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A high resolution stratigraphic framework for the remarkable fossil cetacean assemblage of the Miocene/Pliocene Pisco Formation, Peru

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A B S T R A C T

The Miocene/Pliocene Pisco Formation of Peru contains a rich marine vertebrate fossil record, providing a unique opportunity for the study of paleoecology and evolution, along with the sedimentological context of the fossils. The lack of a high-resolution stratigraphic framework has hampered such study. In this paper we develop the needed stratigraphy for the areas in the Pisco Formation where most of the vertebrate paleontological research is occurring. In the Ica Valley and in the vicinity of Lomas, series of lithologically or paleontologically unique marker beds were identified. These were walked out and documented with GPS technology. Measured sections connecting these marker beds provide a stratigraphic framework for the areas studied. GPS locations, maps of the marker beds on aerial photographs, and outcrop photographs allow field determination of the stratigraphic positions of study areas.

1. Introduction

The Miocene/Pliocene Pisco Formation in coastal Peru provides a unique opportunity for the study of paleoecology and evolution of marine vertebrates. In contrast to other formations the Pisco Formation contains thousands of fossil whales and other marine vertebrates and a great number of these fossils exhibit excellent preservation (Fig. 1), including many fully articulated skeletons and baleen structures (Esperante et al., 2002, 2008; Brand et al., 2004; de Muizon, 1984, 1988; de Muizon and McDonald 1995; McDonald and de Muizon, 2002). The whales represent various taxa, and the systematics of most have not been adequately studied. In addition to whales there are numerous other marine vertebrates, including dolphins, seals, penguins and other birds, sharks, other fish, a terrestrial carnivore, and even ground sloths (de Muizon and McDonald 1995; McDonald and de Muizon, 2002; de Muizon et al., 2004).

This assemblage has been studied in detail from a taphonomic perspective in the upper part of the Pisco Formation in the Ica Valley (Esperante et al., 2002, 2008; Brand et al., 2004), where the great number and preservation of the whales has led to a revised interpretation of the sedimentological context of this fossil assemblage. This initial study site, however, represents a limited stratigraphic interval of the Pisco Formation. This has led to the search for more fossil specimens in the remainder of the Pisco strata, in the Ica Valley and near Lomas for taphonomic study. These efforts and the work of systematic paleontologists have brought to light many new specimens of cetaceans as well as a variety of other marine vertebrates, enhancing the possibilities for the study of diverse aspects of Neogene vertebrate paleobiology. However the lack of a high resolution stratigraphic framework for the Pisco Formation has hampered the accurate placement of these new findings within their correct stratigraphic position and basinal context. This paper addresses the need for a more adequate stratigraphic framework. Excellent exposures along coastal Peru and multiple, laterally extensive dolomite and tempestite beds facilitate the definition of a walkable physical correlation at a basin scale.

In this paper, we develop this stratigraphic framework and insert it within the regional stratigraphy. We provide maps of marker beds that have been walked out and documented with GPS data. Thus, future studies of the fossil assemblage and other aspects of the Pisco Formation will be greatly facilitated.

2. Geological setting

The Pisco Formation was deposited during the most recent of three major marine transgressions along the southern Peruvian

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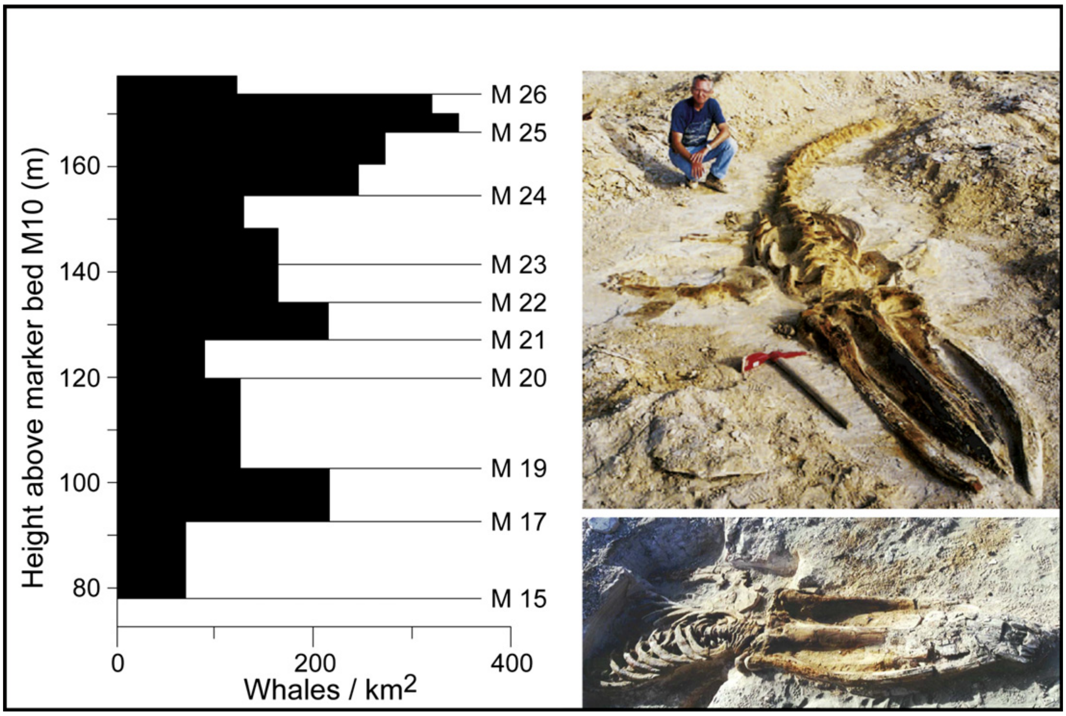

Fig. 1. Density of fossil whales on north Cerro Blanco as a sample of the abundance of marine vertebrates in the Pisco Formation, and two articulated and well preserved fossil whales.

coast, in the Pisco Basin. These transgressions produced a marine sedimentary sequence from Eocene to Pliocene, with a rich vertebrate fossil record, followed by Pleistocene deposits (de Muizon and DeVries, 1985; Marocco and de Muizon, 1988; Dunbar et al., 1990; Dávila, 1993). Stratigraphic nomenclature for the sediments in the East Pisco Basin has varied with different authors (Fourtanier and Macharé, 1986; Dunbar et al., 1988, 1990; DeVries, 1998), and we will use the nomenclature of DeVries (1998). The middle Miocene through early Pliocene Pisco Formation is underlain by the late Oligocene to early middle Miocene Chilcatay Formation (DeVries, 1998).

Earlier studies have provided a general stratigraphic framework for the Pisco Formation (De Muizon and DeVries, 1985). Carvajal (2002) measured additional sections. But facies changes cause difficulty in correlating between measured sections without determining mappable lithologic units that represent time lines linking measured sections. The present paper adds a more detailed stratigraphy with mapped marker beds. This paper does not include a comprehensive geological map, and correlation of the complete stratigraphy of each hill in the study area has not been established. The purpose of our study is best described as a practical stratigraphy in the areas of the Pisco Formation where most of the vertebrate paleontology research is occurring. This stratigraphy allows correlation of collecting areas and determination of the relative age of fossils in such areas. It provides a reliable stratigraphy in order to realize the potential of the rich, excellently preserved marine vertebrate fauna in the Pisco Formation. Additional research on the correlation of tuffs, currently underway (Kevin Nick, personal communication), is expected to further refine the stratigraphy and expand it to additional parts of the Pisco Formation exposures.

3. Methods

In the Ica Valley section a number of laterally extensive marker beds were identified, with distinctive geological and/or paleontological characteristics (Appendix). These beds were walked out, GPS positions and altitudes taken at successive intervals, and strikes and dips of the sediments determined. We labeled each marker bed with an M (Ica Valley) or LM (Aguada de Lomas) followed by a number. GPS locations are also labeled with letters and numbers (Table 1). Faults and folds were identified throughout the section. A section was then measured and described for the entire Pisco Fm exposure in the Ica Valley, from the contact with the Chilcatay Formation near Cerro Yesera de Amara and Cerro Bruja to the highest exposure on north Cerro Blanco, near Ocucaje (Fig. 2).

The section in the Ica Valley was compared with published and unpublished data on biostratigraphy of the mollusks, diatoms, and other fossils, and available radiometric dates.

