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Rice University, Ph.D., 1965
Geology

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PARGUERA LIMESTONE, UPPER CRETACEOUS MAYAGÜEZ GROUP
SOUTHWEST PUERTO RICO

by

Charles Coit Almy, Jr.

A THESIS SUBMITTED
IN PARTIAL FULFILLMENT OF THE
REQUIREMENTS FOR THE DEGREE OF
Doctor of Philosophy

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INTRODUCTION

General Statement

Variations in the sedimentary rocks associated with volcanic island arcs reflect and record events in the development of these arcs. A detailed study of such variations in the character of the Parguera Limestone of southwest Puerto Rico has given information for the interpretation of the events occurring in this portion of the Caribbean island arc during Santonian - Maestrichtian time. The stratigraphic sequence is established, the evolution of the associated volcanic rocks is given stratigraphic meaning, structural development of area is described, and the local Upper Cretaceous paleogeography is inferred from a study of the Parguera unit. This unit was chosen because it interfingers with volcanic rocks and has remained relatively unaltered by subsequent geologic events.

The general geology of the area has been outlined by P.H. Mattson (1957, 1960) and T.R. Slodowski (1956), whose studies form the basis for the detailed mapping. The units within and immediately adjacent to the Parguera Limestone of Mattson (1957, 1960) (Ensenada Formation of Slodowski (1956), or Ensenada Shale and San Germán Limestone of G.J. Mitchell (1922)) were differentiated and sampled. The following data were collected: rock descriptions, modal analyses, insoluble residues, clay mineral suites, and paleontologic dates. The data and their interpretation are presented in this report.
First, the geologic framework of the Parguera depositional area is described with respect to structural geology, rock units underlying the basin, and topography of the basin. Second, the detailed stratigraphy of the Parguera Limestone is presented. Finally, the environment of deposition and the paleogeography of the Parguera units are discussed.

Location

The area studied comprises 50 square miles on the southwest coast of Puerto Rico and extends along the coast from Guánica westward to the west coast at Punta Melones. Parts of the following six 7\ 1/2 minute U.S.G.S. quadrangles are covered: Puerto Real, Cabo Rojo, San Germán, Parguera, Sabana Grande, and Guánica. The area lies between 66°52\ 1/2' W and 67°12' W longitude and 17°57\ 1/2' N and 18°02\ 1/2' N latitude.

Puerto Rico, the smallest and easternmost of the principal Greater Antilles islands, lies in the zone of the northeast trade winds and has a tropical climate. Although the north and east sides of the island have high rainfall and heavy vegetation, the southwest part is almost semi-arid because it lies in the rain shadow of the Cordillera Central.

Location of the area and place names used in the text are presented on Figure 1, and sample localities are shown on Plate I.
Terminology

Generally the petrologic terminology used in this report follows that of Williams, Turner, and Gilbert (1954), Pettijohn (1957), or Purdy (1963a, carbonate grains). Stratigraphic usage follows Weller (1960). Terminology for clay minerals follows the usage of Brown (1961). Ages of the rock units are referred to the European stages as correlated by Pessagno (1961, 1964) for the Caribbean region.

Acknowledgments

Dr. T.W. Donnelly, Rice University, Houston, Texas, suggested the problem and guided the research. Dr. J.D. Weaver, Geology Department, University of Puerto Rico, Mayagüez, Puerto Rico, provided field transportation and field and laboratory equipment, as well as a lectureship for one year. Dr. Peter H. Mattson, Queens College, New York City, New York, aided considerably through discussions in the field. Mr. Peter E. Almy acted as field assistant for two weeks.

Dr. E. A. Pessagno, Jr., Department of Geology, University of California, Davis, California, provided stratigraphic dates based on the microfauna in thin-sections, marls, and insoluble residues. Dr. B. F. Perkins, Shell Development Company, Houston, Texas, identified and interpreted the rudist fauna. Limestone petrography was aided considerably by Dr. Perkins, Dr. Pessagno, and J. W. Keith of Tenneco Oil Company, Houston, Texas. All errors, however, rest
solely with the writer.

Mrs. Charles C. Almy, Jr., helped considerably in the laboratory and in writing. Dr. J. J. W. Rogers and Dr. Jack Hudson, Rice University, together with Dr. Donnelly, critically read the manuscript. The Department of Geology, Tulane University, New Orleans, Louisiana, provided photographic facilities.

The work was partially supported through National Science Foundation grant No. G14407 awarded to Dr. T. W. Donnelly for geologic studies of Puerto Rico and the Virgin Islands.

To all these and more the writer wishes to express his thanks and sincere appreciation.
REGIONAL GEOLOGY AND PREVIOUS WORK

Caribbean Area

Puerto Rico is one of several islands on the crest of the curved welt marking the Caribbean island arc. To the north the sea floor slopes steeply into the Puerto Rican trench and rises on the far side to the Atlantic Ocean floor. To the south the surface drops fairly steeply to the Caribbean Sea floor without an intervening trench. This south slope may be influenced by faulting associated with the Anegada trough.

The island itself consists of an east-west core of Cretaceous volcanic rock and minor limestone and mudstone lenses strongly faulted and folded. This core is mantled continuously along the north coast and in patches along the south coast by gently seaward dipping Miocene and younger sediments. A generalized geologic map of Puerto Rico is presented in Figure 2. Donnelly (1964), Berryhill et al. (1960), Zapp et al. (1948), Mattson (1957, 1960), and Slodowski (1956) provide excellent general reviews and discussions of the literature, as well as the general geology and tectonics of Puerto Rico and the Virgin Islands. Such a review is beyond the scope of this paper and the reader is referred to the above articles.

The stratigraphy of southwest Puerto Rico is discussed in a historical sense, and then the general lithologic distribution and geologic history are presented.
FIGURE 2: GENERALIZED GEOLOGY OF PUERTO RICO

MODIFIED FROM BRIGGS, 1961
Southwest Puerto Rico

G. J. Mitchell (1922) made a geological reconnaissance of the southwest quarter of the island in which he recognized the Tertiary - Cretaceous unconformity, the folding of the Cretaceous rocks, the general WNW structural trend, and certain of the major faults. He named the more distinctive sedimentary units such as the Río Yauco Shale, Peñuelas Shale, and San Germán Limestone. His mapping and stratigraphy have been extensively revised, however, especially by Mattson (1957, 1960) and Slodowski (1956). Meyerhoff (1933) presented an excellent review of Puerto Rican geology but added little to the information then known about the area of this report. R. C. Mitchell's report (1954) is unreliable.

The general geological background for this report is the work in the Mayagüez area and Yauco area done by Mattson (1957, 1960) and Slodowski (1956). The two reports cover the geology from the Cordillera Central south to the coast and from Guayanilla west to the west coast in fair detail. Their mapping north of the Cordillera Central is considerably more generalized. Turner (1955; in progress) is mapping part of this area north of the Cordillera Central.

**Stratigraphy**

Slodowski (1956) established the following sequence in the Yauco area (Fig. 3a):

Older Complex - serpentinite which forms the cores of...
FIGURE 3A - STRATIGRAPHIC SEQUENCE FOR THE YAUCO AREA

AFTER SLODOWSKI, 1956

FIGURE 3B - STRATIGRAPHIC SEQUENCE FOR THE MAYAGÜEZ AREA

AFTER MATTSON, 1960
the major anticlines and which is overlain with erosional unconformity by the rocks of the Younger Complex.

Younger Complex - folded and faulted Lower Tertiary and Upper Cretaceous volcanic rocks with shale and limestone lenses.

Quaternary and Middle Tertiary rocks - shales, sandstones, and limestones that were derived from a relatively stable land area and that mantle the older rocks along the coast.

This report is concerned primarily with the rocks of the Younger Complex of Slodowski, especially the limestones of his Ensenada Formation and the associated volcanic rocks. In comparing Slodowski's study with Mattson's and with the writer's preferred usage, the relative positions of the Río Loco Formation, Sabana Grande Formation, Ensenada Formation, and San Germán Formation should be noted.

First, both Slodowski and Mattson found Río Loco and rarely Sabana Grande volcanics in contact with the serpentinite (Bermeja Complex of Mattson, 1960, p. 323) and both found Sabana Grande Andesites overlying, possibly normally, the Río Loco Formation. However, on the basis of isolated outcrops of Río Loco above the Sabana Grande and an erroneuous date, Slodowski placed the Sabana Grande Andesites below the Río Loco rocks. From Mattson's work, Slodowski's own map, and the writer's work, it is evident that the Río
Loco is older than the Sabana Grande and is in normal stratigraphic position under the Sabana Grande Andesites.

Second, the Ensenada Formation of Slodowski (1956) is, in part, equal to the Parguera Limestone of Mattson (1960, pp. 333-335) and this report and to the Ensenada Shale of G. J. Mitchell (1922, p. 252). Mattson has equated the upper part of the northern outcrop of the Ensenada Formation to the limestones and volcanics of the San Germán Formation, and he places the lower part of the northern outcrop and all of the southern limestone outcrops of the Ensenada Formation in the Parguera Limestone. He correlates the southern outcrop of Ensenada volcanics with the Río Loco volcanic rocks. The writer believes that Mattson's correlations of the northern outcrops may be correct, that his correlations of the southern limestones are correct, but that the southern Ensenada volcanics more properly should be considered Sabana Grande Andesite (p. 30, this report).

Third, Mattson mapped fairly consistently on a lithofacies basis while Slodowski often included parts of lithologically similar units in what, he thought, were genetically or synchronously similar units. For example, although he mapped a separate mudstone unit as the Río Yauco Formation, he also included thick sequences of mudstone in the Río Loco and Sabana Grande Formations. These mudstone sequences have been placed by Mattson in the Yauco Mudstone (1957, pp. 97-98). For this area, Mattson's methods have provided a more useful
picture, and his stratigraphic definitions are followed in this report with only minor exceptions.

Mattson (1957, 1960) gives the following sequence (Fig. 3b) for southwest Puerto Rico:

Bermeja Complex composed of serpentinite, chert, minor spilites, and minor amphibolites. The age is uncertain but possibly pre-Cenomanian (Mattson, 1957, p. 324), and the rocks are the oldest in the area.

Cenomanian? Río Loco Formation composed primarily of andesites characterized by two pyroxenes. It lies with erosional unconformity upon the Bermeja Complex.

Santonian - Maestrictian sequence bounded by unconformities and containing units mapped strictly as lithofacies - the Mayagüez Group. The main interest of this report lies here.

Maestrictian San Germán Formation consisting of an upper, massive, bioclastic limestone (Cotuí) within a sequence of andesites and a lower volcanic agglomerate (Cabo Rojo).

Paleocene Jicara Formation of limestones and fine-grained tuffs lying unconformably upon the underlying rocks.

Middle Tertiary limestones, marls, and shales gently dipping seaward in small patches along the south coast and overlying the Eocene - Cretaceous rocks with major unconformity.
The general strike of the rocks in the Mayagüez area is west-northwest. Within the Mayagüez Group the major facies changes are north-south, the facies changes remaining more or less constant along strike. Southward from the Bermeja Complex in the Cordillera Central the general facies variations of the Mayagüez group may be summarized as follows (Fig. 4):

1. The Yauco Mudstone to the north is the approximate age equivalent of the Parguera Limestone to the south.

2. Sabana Grande Andesites form a thick lens within the lower part of the sedimentary sequence to the north and thin southward. Rarely are they in contact with the Río Loco volcanics or the Bermeja Complex. Mattson did not find the Sabana Grande rocks in the southern Mayagüez area, but the writer has found Sabana Grande rock types beneath the Parguera Limestone in the south in the Yauco and Mayagüez areas. This change made in Mattson's general stratigraphic section is shown on Figure 4 and discussed under Local Geology.

