff, J. A., Allison, M. A., and Gulick, S. P. S. 2010. Offshore transport of sediment during cyclonic storms: Hurricane Ike (2008), Texas Gulf Coast, USA. *Geology*, 38(4): 351-354.

Google Earth 7.1. 2013. *Peruvian Coast 14 31’57.53” S, 75 41’15.11” W.* April 17, 2013. April 17, 2014.

Ingle, J. C., Jr. 1981. Cenozoic depositional history of the northern continental borderland of Southern California and the origin of associated Miocene diatomites, in: Isaacs, C. M. *Guide to the Monterey Formation in the California coastal area, Ventura to San Luis Obispo*. Pacific Section AAPG Special Publication, 52: 1-8.

Kemp, A. E. S., Baldauf, J. G., and Pearce, R. B. 1995. Origins and paleoceanographic significance of laminated diatom ooze from the eastern equatorial Pacific Ocean, In: Pisias, N.G., Mayer, L.A., et al., *Proceedings of the Ocean Drilling Program, Scientific Results*. 138: College Station, TX, Ocean Drilling Program, 641-645.

Kniskern, T. 2007. *Shelf Sediment Dispersal Mechanisms and Deposition on the Waiapu River Shelf, New Zealand.* (Doctoral Dissertation.) College of William and Mary.

Lambert, O., Bianucci, G., Post, K., de Muizon, C., Salas-Gismondi, R., Urbina, M., and Reumer, J. 2010. The giant bite of a new raptorial sperm whale from the Miocene epoch of Peru. *Nature*, 466: 105-108.

León, W. R, Walter, R., Alemán, A. M., Torres, V. R., De la Cruz, O. 2008. Estratigrafía, sedimentología, y evolución tectónica de la cuenca Pisco Oriental. *Estudios Regionales*. Boletín 27, Serie D.

Marty, R. C. 1989. *Stratigraphy and Chemical Sedimentology of Cenozoic Biogenic Sediments from the Pisco and Sechura Basins, Peru.* (Doctoral dissertation.) Rice University.

Myrow, P. M., and Southard, J. B. 1996. Tempestite Deposition. *Journal of Sedimentary Research*, 66(5): 875-887.

Muhammad, Z. 2009. *Sedimentation on a Mixed Siliciclastic/Carbonate Continental Margin over Decadal to Millennial Timescales: Gulf of Papua.* (Doctoral Disseration.) Louisiana State University.

O’Hare, D. J., Nick, K. E., Fleming, M. A., Biaggi, R. E., Poma, O., Coronado, J. L., and Eilers, J. 2012. High resolution correlation and paleoenvironmental transects of fine-grained shallow-marine bay deposits for the Miocene Pisco Formation, west-central Peru. AAPG annual meeting, article 90142.

Plint, A. G. 2010. In: Noel P. James and Robert W. Dalrymple, *Facies Models* (4th ed., 167-199), Newfoundland & Labrador, Canada: Geological Association of Canada.

Sancetta, C., 1989. Processes controlling the accumulation of diatoms in sediments: a model derived from British Columbia fjords. *Paleoceanography*, 4(3): 235-251.

Smith, C. R., Maybaum, H. L., Baco, A. R., Pope, R. H., Carpenter S. D., Yager, P. L., Macko, S. A., and Deming, J. W. 1998. Sediment structure around a whale skeleton in the deep Northeast Pacific: macrofaunal, microbial and bioturbation effects. *Deep-Sea Research Part II: Topical Studies in Oceanography*, 45(1-3): 335-364.

Smith, C. R. and Baco, A. R., 2003. Ecology of whale falls at the deep-sea floor, in: Gibson, R. N., and Atkinson, R. J. A., eds., *Oceanography and Marine Biology: An Annual Review*, 41: 311-354.

Wells, J. T., and Shanks, A L. 1987. Observations and geologic significance of marine snow in a shallow-water, partially enclosed marine embayment. *Journal of Geophysical Research*, 92(C12): 13,185-13,190.

APPENDIX A

OTHER MODES OF BURIAL

Four of the whale cross sections we found were not in channels, and the details of their burials were too disparate to group them into meaningful categories. These four specimens are reported on in this Appendix.

For each location, the results are presented in this format:

1. Description of fossil
2. Description of sedimentary structures
3. Description of sedimentary material
4. Other features

Location 7: Cerro Ballena North

Results

The northern portion of the Pisco Formation terminates against islands of Jurassic volcanics. Near the islands, beds of coarse, fossiliferous volcanic litharenites are common. We found this whale cross section in one of the thicker fossiliferous litharenites (Figures 45 and 46). Only the skull of the whale is present, but the left jugal (eye socket) bone was found in articulated position, and there are many bones in the float. There is no macrobioerosion evident on the bones, and this whale is not in a concretion.

HCS is the dominant sedimentary structure in Units 1, 2, and 3. The contact between Units 1 and 2 is erosional and far from planar. Units 2 and 3 grade into each other, and are indistinguishable at certain places on the outcrop. Unit 4 is a thin, cross-bedded sandstone. Unit 5 is hummocky cross-stratified, with lenses of sandstone. The contact between Units 5 and 6 is erosional. Unit 6, the sandstone in which the whale is buried, is cross-bedded. The contacts between Units 6, 7, and 8 interfinger and grade into each other, and the cross-stratification of Unit 6 gives way to HCS in Units 7 and 8. Unit 9 is also hummocky cross-stratified.

In Units 1-3, 5, and 7-8, sediments are silty, but many thinner beds of sandstone, as well as sandstone lenses in the siltstone beds, are present. Units 4, 6, and 9 are sandstones made up of coarse lithic fragments and small, aragonitic shells (Table 3). All of the shells are disarticulated and many are fractured as well. Fine sediments are lacking in the sandstone units (Figure 47 is a similar sandstone below Unit 1), and the cement in all the sandstone beds is a mixture of gypsum and anhydrite.

The only bioturbation in the outcrop is at the top of Unit 3.

Discussion

The complete encasement of this whale fossil in a sandstone bed fits well with its proximity to one of the Jurassic volcanic islands to the north of the Pisco Basin.

Based on the articulation of the left jugal (eye socket) bone and bones in the float, we determined that the skeleton was articulated upon burial. We suspect that the lack of concretion around this whale is due to the permeability of the coarse sandstone surrounding it—the concretion-forming ions leached away and dispersed before they could form a concretion.

High-energy erosional and depositional events can be inferred from the sedimentary structures present in all beds and the erosional contacts between beds. The HCS in the siltstone units, and in Unit 9, indicate predominantly oscillatory wave motion, whereas the cross-stratification of Units 4 and 6 indicate deposition from unidirectional flow. Units 6-8 present an interesting sequence. The deposition of Unit 6 must have occurred in a highly energetic, unidirectional flow, but the following units, 7 and 8, show HCS more typical of much of the basin. As the cross-stratification of Unit 6 grades into the HCS of Units 7 and 8, we can surmise that the unidirectional current gave way to an oscillatory flow of much lesser magnitude. The contact between Units 8 and 9 is, again, erosional, and the HCS and coarse sand of Unit 9 indicate deposition in a powerful oscillatory current.

The lack of finer sediments in Unit 6 is probably a result of hydraulic sorting. It is unlikely that the source sediment did not contain fines. Disarticulation of the shells in the litharenite is to be expected in anything other than immediate burial, but many were broken as well, which can indicate transport. Very few of the shells showed evidence of predation. There are volcanic rock fragments in the sandstone—their source is very likely the volcanic mountains that border the basin.

The lack of abrasion or macrobioerosion on the bones of the whale indicate that its burial was rapid. If the shells surrounding the whale grew in place over a long period of time, the bones would either be absent or show significant bioerosion.

Figure 45. Whale cross section at Cerro Ballena North. In the photo, it appears that the whale skull may actually be protruding into Unit 7 or Unit 8. The portion of the skull that was encased in the outcrop, however, was completely contained in Unit 6.

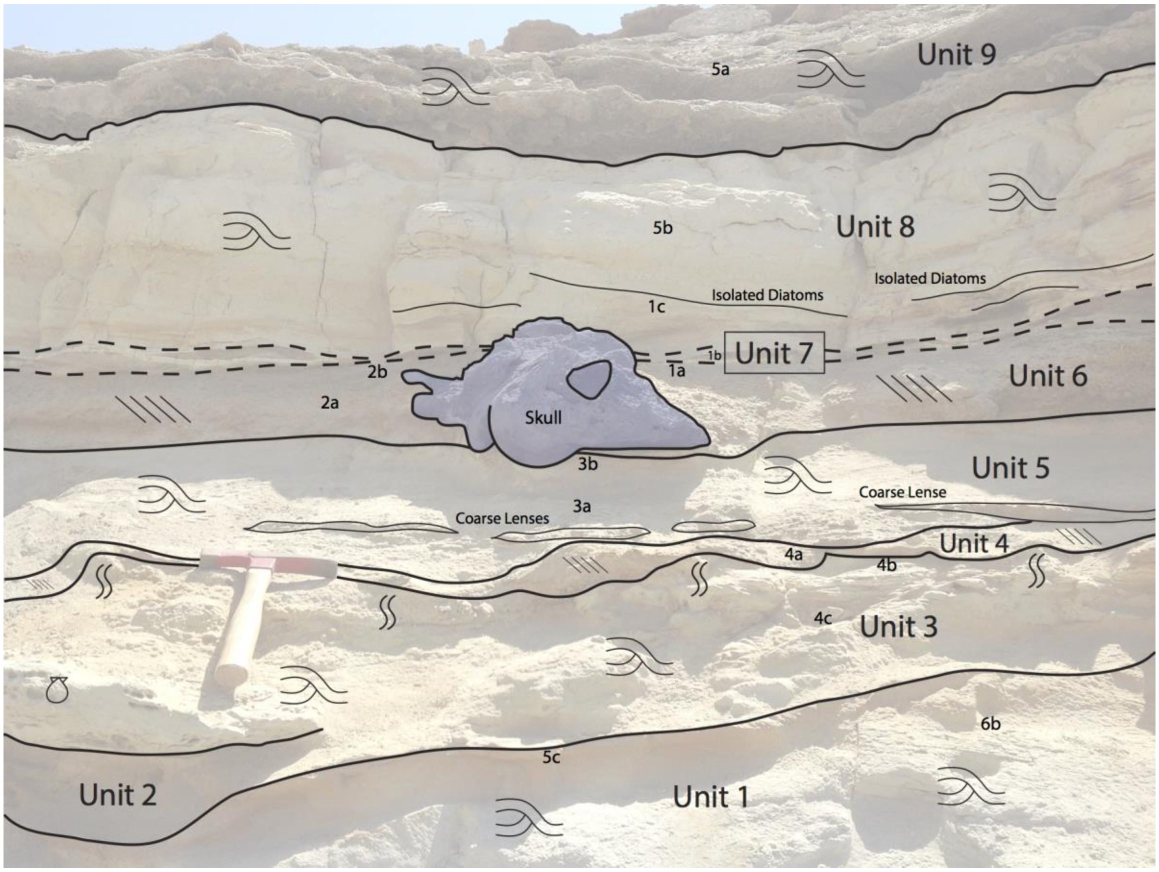


Figure 46. Interpretative overly of Figure 45. Numbers 1a-6b indicate the sampling locations within the area of the diagram.