A section was also measured in the Lomas area (Fig. 3). Lomas is 170 km south of Ocucaje, and there are intermittent exposures of Pisco Formation extending from the Ica Valley to the south of Lomas. Our measured section began at the base of Pisco Fm exposures near the village of Lomas. Strikes and dips of sediments were measured and faults were identified when possible. The more extensive modern sand cover in some parts of this area made structural study difficult. Sediment thickness between the Lomas area and the next identifiable sedimentary bed, a boulder bed at Lomas Junction (LM 1), was estimated, based on the altitude change and the essentially horizontal beds along that direction. The boulder bed was correlated from there to the nearby broad, nearly level valley of Aguada de Lomas, with its extensive sequence of well-exposed beds with little sand cover. A measured section continued across the valley to the base of the hills at the northeast end of Aguada de Lomas.

All GPS measurements were taken with the S. America 69 datum (Table 1). Maps produced by the Peruvian government organization INGEMMET sometimes use the same names for more than one hill or Cerro. In our study area there are two Cerro Blancos and two Cerro Ballenas. We use the unofficial terms south and north to distinguish the members of each pair.

Stratigraphic positions of the classic vertebrate fossil collecting areas were determined, as far as possible. Also the stratigraphic

Table 1
GPS locations and other data for measured sections in the Pisco Formation. Thickness in meters is measured from the indicated marker bed to the one below it. GPS datum is S America 69. Format for each GPS reading is 18L easting/northing. Thickness from LS1 to LM 1 is estimated.

GPS location	Thickness	Marker bed	Easting	Northing
Section at N Cerro Blanco				
Top of C. Blanco	6			
M26-05	7.2	M 26	422619	8411474
M25-05	12	M 25	422669	8411452
M24-05	13	M 24	422774	8411430
M23-05	7.3	M 23	422862	8411440
M22-05	9.8	M 22	422934	8411444
M21-05	7.3	M 21	422996	8411436
M20-05	17	M 20	423046	8411430
M19-05	6.2	M 19	423144	8411426
M18-05	7.1	M 18	423160	8411418
M17-05	5.9	M 17	423172	8411418
M16-05	5.3	M 16	423195	8411416
M15-05	5.3	M 15	423214	8411412
M14-05	15	M 14	423236	8411410
M13-05	18	M 13	423284	8411404
M12-05	33	M 12	423340	8411404
M11-05	8.3	M 11	423488	8411380
M10-05		M 10	423602	8411352
Section at Cerro Hueco la Zorra				
IV52	9	M 10	426956	8401628
M9-11	24.7	M 9	426985	8401564
M8-11	20.6	M 8	427078	8401483
M7-11	4	M 7	427274	8401514
IV47B		M 6	427422	8401552
Section south of Cerro Hueco la Zorra				
IV47	77	M 6	427801	8399396
IV38		M 5	428487	8399214
IV5-25	16	M 5	428308	8398510
IV5-24		M 4	428586	8398246
IV5-23	20	M 4	427633	8396960
IV5-21		M 3	427750	8396862
Section south of Cerro la Bruja				
IV27B	65	M 3	427433	8391042
IV20		M 2	427813	8390008
Section at Cerro Yesera de Amara				
IV7	7	M 2	427857	8386392
IV6		M 1	428094	8386435
Other GPS locations in Ica Valley				
MT-7		M 10	422605	8408706
MT-8		M 10	422185	8407452
MT-14		M 10	424274	8408612
MT-17		M 10	426035	8404982
MT-19		M 10	424406	8401250
M6-11Z		M 6	425764	8403218
ME2		M 5	427086	8398004
MF24		M 4	428554	8397754
MH6		M 3	428399	8392654
MH12		M 3	427386	8395046
MH18		M 3	428377	8397496
MM14		M 2	427922	8396016
MM15		M 2	426852	8389116
IC72		M 1	428530	8390966
Section from near Lomas to Aguada de Lomas				
LM 20	13.6	LM 20	522940	8285691
LM 19	5.2	LM 19	522919	8285649
LM 18	9	LM 18	522861	8285625
LM 17-5		LM 17	522647	8285735
LM 17	27	LM 17	521369	8285137
LM 16	18	LM 16	521177	8285110
LM 15	15	LM 15	521063	8285112
LM 14	17	LM 14	520871	8285200
LM 13	23	LM 13	520766	8285222
LM 12	17	LM 12	520564	8285307
LM 11	14	LM 11	520485	8285284
LM 10	27	LM 10	520331	8285319
LM 9	5	LM 9	520068	8285414
LM 8	9	LM 8	519997	8285483
LM 7	18	LM 7	519778	8285448
LM 6	12	LM 6	519397	8285792
LM 5	36	LM 5	519309	8285818
LM 4	12	LM 4	518752	8286041
LM 3	26	LM 3	518544	8286254
LM 2	11	LM 2	517813	8286686
LM 2-2		LM 2	518295	8286404
LM 1	60	LM 1	517757	8286675
LS 1	6	near Lomas	517431	8281456
L5-11		near Lomas	517198	8281347

position of other published and unpublished specimens collected in the Pisco Formation was determined, as available.

4. Results

4.1. Ica Valley section (south from the village of Ocucaje)

Fig. 2 is a map of the marker beds in the Ica Valley section, from the area of Cerro Yesera de Amara to Cerro Ballena, along the west side of the Ica River, with the beds drawn on a mosaic of satellite photos (from Google Earth). Fig. 4 is a diagram of the vertical relationships of these marker beds, based on GPS data, showing where each part of the section was measured through the entire Pisco Fm exposures in this area. Fig. 5 is a set of photographs to facilitate identification of marker beds.

The base of the Pisco Formation, as generally understood, is in the valley east of Yesera de Amara and southeast of Cerro la Bruja. However, a definite contact with the Chilcatay Formation cannot be unambiguously identified at this time. There is not an identifiable lithological boundary, but rather a boundary zone with a significant faunal change across the boundary. Fig. 6 is a list of families in the Chilcatay and Pisco Formations (de Muizon, 1988; Kindlimann, 1990; Bianucci et al 2010).

We have mapped the units that seem to best characterize the boundary zone, marker bed M 1 and M 2. M 1 (Figs. 2c and 5g) is a unit with bored dolomitic clasts, manganese nodules, and *Chionopsis* bivalves. This unit contains boulders ranging from 0.2 m to more than 3 m in diameter. Other mollusks in this unit include the gastropod *Ficus distans*, the inarticulate brachiopod *Disinisca*, and two bivalve genera - large *Dosinia* and also *Miltha*.

Seven meters above this boulder bed is a unit designated as marker bed M 2 (Fig. 5g and h) with abundant articulated *Chionopsis* bivalves and many whale bones, including well-preserved but disarticulated or partially articulated skeletons. This unit also often contains boulders, up to about 0.5 m in diameter. Some igneous clasts on this unit were encrusted with oysters, large barnacles *Megabalanus*, and colonies of tubes of the polychaete *Gunnarea* (Fig. 7d).

Marker bed M 2 can be traced to the north, to near the southern end of the lower slopes of Cerro la Bruja (Fig. 2c), where there is a facies change in M 2 and associated sediments. This change is associated with their proximity to an outcrop of basement rock, and the sediments close to the basement rock consist primarily of very coarse sandstone. M 2 still contains mollusks and boulders in this area. There is an additional boulder bed several meters above M 2, right at the base of the steep slopes of Cerro Yesera de Amara.

A section was measured from M 2 to the next marker bed, M 3. M3 is displaced by several faults, but can be traced to the north along the east side of Cerro la Bruja (Fig. 2c). M 3 is the uppermost of a set of resistant brown siltstones alternating with softer siltstones. Some of the siltstones (including M 3, the uppermost bed) contain many large articulated bivalves of the genus *Dosinia*.

