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Sedimentological and geochemical study of the late Eocene to early Oligocene Yumaque formation, east Pisco Basin, Peru

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Rice University, 1993
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SEDIMENTOLOGICAL AND GEOCHEMICAL STUDY OF THE LATE EOCENE TO EARLY OLIGOCENE YUMAQUE FORMATION, EAST PISCO BASIN, PERU

by

ERIKA LEE FRANTZ

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE MASTER OF ARTS

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ABSTRACT

Sedimentological and Geochemical Study of the
Late Eocene to Early Oligocene Yumaque Formation,
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by

Erika Lee Frantz

Yumaque formation biosiliceous sediments resemble modern
and Neogene sediments deposited under coastal upwelling conditions.
High biogenic silica accumulation rates (up to 69 g·cm⁻²·yr⁻³),
preservation of fine sedimentary features, and high original organic
carbon, resulted from favorable basin geometries and upwelling of
nutrient-rich water. Light biosiliceous-rich and dark detrital-rich
alternations occur at scales ranging from millimeters to meters. Mm-
scale laminae couplets are interpreted as varves. Spectral analysis of
laminae thickness using a varve-calibrated time scale reveals
significant variance at periods of 5-6 and 8 years, within the El Niño
(ENSO) frequency band, and at 11 years, possibly linked to the 10-12
year solar cycle. Centimeter to meter-scale cyclicity representing
between a few hundred to a few thousand years correlates to solar
and geomagnetic phenomenon. The Yumaque formation and similar
biosiliceous deposits along the eastern Pacific margin may be
indicative of widespread late Eocene biosiliceous sedimentation
around the Pacific.
ACKNOWLEDGEMENTS

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CHAPTER 1: INTRODUCTION

Cenozoic diatomites, diatomaceous mudstones and genetically related porcelanites and cherts are ubiquitous around the Circum-Pacific region. These distinctive marine sediments are typically enriched in siliceous microfossils, organic carbon, phosphorous and carbonate and are often finely laminated. The distribution of these sediments in both a spatial and a temporal sense indicates that many of these deposits are linked to intensified coastal upwelling and anoxic marginal basins, which is in turn related to global paleoceanographic and paleoclimatic changes (Ingle, 1981; Barron & Baldauf, 1989, 1990). The widespread occurrence of Neogene, and possibly Paleogene, biosiliceous sediments is also tied to Pacific plate reorganization which led to synchronous marginal basin development (Ingle, 1981).

Paleogene sediments characteristic of coastal upwelling are present in several areas around the Pacific rim. This study is focused on the geochemical and sedimentological characteristics of the Yumaque formation of Peru, which consists of organic-rich, commonly laminated and biosiliceous sediments which closely resemble younger and more extensively studied Neogene sediments (such as the Monterey Formation of California) (Fig. 1.1). Other Paleogene biosiliceous deposits around the Circum-Pacific region include the Kreyenhagen Formation of California, the Chira Formation of northern Peru, and the San Mateo Shale of Ecuador. Like their Neogene counterparts, deposition of Paleogene diatomites and genetically related biosiliceous rocks can be linked to oceanographic, climatic, and tectonic changes affecting the Pacific ocean and its margins.
Figure 1.1

Photograph of biosiliceous sediments from the Yumaque formation exposed at Playa El Erizal.
Biosiliceous sediments in the modern ocean accumulate beneath regions of high surface water productivity, often associated with coastal upwelling (Baldauf and Barron, 1990). An important exception to this pattern is modern biosiliceous sedimentation in the Southern Ocean which is linked not to coastal upwelling but to the Antarctic Divergence. Upwelling in this region results largely from northward Ekman transport associated with the strong, persistent west-wind drift or prevailing circum-Antarctic westerlies and is reinforced by both wind and density-driven upwelling. In the Tertiary, several factors influenced the deposition and preservation of biosiliceous sediments. Progressive polar cooling, controlled in part by the tectonic opening and closing of oceanic gateways, has changed the surface and deep water circulation patterns which influence the distribution and extent of biosiliceous sediments through time (Baldauf and Barron, 1990). The Paleogene (ca. 65-23 Ma) marks a time of transition between climatic and oceanographic modes of the late Mesozoic and the Neogene. The late Mesozoic represented a nonglacial mode with predominantly warm-water circulation at all depths. This contrasts sharply with the Neogene, a glacial period characterized by predominantly thermohaline cold-water circulation. The late Eocene marks an important period of time in this transition.

Local tectonic regimes help control both the "purity" of the accumulated sediments and their distribution (Ingle, 1980, 1981; Pisciotto and Garrison, 1981; Isaacs, 1984; Barron, 1985). High terriginous influx, even in areas with high mass accumulation rates for biogenic silica, can mask productivity and/or preservation signals. Hence, in order to deposit highly biosiliceous sediments, the terrigenous flux must be low relative to biogenic silica accumulation. During the Miocene in California, basin geometries and subsidence, combined
perhaps at times with rising sea level, led to the isolation of offshore basins from diluting terrigenous debris. Indeed, comparison between biogenic silica and terrigenous accumulation rates for the Monterey indicate that a reduction in local terrigenous supply, rather than oceanographic conditions unique to the Miocene, was largely responsible for the high concentration of deposited diatomaceous silica in the Miocene (Isaacs 1984, 1985).

In addition to the effects that individual basin geometries and subsidence rates may have on terrigenous supply, major tectonic events affect regional basin formation, and regional patterns of sediment distribution. For example, synchronous tectonic development of basins around the Pacific rim in the early Oligocene and Miocene is considered to be partially responsible for the widespread occurrence of Neogene biosiliceous sediments (Ingle, 1981). The regional distribution of Paleogene biosiliceous sediments around the Pacific is not as well established as for the Neogene. However, in addition to the Yumaque formation, highly biosiliceous sediments from the late Eocene to early Oligocene have been documented in northern Peru, Ecuador, and California. These formations may be representative of a widespread pulse of Pacific biosiliceous sedimentation in the late Eocene to early Oligocene. Studies of Paleogene biosiliceous deposits such as the Yumaque formation may provide insight into the tectonic, climatic and paleoceanographic factors influencing marine sedimentation in the early Cenozoic.

PREVIOUS WORK

Geochemical, sedimentological, and stratigraphic work on the Yumaque formation was initiated as part of a larger study of the East Pisco Basin by
research groups at Rice and Duke Universities and the University of New Mexico, led by Drs. Robert B. Dunbar and Paul Baker (Dunbar and Baker, 1988; Marty et al., 1988; Marty, 1989; Stock, 1989; Dunbar et al., 1990). A summary of the stratigraphy that was largely developed by these groups is given in the next chapter. The previous work most directly relevant to this study included the measurement and age dating of the three Yumaque formation sections examined in this study, Fundo Desbarrancado (FD), Punta El Puente (PP), and Playa El Erizal (PE), as well as preliminary analysis of the geochemical characteristics of diatomaceous sediments exposed at FD (Marty et al., 1988).

**Yumaque formation**

The late Eocene to early Oligocene Yumaque formation consists primarily of fine-grained marine mudrocks, phosphatic shales, diatomites, porcelenites, and cherts. A total of six Yumaque sections (including those studied here) have been identified along the Peruvian coast from the Paracas Peninsula to the mouth of the Rio Grande River (at approximately 14° and 15° S, respectively) (Fig. 1.2). Several of these sections, variously dated using biostratigraphy (radiolaria, nannofossils, foraminifera, and molluscs) and $^{87}\text{Sr}/^{86}\text{Sr}$ ratios, are presented in Dunbar and Baker (1988) and Dunbar et al. (1990). Several additional latest Eocene to earliest Oligocene sections have been identified on the basis of diatom assemblages (Fourtanier and Macharé, 1988). On the basis of field work, the total aggregate thickness of the Yumaque formation is estimated to be greater than 150 m.

Most of the previous geochemical and small-scale sedimentological work done was concentrated on the approximately 30 m of laminated diatomaceous rocks exposed at Fundo Desbarrancado (Marty et al., 1988; Marty, 1989).
Figure 1.2

Map showing location of the three Yumaque sections examined in this study, other Yumaque sections in the East Pisco Basin, and the location of drilling sites of Leg 112 of the Ocean Drilling Program (from Suess, von Huene, et al., 1988). Also shown are major features of the Peruvian continental margin including the subducting Nazca Plate and Ridge, major forearc basins, and the extent of Cenozoic (Cz) sediments onshore (after Dunbar et al., 1990). Bathymetric contours spaced every 1000 meters.
Averages of biogenic silica and calcium carbonate contents are 29% and 6%, respectively. The original total organic carbon (TOC) content was estimated (by comparison of measured organic carbon to nitrogen ratios to those reported for modern marine plankton) to be greater than 4% (Redfield et al., 1963; Reimers and Suess, 1983).

Significant variations in the amount of biogenic silica, terrigenous material, and total phosphate were observed between the alternating mm-scale light and dark bands analyzed from 4 samples. Light bands are enriched in biogenic silica (exceeding 60% in some laminae) and impoverished in terrigenous material and phosphate relative to the dark bands. Marty et al. (1988) compared these light and dark laminae pairs to similar couplets observed in the Monterey Formation (which have been interpreted as annual varves) and inferred by analogy that the light laminae may represent dry seasons of high organic productivity and low clastic input, whereas the dark laminae may represent wet seasons of high clastic input and low productivity (Pisciotto and Garrison, 1981). This is presented as tentative evidence for a regular wet season during the late Eocene for coastal Peru.

For the laminated sediments at FD, Marty et al. (1988) present a high biogenic silica accumulation rate, which is consistent with rates from sediments deposited under highly productive surface waters today. The annual sedimentation rate is given as 78 cm/kyr, based upon measurements of light and dark laminae couplets, and assumes that the couplets represent annual deposition. The biogenic silica accumulation rate, which is based upon this sedimentation rate, the dry bulk density (DBD), and the total weight percent biogenic silica measured in the rocks, is given as 17 mg·cm⁻²·yr⁻¹. By analogy to the current siliceous upwelling system off Peru, Marty et al. (1988) inferred
that cold currents (proto-Humboldt current) and strong shore-parallel winds probably combined to produce Eocene upwelling. The presence of cool waters at this time supports the theory that gradual cooling preceded the rapid climatic-oceanographic shift at the Eocene/Oligocene boundary.

Although most previous work on the Yumaque formation concentrated on the southern FD section, a brief comparison between FD and the northern sections is given in Marty (1989). The most dramatic difference reported is in the silica phases present, with opal-A constituting the dominant phase in rocks from the FD section versus opal-CT in rocks from the northern sections. This is corroborated by extensive x-ray diffraction analysis of lithologies from Playa El Erizal which indicates that all of the opal-A in these rocks has been diagenetically altered to opal-CT (Dunbar and Baker, 1988). The northern sections are further described in Marty (1989) as a "muddy" facies with a significant calcareous component and mm-scale light and dark alternations similar to those seen at FD. TOC measurements for the northern sections, reported by Martin (1987) and Dunbar et al. (1990), are similar to those reported for the FD section.

PURPOSE

This study is intended to complement previous onshore and offshore work on the Pisco Basin and to help further our understanding of the factors influencing marine sedimentation along the Peruvian margin in the late Eocene. More specifically, the geochemical and sedimentological characteristics of the Yumaque formation are evaluated in an effort to answer the following questions:
1. How does the Yumaque formation compare to other biosiliceous sediments, especially the extensively studied Monterey Formation?

2. What diagenetic and/or depositional processes are responsible for the sedimentologic differences observed between the northern (PP and PE) and southern (FD) facies?

3. What depositional and/or diagenetic differences are responsible for the light/dark and laminated/massive alternations observed at scales ranging from millimeters to tens of meters?

4. What depositional environment(s) is indicated for this formation?

5. What are the inferred paleoceanographic, climatic and tectonic controls for deposition of the Yumaque formation and how do they fit in with existing theories for the global evolution of Paleogene climate?

Samples collected from FD were analyzed for their total weight % biogenic silica, inorganic and organic phosphate, and organic carbon in order to further establish that they were deposited under high productivity surface waters. The relative percentages of these components, which are characteristically high in sediments from high productivity areas, are compared to values reported for other sediments deposited under upwelling conditions. In order to determine mass accumulation rates for biogenic silica, sedimentation rates are needed. Marty et al.'s (1988) study uses the assumption that the
sediments are varved in order to establish a sedimentation rate. This study attempts to further substantiate the reliability of this assumption in two ways. First, dominant periods of variance in laminae color and thickness were determined by spectral analysis and were compared to frequency spectra observed in known varved records. Second, the physical characteristics of numerous mm-scale light and dark laminae are compared to laminae from sediments deposited in offshore California and Peru which have been interpreted (using independent age control) as varves.

Geochemical and sedimentological analyses of rocks from both PP and PE are focused on two major problems:

1) What are their similarities and dissimilarities with rocks from the FD section, and

2) What are the similarities and dissimilarities between rocks from the meter to ten meter light and dark, and laminated and massive, cycles observed? What is the periodicity of these cycles?

The depositional environment of the Yumaque formation is interpreted by analogy with the Miocene Monterey Formation, using sedimentary structures and lithology following Pisciotto and Garrison (1981). Results from this study are also compared to recent work completed offshore. Ocean Drilling Project (ODP) Leg 112 (Suess and von Huene et al., 1990) drilled ten holes in the Trujillo, Yaquina, Lima, and West Pisco Basins in late 1986 (Fig. 1.2). One of the primary objectives of ODP drilling was to analyze the Tertiary sedimentary record of the offshore. The Eocene section was penetrated at three sites on the middle and lower slope (sites 688, 682, and 683). At all three sites, middle Eocene strata are truncated by an unconformity (the Incaic-Quechua or IQ
unconformity) along which uppermost Eocene, Oligocene and lower Miocene sediment are missing (von Huene and Suess, 1988). Thus, no direct comparison between the Yumaque formation and an offshore equivalent was possible. However, several studies of cored Pliocene and Quaternary laminated sediments that focused on the history and expression of upwelling along the margin were useful for comparison with the Yumaque formation (Kemp, 1990; Wefer et al., 1990; Oberhansli et al., 1990; and Schrader and Sorknes, 1990).

METHODS

During June and July of 1989, field work was directed toward collecting samples from and refining three Yumaque formation stratigraphic sections previously measured and dated (Dunbar and Baker, 1988). Over 60 mudstone samples, as well as several ash and green sand samples, were collected from Fundo Desbarrancado (FD), Punta El Puente (PP), and Playa El Erizal (PE) for petrographic and geochemical analysis (Fig. 1.2). Samples collected during previous field seasons were also used for this thesis.

Fine-scale sedimentary fabrics were examined using a combination of standard thin-section microscopy and scanning electron microscopy (SEM) on small oriented slabs. The detrital grains in both mudstone and sandstone samples were identified by standard microscopy and X-ray diffraction. Thin sections from FD, PP, and PE mudstone samples were examined for fine-scale sedimentary features and detrital composition. The SEM was used to more closely examine the fabric and the biogenic components of sediments from FD. X-ray diffraction on randomly-oriented powders was used to corroborate thin
section observations from all three sections and to identify the clay, silica, phosphate, and carbonate phases present.

The total weight percent biogenic silica was determined for the FD bulk samples, and over 200 subsampled laminae. Biogenic silica was initially analyzed using a time series dissolution technique outlined by DeMaster (1979) and modified to detect volcanic opal by Marty (1989). It was subsequently determined, by smear slide analysis and x-ray diffractometry, that while most or all of the diatoms and radiolarians were dissolved using this method, sponge spicules and other siliceous microfossils (minor silicoflagellates and ebridians) were not. To better estimate the total percentage of siliceous microfossils, including those apparently more resistant to dissolution, a second one-step dissolution method was developed using a stronger base. Between 10 and 15 mg of sample were heated in a 1M NaOH solution for 3 hours at 85ºC. This was determined by experimentation to be an optimal base strength and time duration for dissolving most (or all) of the opaline silica, without leaching silica from detrital grains or clays (discussed further in Results section). Total weight percent silica was determined using the colorimeter technique outlined by DeMaster (1979). These raw biogenic silica values were roughly converted to weight percent biogenic opal by adding 10 weight percent structural H2O to the measured values.

The total weight percentages of carbonate, inorganic and organic phosphate, were determined for all bulk FD, PP, AND PE, samples and the FD laminae. The "carbonate bomb" method of Muller and Gastner (1971) was used to determine the total carbonate. Total, organic and (by difference) inorganic, phosphate measurements were made using the colorimeter method of Aspila et al. (1976) and modified by K. Miskell-Gerhardt (pers. comm, 1987, in Marty,
1989). The weight percent total carbon and nitrogen for all bulk samples and selected FD laminae were measured using a Carlo- Erba elemental analyzer. Total organic carbon (TOC) was calculated as the difference between the total carbon measured and that in the carbonate measured. The weight percent gypsum (plus halite) was determined (for selected samples indicated in the text) by dissolution. Dry bulk density measurements were made by carefully calculating the volumes of cut, oven-dried slabs and then weighing these samples. Colors of dry powdered samples were determined using Munsell Soil Color Charts (1971).

In addition to collecting samples for sedimentological and geochemical analyses, close-up photographs of thirteen continuous meters of FD section were taken in the field for time-series analysis of the laminae. Details of the methods used to collect and process the data are included with the FD results section.
CHAPTER 2: RELEVANT BACKGROUND

This chapter briefly summarizes the Cenozoic stratigraphy and tectonic evolution of the Peru continental margin. The late Eocene and early Oligocene Yumaque formation was deposited in the Pisco Basin, one of a series of forearc basins formed by extensional response to subduction of the Nazca Plate beneath South America (Fig. 2.1, 2.2). A detailed discussion involving the considerable work that has focused on the development of this margin is beyond the scope of this paper, however, a brief overview is given below. A more complete discussion on the tectonic evolution of the Peru continental margin may be found in von Huene and Suess (1988), and references cited therein. Additional references are cited in Dunbar et al. (1990). The stratigraphy and stratigraphic nomenclature for the Pisco Basin described in Dunbar et al. (1990) is summarized here. Formal type sections and boundary descriptions for the Los Choros, Yumaque, and Chilcatay formations have not been approved and, therefore, their designations remain informal. To indicate this, "Formation" appears in this text with a lower case "f" for these formations. The late Eocene and early Oligocene was a pivotal time of global paleoceanographic-climatic and plate tectonic changes. Some of these changes and their potential effect on marine sedimentation in the Pacific are discussed here.

EAST PISCO BASIN STRATIGRAPHY

Approximately 2000 m of Eocene to Quaternary sediments fill the East Pisco Basin. At least 3 major transgressions affected the East Pisco Basin
Figure 2.1

Map of the Nazca Plate and western South America showing the subducting Nazca Ridge, trench axis, and outline of Peru.
Figure 2.2

Map of the major structural trends and forearc basins of coastal Peru. OSH = Outer Shelf High. (Figure taken from Dunbar and Baker, 1988).
during the Cenozoic. These three transgressions are separated by unconformities and span 1) the early Eocene to early Oligocene, 2) the early Oligocene to early middle Miocene, and 3) the middle Miocene to Pliocene. Each transgression resulted in a similar progression of facies. Coarse-grained conglomerates, sandstones, and oyster and barnacle bioherms grade upward and laterally into finer-grained sandstones and siltstones, which are, in turn, capped by biogenic facies (Fig. 2.3). The biogenic facies may comprise diatomites and diatomaceous siltstones and mudstones, or siltstones and mudstones with dolomitic intervals. Dunbar et al. (1990) build upon the previous work of Lisson (1898), Adams (1908), Peterson (1954), Newell (1956), Ruegg (1956), Mertz (1966), Balarezo et al. (1980), Macharé (1987), and INGEMMET (unpublished (?) geologic quad sheets), and propose a new a stratigraphy which divides the sedimentary rocks of the Pisco Basin into 7 units: the Caballas, Los Choros, Yumaque, Chilcatay, Pisco, Canete, and Changuillo formations.

Using this scheme, the Caballas Formation describes a sequence of fluviatile sandstones which occur near the mouth of the Rio Grande and appear to underlie the Eocene Los Choros formation. The Los Choros formation is comprised of up to 700 m of mainly nearshore and inner shelf bioclastic conglomerates and sandstones (Fig. 2.4). In the Paracas Peninsula area the age of the Los Choros formation is well-constrained to mid-to-late Eocene. The Yumaque formation overlies the Los Choros formation. The contact between the two formations appears to be gradational. The sediments of the two transgressive packages overlying the Yumaque formation, the late Oligocene and early Miocene Chilcatay formation and the early Miocene Pisco Formation, are discussed in detail in Dunbar et al. (1990).
Figure 2.3

Generalized composite stratigraphic section proposed by Dunbar et al. (1990) for Cenozoic sediments of the Pisco Basin. Same lithologic key as for Fig. 3.4 and 3.15.
Diatomaceous Siltstone & Diatomite
Phosphate Beds
Dolomite
Tuffaceous Siltstone
Conglomerate & Sandstone
Dolomite Beds & Nodules
Muddy Siltstone with Diatomaceous Intervals
Siltstone
Sandstone & Conglomerate
Diatomite & Porcelanite
Laminated Mudstone
Sandy Siltstone
Fossiliferous Conglomerate & Sandstone
Figure 2.4

Photograph of fine to coarse-grained sandstone of the Los Choros formation exposed at Playa Lagunillas.
STRUCTURAL AND TECTONIC SETTING

Three positive linear trends separate and define two sets of forearc basins along the central Peruvian continental margin (Fig. 2.2; Thornburg and Kulm, 1981; Shepherd and Moberly, 1981; von Huene and Suess, 1988). The slope basins, including the West Pisco Basin, are located between the Upper Slope Ridge and the Outer Shelf High, whereas the shelf basins, including the East Pisco Basin, are situated between the Outer Shelf High and the Coastal Batholith. The age of sedimentary rocks in the Peruvian forearc ranges from Eocene to Recent.

The division of Peruvian sedimentary basins into two distinct sets reflects not only their relation to these structural highs, but also fundamental differences in water depth, sediment fill, and underlying basement. Seismologic studies suggest that the shelf basins are underlain by continental lithosphere, while the slope basins are floored by accreted oceanic crust and sediment (Thornburg and Kulm, 1981). The East Pisco Basin is underlain by fractured and faulted continental crust (Couch and Whitsett, 1981; Kulm et al., 1981).

The western margin of South America records a history of relatively continuous plate convergence since the Early Jurassic (Cobbing and Pitcher, 1972; Mukasa, 1986). The relative velocity and direction of convergence between the overriding continental and the subducting oceanic plates has varied through time. Global studies of plate interaction in convergent margins, summarized by Jarrard (1986), indicate that periods during which compressional tectonism dominate both the arc and forearc can be tied to orthogonal relative plate convergence and higher convergence velocity, or to
subduction of young, hot crust. Times during which the convergence angle is low, and/or very old, cold oceanic crust is being subducted can be tied to subsidence in the forearc basins and/or strike-slip tectonics. When the convergence angle is low, deformation in the region is partitioned between compression in the arc and strike-slip in the forearc.

**Eocene/Oligocene Tectonic Setting**

A significant line of evidence, including sea floor magnetic anomalies, hotspot tracks, and an increase in both island arc and continental magmatism (Kennett et al., 1977, 1985; Masuda, 1984; Noble et al., 1984) indicate that the Late Eocene and Early Oligocene was a time of major global plate reorganization. In the Pacific, the change has been constrained from sea-floor magnetic anomalies and hotspot tracks (including the "bend" in the Hawaiian-Emperor seamount chain, dated at approx. 42 Ma; Claque et al.; 1975) to be about 43 Ma, or Chron 21 time.