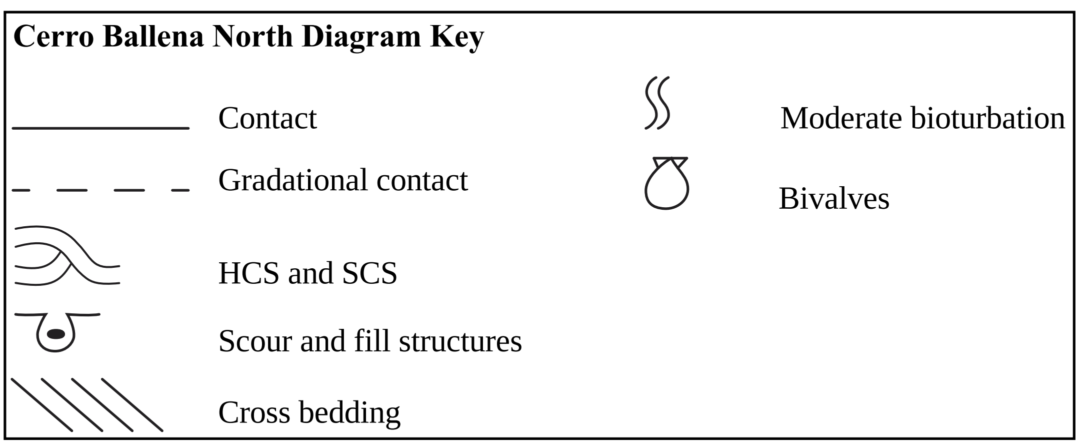


Table 3. Location 7 Unit Descriptions

Unit	Composition and Texture	Sedimentary Structures	Biogenic Structures	Fossils Present
1	Coarse siltstone	HCS; top of unit is an erosional surface	No bioturbation	
2	Coarse, hematite-rich siltstone	HCS	No clear bioturbation	
3	Coarse siltstone	HCS	Top of unit is moderately bioturbated	Contains articulated bivalves about 4 cm across
4	Coarse sandstone	Ripple laminated	Light bioturbation at base of unit	Fragments of small shells
5	Coarse siltstone, with lenses of coarse sandstone	HCS; whale has been pushed down into Unit 5, deformation extends down several cm	No bioturbation	
6	Coarse sandstone	Megaripple marks, the top quarter of unit fines upward, there is a slight difference in hardness about 2/5 of the way up.	No bioturbation	Fragments of small shells
7	Coarse siltstone to medium sandstone	HCS; medium sandstone is cross-bedded	No bioturbation	
8	Coarse siltstone	HCS at base, grading into planar laminations about 10 cm up	No bioturbation	
9	Coarse sandstone	Large-scale HCS	No bioturbation	Fragments of small shells
Whale			No bioerosion on bones; skeleton was completely articulated or very nearly so	

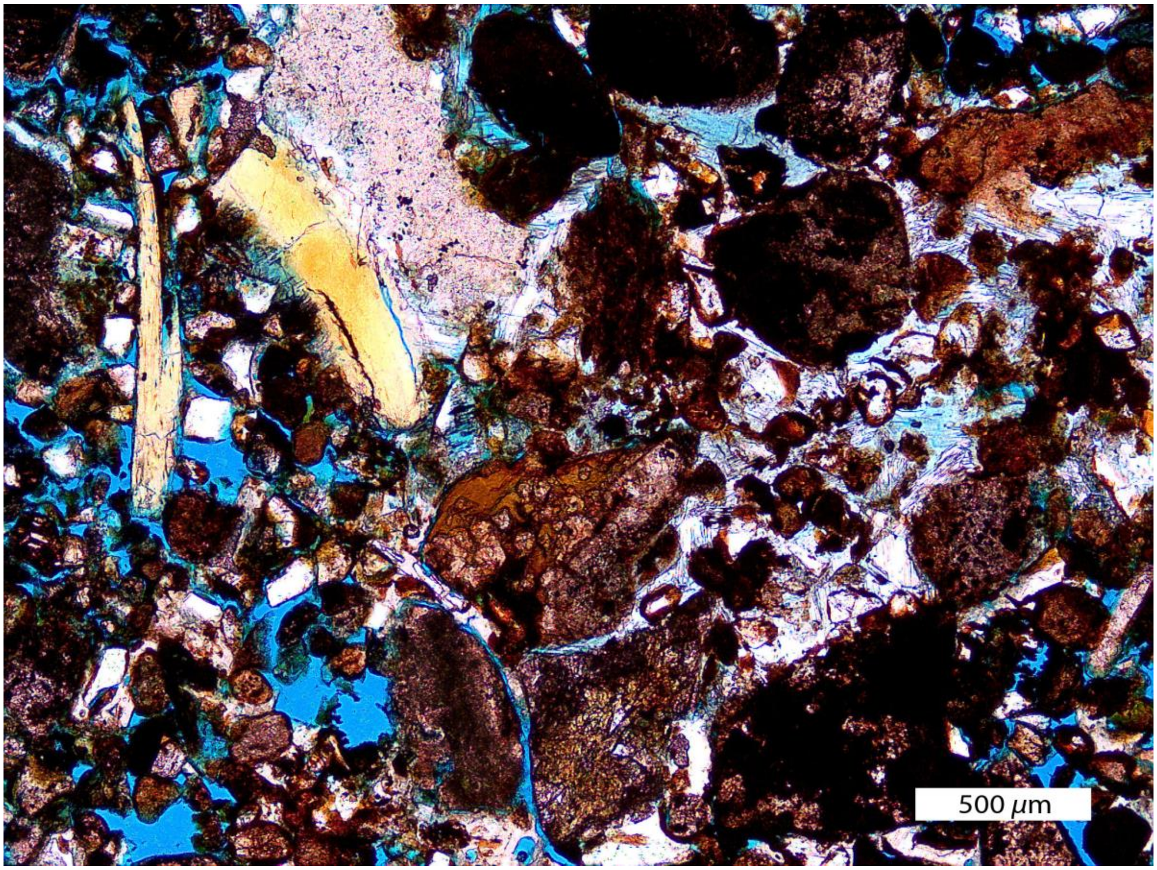


Figure 47. Thin section from a sandstone unit below Unit 1. Dark, rounded grains are volcanic rock fragments. Yellow elongate grains are shell fragments.

Location 8: Cerro Ballena South

Results

The whale cross section at Location 8 contains dentaries, rostrum, and ribs. All bones were articulated, and there is no evidence of macrobioerosion or abrasion on any of the bones.

The predominant sedimentary structure in Units 1-3 and 5 is HCS. The HCS is small-scale here, however, compared to many of the other locations. Unit 4, the thickest tuff at the outcrop, is laminated. The top of Unit 5 and the bottom of Unit 8 (which are separated by a thin tuff) are wave ripple laminated (Figures 48 and 49, Table 4).

This whale is buried in close proximity to several tuffs and altered tuffs (Figures 48, 49, and 50). The thickest tuff disappears completely over the whale, and reappears to the right of the whale. For comparison, at the location known as Yeseras, there is a tuff that is pinched out (Figure 51) and shows evidence of soft-sediment deformation (Figure 52).

Sediments immediately surrounding the whale consist of siliciclastic material, clay, and amorphous material (Table 2, Sample K). The bulk of the amorphous material in the siliciclastic beds is diatoms (Figure 53). Two of the tuff beds in close proximity to this whale are almost pure volcanic glass, and two of the tuffs are altered and have a very high iron content. (See Appendix B for a discussion of the various tuff beds in close proximity to the Cerro Ballena N whale.)

It should be noted that Location 8 is the southernmost specimen on Cerro Ballena mentioned in this paper, but that it is not on the southern part of Cerro Ballena. It has been called Cerro Ballena South to distinguish it from the two specimens located further north.

Discussion

Cerro Ballena South is a little further south from the Jurassic volcanics than Cerro Ballena or Cerro Ballena North. The stratigraphic interval is similar, so the finer-grained siltstones and silty mudstones likely resulted from deeper water and greater distance from the Jurassic volcanics to the north.

Units 1-3 and 5 are clay-rich, and the sedimentary structures present in them are indicative of deposition in lower-velocity, oscillatory currents.

Unit 4, the gray tuff visible to the left of the whale (Figure 50), may indicate substantial sediment input in relatively quiet waters. It disappears completely over the whale, and reappears to the right of the whale. We suggest two possibilities to explain this. The first is that the tuff fell on the whale's back, but slid off. The whale was then covered by more sediment, and when the whale decayed and compaction occurred, the sediment that landed on the whale's back sunk below the level of the tuff. The second possibility is that the tuff covered the whale, but pinched out over it when the whale decomposed and was compacted. In either case, the sediment was in place before the decomposition of the whale.

A pinched-out tuff we found at the Yeseras outcrop (an outcrop that was part of a different study) may lend plausibility to the second hypothesis concerning the tuff disappearing over the Location 8 whale. The pinched-out tuff, however, showed clear evidence of soft-sediment deformation throughout its exposure, while the Cerro Ballena

South tuff contains no such soft-sediment deformation; the lamina in the Cerro Ballena South tuff are undisturbed right up to the point where it disappears over the whale. See Figure 54 for a proposed depositional model for this whale. If this model is correct, then this whale fossil extends vertically through three sedimentary beds.

There is also the possibility that this whale was deposited in a channel, but the clay-rich sediments, the small-scale sedimentary structures present, the lack of other features such as a pebble lag, and the absence of scour and fill structures or other channels in this area make this doubtful.

Figure 48. Cerro Ballena South cross section. Scale is 1 m.

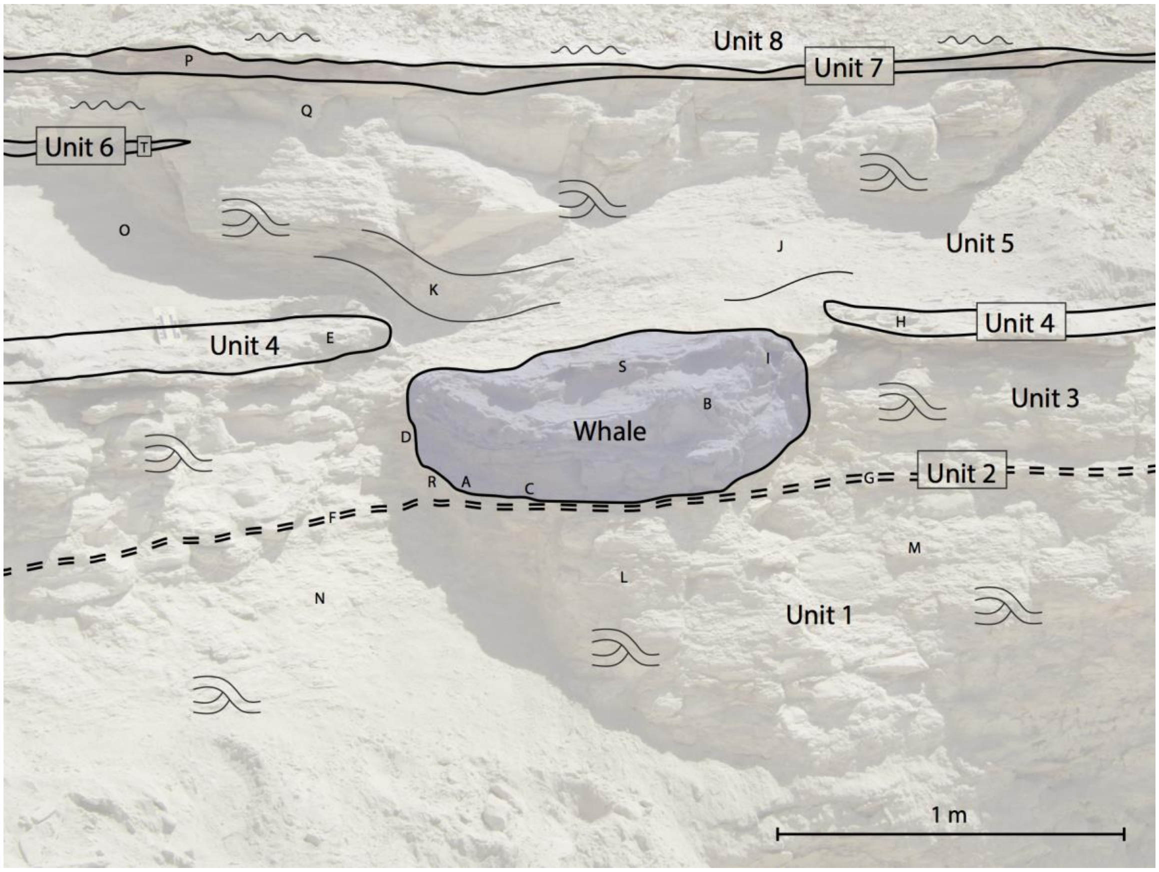


Figure 49. Interpretative overly of Figure 48. Units 1, 3, and 5 were formed from virtually identical sediments. Letters A-S indicate the sampling locations within the area of the diagram.