M 3 continues along the lower slopes of Cerro la Bruja and Cerro el Brujito (Fig. 2b and c). The set of brown siltstones at and below M 3 is visually distinct through this area (Fig. 5i). It also continues around

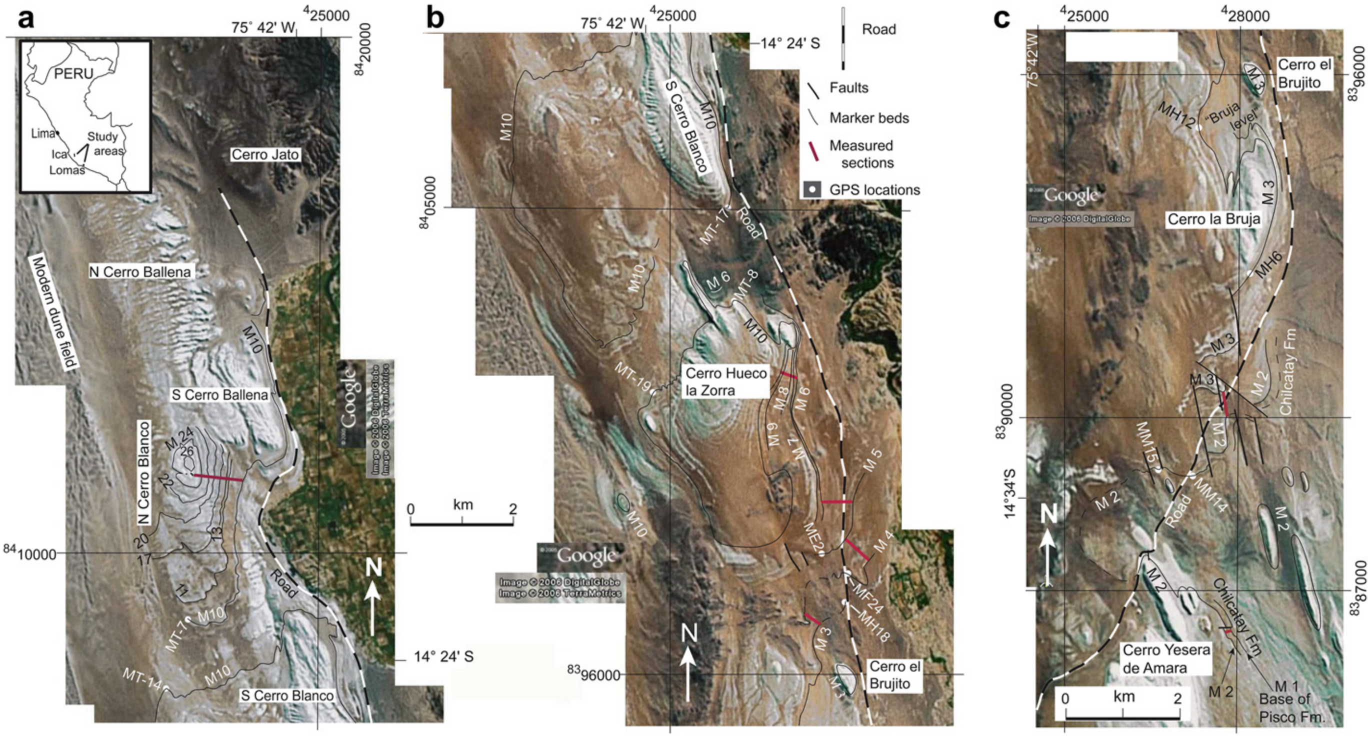

Fig. 2. Map of marker beds and measured sections in the Ica Valley section, drawn on satellite photographs (from Google Earth) from north (Fig. 2a) to south (Fig. 2c). Names such as M 2 are marker beds. Other names (e.g. MH6) are locations of GPS readings, given in Table 1. The "road" on this map is becoming, in recent years, more difficult to follow from Cerro Hueco la Zorra to Cerro Bruja because the local traffic is using a newer route, closer to the river.

the northwest side of Cerro la Bruja and along the west side of the valley west of Cerro el Brujito (Fig. 2b and c). Here it is topped by a whitish unit that weathers into a soft slope. M 3 goes under the sand, but reappears near the road for a short distance (Fig. 2b; location MH18).

Above this there are two other sets of brown resistant beds (sandstones), with articulated *Dosinia* clams in some of the sandstone units. In each set the sandstones alternate with siltstone units. The upper sandstones of each of these sets are respectively, marker beds M 4 and M 5 (Fig. 5e). M 4 contains a variety of mollusks, including *Dosinia* and the gastropods *Cancellaria, Northia*, and some buccinids. Between Cerro el Brujito and Cerro Hueco la Zorra sections were measured from M 3 up to M 6 (Fig. 2b).

M 6 is a coarse sandstone, often containing a thin coquina of inarticulate brachiopods, genus *Discinisca*. The upper surface of M 6 is commonly a megaripple sandstone (Fig. 7a). M 6 continues to the north as a course sandstone bed a few meters above a prominent bench along the base of the west side of Cerro Hueco la Zorra (Figs. 2b and 5f). It then disappears under the sand, but reappears at ground level on the north side of Cerro Hueco la Zorra.

Above M 6 are several beds in the southeastern slope of Cerro Hueco la Zorra, that can be followed in the cliffs of the more northerly part of the same mountain, Three of these were chosen as marker beds (Fig. 5f). The first, M 7, is a bench-forming part of an extensive thickness of whitish chippy sediment. Above that, M 8 is an indurated siltstone, the lowest of three similar beds. M 8 has spotty outcrop in the sloping surface, but was chosen as a marker bed because it can be clearly identified and followed along the cliff. M 9 is a limestone bed about 9 m below M 10. On the sand-covered slope M 9 breaks up into white limestone clasts that litter the slope. Just to the north where it enters the cliff, M 9 is not as visible, but 3 m below it is a prominent orange band that can be easily followed along the cliff, around the north end of Cerro Hueco la Zorra, and along the northwestern side of that cerro.

The most widespread marker bed in this study is M 10. M 10 encircles Cerro Hueco la Zorra (Fig. 5f), and is the prominent unit close to the top of the long finger-shaped point extending north from Cerro Hueco la Zorra towards South Cerro Blanco (Fig. 2b; SW of MT17). M 10 continues along the east side of South and North Cerro Blanco and of Cerro Ballena, forming a prominent bench through much of this area (Fig. 2a, b, and 5c). On the western side of those cerros it doesn't form such a prominent bench, but can be identified and walked out. In the area west of Cerro Hueco la Zorra there is a facies change in M 10. It becomes a white dolomitic siltstone that breaks up into durable 0.2–0.4 m clasts that litter the slope.

Stratigraphy above M 10 has been studied on north Cerro Blanco, and marker beds M 11-26 were mapped in connection with a study of taphonomy of whales (Carvajal, 2002; Esperante et al., 2002; Brand et al., 2004) (Fig. 2a, and Fig. 4). Several of these are shown in Fig. 5a–d.

Marker beds M 13-M 26 are of various lithologies, including dolomite, sandstone, and tuffs (Appendix). They are continuous through Cerro Ballena and North Cerro Blanco. The most physically prominent of these beds above M 10 is M 24, a dolomite that breaks up into numerous persistent, highly indurated clasts, which makes the bed conspicuous and easy to follow (Fig. 5b). This bed and M26 are evident from North Cerro Ballena to Cerro Hueco la Zorra (Figs. 2a and 4).

Table 1 gives GPS locations for each marker bed along a measured transect, and selected additional GPS locations along some of the marker beds, to facilitate their relocation in future research (some locations are labeled in Fig. 2). Fig. 8 shows the sections in the Ica Valley, measured at the locations marked on Fig. 2. The total measured thickness of the Pisco Formation in this valley is 435 m. A small additional amount of section above M 26, along the modern dune field west of North Cerro Ballena (Fig. 2a), was not studied.

The Ica Valley section is bounded on the west by an extensive modern dune field, oriented north–south (Fig. 2a). On the west side