3. Maricao Basalt is found to the north in Yauco Mudstone, but not in the Parguera Limestone to the south.

4. Brujo Limestone forms massive beds of bioclastic limestone within the Parguera Limestone. These are possibly basal and possibly correlate with the massive limestones north of Ensenada (p. 164, this report).
FIGURE 4
DIAGRAMMATIC SECTION, LITHOFACIES OF THE MAYAGUEZ GROUP

MELONES LIMESTONE
PARGUERA LIMESTONE
SAN GERMAN FORMATION
EL RAYO VOLCANIC ROCKS
SABANA GRANDE ANDESITE
RIO LOCO FORMATION

NORTH

YAUCO
MUDSTONE
MARCAO BASALT

SOUTH

MODIFIED FROM MATTSON, 1960, P. 130

8 kilometers
5 miles
5. Above the Parguera rocks are the El Rayo Volcanics, which occur only in the east-central part of the area, and the Melones Limestone in the central and southern part of the Mayagüez area.

Overlying the Mayagüez Group is the San Germán Formation, some of whose rocks (Cotui Limestone, andesites of the San Germán Formation) may be confused with the Parguera Limestone or the Sabana Grande Andesite.

**Structural Geology**

According to Mattson (1960, p. 349) major deformation occurred at two times, pre-San Germán (Maestrichtian) and late Eocene. The major folds are four and trend N 60° W except in the southwest part of the Mayagüez area where they curve from N 60° W to N 60° E (Fig. 5). All the anticlines are oversteepened to the south in the Mayagüez group. Mattson (1960, pp. 353, 358) shows the southernmost anticline overturned and overthrust northward, but the writer believes the structure to be a syncline in normal position (p. 44). Faulting in the Mayagüez and Yauco areas is primarily strike-slip or normal where direction can be determined. Slodowski (1956, p. 118) mapped a thrust fault, the Torres thrust, involving the Sabana Grande Andesite. Its trend is roughly E-W and agrees with that of the major strike-slip faults in both areas (Cordillera, San Germán, Montalva faults). Another major fault set trends N 45° E. A set of smaller faults trends N 20° E (Mattson, 1960, p. 353)
FIGURE 5: STRUCTURES IN THE MAYAGÜEZ AND YAUCO AREAS, P. R.
STRUCTURES WITHIN THE AREA OF THIS REPORT (STIPPLED) ARE MAPPED BY THE WRITER; OTHERS, BY
MATTSON (1960) AND SLODOWSKI (1956)
throughout the area. Minor uplift and gentle warping has occurred since the major periods of deformation.

**Geologic History**

Briefly the geologic development of the Mayagüez-Yauco areas may be outlined as follows:

1. Formation of the Bermeja Complex and its erosion prior to extrusion of the Río Loco Formation.
2. Río Loco accumulation, then erosion(?).
3. Deposition of Yauco Mudstone to the north.
4. Extrusion of the Sabana Grande Andesite interrupting or overwhelming Yauco deposition.
5. Parguera Limestone deposition in the south and continued Yauco deposition in some areas; decrease in Sabana Grande Andesite extrusion.
6. El Rayo Volcanic Rock emplacement in the central Mayagüez area, erosion in the southern area, and finally deposition of the Melones Limestone in the south and central areas with Yauco deposition continuing elsewhere.
7. Folding into the four major anticlines, uplift, erosion.
8. Deposition of the San Germán Formation.
9. Folding, erosion(?), and deposition of the Jicara Formation.
10. Uplift, erosion, and deposition of the Middle Tertiary sequence followed by mild uplift and erosion to the present day.
LOCAL GEOLOGY

The Parguera Limestone consists of a thick, basal, medium-grained calcarenite that decreases upwards in non-carbonate clastic material but does not change in grain size; a fine-grained, foraminiferal mudstone; and a coarse-grained volcanic conglomerate that grades upwards into a coarse-grained bioclastic limestone. The lowermost unit has a fairly continuous glauconitic marker-bed found throughout the area and a thick, bioclastic limestone that replaces much of the basal calcarenite to the east.

The fauna contained in the Parguera Limestone indicates a normal marine salinity and tropical to subtropical climate throughout the section. The assemblages vary with the inferred sedimentary environment in response to such tectonically controlled factors as variations in sediment supply (type and rate) and basinal depth. The rocks are everywhere dated as Santonian-to-Maastrichtian with the basal unit described above being consistently oldest.

The Parguera Limestone overlies a wide range of rock types. An important part of its basal sands (or locally conglomerates) are generally formed of whatever rock is directly underneath. In the Melones area to the west and locally in the Vertero hills, it contains fragments of the underlying Bermeja Complex. At Ensenada the basal sand is rich in volcanic fragments and minerals. Especially notable at Ensenada is the presence of hornblende to the
north and pyroxene to the south. These differences correspond to the different types of andesite flows present (p. 33).

The general southerly dip along the east-west trending belt of outcrop is noticeably reversed in the following places:

1) Melones syncline - both limbs of this east-north-east trending syncline are present.

2) Southwestern tip of the Sierra Bermeja - a small shallow syncline is present here.

3) Parguera syncline - the west-northwest nose is present, and the strike and dip trend around it so that near Isla Guayacán the rocks dip northward.

4) Vertero syncline - both limbs are present in the western half of the Vertero hills.

Vertical faulting has taken place throughout the area, but most especially in the eastern half. The trend is east-west and generally the blocks are upthrown to the south. The Montalva fault zone is a major zone of displacement here.

Because they bear directly on the lateral variations in the vertical development of the Parguera deposits and on the understanding of the order of this development, the configuration and composition of the rocks underlying the Parguera Limestone and the detailed structural geology of the area studied are presented before the detailed description of the Parguera rocks.
Parguera Depositional Surface

**Bermeja Complex**

The Bermeja Complex, where it is in stratigraphic contact with the Parguera Limestone, seems to have formed positive topographic elements on the Parguera depositional surface. For example, the Sierra Bermeja may have been a positive element during Parguera times as it is today. This possibility is suggested by the westward thinning of the Parguera Limestone and the apparent easterly slope of the depositional surface.

Evidence for the erosional unconformity at the Parguera Limestone-Bermeja Complex contact is found in the Sierra Melones, Sierra Bermeja and Vertero hills.

At the contact of the basal Parguera and the Bermeja Complex at Punta Melones, Mattson (1960, p. 335) described a silicified soil zone with the Parguera Limestone lying directly upon it (locality 818, pl. 1). The existence of a fault at this surface is possible, and there may have been movement along this surface whether or not the juxtaposition of the rock types is originally depositional.

This "soil zone" contains rounded pebbles and sand-sized grains of serpentine (?) and chert derived from the underlying Bermeja Complex and some possible volcanic rock fragments. These grains are cemented by coarse-grained silica and calcite and are themselves silicified to some extent. The whole weathers to a tan-to-dark brown rock with a very tough texture.
Immediately overlying the "soil zone" is the tan, fine- to medium-grained, non-carbonate clastic-rich limestone with large gastropods that marks basal Parguera. However, throughout the Sierra Melones this limestone is consistently re-crystallized, partially dolomitized, and partially silicified.

Eastward along the Bermeja - Parguera contact on the north side of the Sierra Melones, a conglomerate of chert and fine-grained basic igneous or metamorphic pebbles set in a fine-grained clay-rich, greenish matrix, appears between the two units (Plate I). Sample localities 243 or 767a show good exposures. The shape and nature of the fragments is similar to those in the "soil zone" of Mattson and the "soil zone" may be the silicified equivalent of this conglomerate. Silification took place by recent weathering on the present coast. Whether or not this conglomerate belongs directly in the Parguera sequence is not known.

This conglomerate is also found along the northeast-southwest trending fault within the Sierra Melones under the basal Parguera Limestone. On the south side of the Sierra Melones, the conglomerate is not seen where the Parguera - Bermeja contact is drawn, and the contact may be faulted.

To the east, patches of Parguera Limestone lie upon flanks of the Sierra Bermeja, but none show any clear contact relations except the area of outcrop at the southwest end of the Sierra Bermeja. Here an "abbreviated" lower sequence, including the silicified tan limestone and a
somewhat glauconitic bed, overlie the chert and serpentine of the Bermeja Complex. The conglomerate was not seen. The serpentine was extremely altered near the contact, possibly through exposure to weathering before Parguera deposition.

In the small knobs east of the Sierra Bermeja and west of the Vertero hills at locality 110c, the Parguera rocks are found resting on Bermeja rocks. Mattson (1960, p. 335) reports the presence of serpentine fragments in the overlying limestone.

In the Vertero hills at Cerro Vertero is a large outcrop of chert (locality 342), and a tan to greenish-tan, medium-grained, calcareous, tuffaceous sandstone that surrounds the chert. Lenses of massive limestone and beds of chert conglomerate occur in the sandstone. The chert is correlated with the Bermeja Complex, and the sandstone and contained limestone beds overlie the chert with erosional unconformity. The general dip of these beds is northward, but they are disturbed by the Montalva fault zone. Volcanic rocks of the Río Loco Formation crop out to the south.

The outcrop of chert may be interpreted as a buried hill within a sedimentary lens of the Río Loco Formation, a buried hill within the basal Parguera Limestone, or a slide block in the basal Parguera Limestone. The enclosing sediments are similar to and are considered to be basal Parguera, and the chert is considered to be a buried hill. The rounded
chert pebbles in the enclosing sediments and the northward
dip of these sediments corresponding to their position on the
south limb of the Verterro syncline support the hypothesis of
a hill buried by Parguera sediments. However, no paleontologic
dates are available, nor were any dips consistently sloping
away from the chert body noted. The other hypotheses are not
considered eliminated.

Neither precipitation of silica contemporaneous with
the deposition of the surrounding sediments nor later
secondary alteration of these sediments sufficiently explains
the presence of the chert of Cerro Verterro for the following
reasons:

1. The contacts are sharp between chert and
   sediment.
2. The sediments show no signs of silicification.
3. Detrital chert is present as discreet, rounded
   pebbles and is similar to the chert that crops out at
   the same locality.

Volcanic Rocks

The volcanic rocks forming the Parguera depositional
surface consist of three closely related rock types. All
these rock types have a groundmass made of altered glass,
plagioclase laths, and euhedral magnetite. All contain
phenocrysts of clinopyroxene, generally euhedral, and plagi-
oclase, which is twinned and moderately zoned in laths and
rimmed and intensely zoned in equant grains. Alteration
products in all cases are chlorite, ore minerals, calcite, clay, and rare plagioclase (on mafic minerals). Each of these rock types may be found as flows and as younger sedimentary fragments in the overlying sediments.

The rocks may be divided mineralogically (Table 1, figure 6) on the basis of their mafic mineral content. The first type contains both hypersthene and augite (Figure 7), the second type contains only augite (Figure 8), and the third contains augite and hornblende (Figure 9). The rock types are also separable on percentages of plagioclase phenocrysts, of matrix, and of total mafic minerals. Alteration has affected the augite andesite generally and the augite-hornblende andesite specifically in the hornblendes. In all cases the feldspars are somewhat altered, especially the rimmed ones. Descriptions and localities of the above rock types are given in Appendix A and Plate I.

