Boletín de la Sociedad Geológica del Perú

journal homepage: www.sgp.org.pe ISSN 0079-1091

Eocene Stratigraphy and Depositional History near Puerto Caballas (East Pisco Basin, Peru)

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ABSTRACT

Eocene sedimentary strata exposed in a half-graben at Puerto Caballas, Peru, and nearby in the lower reaches of the Rio Grande, at the southern extremity of the East Pisco forearc basin, are assigned to the Caballas and Paracas depositional sequences and eponymous formations. The latter sequence, of Lutetian to Bartonian age, consists of continental and estuarine arkosic breccia and sandstone (Los Choros Member) overlain by silty sandstone (Yumaque Member) with pelagic marine microfossils, mollusks, and vertebrates. The older Caballas depositional sequence consists of basal pebbly sandstone (Lomas Member) overlain by red beds (Playa Roja Member), interpreted to be alluvial fan and flood plain deposits, respectively. These beds, in turn are overlain by estuarine (Cuenca Member) and flood plain (Parcana Mainsa Member) deposits. Mollusks of the Cuenca Member indicate a late Ypresian or early Lutetian age and a brackish-water mangrove ecosystem, which supported sea turtles, sharks, and archeocete whales. The onset of sedimentation for the successive sequences correlates with the older Incaic I and younger Incaic II tectonic phases. The ubiquity of texturally and mineralogically immature sediments and scarcity of organic matter and plant fossils reinforces past conclusions that the southern Peruvian and northern Chilean coastal margins have been arid throughout the Cenozoic.

RESUMEN

Los estratos sedimentarios eocénicos en el semigraben de Puerto Caballas, Perú y cerca, en el curso inferior de Río Grande, en el extremo sur de la Cuenca del antearco de Pisco Este, están asignadas a las secuencias de depósito y formaciones epónimas de Caballas y Paracas. La última secuencia, de edad Lutetiana a Bartoniense está compuesta por arenisca y brecha arcósica, continental y estuarial (Miembro Los Choros) cubierta por arenisca limosa (Miembro Yumaque) con microfósiles marinos pelágicos, moluscos y vertebrados. La secuencia deposicional más antigua (Caballas) está compuesta por arenisca guijarrosa basal (Miembro Lomas) cubierta por capas rojas (Miembro Playa Roja), atribuido a los ambientes de un abanico aluvial y llanura aluvial, respectivamente, que a su vez están cubiertas por depósitos estuarios (Miembro Cuenca) y depósitos de llanura aluvial (Miembro Parcana Mainsa). Los moluscos del Miembro Cuenca muestran una edad del Ypresiense tardío o Lutetianse temprano y un ecosistema salobre de manglares que sustentaba tortugas marinas, tiburones y arqueocetos. El comienzo de la sedimentación para las secuencias sucesivas se correlaciona con las fases tectónicas Incaica I y Incaica II. La ubiquidad de los sedimentos en textura y mineralogía inmaduras y la escasez de materia orgánica, así como fósiles de plantas refuerzan las conclusiones pasadas de que las planicies costeras del sur de Perú y del norte de Chile fueron áridas durante el Cenozoico.

Palabras claves: Eocene, stratigraphy, paleontology, Pisco, Peru

1. Introduction

The East Pisco Basin of southern Peru extends from Cañete to Nazca (Figure 1). Cenozoic sedimentary strata exposed in this forearc basin belong to four depositional sequences: the Paracas (Lutetian to Bartonian), Otuma (Priabonian), Chilcatay (Chattian to Burdigalian), and Pisco (Langhian to Piacenzian) (DeVries, 1998; DeVries et al., 2006). Each sequence corresponds to an eponymous lithostratigraphic formation, with some authors raising the Paracas Formation to group status with two included formations, the Los Choros (lower) and Yumaque (upper) (Dunbar et al., 1990). In this paper, both lithostratigraphic units are considered members of a Paracas Formation.

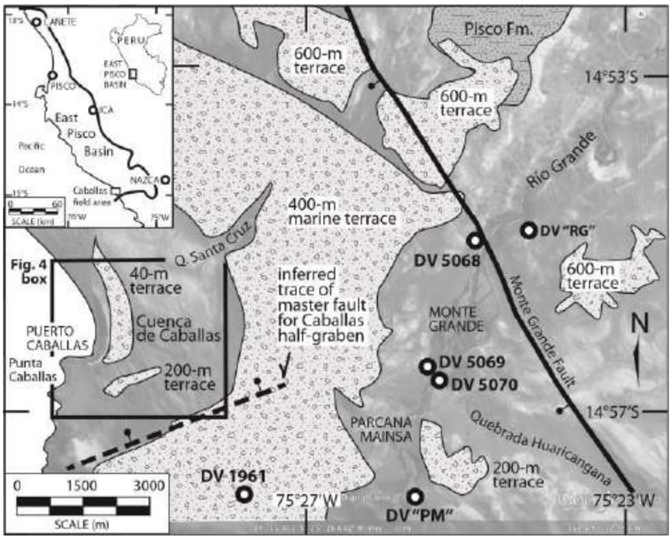


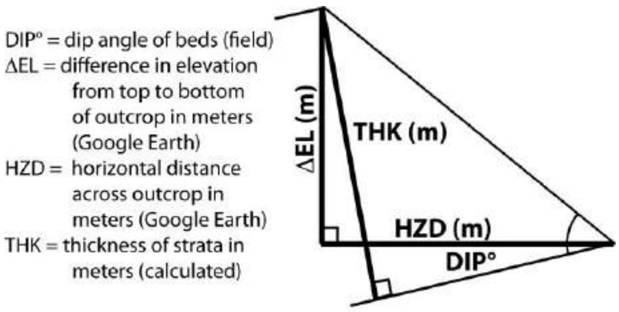
Figure 1. Field area of Puerto Caballas and Monte Grande with selected localities (e.g., DV 5070). Base map is from Google Earth. Area of geological map in Figure 4 is indicated. Marine terraces are labeled according to their notch elevation above sea level. The inferred trace of the master fault associated with the Caballas half-graben is shown, as is the 40-km long Monte Grande Fault, a southwest-dipping, high angle normal fault.

Sandy red mudstones underlie the Paracas depositional sequence in beach outcrops at Puerto Caballas, in a terrace-rimmed depression east of Puerto Caballas (herein termed the "Cuenca de Caballas"), and in the Río Grande valley near Monte Grande in an area known as Parcana Mainsa (Figure 1). Designated the Caballas Formation, first by J. Caldas (1980, unpublished map) and later by Dávila et al. (1987) and Dávila (1989), the red beds, unique for the East Pisco Basin, were guessed to have an Eocene or Paleocene age. Meanwhile, the name 'Caballas' was applied independently by Macharé (1987) to marine siltstones flanking Quebrada Santa Cruz, near Puerto Caballas, and cropping out in the northern East Pisco Basin. These siltstones were assigned an Oligocene to early Miocene age (Macharé et al., 1988), but the strata near Puerto Caballas later proved to be late Eocene, based on the presence of the radiolarian *Dictyoprora pirum* (Ehrenberg, 1873) (Marty, 1989) and the mollusks *Turritella lagunillasensis* Rivera, 1957, and *Andicula occidentalis* (Woods, 1922) (DeVries, 1988; unpublished data, locality DV 581). Hence, in late May, 1988, during an International Geological Correlation Program (IGCP) 156 field trip to the East Pisco Basin, José Macharé, David Dávila, Robert Dunbar, Paul Baker, and this author, among others, met at the Hotel El Carmelo in Ica and agreed to re-name the northern Oligocene-Miocene section the 'Chilcatay Formation' (type section: Lomas Chilcatay, near Carhuas; see DeVries (1988, 1998)) and to reserve the 'Caballas' designation for the pre-Paracas red beds near Puerto Caballas. Some years later, Montoya et al. (1994) still referred to an Oligocene-Miocene Caballas Formation (*sensu* Macharé, 1987), having subsumed the arkoses and red beds at Puerto Caballas into the Paracas Formation, but geologists of the Instituto Geológico, Minero, y Metalúrgicos (INGEMMET) have since recognized the Chilcatay/Caballas distinction (León et al., 2008).