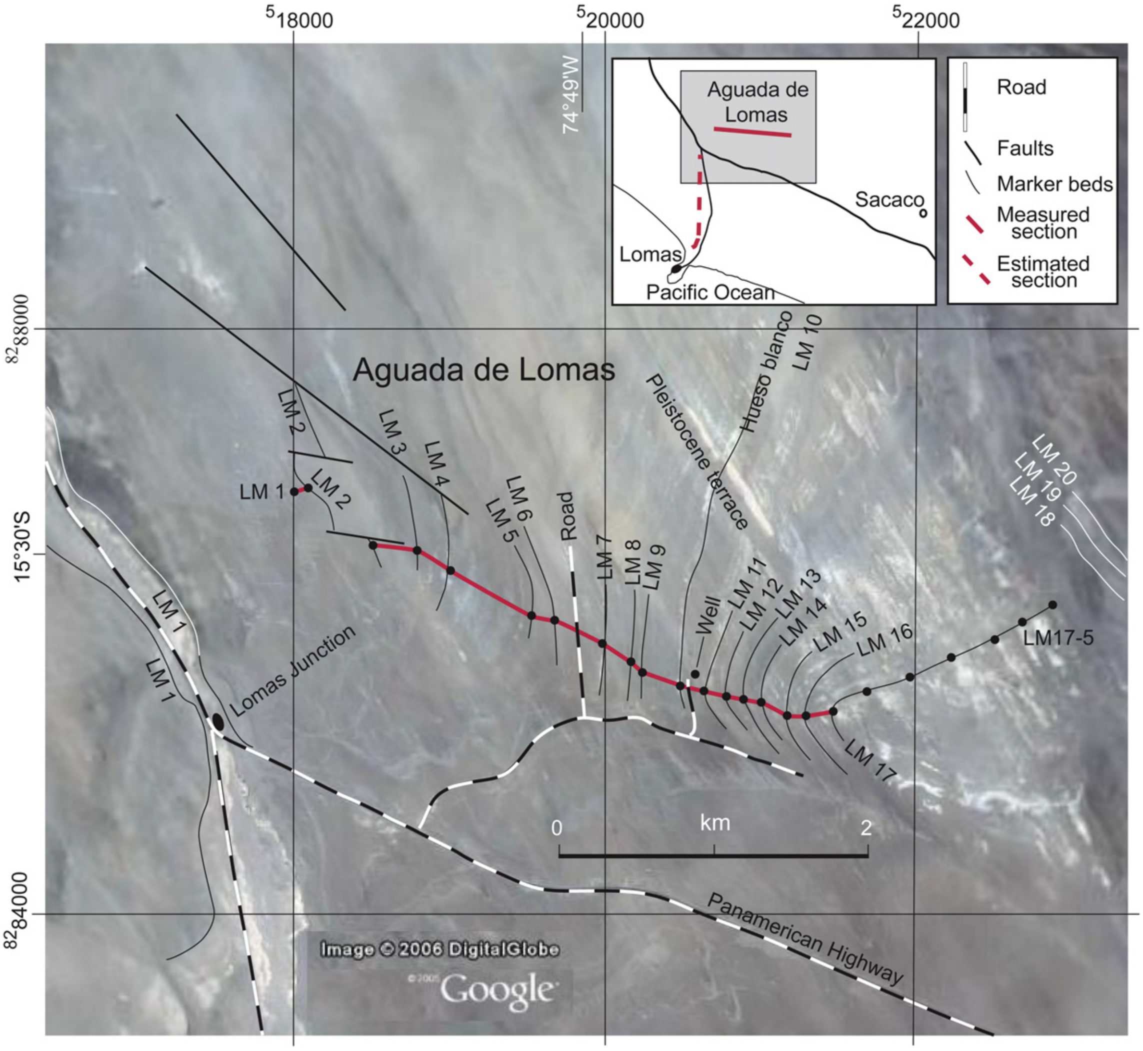

Fig. 3. Map of the measured section and other study areas in the vicinity of Lomas, drawn on a satellite photograph (from Google Earth). Hueso blanco is an area with numerous white bones. The position of LM 1, as labeled in Aguada de Lomas, does not have a line indicating a contact, because the entire surface of the marker bed LM 1 is exposed at ground level.

of that dune field more exposure of the Pisco Formation continues towards the coast. In that area west of the dune field the valley of Corre Viento is bounded on the north and south respectively by Cerro Queso Grande, and Cerro Los Quesos. There are few distinctive beds to facilitate correlation from the Ica Valley to Corre Viento and vicinity. There is, however, a prominent, continuous bed of numerous large articulated *Dosinia* bivalves encircling the eastern rim of Corre Viento and continuing to the north of Cerro Queso Grande. This bed seems to correlate with one of the beds of articulated *Dosinia* in the Ica Valley, in the stratigraphic interval from M 2 to M 4, but it is not clear which of these bivalve beds is equivalent to the similar bed in Corre Viento. If this general correlation is correct, the top of Los Quesos should be approximately correlative with bed M 10. The dips of strata in Los Quesos and across the dunes in Cerro Hueco la Zorra are consistent with this tentative interpretation. Current research using tuffs promises to clarify the correlation across the dune field (Kevin Nick personal communication).

4.2. Stratigraphy in the region near Lomas

Fig. 3 is a map showing the location of the estimated and measured parts of the section in the Lomas area, and Fig. 9 includes a summary of the stratigraphy in this section. In the area from Lomas to Lomas Junction there is a gentle dip, 2–3° to the northeast, then farther south it shifts to the southeast, with the Lomas to Lomas Junction highway being approximately along strike. The dip of 2–3° to the southeast continues for at least 16 km to the southeast of Lomas, between the Pan-American Highway and the coast. Southeast of Río Acarí there is no measurable dip of the Pisco sediments.

Just north of the highway the valley of Aguada de Lomas exposes a 287 m thick series of beds dipping to the east, with the dip gradually increasing from 5° at marker bed LM 1 to 9° at LM 13 (Fig. 3). The east end of the valley, beginning with LM 11, is a gentle syncline, causing exposure of the beds to curve around to the east. Several of these marker beds are pictured in Fig. 5j–o. Additional marker beds have been mapped, up to LM 20, in the hillside at the eastern end of the valley (Fig. 5j).

There are two boulder beds in the section at Aguada de Lomas, beds LM 1 (Fig. 4n) and LM 6. They consist of scattered igneous boulders widely varying in size, up to 1 or 2 m or more in diameter, a few meters apart, in a matrix of fine sand to granules (4–5 mm). Many of the boulders are partly disintegrated. A prominent boulder bed with boulders to 2 m in diameter is exposed in the roadcut at the junction of the Pan-American Highway and the Lomas highway. It can be traced southwest from the junction, and also north along both

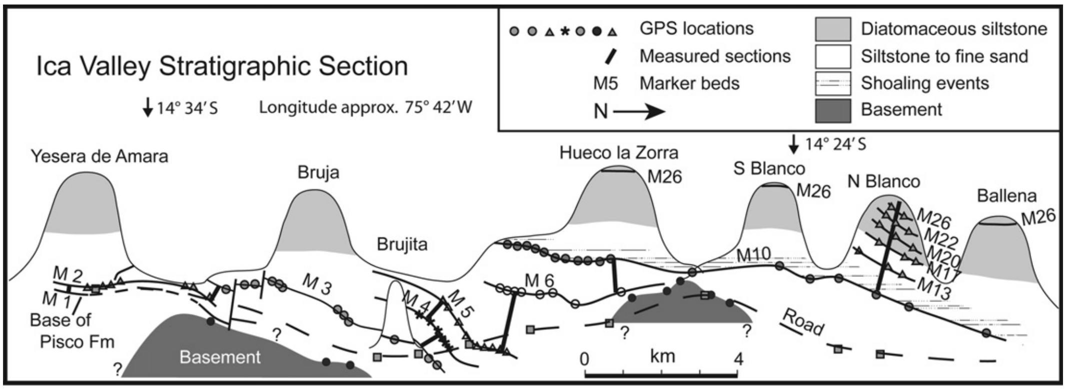

Fig. 4. A diagram showing the vertical relationships and dominant facies in the Ica Valley section, west of the Ica River, based on GPS measurements of location and altitude. Heights of hills (Cerros) are in proportion to the measured altitudes of other features. Marker beds M 24 and M 26 occurred from Cerro Hueco la Zorra to Cerro Ballena, but were only mapped on North Cerro Blanco. Vertical exaggeration is 20 x. Zone of shoaling events is shown above M 10, but this type of zone at M 1 is too narrow to show on the figure. The section in this figure is approximately parallel to the paleo-shoreline, at the base of the Andes Mountains.

sides of the Pan-American Highway. This bed seems to be the same as our marker bed LM 1 at Aguada de Lomas. Bed LM 14 is also a conglomerate of 5–20 cm cobbles (Fig. 5l). The fine matrix of the exposed surface has eroded away, leaving a bed of abundant cobbles.

Stratigraphic relationships outside of the Aguada de Lomas valley are much more uncertain, because of the abundant cover of sand and gravel, and a shortage of adequate tuff beds for correlation. Stratigraphic position of fossil collection sites farther south and west of Lomas have been estimated, using determination of sediment dip wherever it could be measured, with distance and elevation changes. The stratigraphic positions of Sud Sacaco, Sud Sacaco East, and Montemar in relation to Lomas and Aguada de Lomas were estimated in this way. The stratigraphic position of the Jahuay locality was determined in the same manner, in relationship to the boulder bed LM 1, along the Pan-American Highway. It was not feasible to use this method to place Sacaco in our stratigraphy.