These mineralogically different types occur in mappable units. The augite-hypersthene andesite is found south of the Parguera hills within the Parguera sequence and is dated by its enclosing sediments as Upper Campanian - Maestrichttian. The same rock is recorded by Mattson from the area north of the Parguera hills and north of the Verterio hills beneath the Parguera section. The augite andesites crop out immediately beneath the Parguera section in the central part of the area and to the east at Cerro Lajara. The augite-hornblende andesite occurs eastward from Cerro Verterio to Cerro de Abra at the base of the limestone.
TABLE 1

MODAL ANALYSES OF VOLCANIC ROCKS FROM SOUTHWEST PUERTO RICO

I Augite - hypersthene andesites

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Phx</th>
<th>Plagioclase</th>
<th>Cpx</th>
<th>Opx</th>
<th>Hbl</th>
<th>Opk</th>
<th>Qtz</th>
<th>Gms</th>
<th>Pc</th>
<th>Glass</th>
<th>Opk</th>
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</thead>
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<td>A-44c</td>
<td>39.3%</td>
<td>20.9%</td>
<td>-%</td>
<td>-%</td>
<td>-%</td>
<td>-%</td>
<td>16.0%</td>
<td>-%</td>
<td>49.8%</td>
<td>26.7%</td>
<td>23.1%</td>
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<tr>
<td>145c</td>
<td>43.3</td>
<td>14.3</td>
<td>9.3</td>
<td>15.8</td>
<td>2.9</td>
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<td>10.4</td>
<td>0.8</td>
<td>-</td>
<td>2.6</td>
<td>-</td>
<td>56.4</td>
<td>23.3</td>
<td>29.9</td>
</tr>
<tr>
<td>480</td>
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<td>8.6</td>
<td>7.1</td>
<td>13.7</td>
<td>8.4</td>
<td>0.2</td>
<td>1.2</td>
<td>-</td>
<td>60.8</td>
<td>19.0</td>
<td>36.2</td>
</tr>
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<td>901</td>
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<td>-</td>
<td>1.4</td>
<td>-</td>
<td>59.0</td>
<td>13.8</td>
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<td>9.4</td>
<td>13.4</td>
<td>4.0</td>
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<td>-</td>
<td>59.6</td>
<td>22.4</td>
<td>30.4</td>
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</table>

II Augite andesite

<table>
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<tr>
<th>Sample No.</th>
<th>Phx</th>
<th>Plagioclase</th>
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<th>Opx</th>
<th>Hbl</th>
<th>Opk</th>
<th>Qtz</th>
<th>Gms</th>
<th>Pc</th>
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<td>-</td>
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<td>13.6</td>
<td>34.5</td>
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<td>41.3</td>
<td>6.8</td>
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<td>10.1</td>
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<td>-</td>
<td>0.2</td>
<td>2.5</td>
<td>-</td>
<td>49.6</td>
<td>13.4</td>
<td>30.1</td>
</tr>
</tbody>
</table>
### TABLE 1 (Continued)

| Sample | Plagioclase |  |  |  | Cpx |  |  | Qtz |  |  | Gms |  |  |  |  |  |  |  |
|--------|-------------|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 379f   | Pnx 50.1%   | 12.0% | 5.3% | 16.5% | 0.4% | 13.1% | 1.1% | 1.7% | 49.8% | 26.9% | 16.6% | 6.3% |
| 432    | 39.5        | 16.4 | 4.8 | 8.2 | - | 8.9 | 0.7 | 0.5 | 60.6 | 25.0 | 31.2 | 4.4 |
| 553b   | 39.6        | 17.8 | 5.5 | 11.7 | - | 4.0 | 0.6 | - | 60.4 | 24.2 | 26.9 | 9.3 |
| 563    | 47.5        | 28.7 | 1.4 | 3.7 | - | 9.4 | 4.3 | - | 52.5 | 9.4 | 36.5 | 1.5 |
| 669    | 29.9        | 13.8 | 6.8 | 4.9 | - | 3.8 | 0.6 | - | 70.2 | 36.4 | 29.6 | 4.2 |
| 677    | 38.7        | 24.2 | 3.9 | 4.9 | - | 3.0 | 2.1 | 0.6 | 61.4 | 16.7 | 36.4 | 8.3 |
| 708g   | 38.9        | 14.4 | 7.4 | 7.6 | - | 7.8 | 1.7 | - | 61.2 | 22.7 | 27.9 | 10.6 |
| Average| 40.9        | 18.8 | 4.6 | 8.3 | 0.1(?) | 7.0 | 1.6 | 0.5 | 59.2 | 23.1 | 24.3 | 6.5 |

a Localities given on Plate I and in Appendix A.
b Phx = phenocryst, Cpx = clinopyroxene, Opx = orthopyroxene, Hbl = hornblende, Opk = opaque minerals such as magnetite, Qtz = quartz, Gms = groundmass, Pc = plagioclase.
c Not included in the average.
d Chlorite replacing phenocrysts, probably plagioclase, forms 9.1% of rock and was not included.
e Much calcite alteration makes mafic composition uncertain and two pyroxenes may be present. However, the augite andesites are typically calcitized as shown in this rock, and the augite-hypersthene rocks are not.
f Possible intrusive.
g Andesite of the San Germán Formation from end of road 314 included for comparison. Collected by the writer.
FIGURE 6
RELATIONSHIPS AMONG ANDESITIC ROCKS NEAR PARGUERA, PUERTO RICO

WHOLE ROCK

PHENOCRYSTES
Figure 7: Augite-Hypersthene Andesite Porphyry, Locality T-5.
Figure 8: Augite-Andesite Porphyry, Locality 217.

Figure 9: Augite-Hornblende Andesite Porphyry, Locality 432.
When these rocks are compared to those described by Mattson (1960) and Slodowski (1956), the augite-hypersthene lavas are equivalent to the basaltic andesites of the Río Loco Formation, and the other two types are similar to the Sabana Grande Andesites and the andesites of the San Germán Formation (Table 2, fig. 6). There is general agreement on the characterization of the Río Loco rock type, but the analyses presented by Mattson and Slodowski for the Sabana Grande Andesite do not entirely agree. Mattson evidently believed both augite andesite and augite-hornblende andesites characterized the Sabana Grande; and that augite-hornblende lavas, separated from the Sabana Grande types by stratigraphic considerations only, characterized the San Germán Formation. Therefore a clear comparison can be made between the Río Loco as mapped by Mattson and Slodowski and described in this report, but a distinction between Sabana Grande Andesites and andesites of the San Germán Formation requires further study. As a convention, in the area studied both the augite andesite and the augite-hornblende andesite are assigned to the Sabana Grande rock type on stratigraphic grounds, i.e., they lie beneath the basal Parguera rocks and are therefore older than the San Germán Formation. On the geologic map (Plate I) these rock types have been mapped on a purely lithologic basis and not as rocks correlated with the stratigraphic units established by Mattson or Slodowski.

The outcrops of augite-hypersthene andesites south of the Parguera hills indicate that the Río Loco rock type is
TABLE 2

COMPARISON OF MODAL ANALYSES OF VOLCANIC ROCKS FROM SOUTHWEST PUERTO RICO

I. Augite-hypersthene andesite

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Mtx</th>
<th>Phx</th>
<th>Opx</th>
<th>Cpx</th>
<th>Hbl</th>
<th>Pc</th>
<th>Oplk</th>
<th>Qtz</th>
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<td>56.7%</td>
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<td>9.7%</td>
<td>-%</td>
<td>26.8%</td>
<td>1.9%</td>
<td>-%</td>
</tr>
<tr>
<td>S-average</td>
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<td>10</td>
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<td>-</td>
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<td>tr</td>
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<td>10</td>
<td>20</td>
<td>-</td>
<td>15</td>
<td>tr</td>
<td>-</td>
</tr>
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<td>A-average</td>
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II. Augite andesite

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<td>34.6</td>
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III. Augite-hornblende andesite

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<tr>
<td>S-average of k</td>
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<td>23.4</td>
<td>1.6</td>
<td>0.5</td>
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</tbody>
</table>

---

aLocalities are given in Plate I and Appendix A. Other rock types described by Mattson and Slodowski do not closely resemble the rocks analyzed for this report and so are not included.

bMtx = matrix, others same as Table 1.

cMattson (1960, p. 328), andesite of the Río Loco Formation. Average of six analyses whose variation was greater than those presented in this report.

dSlodowski (1957, p. 55), andesite of the Río Loco Formation, estimate.

eSlodowski (1957, p. 56), andesite of the Río Loco Formation.

fAverage from Table 1, this study.

gMattson (1960, p. 339), Sabana Grande Andesite.
hMattson (1957, p. 113), andesite of the San Germán Formation.
iSample from andesite of the San Germán Formation, see Table 1.

jSlodowski (1957, p. 38), volcanic rocks of the Ensenada Formation.
kSlodowski (1957, p. 39), volcanic rocks of the Ensenada Formation.
lSlodowski (1957, p. 19), andesite of the Sabana Grande Formation.
not entirely restricted to a pre-Parguera age as Mattson believed (1960, p. 329). However, the bulk of the Río Loco rock type is found to have a pre-Parguera and pre-Sabana Grande age.

In the eastern half of the area studied, the augite and augite-hornblende andesites occur immediately beneath the Parguera Limestones whereas outcrops of the pre-Parguera augite-hypersthene andesites are rare east of Cerro Vertero. The augite and augite-hornblende andesites become restricted westward and finally disappear near Cerro Parguera so that Parguera rocks in the western Parguera hills rest directly on the augite-hypersthene andesites. This suggests a thin lens or wedge of augite and augite-hornblende (Sabana Grande) andesite to the east between the Parguera and augite-hypersthene (Río Loco) andesite. This wedge probably represents a tongue of Sabana Grande Andesite emplaced over an eastward sloping, somewhat irregular topography developed on the andesites of the Río Loco Formation. Erosion of the wedge was probably restricted in time and amount, as suggested by continued extrusion of Sabana Grande Andesites contemporaneous with Parguera Limestone deposition, as well as their pre-Parguera extrusion in the Hormigueros syncline to the north (Mattson, 1957, p. 75). This relation should possibly be extended southward to the eastern half of the area studied.

The outcrop of the augite-hornblende rock is restricted
to the eastern third of the Verterro hills and the hills north of Ensenada (Plate I). Although faulting complicates interpretation, it is possible that this unit is an upper one overlying the augite andesite to the south and west. The small steep hills between Highway 116 and El Peñón show float occurrences that strengthen this hypothesis, i.e., on the lower slopes occurs the augite andesite while the tops are capped by flows or conglomerates of the augite-hornblende andesite. The absence of the augite-hornblende andesite south of Highway 116 indicates that it did not extend that far at the time of deposition of the lower Parguera units. Whether this is the original southward limit of its extent is not known, as the occurrence or extent of erosion of the pre-Parguera surface is unknown.

Feldspathic basalt porphyry as mapped by Slodowski (1957, Pl. I, pp. 112-113) occurs as small intrusions. The description he gives for these rocks fit the augite-hypersthene rock type in mineralogy and texture. Probably these occurrences represent topographic irregularities developed prior to emplacement of the augite and augite-hornblende andesites or later minor flows or intrusions of the augite-hypersthene andesite.

Similarities in the three volcanic rock types found in the area, such as the rimmed equant plagioclase, unaltered plagioclase laths, or the ubiquitous clinopyroxenes, and the gradational change in major rock type through time suggest a closely related origin for the three rock types. The magma
source for the rock types seems to have been the same and
to have evolved towards a possibly more water-rich, slightly
less mafic rock.

In the northern part of the Mayagüez and Yauco areas,
both Mattson (1960, pp. 337, 339) and Slodowski (1957,
pp. 26-27, 111) report olivine-rich basaltic and andesitic
rocks similar in age to the lower part of the Mayagüez Group,
but these rocks are not found in the southern half of the
areas. Possibly the source may be suggested for those rocks
that is different from the source of the volcanic rocks in
the southern area (Mattson, 1960, p. 356).