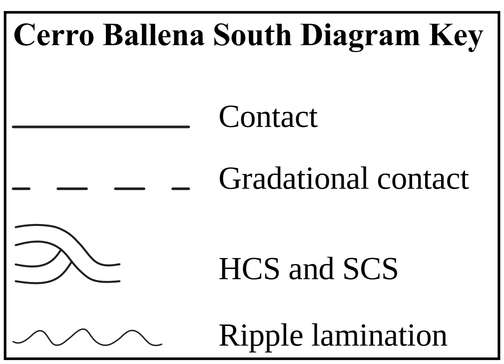


Table 4. Location 8 Unit Descriptions

Unit	Sedimentary Structures	Composition and Texture	Biogenic Structures	Fossils
1	HCS	Diatomaceous, tuffaceous, clayey siltstone	No bioturbation within a few dm of whale	
2	Laminated	Jarosite-rich altered tuff	No bioturbation	
3	HCS	Diatomaceous, tuffaceous, clayey siltstone	No bioturbation	Fish scales
4	Laminated	Volcanic glass	No bioturbation	
5	HCS, ripple lamination	Diatomaceous, tuffaceous, clayey siltstone	No bioturbation	
6	Laminated	Volcanic glass	No bioturbation	
7	Laminated	Hematite and jarosite-rich altered tuff	No bioturbation	
8	Ripple lamination	Diatomaceous, tuffaceous, clayey siltstone	No bioturbation within a few dm of whale	
Whale	None in concretion	Concretion rich in hematite, Mn oxides, and gypsum	No bioerosion on bones, all bones in articulated position	

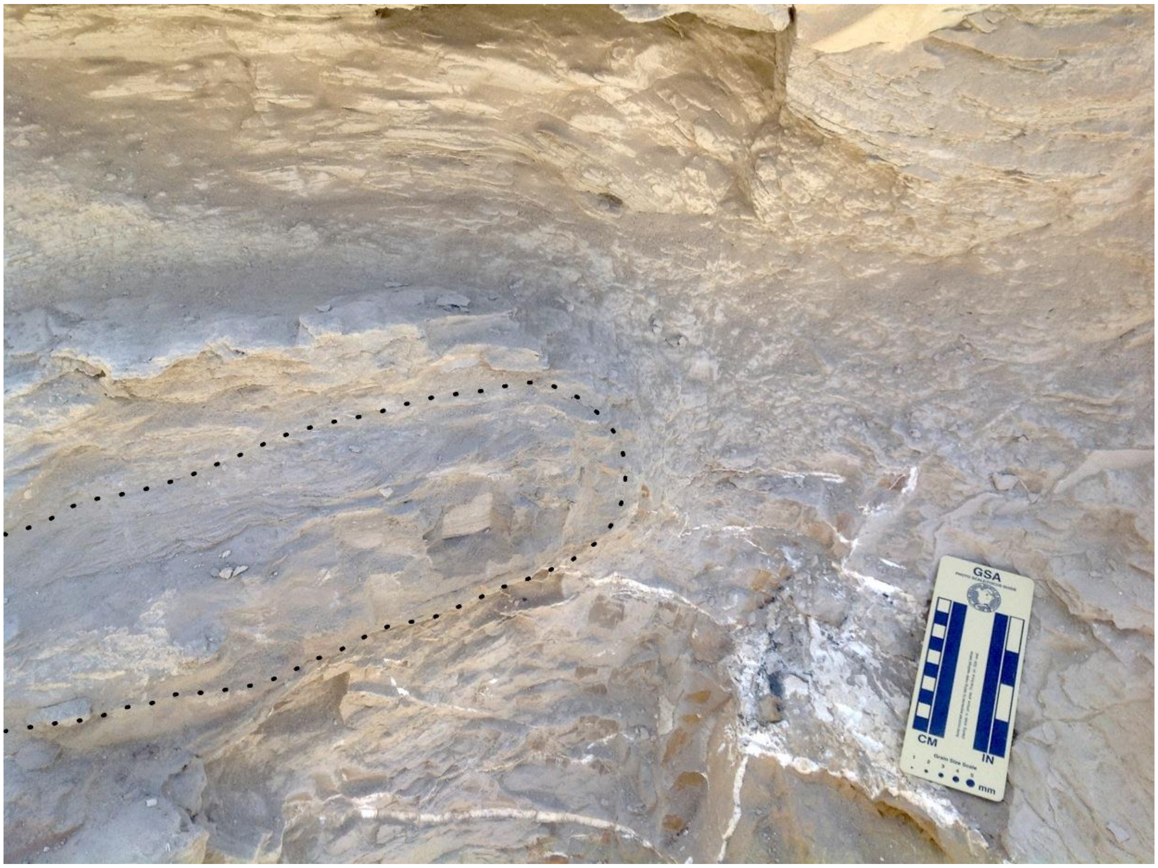


Figure 50. Dotted line marks tuff. Compare the laminae in this tuff with the soft-sediment deformation in the tuff in Figures 51 and 52. The laminae in this tuff are relatively undisturbed by comparison. Scale is 10 cm/4 in.