The discovery by Marcelo Stucchi and Mario Urbina (Departamento de Paleontología de Vertebrados, Museo de Historia Natural, Universidad Nacional Mayor de San Marcos, Lima) of unusual fossil oysters and a fossil marine turtle in the Cuenca de Caballas prompted fieldwork to determine if the bivalves and bones came from beds of the Paracas depositional sequence or older strata. This paper clarifies the stratigraphic position and age of the fossil-bearing beds and their paleoenvironmental setting in the context of a depositional and tectonic history.

2. Materials and Methods

Fieldwork in the area of Puerto Caballas consisted of field mapping, measuring and describing sections, and identifying fossils. Google Earth imagery was used for mapping and to estimate thicknesses of inaccessible or otherwise unmeasured sections (Figure 2). Mollusks were used for biostratigraphic correlation with strata elsewhere in the East Pisco Basin and in the Talara basin of northern Peru (Woods, 1922; Olsson, 1928, 1930, 1931; Rivera, 1957; DeVries et al., 2006; DeVries, 2007) and, in conjunction with lithology, sedimentary textures, and sedimentary structures and trace fossils, to infer paleoenvironments.



$$THK = \sqrt{\Delta EL^2 + HZD^2}\ \sin\left(\tan^{-1}\left(\frac{\Delta EL}{HZD}\right) + DIP^\circ\right)$$

Figure 2. Geometry incorporating Google Earth data and field measurements to calculate thicknesses of sedimentary sections that were either inaccessible or not directly measured.

The Eocene sections are in places obscured by Pleistocene marine terraces. The terraces are referenced by the elevation of their notched inner edges, e.g., the 40-m and 400-m terraces. Using Google Earth imagery, notch elevations above sea level were determined at latitude 14°56'20"S. At other latitudes, regional dips put the notches at different elevations.

Field localities carry designations in the form of "DV 1958." Two localities seen in the field only from a distance are designated as "DV PM" and "DV RG" (Figure 1).

3. Results

3.1. Stratigraphy

Fault-bound outcrops at Puerto Caballas, fossiliferous strata in the Cuenca de Caballas, and continuous sections near Monte Grande provide evidence for a Caballas depositional sequence with the following succession of provisionally named lithologic units (Figure 3): (1) a basal unit of yellow-gray arkosic sandstone and conglomerate (Caballas Formation, Lomas Member) nonconformably overlying a basement peneplain and conformably underlying (2) stratified red-and-green sandy mudstone and caliche-bearing paleosols (Caballas Formation, Playa Roja Member), which up-section are interbedded with and ultimately replaced by (3) pale gray, yellow, or brown sandstone and mudstone (Caballas Formation, Cuenca Member), with some of the latter beds being bioturbated, bituminous, and/or oyster-bearing. At Parcana Mainsa and Puerto Caballas, the mudstones and sandstones are overlain by (4) gray-green bedded sandstone and mudstone with small stringers of coal (Caballas Formation, Parcana Mainsa Member). These four members define a shallow marine transgression across an alluvium-covered coastal plain, followed by the progradation of a coastal flood plain.

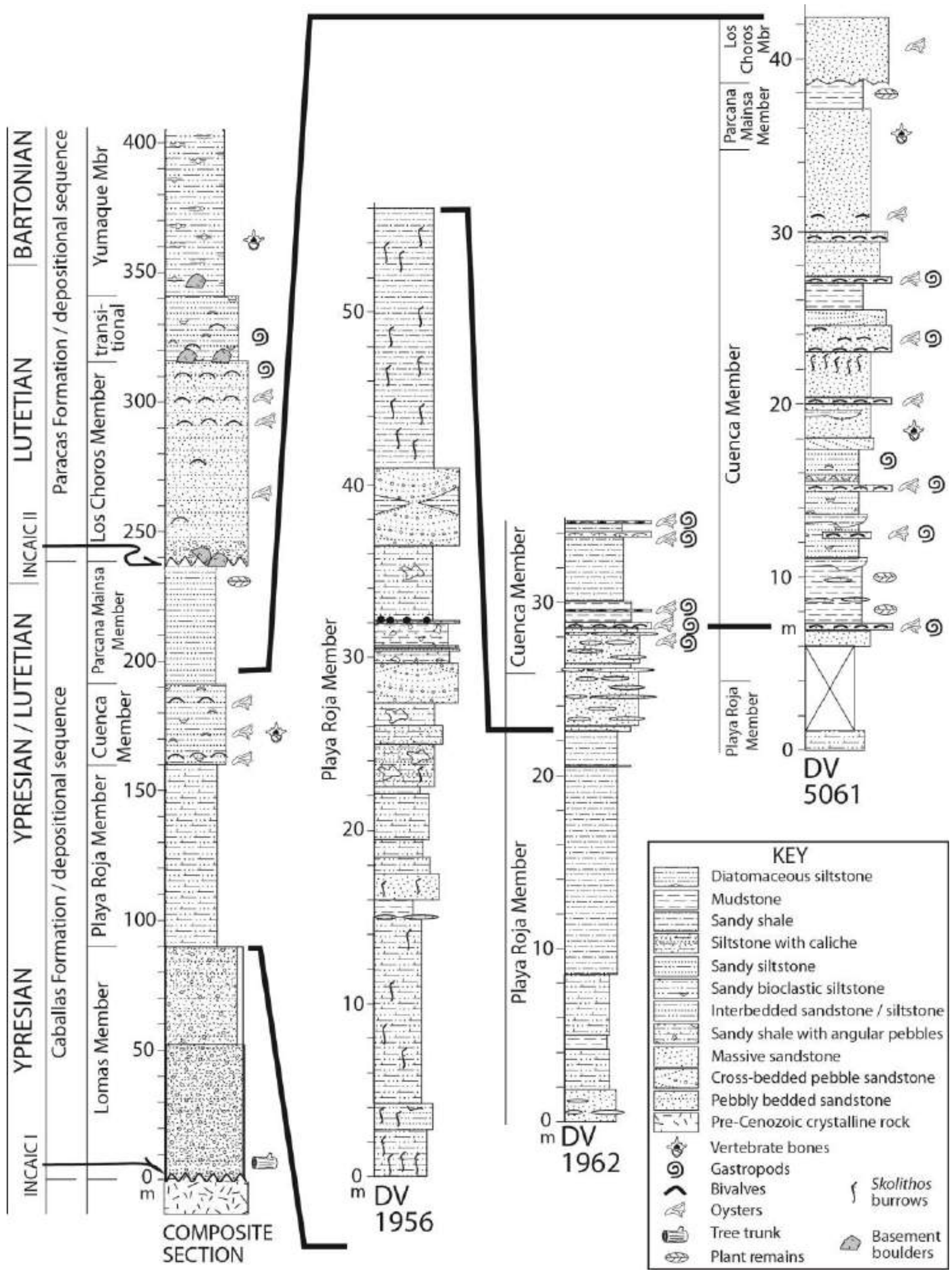


Figure 3. Measured sections of Eocene strata assigned to the Paracas and Caballas depositional sequences. Localities (see Appendix) associated with measured sections are cited at base of each section. The stratigraphic levels are indicated at which the Incaic I and Incaic II tectonic phases are inferred to have affected the section.

The Playa Roja Member is equivalent to the lower Caballas member at Parcana Mainsa and the combined Cuenca and Parcana Mainsa members are equivalent to the upper Caballas member of Vicente et al. (2000).

Strata of the Caballas depositional sequence are truncated by a deeply erosive surface near Monte Grande (Vicente et al., 2000) and a less pronounced disconformity in the Cuenca de Caballas and at Puerto Caballas. Above the erosional boundary are beds of arkosic sandstone, typically mauve-colored, variably conglomeratic, and variably bioclastic, overlain by mustard-colored, pebbly, oyster-bearing sandstone (Paracas Formation, Los Choros Member). The mustard-colored beds are overlain by alternating coarse- and fine-grained marine bioclastic sandstone beds, which grade upward into a thick section of soft-weathering diatom- and foram-bearing silty sandstone with horizons of dolomite-cemented sediment (Paracas Formation, Yumaque Member). The progression of lithologies defines a prolonged marine transgression culminating with outer continental shelf environments.