These estimates, outside of Aguada de Lomas, clearly have their limits, but are the best on site stratigraphical measurements

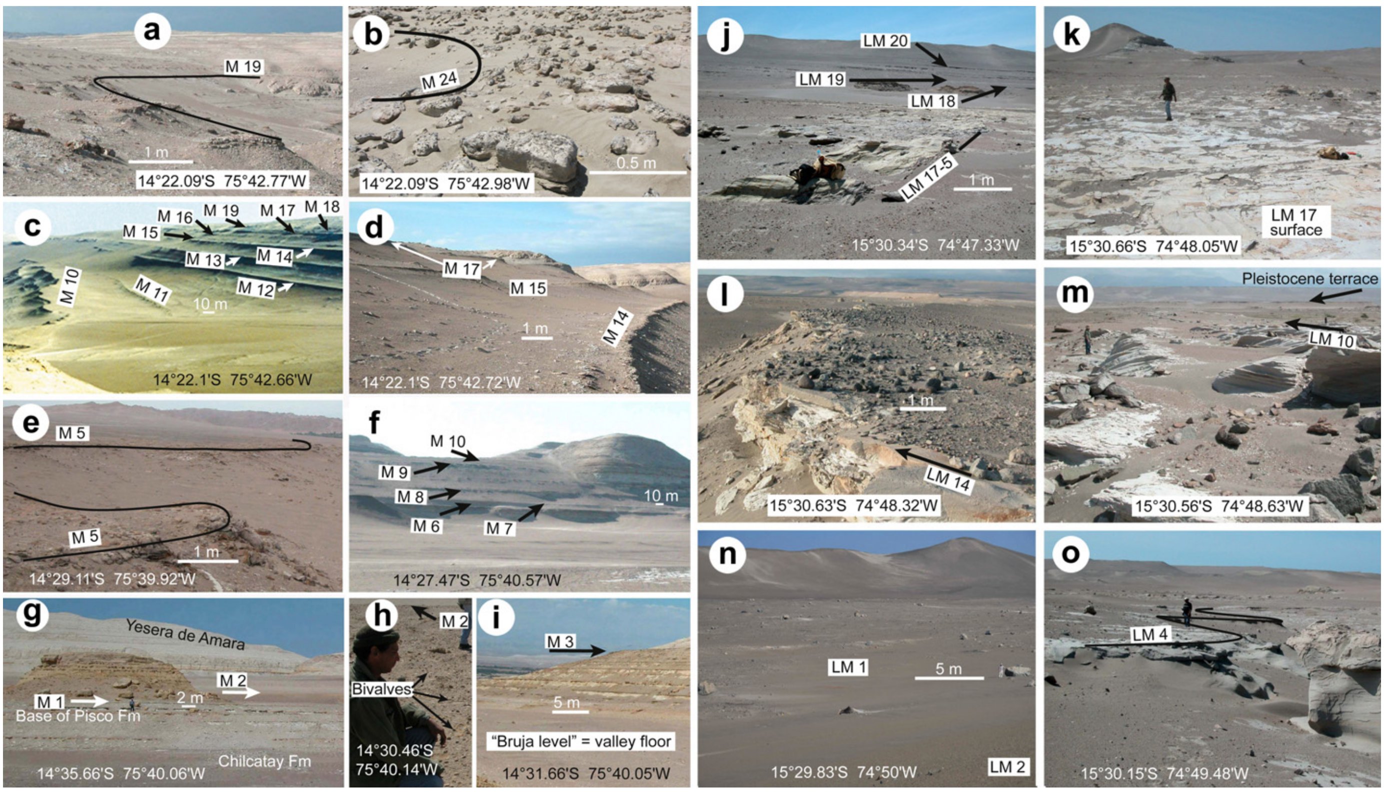

Fig. 5. Photographs of marker beds, to facilitate locating them in the field; a-i in Ica Valley; j-o in Aguada de Lomas and vicinity. (a–d) marker beds on the east face of N Cerro Blanco; (e) M 5 along the road, south of Cerro Hueco la Zorra; (f) M 6 to M 10 along the east face of Cerro Hueco la Zorra; (g) M 2 just east of Cerro Yesera de Amara, and 7 m below it (left arrow) the contact between the Pisco Fm and Chilcatay Fm, at M 1, a boulder bed containing mollusks, manganese nodules and bored clasts; (h) an example of the numerous articulated bivalves often left as a lag deposit from the erosion of M 2; (i) Typical appearance of M 3 along Cerro Bruja, on the northwest corner of the Cerro. The valley floor at this location is sometimes referred to in the Pisco Fm literature as the "Bruja level." (j) LM 17 where it meets the hills on the northeastern end of Aguada de Lomas, showing LM 18-20 on the hillside in the background; (k) LM 17 at its southernmost exposure in Aguada de Lomas, looking east; (l–o) other marker beds in Aguada de Lomas, looking north (l, m, and o) or west (n).

Chilcatay Formation	Pisco Formation
Almost no whales (one undescribed specimen)	Mysticeti - baleen whales (abundant) Cetotheridae - most common in lower Pisco Fm. Balaenopteridae - Bruja level and up
Dolphins: Squalodelphinidae Kentriodontidae Eurhinodelphinidae	Odontoceti - toothed whales Ziphiidae Physeteridae Kogiidae Pontoporiidae Kentriodontidae Delphinidae Monodontidae Phocoenidae
No seals	Seals - abundant
Marine turtles: soft-shelled	Marine turtles: mostly hard-shelled, some soft-shelled
Sharks and rays Myliobatidae Sphyrnidae Otodontidae; *Carcharocles chubutensis*	Sharks and rays Myliobatidae Sphyrnidae Otodontidae; *Carcharocles megalodon*
Lamnidae; *Isurus desori, Isurus oxyrinchus, Lamna sp.*	Lamnidae; *Isurus hastalis, Isurus escheri, Isurus xiphodon, Charcharodon carcharias*
Lamnidae; *Carcharias sp.*	Lamnidae; *Carcharias sp.*
Pristidae	Hexanchidae
Alopiidae	Order Chimerida
Hemigaleidae	Squatinidae
	Heterodontidae
	Triakidae

Fig. 6. Comparison of vertebrate fossil taxa in the Chilcatay and Pisco Formations, showing the distinct faunal change across this formation boundary.

possible for some areas. They are best considered as a stratigraphic hypothesis, to be tested. They can be compared with tuffs and radiometric dates, as available, to seek a satisfactory stratigraphy. If there are faults concealed by the sand cover they will complicate the stratigraphy.

An original covering of Pleistocene sediment in Aguada de Lomas has been mostly removed by erosion, leaving an east-west trending Pleistocene terrace in the northern part of Aguada de Lomas, and scattered additional remnants of Pleistocene in the eastern end of the valley.

5. Discussion

The stratigraphy described in this paper is a lithostratigraphic framework, incorporating a variety of lithologies as marker beds. The available exposures in the Ica Valley begin in the south, near Cerro Yesera de Amara, where the contact with the Chilcatay Formation is present. There is a general dip through the Ica Valley toward the northeast. Consequently in the series of hills composing the Ica Valley section, the exposures are increasingly higher in the section toward the north. On the west side of the modern dune field, Cerro Los Quesos and Cerro Queso Grande are lower in the section than their counterparts on the east side of the dune field, Cerro Hueco la Zorra, Cerro Blanco and Cerro Ballena.

There are no displacement faults in either the Ica Valley or Aguada de Lomas that are large enough to obscure the stratigraphy, but there are a number of small faults. Several of these faults are along the southeast flank of Cerro la Bruja, where basement rock is close to the surface (Figs. 2 and 4), and is exposed just to the east of the Chilcatay-Pisco contact. To the north of this exposure, in the valley between Cerro el Brujito and Cerro Hueco la Zorra the Pisco Fm. plunges toward the northeast. Marker bed M 4 is difficult to follow in part of this area, west of the road, because it approximately follows the surface and is partly eroded.

In the Ica Valley, the sediments associated with marker beds M 1 and M 2 and the interval including M 10 and the sediments above it are distinctive. They seem to be shoaling events, with accumulations