A similar change in global and Pacific plate motions occurred in the latest Oligocene and early Miocene, and was instrumental in the formation of marginal basins. Deposition of biosiliceous rocks around the Pacific Rim has been linked not only to the increase in atmospheric-oceanic circulation resulting from global cooling, but also with this period of tectonism (Ingle, 1981). In California, this plate reorganization is connected with translational development of borderland basins which, due to early Miocene subsidence (Ingle 1980) and rising sea level in the late early Miocene (Vail and Hardenbol, 1979), were effectively isolated from terrigenous material coming off the continent (Isaacs, 1983, 1984). Both the lower and upper boundaries of the Monterey Formation are marked by a sharp decrease in the rate of accumulation of terrigenous
debris, not necessarily an increase in the rate of silica accumulation (Isaacs, 1984). Indeed, in the Santa Barbara area, both the overlying Sisquoc Formation (5.5-3.5 Ma) and possibly the underlying Rincon Shale (25-18 Ma), apparently had higher rates of silica accumulation than the Monterey Formation (Isaacs, 1984). High terrigenous influx in both of these formations, however, masks relatively high silica accumulation; unlike the strikingly biosiliceous rocks present in the upper Miocene strata of the Monterey Formation, both the Rincon and Sisquoc strata are generally nondescript mudrocks (Isaacs, 1984). This tectonostratigraphic setting appears to be a useful analog for the Late Eocene and Early Oligocene of the Peruvian forearc region.

Using the hotspot frame of reference to derive relative plate motion (a technique used for the northern Pacific basin by Engebretson et al., 1985) Pardo-Casas and Molnar (1987) calculated that during the period from Chron 21 to Chron 13 (approx. 43 to 37 Ma) along the central South American margin the convergence velocity was high, and the convergence angle oblique by as much as 30°. This produced a tectonic regime likely dominated by a combination of right-lateral strike-slip and compression. This tectonic episode was expressed as folding and thrusting, accompanied by increased volcanism in the Andes (Noble et al., 1990), and by rapid tectonic subsidence, probably in a right-lateral strike-slip environment, in the forearc basins. This is a good example of strain partitioning in the convergence zone. Such a relationship for the same time period is well documented to the north in Ecuador, where better constraining data are available (Daly, 1989). A modern analog for such a dextral strike-slip dominated system is coastal southern California. Huge strike-slip faults form major positive zones which separate extremely deep "pull-apart" basins, which commonly have a half-graben geometry.
CDP seismic data from offshore Peru, interpreted by C. Azalgara at Rice University (Pers. comm., 1992), indicate that a similar tectonic setting existed in Peru during Eocene time. Seismic stratigraphic relationships show that subsidence in large half-grabens had begun by at least mid-Eocene, and perhaps early Eocene, time. The rapid accommodation in the half grabens provided a depositional setting in which proximal fan-delta and shallow marine facies grade into deeper marine rocks with very low detrital input over just a few kilometers. Numerous sub-basins were formed, separated by local highs (C. Azalgara, Pers. Comm., 1992; and Stock, 1989; Dunbar et al., 1990). Within this tectonic regime, the Yumaque formation probably represents a relatively distal marine facies, deposited during the late transgressive phase of the late Eocene basin succession, in half-grabens away from active faults, which provided clastic sources on their upthrown flanks (Stock, 1989). Differences between the Yumaque formation sections observed along the Peruvian coast (Fig. 1.2) may be because the Yumaque is, in fact, a depositional facies which was coeval, but depositionally dissimilar in the different sub-basins (Dunbar et al., 1990). These sub-basins have been modified by later tectonics, and are difficult to articulate and reconstruct from the sparse present day outcrops available. As in the southern California borderland of the Miocene, some of these basins were probably shielded from detrital input by other, more landward basins, which acted as catchments for the clastic sediments.

A major sequence boundary is observed near the top of the Eocene section on seismic data (C. Azalgara, pers. comm., 1992). Although its precise age is uncertain, it may correlate temporally to a change in plate convergence and velocity at about 37 Ma (Pardo-Casas and Molnar, 1987), and the transition from oblique to more orthogonal convergence at a lower velocity. This is
consistent with ODP Leg 112 results which revealed an erosional unconformity truncating upper Eocene rocks and overlain by Oligocene and lower Miocene rocks.

The present day relationship of the West and East Pisco basins (separated from each other by the Outer Shelf High, Fig. 2.2) is an artifact of post-Eocene tectonic activity (C. Azalgara, pers. comm., 1993). Azalgara considers the basins to have been in a continuous extensional regime during the Eocene. Offshore seismic profiles show that this older depositional geometry was disrupted by two well-defined compressive events: 1) a mid-Miocene regional event which produced a folded and thrust faulted belt parallel to the trench orientation, and 2) a local, East and West Pisco Basin area event in the late Pliocene (C. Azalgara, pers. comm., 1993). Marty (1989) and Dunbar et al. (1990) refer to Caldas et al. (1980) for the only concrete onshore piece of data from which post-Cretaceous right-lateral strike-slip faulting (along the Illescas fault zone) has been established by mapping. As was the case with southern California, convincing geological evidence of dextral offset has been hard to come by during the early phases of investigation of the Peruvian margin.

The tectonic development of the Peru forearc during this time, linked with the global climatic and paleoceanographic changes described below, led to conditions favorable for the preservation of biosiliceous sediment, seen today as the Yumaque formation.

PALEOCEANOGRAPHIC AND CLIMATIC SETTING

Climatic cooling in the Tertiary was not a smooth, gradual trend (Berger, 1982). Instead, proxy temperature indicators such as the $\delta^{18}O$ isotope record
of benthic and planktonic foraminifera and global sedimentation changes, indicate rapid, step-like transitions (Fig. 2.5; Matthews and Poore, 1980; Douglas and Woodruff, 1981; Shackleton, 1984; Shackleton and Kennett, 1975; Miller et al., 1987; Prentice and Matthews, 1988; Baldauf and Barron, 1990; and others). Other records, such as vegetation changes (Wolfe and Upchurch, 1987; Wolfe, 1978), and changes in biogenic sedimentation (Barron and Baldauf, 1989), also suggest stepwise Tertiary cooling.

The widespread occurrence of Pacific Miocene diatomites is apparently related to a combination of paleoceanographic/climatic and tectonic controls which influence both productivity and preservation of biosiliceous debris and the delivery of diluting terrigenous clastics (Ingle, 1981). By the middle Miocene, a strong thermal contrast between high and low latitudes had developed, resulting in invigorated oceanic circulation (Baldauf and Barron, 1990). A related increase in coastal upwelling coupled with synchronous basin formation in the Pacific have been cited as major controls on the deposition of biosiliceous sediments (such as the Monterey Formation) around the Pacific at this time (Ingle, 1981). Earlier, intermediate cooling events may also have resulted in increased biosiliceous sedimentation (Baldauf and Barron, 1990). One of the most significant temperature drops recorded is near the Eocene and Oligocene boundary (Fig. 2.5, 2.6). Many of the $\delta^{18}$O- isotope records of benthic and planktonic foraminifera indicate that this drop occurred very near to 36 Ma (+/- ~0.5 Ma) (Shackleton and Kennett, 1975; Miller and Thomas, 1985; Shackleton, 1986; Miller et al., 1987; Kennett and Stott, 1990; Mackenson and Ehrmann, 1992). An increased latitudinal thermal gradient and ice formation in the southern hemisphere near this time likely caused an increase in biosiliceous sedimentation. The causes, magnitude, and precise timing of this
Figure 2.5

Cenozoic paleotemperature records generalized from benthic and planktonic foraminiferal oxygen isotopic data in Shackleton and Kennett (1985), and benthic foraminiferal oxygen isotopic data in Shackleton (1986) and Miller et al. 1987. The large increase in δ¹⁸O at the Eocene/Oligocene boundary is indicated by an arrow in each of the records.
Figure 2.6

Timing of the Eocene/Oligocene temperature drop recorded in selected $\delta^{18}$O-isotope record relative to the deposition of Yumaque formation rocks exposed at Fundo Desbarrancado.
<table>
<thead>
<tr>
<th>Year</th>
<th>Author(s)</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>35</td>
<td>Shackleton and Kennett, 1975</td>
<td>Benthic forams, DSDP sites 277, 279A, 281</td>
</tr>
<tr>
<td>36</td>
<td>Kennett, 1978</td>
<td>Planktonic forams, subantarctic region, DSDP sites 277, 279A, 281</td>
</tr>
<tr>
<td></td>
<td>Miller and Thomas, 1985</td>
<td>Benthic and planktonic forams, equatorial Pacific, DSDP site 574</td>
</tr>
<tr>
<td></td>
<td>Murphy and Kennett, 1985</td>
<td>Benthic and planktonic forams, Tasman Sea, DSDP sites 593 and 593A</td>
</tr>
<tr>
<td></td>
<td>Shackleton, 1986</td>
<td>Benthic forams, DSDP sites 522, 523, 525A, 527, 528, 529</td>
</tr>
<tr>
<td></td>
<td>Miller et al., 1987</td>
<td>Composite record of benthic forams, Atlantic DSDP sites</td>
</tr>
<tr>
<td></td>
<td>Kennett and Stott, 1990</td>
<td>Benthic forams, Maud Rise, ODP site 689B</td>
</tr>
<tr>
<td></td>
<td>Mackensen and Ehrmann, 1992</td>
<td>Benthic and planktonic forams, Maud Rise and Kerguelen Plateau, ODP sites 749B, 748B, 744B, 738B, 690B, 689B</td>
</tr>
</tbody>
</table>
drop are still debated. A summary of several different studies that have addressed these problems and their findings is given in Fig. 2.7. In addition, Barron et al. (1991) provides a detailed synopsis of the various studies which have concentrated on the initiation of glaciation in Antarctica.

Several other paleoceanographic/climatic changes occurred at or near the Eocene/Oligocene boundary, many of them probably related to the recorded temperature drop. Among these are: 1) a marked decrease in faunal diversity of both planktonic and large benthic foraminifera (Corliss et al., 1984; Kennett and Barker, 1990); 2) a change to planktonic and benthic foraminifera with more polar affinities (Kennett, 1978); 3) a decrease in the abundance of diatoms per gram of sediment by about an order of magnitude between the latest Eocene to the Early Oligocene (Pomerol and Premoli Silva, 1986); 4) deepening of the calcium carbonate compensation depth (CCD) of over one kilometer in the Pacific ocean and of several hundred meters in the Indian and Atlantic Oceans (van Andel, 1975); 5) a progressive increase of illite, chlorite, and sometimes kaolinite, and concomitant decrease in smectite (Chamley, 1985); 6) the widespread occurrence of deep sea hiatuses (Keller, et al., 1987). These changes apparently result from an acceleration of deep sea cold, oxygenated water currents and changes in surface water productivity linked to global cooling (Pomerol and Premoli Silva, 1986).

Recent studies have also indicated significant glaciation in Antarctica and the limited development of continental ice sheets on East Antarctica by late Eocene or earliest Oligocene time (Ehrmann and Mackenson, 1992; Fig. 2.8). These developments are related to the continued evolution of the Circum-Antarctic Current (as southern landmasses moved northward) which effectively decoupled the warmer subtropical gyres from the colder subantarctic and
Figure 2.7

Summary of faunal, sedimentological, isotopic and tectonic/eustatic changes occurring at the Eocene/Oligocene boundary compiled from numerous sources (listed in figure).
<table>
<thead>
<tr>
<th>FAUNAL</th>
<th>SEDIMENTOLOGICAL</th>
<th>ISOTOPIC</th>
<th>TECTONIC / EUSTATIC CHANGES</th>
</tr>
</thead>
</table>
| • Gradual turnover in benthic forams with increased abundance of cool water species. Corliss (1981) | • Significant deepening of CCD in all the oceans.  
  van Andel (1975); Berger (1973);  
  Berger & Winterer (1975);  
  Sliter & et al (1979)  
• Increase in CaCO3 accumulation.  
  Thunell & Corliss (1966)  
• Progressive increase of illite, chlorite, and kaolinite and decrease of smectite and fibrous clay in sediments.  
  Channell (1965).  
• Development of hiatuses and sediment reworking.  
  Thiede et al (1981)  | • δ18O changes in benthic foraminifers indicate temperature drop of  
  4 - 5 °C in bottom water from water from the world ocean.  
  Kellogg (1980);  
  Shackleton & Kennett (1975);  
  Kennett & Shackleton (1976).  
• Rapid, distinctive +ve shift in δ18O between 11°S and 1.5°N in benthic and planktonic forams.  
  Shackleton & Kennett (1975);  
  Kennett and Shackleton (1976);  
  Miller and Fairbanks (1965);  
  Kennett (1986).  
• Positive culmination of δ13C trend.  
  Renard et al (1986);  
• Low inter-specific gradient among planktonic foraminifers may indicate decrease in oceanic productivity due to a major reorganisation of water masses.  
  Boersma (1986)  | • Cooling coincident with sea level regression.  
  Vail et al (1977)  
• Restriction of the Tethys seaway.  
  Ricou, de Lepinay & Marcoux (1986)  
• Volcanic plume observed in Japan,  
  Peru, Australia, New Zealand and  
  Philippines. Wide spread throughout  
  circum Pacific region.  
  Chailia (1978); Masuda (1984);  
  Karig (1975); Nobel (1974).  
• Opening of the Tasmanian sea way, passage of cool surface S. Indian ocean waters  
  around Antarctica.  
  Triggering sea ice formation??  
  Kennett (1982).  
• Strong compressive Alpine phase.  
Figure 2.8

Evidence for Antarctic glaciation and/or formation of a limited continental ice sheet on East Antarctica between the middle Eocene and middle Oligocene compiled from several recent studies (listed in figure). Arrows indicate time ranges (if given) for each record.
<table>
<thead>
<tr>
<th>GEOLOGICAL TIME</th>
<th>GLACIAL DEPOSITS</th>
<th>ISOTOPE RECORD</th>
<th>CLAY MINERALOGY</th>
<th>ICE RAFTED DEBRIS</th>
<th>BIogenic SEDIMENTS</th>
<th>Deep Sea Hiatuses</th>
</tr>
</thead>
<tbody>
<tr>
<td>OLIGOCENE</td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>MIDDLE</td>
<td></td>
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<td></td>
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</tr>
</tbody>
</table>

- **Baiada & Barron (1990):** Greatly expanded biogenic sedimentation in the Southern Ocean.
- **Kennett & Barker, (1993):** Maud Rise, biogenic siliceous sediments replace carbonate sediment facies.
- **Baiada & Barron (1990):** Reviewed Cenozoic development of biogenic sediments and observed greatly expanded biogenic sediments in the Southern Ocean.
- **Prentice and Matthews (1998):** Compared 818O curve of shallow tropical foraminifera with benthic foraminifera, for entire Cenozoic to infer ice volume changes and suggest extensive glaciation on Antarctica, from 42 Ma, with no significant deviations.
Antarctic gyres (Kennett, 1982). Increased latitudinal gradients (Murphy and Kennett, 1985), led to more vigorous atmospheric and climatic circulation which in turn led to increased upwelling of deeper, nutrient rich waters and higher biological productivity. Coastal areas which are affected by eastern boundary currents such as Peru, California and northwest Africa are prone to upwelling caused by wind dispersal of surface waters. Upwelling of cool water increases continental aridity along these margins which results in reduced terrigenous influx to offshore basins.
CHAPTER 3: RESULTS

Results from Fundo Desbarrancado (FD) are presented separately from results from PP and PE. While the general sedimentological characteristics of the closely spaced Punta El Puente (PP) and Playa El Erizal (PE) (Fig. 2.1) sections are very similar, the diatomite and diatomaceous mudstones from the FD section stand out in their relative homogeneity, relatively minor degree of diagenetic alteration and regular, almost continuous mm-scale lamination. These characteristics facilitate a more detailed examination of the fine-scale sedimentary features, in particular the mm-scale laminae. Using the assumption that that light and dark laminae couplets represent yearly deposition, estimates of mass accumulation rates (MAR) for the biogenic and terrigenous components, are calculated and are presented below.

The PP and PE sections, by contrast, include a more widely varying lithology and have undergone considerable alteration. Where it is seen, mm-scale lamination is generally poorly defined. The porcelainites and porcelainitic mudstones from these sections were examined with emphasis on the larger meter to ten meter light and dark/massive and homogenous alternations. Total biogenic silica accumulation rates are estimated using the same "varve" assumption as for the FD rocks. in addition to the porcelainites and porcelainitic mudstones studied, preliminary work was completed on several glauconitic sandstone samples.

The three sections studied are both compared to each other and to other biosiliceous upwelling deposits around the Pacific rim.


Fundo Desbarrancado RESULTS

Results from Fundo Desbarrancado are divided into two separate but related sections. First, results from spectral analysis of laminae is presented as evidence for an annual origin of the mm-scale light and dark couplets. Evidence for this is indirect, provided by comparison of spectra from known marine varved sequences to dominant periods of variance in the thickness and gray scale values of FD laminae. Second, the sedimentological and compositional characteristics of both the bulk rocks and individual laminae are discussed. Comparison of the characteristics of FD laminae couplets to those of known varved records provides additional evidence for an annual origin. Mass accumulation rates are calculated using the assumption that laminations in rocks from FD represent annual sediment layers.

Spectral Analysis of Fundo Desbarrancado Laminae

This study attempts to substantiate an annual origin for lamina couplets in the Yumaque formation using spectral analysis of quantitative thickness and gray scale values. The method used (described in detail below) first assumes that the millimeter-scale light and dark couplets represent an annual layer and uses time series analysis to extract high-frequency periodicities. Comparison of these periodicities to those (such as the ENSO cycle) which are commonly observed in varved records provides indirect evidence for a seasonal origin of the laminated sediments in the Yumaque formation.
Background Information

The term varve refers to any annual sedimentary deposit, regardless of origin, and was first applied to Quaternary glaciolacustrine deposits in Scandinavia where light-coarse laminae alternate with dark-fine laminae in response to spring melting and summer production (De Geer, 1912). Hence, each light-dark couplet represents one year of deposition. Varved sediments have been recognized in other lacustrine deposits where, due to partially or totally anoxic bottom waters, the seasonal flux of sediment (which controls both the composition and timing of deposition) is preserved in the sedimentary record. These deposits offer an incredibly detailed snapshot of past climates as well as excellent time control for lower frequency rhythmicity (Tada, 1991). Anderson (1961) was among the first to realize the potential import of varved sediments in deciphering past climatic variation. Varve records have been recognized as imperfect time series, where certain parameters, such as thickness or composition, often reveal bundles with periodicities common to meteorological or geophysical phenomena. In the high frequency range, a periodicity of 3-7 years, often interpreted as an El Niño-type (ENSO) phenomena is commonly observed (Baumgartner et al., 1985; Anderson et al., 1990; Ripepe et al., 1991). Other periodicities have been recognized at about 11 years, most often interpreted as related to the 10-12 year solar cycle (Herman and Goldberg, 1978), and at 7.5-9, 12-16, 21-24, and 40 years (Fig. 3.1; Fischer, 1986).

Varved sediments have also been recognized in marine environments, especially in areas of strong coastal upwelling, where high productivity leads to anoxic or disaerobic bottom water (less than 0.1 ml/l dissolved oxygen). Poorly oxygenated bottom water inhibits the presence of bioturbating fauna and
Figure 3.1

Periodicities in varve thickness in various varve sequences as revealed in power spectra calculated by Koopmans and by Ware and reported in Anderson (1961). The Todilto varves are from an evapoite setting, the Ireton and Puente varves are marine, the Nyland Fjord varves are estuarine, and the remainder are lacustrine. Periodicities from these records cluster in four bands: 7.5-9 yr, 12-16 yr, 21-24 yr (Hale solar magnetic cycle) and 40 yr. Large dots represent the most prominent cyclicity in their series. (From Fischer, 1986)
preserves very fine sedimentary features. Calvert (1966) was among the first to analyze marine varved sediments. His classic study of diatom-rich, varved sediments from the Gulf of California examined the compositional differences between seasonally deposited laminae (the seasonality of these Recent laminae was determined in part by measuring rates of deposition using radiocarbon dating). Calvert concluded that while the accumulation rate of biogenic material remained essentially constant, the terrigenous input varied seasonally, increasing during the summer months due to increased runoff. Here, the summer months are represented by thicker, darker, and more detrital-rich laminae, and the winter months by relatively thinner, lighter and detrital-poor laminae. Subsequent study of these sediments by Baumgartner et al. (1989), however, showed that damming and control of all the principal rivers draining into the central Gulf has had no perceptible effect upon the deposition of the dark laminae. Their interpretation was that wind strength changes seasonally influence eolian flux from the desert. The expression of seasonally-forced marine sediment fluctuations varies in response to such things as geographic area, depositional environment, and age. Other factors, such as diagenesis, may alter primary signals observed in composition and even the thickness of laminae, and further complicate any simple identification of varved sediments.

Obviously, the difficulty in recognizing varved sediments is minimized in younger deposits where radiocarbon or biostratigraphic dating is more accurate. Often, especially in older sediments, the available time resolution does not allow independent recognition of varves based on rates of deposition. Thus many studies of older deposits, including this one, must rely upon
comparison with known varved sediments or other indirect means to infer a seasonal origin for the laminae observed.

Whether or not it is reasonable to assume that seasonal changes, within a similar geographic/oceanographic area and depositional environment, led to sediment variations in the late Eocene comparable to those observed today is a difficult question. The absolute determination of varved sediments remains problematic except for recent (easy to date) sediments; however, similarities between these sediments and possible fossil records, such as the Yumaque formation, suggest a common origin.

Although rocks from the Yumaque formation resemble Recent varved sediments of offshore California, insufficient time resolution prohibits independent confirmation of an annual origin for the light and dark couplets present. The following method was employed in an effort to further support an annual origin for these sedimentary layers by comparing cyclical variations between time series constructed for FD, under the assumption of annual deposition of laminae couplets, to the variations exhibited by known varved sequences.

**Methods**

Both the thickness and quantitative gray scale values of laminae from Fundo Desbarrancado were spectrally analyzed. In the field, a 13 meter section was photographed continuously at approximately 0.5 m intervals. The photos were taken of a freshly exposed surface, perpendicular to the bedding surface. These color photographs were converted to black and white photographs, enhancing the contrast for each photograph as much as possible using polycontrast filters (Fig. 3.2). Unfortunately, only 4 photos representing
Figure 3.2

Photograph of laminated sediments from Fundo Desbarrancado which were part of a 1.2 m photographic record used for spectral analysis of gray scale values and thicknesses. Each mm-scale light and dark couplet (average thickness per couplet = 0.235 cm) is interpreted as a varve (representing one year of deposition). Visual inspection of the distinct cm-scale color banding in these sediments reveal periodicities which are similar to those detected in power spectra of laminae thicknesses; however, spectral analysis of the gray scale values of laminae did not. Manipulation of the photographs during developing, scanning, and processing, may have obliterated these original color differences. Eight bioturbated intervals, such as the one shown here, were detected in the 1.2 m record used. These intervals are between between 0.3 to 2 cm thick and are either massive or faintly and discontinuously laminated. For spectral analysis, a constant sedimentation rate was assumed and these zones were treated as breaks in the record.
approximately 1.2 meters of continuous section were ultimately deemed of a high enough quality to analyze. These photographs were enlarged to as near to true scale as possible and then digitally scanned.

The digitized data were manipulated using a "free-ware" image processing program, *Image 1.23*, on a Macintosh II CX. This program was deemed sufficient, though not optimal, for this application. Updated image processing software, especially those specifically designed for similar application, may improve analyses and save time in processing the collected data set. Density profile plots were generated perpendicular to the laminae, giving averaged gray scale values (0=black, 256=white) versus the number of pixels. The gray scale values were averaged over a width of 16 pixels, which corresponds to approximately 0.2 cm in most of the scanned photographs. The number of pixels (both width and length) was converted to distance in centimeters using the tape measure included in each photograph and a ruler function in the program. The density profile plots were generated over the best part of each section scanned, avoiding discontinuous fractures, blurred images, and locally deformed areas as much as possible while maintaining a continuous section. Data from these plots, which were equivalent to 2-18 cm long, were stacked into a 1.2 meter continuous section.