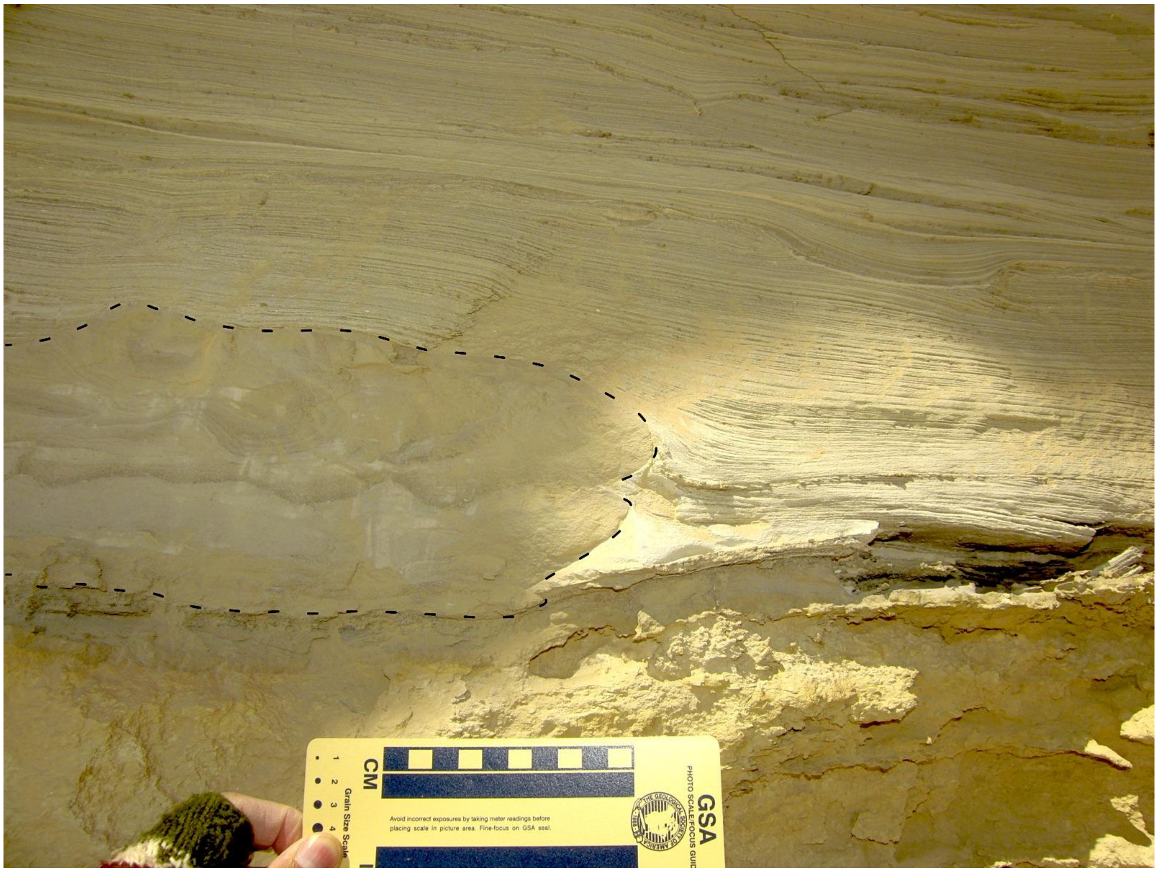


Figure 51. Pinched-out tuff at Yeseras, marked with dotted line

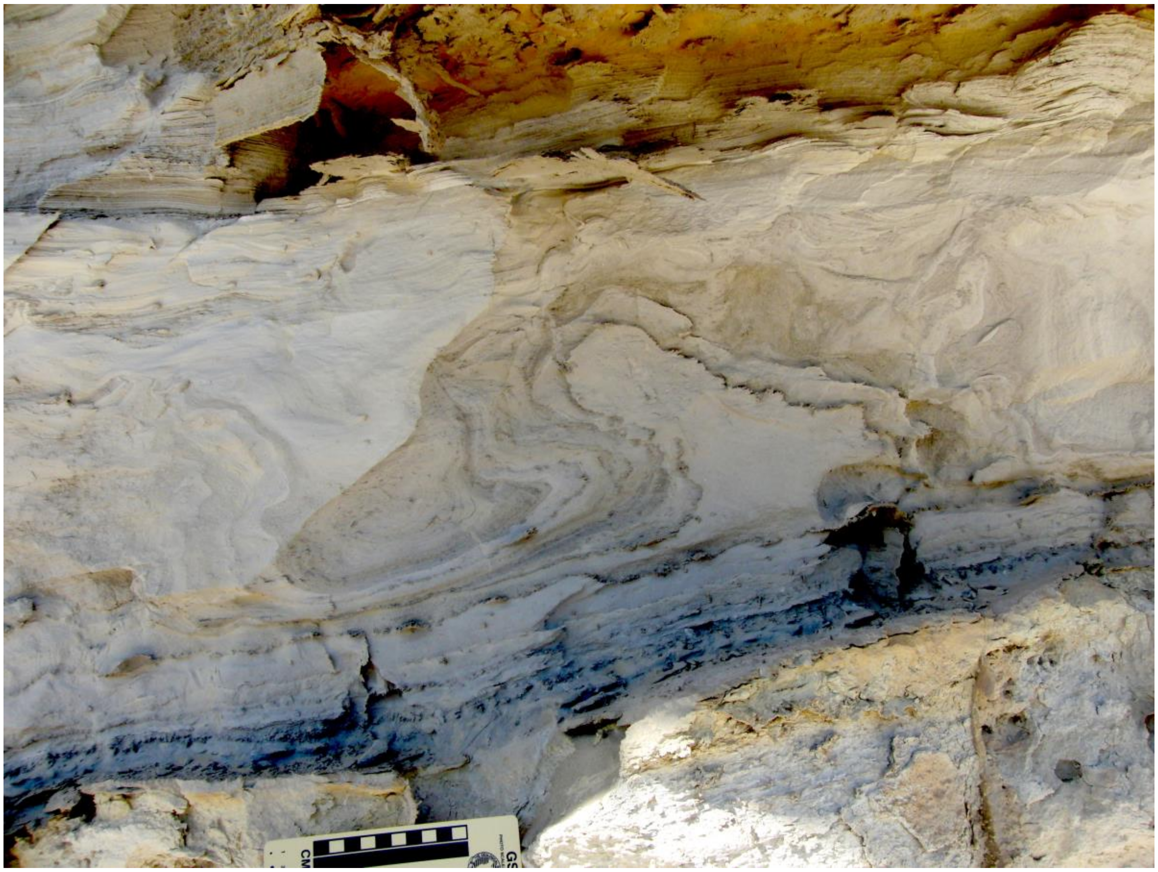


Figure 52. Soft-sediment deformation in tuff at Yeseras. Scale is 10 cm/4 in.

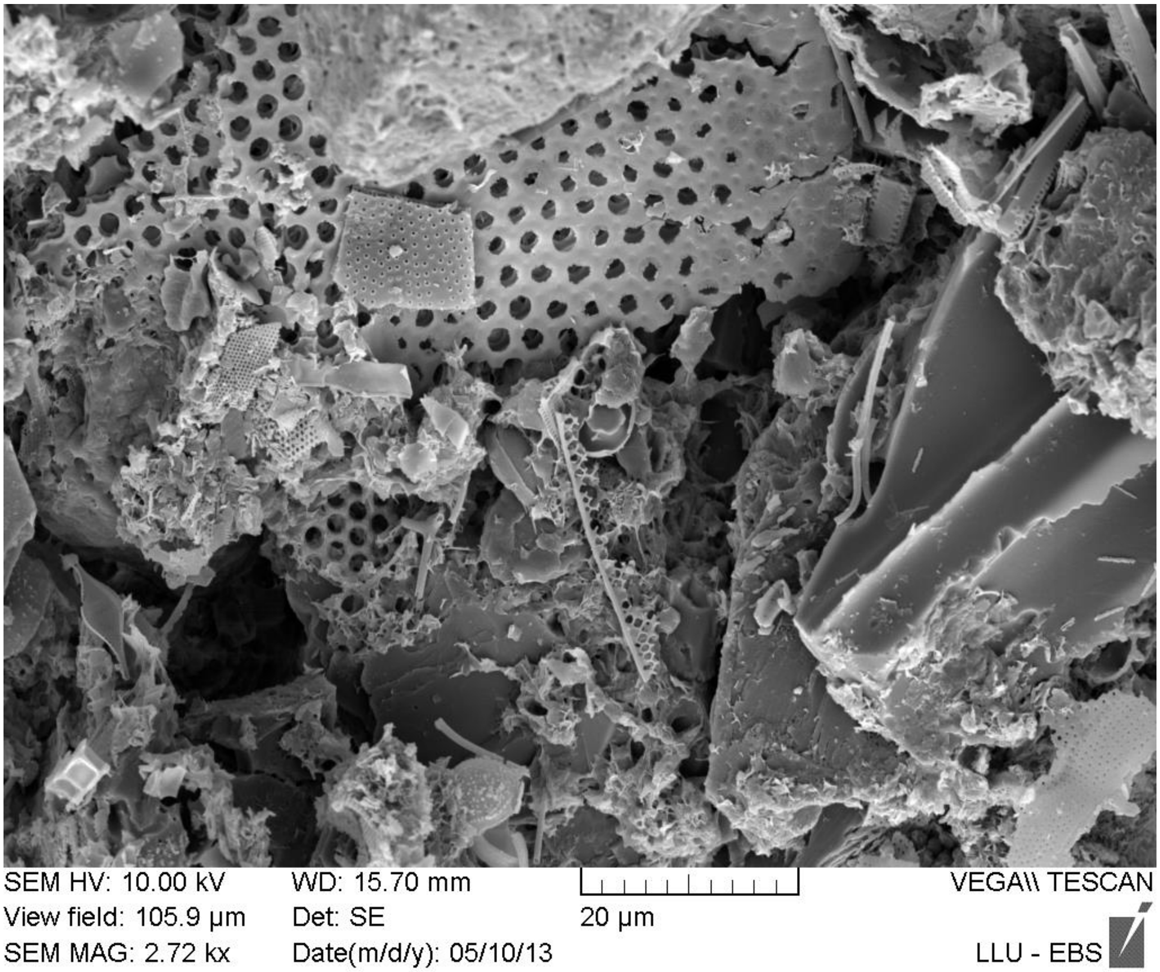
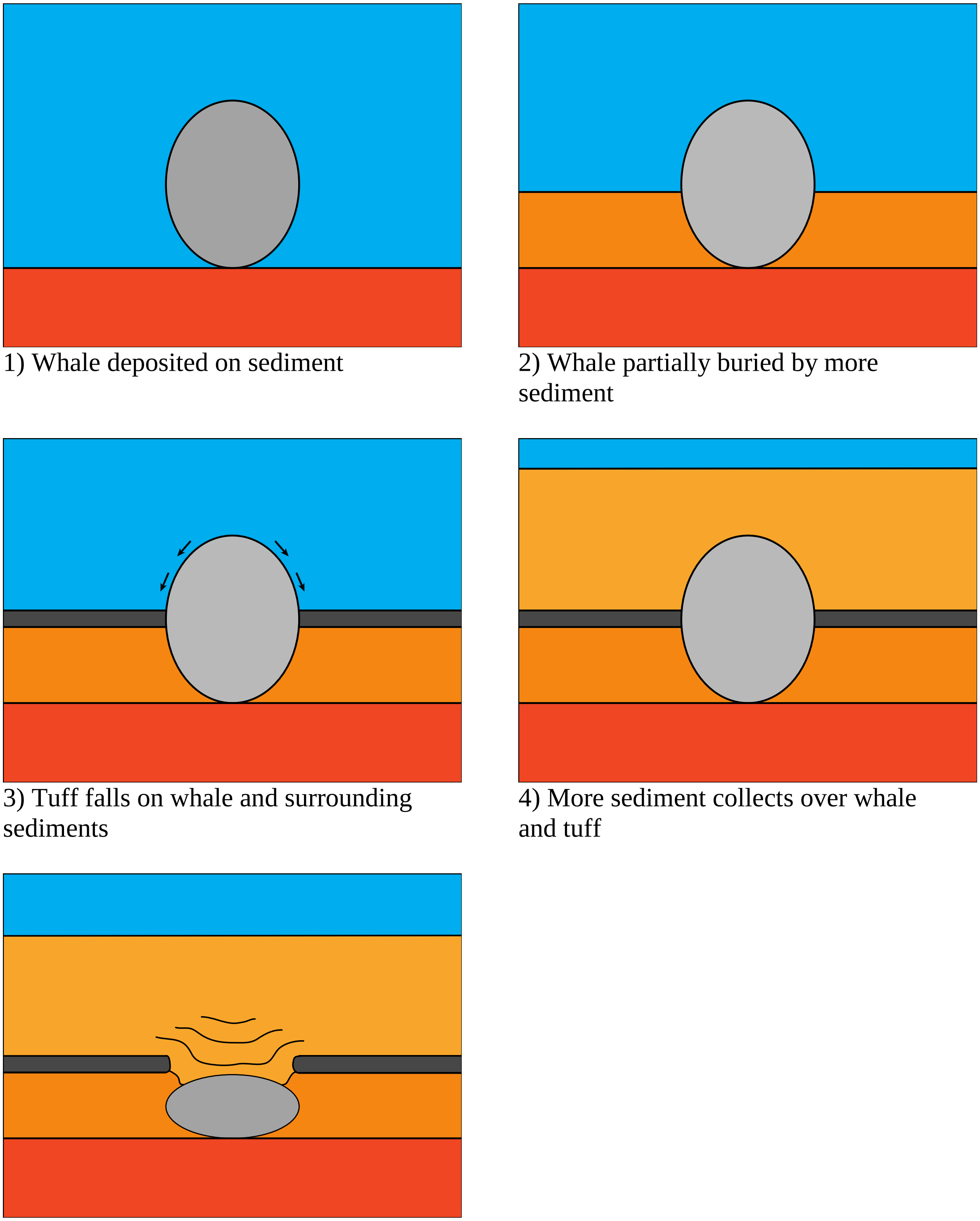


Figure 53. Diatoms in the sediments surrounding the whale at Location 8. There are fewer intact diatoms at this location.



1) Whale deposited on sediment

2) Whale partially buried by more sediment

3) Tuff falls on whale and surrounding sediments

4) More sediment collects over whale and tuff

5) Decomposition of the whale and differential compaction of the whale and sediments leaves no trace of tuff over whale

Figure 54. Proposed model of whale burial

Location 9: Cerro Blanco

Results

The whale at Cerro Blanco is in dorsal position on the southern end of the hill, in an area that is known for significant slumping (Figures 55 and 56). One of the fractures caused by the slumping passed through the whale's concretion. This happened prior the erosion of the hill back to the current outcrop and caused quite a bit of damage to the specimen, but the sedimentary features are still visible. The bones of the whale are broken where the faulting took place, but the whale is in a concretion and the bones that are present are mostly articulated. There is no evidence of macrobioerosion or abrasion on the bones.

The predominant sedimentary structure in the surrounding sediments is small-scale HCS. No apparent change is evident in the sedimentary composition or structure above and below the horizon on which the whale rests.

Siltstone is the dominant lithology at this outcrop, and it consists primarily of amorphous material, feldspars, and clay, with a small amount of quartz (Table 2, Sample K2). The amorphous component of the sediments is primarily diatoms (Figure 57). One small ash layer, primarily composed of volcanic glass, was present under the whale (Table 5, Figures 55, 56, and 58). The tuff bed rests on an erosional surface.

There was no bioturbation found at this outcrop, but we did find fish scales in and around the whale's concretion.

At the same level of elevation, but further north on the hill, a bed of gypsum about 4 cm thick is present immediately above a clay-rich layer about 10 cm thick.

Discussion

This whale's depositional profile is similar to the whale at Location 8, but it is surrounded by fewer tuffs. The HCS, and the erosional surface under the tuff that is present indicate that this whale was deposited above storm wave base, during conditions that were sufficiently energetic to erode silty sediments.