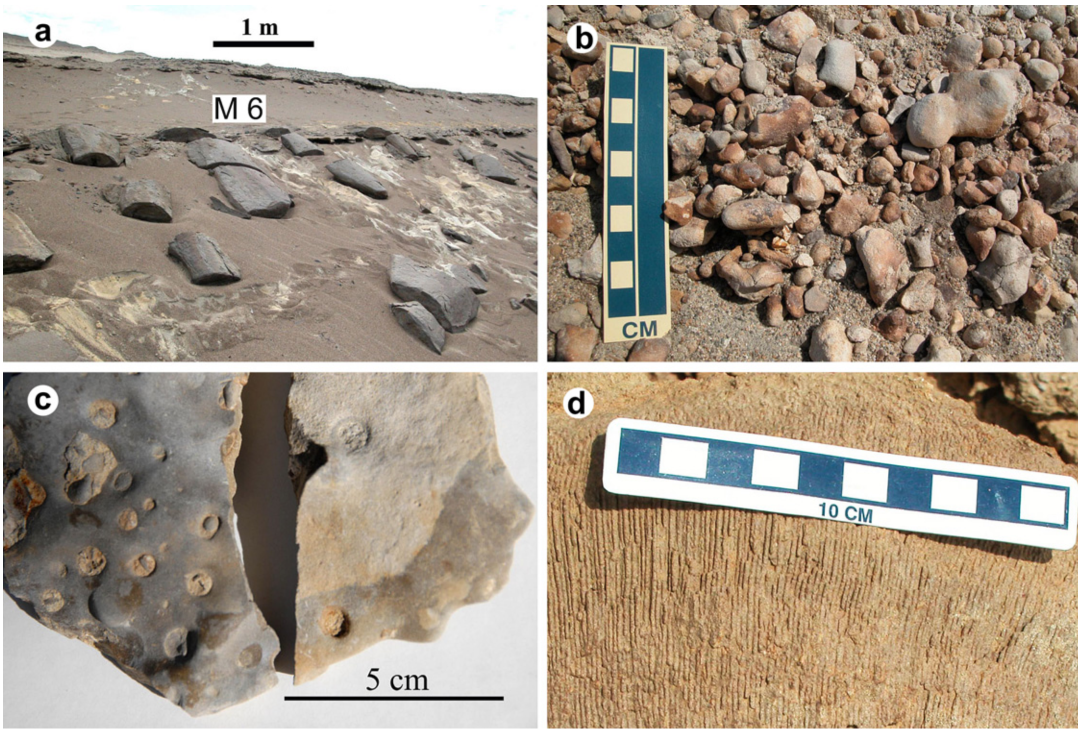

Fig. 7. Photographs of several sedimentary structures and other features. (a) megaripples in M 6, south of Cerro Hueco la Zorra; (b) phosphate nodules above M 10; (c) a cobble from the flat pebble conglomerate, with burrows, in M 10 at South Cerro Ballena; (d) colony of burrows of the polychaete *Gunnarea* growing on a clast in the M 2 marker bed.

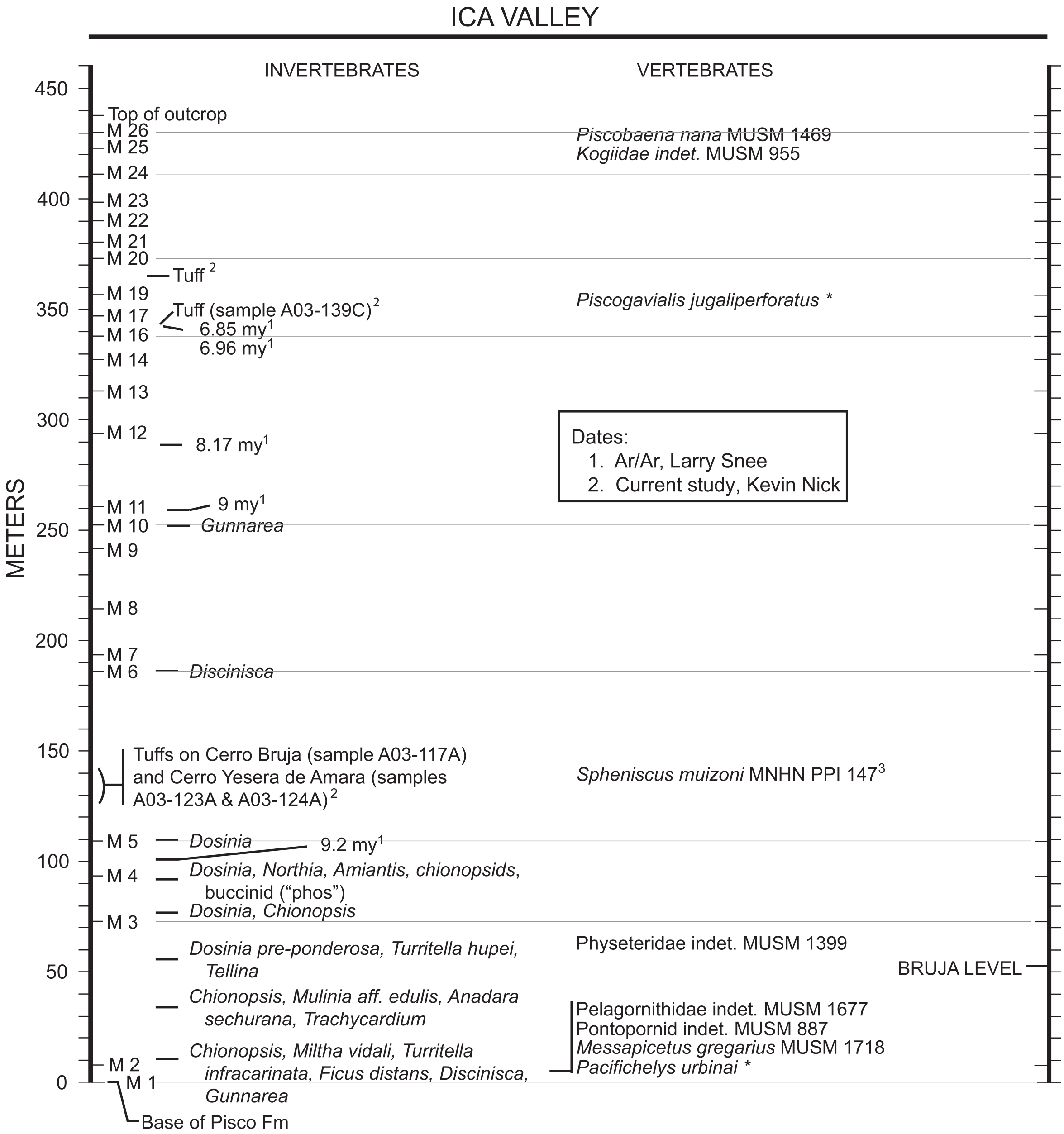

Fig. 8. Measured section through the Ica Valley, showing the available radiometric dates, and stratigraphic position of invertebrate and vertebrate fossils. Bruja Level is a common term for the unit at the base of Cerro la Bruja where many vertebrates have been collected. A list of these taxa was not provided here. Stratigraphic positions of other, described or undescribed specimens currently under study are included. The stratigraphic levels for the Ar/Ar dates listed here, in relation to our marker beds, is not adequately known. Their position in our stratigraphy is our best estimate based on the known locality information.* Indicates identifications of unpublished specimens. [3]Göhlich 2007. MNHN, Muséum national d'Histoire naturelle, Paris, France. MUSM, Museo de Historia Natural de la Universidad Nacional Mayor de San Marcos, Lima, Peru.

of transported bored flat pebbles, and some clasts with encrusting barnacles, oysters, and colonies of dwelling tubes produced by the polychaete *Gunnarea* (Fig. 7d). These same units have abundant phosphate nodules (Fig. 7b). M 10 is the lowest and most prominent of a series of these deposits consisting of transported sediments from a sublittoral source. The sediments include abundant flat pebble conglomerates, with pebbles ranging from 1 or 2 cm to >15 cm in diameter, and less than 1 cm thick. They commonly have many vertical 0.5 cm diameter burrows through them. The clasts and the burrow edges are well rounded (Fig. 7c). This interval above M 10 is at least 20–30 m thick, and may be more, and seems to represent several shoaling events (Fig. 4). M 11 also contains a fragmented whale skull near the south end of South Cerro Ballena, and there are numerous articulated and disarticulated whales at other localities between M 10 and M 11. Abundant phosphate nodules occur as high as M 16.

The upper portion of the Ica Valley section is a diatomaceous siltstone, with high diatom content (Fig. 4). This includes Cerros Blanco and Ballena above M 17. This is also the dominant facies in the upper parts of Cerros Hueco la Zorra, Bruja and Yesera de Amara. Below this the bulk of the sediment is siltstone or fine sandstone. The Pisco sediments often contain sedimentary structures indicating storms or tidal currents (Carvajal, 2002). Well preserved marine vertebrates are present throughout the section.