The stacked data were then visually inspected to determine laminae boundaries. This was done by comparing laminae seen in the original photographs to breaks recorded in the gray scale values. The boundaries were picked using a combination of fixed objective criteria and subjective inspection on my part. Objective criteria used included the exclusion of any:
1) laminae less than .03 cm or greater than 0.3 cm thick;
2) boundary between adjacent laminae not defined by an average gray scale value difference of at least 5 points.
3) laminae boundary apparent in the gray scale values which was not apparent in the original photographs (rare).

Each lamina chosen was represented by both a thickness and gray scale value and both sets of data were analyzed separately. The choice of what to label a discreet laminae is obviously a critical one for this type of study and has been a focal point of debate in similar studies (Anderson, 1982; Baumgartner et al., 1985; Ripepe, 1991). In this study, decisions about what to define as a seasonally deposited lamina were based primarily on comparisons between the different types of laminae observed in thin sections of hand specimens from FD, laminae descriptions of Kemp (1990) for sediments more recently deposited offshore Peru, and descriptions for modern and Miocene age sediments deposited off California.

Wisp and/or discontinuous laminae, which often appeared in microscopic examination of hand specimens to be microlayers of terrigenous silt, were assumed to represent current activity or intraseasonal events and thus were not counted as discreet laminae but were included with their enclosing intervals. This mode of origin is supported by the same interpretation of similar microlayers observed in Pliocene and Quaternary laminated sediments (Kemp, 1990). Most often, these layers occurred within overall light intervals greater
than 3 mm thick and so were excluded by the criteria listed above. Laminae thicker than 0.3 cm often showed evidence for bioturbation, obliterating the original depositional fabric. Rarely, these thicker intervals are detrital-rich (fine silt-sized grains) which, when observed thin sections cut from hand specimens, sometimes exhibit microscopic grading. These intervals may represent low-density turbidites. For the purposes of spectral analysis, the thickness represented by all units thicker than 0.3 cm was treated as a break in the sediment record. The compiled data sets, for both thickness and gray scale values, were analyzed spectrally using a program adapted by Brown University. Cross-spectral analysis between the two data sets was also performed.

**Results/Discussion**

The time series analyzed was over 800 points long, with each point representing one lamina, or one-half of a year. Several strong periodicities are recognized (at the 80% confidence level) in the gray scale measurements. These periodicities, which are centered at approximately 5-6, 8, and 11 years (Fig. 3.3), are recognized in several other varve records (Fischer, 1966 and references cited therein). No cyclicity was observed in laminae gray scale measurements and the gray scale and thickness data sets are not correlative. The absence of recognizable cyclicity in gray scale values of laminae is attributed to several difficulties related to the analytical process. Unequal illumination of the rocks when originally photographed, combined with differential darkroom development of the black and white enlargements used for image analysis (each was treated separately to maximize contrast between laminae), likely obliterated original color signals and subsequent gray scale measurements. Visual inspection of the color banding seen within individual
Figure 3.3

Power spectra of periodicities in sequential varve thickness. The 1.2 m sediment record used represents over 400 years of deposition. Fourier transforms were prepared for 130 year windows. The data set was not detrended and no smoothing or whitening of the data was performed. At least three periodicities are indicated at the 80% confidence level: ~11 yr, ~8 yr, and ~5-6 yr.
photographs indicates periodicities comparable to those recognized in spectral analysis of laminae thickness measurements (Fig. 3.2).

The correlation between cyclicity observed in the thickness of laminae from the Yumaque formation and that observed in other Eocene rocks from a completely different geological and geographic setting is especially interesting; several studies analyzing laminae thickness of lake sediments from different localities of the Mid-Eocene Green River Formation document strong periodicities between 10-15 and 5-7 years, and possible weaker ones at ca. 8 and 33 years (Bradley, 1929, 1931; Crowley et al., 1986; Ripepe et al., 1991).

All of the Green River Formation studies suggest a sun spot origin for the ca. 11-year periodicity observed. Sun spot cycles are caused by relatively dark, sharply defined regions on the solar disc which migrate from higher to lower solar latitudes through a cycle (Herman and Goldberg, 1986). Several cycles are recognized but the 11-year cycle is a prominent feature on most historical records to date. While they have been interpreted to exist in many ancient records much debate exists still regarding the existence and/or expression of this phenomenon beyond recent history.

For the periodicity centered near 5 years, alternative interpretations are given. Crowley et al. (1986) suggest that it is just a harmonic of the sunspot cycle, an analytical artifact. Ripepe et al. (1991), however, interpret this cycle (which is often more strongly pronounced in their record than the sunspot cycle) as representative of El Niño-Southern Oscillation (ENSO) climatic variability. The ENSO phenomena is caused by atmospheric dynamics associated with changes in the atmospheric pressure across the southern Pacific. El Niño conditions off of Peru and, to a lesser extent off California, are characterized by little or no upwelling, low productivity, and higher concentrations of dissolved
oxygen that results in zones of bioturbation. These conditions oscillate with what is often termed anti-El Niño circulation, characterized by increased upwelling and productivity which help to lower dissolved oxygen levels in the oxygen minimum zone and thereby increase varve preservation. An ENSO-related frequency is noted in Pleistocene marine varves off California by Anderson et al. (1989) who related this cycle, seen there between 3-7 years, to the alternations between varves and zones of bioturbation. While "normal" ENSO's lie within a 3-7 year period band, observations over the last four and a half centuries indicates that strong El Niño events have occurred on the average between 6-7 and, on longer-term averages, every 9.9 years (Quinn and Neal, 1987).

The strong periodicity seen at about 8 years in the record presented here is perhaps a variation of an El Niño-type cycle, as suggested by Ripepe et al. (1991) for the weak periodicity observed at 8 years in their record. Furthermore, a periodicity between 7.5 and 9 years is observed in other varved records including the Holocene Russian lake sequences measured by Shostakovich and analyzed by Anderson (1961).

As mentioned in Föllmi et al. (1992), changes in sediment gray values may be caused by multiple independent variables including detrital minerals, volcanogenic components, and biogenic carbonates. Other differences that may be responsible for the observed color changes in Yumaque sediments may include porosity differences or diagenetic processes, including differences in preserved organic matter. What component or, more likely, components are responsible for the resultant color differences is unknown. Likewise, changes in laminae thickness may be tied to a variety of different depositional or
diagenetic causes. Therefore, relating paleoceanographic changes to the periodicities observed is difficult.

Despite these limitations, it is encouraging to find high levels of variance at periods close to those observed in other records. While certainly not overwhelming proof of annual deposition, spectral analysis of the laminae at FD indicate periodicities that are consistent with those seen in similar varved records. Furthermore, if the interpretation that laminated sediments within the Yumaque formation are varved is correct, then the periodicities revealed by spectral analysis here help substantiate the theory that sun spot and ENSO-type cyclicity existed at least as far back as the Eocene. This is discussed in further detail in the Chapter 4.

**Fundo Desbarrancado: Sedimentological and Geochemical Results**

Over 30 m of Late Eocene to Early Oligocene diatomaceous sediments are exposed at Fundo Desbarrancado as part of a package of late Eocene to Early Oligocene units exposed along the onshore western margin of the East Pisco Basin from the Paracas Peninsula to just north of the Rio Grande River (Fig. 1.2; Marty, 1989). This section was first examined in detail and dated by Marty (1989) and Marty et al. (1988). Age control is provided both by radiolarian biostratigraphy and Sr-isotope analysis of early formed dolomite concretions (Marty, 1989; Dunbar, et al., 1990; P. Baker, pers. comm., 1992). The sediments exposed at FD belong to the *Calocyclas Bandyca* radiolarian zone which corresponds to approximately 37.3 to 39.1 Ma, predating the major δ18O-isotope enrichment observed in many deep-sea records at about 36 Ma
(Shackleton and Kennett, 1985; Miller and Thomas, 1985; Shackleton, 1986; Miller et al., 1987; Kennett and Stott, 1990; Mackenson and Ehrmann, 1992).

The section is comprised of finely laminated and massive diatomite with sparsely distributed chert, dolomite and phosphate nodule horizons (Fig. 3.4). Data presented in this study focuses on the fine-scale compositional and sedimentological characteristics of the diatomite and diatomaceous mudstone including the mm and cm-scale light and dark alternations.

**Approach**

Twelve diatomaceous samples, spaced approximately every meter, were analyzed from the lowermost thirteen meters of the FD section. In addition to bulk geochemical and petrographic analyses, over two hundred individual and composite laminae were carefully subsampled from ten of the samples. Both the bulk samples and the subsamples were analyzed for the total weight percentage biogenic silica, calcium carbonate, and inorganic and organic phosphorus (Table 3.1, 3.2, 3.3). Detrital content was estimated as the difference between the total weight and the components measured. In addition, all of the bulk samples and laminae from one sample (FD 7) were analyzed for total weight percent sulfur, nitrogen, and organic carbon. Supplementing these geochemical analyses are bulk density measurements, microscope and scanning electron microscope observations, x-ray diffraction and microprobe analyses.

**Bedding, Structure, and Styles**

Rhythmic bedding is a conspicuous feature of the rocks at FD. In addition to the millimeter-scale light and dark laminae observed throughout the section, centimeter- to ten centimeter-scale light and dark and, less common,
Figure 3.4

Measured section of the Yumaque formation at Fundo Desbarrancado (Marty et al., 1988; Dunbar et al., 1990). Samples from the lowermost 13 m of the section were used for this study.
Table 3.1

GEOCHEMICAL RESULTS FROM FUNDO DESBARRANCADO BULK SAMPLES

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<th>WT. % DETRITUS</th>
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EXPLANATION:

- All values given on a gypsum + halite (salt) free basis. To obtain original measured values, divide by (100/(100-salt)).
- Wt. % Opal measurements = measured biogenic silica + 10% structural H2O
  - Wt. % Opal #2 or "total" refers to measurements obtained using one-step dissolution method described in text, #1 or "diatoms" refers to measurements obtained using DeMasters (1979), #2 - #1 or "spicules" = the difference between the above measured values.
- Wt. % Detrital determined by subtracting the wt.%'s of all measured components from 100%
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TABLE 3.2: Geochemical Results From Fundo Debarcarrondo Subsamples, Continued.
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* "TYPE": L= Light, D= Dark, C (L)= Composite Light, C (D)= Composite Dark
* "Munsell Color" of dry powder (Munsell Soil Color Chart (1971))
* Wt. % Opal measurements=measured biogenic silica + 10% structural H20
  * Wt % Opal #2 (= "total") refers to measurements obtained using one-step dissolution method described in text, #1 (= "diatoms") refers to measurements obtained using DeMasters (1979). #2 - #1 (= "spicules + other") equals the difference between the above measured values.
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<td>0.682</td>
<td>49.8</td>
<td>31.7</td>
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<td>17.1</td>
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<td>7.5YR 6/1.5</td>
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<td>0.671</td>
<td>59.8</td>
<td>41.6</td>
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<td>31.1</td>
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<td>0.646</td>
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<td>29.6</td>
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<td>0.136</td>
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<td>10YR 6/2</td>
<td>0.75</td>
<td>0.690</td>
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<td>25.7</td>
<td>14.9</td>
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<td>42.3</td>
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<td>16 L</td>
<td>10YR 6/2</td>
<td>0.083</td>
<td>0.663</td>
<td>45.4</td>
<td>26.2</td>
<td>19.2</td>
<td>11.0</td>
<td>41.2</td>
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<tr>
<td>17 C(D)</td>
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<td>61.2</td>
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<td>44.6</td>
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<tr>
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<td>7.5YR 6/1.5</td>
<td>0.603</td>
<td>0.644</td>
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<td>0.665</td>
<td>61.6</td>
<td>55.5</td>
<td>6.0</td>
<td>1.3</td>
<td>36</td>
<td>0.17</td>
<td>0.144</td>
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<tr>
<td>25 C(L)</td>
<td>10YR 6/1.5</td>
<td>0.37</td>
<td>0.645</td>
<td>58.7</td>
<td>37.4</td>
<td>25.3</td>
<td>4.8</td>
<td>31.4</td>
<td>0.25</td>
<td>0.186</td>
</tr>
<tr>
<td>26 L</td>
<td>7.5YR 6/1.5</td>
<td>0.17</td>
<td>0.645</td>
<td>79.9</td>
<td>67.0</td>
<td>12.9</td>
<td>3.5</td>
<td>15.9</td>
<td>0.19</td>
<td>0.146</td>
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</tbody>
</table>

EXPLANATION:
- "Munsell Color" of dry powder (Munsell Soil Color Chart (1971))
- All values given on a gypsum-halite (salt) basis. To obtain original measured values, divide by (100/100(1-wt%salt)))
- WT. % Opal #2 or "total" refers to measurements obtained using one-step dissolution method described in text, #1 or "diatoms" refers to measurements obtained using DeMasters (1979), #2 or "spicules" is the difference between the above measured values.
- WT. % Detrital determined by subtracting the wt.-%'s of all measured components from 100%.
homogenous and laminated alternations are also present (Fig. 3.2). A
discussion of the different types of laminae observed follows. The preservation
of laminae indicates the exclusion of bioturbating infauna, and thus low oxygen
levels during deposition, while the homogenous intervals may indicate
fluctuations in the oxygen minimum zone through time. Judging by their
general sedimentary fabric, the sediments at FD represent deposition under
oxygen levels which often approached zero. Using Savrda and Bottjer's (1987)
laminae preservation index (which is based on the extent and type of burrowing
observed), these rocks were deposited under anoxic to anaerobic conditions.
Light and dark alternations on all scales are linked to compositional changes
with the light intervals being in general rich in siliceous microfossils and poor in
calcium carbonate relative to the dark intervals (see below for a more complete
discussion). The larger cm-scale cycles observed may be linked to ENSO and/
or sunspot cycles as discussed in the previous section.

Small-scale normal faulting is observed throughout the section (Fig. 3.2).
The faults are generally at a high angle to the bedding and the offset is not
usually more than a few centimeters. Slumped intervals are also present.
Examination of a sample encompassing one such interval, FD 10, reveals that
these intervals are generally siltier with abundant detrital minerals, relatively
high inorganic and organic phosphorus, and large benthic foraminifera,
perhaps indicating a source closer to the coastline and above or at the
boundaries of the oxygen minimum zone.

**Bulk Samples**

Finely laminated diatomaceous rocks from FD are rich in siliceous
microfossils (dominantly diatoms and sponge spicules), with a relatively high
calcium carbonate content (averaging 8%). Original total organic carbon is estimated to be at least 4%, from comparison between measured C:N ratios to ratios present in modern marine plankton (Marty, 1989). They are generally buff to light tan, with subtle color changes between the light and dark laminae. Munsell Soil Color chart values for dry powdered bulk samples as well the laminae are included with compositional results in Tables 3.1, 3.2, and 3.3 (Munsell Color Company, 1971).

All of the bulk sample compositional values are presented on a gypsum- and halite-free basis. These two salts, which account for between 10 and 20% of the total rock, are a post-depositional feature, probably precipitated in pore spaces during uplift. Using a simple water dissolution experiment and subsequent confirmation using x-ray diffraction of both the undissolved sample and the evaporative residue from the supernatant, weight percent salt values were determined for all of the bulk samples (Table 3.1).

X-ray diffraction reveals only a few major components for all of the samples analyzed. These are opal-A, halite and gypsum, calcite, sodic and potassium-rich feldspars, and quartz. Minor components sometimes observed on X-ray diffractograms include carbonate fluorapatite, pyrite, smectite-illite, and minor opal-CT. Organic carbon, phosphorus, and nitrogen (determined using the Carlo-Erba analyzer) are also present in very small quantities (less than 1% of the total weight).

Significant differences with Marty et al. (1988) were discovered in the weight percent biogenic silica determined. They report average opaline silica contents of only 30%, whereas rocks from within 1 to 2 meters of the same horizons which were sampled for this study indicate an average weight percent biogenic silica content of at least 57% (or 63%, if expressed as weight percent
opal with 10% water by weight). This difference can be explained in part by the fact that they did not correct his values for salt content but, more significantly, by the fact that the dissolution method used (DeMaster, 1979) does not adequately dissolve all of the opaline silica in these rocks (discussed in more detail below).

Calcium carbonate values compare favorably with Marty's (1989) results, with an average weight percent of 8% (vs. 6%). Other measured components, organic carbon and phosphorus, carbonate flourapatite, and pyrite, generally represent less than 2% of the total rock. By elimination of all measured components, detrital minerals account for between about 20 to 35% of the total rock. As discussed below, this range represents the maximum values possible, actual values may be 5 to 15% lower.

**Laminae**

The individual laminae and composite laminae studied show much broader compositional range than the bulk samples analyzed (Table 3.2). For example, opaline silica accounts for as much as 92 wt% in some light laminae and as little as 20 wt% of dark and composite laminae. Likewise calcium carbonate is absent in some laminae and in others (usually dark or dark composite laminae) reaches more than 15% of the total weight. Unfortunately, due to very small sample size, only the laminae from FD 7 could be analyzed for gypsum and halite. Therefore, unlike compositional values from the bulk samples which have been corrected for salt, all of the values presented for the laminae (with the exception of those from FD 7, Table 3.3) represent raw measurements. The presented values are probably 5 to 20 wt.% lower than their original compositions and estimates of detrital contribution are less reliable. While not as accurate nor as complete as desirable, these values are
useful for comparisons between laminae and examining the relative proportions among different components.

Results from four general types of laminae are presented (Table 3.4). The correlation between different components for each type is given in Fig. 3.5. "Light" laminae are generally thin intervals (approximately <1 to 2 mm), characterized by relatively high opaline silica values and low carbonate and detrital contents. These laminae also have low total and inorganic phosphorus values and lower total organic carbon values. "Dark" laminae are also thin but exhibit low opaline silica values, and high carbonate, detrital contents, phosphorus, and organic carbon values relative to the light laminae. "Composite dark" laminae and "composite light" laminae may show wispy or discontinuous lamination or may be homogeneous. In a few cases, they may consist of very fine laminae (less than 0.3 mm) which were too thin to subsample. They are generally thicker than the light or dark laminae (usually between 1.5 and 3 mm) and show intermediate compositional values. In general, the composite dark laminae resemble the dark laminae in composition whereas the composite light laminae more closely resemble the light laminae.

**Dry Bulk Density**

Dry bulk density (DBD) measurements were made for all bulk samples as well as the laminae and composite laminae from FD 7. This method yielded accuracy to approximately +/- 0.1 g/cm³. Correction for post-depositional salt precipitation was made by simply subtracting the weight percentage of salt from the density measurements:

\[
\text{DBD}_{\text{Without Salt}} = \text{DBD}_{\text{Measured}} - \left( \frac{\text{Total Salt} \times \text{DBD}_{\text{Measured}}}{100} \right)
\]
Figure 3.5

Correlation chart showing the correlation factors (R) for different components in each of the different subsample types of FD rocks as determined by linear regression. N.C. : R < .20; (+), (-) : .20 < R < .40; (++) (--) : .40 < R < .60; (+++) (++++) : .60 < R < .80; (++++) , (---) : R > .80.
<table>
<thead>
<tr>
<th></th>
<th>BIOGENIC S (TOTAL)</th>
<th>DIATOMS-RAD'S</th>
<th>OTHER BIOG.</th>
<th>CACCI</th>
<th>P (TOTAL)</th>
<th>P (UNORGANIC)</th>
<th>P (ORGANIC)</th>
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<td>AVE D L CD CL</td>
<td>AVE D L CD CL</td>
<td>AVE D L CD CL</td>
<td>AVE D L CD CL</td>
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<td>(+)</td>
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<td>N.C.</td>
<td>N.C.</td>
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<td>(+)</td>
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<th>CACCI</th>
<th>P (TOTAL)</th>
<th>P (UNORGANIC)</th>
<th>P (ORGANIC)</th>
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<td>(+++)</td>
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<td>(-)</td>
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<td>(+)</td>
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<td>(+)</td>
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Table 3.4

Compositional data of 211 subsamples (of 10 rocks) from Fundo Desbarrancado compiled by type. Each value represents the mean value +/- 1 standard deviation.

<table>
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<tr>
<th>All Measurements mean +/- 1 std. deviation</th>
<th>All</th>
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<th>Light Homog.</th>
<th>Dark Laminated</th>
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<tr>
<td>Number of Lams.</td>
<td>211</td>
<td>74</td>
<td>49</td>
<td>44</td>
<td>44</td>
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<tr>
<td>Thickness (cm)</td>
<td>.206 +/- .119</td>
<td>.138 +/- .071</td>
<td>.269 +/- .125</td>
<td>.133 +/- .051</td>
<td>.320 +/- .144</td>
</tr>
<tr>
<td>Total biogenic silica* (wt %)</td>
<td>57.0 +/- 11.2</td>
<td>62.2 +/- 10.8</td>
<td>57.9 +/- 7.3</td>
<td>46.9 +/- 7.0</td>
<td>47.2 +/- 6.2</td>
</tr>
<tr>
<td>Diatoms and Radiolarians** (wt %)</td>
<td>36.1 +/- 10.5</td>
<td>46.0 +/- 11.3</td>
<td>36.5 +/- 6.4</td>
<td>27.2 +/- 5.5</td>
<td>27.6 +/- 5.5</td>
</tr>
<tr>
<td>Sponge spicules/other*** (wt %)</td>
<td>20.9 +/- 5.3</td>
<td>22.2 +/- 6.8</td>
<td>21.3 +/- 5.4</td>
<td>19.7 +/- 3.7</td>
<td>19.6 +/- 3.9</td>
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<tr>
<td>CaCO3 (wt %)</td>
<td>5.8 +/- 2.8</td>
<td>4.4 +/- 2.1</td>
<td>5.5 +/- 3.2</td>
<td>6.0 +/- 2.6</td>
<td>7.2 +/- 3.1</td>
</tr>
<tr>
<td>Detrital Component (wt %)</td>
<td>37.2 +/- 14</td>
<td>27.4 +/- 12.9</td>
<td>36.6 +/- 10.5</td>
<td>47.1 +/- 9.6</td>
<td>45.6 +/- 9.3</td>
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<tr>
<td>Inorganic Phosphorus (PPM)</td>
<td>825 +/- 250</td>
<td>617 +/- 189</td>
<td>887 +/- 190</td>
<td>958 +/- 213</td>
<td>973 +/- 241</td>
</tr>
<tr>
<td>Organic Phosphorus (PPM)</td>
<td>87 +/- 66</td>
<td>76 +/- 63</td>
<td>83 +/- 62</td>
<td>87 +/- 66</td>
<td>112 +/- 77</td>
</tr>
<tr>
<td>Total Phosphorus (PPM)</td>
<td>912 +/- 277</td>
<td>693 +/- 210</td>
<td>970 +/- 212</td>
<td>1044 +/- 223</td>
<td>1086 +/- 255</td>
</tr>
</tbody>
</table>

* Biogenic silica from one-step dissolution experiment.
** Biogenic silica from time series dissolution experiment (DeMaster, 1979; Marty, 1989).
*** Difference between above two numbers.
As may be expected for a rock rich in opaline silica, these rocks have low (DBD) values, averaging only 0.74 g/cm³. After correcting for salt content, DBD averages just 0.64 g/cm³. Based on average grain densities of the different components measured and dry bulk densities (both corrected for salt content), porosity in these rocks is as high as 60 to 70%.

In general, the bulk rocks containing more detritus have a higher, corrected DBD than do rocks with a lower detrital but higher biogenic silica content. Similarly, the dark, more detrital-rich laminae have slightly higher DBD’s than do the lighter laminae.

**Biogenic Silica**

Biogenic silica in the Fundo Desbarrancado section is dominantly present as opal-A, although minor opal-CT may be present in some samples (Fig. 3.6). Microscopic and scanning electron microscopic examination of strewn slides and of thin slabs respectively, reveals that the biogenic silica is present as broken and, more rarely intact, diatoms, sponge spicules, and minor radiolarians, silicoflagellates, and ebridians (Fig. 3.7 and 3.8). Diatoms are the dominant siliceous microfossil in all laminae, but are more abundant in the light laminae and composite light laminae than in the dark and composite dark intervals. This observation is supported by both qualitative microscopic observations and semi-quantitative dissolution studies, described below.