Because of the damage to the whale caused by the fault, it was difficult to discern the exact state of articulation of this specimen. It might have been slightly disarticulated upon burial, or the slight disarticulation present could have happened as a result of slumping of the hill. No taphonomic difference was apparent between the top and the bottom of the skull, which suggests that the entire skull was buried at approximately the same time. This fits with the sedimentology, as there appears to be no depositional hiatus at the sediment/water interface on which the whale was deposited.

The fish scales present in the whale's concretion indicate that they were buried and preserved at the same time as the whale, and may indicate that at the time of the whale's death, conditions persisted in the basin that caused the deaths of a large number of fish. (At other locations in the Pisco Formation, we have found large numbers of disarticulated fish bones, both great and small.)

The bed of gypsum overlying clay seems to be a typical evaporite deposit, and is probably stratigraphically lower than the whale due to the slumping of the hill. It might indicate that at least this portion of the basin dried out (though perhaps not completely) during the basin's deposition. If this were the case, it would fit well with the gypsum veins found at this site and at several other sites that were blocking ion movement through the sediments, and be another piece of evidence pointing to saturation of the basin waters with gypsum.

On the other hand, clay is a good permeability barrier, and the presence of the clay at that stratigraphic interval might have provided a place for gypsum to accumulate at a later date. This bed would be a good candidate for further study.

Figure 55. Whale at Cerro Blanco with slump visible to the right of the concretion. Scale is 10 cm/4 in.

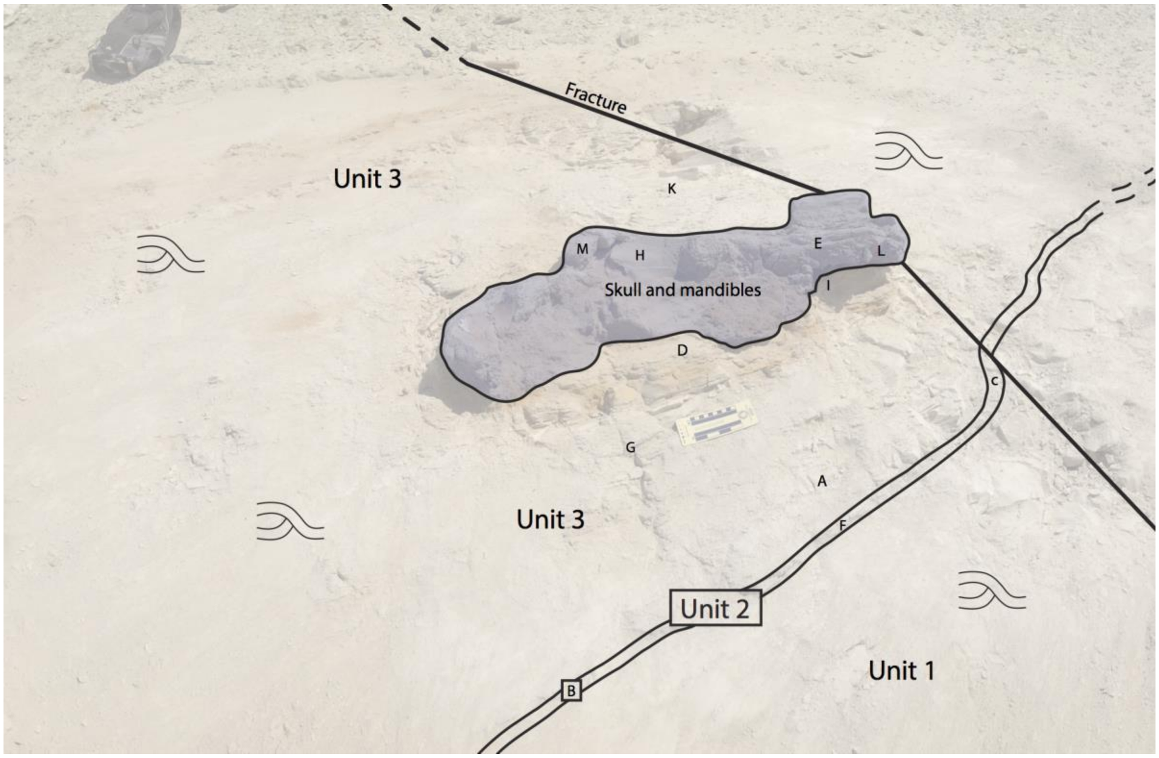
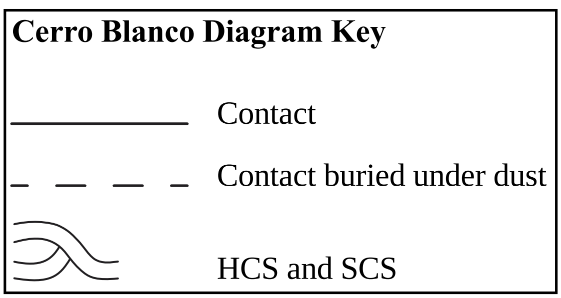


Figure 56. Interpretative overly of Figure 55. Letters A-M indicate the sampling locations within the area of the diagram. Scale is 10 cm/4 in.



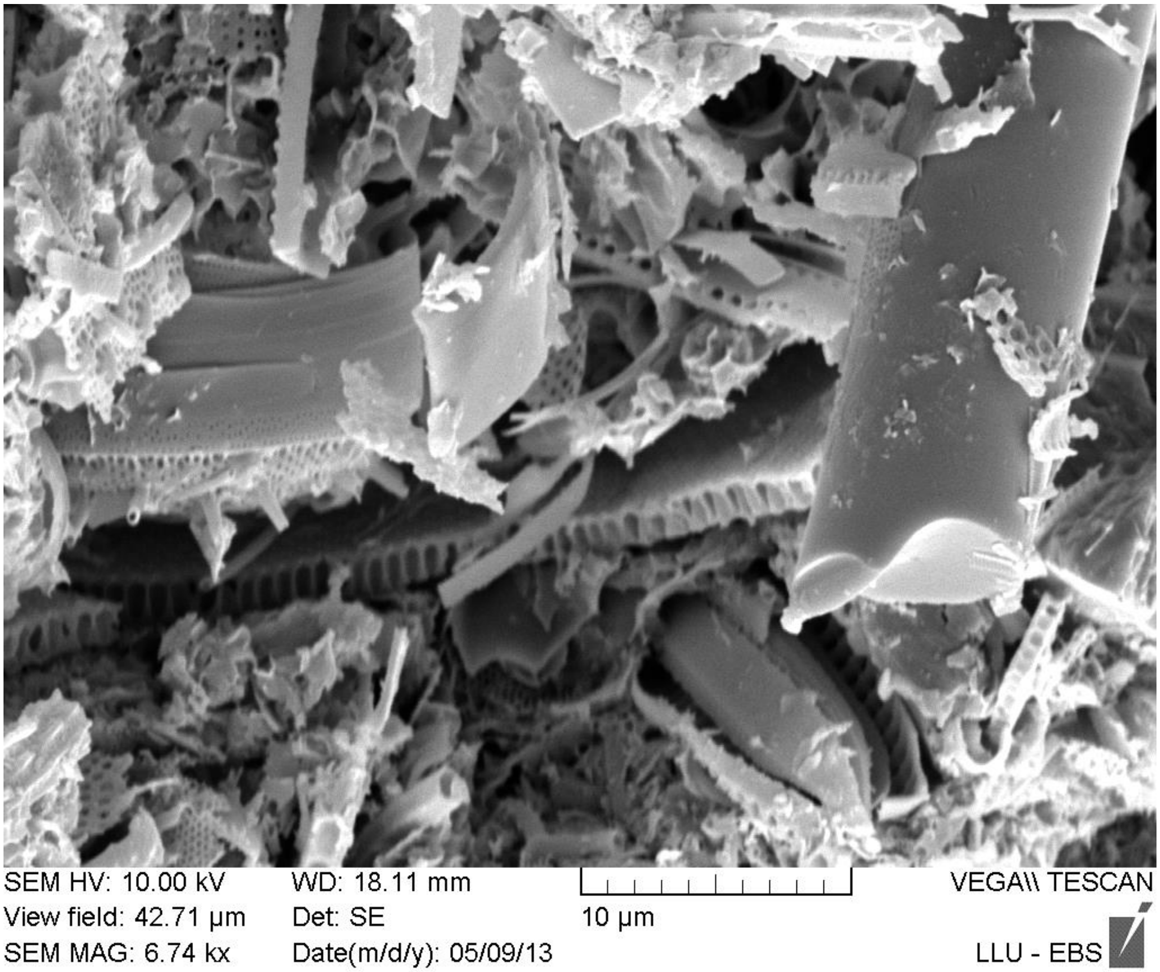


Figure 57. SEM image showing that the amorphous content of the sample is mostly diatoms

Table 5. Location 9 Unit Descriptions

Unit	Sedimentary Structures	Composition and Texture	Biogenic Structures	Fossils
1	HCS	Diatomaceous, tuffaceous, clayey siltstone	No bioturbation	
2	Laminated	64% volcanic glass and 36% feldspars	No bioturbation	
3	HCS	Diatomaceous, tuffaceous, clayey siltstone	No bioturbation	
Whale	None in concretion	Diatomaceous, tuffaceous, clayey, hematite-rich siltstone	No bioerosion on bones; skeleton was completely articulated or very nearly so	Fish scales were found in the concretion with the whale

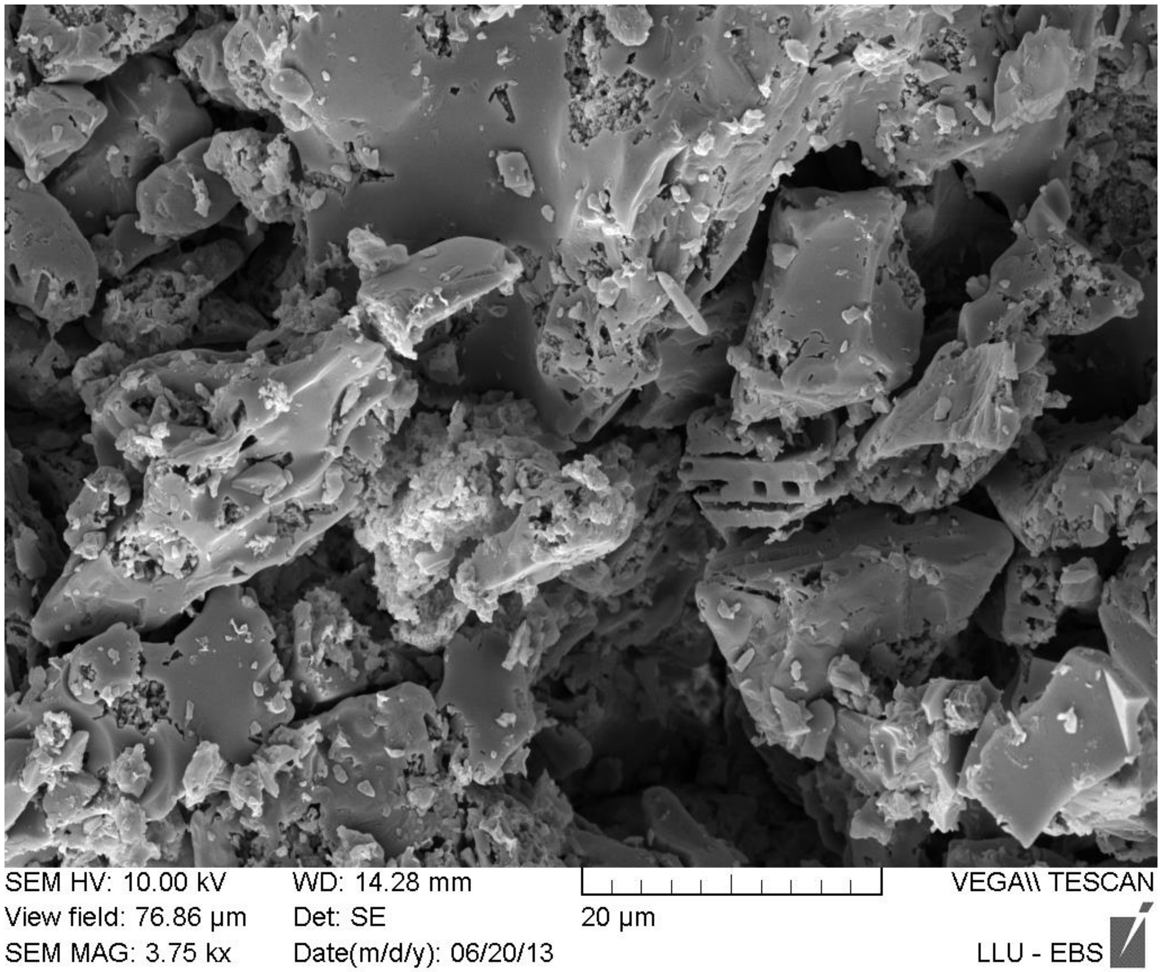


Figure 58. SEM image of ash layer, showing that its primary component is volcanic glass