Summary: Three pre-Parguera andesitic rock types can
be distinguished in the area of this report. In order of
their major stratigraphic appearance they are augite-
hypersthene andesite, augite-andesite, and augite-hornblende
andesite. On a purely lithologic basis the first correlates
with the Río Loco rocks of Mattson and Slodowski and the latter
two are equivalent to the Sabana Grande and possibly the San
Germán andesites. None are restricted to a certain strati-
graphic level, although their periods of major development
form a gradational stratigraphic sequence. For example,
the major development of the Río Loco andesite is pre-
Parguera, but minor flows do occur within the upper Parguera
sequence. Possibly the rock types indicate a common origin
and evolutionary sequence.
Topography

The positive elements of the Parguera depositional surface have been consistently the locally uplifted blocks of the Bermeja Complex. These rocks are lapped onto by the younger rocks and the various rock units generally thin towards the Bermeja blocks. In the area studied, the Sierra Bermeja is the largest and best example of a positive block of Bermeja Complex rocks.

By Parguera time, deposition of the Río Loco rock type, its erosion, and the deposition of the Sabana Grande rock types near Ensenada and subsequent reworking of all of these probably reduced the pre-Parguera surface to relatively flat topography. However, the surface was bevelled so that successively older rocks were exposed to the west. As indicated by the westward thinning of the Parguera Limestone, especially in the basal part, the Sierra Bermeja was topographically higher than the surrounding terrain. Whether or not the relief of the Sierra Bermeja was greater or lesser than its relief today is not known, nor it is known whether or not it was ever completely buried by the Upper Cretaceous section.

Faulting in the Sierra Melones area resulted in blocks upthrown to the north rather than to the south as is found elsewhere in the area. Also, the thin patches of Parguera rocks along the north side of the Sierra Bermeja seem related in character and dip with those of the Sierra Melones. If the continuity of the main mass of the Sierra Bermeja projects, as mapped, between the Sierra Melones and the small
shallow syncline at the southwest tip of the Sierra Bermeja, the Parguera rocks of the Sierra Melones may have originally been restricted to and separated from the main mass of Parguera rocks now found at the surface. The differences observed in these two areas of Parguera outcrop can be explained by this possible separation.

The chert outcrop at Cerro Vertero described above is possibly a buried hill and is indicative of local relief on the depositional surface.

Along the north side of the Parguera hills, between Punta Papayo and Highway 304, the basal unit seems thinner and the glauconitic beds are less prominent or apparently absent. It is possible this is caused by positive relief in the underlying volcanic rocks. However, minor faulting or facies change could produce similar results.

North of Highway 116 and west of Ensenada, there are four isolated hills, two of which are capped by basal Parguera rocks and two of which are capped by the thin volcanic conglomerate found just under the Parguera Limestone in the area about Ensenada. These have been mapped as a fault block upthrown with respect to the surrounding blocks. However, the levels of the units marking the relative elevations are not entirely even and may indicate some relief on the Parguera depositional surface rather than displacement by faulting.

The manner in which the pre-Parguera surface is bevelled indicates a possible initial easterly slope. The easterly
slope would provide a basin of deposition deeper at Ensenada
to permit accumulation of the eastward thickening Parguera
section. A transgressive sea would provide for the reworking
of the Sabana Grande Andesites and the continuous upward
growth of the reef-like masses at Ensenada.

Summary

The Parguera depositional surface consists of the fol-
lowing rock types from west to east: serpentine, chert, and
amphibolite of the Bermeja Complex; augite-hypersthene
andesite of the Río Loco Formation; augite-andesite of the
Sabana Grande Andesite; and augite-hornblende andesite of
the Sabana Grande Andesite. The basal Parguera rocks con-
tain much material directly derived from the rock types on
which they were deposited, as well as a mixture of generally
volcanic detritus.

The surface possibly had an eastward component to its
slope. Low irregularities were developed on the volcanic
rocks and more distinct positive topography was developed on
the rocks of the Bermeja Complex. Positive relief of the
Bermeja rocks may have restricted or separated the Parguera
rocks of the Sierra Melones from those of the Parguera hills.

Structural Geology

Major structural trends vary about an east-west direction
(Figure 5). Faults are generally normal with steep-to-vertical
fault planes. Folds are open and asymmetrical with the
steeper synclinal limb to the north. The structures post-date the Parguera rocks.

The east-west trend of the normal faults in the Parguera-Ensenada area parallel the trend of the island arc, of the anticlinorium that exposes the older rocks of Puerto Rico in the island's center, and of the three major faults in the region, the Cordillera fault, the San Germán fault, and the Anegada trough. These larger faults are considered to be strike-slip faults (Mattson, 1960, pp. 353-354; Donnelly, 1964, pp. 691-692). They cut obliquely across the west-northwest trend of most of the faulting on Puerto Rico and of the folds north of the Lajas Valley. The cause of faulting in Puerto Rico has often been considered to contain an important element of thrusting or overturning. The faults found in the area studied do not support this, and Donnelly (1964, pp. 687, 692) has suggested that such movement is not important relative to vertical movement or east-west strike-slip movement.

Folds in the Mayagüez and Yauco areas as mapped by Mattson (1960) and Slodowski (1956) trend generally west-northwest except for the arcuate trend in the southwestern part of the island where Mattson found east-northeast trending folds. This arcuate trend - from east-northeast at Melones to west-northwest at Parguera - is well shown on the geologic map (Plate I) and is partly and locally related to the block of the Bermeja Complex forming the Sierra Bermeja.
The cause of folding in the Mayagüez area was considered by Mattson (1960, p. 353) to be a compressional stress oriented N 30° E - S 30° W to give the dominant west-northwest trends. The arcuate trend and Parguera fold thrust northward were formed as follows (Mattson, 1960, p. 353):

"...departures from the regional orientation... may result from a deforming force acting on the thin edges of a thick sediment lens. The sediments at the edge might be affected by basement alignments, and form folds oriented differently than those elsewhere. Also in such a situation forces not ordinarily pre-dominant might influence relatively thin bodies of sediment in seemingly contradictory ways."

As discussed below and mentioned above, laterally compressive stresses that give rise to extensive thrusting are not indicated by detailed mapping of southwest Puerto Rico.

The various structures shown on Plate I are discussed by areas, rather than by type, because the folding and faulting seem to be related and possibly to have affected one another.

Sierra Bermeja

The major positive structural element in the area is the Sierra Bermeja. Similarly, to the north and east the Bermeja rocks seem to form positive blocks about which the younger rocks have been deposited and deformed. These blocks generally trend east-west or west-northwest and form
anticlinal cores or upfaulted blocks that have had a long history of relative upward movement.

Mattson (1960, p. 350) shows the Sierra Bermeja as an east-northeast trending anticline. Along its southeast side is a long, slightly sinuous fault, the Bermeja fault, which lies wholly within the Bermeja Complex and whose age, magnitude and direction of movement are unknown. In light of the important vertical component of movement found in the immediate area and the apparent positive nature of the Bermeja blocks here and elsewhere, a strong vertical component probably was present in the movement of the Bermeja block. The anticline may in part curve to the east and connect with the anticline between the Paraguera hills and the Vertero hills. It is possible that it also plunges under the Lajas Valley. However, trends on the north side of the valley would cross this trend, so that the fold must die out or change to a more easterly direction. To the west the Bermeja anticline plunges west-southwest beneath the coastal plain, but traces of the Bermeja Complex indicate that the fold may fan out into a series of small folds with the Sierra Melones on the more northerly flank of the main axis and a small synclinal Paraguera Limestone outcrop on the southeastern flank.

**Sierra Melones**

The structure in the Sierra Melones (Plate I) is somewhat more complicated than indicated by Mattson (1960, Pl. I).
The Melones syncline of Mattson is faulted downwards along its northern limb and two adjacent synclines are formed. On its southern limb it may similarly be down-faulted forming a graben; or the Parguera sequence, which underlies the Melones Limestone, may be considerably thinned by its onlap onto the underlying Bermeja Complex. Contacts are covered, but the latter hypothesis is slightly favored.

Mattson indicates the northern limb of the Melones syncline is overturned; but detailed mapping shows these the supposed overturned dips to be normal dips on the south-eastern limb of a southwesterly plunging syncline lying northwest of Mattson's original Melones syncline (Plate I). The fine-grained foraminiferal mudstones overlie the tan silicified unit that marks the base of the Parguera unit in normal stratigraphic succession. These mudstones are surrounded by the basal unit on three sides and the dips recorded on the two opposing sides indicate a syncline.

Because no evidence of an anticline was found, the fault mentioned above, downthrown to the south, was mapped between the two synclines. Probably they were folded as one syncline and then faulted. Their trends are parallel.

The zone of silification, outcrop of the conglomerate below the Parguera at locality 796, lack of dip reversals in the Melones Limestone, lack of stratigraphic symmetry in any proposed anticline, the zone of disturbed dips along the proposed fault, and missing Melones section along the fault suggest the presence of the fault. There is also a marked
topographic expression typical of faulting along this zone.

The fault proposed by Mattson along the north side of the Sierra Melones may not be necessary and is not included in the present report. The presence or absence of the conglomerate below the Parguera unit and the variation in thickness of the basal Parguera can be satisfactorily explained by the variation in topographic relief developed on the underlying Bermeja Complex and then covered by the Parguera Limestone.

Parguera Area

Along the north side of the Parguera hills, Mattson mapped a thrust fault on which the Parguera Limestone had been overturned and overthrust to the north. One paleontologic date, at his locality 2352, was early Maestrichtian and was tenuously supported by a date at 2434 of early-middle Campanian. To the south were dates of definitely Lower Campanian age, and many throughout the outcrop gave the range Campanian - Maestrichtian. Therefore, the northern side of the east-west trending hills would be younger than the south side. The rocks all dip steeply south or south-southwest except to the west where they dip southeast or east. Mattson (1960, p. 353) states that "Paleontologic evidence... shows that the Parguera hills form an anticline overturned and thrust to the north," and again, "... the beds in the northern limb of the Parguera anticline are overturned, however (according to paleontological evidence), (sic) and a thrust
fault must exist to relate this structure to the structure of the rocks to the north." He further states that the thrust fault was not seen in the field. Mattson also believed that geopetal data with regard to graded bedding seen in the field was unreliable. The presence of the Río Loco rock types on the south side of the hills led him to believe the volcanic rocks marked an anticlinal core.

Mattson (personal communication) pointed out to the writer that the thrust fault would have to extend under the Parguera rocks in the Verterto hills as well to form a coherent structure. As demonstrated above, he was aware that the structure opposed the more northerly structures, but the paleontology required the existence of the overturned anticline and thrust fault.

A second suggestion proposed by Mattson and L. Glover (personal communication) hypothesized that the whole of the southern Parguera outcrop had been brought in by gravity sliding from the south along the plane of contrasting rock competence provided by the Lower Parguera - Río Loco contact. Although this may explain the occurrence of Río Loco rocks to the north and south of the Parguera range and the occurrence of different rock types under the Parguera Limestone and the existence of a normal Parguera section over a thrust fault, observations listed below indicate the Parguera rocks are essentially in the place where they were formed with regard to the underlying rocks. This hypothesis was put forward to reconcile the normal stratigraphic section in the
Parguera hills established by the writer with the occurrence of Río Loco lavas, supposedly restricted to a pre-Parguera occurrence, both to the north and south of the Parguera hills.