All of the bulk and lamina samples were first analyzed for biogenic silica using the dissolution method of DeMaster (1979), which was modified and used on FD rocks by Marty (1989). This method, as briefly described in the Methods section, yielded similar results to those reported by Marty (1989), with extracted biogenic silica values averaging approximately 30 wt%. However, subsequent
X-ray diffraction patterns for samples from Fundo Desbarrancado (FD), Punta El Puente (PP), and Playa El Erizal (PE) showing effect of detrital component on diagenesis in biosiliceous rocks from each section. Q= Quartz, Cr= Cristobolite, C= Calcite, Fsp= Feldspar (probably albite), Tr= Tridymite. For each section, diagenesis of silica increases as detrital content increases. This is demonstrated quantitatively for rocks from FD, and semi-quantitatively for rocks from PP and PE where detrital content is observed to increase in different rock types in the following order: Light, laminated< Dark, laminated< Light and Dark massive rocks (see text). Silica diagenesis proceeds from opal-A to opal-CT to quartz; the progression from opal-CT to quartz is accompanied by a sequential decrease in opal-CT d-spacings.
Opal CT + Quartz
(4.08 - 4.09)

Opal CT 4.07A

Opal CT 4.10 A

Opal A + Opal CT

Opal A

CT

Cr

C

Fsp

O

PE 19
Dark, Laminated

PE 20
Light, Laminated

PP 53
Dark, homogeneous

PP 54
Dark, laminated

PP 42B
Dark, laminated

PP 42A
Light, laminated

PP 62A
Light, Laminated

FD 2
Laminated
Detrital minerals = 22%
CaCO3 = 6.6%

FD 10
Laminated
Detrital minerals = 27%
CaCO3 = 13.6%

FD 1
Laminated
Detrital Minerals = 32%
CaCO3 = 5.1%
Figure 3.7: Scanning Electron Micrograph of a diatom from Fundo Desbarrancado (FD 7) at 1,500x. Fragmentation of the diatom probably occurred during preparation of the sample.
Figure 3.8

Scanning Electron Micrograph of biosiliceous debris in dark laminae from a Fundo Desbarrancado sample (FD 7) at 1000x. Note broken diatom frustules and sponge spicules. Differences are observed between light and dark laminae within each sample, with the amount of diatom debris being greater in the light laminae than in the dark.
examination of the undissolved residue using x-ray diffraction and microscopy determined that not all of the opaline silica was extracted using this method. While most of the diatoms and radiolarians were dissolved using this method, many, if not all, of the sponge spicules and more rare silicoflagellates and ebridians survived dissolution. This differential dissolution is probably due to the high surface area to volume ratio for diatoms and radiolarians in comparison to the spicules. The first stage of dissolution is "structural dissolution", which removes fine and ultra-fine skeletal structures of diatoms and radiolarians, leaving the spicules intact (Mann and Heidelberg, 1985). The spicules begin to dissolve during the next phase of surface corrosion.

In order to obtain more accurate biogenic silica measurements, a stronger base was used in a one-step dissolution experiment, as described in the Methods section. This method yielded biogenic silica values nearly twice as high as those determined by the other method, averaging over 50% of the total rock. Microscopic examination of the residue following this dissolution experiment indicates that detrital minerals were not affected; they did not appear to be etched, and contain approximately the same proportions of quartz and feldspar as the untreated samples. Although it was independently determined that these samples contain little clay (see detailed discussion under "Clay Minerals"), clay standards were analyzed using the same parameters as the samples to determine how much Si is extracted using this method. Analyses were run twice on pure illite, montmorillonite and kaolinite standards yielding an average of 4, 6, and 9% total extracted silica, respectively. These low percentages coupled with the fact that very little clay is indicated for in these rocks (probably less than 5% in the bulk rocks and in most laminae) reinforces
the idea that most or all of the increase in silica extracted is attributable to the increased dissolution of siliceous microfossils, primarily sponge spicules.

Following the second dissolution experiment, the undissolved residue was again examined using microscopy and x-ray diffraction revealing that most, if not all, of the biogenic silica was extracted. However, some spicules, which appeared etched, did remain in several samples. Therefore, biogenic silica values obtained by this method may be considered minimum values with an estimated error of 5-10%. Using these new values, and the observation that the first dissolution method dissolved all or most of the diatoms and radiolarians but not the spicules and other siliceous microfossils, semi-quantitative percentages of these two groups of siliceous organisms were obtained. In most figures, values from the first dissolution method are informally referred to as "diatoms and radiolarians" and the difference between these values and the total silica extracted in the second experiment is referred to as "spicules and other". In the tables, these numbers are presented as wt% Si#1, representing numbers derived from the first dissolution experiment, using the dissolution method of DeMaster (1979), and wt% Si#2, representing the total biogenic silica derived by the one-step dissolution method. The difference between the two is taken as an estimate of the content of sponge spicules and other siliceous microfossils in the rock. While only approximate, on the average, diatoms and radiolarians account for over 60% of the total biogenic silica extracted with this number tending to be higher in the light and composite light intervals (67 and 63%, respectively) and lower in the dark and composite dark intervals (58% for both) (Table 3.4). The estimates given for the different percentages of siliceous microfossils present based on their relative solubility are only approximate. An
error of approximately +/-5% is indicated, based on visual inspections of the residue before treatment and after both dissolution experiments.

Detrital Minerals

The detrital component of the bulk rocks and laminae was determined using x-ray diffraction, microscopic examination of both thin sections and strewn slides, and semi-quantitative microprobe analysis. The dominant minerals are albite, potassic feldspar, and quartz, with minor clay and pyrite. Qualitative microprobe analysis of the feldspars indicates a wide compositional range. Albite, the end member for both groups, is the dominant mineral observed but grains with significant calcium or potassium were infrequently observed. The minerals observed are well-sorted, ranging between 10 and 100 µm, with most grains between 30 and 50 µm. In general, the feldspars are present as euhedral, angular grains with very little alteration visible. Twinning is well-preserved in the plagioclase grains. Quartz grains do not appear to be quite as abundant as the feldspars and are present as very angular and clear grains, usually between 30 and 60 µm. The presence of mainly euhedral albite and quartz suggests an andesitic source. The lack of significant alteration observed in the detrital grains, and the generally good sorting and small grain size, may suggest either fluvial transport over a short distance or eolian transport during dust storms.

The relative percentage of all detrital minerals was determined by adding the weight percentages of all other components measured (opal-A, gypsum and halite, carbonate, carbonate apatite, organic matter, etc.) and subtracting from the total weight. Since minimum values for the largest single component, opal-A (calculated with 10% H2O in their crystal structure), are given, the percentage
detrital minerals calculated in this way are considered maximum values with an estimated error of 5-10%. Furthermore, since small sample sizes for all of the laminae and composite laminae (except those of FD 7) prohibited direct measurement of the total salt present, detrital mineral percentages could only be estimated with confidence for the bulk samples and FD 7 laminae.

In the bulk samples, the total weight percent of detrital minerals ranges between 21 and 36%, with an average of 27%. The laminae from FD 7 exhibit a similar average (25%) but a considerably broader range, with some dark laminae exceeding 50% and some light laminae possessing less than 10% detrital minerals (Table 3.3). This difference in the relative abundance of detrital minerals of light and dark laminae is confirmed by microscopic observations of both thin sections and strewn slides (Figs. 3.9 and 3.10).

**Clay Minerals**

In the Fundo Desbarrancado section, no clay minerals were detected by x-ray diffractometry of bulk samples. However, after treatment with 12 M HCl (to remove any carbonate) and heating in a 1 M solution of NaOH for five hours (to remove the biogenic silica), two air-dried FD samples exhibited small, broad peaks between 14 and 17Å, characteristic of mixed layer clays. The presence of small and broad peaks reflects low abundance even after carbonate and most of the biogenic silica is removed (approximately 75 to 90% of the total sample), and possibly poorly crystallized phases as well. The average total clay percentage is estimated as less than 5-10%.

The two FD samples exhibiting clay peaks (FD-10 and FD-7) were subsequently analyzed both after heating to 550°C for 1 hour, and after glycolation. After heating, the 14 to 17Å peak collapsed to approximately 10Å,
Figure 3.9

Photo micrograph of light and dark laminae from a Fundo Desbarrancado sample (Fd 5) at 2.5x with crossed nicols. Light laminae appear dark because of an abundance of (isotropic) opal-A. Dark laminae appear lighter because of their higher abundance of birefringent minerals and calcite filled foraminifera. Figure 3.12 shows a close-up of "B".
Figure 3.10

Close-up photo micrograph of "B" in Figure 3.11 showing boundary between a light and a dark lamina (10x, crossed nicols). Birefringent minerals in the dark lamina include disseminated calcite, plagioclase and quartz grains.
confirming the presence of an expandable mineral component. However, glycolation resulted in negligible expansion and no increase in the intensity of the basal peak. This may indicating the presence of vermiculite as reported by Clayton and Kemp (1990) for samples sharing very similar x-ray diffraction characteristics in Quaternary rocks collected from the Peruvian continental margin during ODP Leg 112.

**Carbonate and Apatite**

Calcium carbonate (usually calcite but perhaps sometimes low Mg-calcite as well) is present both as planktonic and benthic foraminifera and as fine-grained cement, averaging about 8% in the bulk samples (Fig. 3.10). In all but one sample (FD 5), the foraminifera are well-preserved and concentrated in the dark and composite laminae. In FD 5, foraminiferal casts are observed in about the same abundance as the other samples, suggesting that dissolution, rather than a change in deposition, is responsible for its relatively low carbonate content (about 2%).

Larger benthic forams (1-2 mm) were observed in only one rock, FD 10, and are probably transported specimens from a slumping event. In all other samples, only planktonic foraminifera were positively identified and these were concentrated in the dark and composite laminae. Average values for total carbonate (uncorrected for salt content) in the laminae are highest in the composite dark laminae, followed by the dark, composite light and light laminae (7, 6, 5 and 4% respectively). The different percentages are probably due to greater and lesser abundances of planktonic foraminifera. The amount of disseminated calcite cement appears to be evenly distributed throughout most samples.
Apatite accounts for an average of less than 2% of the total weight of the samples examined. It is present as either carbonate apatite or carbonate flourapatite, as determined by x-ray diffraction. The total percentages were calculated from inorganic phosphorus measurements, with all of the inorganic phosphorus attributed to carbonate apatite or carbonate flourapatite. The relative abundance of the apatite minerals in the laminae follow the trends of calcium carbonate.

**Organic Matter**

Total organic carbon (TOC), nitrogen, and phosphorus were measured for all of the bulk samples and laminae from FD 7 (Tables 3.1 and 3.3). Measured values of organic carbon average less than 1% of the total rock, however, it is likely that much of the original organic carbon has been leached during surface weathering of the outcrop. By comparing organic carbon to nitrogen ratios in dolomite layers from FD to those of living marine organisms, Marty (1989) estimates that the original organic carbon values were at least 4%. This estimate compares favorably to TOC percentages measured in Pliocene to Miocene diatomaceous rocks underlying the upwelling margin off Peru (ten Haven et al., 1990). Present organic carbon values in the bulk samples and laminae exhibit a negative correlation to total biogenic silica and positive correlations to calcium carbonate, total phosphorus, and detrital minerals (Fig. 3.5). In FD 7 laminae, the highest values are observed in the detrital-rich dark laminae and the lowest in the more biosiliceous light laminae. The same correlation between TOC and detritus is observed in rocks recovered from ODP Leg 112 off Peru. Patience et al. (1990) suggest two possible interpretations for this: 1) this may suggest a terrigenous source (clay) for the organic carbon
remaining in the FD rocks, or 2) it could represent a preservation signal, with organic matter generally better preserved in the dark, less porous (lower DBD's) and more detrital-rich laminae than in the lighter, more diatomaceous, laminae.

Organic phosphorus contents are generally very low, averaging less than 0.015% of the total rock. This is lower than values for siliceous pelagic sediments and lower by an order of magnitude than typical measurements for sediments deposited under upwelling conditions (Baturin, 1982). Modern diatomaceous algae may contain anywhere from 0.4 to 3% phosphorous by weight (Baturin, 1981 and references cited therein). Thus, using conservative estimates of both the average total weight percentage of diatoms in the FD samples (30%), and a relatively low phosphorous content of their tissues compared to modern algae (0.4%), organic phosphorous values of FD rocks should average over 0.1%. This suggests that much of the organic phosphorous was either released from the sediments at some stage during diagenesis or that it was reprecipitated as an inorganic apatite mineral. If however, most of the inorganic phosphorus measured is assumed to have been originally deposited within organic matter, then the total phosphorus measured (averaging) corresponds well to that of sediments deposited under high productivity conditions. All the inorganic phosphorus could not have had an organic origin since fish debris was recognized in at least some of the samples. However, it is likely that at least some of it is probably organic origin, given the anomalously low organic phosphorus measurements.
Fundo Desbarrancado: Summary and Discussion

The preservation of millimeter-scale laminae in the sediments present at FD suggests deposition under very low oxygen conditions. The rocks at FD are generally very biosiliceous and were probably organic-rich when originally deposited. The biosiliceous component of bulk rocks ranges between approximately 55 and 75 wt.%, with diatoms and radiolarians accounting for about 31-48 wt%. Sponge spicules, and minor silicoflagellates and ebridians, account for the remainder of the siliceous microfossils in these rocks. On the average, calcium carbonate, present mostly as foraminifera, accounts for about 8 wt.%. Organic matter, carbonate fluorapatite, pyrite, and perhaps some minor clay, account for less than 1% of the total weight of the rocks and individual laminae. Detrital minerals (mainly quartz and albite), along with minor clay, account for the remainder of these samples.

The subsampled laminae and composite laminae exhibit much broader compositional ranges. In general, the light laminae are enriched in diatoms, but impoverished in detrital minerals and CaCO₃ relative to the dark laminae. Little variation is observed in the weight percent sponge spicules measured in light and dark laminae (Table 3.4). Composite laminae generally show intermediate compositions between light and dark laminae.

Sedimentation and Mass Accumulation Rates

Mass accumulation rates (MAR) can be calculated for the different components if the sedimentation rate and dry bulk density of the sediments is known by the formula:
LSR (cm/kyr)*DBD*%comp/100=MARcomp,

where LSR=linear sedimentation rate, DBD=dry bulk density and %comp=total wt% of a component. Mass accumulation rates (MAR) for the individual components of FD rocks, such as biogenic silica, were calculated using their relative weight percentage of the total rock, on a gypsum and halite-free basis (Fig. 3.11). For the FD samples an average linear sedimentation rate (LSR) of 235 cm/kyr was calculated from average thicknesses of laminae couplets measured in hand specimens (and from laminae thicknesses which have been measured from scanned photographs) after assuming that each light and dark couplet represents an annual layer. This rate is higher than the varve-calibrated rate of 78 cm/kyr calculated by Marty et al. (1988) using laminated rocks from the same section and is somewhat high compared to sedimentation rates calculated for other upwelling deposits (Fig. 3.12). A possible reason for this is that some of the thin (<0.3 mm), wispy and/or discontinuous laminae interpreted here as representing an intraseasonal event, were interpreted by Marty et al. (1988) as representing seasonal deposition. Another possibility is that the laminae thicknesses in the section are not consistent, with the intervals analyzed here representing higher sedimentation rates than the laminated intervals used for Marty et al.'s (1988) calculation. Both possibilities could contribute to overestimates of overall sedimentation and mass accumulation rates.

MAR's calculated from this sedimentation rate and an average dry bulk density of 0.63 g•cm\(^{-3}\) are higher than Marty et al.'s (1988) and studies of other upwelling sediments (Fig. 3.12). For biogenic silica, for example, a MAR of over 80 g•cm\(^{-3}\)/kyr is calculated. This is substantially higher than the value of
Figure 3.11

Mass accumulation rates (MAR) of major components of bulk rocks from Fundo Desbarrancado. Values are calculated using a varve-calibrated sedimentation rate of 0.235 cm/yr and measured percentages of each component. Note large variations in detrital and "diatoms+radiolarian" accumulation rates and relative constancy of "sponge spicules + other".
Figure 3.12

Comparison of Mass accumulation rates between the Yumaque formation (represents values from bulk FD samples) and Recent and Neogene upwelling sediments from Peru and California.
<table>
<thead>
<tr>
<th>LOCATION AND/OR FORMATION</th>
<th>APPROXIMATE AGE</th>
<th>TOTAL ACCUMULATION RATES ** (M/MY)</th>
<th>AVE. THICKNESS (METERS)</th>
<th>ACCUMULATION RATE ESTIMATES IN G/ (CM^2) YR(1000yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yumaque Formation - this study*</td>
<td>L. Eoc. to E. Olig.</td>
<td>2350</td>
<td>150 m ***</td>
<td>149</td>
</tr>
<tr>
<td>Yumaque Formation - previous work* (Marly et al., 1989, Marly, 1989)</td>
<td>L. Eoc. to E. Olig.</td>
<td>780</td>
<td>**</td>
<td>81</td>
</tr>
<tr>
<td>Offshore Peru, 11 to 14°S ***** (from Schaddegger &amp; Krissek, 1981, &amp; references cited therein)</td>
<td>Recent</td>
<td>300 to 3400</td>
<td>(? )</td>
<td>9 to 75</td>
</tr>
<tr>
<td>Monterey Formation, California (from Isaacs, 1984, &amp; ref.'s cited therein)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clayey, Siliceous Member</td>
<td>L. Mocene</td>
<td>96 to 500</td>
<td>150</td>
<td>2.3 to 11</td>
</tr>
<tr>
<td>Upper Calcareous to Siliceous &amp; Transitional Marl to Siliceous Members</td>
<td>Early L. Mocene</td>
<td>130 to 170</td>
<td>70</td>
<td>2.9 to 3.8</td>
</tr>
<tr>
<td>Carbonaceous Marl</td>
<td>M. Mocene</td>
<td>110 to 140</td>
<td>75</td>
<td>2.5 to 3.2</td>
</tr>
<tr>
<td>Lower Calcareous to Siliceous Member</td>
<td>E. to M. Mocene</td>
<td>180 to 370</td>
<td>120</td>
<td>4.5 to 8.4</td>
</tr>
<tr>
<td>Sisquoc Formation, California (from Isaacs, 1984, &amp; ref.'s cited therein)</td>
<td>E. Pliocene</td>
<td>&gt;750 to &gt;3700</td>
<td>&gt;500</td>
<td>&gt;15 to &gt;72</td>
</tr>
<tr>
<td>Rincon Shale (from Isaacs, 1984, &amp; ref.'s cited therein)</td>
<td>E. Mocene</td>
<td>360 to 570</td>
<td>500</td>
<td>8.5 to 14</td>
</tr>
</tbody>
</table>

*All values (except thickness) represent averaged measurements from Fundo Desbarrancado bulk samples.

** Total Accumulation Rates for the Yumaque Formation represent compacted thickness & therefore represents a minimum value. Values for the Monterey Formation have been decompacted assuming an original porosity of 90% (see Isaacs, 1984).

***This value is based on the compacted thickness of the Yumaque Fm. at Playa El Erizal (Dunbar et al, 1990). Compacted thickness of Fundo Desbarrancado section is only about 25 m.

****Above organic carbon values represent actual measured values whereas values in parentheses represent estimated original values (see text).

***** Ranges given represent values from 6 cores taken at water depths ranging from 186 to 411 meters.
17 g•cm\(^{-3}\)/kyr reported by Marty et al. (1988) and the values of 0.5 to 16.8 g•cm\(^{-3}\)/kyr measured from eight cores off coastal Peru today (Scheidegger and Krissek, 1981; DeMaster, 1981). Almost half of the discrepancy with Marty et al.'s estimate may be accounted for by the increased estimate of the total weight percentage of biogenic silica reported here. If an estimate of 50 wt.% (versus 28.5 wt.%) biogenic opal is used along with their dry bulk density and LSR estimates given, then a biogenic silica MAR of 30 g•cm\(^{-2}\)/kyr is obtained. The discrepancy between the MARs reported here and those of other upwelling deposits may be explained in part by the fact that the sedimentation rates used in these studies often are extrapolated over laminated and massive intervals whereas the rate presented here for FD sediments reflects the sedimentation rate for laminated intervals only. Isaacs (1984) reports that in the Monterey Formation, for example, biogenic silica-rich beds which are laminated have sedimentation rates which are between 2 to 10 times higher than member averages. She concludes that the massive intervals represent comparatively slow accumulation during periods of weak to moderate primary productivity with either a less intense or displaced oxygen minimum zone (increased dissolution of biogenous material is another possibility). The discrepancy between the biogenic silica accumulation rates reported here and those from Recent Peruvian cores, which are not continuously laminated, may be explained in part by this phenomena.

Even if the LSR reported here is overestimated, the relative differences between the MAR's of different components calculated using this rate should remain unchanged. Therefore, it is possible to examine which biogenic or detrital components maintained a constant flux and which varied seasonally and/or interannually. For the bulk samples, the detrital content is the largest
influence on the overall MAR. When detrital input was high, overall MAR's were also high and vice versa (Fig. 3.11). The accumulation rate of detritus is negatively correlated to the accumulation rate of diatoms and radiolarians (hereafter referred to only as "diatoms" as they are the dominant microfossil within this group). Accumulation rates for both CaCO₃ and sponge spicules are fairly constant, varying over only a short range. The remaining 1-3% of these rocks ("other"), consists of carbonate fluoroapatite, pyrite, and organic carbon, nitrogen and phosphorus. These relationships indicate that on a hand specimen scale, the relative contribution of detritus and diatoms was the largest controlling factor on the composition of these rocks. The accumulation rates of both vary over a broad range (24 g·cm⁻³/kyr), indicating significant fluxes at this scale.

Centimeter-scale changes in MAR's were also examined for the one sample (Fig. 3.13). Six light and dark intervals, averaging about 1.5 cm thick each, were examined. This sample was mildly bioturbated, however, using the LSR of 235 cm/kyr, each cycle represents approximately 5 to 6 years of deposition. This corresponds roughly to the periodicity recorded for ENSO-type phenomena (Baumgartner et al., 1985; Anderson, et al., 1989; Ripete et al., 1990). Like in the hand specimens, MAR's of detritus and diatoms revealing the largest fluxes observed. Here however, the MAR of CaCO₃ also exhibits significant variations which are positively correlative to the detritus flux. Once again, the sponge spicule contribution appears to be roughly constant. In general, the lighter intervals are less dense and are relatively diatom-rich in comparison to the detrital and CaCO₃-rich dark intervals.

Due to small sample sizes and the relatively large amount of sample needed, salt contents and DBDs were not determined for any of the
Figure 3.13

Mass accumulation rates (MAR) of major components of subsamples from FD 7. Values are calculated using a varve-calibrated sedimentation rate of 0.235 cm/yr and measured percentages of each component. Subsample results were grouped according to cm-scale light and dark bands, which may reflect ENSO-type variability. Note large variations between all components at this scale, with detrital and calcium carbonate accumulation rates higher in the darker than in the lighter bands. Likewise, lighter bands exhibit higher accumulation rates for biosiliceous components than do the dark bands. Total accumulation rates remain nearly constant.
subsampling laminae except for those from FD 7. Furthermore, intraannual age control is not available. For these reasons, it was not possible to calculate MAR'S for the different types of laminae. As mentioned previously, however, geochemical results from the different types of subsampled mm-scale intervals (light, dark, composite light and composite dark) were separated and then averaged. These averages, the amount of variance observed, and petrographic observations for each type are summarized in Table 3.4. In general, the trends observed in the weight percentages of components measured between light and dark laminae are the same as for the MARs reported for the cm-scale light and dark cycles. The light laminae have highest total weight diatoms, and the lowest total weight % detritus. Conversely, the dark laminae exhibit the lowest total weight % diatoms and the highest total weight % detritus. Neither CaCO₃ nor sponge spicules show significant fluctuations in their weight percentages between light and dark laminae. Further study analyzing the salt content and DBDs of a number of adjacent light and dark laminae, combined with assumptions regarding the time interval represented by both light and dark laminae, may help to establish estimates of MARs at the lamina scale.