Figs. 2, 4, and 5, Table 1, and Appendix provide the information that allows determination, in the field, of one's position in the Ica Valley stratigraphic section. Fig. 3, Table 1 and Appendix have the same information for the section at Lomas. The marker beds can be

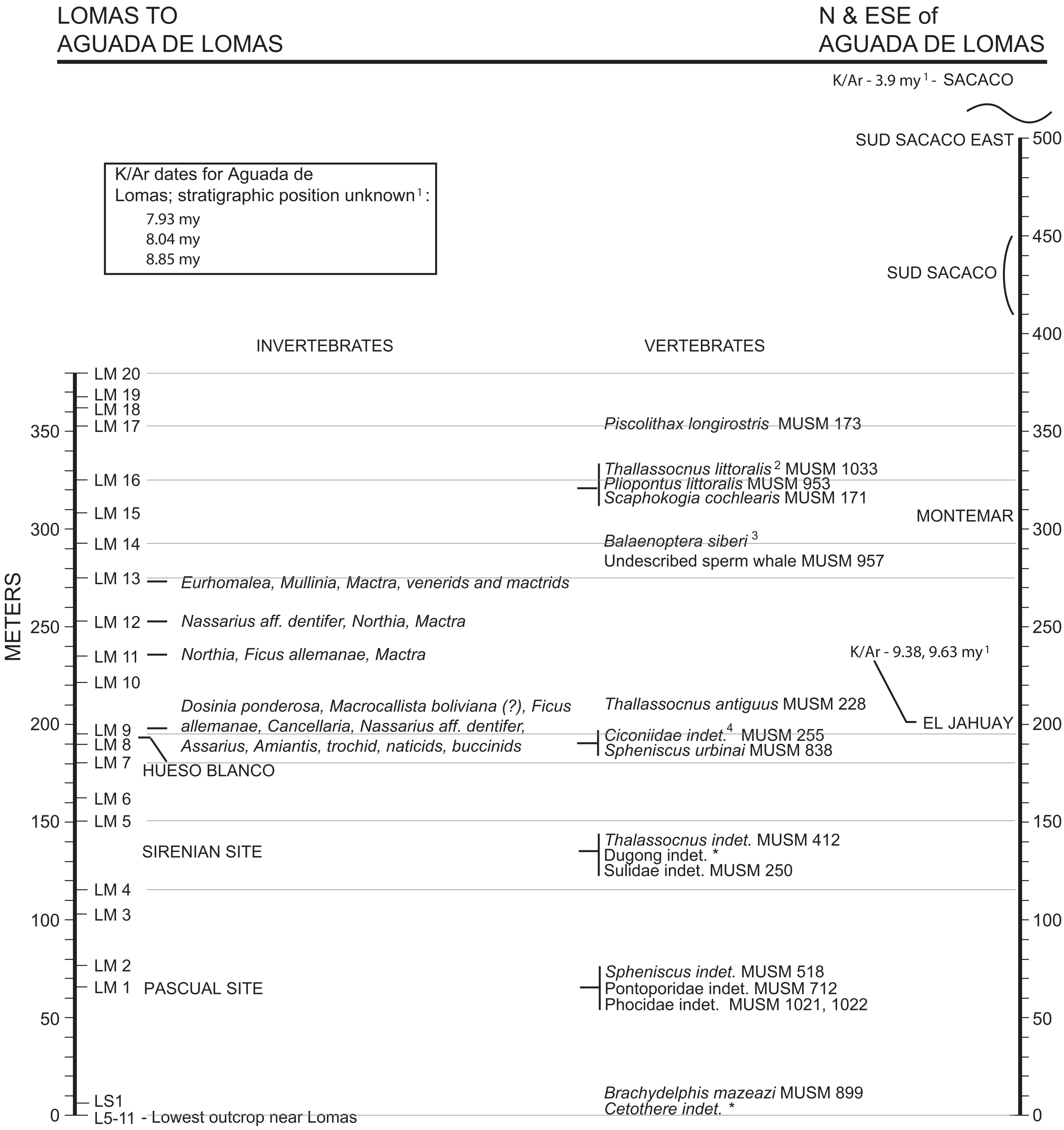

Fig. 9. Stratigraphic sections in the Lomas and Sacaco region. Left – measured section through the Aguada de Lomas valley, and estimated stratigraphic relationship to the lowest Pisco Formation sediments near Lomas. Right – stratigraphic relationship of the Lomas area with the El Jahuay site, and with areas south and east of Aguada de Lomas. The stratigraphic relationships along the right side were partly measured and partly estimated, as described in the text, because of abundant sand cover. Included are radiometric dates (de Muizon and Bellon, 1986), and stratigraphic position of invertebrate and vertebrate fossils. El Jahuay, Montemar, Sacaco, and Sud Sacaco are well known names for localities where many specimens have been collected. A list of taxa from these sites is not included here. Stratigraphic positions of other, described or undescribed specimens currently under study are included (all from Aguada de Lomas). Hueso blanco, the Sirenian site, and the Pascual site are local names for other collecting sites, familiar to Pisco Formation investigators. [1] de Muizon and Bellon, 1986; [2] McDonald and de Muizon 2002; [3] Pilleri and Pilleri 1989, [4] Urbina and Stucchi 2005. MUSM, Museo de Historia Natural de la Universidad Nacional Mayor de San Marcos, Lima, Peru.

located with the GPS positions (Table 1), photographs of key marker beds (Fig. 5), and lithological descriptions in Appendix. Marker beds can then be followed to determine their relationship to other locations along their exposure. Positions between marker beds can be located by measuring up from the nearest marker bed.

Further research would be beneficial to determine and map additional marker beds in the upper parts of other hills along the Ica Valley section. This task is complex because of the facies changes from one hill to another. More precise mapping of the exposures west of the modern dune field and more precise correlation with the Ica Valley section are also needed. All of this is being facilitated by ongoing study of tuffs in the region, using correlation by comparison of radiometric dates and composition of the tuffs in different locations (Kevin Nick personal communication).

More precise physical stratigraphic study in the area of Lomas, outside of the Aguada de Lomas valley, will be difficult to impossible unless more tuffs can be found and correlated. It has been concluded that the most recent vertebrate fossil localities in the Pisco Formation are at Sacaco (de Muizon and Bellon, 1986).

Radiometric data support this, but without additional physical data from tuffs, improvements in stratigraphic correlation of Sacaco, Sud Sacaco and Montemar with other Pisco Formation localities will depend primarily on biostratigraphy.

The available radiometric dates are not adequate for correlation between Lomas and the Ica Valley, because the location of the dated intervals in Aguada de Lomas are not known. This is a general problem with the existing radiometric dates, since the locations where the samples were taken, in relation to our marker beds, is not adequately known. It will be important for future studies to remedy this.

The Ica Valley section was carefully searched for evidence of any large displacement faults that could obscure the true stratigraphic relationships. No large displacement faults were found, and in most places lithologic units could be followed along the topography between the more prominent hills, confirming the continuity of the sediments from one large hill to the next. The most uncertainty was between Cerro Yesera de Amara and Cerro Bruja. However, marker bed M 2 with its unique physical characteristics and continuous content of abundant articulated bivalves could be followed all through this area. The numerous articulated bivalves in this and other marker beds are a prominent feature. An extensive bed with numerous bivalves, all articulated, was deposited rapidly before or very soon after death of the bivalves. It does not seem that such a bed could be time transgressive. Also, shoaling events are likely to be continuous for long distances and thus should be good sequence markers (Catuneanu et al., 2009).

This stratigraphic framework is a step toward a more comprehensive stratigraphy of the Pisco Formation that has been needed for some time. If collecting sites for new fossil specimens are precisely located with GPS data, their stratigraphic position and age can be verified as additional stratigraphic work is done.

Acknowledgments

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Appendix. Description of Pisco Formation marker beds.

Ica Valley

M 1: Boulder bed and pebble conglomerate with phosphate-rich pebbles in sandy siltstone. Contains medium and large boulders, up to several meters in diameter. Also contains bivalve shells. Forms a modest bench east of Cerro Yesera de Amara.

M 2: A tan to orange bench and low cliff east of Cerro Yesera de Amara. Contains disarticulated and articulated vertebrate bones, and bivalves, and in some places boulders to 0.5 m or more in diameter. In other areas is not a bench, but contains innumerable *Dosinia* bivalves. About 10 m above M 2, in the vicinity of Cerro Yesera de Amara, is another boulder bed, with boulders up to a meter in diameter.

Note: in appearance, M 3, M 4, and M 5 show a repeating pattern; each is the highest bed in a set of dark colored, more resistant sedimentary units, contrasting with a white chippy siltstone unit that forms a soft whitish slope above it.

M 3: Highest of a set of tan to brown tuffaceous siltstone units with a white chippy siltstone that forms a soft slope above it. Widespread unit.

M 4: The marker bed, the highest unit in the set, is an orange to purple and black sandstone, often with black manganese staining. In places is a coquina with large bivalves and gastropods.

M 5: Marker bed unit is a brown to tan very fine-grained sandstone. Weathers to a shelf with some cliffy portions. Bed breaks up to a blocky surface. This bed has an opening bulldozed through it where the local "road" crosses it.

M 6: Dark, coarse grained sandstone, forming a prominent bench along the east side of Cerro Hueco la Zorra. In places exhibits megaripples with a period of 1–1.5 m, and crests oriented at 130°. Commonly contains inarticulate brachiopods in the sand or as a coquina at the bottom of the sandstone.