The writer feels that the following evidence indicates the Parguera Limestone is in place and is strong enough to warrant discarding the Parguera thrust fault and Parguera anticline:

1. The nature of all the other folds in the area is open folding with anticlinal oversteepening towards the south.

2. The stratigraphic section within the Parguera Limestone throughout the area is clearly established and unequivocal. It is the same in the Parguera hills, in the Vertero hills, in the Sierra Melones and in the hills near Ensenada. Mattson considers the Sierra Melones section to be in normal stratigraphic order relative to the underlying Bermeja Complex (Parguera deposited over a silicified soil with no intervening fault) 1960, p. 335. Slodowski indicates a normal section throughout the area around Ensenada, yet the same stratigraphic sequence can be shown to exist in these places, especially at Cerro Lajara, as in the Parguera hills.

3. In the areas where the section is considered undisturbed, the lower part contains fragments characteristic of the rock type locally beneath the Parguera Limestone. This is true of the basal limestone in the
Verterro hills where Mattson noted serpentine fragments in the basal Parguera Limestone, and it is also true of the limestones immediately overlying the volcanic rocks in the Parguera hills. This precludes the presence of any thrust plane or glide plane under the Parguera or Verterro hills.

4. Wherever the contact of the base of the Parguera with the underlying rock unit is exposed, it is undisturbed and seems to be depositional.

5. The rocks differ across the axis of the Parguera anticline. To the north the fine-grained mudstones are in sharp contact with the volcanic conglomerate. To the south of the axis these rocks grade into calcareous, fossiliferous, volcanic conglomerates and finally into very coarse-grained, bioclastic, rudist-bearing limestones.

6. On the southwest part of the fold, the dips are to the northeast. If the overturned symbols are removed from Mattson's reported dips, a syncline is shown that plunges east-southeast and has a steep north limb.

7. In thin section, those graded beds that were originally graded beds, i.e., not caused by recrystallization of the limestone to give false grading, consistently indicate no overturning.

8. Geopetal structures, such as lime mud filling in shells, in several oriented thin-sections (for
example at localities 433c and 201) consistently indicate a syncline in normal stratigraphic position. The thin-sections are taken from several stratigraphic horizons and from several different localities along the Parguera hills.

9. Detailed paleontologic dating for this report gives a date of Lower Campanian for the foraminiferal mudstones. These same rocks also show younger dates to the south, in the calcareous volcanic conglomerate and coarse-grained limestones the dates obtained are Upper Campanian - Lower Maestrichtian. The basal Parguera units generally give a range Santonian - Campanian or Santonian - Maestrichtian and so are non-diagnostic for the present problem. This same sequence of dates is found in other areas such as the Sierra Melones, Vertoero hills, and Cerro Lajara west of Ensenada. The one date that influenced Mattson is considered anomalous. It may be explained as a locally downfaulted block of Parguera Limestone.

On the basis of the above evidence, the Parguera anticline is replaced by the Parguera syncline, an east-southeast plunging syncline with a steep northern limb. At sample localities 889a-c and 891, marked, fairly consistent dip reversals occur that may indicate a position near the east-southeastern nose or near the synclinal axis of the Parguera syncline. Otherwise the extent and nature of the syncline to the southeast are unknown.
Possible faulting along the north side of the Parguera hills is not denied, but the presence of a large thrust fault is negated by the reasoning given above. Extensive faulting along the south side of the Vertero hills suggests vertical faults, upthrown to the south, may be present along the north side of the Parguera hills. These possible faults were not noted in the field and have not been placed on the map.

Other minor faults in the Parguera hills were mapped as required by displaced stratigraphic markers or strongly disturbed dips. On the west side of the entrance to Bahía Fosforescente an excellent exposure of the lower half of the Parguera section reveals several small faults that cut beds dipping 60° south. One fault is nearly horizontal with the rocks above displaced 30-40 feet northward. At first this seems to complement Mattson's thrust fault, but the fault would be a normal fault relative to the stratigraphic section, not a thrust fault. Another fault is seen that strikes N 38° E and dips 63° SE with little displacement, but it is marked by a zone of breccia. Faults similar to these are seen throughout the Parguera section in the area studied, e.g., Punta Papayo.

Penecontemporaneous slumping in the foraminiferal mudstone is very well developed not only at Bahía Fosforescente, but also on Isla Matei and especially at Punta Papayo. This slumping complicates the structural pattern throughout the area and is particularly characteristic of these mudstones.
Vertero Hills

Between the Vertero hills and the Parguera hills is an east-southeast trending outcrop of the volcanic rocks underlying the Parguera Limestone. It extends from the eastern tip of the Sierra Bermeja towards Salinas Fortuna. Its position, the northerly dips in the beds on the south side of the Vertero hills, and the southerly dips in the Parguera hills mark an anticline, named the Salinas Fortuna anticline from Salinas Fortuna at its eastern end. It is an open fold in normal position and may be an extension of the Bermeja anticline. This suggestion is mildly strengthened by the outcrop of Bermeja chert at Cerro Vertero. As suggested by the outcrop pattern of the volcanic rocks on Plate I, the anticline may extend as far eastward as Highway 116 northwest of Ensenada. Lack of any dip direction except south in any of the hills east of Salinas Fortuna and north of the proposed extension of the anticline precluded this extension on the map. The anticlinal structure may have been masked by the extensive block faulting in the Ensenada area.

The time of formation of the Salinas Fortuna anticline is unknown. It may have formed after the deposition of the Parguera Limestone, or it may possibly have been earlier and have provided a source of the coarse-grained non-carbonate clastic material found in the overlying Parguera
Limestone. Such an interpretation emphasizes the effect of movement of local blocks by providing a local source for the coarse-grained material and by not requiring the transportation of such material from the north around or over other blocks.

In the western Verterro hills the Verterro syncline (Mattson, 1960, pp. 330, 349) occupies the crest of the hills. Its trend is somewhat variable between east-southeast and due east. Possible closure on the western end indicates a shallow plunge to the east. The syncline is terminated just east of Cerro Verterro by the Montalva fault. At this point a minor anticline and a very small syncline occur north of the Verterro syncline. From this point eastward the rocks in all exposures of the Parguera Limestone have a major southerly component in their dip and no more important folds are seen. Erratic dips in the eastern area are usually associated with these block faults.

The Montalva fault was named by Slodowski (1956, p. 117) for the fault he mapped along the southern edge of the Verterro hills. At Cerro Verterro Mattson (1960, p. 353) states that there is essentially no displacement. If the hypothesis tentatively accepted here, that the chert outcrop near it at Cerro Verterro is surrounded by basal Parguera rocks, then only minor displacement has taken place. If the sediments surrounding the chert blocks are basal Río Loco, then considerable upthrow is indicated. Farther west the fault dies out.
To the east, rocks of the mudstones above the eastward thickening basal Parguera unit are in fault contact with the Sabana Grande Andesite that underlies the Parguera in the eastern Verterro hills. The displacement increases eastward along the fault to the area north of Ensenada. Here several east-west faults with large displacements have been offset by north-south faults. Probably the Montalva fault corresponds to one or several of these east-west faults. Because of the many faults associated with it, the Montalva fault should actually be designated the Montalva fault zone. Some of the faults in this fault zone trend more nearly east-southeast than east-west, especially near the eastern end of the Verterro hills.

**Ensenada Area**

In the hills north and west of Ensenada, the rocks dip consistently south. The section is repeated very often by steep east-west striking faults that have tilted blocks of the basal Parguera southward. The anticline mapped south of the old (now drained) Laguna Guánica by Slodowski (1956, Plate I) was not found. The only northward dips were in the Jicara Formation which supposedly rests with angular unconformity upon the Parguera Limestone (Ensenada Formation of Slodowski).

The Montalva fault zone possibly correlates with the northernmost east-west striking fault which extends west from
a point just south of El Peñón. These correlations are based on the large displacements on the various segments of the fault.

The large fault south of Cerro Lajara corresponds to one mapped by G. J. Mitchell (1923, pp. 266-269) which he felt extended from Ensenada to Punta Melones. Detailed mapping by the writer indicates considerable vertical displacement but does not indicate the continuous lateral extent shown by Mitchell. That east-west faulting is important along the south coast is indicated by the existence of this fault, the Montalva fault, and the Bermeja fault which together give a nearly continuous zone of faulting from Ensenada to Punta Melones. Meyerhoff (1933, p. 75) considered the fault at Cerro Lajara unimportant or non-existent, and Slodowski (1956, Pl. I) evidently concurred, for he did not mention it.

Dips on both sides of the fault are steep to the south. Thus, the fault is upthrown on the south. Mitchell (1922, pp. 267-269) indicates a fault downthrown to the south and illustrates the drag he saw in the Tertiary rocks indicating such a movement. The writer did not see the drag features and also did not observe Tertiary beds in the area to be close enough to the fault to be strongly affected. However, dips in the Parguera Limestone are certainly affected along the fault zone.

The other nearly east-west striking faults are minor and are indicated by the displacement of the stratigraphic
units.

The more northerly striking faults are of minor importance but locally have a significant effect on the distribution of the faulted blocks. Their appearance, combined with the apparent loss of folding, possibly indicates a minor but possibly important change in structural style along the south coast.

The occurrence of Slodowski's rotational northwest-trending fault from Ensenada to the east-to-southeast bend in Highway 116 is questioned, but not eliminated. An alternate interpretation is presented on Plate I, however.

Discussion

From the geologic map (Plate I) and from the description above, the faulting is sub-parallel to the fold trends and is characteristic of deformation involving primarily vertical uplift. The folds all have the common characteristics of asymmetrical anticlinal oversteepening to the south, intimate association with the Bermeja Complex, and an open shape. From stratigraphic data, blocks of the Bermeja Complex, such as the Sierra Bermeja, have been positive elongate east-west structural elements since pre-Río Loco times.

Preliminary gravity (Bromery and Griscom, 1964, p. 65) and magnetic data (Griscom, 1964, pp. 45-48; Dennis and Gunn, 1964, pp. 30-31) indicate that the Bermeja Complex (the surveys made were based on serpentine as the
representative rock for the Bermeja Complex) occurs as large blocks. The block studied in detail, that in the center of the Guanajibo anticline near Mayagüez, has a shallow dip northward and a steeply dipping southern edge. The magnetic data indicate a magnetization contrast extending 5,000 to 10,000 feet in depth. The gravity data indicate a density contrast extending to 8,000 feet. Profiles across the Sierra Bermeja and the Sierra Melones (Dennis and Gunn, 1964, pp. 36-38) have an asymmetry similar to that of the Guanajibo area and may mark similarly shaped blocks. Dennis and Gunn state that a magnetic minimum corresponds to the Bermeja Complex, whereas Griscom finds a magnetic maximum. A northward dipping mass would displace the maximum northward away from the outcrop, and maxima are indeed found in this position in the three profiles of Dennis and Gunn for the Sierra Melones and Sierra Bermeja areas. Thus the maxima represent the tilted blocks of Bermeja rocks.

For the areas studied, vertical displacement has controlled the formation of the structures seen. The displacements have been caused primarily by major movements of large blocks of the Bermeja Complex. The positive displacement of these blocks has continued since pre-Río Loco times and has given rise to the asymmetrical folds found in the area. Upward movement of major blocks provided basins for the deposition of the sedimentary and volcanic rocks which lap
upon the sides of these large blocks and in some cases cover them. Similar movement on lesser blocks caused the folds which are formed as sedimentary beds draped over the rising blocks. If the general uplift takes place as a series of basement blocks uplifted and tilted slightly northward the folds become asymmetrical with the anticlinal limbs steeper on the south. The minor uplift seems to have continued through Cretaceous time with one period of major uplift in the Lower Maestrichtian to interrupt Parguera deposition. A milder later uplift is indicated by the gentle folds in the San Germán Formation that overlies the sharper folds of the Parguera (Mattson, 1960, p. 349).