Comparison With Neogene and Recent Varved Records

In general, the geochemical and sedimentological characteristics of FD Yumaque rocks favorably compare with observations from the following known, or inferred, varved sediments formed under upwelling conditions: Recent sediments from the Gulf of California (Calvert, 1966; Soutar et al., 1981; Baumgartner, 1989), Pliocene to Holocene biosiliceous rocks from offshore Peru (Kemp, 1990; Patience et al., 1990), and rocks from the Neogene
Figure 3.14

Comparison between Yumaque formation laminated sediments and known varved sediments giving general descriptions of each and showing the overall similarities between them.
<table>
<thead>
<tr>
<th>FORMATION / LOCATION</th>
<th>AGE</th>
<th>COMMENTS / OCCURRENCE</th>
<th>LAMINA THICKNESS (MM) (* Computed)</th>
<th>DESCRIPTION OF LIGHT &amp; DARK LAMINAE</th>
</tr>
</thead>
</table>
| YUMAGUE FORMATION      | L. EOC. - E. OLIGO | FO: laminar well-defined, almost continuous in section. PP & PE: laminar often wavy and/or discontinuous, see description for Monterey. | FO:  LIGHT: 1.3 *DARK: 1.3 *COUPLETS: 2.38  (PP & PE: 5 - 10 lam.) (this study) | LIGHT: Biosiliceous-rich (diatomsradioarriae) & detritus-poor; less dense.  
DARK: Detritus-rich & biosiliceous-poor; slightly more TOC & P (total) than light laminae; more dense.  
(Marty et al., 1986; this study)                                                                                                                                                                                                                     |
| E. PISCO BASIN         |            |                                                                                      |                                    |                                                                                                                                                                                                                                                      |
| ODP LEG 112            | PLIO & QUAT | Close and regular laminae spacing influx of either terrigenous or biogenic component or both variable seasonally, highest sedimentation rates for laminae sediments at least 150 mm/ky at Site 656  
(Kemp, 1990)                                                                 | LIGHT:  - 2  *DARK:  - 2  *COUPLETS:  - 4  
(Kemp, 1990) | LIGHT: "Oozes" or "Composite Oozes" laminae, intact to fragmented diatom frustules, may include terrigenous microlayers interpreted as a response to current activity; not settling from surface layers.  
DARK: Terrigenous-rich; great variability: one or combination of diatomaceous mud, detritus-poor mud, silt mud, or silt enriched in TOC relative to light laminae.  
(Kamp, 1990; Patience et al. 1990)                                                                                                                                                                                                                   |
| PERU SHELF & SLOPE     |            |                                                                                      |                                    |                                                                                                                                                                                                                                                      |
| GULF OF CALIFORNIA     | RECENT     | Deposition of dark laminae tied either to increased winter runoff (Calvert, 1966) or inc. tidal sediment transport during summer months  
(Baumgartner et al., 1985); ENSO cyclonicity (Baumgartner et al., 1985)                                                                 | LIGHT:  0.2 - 3.0  *DARK:  0.2 - 3.0  *COUPLETS:  0.7 - 5.4  
(Calvert, 1966) | LIGHT: Diatom-rich, silty clay (52.4% opal, 7% quartz); some thick light laminae contain thin laminae of darker material, under crossed nicols, laminae almost isotropic; less dense.  
DARK: Terrigenous-rich, silty clay (56.3% opal, 10% quartz); under crossed nicols, show abundance of silt-sized birefringent grains; often normally graded, more dense.  
(Calvert, 1966; Sauter & Carr, 1977)                                                                                                                                                                                                                   |
| N.W. MEXICO            |            |                                                                                      |                                    |                                                                                                                                                                                                                                                      |
| MONTEREY FORMATION     | MIOCENE    | Best defined, most even, varve-like lamination in clay-poor silice-rich beds; in general massive diatom-rich beds alternate with regularly laminated silice-rich beds; lamination in fm. is common but not ubiquitous  
(Isaacs, 1984)                                                                 | LIGHT:  0.4 - 0.8  
(Pascotto & Garrison, 1981) | LIGHT: Biosiliceous-rich; greenish to grayish to yellowish hues, unburrowed, more diatoms and foraminifera.  
DARK: Terrigenous-rich; disseminated organic matter, local pellets and clay-rich layers.  
(Pascotto & Garrison, 1981; Cowan & Garrison, 1981)                                                                                                                                                                                                     |
| (U.SILICEOUS MEMBER)   |            |                                                                                      |                                    |                                                                                                                                                                                                                                                      |
| CALIFORNIA             |            |                                                                                      |                                    |                                                                                                                                                                                                                                                      |
| ONNAGAWA FORMATION     | MIDDLE MIOCENE | Nearly 50% of the siliceous rocks are laminated. lamination in both light & dark layers; lamination interrupted by homogeneous intervals, a few mm's to 10's thick; lam in from higher productivity  
(Tada, 1991)                                                                 | LIGHT:  0.50 - 0.60  *DARK:  0.25 - 0.3  
(Couplet:  0.63 - 0.38  
(Tada, 1991) | LIGHT: Biosiliceous-rich; pale brown to transparent, rich in monocrystalline quartz and/or dolomite crystals;  
Biogenic silica: MAR = 20 - 30 (Moore, 1976) (higher than dark lam. is by factor of two); detritus account const.  
DARK: Terrigenous-rich; brownish-black, rich in detritus grains, pyrite, and biogenic fragments; TOC higher in some dark layers; detrital account; biogenic silica account less than light layers.  
(Tada, 1991)                                                                                                                                                                                                                                             |
| NORTHERN JAPAN         |            |                                                                                      |                                    |                                                                                                                                                                                                                                                      |
Monterey Formation of California (Pisciotto and Garrison, 1981; Govean and Garrison, 1981) and Onnagawa Formation of Japan (Tada, 1991) (Fig. 3.14).

In all of these examples, mm-scale dark, detrital-rich laminae alternate with lighter, more biosiliceous laminae assumed or, in the Recent sediments in the Gulf of California, known to represent an annual depositional layer. Where reported, the dark laminae are also denser and sometimes more TOC-rich than the light laminae.

An annual origin for these light/dark couplets in the older rocks is supported by linear sedimentary rates (LSR) calculated using independent age estimates. In all of the rocks but those from the Onnagawa Formation, each couplet is approximately .8 to 5 mm thick (compacted thickness) with no significant thickness differences observed between the light and dark laminae. This corresponds to LSRs ranging between 80 cm/kyr (Monterey Formation) to 500 cm/kyr (Gulf of California) which encompass the estimated LSR for FD rocks (235 cm/kyr).

**PUNTA EL PUENTE AND PLAYA EL ERIZAL RESULTS**

Descriptions and results from Punta El Puente and Playa El Erizal are presented together. From their lithological similarities, close proximity and limited age control, they are interpreted to be roughly correlative. Both sections are locally phosphatic (up to 1%), muddy porcelanites which show millimeter to meter-scale light and dark, and sometimes laminated and massive, alternations (Plates 3.1 and 3.2 (in back pocket); Fig. 3.15). Intercalated with the mudstone are glauconitic sand, ash, as well as calcite and dolomite nodule beds. This assemblage of lithologies is characteristic of highly productive coastal
Figure 3.15

Measured section of the Yumaque fm. at Playa El Erizal (Dunbar et al., 1990).
upwelling deposits off the Peruvian, Californian, and NW African margins today and in the geological past (Baturin, 1981). Both sections are well-exposed in cliffs along the coastline with PP and PE approximately 10 and 20 km, respectively, to the south of the Paracas Peninsula. A combination of age estimates from nannofossils, foraminifera, and $^{87}$Sr/$^{86}$Sr ratios, indicates a late Eocene age for the PE section and the lowermost 83 meters of the PP section (Dunbar, et al., 1990). The upper approximately 150 meters of section at PP is much younger and probably belongs to the late Oligocene to Miocene Chilcatay formation.

Results, including field and petrographic observations, and total calcite, phosphorus and organic carbon measurements, are presented for samples from the entire PP section (including the younger rocks) and from the uppermost 20 meters of the PE section. Unfortunately, access and time constraints did not permit sampling of the lower portion of the PE section. Attention was focused both on the compositional and sedimentological differences between the prominent centimeter and meter-scale light and dark (and, to a lesser extent, laminated and massive) alternations in the mudstones and on the silica diagenesis of these rocks. Eocene rocks from both PP and PE are very biosiliceous, with high inferred original organic content. Miocene rocks from PP, on the other hand, seem to record a change to more tuffaceous and detrital-rich, less organic-rich, and perhaps more proximal, sedimentation.

**PUNTA EL PUENTE**

Punta El Puente consists of over 250 meters of both laminated and massive porcelanitic mudstones and siltstones intercalated with glauconitic
sand beds, ash beds, and both calcite and dolomite concretions (Plates 3.1 and 3.2). This section was first measured by M. Allen, R. Marty, and R. Dunbar in 1986. Subsequent age dating using both biostratigraphy (foraminifera and nannofossils) and $^{87}$Sr/$^{86}$Sr ratios indicate that a major unconformity exists somewhere within the interval between 110 m (age dated as Miocene) and 11 m (dated as late Eocene) (Dunbar, et al., 1990; Plates 3.1 and 3.2). Most likely, the large glauconitic sand interval between roughly 91 and 83 meters represents the unconformity between these younger rocks (collectively named "Miocene rocks" in this study) and the Yumaque formation. All dated rocks above 91 m are Miocene, and possibly Early Miocene, probably corresponding to the Lower Oligocene to Middle Miocene Chilcatay formation (Plates 3.1 and 3.2). The late Eocene Yumaque formation rocks are present only in roughly the lowermost 83 meters at Punta El Puente. Samples collected and analyzed from below and above the glauconitic sand interval, assumed to represent the unconformity, are differentiated and discussed separately. Results from the younger rocks, which are not the focus of this study, are presented first and followed by descriptions and discussion of the Yumaque formation rocks exposed at PP and PE.

**Punta El Puente: Miocene Rocks (Chilcatay Formation)**

Rocks above the glauconitic sand interval are similar to the rocks below, but differ in several important respects, as seen both in the field and in petrographic and laboratory analyses. Most notably, the rocks above the unconformity are siltier and more rarely laminated than the Yumaque formation. Furthermore, the style of lamination is distinctly different above and below the
unconformity and a different origin is inferred (see discussion below and in the following section). Both outcrop and thin section observations also suggest that the Miocene rocks are more detrital-rich and tuffaceous than the late Eocene rocks exposed at PP. In the field, discreet ash intervals were more frequently observed in the Miocene rocks and several mudstone and silty mudstone samples collected contain abundant glass shards. Also, the section above the unconformity contains more and thicker green sand intervals, with at least three 0.5 to 1 meter thick glauconitic sand intervals compared to none this thick in the older part of the section (Plates 3.1 and 3.2).

Field and Thin Section Observations

Most of the rocks above the unconformity are light to medium brown massive siltstones to mudstones. Lighter, finer-grained, and calcareous massive rocks alternate approximately every 1 to 4 meters with darker (medium brown), generally more resistant, and siltier beds. The alternating beds are sometimes as thin as a few tens of cms and as thick as 5 to 6 meters. Both the light and the darker homogeneous rocks contain abundant fish debris. Petrographic analysis indicates between 30-70% detrital minerals in these rocks. Alteration and poor thin section quality prohibited more precise percentage estimates. Most of the detrital component is present as small (< 10 μm), altered grains which appear to be mostly euhedral. The only minerals positively identified in this size range were quartz and plagioclase. It was not possible to determine whether or not alteration of these minerals took place prior to or after deposition. While the small grain size fraction of detrital minerals dominates all of the rocks examined, some of the dark homogeneous samples also contain between 2-7% detrital minerals which are between
roughly 100-200 μm. These grains are also highly altered and again only subhedral to euhedral quartz and plagioclase grains were positively identified. The remainder of the rock looks glassy and is isotropic. X-ray diffraction confirms the presence of significant opal-CT, although what percentage is of a biogenic versus volcanogenic origin is undetermined.

Rounded, glauconitic sand grains (approx. 100-200 μm) account for less than 1% of some of the light, homogeneous rocks examined. In some of the dark, homogeneous intervals, up to 15% volcanic glass shards were identified. Foraminifera or foraminiferal casts were identified in both the light and dark mudstones, with alteration inhibiting relative percentage estimates. However, microscopic examination indicates that in the lighter rocks they are at least partially filled with calcite whereas in the darker rocks, they are filled with zeolite. Observations from thin sections impregnated with blue epoxy indicate that samples from the light homogeneous rocks are highly porous relative to the other rocks examined. Visual inspection of the thin sections suggests a dramatic difference of possibly 20% of porosity or more between the light and the darker homogeneous rocks.

Where present, laminated mudstones occur as thin, 5-20 cm, dark brown, beds alternating with the generally lighter (light and medium brown), thicker (typically 0.5 to 1.5 meters), and less resistant massive beds described above. The laminated intervals consist of mm-scale light and dark alternations of uneven thickness which are often contorted and microfaulted. As with the FD section and the PP rocks below the unconformity, the microfaults always display normal offset, rarely exceeding 1-2 cm. Examination of cut slabs and thin sections from the 5-20 cm thick, dark laminated intervals typically reveals between two to five fining upwards cycles. Light-colored, medium to fine-
grained sandstone fines upwards into siltstone and silty mudstone overlain by unevenly spaced alternating light and dark parallel laminae which are sometimes capped by very fine-grained, generally dark, convoluted laminae exhibiting flame structures (Fig. 3.16). These cycles correspond closely to structural subdivisions C and D, and possibly E, of the idealized Bouma sequence for turbidity current deposits (Fig.3.17).

**Geochemical Observations**

the darker laminated mudstones (turbidites) (Table 3.5, 3.6). Average values for total weight percent calcium carbonate, organic and inorganic phosphorus and organic carbon range between >1-11%, .0081-.017, .068-.14, and .01-.59, respectively. The light homogeneous intervals have the highest averaged total weight percentages of calcium carbonate (ranging between 7-14%), inorganic and organic phosphorus, and organic carbon of all Miocene samples examined. The most striking feature of the light homogeneous rocks is that the total weight percent calcium carbonate averages almost 10% higher than all other rocks. Average inorganic and organic phosphorus (P\textsubscript{i} and P\textsubscript{o}, respectively) and total organic carbon (TOC) weight percentages for the light homogeneous intervals are 0.18, 0.02, and 0.6%, respectively.

The dark homogeneous intervals are depleted in calcium carbonate relative to the lighter intervals. Part of this difference arises from the fact that foraminiferal molds in the darker rocks are filled with zeolite versus the calcite which at least partially fills these molds in the lighter rocks. In any case, this difference is seen as largely reflecting diagenetic differences. Whether or not depositional differences in the amount of calcium carbonate existed cannot be
Figure 3.16

Sketch illustration of small-scale cyclicity in hand sample from the Chilcatay Fm. at Punta El Puente. At least three, possibly four, distinct cycles of low-density turbiditic deposition are seen here. Cycle bases are distinguishable by the sand laminae (cycles 2 and 3), and massive intervals (cycles 1 and 3).
Figure 3.17

<table>
<thead>
<tr>
<th>Grain Size</th>
<th>Bouma (1962) Divisions</th>
<th>Interpretation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mud</td>
<td>Pelite</td>
<td>Pelagic sedimentation or fine grained, low density turbidity current deposition</td>
</tr>
<tr>
<td>Sand-Silt</td>
<td>Upper parallel laminae</td>
<td>? ? ?</td>
</tr>
<tr>
<td></td>
<td>Ripples, wavy or convoluted laminae</td>
<td>Lower part of Lower Flow Regime</td>
</tr>
<tr>
<td>B</td>
<td>Plane parallel laminae</td>
<td>Upper Flow Regime Plane Bed</td>
</tr>
<tr>
<td>A</td>
<td>Massive, graded</td>
<td>? Upper Flow Regime Rapid deposition and Quick bed (?)</td>
</tr>
<tr>
<td>PP SAMPLE</td>
<td>MUNSELL</td>
<td>DRY BULK DENSITY g/cm³</td>
</tr>
<tr>
<td>-----------</td>
<td>---------</td>
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<tr>
<td>32</td>
<td>10YR 6/2</td>
<td>1.939</td>
</tr>
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</table>

**TABLE 3.5: Geochemical Results from Punta El Puente Miocene Rocks**
TABLE 3.6: Summary of Compositional Data from Punta El Puente Miocene Rocks

<table>
<thead>
<tr>
<th>COMPONENTS</th>
<th>All components given as the mean +/- 1 standard deviation</th>
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</thead>
<tbody>
<tr>
<td><strong>BED TYPES</strong></td>
<td>Sample #’s</td>
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<tr>
<td>Light Laminated</td>
<td>PP9A,9B,25B</td>
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<tr>
<td>Light Massive</td>
<td>PP10,11,12, 13,14,29,32</td>
</tr>
<tr>
<td>Dark Laminated</td>
<td>PP16,17</td>
</tr>
<tr>
<td>Dark Massive</td>
<td>PP6,7,18A,31</td>
</tr>
</tbody>
</table>
determined. The measurements for inorganic and organic phosphorus, and TOC, are only slightly lower than measured in the lighter rocks, averaging 0.13, 0.008, and 0.34, respectively.

Rocks from the predominantly dark laminated, turbiditic, intervals differ markedly from both the light and dark homogeneous intervals. Like the darker homogeneous rocks, calcium carbonate values are very low, 1% or less in all of the rocks studied. Unlike the darker or lighter rocks however, organic and inorganic phosphorus and TOC values are all extremely low, averaging 0.02, 0.012, and 0.01, respectively. These extremely low values indicate that the original source of these redeposited sediments was either from marine sediments deposited under low productivity or low preservation conditions or was continental.

**Glaucositic Sand Beds**

Numerous glauconitic sand beds are present in the Miocene rocks from PP. They range in thickness from a few centimeters up to a few meters and are often associated with small phosphate pebble lenses. Two types of glauconitic sand grains, often present together in the same section, were recognized microscopically. The most common are 70 to 300 μm, spheroidal to ellipsoidal, dark green grains. They are either structureless or exhibit radial fractures. The other type of grain is roughly the same diameter, sometimes slightly smaller, spheroidal and lighter green. These grains show oolitic structures, concentrically banded with a detrital grain, rock fragment, or foram often present in the center of the grain. Glaucositic grains generally account for between 50 and 90% of the total sandstone. Other grains present include angular volcanic rock fragments and/or euhedral to subhedral quartz, plagioclase, and possibly
pyroxene and hornblende, grains which are approximately the same size as the
glaucosic grains. The matrix is a greenish clay and the rocks are often
cemented with gypsum and halite.

The three largest (about 70 cm to 1.5 m) sand beds within the Miocene
rocks, and the large bed representing the unconformity between the Miocene
and Eocene rocks, exhibit sedimentological evidence for transport from another
area within or proximal to the basin. The basal surface is often scoured and
mudstone rip-ups are often observed within the sand. The beds are normally
graded, often showing several depositional cycles, and usually ranging from
coarse to medium- or, rarely, fine-grained sand.

**Ash Beds**

Ash beds are commonly observed in the Miocene rocks. They are
generally between 1 to 10 cm thick and occur, randomly spaced, within both the
light and dark homogeneous beds. The ash has been extensively altered to
illite-smectite, and possibly chlorite. The two samples examined
microscopically contain between approximately 5-20% phenocrysts, generally
between 100 to 200μm. Alteration of these minerals and poor thin section
quality inhibits percentage estimates or complete identification of all possible
minerals, but both quartz and feldspar were identified.

**Calcite and Dolomite Nodules**

Calcite and dolomite nodules and nodular layers are common in this
section. They are typically between 50 cm to 1.5 meters in diameter and usually
conform closely to bedding planes. No work was completed on these rocks for
this study and no published material on the nodules from this section was found.

**Summary**

Miocene mudstones and siltstones from PP may be divided on the basis of field, thin section and geochemical observations into three major categories with unique features (Table 3.6). The light colored homogeneous mudstones are calcareous, relatively porous, and composed primarily of altered detrital grains sized less than 10 μm. Calcite-filled foraminiferal molds and rare glauconitic rounded grains are also observed. These rocks are also the most phosphatic and organic carbon-rich of the samples studied. The darker homogeneous rocks are almost devoid of calcium carbonate (although the original content may as been as high as the lighter rocks) and are more detrital-rich than the light rocks, especially the coarser (100-200 μm) fraction. Phosphorus and organic carbon values are similar but average less than the lighter rocks. These rocks also contain up to 15% preserved volcanic glass shards. Both the larger coarser-grained detrital fraction and the preserved glass shards point to a larger overall volcanigenic component in the darker beds (see discussion of ash beds below).

It is possible to explain the differences observed either in terms of increased detrital input during the deposition of the darker beds or increased production and/or preservation of biogenic material during the deposition of the lighter beds. The thin, dark laminated intervals are interpreted as turbidites. They are normally graded, from fine-grained sandstone to mudstone, and contain very little calcite, phosphorus or organic carbon. The source region for these sediments is inferred to have been either an area of very low productivity,
or preservation potential, or continental. Glauconitic sand beds also represent redeposited sediments. These beds suggest that the Miocene mudstones were deposited either at the base of a slope or possibly near a banktop. Deposition could have either followed a relative drop in sea level or may have been triggered by tectonic activity.

**Punta El Puente: Yumaque Formation**

The Yumaque formation rocks below the unconformity at PP look very different from the Miocene rocks examined. The most striking difference noticeable in the field is a dramatic change from fine-grained, mostly laminated, Eocene rocks to siltier rocks which are largely massive. Distinct cyclical color changes are apparent both above and below the unconformity but more pronounced and regularly in the older rocks. Other notable changes that are recognizable in the field are a greater abundance of calcite and dolomite nodular layers, fewer, and much thinner, sand beds, and less ash.

Porcelanitic mudstones are divided into four major categories: light-laminated, dark-laminated, light-massive, and dark-massive (Table 3.7, 3.8). Noticable textural, compositional, and diagenetic differences between the different rock types are documented. Possible depositional and diagenetic causes for these differences, and similar differences noted at Playa El Erizal are discussed in more detail in the Discussion. Unfortunately, in the field it was difficult to discern between laminated and massive intervals without exposing a fresh surface each time. Therefore, detailed thickness measurements of the meter-scale massive and laminated alternations are not well-documented, and the detailed centimeter to meter-scale cyclicity recorded in Plate 3.2 refers
### TABLE 3.7: Geochemical Results from Punta El Puente Yumaque Formation Rocks

<table>
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<tr>
<th>PP SAMPLE</th>
<th>MUNSELL</th>
<th>DRY BULK DENSITY g/cm³</th>
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<th>PHOSPHATE IN PPM</th>
<th>WT% N</th>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>TOTAL</td>
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<td></td>
<td></td>
<td></td>
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<td>BED TYPES / LOCATION</td>
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<td>All components given as the mean +/- 1 standard deviation</td>
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<td>----------------------</td>
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<tr>
<td></td>
<td>CaCO3 wt%</td>
<td>Inorganic P (PPM)</td>
<td>Organic P (PPM)</td>
<td>Total Organic Carbon wt%</td>
<td>Dry Bulk Density g/cm³</td>
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<tr>
<td>Playa El Erizal</td>
<td>PE12, 15, 20</td>
<td>6.6 (2.7)</td>
<td>560 (31)</td>
<td>286 (195)</td>
<td>0.657 (0.156)</td>
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<td>863 (238)</td>
<td>141 (101)</td>
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<td>270 (218)</td>
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<td>869 (107)</td>
<td>0.704 (0.366)</td>
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directly only to color changes. Both the lighter and darker rocks were most often laminated. The more infrequent massive rocks observed were predominantly dark. This observation holds true for the rocks studied at Playa El Erizal as well. Following a summary of results from the mudstones, the sand, ash and nodule beds are briefly discussed.