M 7: A persistent whitish bench, low in a thick exposure of tuffaceous white siltstone, forming chippy white flakes at the surface. M 7 is the lowest of three such benches along the south-eastern flank of Cerro Hueco la Zorra, but is the only bench to continue along the cliff-forming, main part of Cerro Hueco la Zorra.

M 8: Tan to orange well-indurated siltstone 10–15 cm thick. The lowest of three similar units along the eastern flank of Cerro Hueco la Zorra. Along the slope it outcrops as a series of mounds, but forms a continues bench along the cliff to the north.

M 9: A cliffy siltstone, very well cemented with dolomite. Forms a persistent bench along the slope and along the cliff. Forms a talus apron of gray carbonate clasts averaging 10 cm thick and 30 cm in diameter. In the cliff there is a conspicuous orange band about 3 m below M 9.

M 10: Makes the most prominent bench along the east side of Cerro Ballena, south along north and south Cerro Blanco. Can be followed all the way around those Cerros and also Cerro Hueco la Zorra. Fine sandstone with siltstone stringers and some diatomite flecks. Weathers into indurated chippy polygons. Lower part often has conglomerate with 2–5 cm pebbles and some larger flat pebble conglomerate. In some areas on the west side of Cerro Hueco la Zorra M 10 displays a facies change in a short distance, to an indurated dolomitic siltstone that breaks up into numerous 0.2–0.5 m diameter cobbles that cover the surface.

M 11: Small but widespread bench with characteristic features. Poorly cemented grain supported conglomerate with little matrix at the top. Clasts are siltstone, from subcentimeter diameter to 6–10 cm flat pebble conglomerate, often bored. Partly black from abundant manganese, and often contains phosphate nodules. Occurs in a series of beds separated by siltstones.

M 12 to 26: are described from north Cerro Blanco, and some of them can be traced to other adjacent cerros.

M 12: Small, fairly continuous bench along the east slope of north Cerro Blanco. Tan, very fine grained sandstone with volcanic ash. Locally underlain by a layer of purple-brown chert. Between M 12 and M 13 are abundant bored flat pebbles and small rounded clasts, coming from layers not well exposed.

M 13: Outcrop of a series of three beds that weather to tan to light gray papery gypsiferous shale. Fresh samples are fine grained quartz sandstone or tuffaceous sandstone.

M 14: Widespread 15 cm ledge, of indurated tan to gray sandy dolomitic sandstone.

M 15: Similar to M 14, but with intermittent exposure along the slope.

M 16: A white layer of volcanic ash with occasional biotite. Part of this unit weathers to papery white gypsic shale. Often the white ash is covered with sand, but is very conspicuous when the cover is cleared away. Beginning 1.5–2 m above M 16 are 3 or 4 white tuff beds, some continuous and some discontinuous. The middle one of these beds has been dated.

M 17: A closely spaced set of beds, capped by a dolomitized siltstone. Under that siltstone is a layer of black coarse sandstone, and then white, and orange-yellow layers. Along the east face of north Cerro Blanco M 17 is a meter below the break in the slope, with a more gentle slope above it. Between M 17 and M 18 is a prominent black, coarse sandstone unit that is widespread.

M 18: The uppermost of three black, gypsiferous units of fine grained tuffaceous siltstone, within a total of about 1 m. Each unit is a few centimeters thick and weathers to black, curled flakes.

M 19: The lowest of a series of beds that form numerous, roughly equally spaced, hummocky mounds of diatomitic mudstone. Below M 19 the hillside is fairly smooth; above M 19 it is very hummocky. This pattern can be followed for long distances. Midway between M 19 and M 20 is a black, sandy, 10 cm tuff that can be traced for long distances. It is generally not visible on the surface, because of sand cover, but usually forms a small but characteristic break in the slope, often with papery flakes on the surface. After experiencing its appearance it can be readily recognized. Beds M 16 to 18 form a helpful, often recognizable pattern; the white tuffs of M 16 and those above it, then the black, white and orange units of M 17 followed by a thick, black course sandstone. Above that are the three black ash layers of M 18.

M 20: Tan and orange weathering laminar bedded tuffaceous siltstone, with siltstone ripups of up to 10 cm diameter. Exposed as an irregular cliffy bed, with mounds at its outer edge. This unit is not lithologically unique, but can be consistently traced as a continuous bench.

M 21: Gold to orange gypsiferous siltstone. Also not very lithologically unique, but forms a persistent bench with an orange surface. The hillside below M 21 has numerous hummocky mounds, but above M 21 is an interval without mounds.

M 22: Similar sediment and bench to M 21. Find M 20 – M 22 by GPS position, and then they can be followed.

M 23: Black gypsiferous volcanic tuff, weathers into characteristic curled papery material.

M 24: A very prominent bed of light gray to tan dolomitic siltstone, that breaks up into indurated cobbles and boulders 10–15 cm thick and 30–50 cm in diameter that litter the surface.

M 25: A thin bed of gray-white diatomite that weathers into a line of broken, slightly curled durable pieces on the surface.

M 26: A unit that forms the crest of the hill. Sediment is pure white glassy siltstone that weathers to a unique soft, gray, rounded, puffy-looking surface.

Lomas and Aguada de Lomas

The horizontal floor of Aguada de Lomas is a series of beds dipping gently to the east. Marker beds are the units on top of ridges and forming the dipping surfaces, or prominent, laterally extensive outcrops between the ridges. Just under the surface is a high water table, which influences the nature of some outcrops.

LM 1: Valley floor at west end of valley; a coarse conglomerate with many metamorphic and igneous boulders, up to 1–2 m or more in diameter.

LM 2: Bench above LM 1; covered with gravel; dips to southwest; no distinctive character.

LM 3: Next bench above LM 2; same description as LM 2.

LM 4: Gray sandstone bed in valley between ridges. Just beyond it there is an extensive area of gypsum-coated Pisco between LM 4 and LM 5.

LM 5: Gray sandstone outcrop, forming a resistant surface part way up a gentle slope. Contains contorted bedding and dewatering structures on an outcrop scale.

LM 6: Gravel-covered sandstone ridge, dipping east. Numerous igneous and metamorphic cobbles and boulders on surface, up to a meter in diameter. There is a road between LM 6 and LM 7, and on the slope east of the road, numerous vertebrate bone fragments, in a bed (under the sand) of mollusk shell fragments and pebbles.

LM 7: An approximately 10 m wide undulating, nearly flat white limestone, in the midst of a sand and gravel-covered area. The limestone breaks up into indurated clasts 20–60 cm in diameter that litter the surface.

LM 8: Indistinct ridge of indurated fine grained sandstone, less than a meter high, at the edge of a sand and plant covered area. The sand is wet with groundwater and forms a duricrust.

LM 9: Mollusk bed, not well preserved, in fine grained sandstone with carbonate cement. Surface gray to black or brownish purple.

LM 10: Prominent white to buff cliffy outcrop of fine grained sandstone with volcanic ash and diatom flecks. Just east of the outcrop is a road to a well.

LM 11: A tan to green, fine grained immature quartz sandstone cliff, with abundant hematite cemented concretions and burrows. A bed of gastropods and pelecypods is on top of the sandstone unit, and on the surface many white vertebrate bone fragments. On this ridge is an old road.

LM 12: Thin, discontinuous but significant bed of disarticulated bivalves, in a flat area. Sediment is fine grained mostly quartz sandstone.

LM 13: Top unit in a cliff with several beds of disarticulated bivalves, including a bivalve coquina capping the ridge, which dips to the east.

LM 14: A prominent cliff of tan to buff weathering siltstone with volcanic ash. Covering the dipping surface are numerous pebble to boulder sized clasts, but mostly 10–30 cm diameter rounded mafic cobbles.

LM 15: A bench 1–3 m high, of fine grained sandy siltstone with dolomite cement. Surface below outcrop littered with blocks of the sediment a few cm thick by 30 cm diameter. Gray weathering fine-grained sandy siltstone.

LM 16: A bench 2 m high capped by tan to gray conglomerate with many flattened pebbles.

LM 17: Minor bench along the edge of an extensive valley floor cover of white, poorly consolidated diatomitic sandy siltstone, with tan and orange areas. LM 17 is the top unit exposed in the valley floor. LM 18-20 are exposed in the hillside at the east end of Aguada de Lomas.

LM 18: A 1 m high, dark gray appearing, vertical cliff of sandstone, conglomeratic sandstone, and laminated tuffaceous sandstone.

LM 19: Bed not prominent in outcrop, but weathers to a series of light-gray blocks of dolomite that form a prominent apron below the bed.

LM 20: A cliff-forming unit, laterally extensive, of tan siltstone capped by a hard sandstone. This is the last exposed unit in this area, with a sand and cobble covered slope above it.

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