Later vertical uplift of a large block produced the normally faulted and tilted blocks of the Ensenada and Vertero areas. Some strike-slip movement on the major fracture zones in the region may have been developed at this time.

Independent vertical or strike-slip movement along the major pre-Miocene faults that divide Puerto Rico into several large blocks may possibly have permitted the internal geologic development of any one block to proceed somewhat independently of the development of other blocks. Such "tectonic isolation" could explain the development of the fairly consistent lithologies of the Parguera area next to the great variable masses of volcanic material and interlensed
sediments. Accumulation of material or erosion may be locally developed within the blocks, but would not necessarily correlate between blocks. Thus, a locally consistent, but regionally confused, stratigraphic section would develop.

The vertical tectonics suggested above imply a rising island arc. Donnelly (1964) provides a plausible model for just such movement and the writer believes that the structures seen in the field and shown on the geologic map fit this hypothesis far better than the theories of lateral compression and folding often mentioned in connection with island arcs and orogenic belts (Hess and Maxwell, 1953; Mattson, 1960, p. 353, for example).

Briefly, according to Donnelly (1964), interaction of a hydrous and anhydrous crust and upper mantle gives rise to a thickening of the hydrous crust, vertical uplift, and volcanic activity over the thickened portion along the zone of contact. Puerto Rico and the Virgin Islands are used as a model of a portion of the Caribbean arc. The boundary zone is along the Puerto Rican trench and the hydrous crust and upper mantle underlie the Caribbean Sea. The hypothesis adequately explains the major features of the island arc and provides a mechanism for the vertical movement in the upper crust indicated by the structures found in the area studied.
Summary

Folds are open, trend arcuately west-northwest to east-northeast from east to west and are influenced by movements of the blocks of Bermeja Complex rocks. Faults are very steep, normal, upthrown on the south side (except in Sierra Melones) oriented east-west, and are later than the folds in the sedimentary rocks. The Sierra Melones fault, upthrown to the north, reflects the position of the Melones syncline on the northern flank of the Sierra Bermeja.

Gravity and magnetic data support the theory that the structures of southwest Puerto Rico are caused by the movement of "basement" blocks. The structures and stratigraphic relationships described indicate a strong vertical component to this movement. Donnelly (1964) has proposed a hypothesis that accommodates this data as well as the larger geologic aspects of the Caribbean island arc.
STRATIGRAPHY OF THE PARGUERA LIMESTONE

Within the framework established above, the Parguera Limestone was deposited upon an erosional unconformity. Because Sabana Grande Andesite was affected by this erosion, as well as interfingered with rocks of an age equivalent to that of the lower and middle Parguera section, this unconformity is considered to mark only a brief time span where it is developed on Sabana Grande type rocks.

The stratigraphic sequence begins with a basal, calcareous, tuffaceous sandstone that shows an increase in the bioclastic component and glauconite upwards (Bahía Fosforescente Member). In gradational contact with this unit is an overlying sequence of foraminiferal mudstones containing interbedded, current-worked, bioclastic beds near the upper and lower contacts (Punta Papayo Member). Above the mudstones and in sharp contact with them is a volcanic conglomerate which grades upwards into a very coarse-grained limestone (Isla Magueyes Member). Within this unit occur augite-hypersthene andesite lava flows. The upper unit is found only near Parguera; the lower two coarsen and thicken eastward with a bioclastic limestone becoming the dominant rock in the basal unit.

First, the petrologic data and its manner of collection are presented. Then the units outlined above are described using this data, beginning with the basal Parguera.
Petrologic Data

Delineation of the members forming the Parguera Limestone is based on field mapping of distinctive rock types or suites of rock types, and the distinctions are augmented by thin-section study. Insoluble residues and clay mineralogy provide accessory information, but they are not the basis for the establishment of any major unit or facies within the Parguera Limestone. Paleontological dates supplement structural data to indicate that the stratigraphic sequence is in normal stratigraphic position. Paleontology, combined with carbonate petrography, provides information on the environment of deposition.

Field Mapping

The area studied was mapped by standard geologic field methods at a scale of 1:10,000 on 3-3/4 minute quadrangle maps of the Departamento de Obras Públicas, Gobierno de Puerto Rico, Santurce, Puerto Rico. The quadrangles covered are parts or all of the following: Cabo Rojo, Northeast and Northwest; Parguera, Northeast and Northwest; Guánica, Northeast and Northwest; Sabana Grande, Southwest; San Germán, Southwest; and Puerto Real, Southeast and Southwest. The data gathered has been reduced and is presented here at a scale of 1:20,000 as Plate I.

The structural features and the pre-Parguera surface, with respect to topography and the rock type forming it,
have been previously discussed in detail. The most striking feature of the Parguera units is their regular east-west trend and fairly consistent lithologic character in a region of geologically rapid and sudden change that generally is assumed to be associated with a developing island arc.

Two unconformities are noticeable on Plate I. The first is at the base of the section and is distinctly marked by the occurrence of Parguera Limestone above different rock types of different trends. The second is developed upon the Punta Papayo Member and is marked by the uneven thickness of the mudstones in the Parguera and the Melones areas.

The eastward thickening in the Bahía Fosforescente Member, accompanied by the thinning of the sandstone and development of the bioclastic limestone in this unit, is apparent from the map. The thinning of this unit is also noticeable where it is close to the Sierra Bermeja, as is seen in the outcrop on the southwest end of the Sierra Bermeja.

The Isla Magueyes Member is restricted to the south side of the Parguera hills. The Melones Limestone is restricted to the Sierra Melones on the north side of the main block of the Bermeja Complex in the area mapped.
Petrographic Data

Two hundred seventy samples were selected and thin-sections were made. Of these, thirty-nine thin-sections were point-counted to provide a quantitative analysis of each of the major rock types. Representative hand-specimen and thin-section descriptions are given in Appendix B. The point-count data is presented in Table 3.

Categories used in modal analysis: In point counting, four major categories were used; carbonate skeletal grains, carbonate non-skeletal grains, non-carbonate clastic grains, and matrix. The more common skeletal grains counted were algae, larger Foraminifera, other Foraminifera, rudistid pelecypods, other mollusks, echinoids, radiolarians, sponges, corals, and unknown skeletal grains. Possible bryozoans and ostracodes were rare constituents, and were noted as present or absent only. Carbonate non-skeletal grain types counted were aggregate grains, coated grains, pellets, and limestone lithoclasts (or intraclasts of Folk, 1958). Non-carbonate clastic grains were counted as glauconite or chlorite (confirmed by X-ray diffraction), volcanic lithoclasts, plagioclase, quartz, dark opaque minerals ("ore" minerals, e.g., magnetite, some hematite, chromite, etc.), and mafic minerals (hornblende or pyroxene). Matrix was not subdivided, but its type - sparry calcite, lime mud - was noted.
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MODAL ANALYSES, PARGUERA LIMESTONE

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*Note: The table includes data for various samples, each with specific values for different types of clastic grains. The data is presented in a tabular format, showing the percentages of each type of grain and the total percentages. The table also includes information about the matrix and total alteration.
Table 3 (Continued)

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Table 3 (Continued)

a Samples in order from west to east for each lithologic group.
b Massive Melones Limestone, 756d may belong to Punta Papayo Member.
c Bioclastic limestone, Isla Maguayes Member.
d Volcaniclastic-rich limestone, Isla Maguayes Member.
e Tuffaceous limestone, Punta Papayo Member.
f Foraminiferal mudstones, Punta Papayo Member.
g Calcarenite, Punta Papayo Member.
h Upper calcarenite, Bahía Fosforescente Member.
i Glauconitic zone, Bahía Fosforescente Member, 80 not in average.
j Gray limestone facies, Bahía Fosforescente Member.
k Tan calcarenite, Bahía Fosforescente Member.
l Pellets included: 146c; 80; 746; 571-5.3%; 577-3.5%.
m Chlorite included: 146c; T-3; 446-0.6%.
n Serpentine(?): 186-4.9% of total.
o Mafic: 746-1.4%.
p Bryozoans or encrusting forams included: 446-0.2%; 146c-2.6%.
q Coral included: 83-1%; 186-1.3%.
r Pelecypod: 76le-15.4%.
s Gastropod: 186-3.4%.
t Matrix: lime or clay mud.
u Matrix: mixed mud and calcite spar.
v Matrix: calcite spar.
w Alteration: Rind on skeletal grains.
x Alteration: Secondary carbonate recrystallization.
y Alteration: Secondary silica or iron oxide.
Algae were primarily of the encrusting coralline type and identifiable as Archaeolithothamnion sp. Rare grains of elongate coralline algae and plates of Halimeda-like algae were also seen and noted. The last was particularly characteristic of the Isla Magueyes Member, while the former two, though ubiquitous in the bioclastic limestones, were especially abundant in the thick limestones of the eastern part of the basal Parguera. Identifications were based on Johnson, 1961, and corroborated by B. F. Perkins and others (personal communication). However, the algae were not subdivided during counting.

Foraminifera were divided into two groups, larger Foraminifera and other Foraminifera. This division was as close a division as could be made between planktonic and benthonic forms. The larger Foraminifera were consistently associated with the very coarse-grained deposits, especially those with a high volcanic-elastic content. The smaller Foraminifera were not consistently divisible into planktonic and benthonic forms in thin-section (R. R. Lankford, personal communication), but the broad statement that planktonic forms are dominant throughout the Punta Papayo Member can be safely made (Pessagno's data, personal communication). Many were identifiable to species (Pessagno, personal communication) but not consistently enough for point-counting.
Radiolitid and caprinid rudistid fragments were pointed out to the writer by B. F. Perkins and others (personal communication). Because there seemed to be no preference of one for any particular rock unit or rock type and because the radiolitid type was consistently the more abundant, the two were combined into the one category rudists.

The category other mollusks consists of fragments showing the lamellar and prismatic structure typical of mollusks. Shape was also a major identifying factor, as was method of recrystallization. Shape was the general criteria for distinguishing between gastropods and pelecypods. As far as could be determined pelecypods far outnumbered gastropods, but this is very possibly a result of differential preservation, because in some places (basal unit) abundant thick-shelled gastropods were found. Bøggild (1930) was used as a guide.

Echinoid fragments were identified by their characteristic unit-crystal extinction. Both spines and plates were seen and the distinction noted, but not counted separately.

Radiolarians were very well preserved and especially abundant in the lower part of the Punta Papayo Member. They were not separated to species because there seemed to be no usable differences in their occurrences, and they are not consistently identifiable (although they are more so than the Foraminifera) for point-count purposes.
Sponges were identified by their siliceous spicules which were generally disarticulated. Rare whole sponges were encountered in hand-specimen, but seen only once in thin-section. One slide may have a calcisponge. These data were noted but not counted separately.

Aggregate grains are of several types as discussed by Illing (1954), Ginsburg (1956), and Purdy (1960, 1963a) for Bahamian and Floridan grain types and by Behrens (1963) for the Glen Rose Limestone (Lower Cretaceous) of Texas. The aggregate character, the environment of formation, the similar petrographic nature, and the extensive recrystallization in the Parguera rocks are the reasons for placing the various types of aggregate grains (mud aggregates, organic aggregates, grapestone grains, cryptocrystalline grains) into one category. The aggregate grain is initially composed of fine-grained calcite mud and microscopic skeletal fragments. Organic mucoid material provides the original binder and recrystallization and calcium carbonate precipitation provide the more permanent cement. All indicate quiet to slightly agitated, generally shallow waters and occur with lime mud to fine sand-sized carbonate grains. Pellets, although distinctive in origin, require environmental conditions for preservation similar to other aggregate grains, and they are not counted separately.