Field and Thin Section Observations

Most of the rocks below the unconformity at Punta El Puente are light to medium brown finely-laminated muddy porcelanites to porcelanitic mudstones. The most distinctive feature of these rocks is the cyclical alternation of light and dark intervals at cm to m scales. For the description of these cycles and subsequent discussion, the mm-scale alternations are referred to as first order (1°) cycles, the cm (to m-) scale alternations as second order (2°) cycles, and the m-scale alternations as third order (3°) cycles (Fig. 3.18). The first order cycles bear some similarities to the mm-scale laminae observed at FD; however, the degree to which the lamination is pronounced in the PP rocks is variable, with some rocks exhibiting the kind of fine lamination seen at Fundo Desbarrancado, but most exhibiting only wavy or faint and discontinuous lamination. Where pronounced, the laminae are generally thinner (between 0.025 and 0.5mm thick) than those observed at FD, possibly as a result of greater compaction during the transformation of siliceous tests (opal-A) to opal-CT (Fig. 3.19).

The second order cycles generally consist of a thick light member, between a few tens of centimeters to a meter thick, and a thin darker member, which is usually from a few centimeters to tens of centimeters thick. The lighter intervals, which average about 70 cm thick, are usually laminated and are
Figure 3.18

Photograph showing second and third order cyclicity in Yumaque rocks from the Punta El Puente section. Second order cycles are consist of a dark member with an average thickness of about 15 cm and a light member with an average thickness of about 70 cm. Second order cycles are super imposed on third order cycles consisting of alternating light and dark members approximately 1 to 4 meters thick each.
Figure 3.19

Schematic porosity-depth pattern for Monterey Formation diatomaceous rocks and diagenetic equivalents at moderate burial depths (about 400-2000 m). In individual layers an abrupt reduction in porosity is associated with each of the two silica phase transformations, but slightly different temperatures for the transformations in rocks of different composition can result in a comparatively broad zone of porosity reduction. (From Isaacs, 1981)
generally more resistant than the darker beds. The darker beds have an
average thickness of 15 cm and may be laminated or massive. Unlike the thin,
dark beds in the Miocene section which bear a superficial resemblance to these
intervals, no sedimentary structures (such as scouring, graded bedding or
ripples) were present to suggest a turbiditic origin for the dark, thin beds. The
third order cycles consist of 1 to 3 meter thick light and dark members with
superimposed first and second order cyclicity.

In the laminated rocks, distinct differences are recognized between the
light and dark laminae which closely resemble those observed in the FD rocks.
Specifically, the light laminae contain relatively few detrital grains and
foraminifera or foraminiferal casts. The dark laminae, by contrast contain more
detrital grains, foraminifera and/or foraminiferal casts, and more fish debris.
These differences mirror those of the overall light laminated rocks and dark,
laminated rocks. Also, the dark finely-laminated rocks appear to be less porous
than the lighter laminated rocks. In comparison to the laminated rocks, both the
dark and, more rare, light massive rocks contain more foraminifera and detrital
grains.

The foraminifera in all of the rocks are either present as casts, partially
filled with calcite, or, most commonly, are filled with zeolite. The detrital grains in
all of the rocks are usually between 20 and 40 μm, are subhedral to euhedral,
and are commonly altered. As with the Miocene rocks, of the detrital fraction
only quartz and feldspar were positively identified in thin section. X-ray
diffraction confirmed the presence of quartz, plagioclase and possibly a
potassic feldspar, minor illite, and possibly some mixed smectite-illite (see
discussion on clay mineralogy). Unlike the Miocene rocks, no large, 100-
200mm, detrital grains were observed in any of the mudstones. In both the light
and dark massive rocks, less than 1% small (approximately 1-5mm) opaque grains were observed, which were confirmed as pyrite using x-ray diffraction. Some rounded orangish to greenish glauconitic grains were also rarely observed in the massive rocks. In general, all of the rocks have a glassy appearance and except for the detrital components noted, are isotropic. Total detrital content of these rocks is estimated as between 5 and 50%, with the abundance increasing in order from light laminated to dark laminated to light and dark massive rocks. It is difficult to determine if there is any significant difference in detrital content between the light and dark massive rocks.

The remainder of these sediments is considered to be diagenetic opal-CT, with perhaps minor opal-A (Fig. 3.6). It was not conclusively determined whether or not the opal-CT is derived from an original biogenic or volcanigenic source. However, judging from the similarities between these rocks (especially the laminated rocks) and the FD rocks, and the paucity of detrital minerals in many of the rocks, a significant portion of the opal-CT is considered to be diagenetically-altered biosiliceous debris (Fig. 3.20). If this is indeed the case, then the mudstones from PP are as biosiliceous as the rocks from FD.

**Geochemical Observations**

Geochemical analysis of these rocks reveals distinct compositional differences between both the light and darker laminated mudstones and the light and dark massive mudstones. Average values for total weight percent calcium carbonate, organic and inorganic phosphorus and organic carbon range between >1-4%, .09-.54, .037-.087, and .34-84%, respectively (Table 3.7). Interestingly, the light laminated intervals have the lowest averaged total weight percentages of calcium carbonate (ranging between 0.3 and 4.25%), fig
Figure 3.20

Scanning Electron Micrograph of biosiliceous (opal-CT) rocks at Punta El Puente.
PLEASE NOTE

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inorganic and organic phosphorus, and organic carbon of all the Eocene samples examined at PP. Average inorganic and organic phosphorus (P\textsubscript{i} and P\textsubscript{o}, respectively) and total organic carbon (TOC) weight percentages for the light laminated rocks are 0.09, 0.014, and 0.3%, respectively. The low TOC in these rocks is probably a diagenetic artifact, perhaps caused by high original porosity in these rocks which in turn led to leaching. The dark laminated rocks contain approximately the same amount of calcium carbonate (close to 2%) but significantly more inorganic and organic phosphorus, and TOC, averaging approximately 0.20, 0.03 and 0.77 wt.%, respectively.

The light massive rocks are similar to the dark, laminated rocks in inorganic and organic phosphorus measured (0.13 and 0.003%, respectively) as well as in TOC weight percent measured (0.84%). These rocks are also the most calcite-rich, averaging about 4%, of all the Eocene mudstones sampled from PP. This is thought to mainly be a diagenetic, not depositional, feature resulting from the filling of foraminiferal molds with calcite instead of zeolite. The dark massive rocks again contain less than 2% calcite and approximately between 0.7 and .8% TOC. However, these rocks stand out in their relatively high inorganic and organic phosphorus contents of 0.54 and 0.09, respectively.

Summary

Eocene rocks from PP exhibit distinct compositional, textural, and diagenetic differences between light and dark, and laminated and massive rocks (Table 3.8). Superimposed first, second, and third order cyclicity is recognized as light and dark mm to m-scale alternations. Many of the compositional and textural trends seem to mirror those observed at FD however diagenetic overprinting complicates simple comparisons, especially with
respect to biogenic silica and carbonate. Where fine-scale lamination is preserved, the light laminae are impoverished in detrital minerals, foraminifera, and fish debris, and probably enriched in biogenic silica, relative to the dark laminae.

On a hand specimen scale, the light, laminated rocks are surprisingly low in phosphorus and TOC relative to the other rocks. It is strongly suspected that this is a diagenetic effect related to higher original porosity of these rocks. The remaining three general categories of rocks exhibit similar TOC weight percentages (0.7-.8%), however both dark, laminated and massive rocks exhibit higher phosphorus values than the light, massive rocks.

PLAYA EL ERIZAL

The Playa El Erizal section consists of over 120 meters of laminated and massive porcelanitic mudstones which, like the PP section, show m-scale cyclicity, are intercalated with siltstone and sandstone beds, ash beds, and dolomite concretions (Dunbar and Baker, 1988; Dunbar et al., 1990; Fig. 3.15). At this locality, Yumaque formation rocks may unconformably overlie a nearshore facies (Paracas Formation ?) which in turn nonconformably overlies crystalline basement rocks; however, the contact between Yumaque rocks and the so-called Paracas Formation has not been firmly established and warrants further investigation (Fig. 3.21). Several large normal faults and numerous small-scale normal faults (similar to those observed at both FD and PP) cut this section. Age control, provided by $^{87}\text{Sr}/^{86}\text{Sr}$ ratios from dolomite nodules near the top of the section, indicates a late Eocene age for this section (Dunbar et al., 1990). This study presents petrographic observations and geochemical results
Figure 3.21

Photograph of different contacts exposed at Playa El Erizal. The Yumaque and Los Choros formation contact has not been firmly established at this or at other sites and definitive identification of the Los Choros formation at this site has not been made. The contact between Yumaque formation rocks and those of the Los Choros formation warrants further investigation.
Angular Unconformity between Los Choros Fm. and Yumaque Fm.

Non-conformity between basement and Los Choros Fm.
for mudstones from approximately the uppermost 30 meters of section exposed and again focuses on the geochemical and sedimentological differences between light and dark, and to a lesser extent, laminated and massive, rocks.

Field and Thin Section Observations

The section at PE closely resembles late Eocene rocks from the PP section, approximately 20 kilometers to the north. The lowermost 50 meters are dominated by massive porcelanitic mudstone, with rare laminated intervals. The overlying rocks are mostly laminated, and exhibit larger scale cyclicity comparable to the third order cycles observed at PP. Cycles comparable to the second order cycles at PP are likely present at PE but, because the PE section was not as carefully examined as the PP section, were overlooked. Like the laminated intervals at PP (first order cycles), the degree to which the mm-scale lamination is pronounced in PE rocks is variable, with some rocks exhibiting the kind of fine lamination seen at Fundo Desbarrancado, but most exhibiting only wavy or faint and discontinuous lamination like the rocks from PP. The laminae are also approximately the same thickness as those from PP averaging between 0.025 and .05 cm. Again, they are significantly thinner than the laminae observed at FD (which average approximately .1 to .15 cm), possibly reflecting compaction during the transformation of siliceous tests from opal-A to opal-CT (Fig. 3.19).

Although PE cyclicity on the same scale as the second order cycles observed at PP was not noted, cycles resembling the third order cyclicity at PP are common in the PE section. Typically, 2 to 4 meters thick laminated intervals alternate with 1 to 3 meters thick massive intervals (Dunbar et al., 1990). Alternations between laminated and massive rocks are often, but not always,
tied to color changes in the section, with the light rocks often corresponding to laminated intervals and the darker rocks tending to be massive. This observation, first documented in Dunbar and Baker (1988) is similarly noted for Yumaque rocks exposed at PP.

In the laminated rocks, differences between individual light and dark laminae are similar to those described for both FD and PP Yumaque rocks. Specifically, the darker laminae contain more detrital grains and foraminifera and/or foraminiferal casts, and fish debris than the lighter laminae. While the detrital grain content varies considerably between individual lamina, visual estimates from both thin sections and smear slides indicate between 20 to 50 weight percent detrital grains in the dark laminae versus 5 to 30 weight percent in the light laminae. As with rocks from PP, the differences seen between the light, mostly laminated, and the dark, mostly massive, rocks, mirror those observed between the light and dark laminae studied.

Most of the detrital grains are between 20 and 60 µm; subhedral to euhedral quartz and plagioclase grains are the only minerals positively identified in thin section. Although twinning is often preserved in the plagioclase grains, many of these grains appear altered and the quartz grains often have a cloudy appearance. While only plagioclase and quartz were identified microscopically, analysis of x-ray diffractograms suggests the presence of minor illite and perhaps some mixed illite-smectite in the dark, massive samples. No clay x-ray diffraction peaks were identified in the lighter, laminated rocks, indicating that either these rocks contain negligible clay or, more likely, that clay is less abundant or at least more poorly crystallized than the darker rocks.
In one of the dark, massive samples (PE-9), larger detrital grains and volcanic rock fragments, both from 100 up to 300 \( \mu \text{m} \), account for between 3 and 7\% of the total rock. This rock, which otherwise resembles the other dark, massive rocks examined, is from a dark, massive, interval (approximately 3 meters thick) which also contains several, thin (2 to 4 cm), sandy lenses. Again, altered quartz and plagioclase were positively identified, however, unlike the smaller grain size fraction, both biotite and rounded, highly birefringent grains with alteration rims, tentatively identified as pyroxene, were also observed. The rock fragments are rounded and contain abundant small (20-40 \( \mu \text{m} \)), euhedral quartz and plagioclase grains in a dark, isotropic matrix assumed to be (altered?) volcanic glass. This rock does not significantly differ geochemically from the other dark, massive rocks studied. Unlike the smaller detrital fraction observed in all other mudstones studied at PE, however, these larger detrital grains and rock fragments could not have been transported by suspension (Boggs, 1987). Furthermore, careful microscopic inspection reveals that the detrital grains are normally graded (due to the relatively small grain sizes involved, this is not readily apparent macroscopically). These observations suggest a distal (?) turbiditic source for this rock. How common turbidites may be in this section is an interesting question, which requires more detailed sampling to answer.

As mentioned earlier, foraminifera and/or foraminiferal casts, are relatively common in PE mudstones and are most abundant in the dark, massive rocks, accounting for between 3 to 10\% of the rock. They are slightly less abundant in the laminated rocks, accounting for about 3\% up to about 5\% of the total rock, and are most common in the dark laminae. The diameter of these fossils generally ranges between 100 to 400 \( \mu \text{m} \). Within the massive
rocks, the foraminifera are either filled, or partially filled, with zeolite or they are present as casts. Where filled, the internal structure (chambers) of the foraminifera are well-preserved. However, even where they are essentially empty, very thin membranes (probably also zeolite) often define internal structure. In the laminated rocks (both the one dark and the light samples), the foraminiferal casts are roughly aligned parallel to the lamination. Unlike the massive rocks studied, they are usually filled with calcite (rare unfilled casts were also observed). It is probably largely this difference which accounts for the difference in the weight percent carbonate observed between the massive and laminated rocks (discussed below).

Like the mudstones from PP, all of the rocks have a glassy looking, isotropic matrix. X-ray diffraction indicates that opal-CT is the major component in these rocks. As with the PP mudstones, most of the opal-CT is interpreted as diagenetically altered siliceous organisms, although variable amounts of altered volcanic glass may also be present. More detailed work, probably including bulk chemical analyses, on both the PP and PE mudrocks is needed to determine the relative contribution of siliceous organisms and volcanic glass to the opal-CT in these rocks. Interestingly, x-ray diffraction patterns of the PE mudstones suggest that some of the opal-CT has undergone further diagenetic alteration to quartz. This transformation appears to be more pronounced in the darker, more detrital-rich, rocks (Fig. 3.6). The implications of differential silica phase transformation, in PE as well as FD and PP rocks, are presented in the Chapter 4.
Geochemical Characteristics

Geochemical analysis of these rocks reveals distinct compositional differences between both the light and darker laminated mudstones and the light and dark massive mudstones which are different than those observed at PP (Table 3.8, Table 3.9). The total weight percent phosphorus (inorganic and organic) and organic carbon measured, averages 0.05, 0.01, and 0.6%, respectively. The light laminated intervals have the highest averaged total.

Twelve weight percentages of calcium carbonate (6.6 wt%), and organic phosphorus (0.02 wt%) of all the rock types and intermediate values for TOC (0.66 wt%) and inorganic phosphorus (0.05 wt%). The only dark laminated rock analyzed contains approximately the same amount of calcium carbonate (6.3 wt%) but significantly more inorganic phosphorus, and TOC, averaging approximately 0.14 and 1.3 wt.%, respectively. This organic carbon value is the highest measured in this study for any rock from any of the sections. It would be interesting to analyze more of the dark, laminated rocks to see if they are consistently more organic-rich.

The light massive rocks have the lowest inorganic and organic phosphorus and TOC values of all the rocks at PE, averaging only 0.02, 0.007, and 0.28 wt%, respectively; the dark massive rocks have only slightly higher values averaging 0.04, 0.01, and 0.58 wt%, respectively. Unlike the massive rocks a PP, both the light and dark massive rocks at PE contain significantly less calcium carbonate (< 1 wt%) than the laminated rocks. This is thought to mainly be a diagenetic, not depositional, feature resulting from the filling of foraminiferal molds with calcite instead of zeolite.
## TABLE 3.9: Geochemical Results from Playa El Erizal Yumaque Formation Rocks

<table>
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<th>PE SAMPLES</th>
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<th>DRY BULK DENSITY g/cm³</th>
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<th>PHOSPHORUS IN PPM</th>
<th>WT.% TOTAL ORGANIC CARBON</th>
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PP AND PE YUMAQUE FORMATION: COMPARISON & SYNTHESIS

The muddy porcelanites from PE resemble those from PP in their lamination and bedding styles and composition. First order cycles consist of laminae which are usually between 0.25 to 0.5 mm thick each and are often wavy and/or discontinuous. They are composed primarily of opal-CT with significant detritus in the dark laminae and a relatively minor amount in the light laminae. Second order cyclicity is recognized in the PP section but not at PE. It is likely that similar cycles are present in PE rocks so that this difference is attributable merely to the scale of observation. Third order cyclicity (m-scale) is recognized at both sections.

Like the rocks from PP, on average the detrital component accounts for approximately 30% of the total rock and consists largely of small, angular and euhedral to subhedral quartz and feldspar grains. Detrital content of the different rock types varies between about 5 to 50%, increasing in order from light laminated to dark laminated to light and dark massive rocks. Unlike the rocks from PP, the laminated rocks from PE contain significant calcium carbonate (up to almost 7 wt%). This difference is largely attributed to diagenetic differences in the filling of pore spaces, especially of foraminiferal casts. Also, inorganic and organic phosphorus values are significantly higher, and TOC lower, in the PP massive and laminated rocks compared to the same types of PE rocks.

Estimated Mass Accumulation Rates for PP and PE

The laminae observed within rocks from the northern PP and PE sections are not as clearly defined nor as continuous as those present in rocks from FD.
However, assuming that the light and dark laminae couplets at PP and PE also represent varves, semi-quantitative mass accumulation rates (MAR) may be estimated for these sections.

A dramatic density difference is observed between rocks from the northern sections and FD, averaging 1.90 g·cm⁻³ in siliceous rocks from PP and PE compared to 0.74g·cm⁻³ in FD rocks (uncorrected for salt). This density change is related at least in part to the diagenetic change from opal-A to opal-CT, which in rocks originally containing 70% biogenic silica, can result in porosity differences of up to about 30% (Isaacs, 1981; Fig. 3.19). Using this DBD value and a linear sedimentation rate calculated from well-defined laminae couplets of between 0.05 to 0.1 cm/yr, an average total mass accumulation rate of between 95 and 190 g·cm⁻²·y⁻³ is obtained. This range encompasses the value of 149 g·cm⁻²·y⁻³ estimated for the FD section.

Taking this approach one step further yields estimated accumulation rates for biogenic silica. If the average detrital component of these rocks is estimated as 30 wt.%, then opal-CT (the only other major component recognized) accounts for roughly 60 to 70 wt% of the total rock. Based on the ranges given for the average sedimentation rate and the weight % opal-CT, a biogenic silica accumulation rate of between 57 to 133 g·cm⁻²·y⁻³ is estimated for the laminated rocks at PP and PE. This rough calculation is also close to the estimate of 85 g·cm⁻²·y⁻³ for FD rocks.

The assumption that the clearly defined light and dark laminae couplets represent an annual layer is reasonable if the same assumption is accepted for FD rocks, as they show the same general sedimentological and geochemical characteristics. Calculation of average sedimentation rates for PP and PE rocks based on this assumption, however, is more problematic. As a linear
sedimentation rate, the deposition of massive intervals within the PP and PE sections which may have accumulated at a slower rates are not accounted for. Also, the laminated intervals from these sections are not regularly laminated and the accumulation rates calculated from the most clearly defined and regular laminae within these intervals are likely a maximum rate. Furthermore, although the percentage of opal-CT can be estimated from thin section and Xrd analysis, the relative contributions of biogenic and volcanigenic silica were not determined. Therefore, the total and biogenic silica accumulation rates are only rough, and probably maximum, estimates.
CHAPTER 4: DISCUSSION AND CONCLUSIONS

This section discusses some of the interesting features of the Yumaque formation and proposes depositional models for the Fundo Desbarrancado and the Punta El Puente and Playa El Erizal sections. At the end, the major findings and implications of results from this study are briefly summarized.

Silica Diagenesis

The most striking diagenetic feature observed in the Yumaque formation is the conversion of opal-A to opal-CT. Unlike the Fundo Desbarrancado section in which the dominant silica phase present is Opal-A, in Yumaque rocks from both the Punta El Puente and Playa El Erizal sections the dominant silica phase is Opal-CT (Fig. 3.6). This difference is interpreted as the result of diagenesis which has been influenced by unique burial histories and, perhaps to lesser degree, compositional differences. Carbonate diagenesis in the biosiliceous rocks from all three sections is also discussed.

From studies concentrating on the diagenesis of fine-grained siliceous rocks, a typical diagenetic sequence of silica minerals, Opal-A > Opal CT > Quartz, has been established (Murata and Nakata, 1974; Murata and Larsen, 1975; Murata et al., 1977; Pisciotto, 1978, 1981; Isaacs, 1980, 1981, 1982; Iijima and Tada, 1981; Tada and Iijima, 1982; Isaacs, et al., 1983). The rate of silica phase transformation is dependent on many factors including: temperature, pressure, pH, pore fluid chemistry, specific surface area and lithology (Kastner and Gieskes, 1981). While temperature is probably the most important rate controlling factor (Kastner and Gieskes, 1983), numerous field studies (Bramlette, 1946; Millot, 1970; Pisciotto, 1978; and others) have
suggested that lithological factors such as silica-clay and carbonate ratios may also strongly influence the rate of transformation.

If temperature and pressure were the only factors controlling the transformation, then a constant stratigraphic sequence with siliceous ooze overlying porcelanite and porcelanite overlying chert would be expected, yet numerous exceptions have been observed. Isaacs (1982, 1983) and Isaacs et al. (1983) examined the influence of sediment composition on silica diagenesis in the Monterey Formation and found a consistent relationship between detrital mineral content (relative to silica) and the rate of silica phase transformations (Fig. 4.1). These studies are consistent with Kastner et al.'s (1977) experimental work which determined that detrital content increases the temperature needed for the transformation from opal-A to opal-CT. Hydrothermal experiments (Kastner et al., 1977; Kastner and Gieskes, 1983) have confirmed that lithological differences can strongly influence the rate of silica phase transformation. Kastner et al. (1977) found that the rate of opal-A to Opal-CT transformation between 50° and 150°C is enhanced in the presence of carbonate whereas the presence of clay minerals, particularly smectite, retards the transformation. Kastner (1979) proposes a general decrease in the rate of transformation from opal-A to opal-CT as follows: siliceous ooze + carbonate > pure siliceous ooze > siliceous ooze + clay minerals and/or pyroclastic sediment.

Effect of Detrital Content (and Carbonate) on Silica Phase Transformation

Although quantitative measurements of the total detrital percentage of rocks from PP and PE were not made, qualitative estimates indicate that rocks from these two sections have roughly the same detrital content (average equal
Figure 4.1:

Diagenetic model showing empirical relationship between detrital mineral content, kinetics of silica phase transformations, and opal-CT d-spacings as burial temperature and depth increase in the Monterey Formation (After Isaacs, 1982; Keller and Isaacs, 1985). Silica and detrital mineral contents are calculated as a product of the sum of silica+ detrital minerals. (From Isaacs, 1988).
to approximately 30%). As discussed earlier, a considerable range in the total percentage of detritus is observed between individual rocks from these two sections, varying between about 5% up to 70%. However, these end-members were seldomly observed; detrital minerals generally account for between approximately 20 to 50% of the total rock. This estimate is higher than the more quantitative estimate of approximately 20 to 30% detritus for FD rocks. Thus, from the current understanding of silica phase transformation, one would expect that, all other factors held equal, opal-A in rocks from FD should have transformed more quickly to opal-CT than in the more detrital-rich rocks at PP and PE. This, of course, contradicts what is actually observed.