3.1.1. Caballas Formation, Lomas Member

The basal unit of the Caballas Formation, provisionally named the Lomas Member, is exposed on steep hills southeast of Puerto Caballas (Figures 4, 5.A), except where obscured or truncated by the 40-m, 80-m (not shown), 200-m, and 400-m Pleistocene terraces. Other outcrops are exposed in beach escarpments and intertidally near the southern entrance to the settlement of Puerto Caballas (DV 1963) and north of prominently visible red beds (DV 5078a).

The Lomas Member consists of a fining-up sequence of poorly sorted, medium-bedded, coarse- to medium-grained, yellow-gray arkosic sandstone and breccia (DV 1960) that nonconformably overlies metamorphic rocks of the Precambrian-Cambrian San Juan Formation (Montoya et al., 1994) and volcanoclastic beds mapped as either the Cretaceous Tunga andesite (Montoya et al., 1994) or the Jurassic Guaneros Formation (Leon et al., 2008). The thickness of the Lomas Member on the slopes southeast of Puerto Caballas is calculated to be 90 meters. Angular pebbles are typically less than five centimeters in diameter. Shallow channel-form scours are present, several meters in diameter, with thin drapes of coarse-grained sandstone and indistinctly bedded breccia conforming to the shape of the scour. No paleosols or fine-grained beds were seen, nor any fossils except a two-meter-long horizontal tree trunk (DV 1963). The mineralogically and texturally immature sediments are inferred to have been deposited on an alluvial fan in an arid or semi-arid setting.

3.1.2 Caballas Formation, Playa Roja Member

Sandy red mudstone assigned to the provisionally named Playa Roja Member of the Caballas Formation is exposed along the beach escarpment north of Puerto Caballas (DV 1956, 1957, 5074), high in the hills southeast of Puerto Caballas (DV 1960), in the southern part of the Cuenca de Caballas (DV 1954, 1962), and at Parcana Mainsa (DV "PM").

At Puerto Caballas (DV 1956), a measured section (Figure 3) of the Playa Roja Member, lacking a visible base, consists of 55 meters of interbedded sandy mudstone with two-meter wide channel-form lenses of single-set, cross-bedded, pebbly arkosic sandstone (Figure 5.B) and laminated mudstone and paleosols, the latter mottled with elongate root traces and speckled with small nodules of calcium carbonate (caliche) and large angular grains of feldspar and quartz (Figure 5.C). Heavily oxidized beds are brick-red or purple; those deposited or diagenetically altered under reducing conditions are gray-green. No fossils, plant or animal, were found.

In the Cuenca de Caballas, red beds are intercalated with beds of yellow-gray coarse-grained sandstone containing abundant oysters and cerithioid marine gastropods (DV 1962). The top of the Playa Roja Member is defined as the base of the first bed with densely packed oysters (Figure 3).

At Parcana Mainsa (DV "PM"), red beds with intercalations of coarsely textured yellow-orange-weathering sediments, calculated to be about 60 meters thick (measured by Leon et al. (2008) at 55 meters thick), are in fault contact with the underlying Jurassic Guaneros Formation (Figure 5.D). Lithologic descriptions by Leon et al. (2008) indicate larger clast sizes and higher energies of deposition than evidenced by outcrops at Puerto Caballas.

The red beds of the Playa Roja Member and their associated sedimentary structures at Puerto Caballas and in the Cuenca de Caballas are consistent with deposition in small river channels and on flood plains along a semi-arid coast (Einsele, 2000). Bioturbation cited by Leon et al. (2008) is not necessarily evidence of marine incursions; burrowing can happen in fluvial and flood plain settings (e.g., Buatois et al., 2007). Deposition at Parcana Mainsa was influenced by the topography of nearby basement-rock footwalls and synsedimentary extensional faulting (Vicente et al., 2000; Leon et al, 2008). Penecontemporaneous faults or slumps and small post-depositional listric faults are visible at Puerto Caballas.

3.1.3 Caballas Formation, Cuenca Member

Fossiliferous strata overlying the Playa Roja Member in the Cuenca de Caballas are assigned to the provisionally named Cuenca Member of the Caballas Formation. At locality DV 1962, 20 meters of brick-red, caliche-bearing, sandy mudstone and massive pale-green sandstone of the upper Playa Roja Member are conformably overlain with 30 meters of indurated sandy coquinas intercalated with, lower in the section, medium- and thick-bedded olive-green or brick-red mudstone and, higher in the section, olive-green or charcoal-gray, clayey, massive, pervasively bioturbated sandstone beds and 10-m wide mudstone lenses (DV 1954, 1962, 5061; see Figure 3) with one or more of the following: *Ophiomorpha* burrows, disseminated carbonaceous plant debris, bimodal sandy ripples, rip-up clasts of gray mudstone, and dispersed articulated and disarticulated oysters and cerithioid gastropods (Figure 5.E). Palynological analyses yielded no pollen (D. Jarzen, written communication, 2008). Coquinas consist of concentrated accumulations of paired and disarticulated oyster valves, some bearing imprints of twigs or valves of the anomiid bivalve, *Carolia*. Other mollusks include cerithioid and pyramidellid gastropods and a diverse assemblage of less common taxa (neritid and turritellid gastropods; corbiculid, venerid, and mactrid bivalves), small shark teeth, and a single archeocete vertebra. Just below the uppermost gray-green mudstone, a partial skeleton of a marine turtle was found in yellow-gray medium-grained sandstone.

Fossil mollusks of the Cuenca Member indicate a brackish-water setting, possibly with mangroves present (Olsson, 1928; Strougo, 1983; Squires, 1991, 1999; Kowalke, 2001). Sedimentary lithologies, bed geometries, and structures indicate the former existence of a patchwork of quiet-water, low-oxygen, ponded muds with adjacent channels and sandbars subject to modest winnowing action by tidal currents or waves, not unlike those described from Miocene beds in Argentina (Scasso et al., 2012) and Eocene beds in Egypt (Strougo and Azab, 1982).

3.1.4 Caballas Formation, Parcana Mainsa Member

The continuous section of the Caballas depositional sequence at Parcana Mainsa (DV "PM") includes brick-red and gray-green beds of the Playa Roja Member at the base of the outcrop (Figure 5.D; see also Leon et al., 2008, Figure 4.4B). Conformably overlying the red beds are yellow beds (calculated to be 40 meters thick; measured by Leon et al. (2008) at 45 meters thick) with a single dark gray horizon near the top. These beds may belong to the Cuenca Member, although being farther inland, a marine influence might be less evident than in the Cuenca de Caballas. Above the beds of the Cuenca Member and below the erosional base of the Paracas depositional sequence are about 35 meters of smoothly textured pale-green beds with blotches of brick-red color, herein provisionally named the Parcana Mainsa Member of the Caballas Formation. Similar beds as well as a few beds of the underlying Cuenca Member rest upon a basement peneplain upstream of Monte Grande at locality DV "RG" (Figure 5.G). Evidence of the lithology of the Parcana Mainsa Member is provided in an outcrop of the beach escarpment north of Puerto Caballas (DV 1958, 5077), where an erosive contact separates underlying deformed green-gray and white mudstone with stringers of coal from overlying conglomerate and gravel of the Los Choros Member (Figure 5.F). In the absence of marine fossils, the Parcana Mainsa lithology is interpreted to represent a floodplain environment.