Coated grains are those in which calcium carbonate has
been added in concentric layers around some other grain type as nucleus. In most cases only one or two layers are present. The coating is essentially an oolite coating, but the mass of the nucleus generally is equal to or greater than the added coating. The orientation of the fine crystals in each layer was tangential, concentric, or random as discussed by Dalrymple (1964) and Purdy (1963a). The rare oolites present in the Parguera rocks were counted in this category. These grains usually mark areas supersaturated in calcium carbonate that have well-agitated waters.

Glaucnite and chlorite occur as sand-sized or coarser grains and aggregates. The glauconite ranged from very dark green through yellowish green to light green while the chlorite usually had a more bright bluish tint to its color range. Glaucnite is well crystallized, whereas the chlorite occurs as randomly to somewhat spherulitically oriented, fibrous grains of very low birefringence. The differences were confirmed by X-ray diffraction. The glauconite was primarily 10Å material (mica-clay or illite in the broad sense) (Bradley and Grim, 1961) or mixed-layer 10Å material and other clays, while the chlorite consistently fit the criteria set by Brindley (1961) for chlorite (10Å, no collapse at 600° C). The chlorite occurs as angular to sub-rounded grains. The glauconite occurs as pellets, rounded grains, angular grains, cavity fillings in fossils, fillings
of flattened worm burrows on bedding planes, shredded flakes, and replacement for shell material. The glauconite is probably not detrital, but diagenetic in origin. Segregation of these sand-sized grains was noticed. The chlorite is associated with the presence of large volcanic rock fragments, especially in the Isla Magueyes Member, and the glauconite is abundant in the basal unit and rare or absent throughout the rest of the Parguera section. The chlorite is detrital material derived from the alteration of volcanic mafic minerals and plagioclase, as seen in the volcanic rock fragments associated with the chlorite in the limestones or as seen in the volcanic rock specimens themselves. Chlorite is included in the volcanic lithoclasts because of its close association and minor occurrence.

Volcanic lithoclasts are fragments of andesite flows generally, are well rounded to angular, and occur in sizes from fine sand to cobbles. The size and sorting of the fragments vary with the size and sorting of other associated detrital grains. The grains have a dark gray to reddish brown matrix with plagioclase needles in the matrix and minor plagioclase and mafic phenocrysts that vary according to the particular rock present.

Chert lithoclasts are well-rounded, white to cream, and microcrystalline. The well-rounded and well-sorted nature of the grains indicate they are transported detritus and
not secondary nodules. Possibly, though it could not be proven, they are derived from the rock of the Bermeja Complex. This source has the only major bodies of chert currently known in this part of Puerto Rico. Such an occurrence would prove the emergent nature of the Bermeja Complex for at least part of Parguera time.

Plagioclase is distinctive and detrital. Its angular and broken, or commonly rounded, shape indicates that it is not authigenic.

Quartz is likewise distinctive. It is a rare detrital mineral material, except as the microcrystalline chert discussed above. Secondarily as silica replacement, it occurs rarely to commonly in the rock matrix or in selected fossil material. It also occurs as authigenic growth - double-ended crystals in aggregates or single crystals - in the purer bioclastic limestones. Quartz was counted only when it was detrital quartz (not chert).

"Opaque minerals" or "ore minerals" represent such minerals as magnetite or chromite or hematite. These were counted when it was determined that they were detrital grains. Rarely detrital hornblende and pyroxene were found and were included in this category. Their presence has been noted in Table 3.

Matrix material was counted as one unit and its composition noted as spar or clay or lime mud or some similar material.
Alteration was counted separately or at least noted. Alteration such as the development of certain rinds on bioclastic sand-sized grains in the lower units were counted separately because the change took place in the depositional environment before burial. These grains are not coated grains because the rind was within the original grain boundary, rather than added outside of it as in the coated grains. These rinds may represent algal boring (J. W. Keith, personal communication; Dalrymple, 1964) or abrasion by wave and current reworking. Alteration also consists of silicification, iron staining, or recrystallization of the calcite grains or matrix. These changes and others were still counted as original grains if the alteration took place after deposition.

Although these grain types are commonly subdivisible into other significant groups, recrystallization, uniformity of treatment, a reasonable boundary on the number of categories, and consistent identification are the reasons further subdivisions were not made. The presence of identifiable members of any of the above categories and the degree of apparent transport of the grains in any group were noted for each sample.

Point-count conventions: The grains were counted as detrital fragments as found in the sedimentary environment at the time of deposition and burial. Skeletal grains can
be both introduced as detritus and derived from the local non-transported fauna. Non-skeletal carbonate grains likewise can be introduced (lithoclasts) as well as locally produced (aggregate grains, pellets). If alteration was subsequent to the time of final deposition (the grain did not move relative to its neighbors after this time), the grain was counted as itself. Enclosed holes in a skeletal grain were counted as the enclosing grain, and re-entrants and open cavities were counted according to the grain under the cross-hairs.

Five-hundred points were counted. This gives an accuracy equal to or better than the variation between samples (thin-sections) of the same rock. This accuracy may be stated as ±4.5% of the amount of a constituent present, if that constituent forms 50% or more of the rock (see Purdy, 1960, 1963a; Chayes, 1956, for a full discussion of the statistics of modal analysis).

**Insoluble Residues**

Insoluble residues were determined in three groups. A small group of samples was rerun for each change of conditions and the error was ±3% of the initial rock weight and ±10% of the residue weight (error range for residue weight compared to itself increases with decreasing residue percentage). These errors are no greater than obtained by rerunning the same samples under the same conditions.
Samples were run as follows: fifty samples in 4.4 M acetic acid, fifty-five in 0.2 M hydrochloric acid, and one-hundred and nineteen in 0.83 M hydrochloric acid. In the first group, seventy-five grams of sample were used, and in the last two groups fifty grams of sample were used. All samples were dissolved from small blocks of rock and were not ground prior to acid treatment.

The total insoluble residue was weighed and separated into size fractions of 62μ - 120μ, 120μ - 230μ and greater than 230μ. The clay-silt fraction (< 62μ) was obtained by difference. The weights recorded for these fractions were measured only when total disaggregation, as determined through the microscope, could be proven. Non-carbonate clastic grains which were formed within the basin (sponge spicules, authigenic quartz, radiolarians), were also excluded from consideration and the content was noted.

These size-fractions of disaggregated non-carbonate clastic material are a measure of the "isolation" of the depositional area from the associated land mass. Isolation is used here in the broad sense to include such isolating factors as distance, geography (e.g., bottom topography) oceanography (e.g., current bypass) or even initial sediment supply. It is difficult to separate the effects of any one or several factors from those of any other factor.

The competence of currents and degree of water agitation
are better measured by the component that has to have been introduced from without the depositional basin, i.e., the non-carbonate clastic component. As discussed by Purdy (1963a) the sand-sized and larger carbonate grains are only a measure of what was formed in the depositional basin and not what has been carried about. The carbonate grain-size variations are a measure of local grain-type production as well as possible transport. However, where "isolation" from the sources of non-carbonate clastic material permitted development of nearly pure limestones, the amount of lime mud (carbonate grains less than 1/16 mm. or the matrix of the modal analysis) was used as a measure of water movement and agitation (Purdy, 1963a; Behrens, 1963). This cut-off roughly matches the grain sizes counted as mud matrix in the point-counting and is equivalent to the clay-silt cut-off of the non-carbonate clastic material.

Insoluble residue data are summarized in Figures 10 and 11, and descriptions of typical residues are given with the representative rock descriptions in Appendix B.

The insoluble residues are used to characterize the various units, and the data must be explained in describing the depositional environment, but the data are not the basis for the subdivision of the Parguera Limestone into its major units.
FIGURE 10: LATERAL VARIATIONS, INSOLUBLE RESIDUES
FIGURE 11
VERTICAL VARIATION, INSOLUBLE RESIDUES

- % TOTAL RESIDUE
- % CLAY-SILT

PER CENT OF WHOLE ROCK
Clay Mineralogy

The clays were freed from the rocks with acetic or hydrochloric acid in the following concentrations: fifty samples in 4.4 M acetic acid, fifty-five samples in 0.2 M hydrochloric acid, and one-hundred and nineteen samples in 0.5 M acetic acid. All were treated at room temperature. The first two groups of samples are derived from the first two groups of insoluble residues discussed above. Although duplicate analyses indicated little difference among determinations made from the different groups, the samples in the last group were used as the basic data and the first two groups as auxiliary data. The conditions for removal of clays from limestones given by Ray, Gault, and Dodd (1957, p. 683) and Ostrom (1961, p. 128) were used as guidelines for this study.

After making the sedimented slides from a less than two micron fraction of the clays for each sample (size sorting done by settling), the slides were analyzed on a Philips Norelco X-ray diffractometer. Only the layered structure perpendicular to the C-axis was studied.

Following the recommendations and methods of Brown (1961) and Biscaye (1964) X-ray traces for clay-sized material were made from oriented slides treated as follows:

1) Untreated slide, $2^\circ \theta$ to $30^\circ \theta$
2) Ethylene glycol treated slide $2^\circ \theta$ to $30^\circ \theta$
3) Heated slide-600° C for 1½ hours, 2⁰2⁰ to 15⁰2⁰
4) Untreated slide at slowest scan, 24⁰2⁰ to 26⁰2⁰ for the differentiation of kaolinite and chlorite by the method of Biscaye (1964b).

The minerals identified are defined by their X-ray characters as based on the literature and the analytical techniques used. The classes established may not be strictly mineralogically correct, but they permit workable groups of similar clay material to be established. For example, illite is used for any 10⁰ mica-clay including glauconite (Bradley and Grim, 1961). These techniques permitted the following classes to be established: montmorillonite, illite, chlorite, kaolinite, mixed layer clays, quartz, and plagioclase feldspar. Other minerals are rare. In some cases certain types of the above classes could be discriminated.

Montmorillonite is defined as the 14Å peak that expands to 17Å with ethylene glycol and collapses to 10Å with heat treatment (MacEwan, 1961, pp. 143-207).

Illite is marked by strong 10Å, 5Å, and 3.33Å peaks. The 10Å peak is the most diagnostic (Bradley and Grim, 1961, pp. 208-241).

Kaolinite was identified as the 7.16Å, 3.58Å peaks (Biscaye, 1964a, 1964b). If a sample had no chlorite (any
14Å peak present disappeared on heating), then further proof of the presence of kaolinite was available (Brindley, 1961, pp. 51-131).

Chlorite is indicated by 7.08Å and 3.54Å peaks and a 14Å peak that is variable in its position (13.8 - 14.2Å) and in its presence or absence on the untreated and glycolated records. On the heated record a sharp peak occurs near 14Å (Brindley, 1961, pp. 242-296).

No conclusive evidence for the existence of vermiculite in important quantities was found in the Parguera rocks. Following the hypothesis of Weaver (1956, 1958), Whitehouse et al. (1960), and Griffin (1962), that a sedimentary clay suite depends primarily on the source area supplying the sedimentary material, there should be little vermiculite present because a likely source for great amounts of vermiculite is not known for the Parguera sediments.