Due to diagenetic changes, it is difficult to address the possibility that the amount of carbonate present in rocks from the three sections influenced the transformation. However, it does not appear that significant differences (more than 5%) existed in the original total percentage of carbonate between the three sections (see discussion on carbonate diagenesis below). Furthermore, Isaacs (1982) examined the influence of carbonate on silica diagenesis by looking at adjacent rocks with and without disseminated carbonate. Contrary to the hydrothermal experiments (Kastner et al., 1977; Kastner and Gieskes, 1983), almost no carbonate influence was detected when rocks with equal proportions of biogenic silica and detrital minerals were compared. The only exception found was in rocks with disseminated carbonate in which the biogenic silica content was at least 8 times more abundant than clay. In these rocks, a minor amount of diagenetic quartz formed early in diagenesis, usually within benthic foraminiferal tests. From the same study, however, adjacent rocks with similar silica to clay ratios, but little or no disseminated carbonate, contain no observable diagenetic quartz. Although rocks from all three sections examined
here likely have biogenic silica to clay ratios of at least 8, and contain widely variable amounts of disseminated carbonate, no such phenomena was observed in the Yumaque formation.

The difference between the different silica phases present is interpreted here as arising from differential burial temperatures between the FD section and the northern sections. Because geothermal gradients may vary widely over short distances in tectonically active fore-arc settings (Dickinson and Seely, 1979), either higher geothermal gradients or different burial depths could be responsible for the major silica phase differences observed. The lithological differences are only tied to the subtle diagenetic differences between rocks within each of the three sections.

At Fundo Desbarrancado, for example, the more detrital-rich rocks appear in x-ray diffractograms to contain opal-A exclusively whereas in samples with less detritus minor amounts of opal-CT are also indicated (Fig. 3.6). The relative weight percent carbonate, on the other hand, does not seem to influence this transformation; rocks with nearly equal amounts of carbonate exhibit varying amounts of opal-CT. For example, FD-1 which has approximately 5% total weight carbonate exhibits no opal-CT peak whereas FD-2, which has a comparable carbonate content (about 6%), exhibits definite opal-CT peaks superimposed on a broad opal-A hump. Their estimated detrital content, on the other hand, varies by about 10%. In addition to the opal-A and opal-CT observed in the rocks studied, rare black chert nodules and beds are present in the upper part of the section (Fig. 4.2). Similar nodules, or beds, in the Monterey Formation partially to completely replace some clay-poor calcareous rocks early in diagenesis (Isaacs, Pisciotto, and Garrison, 1981). Measurement of compaction around Monterey chert nodules show that the
Figure 4.2:

Photograph of chert nodules/layer in diatomaceous sediments from Fundo Desbarrancado.
nODULES formed when the host rocks had 50 to 60% porosity, clearly indicating that the host rocks were diatomaceous (Isaacs, 1980).

Yumaque formation rocks from PP exhibit a similar, though less quantified, relationship between detrital content and silica phase transformation. Here, the dominant phase present is opal-CT. However, the d-spacing of the dominant opal-CT peak (d(101)) varies from about 4.09-4.11Å in the light, laminated rocks to approximately 4.07Å in the dark, laminated rocks and 4.05Å in the dark, massive rocks (Fig. 3.6). This more or less predictable progression does not correlate either to stratigraphic position or carbonate content but, as discussed previously, the detrital content in these rocks is observed to increase in the same order. Thus, the decrease in d-spacing, documented for the continued diagenetic transformation from opal-CT to quartz with increasing temperature (Iijima and Tada, 1981; Pisciotto, 1981; Isaacs, 1982), appears to be linked to the increasing detrital content of these rocks (Fig. 4.1).

At PE, where the dominant silica phase is opal-CT but incipient diagenetic quartz is also indicated, the relationship between detrital content and silica phase transformation is also consistent with Isaacs (1982) model for the effects of detrital mineral content on opal-CT d-spacings (Fig. 4.1). Of the few samples analyzed using x-ray diffractometry, a relatively sharp opal-CT peak is observed at 4.09Å for the light, laminated rocks and 4.08Å for the more detrital-rich dark, laminated rocks (Fig. 3.6). Diagenetic quartz is indicated by x-ray diffraction and is sometimes observed filling foraminifera. Although increases in detrital mineral content are observed to increase the transformation rate from opal-CT to quartz (Isaacs, 1982), no significant difference in the total amount of detritus is recognized between the PP and the PE sections. Hence, the
presence of diagenetic quartz in these samples may suggest a slight increase in the burial temperature (or depth) for the PE rocks relative to the PP rocks. Alternatively, carbonate, which averages approximately 4% higher in the laminated rocks at PE than in rocks from PP, may be responsible for the incipient diagenetic quartz. As discussed in greater detail below, the increased carbonate content in the PE laminated rocks relative to the PP rocks is interpreted as largely a diagenetic effect. Assuming that the original carbonate content of the two sections was essentially the same and that the rocks were buried to the same temperature (either due to similar depth of burial or different geothermal gradients), then carbonate dissolution in these rocks may have preceded the formation of diagenetic quartz.

Temperature and Burial Depth Estimates of Silica Phase Transformation

All of the Yumaque sections studied have been uplifted since burial and the overlying sediment has been partially to completely eroded. Furthermore, the past (late Eocene) thermal regime is unknown. Due to these limitations, values for the depth and temperature of silica transformations in the Yumaque are estimated by analogy to the Monterey Formation and are presented as rough estimates. The Monterey Formation is considered to be a reasonable analogue by virtue of its lithological and inferred depositional similarities with the Yumaque formation. On the other hand, dissimilarities between the thermal histories of the two formations undoubtedly exist, due both to their different ages and plate tectonic settings. Thus, the comparative burial depths are only rough estimates. More rigorous analysis of the thermal history of the Yumaque formation is needed to provide more accurate estimates.
Using an empirical silica-phase zonation (calibrated to temperature from two points of phase transformation in diatomaceous/ siliceous strata presently at maximum temperature and depth of burial), Isaacs (1985) proposes that in rocks with 30% relative abundance of detritus, opal-A in Miocene Monterey Formation rocks transforms to opal-CT at 45° C and opal-CT transforms to quartz at 79° C. Temperature estimates for other relative detrital abundances are given in Fig. 4.1. These estimates, which compare favorably to other temperature estimates (Pisciotto, 1981b), are based on an average geothermal gradient of 48° C/km. This estimate falls within the range of 43 to 50° C/km calculated for ODP Sites 682, 683, 685, and 688 along the Peruvian continental margin, (based on the relations between depths to bottom-simulating reflectors (BSRs), bottom-water temperatures, and the pressure-temperature stability field of gas hydrates) (Kvenvolden and Kastner, 1990). Of course, the greater amount of time involved for the diagenesis of late Eocene rocks may decrease the minimum temperature (hence depth) needed for these transformations. Therefore, the following proposed burial depths should be considered as maximums.

Using a geothermal gradient of 48° C and an average detrital abundance of 30%, approximate burial depths of 900 m and 1600 m are attained for the opal-A to opal-CT transition and opal-CT to quartz transformations, respectively. If the average relative detrital mineral abundance in FD rocks is taken as 30%, then these rocks were buried to a depth no greater than about 900 meters (or about 45° C). The presence of minor opal-CT in rocks with relative detrital abundances of less than 10% below this average, however, suggests that this maximum value is close to the actual burial depth/temperature. Using the same geothermal gradient and percentage detritus for the PP and PE rocks, an
average depth of somewhere between 900 and 1600 m is indicated. Of course, as mentioned earlier, the detrital content of PP and PE rocks varies considerably between the different subgroups of siliceous rocks and the actual depths calculated using Isaac's model may vary anywhere between about 1000 to 1700 m (50 to 80°C). More reliable estimates of the total detrital content in these rocks, coupled with more precise x-ray diffraction results, is needed to more closely estimate the maximum burial depth of these sections.

While the thickness of units overlying the Yumaque formation in the Pisco Basin is highly variable (Dunbar et al., 1990), estimates of maximum overburden thicknesses compare well with burial depths estimated from silica phase transformations observed in Yumaque rocks. If the maximum thicknesses for the overlying units documented in Dunbar et al. (1990) are used, a maximum overburden thickness of approximately 1200 m is obtained. This does not take into account the possibility of undiscovered sections which are thicker or eroded sections. Thus, the actual maximum overburden thickness could be considerably higher, possibly reaching the approximate depth of 1700 m necessary for the opal-CT to quartz transformation. However, the greater amount of time available for the diagenetic alteration of these rocks compared to the Miocene Monterey rocks coupled with the scarcity of diagenetic quartz observed in the Yumaque rocks studied indicates that this threshold burial depth was not obtained.

**Summary**

Analysis of the silica phases present at FD, PP, and PE, reveals distinct diagenetic differences between the FD rocks and the rocks at PP and PE. In general, the rocks at FD are largely composed of opal-A whereas at both PP
and PE the dominant silica phase present is opal-CT. Differences in the relative
detrital content (and perhaps carbonate content) of rocks at all three sections
has led to slightly different degrees of phase transformation. This has resulted
in rocks with minor opal-CT at FD, variable opal-CT d-spacings at PP and PE,
and minor amounts of diagenetic quartz at PE. These compositional differences
cannot, however, account for the major silica phase difference observed
between rocks at FD and those at PP and PE. Using Isaac's model for burial
depths/temperatures developed for the siliceous rocks of the Monterey
formation, burial depths of approximately 900 m (45°C) and between 1000 to
1700 m (50 to 80°C) are indicated for the FD section and the PP and PE
sections, respectively. However, as mentioned before, geothermal gradients in
fore-arc basins can be highly variable

**Carbonate Diagenesis in Siliceous Rocks**

In carbonate-rich rocks from FD, PP, and, PE, the carbonate usually
occurs as tests of foraminifera and also as fine-grained cement. At FD, the total
weight percent carbonate averages about 8%, considerably higher than values
measured at either PP or PE. The number of foraminifera observed is positively
correlated with the carbonate content measured in FD samples. The average
abundance of foraminifera observed in rocks from PP and PE is roughly similar
to that seen at FD. Therefore, the differences in measured carbonate from the
three sections is probably more attributable to the fact that many of the
foraminifera in rocks from PP and PE are now replaced with zeolite or, more
rarely diagenetic quartz, than to depositional differences.
At Fundo Desbarrancado, very little or no carbonate dissolution of foraminifera is observed and measured values are probably close to original values. Relatively minor fine-grained cement (visually estimated as less than about 2% of the total carbonate measured) appears to be equally disseminated throughout the rocks examined. If the carbonate in this cement did not originally come from the FD rocks, the measured values may be slightly higher than the original carbonate content of the rocks. In the carbonate-poor rocks at PP and PE, foraminifera are often either present as casts or are replaced with zeolite. An exception to this are the laminated rocks at PE in which calcite does fill, or partially fill, the foraminifera recognized and in which carbonate values average over 6%. Examination of thin sections reveals that the carbonate-poor rocks usually contain as many or more recognizable foraminifera (3 to 7%) as the rocks with higher measured values of carbonate. It is difficult to quantify these differences, however, and it is also suspected that, due to diagenesis, many foraminifera are no longer recognizable. In light of these difficulties, the original carbonate in rocks from both PE and PP is roughly estimated at between 2 and 10% of the total weight, and, judging from the total number of foraminifera observed in thin sections, may have been slightly higher in the massive rocks than in the, usually lighter, laminated rocks.

Clay Mineralogy

Marty (1989) proposes that the northern porcelanitic Yumaque exposures are significantly more clay-rich than the diatomaceous Fundo Desbarrancado section to the south. Results from this study indicate that, contrary to Marty's (1989) observation, clay minerals (illite and/or illite-smectite) are present in very small quantities in both the northern and southern sections.
Rocks from all three sections were analyzed using x-ray diffraction (Xrd) on bulk and fine-fraction powders. In only a few rocks were any clay peaks detected at all, and even in these samples the clay peaks were very small relative to the opal-CT peaks observed. This absence of clay mineral Xrd peaks, even in samples from which most of the carbonate and biogenic silica has been removed, indicates that clay minerals account for less than 5-10% of rocks analyzed for this study.

In the Fundo Desbarrancado section, no clay minerals were detected in x-ray diffractometry of bulk, untreated, samples. However, after treatment with full-strength HCl (to remove any carbonate) and heating in a 1 M solution of NaOH for five hours (to remove the biogenic silica), two air-dried FD samples exhibited small, broad peaks between 14 and 17Å, characteristic of mixed illite-smectite. The presence of small and broad clay peaks, even after removal of carbonate and most of the biogenic silica (approximately 75 to 90% of the total sample), reflects low abundance and possibly poorly crystallized phases as well. The two FD samples (FD-10 and FD-7) were subsequently analyzed both after heating to 550°C for 1 hour, and after glycolation. After heating, the 14 to 17Å peak collapsed to approximately 10Å, confirming the presence of an expandable mineral component. However, glycolation resulted in negligible expansion and no increase in the intensity of the basal peak. Quaternary samples collected from the Peruvian continental margin during ODP Leg 112 sharing very similar x-ray diffraction characteristics are interpreted as vermiculite (Clayton and Kemp, 1990).

Illite was detected in two samples from Punta El Puente and in one sample from Playa El Erizal (PE-19). The presence of sodian illite was determined using x-ray diffractometry of powdered bulk samples. In all three of
these samples, the 10 Å (001) and 1.49 Å (060) clay peaks were very small relative to the opal-CT peaks and poorly defined. No other clay minerals were positively identified by either x-ray diffractometry, even following heating of the powders to 550 °C for 1 hour and treatment with ethylene glycol, or thin section analysis.

The presence of illite and minor illite-smectite, and lack of any other recognizable clay minerals, in the Yumaque sections studied suggests that the Peruvian coast was largely arid as far back as the late Eocene, contradicting Marty's (1989) and Marty et al.'s (1989) initial hypothesis of a regular wet season in late Eocene time. Illite (and smectite) are usually formed in immature soils under only moderately intense chemical weathering (Boggs, 1987). In marine sediments today, illite concentrations delineate the extent and relative contribution of river-borne solids (Fig. 4.3). Illite concentrations are high in areas where the soil and sediment source are relatively immature. Arid areas, like much of the western coast of South America, where rivers erode and carry relatively unaltered Andean rocks, exhibit high illite concentrations in marine sediments (Kennett, 1982).

**Rhythmic Bedding**

Rhythmic bedding, reflecting fluctuations in sediment composition, microfossil assemblages, color, texture, etc., is a feature common to many sediments and sedimentary rocks of different depositional environments and ages. The expression of cyclicity in sediments takes many forms. Sometimes, a variation in biotic productivity is observed (Herbert and Mayer, 1991), other
Figure 4.3: Iliite concentrations in the less than 2μm fraction of surface sediments of the world ocean. Concentrations of illite in marine sediments today delineate the extent and the amount of contribution of river-borne solids. (After H.L. Windom, 1976 in Kennett, 1982).
times dissolution or dilution cycles, with a variation in the influx of terrigenous debris, are recorded (Roof et al., 1991). Examples of rhythmically bedded sequences include lacustrine and playa sediments, such as the Castille Formation of Texas (Anderson et al., 1972) and the Green River Formation of Wyoming (Fischer and Roberts, 1991), shallow marine carbonate sediments, such as the Latemar Limestone in the Dolomites region, Italy (Hinov and Goldhammer, 1991), and hemipelagic diatomaceous sediments such as the Miocene age Monterey Formation of California (Pisiciotto and Garrison, 1981) and Onnagawa Formation of Northern Japan (Tada, 1991), and latest Pliocene and Pleistocene sediments from the Japan Sea (Tamaki, Suyehiro, Allen, et al., 1992; Föllmi et al., 1992; Dunbar et al., 1992). Significant attention has recently been focused on these and other numerous examples because of their probable relation to astronomical signals (see Fischer and Bottjer (1991) for a review).

Cyclical light and dark alternations in Yumaque formation rocks from FD, PP, and PE were examined at several different scales. At FD, attention was focused on both mm and cm-scale light and dark alternations while examination of the rocks at PP and PE was focused on the larger, cm to m-scale, cycles. At all scales, the light layers tend to be more biosiliceous and detrital-poor relative to the dark layers.

Fundo Desbarrancado

The most distinctive feature of the rocks from FD is the well-defined, regularly spaced mm-scale lamination present almost continuously in the diatomaceous rocks (Fig. 3.2). Textural and compositional examination of these light and dark couplets reveals many similarities to known varved sediments.
(Fig. 3.14). Spectral analysis of laminae thickness using the assumption that these couplets indeed represent varves reveals several periodicities which are commonly observed in varved sediments, including the Eocene age Green River Formation (Ripepe et al., 1991). These periodicities, observed at around 5-6, 8, and 11 years, have been interpreted as representing ENSO (5-6 and 8 years) and solar-type (11 years) phenomenon. The spectral analysis results are supported by observations of cm-scale color banding in the FD rocks. Using the same assumption that each light and dark couplet represents annual deposition, these bands reveal periodicities similar to those indicated by spectral analysis.

It is interesting that periodicities roughly similar to ENSO variability today are recognized in many ancient records including the one presented here. However, linking these records to ENSO-type changes presents some problems. ENSO variability today is related to surface pressure difference oscillations across the Pacific Ocean and is associated with major changes in rainfall patterns and wind fields of the tropical Indian and Pacific oceans (Philander, 1990). The southern oscillation perturbs both Hadley and Walker thermal circulation patterns and is associated with fluctuations in the intensity and the positions of the regions of rising moist air. Both variations in sea surface temperature patterns and variations in the heating of the continents influence the interannual movements of the convective zones. Modelling of El Niño events reveals that cycle lengths and intensities are influenced by even small changes in the starting parameters used (Enfield, 1988). The expression of ENSO, or even its presence, during different climatic and paleoceanographic settings beyond the Pleistocene is hotly debated (DeVries, 1987).
The Eocene ocean was configured much differently than today's ocean, with Circum-equatorial flow of surface water much less restricted (Fig. 4.4). The Panamanian seaway was still open in the eastern Pacific and a large opening still existed between the Indonesian arc and Australia. Without the closure of the Indonesian gateway the warm pool of water that now collects in the southwestern Pacific, triggering El Niño events, would have been less confined and the warm eastward flowing equatorial counter current may not have been as strong as today. Also, with the Panamanian gateway still open, the southward deflection of warm equatorial water along the Peruvian coast may not have been as pronounced as today. Thus, the Eocene oceanic configuration may have resulted in ENSO variability much different from today's or even have precluded its existence. If a similar phenomenon did exist, it may have likely been less pronounced and with a longer periodicity than observed today. This may partially explain why the record presented here shows dominant variance at periods of 5-6 and ~8 years, whereas modern records most commonly exhibit ENSO variability at 3-4 years.

**Punta El Puente and Playa El Frizal**

A distinguishing characteristic of the siliceous facies of the Monterey formation is the presence of rhythmic bedding, visible on several scales. Superimposed cycles are represented by millimeter thick laminations, 5 to 10 centimeter thick beds, and alternations on the order of 2 to 4 meters thick (Fig. 4.5). As described first by Bramlette (1946) and later confirmed by other workers, these alternations typically represent couplets with a clastic or
Figure 4.4:
A series of paleogeographic maps for Paleocene (60 million years), Eocene (40 million years), and Miocene (20 million years). Each map indicates shoreline position, paleolatitude, and topography (low = no shading; middle = stipple; and high = lines). Note gradual closing of the Panamanian and Indonesian seaways with time. From Barron, 1985.
Figure 4.5:

Schematic representation of the types and occurrences of cycles in the siliceous facies of the Monterey Formation. Numbers in years represent durations of the siliceous members of couplets within each type of cycle. Values in mm, cm, and meters are ranges in thicknesses of these siliceous members. The column on the right shows the approximate distribution of each type of cycle within the siliceous facies; letters correspond to letters in parentheses designating different types of cycles. (from Pisciotto and Garrison, 1981)
1st ORDER CYCLES
(seasonal-marine varves)
a) Diatom-clay couplets
(0.4–0.8 mm)

3rd ORDER CYCLES
(1800–3750+ years)
e) Clastic-biogenic
f) Diagenetically-enhanced
g) Massive-laminated
(1–5 m)

2nd ORDER CYCLES
(12–200 years)
b) Clastic-biogenic
c) Diagenetically-enhanced
d) Massive-laminated
(1–20 cm)

Top of Siliceous Facies

diatomite

c b c d e f g

Base of Siliceous Facies

chert and porcellite
terrigenous unit and a siliceous or biogenic unit. Pisciotto and Garrison (1981) also document laminated and massive alternations which occur in otherwise uniform siliceous rocks.

Similar cycles are observed in the rocks from PP and PE. Both sections contain mm-scale (.05-.1 cm) light, biogenic, and dark, detrital-rich alternations superimposed on larger cm to m-scale light/dark and laminated/massive cycles. If the mm-scale lamination represents varved sedimentation, and a linear sedimentation rate is assumed for the section, then an approximate periodicity can be established for the larger scale cycles at both sections.

Second order light and dark alternations at PP consist of thin, dark, detrital-rich beds, with an average thickness of 15 cm and thicker, light and more biosiliceous beds with an average thickness equal to 70 cm (Fig. 3.18). Using a varve-calibrated linear sedimentation rate between .05 to .1 cm/yr, the siliceous members of these second order cycles represent durations of approximately 700 to 1400 years. Third order cycles at both sections consist of light, more biosiliceous members and darker, more detrital-rich members, both usually between 1 to 4 meters thick. An average thickness of 2 meters for the biosiliceous members suggests that these light beds represent between 2000 and 4000 years of deposition. This frequency correlates well with the third order Clastic-Biogenic cycles described for the Monterey Formation which represent between 1800 to 3700 and the laminated/massive cycles, representing between 1800 to 3700 years in biosiliceous rocks from the Monterey Formation (Pisciotto and Garrison, 1981).

Cycles which are of approximately the same thickness as the third order cycles described above and earlier in the text for the Yumaque formation are also observed in nearshore clastics of the Los Choros formation at Punta El
Prieto (R. Wright-Dunbar, pers. comm., 1993). The time duration represented by these cycles are presently unknown. In the Los Choros formation, ~3 to 5 meter cycles consist of coarsening upwards cycles and are interpreted as representing progradation of the shoreface (R. Wright-Dunbar, pers. comm., 1993). Whether or not these cycles are correlative to eustatic and/or tectonic changes is indeterminate without more data, especially age control. It is possible that the similar scale cycles observed in Yumaque formation rocks exposed at PP and PE likewise record eustatic and/or tectonic changes affecting more distal portions of the basin.

Alternatively, if the estimated varve-based sedimentation rates are correct, then both the second and third order cycles observed in the Yumaque rocks could possibly be tied to paleoceanographic changes triggered by solar and/or magnetic field activity. Anderson et al. (1990) report varve-bioturbation cycles in Pleistocene marine varves, ranging from ~90 to ~2400 years. A ca. 200-year cycle has been recognized in historical mean Zurich sunspot number records and is thought to be the expression of the Wolf, Sporer, Maunder, and Dalton sunspot minima and also, perhaps, changes in the earth's magnetic field (Herman and Goldberg, 1978; Anderson et al., 1990). A ~2,400-year cycle, recognized in recent $^{14}$C production variations and in sedimentary records, is believed to be induced by geomagnetic field-solar activity changes (Damon, 1990; Damon and Sonett, 1990). At present, the historical persistance of these lower frequency solar cycles has not been established nor have the precise causes been firmly established. For the late Eocene to early Oligocene Yumaque formation, any relationship between the cyclicity observed and inferred solar and/or magnetic cycles observed today remains highly speculative. Confirmation of the time durations represented and more detailed
examination of longer records will help to determine the causes of cm to m-scale cyclicity in the Yumaque formation.

**Depositional Environments**

Despite their differences in age and location, at least two lines of evidence point to similar depositional environments for the Yumaque formation and Monterey Formation of California. First, the highly biosiliceous rocks that are the focus of this study and rocks from the upper siliceous member of the Monterey Formation exhibit similar lithologic associations, bedding, structures and cycles. Additionally, the inferred structural style of the late Eocene Peruvian margin (from both onshore studies and from recent unpublished offshore seismic data; C. Azalaga, pers. comm., 1992) closely resembles the borderland basin-type structural style of California at the time of Monterey deposition. This section compares the two formations and proposes analogous depositional environs for the Yumaque formation to those presented by Pisciotto and Garrison (1981) for the Monterey Formation.