Location 10: Cerro Yesera de Amara

Results

The whale at Cerro Yesera de Amara is on a modern erosional slope. As a result, the majority of the skeleton is exposed (Figure 59). Except for the whale's broken neck, the bones that are present (those that have not been removed by modern weathering) are completely articulated. Though this specimen is more exposed than the rest, it was included in the study because sedimentary details can be seen around the tail of the whale (Figures 60 and 61).

A great deal of bioturbation is present at this outcrop, but the undisturbed portion of the sediments in Unit 2 is diatomaceous and finely laminated. The bioturbated sediments are siliciclastic. The units around the whale are mostly siliciclastic and diatomaceous (Table 6, Figures 62, 63, and 64), but volcanic glass is present as well (Figure 65).

Beds a few meters above and below the whale range from moderately to completely bioturbated. The bed immediately under and surrounding the whale is partially bioturbated up to the level of the whale, but becomes completely bioturbated surrounding the whale (Table 6, Figures 60, 61, and 66). No macrobioerosion is visible on the whale's bones, however. A shark tooth was found at the edge of the concretion, but no scavenging marks were visible on the bones.

Discussion

It is likely that the bioturbation present indicates somewhat slower sediment deposition or a short depositional hiatus. If this were the case, it would help explain the shark tooth found in the concretion, probably an indicator of scavenging.

Between the wave ripple lamination in the bed under the whale, the bioturbation, and the lack of bioerosion on the bones, we can derive certain time constraints regarding the deposition and preservation of this whale. The sedimentary structures visible indicate the presence of bottom currents, and the bed under the whale is only partially bioturbated. These could be escape burrows, while the thorough bioturbation of the sediments surrounding the whale may indicate that they remained closer to the sediment-water interface for some time after their deposition. The lack of macrobioerosion on the bones, however, indicates that another depositional event placed the whale out of reach of scavengers, probably before too much of the flesh was gone, judging by the concretion around the whale. Due to the abundant bioturbation at this stratigraphic interval, we can rule out anoxia as a mechanism for preventing scavenging of the whale.

Figure 59. Whale fossil at Cerro Yesera de Amara

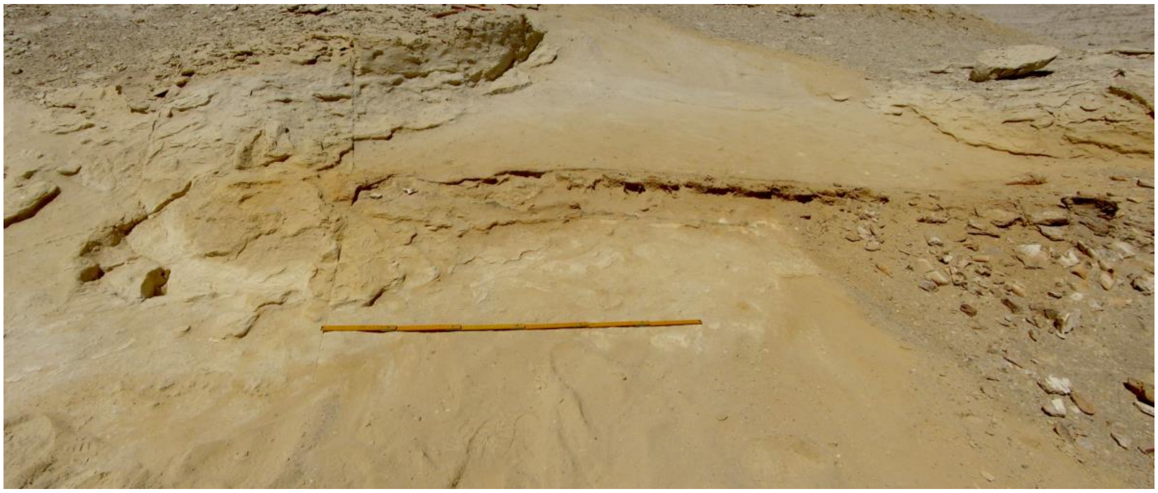


Figure 60. Cerro Yesera de Amara whale cross section. The whale backbone disappears into the hill above the 30-cm mark on the meterstick. The bones visible to the right are mostly ribs that have been freed by the weathering of the hillside. The slope to the right is shallow, but the slope to the left is quite steep, enough to give us a good view of the sedimentary and biogenic structures surrounding the whale. The scale is 1 m.

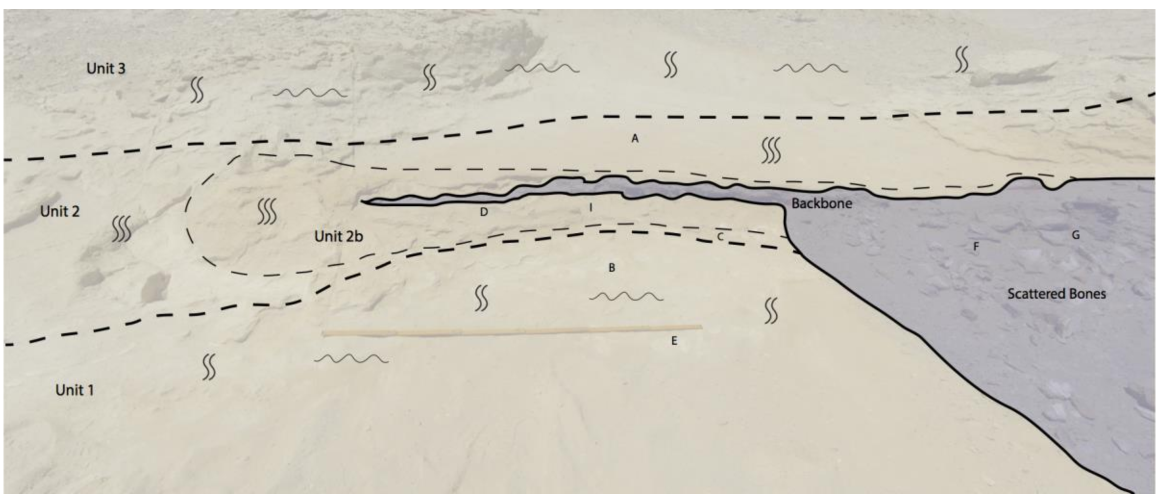


Figure 61. Interpretative overly of Figure 60. Letters A-G indicate the sampling locations within the area of the diagram. The scale is 1 m.

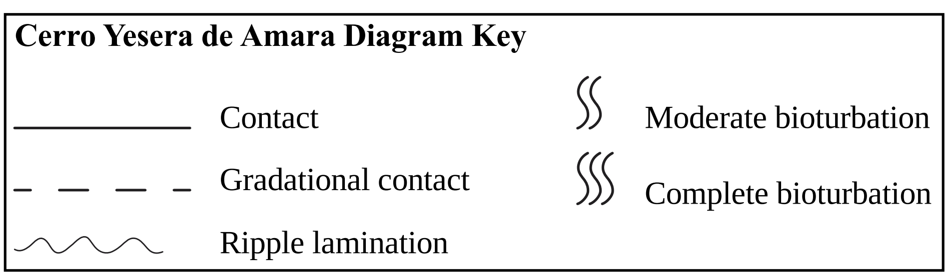


Table 6. Location 10 Unit Descriptions

Unit	Sedimentary Structures	Composition and Texture	Biogenic Structures	Fossils
1	Wave ripple lamination	Diatomaceous, tuffaceous, sandy, clayey siltstone	Moderate bioturbation, burrows ~3 cm in diameter	
2	Overwritten by bioturbation	Diatomaceous, tuffaceous, sandy, clayey siltstone	Complete bioturbation	
2b	Laminations	Hematite-rich, diatomaceous, tuffaceous, sandy, clayey siltstone	Sedimentary structures are not clear	Shark tooth
3	Wave ripple lamination	Diatomaceous, tuffaceous, sandy, clayey siltstone	Heavy, but not complete bioturbation	
Whale	Some laminations in concretion	Diatomaceous, tuffaceous, sandy, clayey hematite-rich siltstone	No bioerosion on bones, skeleton completely articulated	

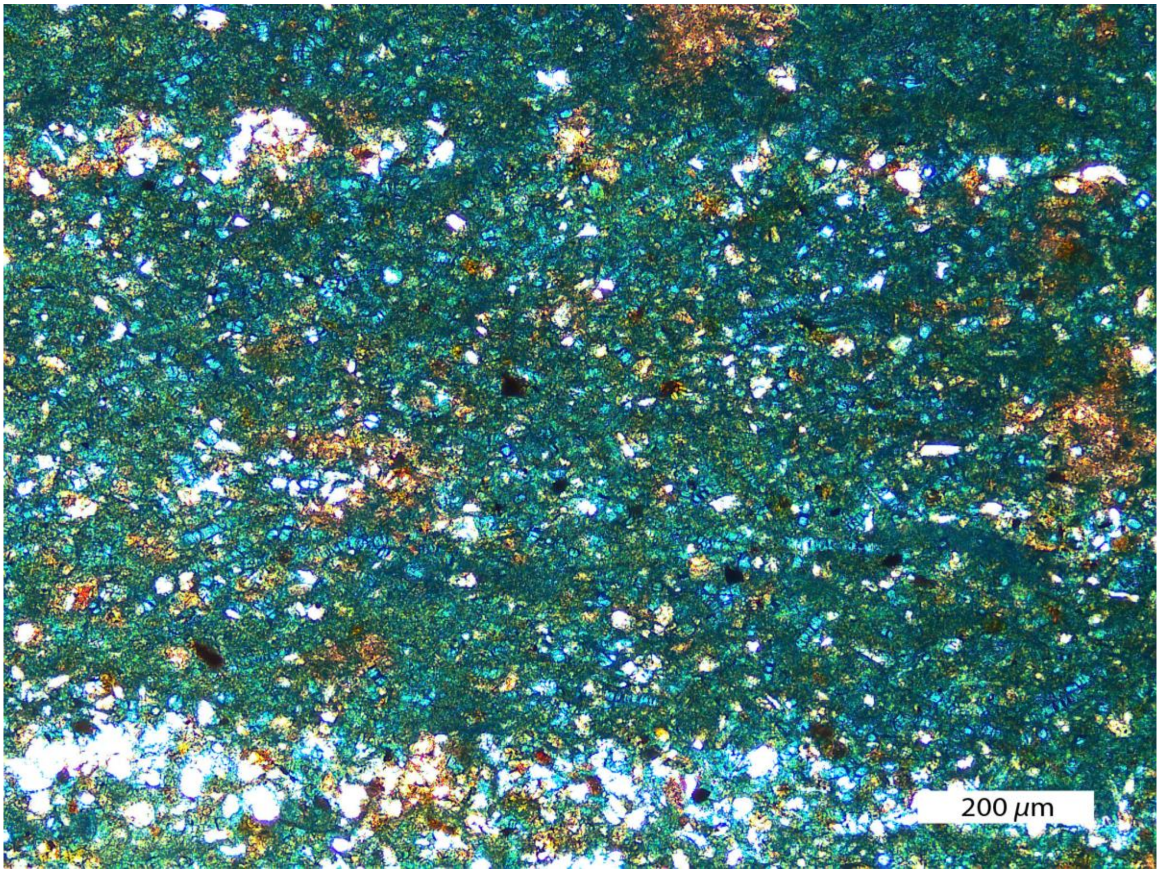


Figure 62. Thin section of Sample H, taken near Figure 66. Undisturbed lamina. This was taken from the non-bioturbated part of the moderately bioturbated bed immediately under the whale.