3.1.5 Paracas Formation, Los Choros Member

The Los Choros Member can be divided into two units, one grading into the other. The two units together are measured or calculated to be about 80 meters thick in the Cuenca de Caballas (DV 1953, 5072, 5073) and at Parcana Mainsa (locality DV "PM;" measured at 70 meters thick by Leon et al. (2008)). Unit I, mauve-colored and coarse-grained, lies above an erosive surface with tens of meters of relief. At Parcana Mainsa, in the Cuenca de Caballas, and at Puerto Caballas, the surface cuts down into the Parcana Mainsa Member and even the Cuenca Member of the Caballas Formation (Figure 5.D). At locality DV "RG," Los Choros beds of Unit I rest directly upon basement rock (Figure 5.G). The lithology of Unit I varies. At locality DV "PM," the base consists of jumbled house-sized angular boulders, which are overlain with thick-bedded sandstone and conglomerate. On the western flank of the Río Grande, upstream (DV 5068) and downstream (DV 5070) of Monte Grande, Unit I consists of medium- and thick-bedded, mauve-colored, afossiliferous, arkosic conglomerates with very angular, very poorly sorted clasts of coarse-grained quartzo-feldspathic granodiorite and, less commonly, rounded cobbles and pebbles of andesite and metamorphic rock (Figure 5.H).

In the Cuenca de Caballas, Unit I consists of massive and thick-bedded, coarse-grained, arkosic sandstone with scooped and scoured surfaces carved into red siltstone (Figure 5.I), stringers of rounded igneous and metamorphic pebbles, red-bed mud-chips, and a few disarticulated oyster valves. At Puerto Caballas, inferred basal beds of Unit I contain rounded and subangular cobbles with andesitic, quartzitic, and foliated metamorphic lithologies in a matrix of poorly sorted fine-grained arkosic conglomerate and coarse-grained sandstone. Better sorted coarse-grained sandstone a few meters higher in the section are heavily bioturbated with *Ophiomorpha* traces.

Unit II of the Los Choros Member at Puerto Caballas consists of mustard-colored medium- and coarse-grained sandstone, often bioturbated (*Ophiomorpha*, *Gyrolithes*); fine-grained conglomerate; and thin beds of bioclastic sandstone with fragmented small valves of oysters (Figure 5.J) and, rarely, small marine epitoniid gastropods. Outcrops of Unit II in the Cuenca de Caballas are capped with coarse-grained sandstone and fine-grained cobbly conglomerate with oysters and a moderately diverse assemblage of marine mollusks. Embedded in the coarse-grained cap of Unit II are one- to two-meter-diameter angular boulders of basement rock and equally large lithoclasts of red mudstone. The boulders are closely spaced in western outcrops (DV 585, 1959, 5072, 5073), but only one kilometer to the east, single boulders are separated by tens of meters (DV 5065, 5066). Oyster-bearing outcrops of Unit II near Monte Grande (DV 5069) have several horizons with numerous angular small boulders of crystalline basement rock.

The mustard-yellow sandstones of Unit II of the Los Choros Member in the Cuenca de Caballas grade upwards into tuffaceous and diatomaceous silty sandstone of the Yumaque Member (DV 1953), with mollusk-bearing gray-white, medium-grained sandstone alternating with finer-grained sandstones.

Features of the Los Choros Member salient to a paleoenvironmental interpretation include the deeply erosive basal surface of Unit I, its extremely coarse-grained texture and lack of paleosols, and its lack of marine fossils near Monte Grande, contrasting with a subdued erosive relief, a less coarse-grained texture, and the presence of oysters, a boulder bed, and marine bioturbation in the Cuenca de Caballas and at Puerto Caballas. Also relevant to a paleoenvironmental interpretation are the oyster-bearing sandstones of Unit II at Monte Grande, Cuenca de Caballas, and Puerto Caballas.

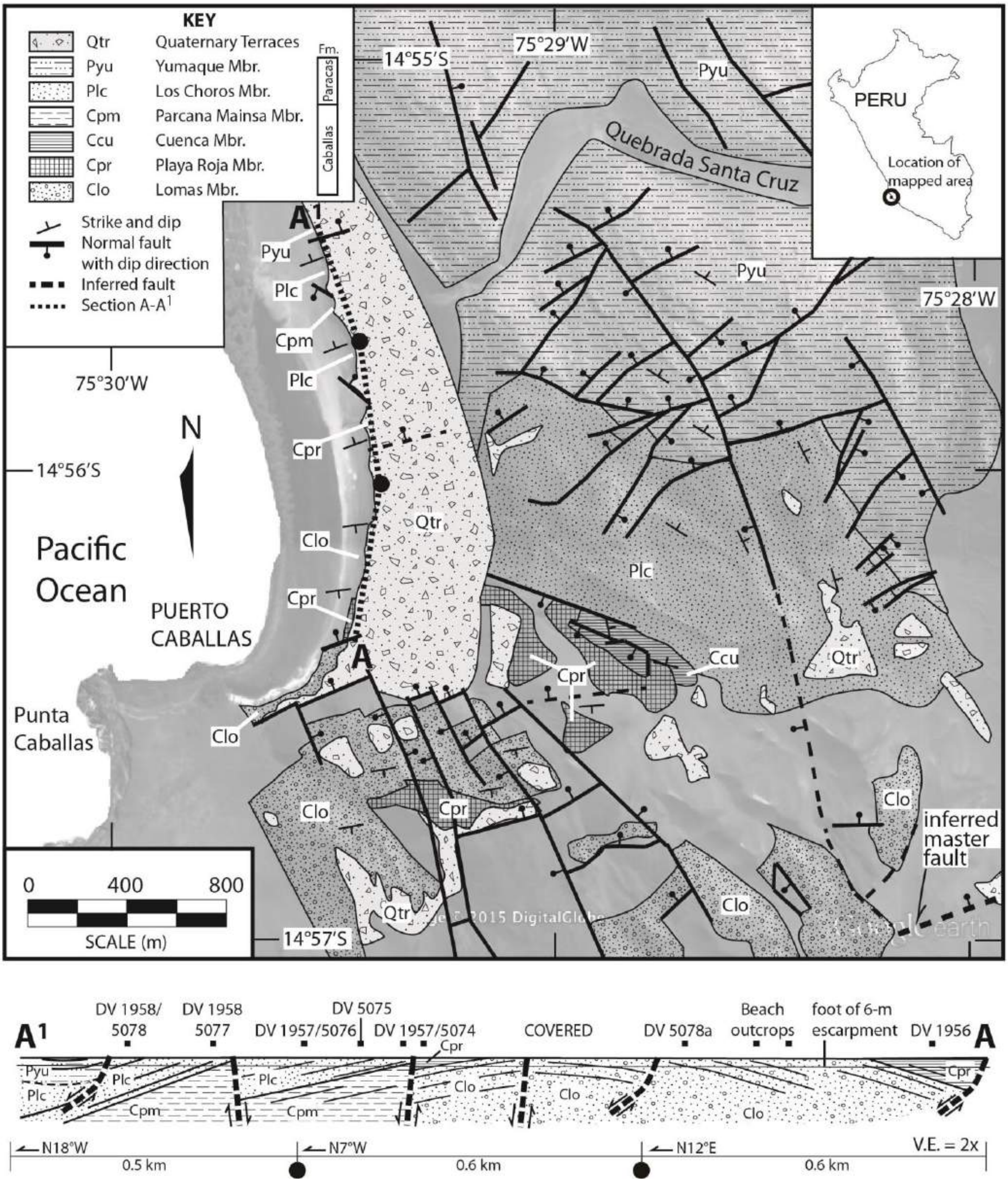


Figure 4. *Geological map of the Cuenca de Caballas. The inferred master fault for the Caballas half-graben appears in the lower right corner of the figure. The base map is from Google Earth. Cross section A-A¹ runs in three segments along the beach escarpment at Puerto Caballas. All fault traces are inferred below the base of the sea cliffs.*