Pisciotto and Garrison propose four major depositional settings for different examples of rocks from the Monterey Formation, giving their diagnostic characteristics and possible modern depositional analogues (Fig. 4.6 and 4.7). On the basis of sedimentary features and lithological units present, the finely and almost continuously laminated rocks from the southern FD section were deposited in an anoxic basin (basin floor and lower slope). No observed sedimentary structures indicate storm wave activity (such as hummocky cross-bedding); thus, these rocks are inferred to have been deposited below storm
Figure 4.6:

Simplified sketches of depositional environments of the Monterey Formation (descriptions of rocks found in each depositional environment, and modern analogues, are given in figure 4.6). Comparison between rocks from the upper siliceous member of the MontereyFm. and Yumaque formation rock types, indicates that rocks from the Fundo Desbarrancado section were deposited in an anoxic basin (D) and rocks from Punta El Puente and Playa El Erizal were most likely deposited in outer shelf/upper slope environment (A). (From Pisciotto and Garrison, 1981).
Figure 4.7:

Summary of depositional settings and their diagenetic characteristics represented by the Monterey Fm. and comparisons with modern environments. (From Pisciotto and Garrison, 1981).
<table>
<thead>
<tr>
<th>DEPOSITIONAL SETTINGS</th>
<th>DIAGNOSTIC CHARACTERISTICS</th>
<th>EXAMPLES FROM THE MONTEREY FORMATION</th>
<th>SIMILAR MODERN DEPOSITIONAL SETTINGS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isolated Bank Top</td>
<td>Thin sequences; well-sorted to moderately well-sorted foraminiferal, glauconitic and oolitic-pebbly phosphatic sands; locally may find phosphatic nodules and/or crusts.</td>
<td>Early to middle Miocene phosphatic sandstones at the base of the Monterey Formation on the “Lockwood High”, Monterey County (Graham, 1976a, Garrison and others, 1979).</td>
<td>Submarine ridges and bank tops, offshore Southern California (Dietz and others, 1942; Emery, 1960).</td>
</tr>
<tr>
<td>Aerated Basin and Basin Slope</td>
<td>Middle to lower bathyal benthic foraminiferal assemblages. Mostly burrowed, massive rocks but with some alternations of laminated and massive rocks in slope facies near the lower edge of the oxygen minimum zone; this facies may also be locally phosphatic. Redeposited foraminiferal sandstones with shallow water assemblages, (2) thin pebbly-skeletal phosphatic turbidites, and (3) thick siliciclastic turbidite fans.</td>
<td>Upper part of the Monterey Formation (Miochian) at Lompoc, Santa Barbara County (Barron, 1973; Govean, 1980) and near Newport Beach, Orange County (Ingle, 1967, 1972; Barron, 1978a; Ingle and Barron, 1978a; Govean, 1980). Elk Hills Shale member (Miochian), southern San Joaquin Valley (Maher and others, 1975).</td>
<td>Floor and lower slopes of the Guaymas Basin, Gulf of California (Calvert, 1964, 1966a, 1966b). Outer basins in the southern California border and (Gorsline and Emery, 1958; Emery, 1960; Gorsline, 1960). Panama Basin (Moors and others, 1973).</td>
</tr>
<tr>
<td>Anoxic Basin and Basin Slope</td>
<td>Dark, laminated rocks with abundant organic matter, pyrite, scattered phosphate nodules and authigenic dolomite. Micritic and burrows absent or extremely rare. Foraminiferal assemblages dominated by bathyal, low oxygen assemblages; foraminifera may be very abundant, but species lack diversity. Redeposited layers common to rare, displaying the same range of variation as in aerated basins.</td>
<td>Sandholdt member (Retician-Lusitanian) in the Arroyo Seco area, Monterey County (Graham, 1976a). Sandholdt member (Retician-Lusitanian) on the SW flank of the “Lockwood High”, Monterey County (Graham, 1976a; Garrison and others, 1979). Lower part of the Monterey Formation in the Santa Maria basin (Piacettta, 1970).</td>
<td>Santa Barbara Basin (Emery, 1960; Emery and Hulsèmann, 1962; Berger and Soutar, 1970; Soutar and Grill, 1977; Dunbar and Berger, 1961).</td>
</tr>
</tbody>
</table>
wave base (approximately 50 m). Paleobathymetric analysis is needed to confidently determine a depositional depth.

The porcelanitic rocks at PP and PE, were probably deposited in an outer shelf to upper shelf depositional environment. These sections both show cm to m-scale massive and laminated alternations, indicative of fluctuating oxygen levels during deposition. The lamination, where present, is often wavy and/or discontinuous indicating that oxygen levels were not as consistently low during the deposition of PP and PE laminated rocks as it was for FD laminated rocks. Phosphate is more abundant, both as pebble layers and within the muddy porcelanites in the PP section and glauconitic sand beds are more common in both the PP and PE sections than in the FD section. These rocks resemble Recent upwelling sediments offshore Peru, the site given as a modern analogue for this type of setting in Pisciotto and Garrison (1981).
CONCLUSIONS

1) Sediments of the Yumaque formation closely resembles both modern and Neogene biosiliceous sediments deposited under upwelling conditions along the Peruvian and California margins. Mm-scale light biosiliceous-rich and dark detrital-rich laminae couplets in all three sections are interpreted as varves, giving a varve-calibrated linear sedimentation rate (LSR) of 235 cm/kyr at FD and 50 to 100 cm/kyr for PP and PE. A mass accumulation rate of 69 g·cm⁻²·yr⁻³ calculated for biogenic silica in laminated rocks from FD and between 57 to 133 g·cm⁻²·yr⁻³ for PP and PE. The MAR for biogenic silica reported here is approximately 4 times that reported by Marty et al. (1988). This difference is attributable both to the higher biogenic silica values and sedimentation rates calculated in this study. Dissolution of a more resistant biosiliceous component using a different analytical method from Marty et al. (1988) accounts for nearly half of the discrepancy in MARs reported for Yumaque rocks exposed at FD.

2) Two major differences are noted between the FD section and the northern PP and PE sections:

- FD biosiliceous rocks are largely opal-A whereas the silica in PP and PE biosiliceous rocks has been diagenetically altered to opal-CT. This difference may be attributed either to burial of the northern rocks to greater depths. Based on Isaacs' (1983) temperature model for silica transformations and an average geothermal gradient of 48°C (comparable to present-day gradients in the Peruvian forearc, Kvenvolden and Kastner, 1990) an average burial depth of less than 900 m is indicated for the FD
section, and between 900 and 1600 m for the PP and PE sections. Alternatively, the diagenetic differences observed may be attributed to variable geothermal gradients in different parts of the basin.

- The FD section is characterized by mostly laminated intervals with clearly defined laminae whereas lamination in the PP and PE rocks is confined to meter-scale beds, with most commonly wavy and or discontinuous, laminae are, that alternate with massive (bioturbated) beds.

3) If laminae couplets at FD represent annual layers, then periodicities are observed at around 5-6, 8, and 11 years. These time durations correspond well to those of cycles observed in other varved records and are interpreted as possibly representing ENSO-type phenomenon (5-6 and 8 years) and sunspot cyclicity (11 year cycle).

4) Based on a varve-calibrated time scale, cm to m-scale alternations observed in the PP and PE sections are similar to those observed in the Monterey Formation. Biosiliceous members may represent time intervals of between 700 to 1400 years for second order cycles and between 2000 to 4000 years for third order cycles. These cycles may be attributed either to eustatic-tectonic sea level changes or to geomagnetic-solar variations.

5) By analogy to depositional settings of modern upwelling deposits and those inferred for rocks of the Monterey Formation, FD rocks were probably deposited in an anoxic basin either on the basin floor or lower slope. The rocks from PP
and PE, on the other hand, were most likely deposited near the intersection of
the oxygen minimum zone with the outer shelf or upper slope.

Offshore seismic and onshore field studies indicate that subsidence in
large half-grabens had begun by at least mid-Eocene, and perhaps early
Eocene, time; this was accompanied by the formation of numerous sub-basins
separated by local highs, providing clastic sources (C. Azalgara, Pers. Comm.,
1992; and Stock, 1989; Dunbar et al., 1990). Within this tectonic regime, the
Yumaque formation probably represents a relatively distal marine facies,
deposited during the late transgressive phase of the late Eocene basin
succession. Paleobathymetric analysis is needed to further define depositional
depths.

Sediments from the Yumaque formation indicate high productivity
associated with coastal upwelling along the Peruvian margin at least
periodically in the late Eocene to early Oligocene. This is supported by the
lithologic associations, bedding styles, and composition of rocks at FD, PP, and
PE, which closely resemble those observed in modern and Neogene upwelling
deposits. High biogenic silica accumulation rates, preservation of fine
sedimentary features and high (estimated) original total organic carbon (at least
4%) resulted from favorable basin geometries and upwelling of nutrient-rich
water.

This mode of origin is the same as that inferred for the Monterey
Formation of California and other Neogene biosiliceous deposits around the
Pacific rim. The presence of similar late Eocene biosiliceous deposits along the
eastern Pacific margin, such as the Chira formation of northern Peru and the
Kreyenhagen Formation of California, may likewise indicate a widespread
pulse of biosiliceous sedimentation in the Pacific. Further work is needed to
delineate the regional distribution of late Eocene to early Oligocene biosiliceous deposits in order to test this hypothesis.

Based on radiolarian zonations, the deposition of laminated biosiliceous Yumaque rocks exposed at FD predates the major Eocene/Oligocene cooling step (as indicated by $\delta^{18}O$-isotope paleotemperature records of benthic and planktonic foraminifera) by probably 1-2 Ma. This suggests, as previously postulated by Marty et al. (1988), that cool waters were forming in the Southern Ocean before the major cooling step noted and likewise may indicate the intensification of thermally driven atmospheric and oceanic circulation prior to major ice formation in Antarctica.
REFERENCES CITED


Daly, M. C., 1989, Correlations between Nazca/Farallon plate kinematics and forearc basin evolution in Ecuador, *Tectonics*, (8), pp. 769-790.


Ehrmann, W. U., and A. Mackenson, 1992, Sedimentological evidence for the formation of an East Antarctic ice sheet in Eocene/Oligocene time,


Pardo-Casas, F., and P. Molnar, 1987, Relative motion of the Nazca (Farallon) and South American plates since Late Cretaceous time, *Tectonics*, (6), pp. 233-248.


Ruegg, W., 1956, Geologie zwischen Canete-San Juan 13° 00′-15° 24′ Sudperu, Geol. Rundsch., (45), pp. 775-858.


Vail, P. R. and J. Hardenbol, 1979, Sea-level changes during the Tertiary, Oceanus, (22), pp. 71-79.


LITHOLOGIC DESCRIPTION

Calcareous silty mudstone to siltstone; some fish debris.

For 3 m above thick sand bed: thin (10-15 cm) sandstone beds, greenish, fine grained, intercalated w/brown massive siltstone.

75 cm thick greenish sandstone: well sorted, well-rounded, med. to coarse grained w/black and green sand grains (qtz. + fsp.); non-calcareous cement; low angle (>10°) cross-stratification; gastropod? shell at base.

Brown silty mudstone to siltstone.

Large calcitic nodules; appear to be brecciated.

Brown silty mudstone and siltstone; sometimes calcareous.

Numerous small normal offset (1-5 cm) faults dipping at 75° to the NE, strike SE/NW.
Large calcitic nodules (1-1.5 m in diam.); appear to be brecciated.

Calcereous brown silty mudstone and siltstone.

Large calcitic nodules; appear to be brecciated.

Calcereous brown silty mudstone and siltstone.

Nodular beds w/calcitic concretions.

Several normal faults:
oriented 130/55 SW
w/8 m of total displacement;
one other normal fault w/displ. of 1 m.

PP63 (1986) nanofossil zone (Discoaster druggi) of Okada and Bukry (1980):
M. Filewitz, pers. comm. in Dunbar et al. (1990).
Calcereous brown silty mudstone to siltstone

1 m thick gray siltstone bed (ash)

Mudstones, sometimes calcereous; few forams and fish scales.
Mudstone; calcareous nodular beds; nodules approx. 1 x 3 m. PP60 (1986) 87Sr/86Sr = .708387: latest Oligocene to early Miocene (P. Baker, Pers. Comm., in Dunbar et al., 1990).

Brown siltstone.

Dark green sandstone: top of bed appears scoured; med to coarse-grained, well rounded, black and green sand grains, poss. phosphatic clasts, rip-ups of contorted, laminated mudstone in center of bed; numerous 1-6 cm long vert. burrows from cent. to top of bed; poss. phosph. nodule lens 20 cm from base.

Light brown homogenous calcareous mudstone within interbeds of dark, shaly mudstone that does not react in HCL (dol? or porcelanite?); vert. burrows 1-5 cm long, fish debris, forams and biotite flakes.

10 cm laminated bed w/sharp color banding.

3 - 4 m interval of nodular mudstone bed with calcitic nodules 2 m in length near top, w/ smaller dolomitie nodules at the base (.5 m in length).

Light brown massive mudstone w/darker, laminated intervals 8-10 cm thick. Dark layers are more resistant (porcelanitic?)
Light brown massive mudstone w/darker, laminated intervals 8-10 cm thick. Dark layers are more resistant (porcelanitic?) and have mm-scale laminae which are generally undisturbed, but may be locally contorted. Light layers are are 70 - 100 cm thick, less resistant and generally homogenous and have burrows (vert and horiz.) about 5 cm long; flame and other water esc. structures visible at contacts betw. light and dark layers.

fine-grained sandstone w/brown matrix

Muddy siltstone and siltstones.

tuffaceous layer

Muddy siltstone and siltstones.

PP42 (1986) Miocene (Uvigerina carapatina, Lenticulina sp., Bathysiphon sp.)

calcite nodules
Muddy siltstone and siltstones; thin beds (5-10 cm) w/ some variations in hardness; forams, occ. fish debris, a few coarse black sand grains which are well-rounded.

As above and below; thinner bedded interval (approx. 5 cm).

Muddy siltstone and siltstones; thin beds (5-10 cm) alternating soft and hard beds; forams, occ. fish debris, a few coarse black sand grains which are well-rounded.

SECTION FROM 40-88 M DESCRIBED IN FIG. ??

40-44m: slumped interval

Lenticular, brecciated bed appx. 20 cm thick.

Concretionary calcitic bed.
Brown laminated nodular mudstone.

Concretionary calcitic bed.
Brown laminated nodular mudstone.

Brown laminated mudstone.

Concretionary calcitic bed.
Brown laminated mudstone w/dolomitic nodules.
Concretionary calcitic bed.

Brown laminated mudstone w/dolomitic nodules, fish scales and forams.

PP8 (1986) 87Sr/86Sr ratios in authigenic dolomites 0.70784, Late Eocene [P. Baker, pers. comm., in: Dunbar et al., 1990].

3-10 cm thick beds of dolomitic, concretionary, very fine grained sandstone.
Brownish-grey laminated mudstone w/siltstone; abundant benthic forams; phosphate nodules.

Hard. laminated layer w/calcitic nodules.
Massive siltstones/mudstones w/rare forams; tar on exposed surface.
15 cm lenticular bed of sandstone w/muddy rip-up clasts; some phosphate.

Laminated siltstones and mudstones w/fish scales, calcite nodules near base; appears to be foliated and/or lineated; poss. stylolites?.
Concretionary calcitic bed.
Brown laminated mudstone w/dolomitic nodules.
Concretionary calcitic bed.
Brown laminated mudstone w/dolomitic nodules, fish scales and forams.
3-10 cm thick beds of dolomitic, concretionary, very fine grained sandstone.
Brownish-grey laminated mudstone w/siltstone; abundant benthic forams; phosphate nodules.
Hard. laminated layer w/calcitic nodules.
Massive siltstones/mudstones w/rare forams; tar on exposed surface.
15 cm lenticular bed of sandstone w/muddy rip-up clasts; some phosphate.
Laminated siltstones and mudstones w/fish scales, calcite nodules near base; appears to be foliated and/or lineated; poss. stylolites?

LEGEND

Concretions
Sandstones
Siltstones and mudstones; undiff.
Siltstones and mudstones; undiff.
Tuffaceous mudstone beds
Age control point
Columnar stratigraphic section at Punta El Puente, Piaco Basin, Peru.
Annotated with sample locations.
Measured 7/3/1990 by E. L. Frantz and R. Cruzado
Scale 1:50

Some vertical exaggeration of thin beds to show detail.

- Brown, mm-scale laminated mudstone.
- 20 cm thick mixed interval: med. brown homogeneous mudstone (with biotite?)
  flakes) with green sandstone lenses (pass. rip-up clasts) and concretions.
- Green massive sandstone, med. to coarse-grained, well sorted, angular detrital grains
  and rock frags., rounded glauconitic grains; contact with underlying sandstone
  unit is distinct.
- 8 cm thick, med. grained, well sorted, massive yellow sandstone bed, top partially eros.
- Green massive sandstone, med. grained, well sorted.
- 10 cm thick yellow-orange sandstone bed, med. grained, well sorted; sharp upper
  contact defines base of overlying sandstone unit.
- Green massive sandstone, med. grained, well sorted.
- 8 cm thick yellow-orange sandstone bed, med. grained, well sorted; sharp upper
  contact defines base of overlying sandstone unit.
- Very green massive, med grained, well sorted sandstone; burrowed.
- Yellow-orange, med. grained, well sorted sandstone; extensively burrowed.
- Green massive sandstone, fine to med. grained, well sorted.
- Yellow-orange sandstone, med. to coarse grained, well sorted.

Green, massive, med. to coarse sandstone (not burrowed, no gypsum veining).
- 80 cm from base, calcite concretions, approximately 20 cm long by 12 cm high

Conglomerate: fine to med. grained, yellow-orange sandstone matrix
with angular green sandstone clasts.
Conglomerate: altered laminated siltstone to mudstone clasts
(up to 10 cm long by 7 cm wide) surrounded by green, medium to coarse-grained
sandstone. Top of bed is scoured.
Green sandstone with large (up to 30 cm high by 15 cm long) dolomite(? ) nodules
interspersed throughout bed.
Medium brown finely (mm-scale) laminated siltstone to mudstone with obvious fish debris. Laminated (mm-scale) mudrocks begin at about 78.48 m; at 78.51 m one sees a transition with very faint convoluted laminae. Lenses of green sandstone present in top 1.5 meters. Gypsum veins follow bedding planes, often see concentrations resting on top of veins, numerous concretions.

Scoured or channelled surface. "Waves" about 2 m in length

4 cm thick dark brown laminated mudstone.

Light brown, laminated mudstone. Fish debris, forams.

3 cm thick dark brown, laminated mudstone.

Light brown, laminated mudstone. Fish debris, forams and small-scale cross-lamination.

3 cm thick, dark brown laminated mudstone, extensively veined.

35 cm thick light brown, laminated mudstone. Fish debris, forams.

15 cm thick, very dark brown laminated mudstone. More extensive veining than light brown mudstones and is more fissile.

Light brown, laminated mudstone. More resistant than dark mudstones; boundary with underlying dark brown mudstone bed gradational.

Dark brown laminated mudstone, top and bottom contacts gradational.

Light brown laminated mudstone, top contact gradational, bottom contact sharp.

Dark brown laminated mudstone, top and bottom contacts very sharp. Includes small pebbles (up to 1 cm long, 1/2 cm wide, pinkish) concentrated in lag layer 4 cm above base of bed.

Light brown laminated mudstone bed with sharp top and bottom contacts.
Light brown laminated mudstone with poorly defined laminations at top, laminations become finer and better defined near base.

4 cm thick dark brown mudstone interval with extensive gypsum veins. Also has lags (possibly phosphatic pebbles?).

Light brown laminated mudstone with abundant calcite nodules (~10 to 30 cm long and 5-10 cm high) approximately 4 cm from top of bed. Node preserves laminations.

5 cm thick dark brown mudstone with subtle top and bottom contacts, extensively veined.

Light brown, finely laminated mudstone with extremely subtle top and bottom contacts.

18 cm thick dark brown mudstone with subtle top and bottom contacts.

Light brown mudstone bed with sharp bottom contact.

Light brown mudstone bed with good lamination and abundant fish debris.

Dark brown mudstone bed, contacts not visible.

Light brown mudstone bed, good lamination.

Mudstone beds, transitional in color from light to very dark brown (overall dark brown).

18 cm thick dark brown mudstone bed bioturbated by a 8 cm thick gypsum vein.

3 cm thick light brown laminated mudstone bed, sharp contacts.

4 cm thick dark brown laminated mudstone bed, sharp contacts.

72 cm thick light brown laminated mudstone bed, sharp contacts.

4 cm thick dark brown laminated mudstone bed, sharp contacts.

45 cm thick light brown laminated mudstone bed, sharp contacts.

40 cm thick dark brown laminated mudstone bed, sharp contacts.

7 cm thick greenish, fine-grained sandstone.

Homogeneous, medium to coarse-grained, dark brown sediments, bivalve-rich.

10 cm thick ash layer.

Mixed light and dark brown mudstones in an overall light brown interval. Individual color bands hard to discern. Dark brown beds only a few cm's thick, light brown beds are 10's of cm's thick. Laminae are very fine and well preserved, rocks are brittle and flinty. Top of interval marked by secondary cliff: more resistant interval = 56.94 to 52.17 m.

Layered calcareous nodules 1/2 m to 1 m at 17 meters.
Dark reddish brown mudstone bed with poorly preserved laminae. Carbonate nodules (~20 cm by 8 cm) on top of underlying ash and also directly above 52.17 m (bottom is within dark brown interval).

* Altered ash. Gray interval, looks like it fills a channel, variable thickness from ~10 cm to 40 cm.

72 cm thick light brown laminated mudstone bed with sharp contacts
6 cm thick dark brown laminated mudstone bed with sharp contacts
15 cm thick light brown laminated mudstone bed with sharp contacts
5 cm thick dark brown laminated mudstone bed with sharp contacts
35 cm thick light brown laminated mudstone bed; some very subtle dark brown intervals
10 cm thick dark brown laminated mudstone bed with gradational top contact, sharp bottom contact.
5 cm thick light brown laminated mudstone bed with sharp contacts.
10 cm dark brown laminated mudstone bed with sharp contacts
37 cm thick light brown laminated mudstone bed with sharp contacts.
15 cm thick dark brown laminated mudstone bed with gradational top contact, sharp bottom contact.
1 meter thick light brown laminated mudstone bed with sharp contacts.
No gypsum veining until 48.04 m.

1 cm thick green, fine grained sandstone bed.
1.3 cm thick dark brown laminated mudstone with sharp contacts. Some convolutions and micro
Green bed that feels like talc, laminated at bottom, massive at top.
Brown laminated mudstone with 1 cm thick green layers.
10 cm thick gray ash layer.
9.3 cm thick light brown laminated mudstone with a 1 cm thick green sandstone bed at 46.75
2 cm thick green sandstone bed at 46.32 m, and a 1 cm thick green sandstone bed at
45.3 cm thick green sandstone bed at 46.54 m and 46.32 m. Between the green sandstone interbeds is light brown laminated mud!

Dark brown laminated mudstone, less resistant than sediments above and below
2 cm thick green sandstone interbed + gypsum at 46.07 m.
80 cm thick light brown, finely laminated mudstone bed.
9 cm thick dark brown, more resistant, well laminated mudstone bed;
2 cm green clay interval at base.

4 cm thick grey well laminated mudstone bed; overall section is getting darker
1 cm thick altered ash interval at 44.30 m.
10 cm thick very dark brown mudstone, less resistant than intervals above or below, top
and bottom contacts sharp.

-30 cm of light brown, faintly laminated mudstone.

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**LEGEND**

- Calcareous concretions
- Pebby lag
- Burrows
- Contorted laminations in mudstone
- Volcanic ash layer
- Dark colored laminated intervals
- Light colored laminated intervals
- Sandstone intervals