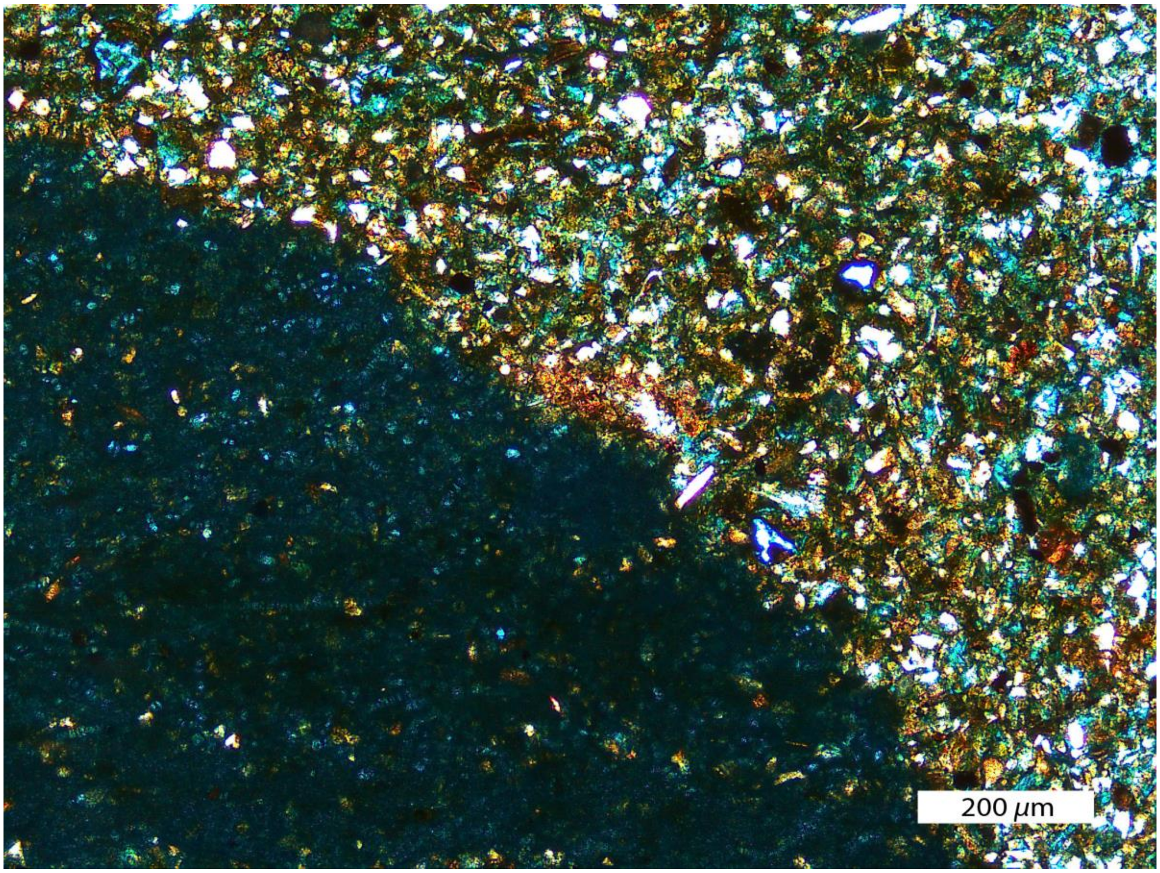


Figure 63. Thin section of Sample H. The darker sediments to the left are the same laminated sediments shown in Figure 62, but the exposure has been adjusted. The portion of slide to the right is bioturbated. The left portion is darker because the sediments are much finer-grained. Some of the same lamination visible in Figure 62 is visible in the left portion of this slide.

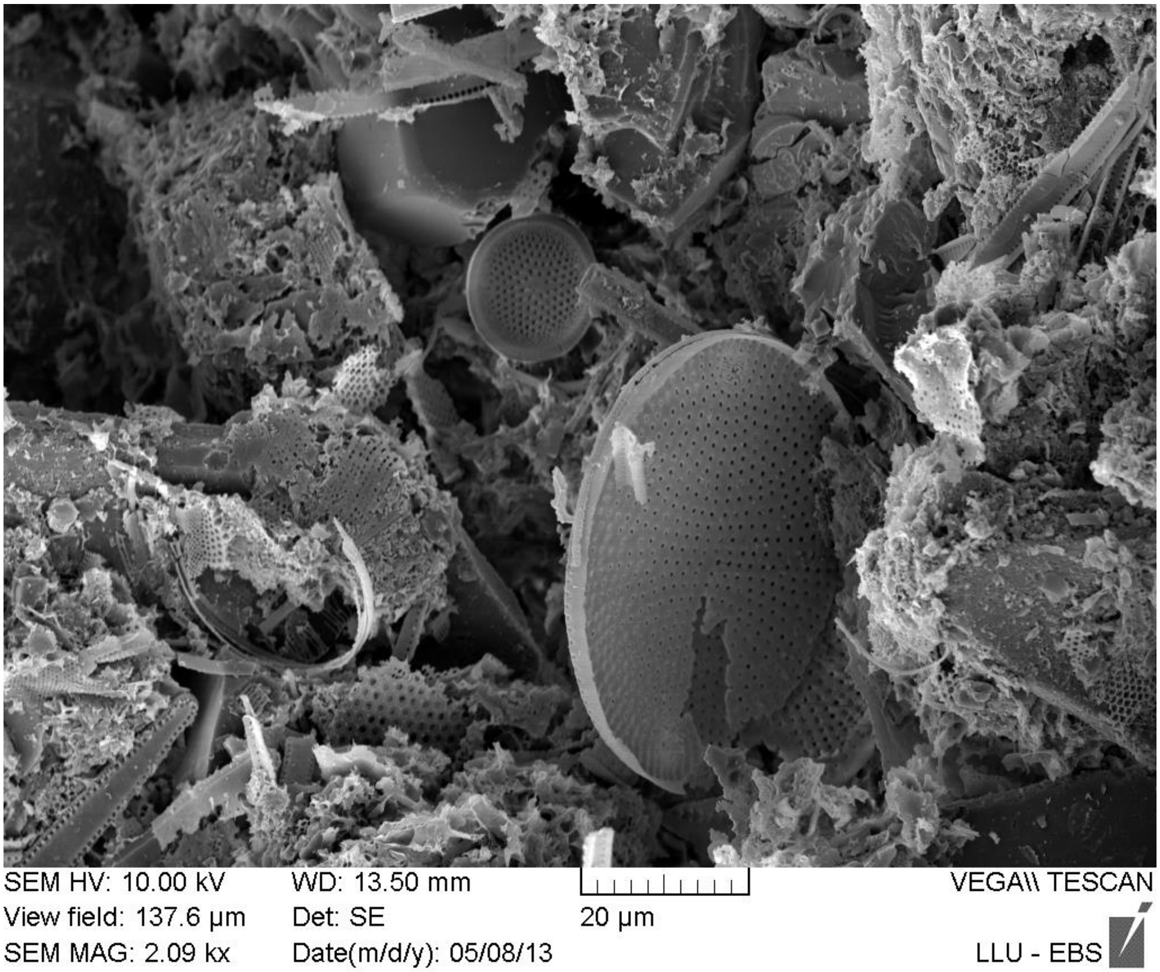


Figure 64. SEM image of diatoms in sediments surrounding the Cerro Yesera de Amara whale

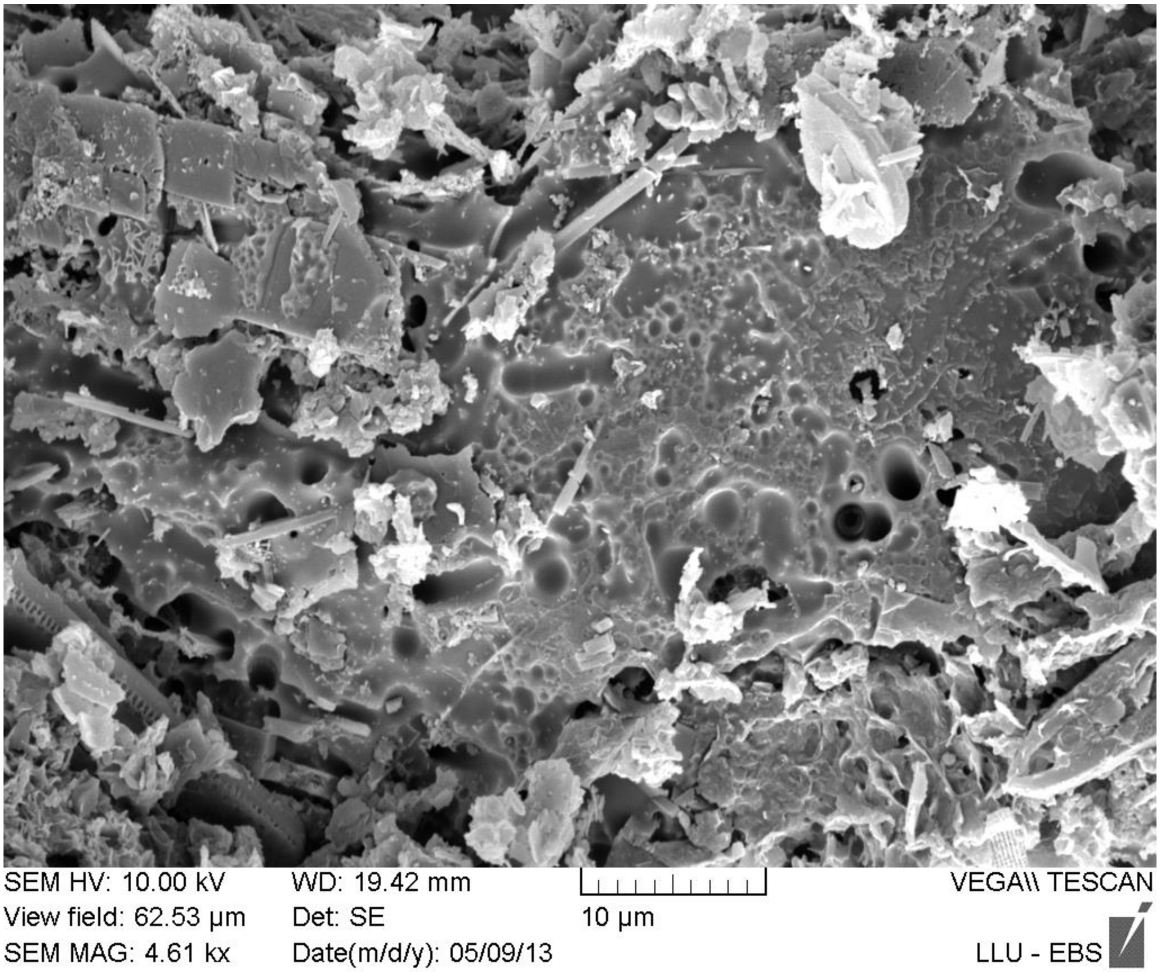


Figure 65. Volcanic glass in sediments surrounding the Cerro Yesera de Amara whale. Unlike the other locations (except Antenna), there are no distinct tuff beds here. There is volcanic glass mixed in with the other sedimentary material, however.