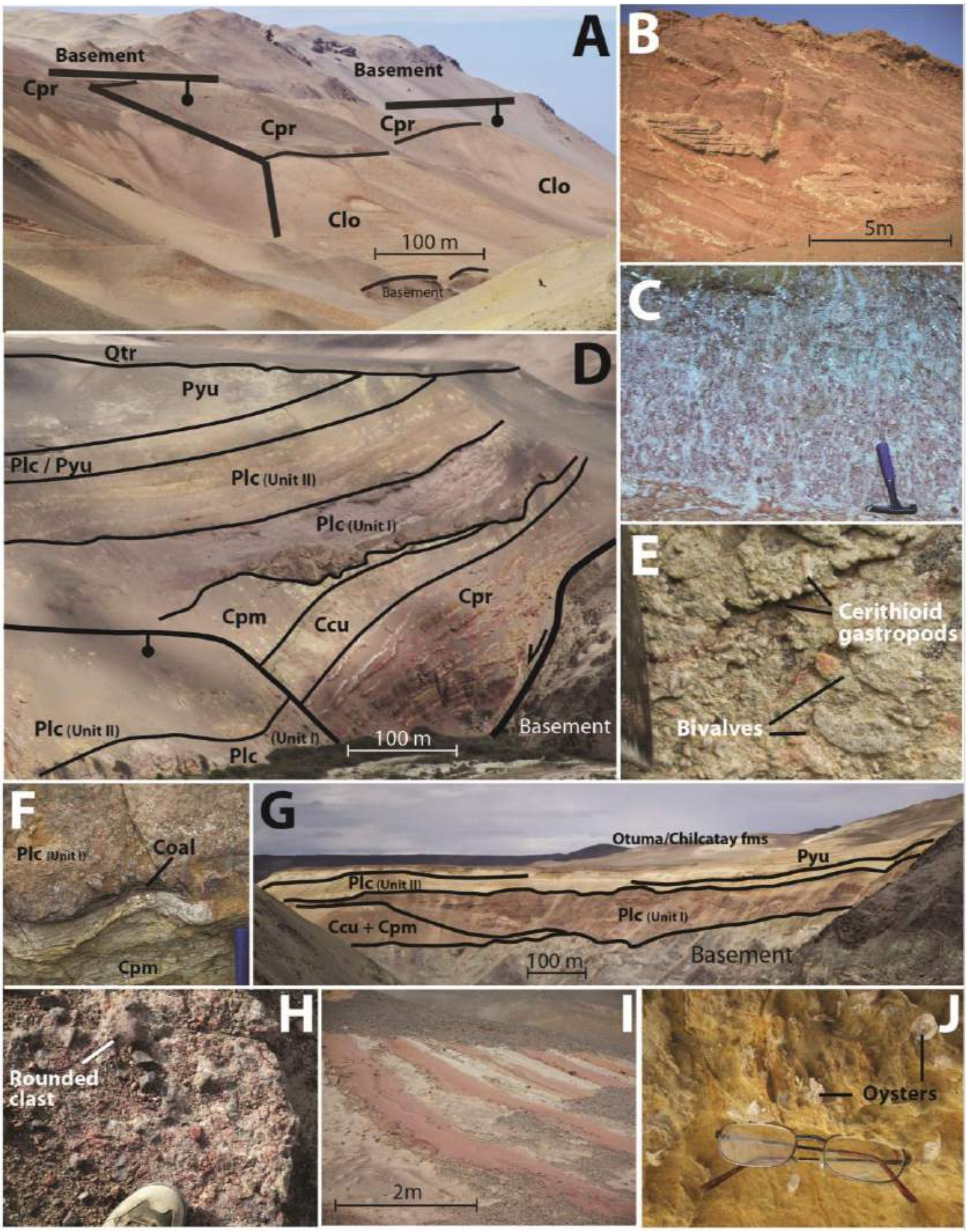


Figure 5. *Photographs of significant outcrops and lithologies.* ***A.*** *Hills southeast of Puerto Caballas (DV 1960) with outcrops of the Lomas (Clo) and Playa Roja (Cpr) members of the Caballas Formation. Faults are parallel to the Caballas half-graben's master fault, which lies behind the skyline. Throw direction is indicated with ball-and-peg symbol.* ***B.*** *Point-bar cross-bedded sandstone and red sandy mudstone (DV 1956) of the Playa Roja Member of the Caballas Formation. Height of cliff about 6 meters.* ***C.*** *Root traces with caliche nodules in red-bed paleosol (DV 1956) of the Playa Roja Member of the Caballas Formation.* ***D.*** *Outcrop at Parcana Mainsa (DV "PM") on the east side of the Río Grande (visible at lower right). Lithostratigraphic units include the Playa Roja (Cpr), Cuenca (Ccu), and Parcana Mainsa (Cpm) members of the Caballas Formation and Los Choros (Plc, Unit I and Unit II) and Yumaque (Pyu) members of the Paracas Formation, as well as Quaternary alluvial terrace (Qtr). Contact between the Caballas and Paracas depositional sequences lies at base of Plc (Unit I). Compare with Leon et al. (2008), Figure 4.4B.* ***E.*** *Bioclastic sandstone (DV 5061) of the Cuenca Member of the Caballas Formation with dispersed bivalves and cerithioid gastropods.* ***F.*** *Contact (DV 5077) between underlying Parcana Mainsa Member (Cpm) of the Caballas Formation and overlying Los Choros Member (Plc Unit I) of the Paracas Formation. Coal stringers noted at top of Cpm.* ***G.*** *View up the Río Grande (DV "RG") from locality DV 5068 showing outcrops of the upper Caballas and entire Paracas depositional sequences. See Figure 5.D for lithostratigraphic codes.* ***H.*** *Arkosic breccia (DV 5070) of the Los Choros Member (Unit I) of the Paracas Formation. In addition to abundant angular clasts with large feldspar phenocrysts are rare rounded cobbles of varied lithologies.* ***I.*** *Alternating sandy red mudstone and bioclastic sandstone (DV 1953) of the Los Choros Member (Unit I) of the Paracas Formation. Beds are about one-half to one meter thick.* ***J.*** *Disarticulated and transported oyster valves in mustard-colored sandstone (DV 1957) of the Los Choros Member (Unit II) of the Paracas Formation.*

Near Monte Grande, strata of Unit I are thought to be alluvial fan deposits proximal to block-faulted basement highlands exposing paleo-outcrops of the granitic/granodioritic San Nicholás Batholith. An interpretation of Unit I deposits as turbidites and olistostromes (Vicente et al., 2000) is rejected based on the coherence of Unit I continental strata and their conformable relationship with equally coherent underlying estuarine strata (see below).

Closer to Puerto Caballas, strata of Unit I represent alluvial deposits distant from a highland source and grading into estuarine deposits. The appearance of only oysters in Unit I indicates some degree of ecological restriction, possibly a constant or intermittent fresh-water influence. The boulder bed that caps Unit I in the Cuenca de Caballas may represent a tsunami or storm/flood event (Paris et al., 2011). The ubiquity of oysters and finer-grained sandstone throughout Unit II, the presence of numerous boulder beds in Unit II near Monte Grande, and the preservation of *Gyrolithes* in the Cuenca de Caballas indicates an expanding marginal marine environment lying seaward of alluvial plains that was still subject to episodic flooding or tsunamis (Dworschak and Rodrigues, 1997; Paris et al., 2011). In the Cuenca de Caballas, at least, the diversity of marine mollusks associated with the boulder-bed cap of Unit II indicates that ecological restrictions had vanished and that the nearshore environment was fully marine. The diversity of mollusks persists in the medium-bedded sandstones that are intercalated with silty sandstones. The stratigraphic interval of intercalated lithologies represents a gradual transition from inner shelf (Los Choros) to outer shelf (Yumaque) environments.

3.1.6 Paracas Formation, Yumaque Member

The silty sandstone with intercalated dolomitized sandstone beds of the overlying Yumaque Member forms the northern rim of the Cuenca de Caballas and spans Quebrada Santa Cruz (Figure 4). Yumaque beds contain pelagic microfossils, thin-shelled pectinid bivalves, scales of anchovy and sardines, and partial skeletons of archeocetes (Dunbar et al., 1990; DeVries, 1998). Sedimentary structures (minor rippling, thin beds of fining upward sediments) and fossils indicate a shelf environment just at wave base or subject to weak longshore currents. At least one horizon near the transition with the underlying Los Choros Member contains widely scattered boulders of basement crystalline rocks.