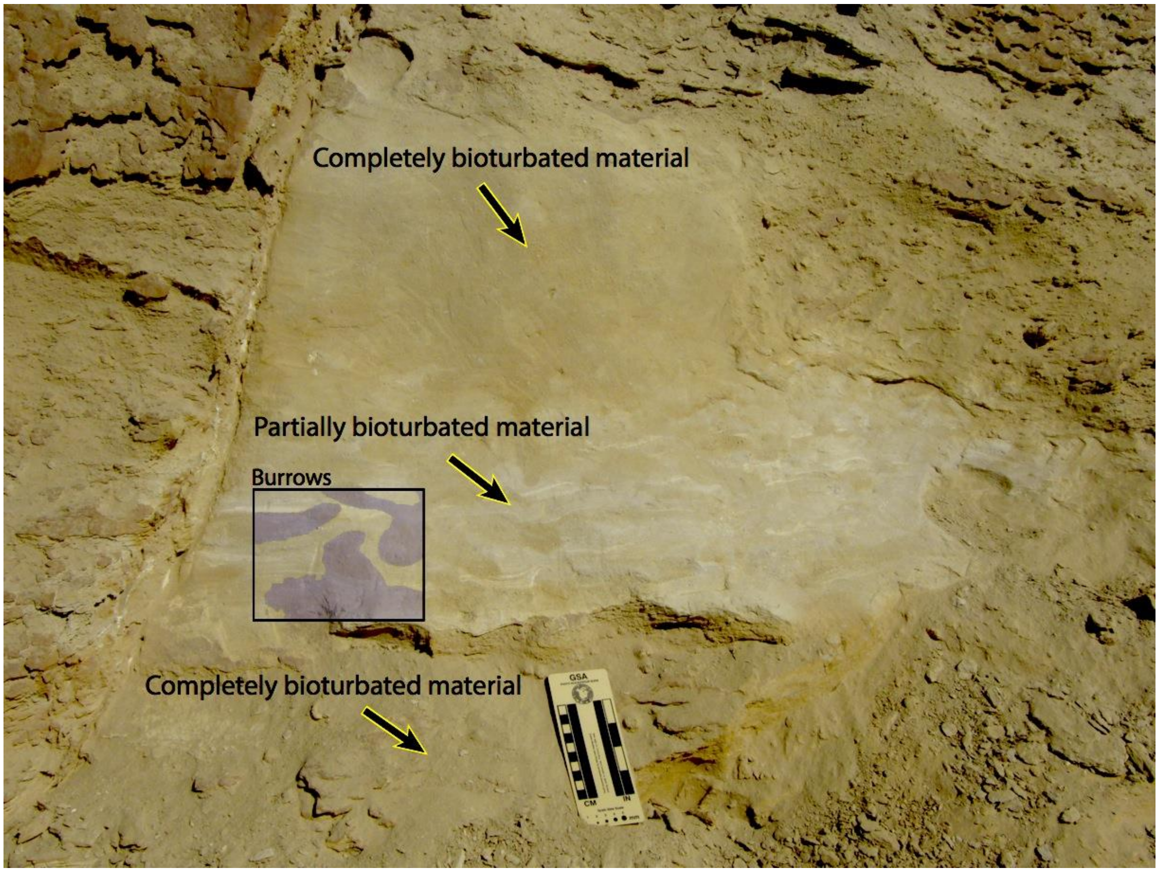


Figure 66. Detail of sedimentary structures behind whale, showing the partially bioturbated bed grading into a completely bioturbated bed. The whale rests on the horizon that is the bottommost part of the completely bioturbated rock.

APPENDIX B

TUFF BEDS AT THE CERRO BALLENA SOUTH OUTCROP

The whale at Cerro Ballena South is resting on top of what may be an altered tuff and is surrounded by another tuff, and one more high-silica tuff and another bed that may be an altered tuff were deposited less than a meter above it. The thick tuff that fell while the whale was resting on the bottom is a very high-silica tuff primarily consisting of volcanic glass (Table 7). The bed that may be an altered tuff immediately under the whale, and the continuous red bed about a meter above it have very high hematite and jarosite content, which may indicate a mafic source (Table 7).

Based on the XRD analysis, it was unclear whether the mineral present was alunite (potassium aluminum sulfate) or jarosite (potassium iron sulfate). The source of the hematite was probably weathered jarosite, however, so we have listed jarosite as the mineral. Another reason we chose jarosite over alunite was that the alunite that matched the peaks on the XRD graph was high in chromium, which did not show up in energy-dispersive X-ray spectroscopy.

Though all four of the beds in question are referred to as tuffs in the text because of the context of their deposition, there are some problems with the hypothesis that these high-iron beds are tuffs. The first and most obvious is that mafic ash falls are not common, due to the low viscosity of mafic magma and the correspondingly lower potential for an explosive, ash-generating eruption. A second possible problem is that jarosite is a typical byproduct of pyrite weathering, and the source of the iron and sulfur in the pyrite could have been something other than volcanic ash. These high-iron, low-silica beds would be good candidates for further study.

Table 7. XRD Analysis of Cerro Ballena South Tuff Composition

	Sample	Feldspars	Gypsum	Hematite	Illite	Jarosite	Quartz	Amorphous
Tuff immediately above whale	E	18.8	7.2	0.0	0.0	0.0	0.0	73.9
Green bed under whale	F	20.6	0.0	0.0	0.0	39.7	9.5	30.2
Gray tuff above whale	T	41.4	0.0	0.0	31.4	0.0	12.9	14.3
Red bed above whale	P	24.6	2.9	21.7	0.0	33.3	11.6	5.8

APPENDIX C

SUGGESTIONS FOR FURTHER RESEARCH

- The bones of many of the whales show a high association with gypsum cement and some gypsum replacement. Leucophosphite, the other mineral present (Figure 67), contains many of the elements that the original bone did. From the preservation of the diatoms and volcanic glass shards surrounding the bones, it is quite probable that the pore waters were saturated with silica. The preference for sulfates over silica in the preservation of bones gives us a clue to the chemistry of the basin, which might yield interesting results.
- One of the biggest surprises in this study was the discovery of gypsum veins blocking concretion ion seepage through sediment. Also interesting is that one of the beds I had originally assumed to be a diatom drape in a channel turned out to be gypsum and anhydrite. It appeared to be in the bedding plane, and if this is true, it probably means that the gypsum was deposited with the sediment. On Cerro Blanco, I found a 3-4-cm-thick layer of gypsum overlying a 10-cm-thick bed of clay, a possible evaporite deposit. It is conceivable that much (but not all) of the sediment studied in this research project was deposited while the basin was supersaturated with gypsum. Investigation of this could provide clues to the whales' preservation, as well as the paleoenvironment of the basin.

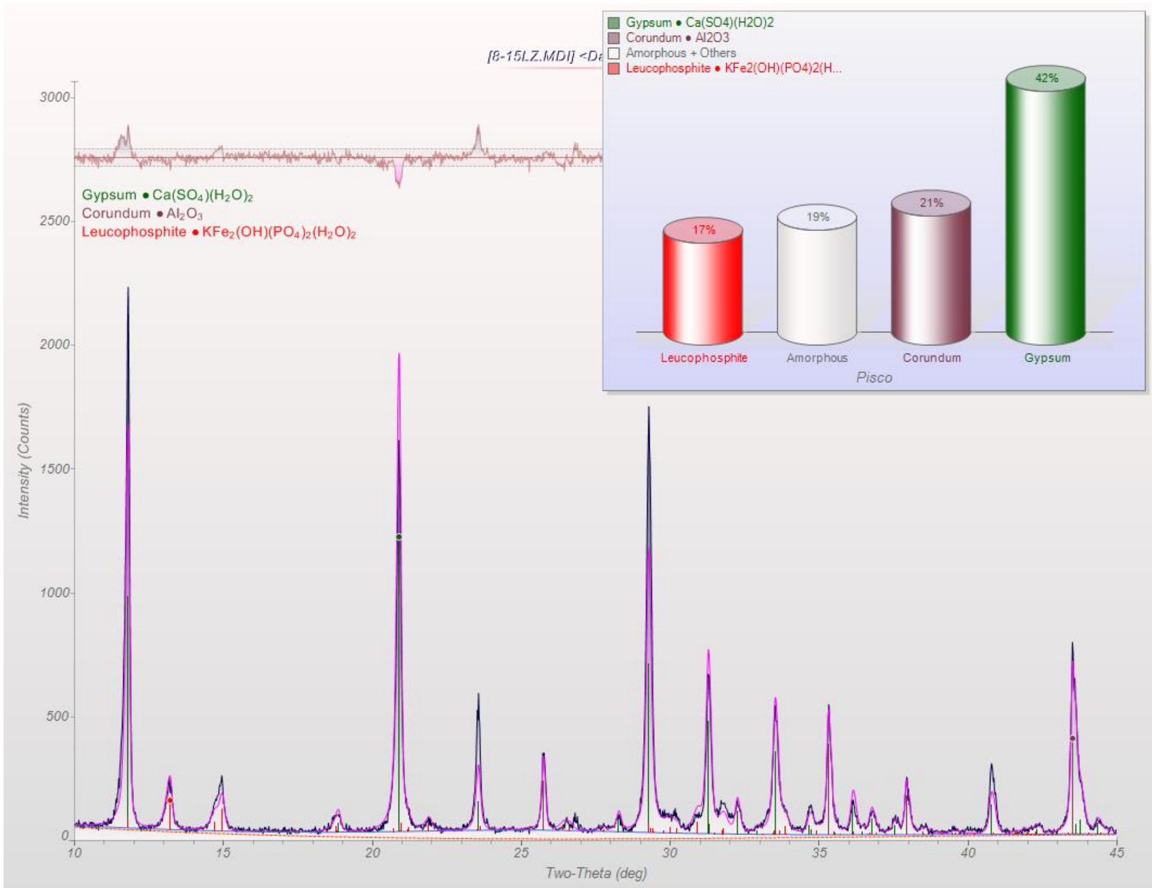


Figure 67. XRD scan showing the content of a bone taken from Location 5, Cerro Hueco la Zorra. Corundum was added as a standard.