3.1.7 Beach escarpment outcrops at Puerto Caballas

Eocene sedimentary rocks exposed in a low escarpment that extends for two km along the beach north of Puerto Caballas have been interpreted as correlative strata on opposing arms of a broad anticline with an axis extending approximately east-west (Macharé, 1987; Montoya et al., 1994). More structurally prominent than the anticline, however, are several large-offset normal faults that divide the escarpment outcrops into discrete blocks.

Fault blocks at the southern end of the beach cliff reveal southward dipping yellow-orange arkosic sandstone and fine conglomerate of the Lomas Member (DV 5078a and unnumbered intertidal outcrops; see Figure 4), overlain by banded brick-red and pale-green muddy sandstones Figure 5.B) of the Playa Roja Member (DV 1956). Farther north, a small outcrop of northwest-dipping brick-red mudstone of the Playa Roja Member (DV 5074) indicates the presence of a different fault block. The next two fault blocks to the north show northwest-dipping beds of mauve-and-mustard colored massive and medium-bedded coarse-grained sandstone with a few horizons of conglomerate. The mauve-colored bioturbated beds predominate lower in the section and the mustard-colored oyster-bearing beds prevail higher in the section (DV 1957, 5075, 5076), exactly as is the case for nearby measured sections (DV 5072, 5073) of the Los Choros Member. The northernmost fault block displays a synform of thin silty sandstone beds of the Yumaque Member (DV 1958, 5078).

At locality DV 1958/5077, balls of coarse-grained, angular, conglomeratic, red arkosic sandstone are embedded in a swirl of white sandstone and mudstone. Overlying the deformed bedding are channel-form beds of red arkosic conglomeratic sandstone of the Los Choros Member. Underlying the deformed mudstone beds are lenticular and continuous beds of medium-grained greenish-gray sandstone and brownish-gray mudstone with 30-cm long wedges of coal; these beds are inferred to belong to the Parcana Mainsa Member.

3.1.8 Informal lithostratigraphic units of Stock et al. (1988)

Cenozoic sedimentary beds extend eastward from Monte Grande towards Cerro Huaricangana. Stock et al. (1988) applied two informal formational names to these strata in Quebrada Huaricangana: 'Huaricangana' and 'Monte Grande.' The former term applies to clinoform coarse-grained, pebbly, bioclastic sandstone and conglomerate that lap onto an uneven surface of basement rock and grade upward into thin-bedded and laminated coarse- and fine-grained sandstone. The overlying 'Monte Grande formation' consists of siltstone, dolomite, and phosphatic horizons.

The 'Huaricangana formation' had been correlated with the upper Eocene Paracas Formation by Stock et al. (1988) based on occurrences of nautiloids and the gastropod, *Turritella woodsi* Lisson, 1925. Subsequent recognition that Eocene specimens of *T. woodsi* are restricted to the latest Eocene Otuma Formation (DeVries, 1998) and also occur in basal beds of the Chilcatay formation (DeVries, 2007) make the 'Huaricangana'/ Paracas correlation unlikely and, together with evidence of the Chilcatay transgression extending to Cerro Poroma, near Nazca (DeVries, 1998), demonstrates that contrary to Vicente et al. (2000), the Caballas, Paracas, and Pisco depositional sequences are not the only Cenozoic marine sequences to be found at the southern end of the East Pisco Basin.

Perpetuating the name 'Monte Grande' for Cenozoic marine strata in the East Pisco Basin is inadvisable, inasmuch as the same name has been applied in published literature (Montoya et al., 1994) to Jurassic clastics, volcanoclastics, and carbonates in the same area. The dolomitic siltstones referred to the informally named 'Monte Grande formation' by Stock et al. (1988) might well be the fine-grained upper portion of the Otuma or Chilcatay formations (DeVries, 1998).

3.2. Age of Cuenca and Los Choros members

A late early Eocene age for the Cuenca Member is inferred from the presence of fossil mollusks also found in lower Eocene strata from the Talara Basin of northern Peru. The two most distinctive Eocene bivalves of the Cuenca Member are *Carolia* (*Parinomya*) *parinensis* Olsson, 1928, an anomiid bivalve with numerous tiny, radial, digitate extensions of commarginal growth lines, and *Septifer euglyphus* (Woods, 1922), a small mussel with a sharp dorsoventral crest and a finely ridged anterioventral surface (Figure 6). In the Talara Basin, specimens of *C. parinensis* and *S. euglyphus* are found in the Parinas and Restin formations (and for the latter species, the Salina Formation), thought by Olsson (1928) to be middle Eocene but considered (often as differently named formations, e.g., the Clavel and Chacra formations) by Weidey and Frizzel (1940), Travis (1953), Stainforth (1955), Higley (2004), and Martinez et al. (2005) to be early Eocene to early middle Eocene.

Gastropods from the Cuenca Member include *Pseudoliva coronaria* Olsson, 1930, known in the Talara Basin from the middle Eocene Talara Formation or group (Higley, 2004; Martinez et al., 2005), and *Potamides occidentalis* Woods, 1922, and *Turritella keswickensis* Olsson, 1928, both known from the lower Eocene Parinas and Restin formations (Clavilithes series of Woods (1922)). The rare occurrence of *Cristispira paracasensis* (Rivera, 1957), previously considered an index species for the middle Eocene Los Choros Member (DeVries, 2007), interjects some uncertainty about the age of the Cuenca Member. On the other hand, *Turritella lagunillasensis* Rivera, 1957, also an index species for the Los Choros Member and present as such near Quebrada Santa Cruz (DV 581), is absent from the Cuenca Member.

Allowing for the fact that the complete ranges for most Peruvian Eocene molluscan species are not well constrained, the fossil evidence points to a late early to early middle Eocene (late Ypresian to early Lutetian) age for the Cuenca Member. Azalgara (1994) cited an article by D. Davila, A. Sanchez, E. Villavicencio, and J. Torres, slated for release in 1993 but never published, in which a Paleocene-to-Eocene age was assigned to the Caballas Formation based on benthic foraminifera.

The archeocete vertebra collected from the Cuenca Member constitutes the oldest whale from South America (older than the basilosaurid from the Priabonian Otuma Formation of the East Pisco Basin (Martinez-Caceres and de Muizon, 2011) and late Lutetian or Bartonian archeocetes from near the base of the Yumaque Member of the Paracas Formation (Uhen et al., 2011)) and is comparable in age to an archeocete mandible collected from the La Meseta Formation of Isla Marambio (Seymour Island), Antarctica (Reguero et al., 2011).

Too few species of fossil mollusks are found in Unit I of the Los Choros Member to infer an age. The diverse molluscan fauna of Unit II includes a few species known from the Los Choros Member elsewhere in the East Pisco Basin (e.g., *Glycymeris arquilloensis* Rivera, 1957; *Turritella lagunillasensis* Rivera, 1957; and some that occur in middle Eocene beds in northern Peru (e.g., *Pseudoliva parinasensis* Olsson, 1928). Bartonian microfossils from the overlying Yumaque Member (Dunbar et al., 1990; DeVries, 1998; DeVries et al., 2006) set a younger age limit for the Los Choros Member.

3.2. Structural Geology

Sedimentary strata discontinuously exposed along a beach escarpment north of Puerto Caballas (Figure 4) were mapped by Macharé (1987) as correlative strata on opposing limbs of a broad anticline. Field work undertaken during this study shows that beds on the opposing limbs are not correlative with each other; that the most significant structures are normal (possibly listric) faults associated with a half-graben; and that the apparent anticline is probably a rollover antiform.

The half-graben's master normal fault, dipping steeply to the northwest, passes from south of Punta Caballas northeastward through the hills and beneath the 400-m marine terrace that lie southeast of Cuenca de Caballas (Figures 1, 4). Southeast of the master fault, the footwall block is composed of pre-Cenozoic basement rock, which is truncated by the 400-m Pleistocene terrace and blanketed with alluvium and fossiliferous marine sandstone (DV 1961).

Northwest of the master fault, near the beach, two blocks downdropped to the northwest are comprised of basement rock nonconformably overlain by beds of thick-bedded arkosic sandstone (Lomas Member) and, at the top of the section, red mudstone (Playa Roja Member) (DV 1960), with all beds dipping five degrees to the southeast. The northeast-southwest-striking normal faults are offset at intervals of two to four hundred meters by a set of northwest-southeast-striking, steeply dipping normal faults, usually downdropped to the southwest (Figure 4). Moving north, another block, situated at the south end of the beach escarpment, exposes red beds and yellow-orange arkose (DV 1956, 5078a) dipping 35 and 15 degrees to the southeast, respectively. The red beds are cut by small northwest-dipping listric faults. Farther north, blocks are bound by faults parallel to the master fault or the second set of normal faults (DV 1957, 1958, 5074, 5076). The blocks consist of afossiliferous arkosic sandstone and red mudstone (Lomas and Playa Roja members) and, to the north, oyster-bearing arkosic sandstone (Los Choros Member) dipping five to 20 degrees to the northwest. Farthest north is a synform of thin-bedded silty sandstone (Yumaque Member), which is separated from arkoses (Los Choros Member) to the south by a northwest-dipping normal fault.

Strata in the Cuenca de Caballas are cut by same two sets of normal faults observed near the beach, as are beds surrounding Monte Grande, as noted by Vicente (2004). The displacement of Yumaque strata along both sets of normal faults shows that northwest-southeast extension producing the half-graben and subsequent northeast-southwest extension occurred after the late Eocene.

The two sets of closely spaced faults also affect strata below the Eocene/Pisco Formation angular unconformity on the southern nose of Cerro Terrestral (DV 1456) but do not pervasively extend into Pisco strata (e.g., DV 522, 1454), nor into Pisco beds in the upper Quebrada Huaricangana (DV 534), indicating that the Caballas half-graben developed during the Oligocene or early to middle Miocene. Half-grabens formed elsewhere on the southern Peruvian margin (Azalgara, 1994) at Quebrada Perdida and Bajada del Diablo/Camino de los Burros, but during or after the late Miocene (DeVries et al., in press).

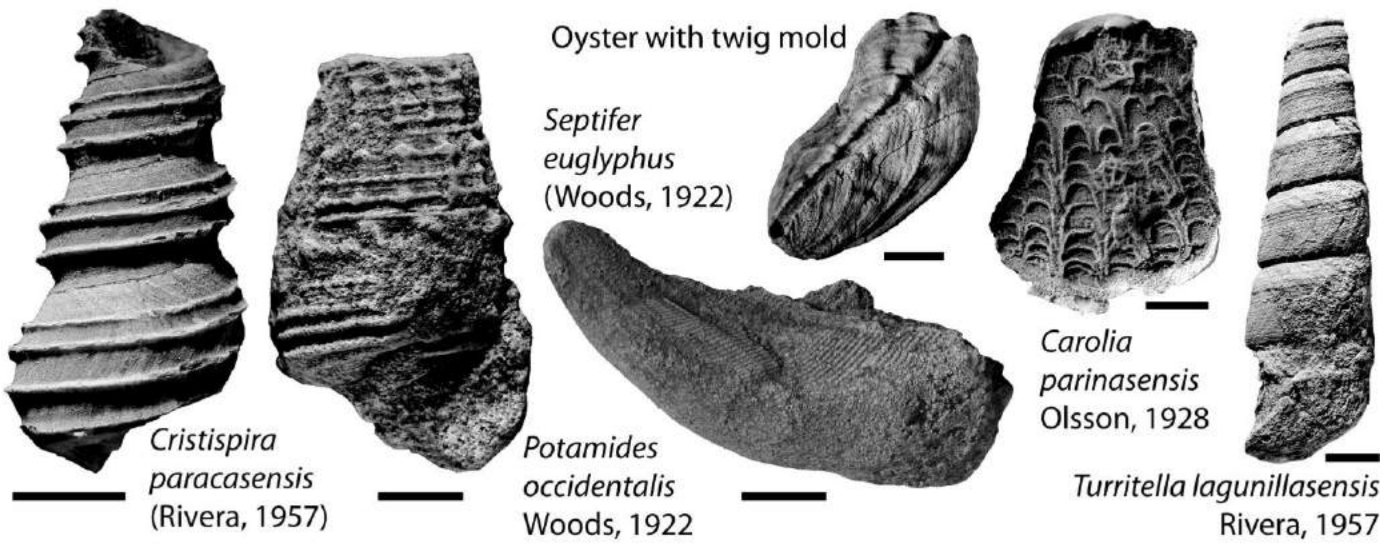


Figure 6. *Fossil mollusks from Eocene strata near Puerto Caballas. Turritella lagunillasensis Rivera, 1957 is from the Los Choros Member of the Paracas Formation. All other species are from the Cuenca Member of the Caballas Formation (DV 1954, DV 5061). Carolia specimen is a rubber mold taken from the attachment scar of an oyster. Scale bars are 5 mm.*

The Caballas half-graben is affected by two regional tilts. The subduction of the Nazca Ridge (Saillard et al., 2011) has produced an uplift greater than 800 meters of Cerro Huaricangana since the late Pliocene (Hsu et al., 1992; Macharé and Ortlieb, 1992; Vicente et al., 1996). (The presence of specimens of the Pliocene bivalve, *Chlamys vidali* Philippi, 1887, collected by Atchley (1956) on an 800-m terrace near the Marcona iron mine, argues against the late Eocene origin for the most elevated terraces proposed by Vicente et al. (2000)). The Huaricangana uplift has resulted in a broad regional dip of 0.5 degrees to the northwest that affects Pleistocene marine terraces in the Caballas area. A second regional tilt, about 0.5 degrees to the east, is associated with Pliocene and post-Pliocene uplift and compression (Vicente et al., 1996). Beds along the axis of the Caballas rollover antiform dip even more steeply inland, about five degrees, suggesting compression and asymmetric uplift during the late Miocene.

In the Monte Grande area, structure is greatly complicated by a 40-km-long, northwest-striking, southwest-dipping, high angle normal fault, which follows cliffs on the northeast flank of the Monte Grande valley (Figure 1) and parallels the set of faults crosscutting downdropped strata of the Caballas half-graben. The Monte Grande Fault vertically offsets the basement nonconformity by 200 meters at the mouth of the Río Grande canyon and an equal amount, post-early late Miocene, west of Cerro Terrestral at 14°50'S. Olistostromes and synsedimentary deformation attributed to Eocene motion on the Monte Grande Fault (Vicente, 2004) should be re-considered in light of the Oligocene to middle Miocene age for the development of the Caballas half-graben and the late Miocene age for much of the Monte Grande Fault's activity.

4. Discussion

4.1 Tectonic and Depositional History

The presence of late Ypresian or early Lutetian mollusks in the Cuenca Member of the Caballas Formation constrains scenarios for the tectonic development of south-central Peru. The timing of compression, erosion, and extension in the region is often referenced to 'tectonic phases.' Three phases are recognized: Peruvian (late Cretaceous), Incaic (Paleogene) and Quechua (Neogene) (Benavides, 1999). Since the Los Choros Member, which overlies crystalline basement throughout most of the East Pisco Basin, is known to have a middle Eocene age (Rivera, 1957; Dunbar et al., 1990; DeVries, 1998), many authors have assumed the underlying peneplain was formed during the "Incaic II" compressive phase at 43-42 Ma (Benavides, 1999; Noble et al., 1999; Quang et al., 2005; León et al., 2008). The late Ypresian or early Lutetian age proposed herein for the Cuenca Member of the Caballas Formation and the existence at localities DV "RG" and DV "PM" of Cuenca and Parcana Mainsa sediments that (a) cover a flat basement erosional surface and (b) lie beneath an erosive unconformity and overlying sediments of the upper Lutetian Los Choros Member (Figures 5.D, 5.G) indicate that a peneplain existed prior to the Incaic II phase, i.e., it could have formed during the Incaic I compressive phase at 59-55 Ma (Benavides, 1999). Noble et al. (1979) allowed for such an early erosional event, while Cobbing (1978) argued forcefully for a Paleocene to early Eocene age for the peneplain.

Following the formation of the postulated late Thanetian or early Ypresian Incaic I peneplain, the coastal plain near Puerto Caballas was covered with alluvial arkosic sand and gravel (Lomas Member), with little or no soil development. As slope gradients diminished, either the result of regional tectonism or eustatic sea level rise (the details of early Eocene eustacy are poorly understood; see Sluijs et al., 2008), lightly vegetated floodplains floored with well-oxidized sediments replaced alluvial fans (Playa Roja Member). The floodplains were then inundated and overrun during the late Ypresian or early Lutetian by fan deltas and estuaries (Cuenca Member) fringed with mangrove vegetation. (The desert mangrove forest of San Pedro de Vice, Provincia de Sechura, northern Peru might serve as a modern analog). In the last stage of Caballas deposition, estuarine sediments were buried by prograding coastal plain deposits (Parcana Mainsa Member), for which the scarcity of oxidized iron minerals and presence of carbonized wood points to deposition under more reducing conditions.

Estuarine sediments of the Cuenca Member conformably overlie red beds of the Playa Roja Member in the Cuenca de Caballas and at locality DV "PM," but nonconformably overlie the basement peneplain at nearby locality DV "RG." It may be inferred, therefore, that older continental deposits of the Lomas and Playa Roja members were confined to low-lying basins, probably grabens formed during an early Ypresian extensional stage of the Incaic I phase.

The angular unconformity separating the Caballas Formation from the overlying Los Choros Member of the Paracas Formation signifies a latest Ypresian interval of extension and graben formation during an early stage of the Incaic II tectonic phase (see below).

The deeply erosive surface carved into the upper strata of the Caballas depositional sequence (Figures 5.D, 5.G) coincides in timing with the Incaic II tectonic phase. The large angular clasts of coarse-grained quartzo-feldspathic granodiorite in basal beds of the overlying Los Choros Member near Monte Grande indicate an unroofing of the San Nicholas Batholith, which is widely exposed today on the northeast flank of nearby Cerro Huaricangana (Montoya et al., 1994). The size of the granodiorite clasts, some many meters in diameter, indicate that basement outcrops were nearby, probably horsts created during the proposed stage of early Incaic II extension.

For the next two million years, angular boulders of basement rock and lithoclasts of Caballas sediments were transported to the Los Choros shoreline. By about 40 Ma, the Paracas transgression had moved the shoreline farther inland and the area around Monte Grande, Cuenca de Caballas, and Puerto Caballas became blanketed in silty sediments of the continental shelf.

Strata of the Caballas depositional sequence, which were deposited on the southwestern rim of the East Pisco Basin, may be the onshore expression of an early to middle Eocene seismic stratigraphic sequence ("E_0") from the West Pisco Basin identified by Azalgara (1994). The latter basin evidently experienced a different tectonic history than its onshore neighbor, since it exhibits two middle Eocene seismic sequences related to graben formation ("E_1" and "E_2") that are not correlative with outcrop unconformities in the East Pisco Basin. In contrast, younger "E_3" and "E-O" seismic sequences in the West Pisco Basin may be correlative with the Los Choros and Yumaque members of the Paracas Formation, respectively (Azalgara, 1994).

4.2 Paleoclimatic Implications

The combination of texturally and mineralogically immature arkoses and red mudstones comprising the Lomas and Playa Roja members of the Caballas Formation most likely reflect deposition under dry conditions (Berner, 1969), although more humid conditions would not be precluded by red beds alone (Besley and Turner, 1983) nor arkoses alone (Pettijohn et al., 1987). While a freshwater influence is indicated by the molluscan fauna of the Cuenca Member of the Caballas Formation (the lower or lower middle Eocene cerithioid-oyster sandstones of the Cuenca Member are the oldest Cenozoic example of brackish-marine conditions in southern Peru), the scarcity of plant remains indicates the early Eocene sea was advancing across a semi-arid landscape. Numerous studies of sedimentary facies and supergene sulfide deposits on the Pacific slope of the Andes in southern Peru and northern Chile reached the same conclusion – that since the early to late Eocene, the region has been arid to semi-arid, only to become even more arid (hyperarid) during the Pliocene (Clark et al., 1990; Quang et al., 2005). In contrast, the coast of central Chile appears to have been warm and humid during the early Eocene, judging from neotropical paleofloras preserved in the Arauco Formation at about 37°30'S (Collao et al., 1987; Gayo et al., 2005; Hinojosa, 2005).

5. Conclusions

The discovery of a diverse brackish-water molluscan fauna in sandstones overlying well-known red beds at Puerto Caballas inspired a more careful description of Eocene strata in the area. The result of this closer geological scrutiny has been a recognition of the half-graben structure and probable roll-over antiform in the Cuenca de Caballas; the correlation of discrete Caballas and Paracas depositional sequences with the major Andean Incaic I and Incaic II tectonic phases; and a greater appreciation for the semi-arid environment prevalent on the coastal margin of Peru during the early and middle Eocene. Each of these conclusions, however, can also be viewed as a hypothesis subject to more sophisticated analysis. The structural regime of the lower Rio Grande valley and adjacent Cerro Huaricangana and its Neogene interplay with the subducting Nazca Ridge is hardly understood; the sequence of Eocene tectonic events affecting contemporaneous and post-tectonic sedimentation has not been closely examined; the observations regarding depositional environments of the

Parcana Mainsa Member are in part conjectural; and the search for pollen and other indicators of estuarine ecosystems in the Cuenca Member has so far been cursory.

Acknowledgements

Mario Urbina (Departamento de Paleontología de Vertebrados, Museo de Historia Natural, Universidad Nacional Mayor de San Marcos, Lima) provided invaluable field expertise and assistance. David Jarzens (University of Florida, Gainesville) examined samples for pollen. David Lindberg (Museum of Paleontology, University of California, Berkeley, USA) facilitated access to Atchley's collection of mollusks from Marcona's marine terraces. Daniel Peña S. (Repsol Exploración, Lima) and Steven Bergman offered useful critiques. Spanish translation was provided by Aldo M. Benites-Palomino and Giancarlo Olmedo of the aforementioned Departamento de Paleontología de Vertebrados. Fieldwork was in part funded by the Granville Research Institute (Granville, Ohio, USA).

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Appendix

Locality latitude and longitude.

DV 522	14°50'19"S	75°21'50"W
DV 534	14°55'52"S	75°18'26"W
DV 581	14°58’09”S	75°19’16”W
DV 585	14°55’50”S	75°29’07”W
DV 1454	14°48'48"S	75°24'37"W
DV 1456	14°51'21"S	75°25'47"W
DV 1953	14°56’04”S	75°28’29”W
DV 1954	14°56’20”S	75°28’54”W
DV 1956	14°56’19”S	75°29’28”W
DV 1957	14°55’49”S	75°29’27”W
DV 1958	14°55’35”S	75°29’31”W
DV 1959	14°55’53”S	75°29’07”W
DV 1960	14°56’46”S	75°29’18”W
DV 1961	14°56’50”S	75°29’15”W
DV 1962	14°56’25”S	75°28’48”W
DV 1963	14°56’32”S	75°29’40”W
DV 5061	14°56’19”S	75°28’58”W
DV 5065	14°56’10”S	75°29’21”W
DV 5066	14°56’04”S	75°28’23”W
DV 5068	14°54’59”S	75°24’51”W
DV 5069	14°56’32”S	75°25’32”W
DV 5070	14°56’33”S	75°25’23”W
DV 5072	14°55’58”S	75°28’53”W
DV 5073	14°55’53”S	75°28’48”W
DV 5074	14°55’51”S	75°29’25”W
DV 5075	14°55’48”S	75°29’27”W
DV 5076	14°55’43”S	75°29’29”W
DV 5077	14°55’40”S	75°29’31”W
DV 5078	14°55’36”S	75°29’32”W
DV 5078a	14°56’06”S	75°29’26”W
DV "PM"	14°58’05”S	75°25’30”W
DV "RG"	14°54’36”S	75°24’06”W