Mixed-layer clays are marked by first order (001) peaks intermediate between the first order peaks of montmorillonite (glycolated record) and illite (17Å - 10Å). These mark the possible combinations chlorite-montmorillonite, montmorillonite-illite, chlorite-vermiculite, and illite-chlorite-montmorillonite (Weaver, 1956, pp. 202-221; MacEwan et al., 1961, pp. 393-445). The mixed-layer is probably random in the distribution of its component clays (Weaver, 1956, pp. 202-221). Mixed-layer clays are also indicated by a
spread from 14Å to 17Å of a glycolated peak, peaks at spacings greater than 17Å on the glycolated trace, broad asymmetrical peaks, broad peaks with several small peaks on top, or a series of small peaks between 10Å and 17Å (glycolated trace). A heated record with an intermediate peak (10Å-17Å) probably indicates chlorite-illite, chlorite-illite-montmorillonite, or chlorite-montmorillonite interlayering (Weaver, 1956).

Quartz has a distinctive set of peaks, one of which (3.34Å) essentially coincides with the third order (003) peak of illite (3.33Å). The peak picked as diagnostic for any form of quartz was the 4.26Å peak. Quartz is a minor constituent of most samples, especially those that were ground prior to solution.

Plagioclase feldspar is commonly present, especially in those rocks with an important tuffaceous component. The peaks used to indicate feldspar are 6.4Å, 4.03Å, 3.88-3.65Å, 3.20-3.18Å. The correlation of the presence of plagioclase with the more tuffaceous rocks and the fact that most of the rocks were ground before treatment indicate the plagioclase found in these analyses is detrital and not authigenic.

The data summarized in Figure 12a indicate a vertical change in the complex clay suites of the following generalized nature: chlorite, kaolinite, and mixed-layer clays; and illite, montmorillonite with chlorite and mixed-layer clays. These assemblages correlate respectively with the basal unit
FIGURE 12: VARIATIONS IN CLAY MINERALOGY
and the mudstones, and the volcaniclastic limestones of the Parguera Limestone.

The estimates of clay abundance for each rock unit were crudely made by separating the 166 analyses into groups according to major rock types and major geographic occurrences and by then rating the clays in each sample as to their presence (minor, common, abundant) or absence. A very rough estimate of the more common constituents in each rock unit and the lateral variations in these constituents was obtained. These data are presented in Figure 12b. The data must not be taken as absolute nor as any more important than suggesting possible trends in clay mineral distribution. The abundance of mixed-layer clays in the samples prevents any better quantitative estimates being easily made (Weaver, 1956).

**Paleontology**

Reworking of the sediments and recrystallization have strongly affected the original faunal assemblages, even if only those organisms with preservable hard parts are considered. Secondly, this study is oriented towards lithology as the important consideration with organisms being treated as grain types and with paleontology serving to date the various rock units. Although this view is certainly not the correct one for any final discussion of this or any other sedimentary unit, the major subdivisions and the major indications of physical environment were more easily obtainable.
from the petrology of these rocks than from their paleontology. Also the paleontologic character of the Parguera units is rather strongly controlled by the lithologic character of the various units.

Paleontologic data for this report occurs as a macrofauna of individual fragments or whole specimens and fragments identifiable in thin-section, a similar macroflora (algae), and a microfauna found in insoluble residues, washed marls, or thin-section. Generally the material is fragmental; rarely it forms assemblages in situ or little moved from the place of growth. The latter are marked by the following samples: sponges in growth position (locality 549); corals and algae in position of growth (locality 369, 553a); whole rudists slightly or not at all moved (north and west of Ensenada, Isla Magueyes, western Parguera hills at localities 200 and 905); possibly the localized rich occurrences of heavy-shelled biconical? gastropods in the basal unit at Melones and in the western Parguera hills; the larger Foraminifera of the Isla Magueyes Member; and rare encrusting Foraminifera on volcanic cobbles (locality 146c).

The macrofauna are listed in Table 4. The only specific or generic identifications were made of the Rudistacea by Dr. E. F. Perkins of Shell Development Co., Houston, Texas. The rudist assemblage is invariably associated with medium-to coarse-grained bioclastic limestones with little non-carbonate clastic material. In thin-section and hand specimen
### TABLE 4

PALEONTOLOGICAL DATA

A. Fossil List

Microfossils:

1. Archaeoglobigerina sp.
2. A. blowi n. sp., n. gen.
3. Dictyomitra sp.
4. D. multicostata
5. Globigerinelloides prairehillensis, n.sp.
6. G. volutus
7. G. sp. cf. G. yaucoensis
8. Globotruncanana sp.
9. G. arca
10. G. austenensis
11. G. bulloides
12. G. calcarata
13. G. conica
14. G. contusa
15. G. elevata
16. G. Fornicata
17. G. gansseri
18. G. lapparenti
19. G. linneiana
20. G. loeblichii
21. G. multicostata
22. G. plummerae
23. G. rosetta
24. G. stephensoni , n. sp.
25. G. stuarti s.s.
26. G. stuartiformis
27. G. Trinidadensis?
28. G. ventricosa
29. Heterohelix sp.
30. Lepidorbitoides sp.
31. Lithophylum sp.
32. Lithostrobus sp.
33. L. pseudoconulus
34. L. punctulatus
35. Planoglobulina sp.
36. Pseudoaulophacus sp.
37. P. floresensis
38. P. gallowayi
39. P. lenticulatus
40. P. paragueraensis
Table 4 (Continued)

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</tr>
</thead>
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<tr>
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<td>Pseudorbitoides sp.</td>
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<td><em>P. israelskyi</em></td>
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<tr>
<td>43.</td>
<td>Pseudotextularia elegans s.s.</td>
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<td>44.</td>
<td>Rugoglobigerina sp.</td>
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<td>45.</td>
<td>R. rugosa</td>
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<td>46.</td>
<td>R. scotti</td>
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<td>47.</td>
<td>Rugotruncana subcirrumpodifer</td>
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<td>48.</td>
<td>Sulcoperculina?</td>
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<td>49.</td>
<td><em>S. dickersoni</em></td>
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<td>50.</td>
<td>Sulcorbitoides? sp.</td>
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<td>51.</td>
<td>Vaughanina cubensis</td>
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<td>52.</td>
<td>Benthonic Foraminifera (arenaceous)</td>
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<td>Radiolaria</td>
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Macrofossils:

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<td>Durania sp. (Rudist)</td>
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<td>D. nicholasi? (Rudist)</td>
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<td>Granocardium? (Pelecypod)</td>
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<td>60.</td>
<td>Hippurites n. sp. (Rudist)</td>
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<td>61.</td>
<td>Sauvagesia macroplicata (Rudist)</td>
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<td>62.</td>
<td>Titanosarcolites? sp. (Rudist)</td>
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<td>63.</td>
<td>Encrusting forms: Foraminifera, Bryozoa</td>
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<td>Mollusk fragments</td>
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<td>68.</td>
<td>Biconical to obconical gastropods</td>
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<td>Radiolitid rudist</td>
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Table 4 (Continued)

B. Dates and Fossils Arranged by Stratigraphic Units

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<td>M</td>
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<td></td>
<td>758</td>
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<td>791b</td>
<td>M</td>
<td>LC-LM</td>
<td>31, 48?</td>
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<td>14,835N 96,910E</td>
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</table>
Table 4 (Continued)

\begin{itemize}
  \item[a] M = Sierra Melones, WP = western Parguera hills, EP = eastern Parguera hills, V = Vertero hills, E = Ensenada.
  \item[b] Cret = Cretaceous, S = Santonian, C = Campanian, M = Maestrictian, L = Lower, Lm = Lowermost, M = Middle, U = Upper.
  \item[c] Fossils keyed to Table 4a.
  \item[d] Coordinates on Puerto Rican metric grid system.
\end{itemize}
large fragments or whole specimens are abundant in these rocks, but are rarely sufficiently well preserved for identification. According to Perkins the paleoecology of these species is not established, but their stratigraphic occurrence here and elsewhere is restricted to sediments formed in strongly agitated, very shallow, normal marine waters and they commonly are associated with reefs. This assemblage is dated by Perkins as Campanian - Maestrichtian, no older than Campanian.

This rudist assemblage is somewhat different from that given by Mattson (1960, pp. 336, 359) for the Parguera Limestone and the dates conflict somewhat with those he gives. The first difference may be caused primarily by differences in collection. The second difference is based on the source of the dates. These dates are derived from more recent work on large collections of associated fauna from throughout the Caribbean by personnel at the U.S. National Museum, whereas Mattson's dates are from an older work and a more limited collection. The macrofauna are further discussed under their respective units.

Microfaunal determinations were made by Dr. E. A. Pessagno, Jr., from thin-sections, insoluble residues, and washed marls. His data are presented in Table 4. The foraminiferal mudstone provided much of the planktonic material, and the volcanoclastic limestone above contained many large Foraminifera. The material was used primarily to
determine the ages of the various units. Paleoeologic information has been slighted, or was unattainable, but observations available are presented under the respective stratigraphic units.

Dates for the various units of the Parguera Limestone provided by Pessagno and Perkins (personal communication) are presented in Table 4. Pessagno's regional correlation chart and local stratigraphic divisions are presented in Figure 13. As discussed in the section on the Parguera syncline, the one date of Maestrictian for the basal Parguera given by Mattson is anomalous. Otherwise, there is good agreement on the age dates in all these studies - the Parguera Limestone ranges from Lowermost Campanian, possibly Santonian, to Lower Maestrictian (Mattson, 1960, p. 334; Slodowski, 1956, p. 51). Its upper units are equivalent in age to the lower part of the Melones Limestone and only slightly older than the Cotui Limestone (Mattson, 1960, p. 336). Dates of individual units are given under their respective stratigraphic descriptions.

Summary

Field mapping, supplemented by petrographic data from thin-section study, was used to delineate the three members within the Parguera Limestone and to outline their major facies. Description of these units and facies was further complemented by insoluble residue and clay mineral studies.
## SYSTEM OF ZONATION

<table>
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<tr>
<th>European Stage Name</th>
<th>North American Stage Name</th>
<th>Assemblage Zone</th>
<th>Subzone</th>
<th>Zone</th>
<th>Pedimental Sandstone (Composite)</th>
<th>Texas</th>
<th>West Indies</th>
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<td>Abathomphalus meyendorff</td>
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<td>Rugosochitonus Shevchenko</td>
<td>Rugosochitonus Shevchenko</td>
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<td>Globorotalia fema nuculana</td>
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<td>Marginotruncana Canavella</td>
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<td>El Aba Lms.</td>
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<td>Greater Fm.</td>
<td>Rio Loco Fm.</td>
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</table>

**KEY:**
- **---** not found in contact with each other
- **-** uncertainty limit
- **-+-** new subspecies

**FIGURE 13:** REGIONAL CORRELATION ACCORDING TO PESSAGNO

MODIFIED AFTER PESSAGNO, 1964, PERSONAL COMMUNICATION
Paleontological studies were conducted primarily to determine and confirm age and structural relationships of the various lithologies, but some of the work also yielded important paleo-environmental and paleoecological data. After the lithologic and time framework is established for southwest Puerto Rico, paleoecologic work will be important in this area.

Stratigraphic Succession

A typical section of the Parguera Limestone is discussed first; then each member is presented in detail, first with respect to the type section and then with respect to its lateral variations from west to east by areas - Sierra Melones, Parguera hills, Vertero hills, and Ensenada. Finally, regional correlations are outlined. The reader should use Plate I during the following discussion.

Typical Section

A type area is proposed here that agrees with Mattson's type area (Mattson, 1960, p. 333) for the Parguera Limestone. This type area consists of the Parguera hills and the areas south of them to the coast.

Because there is no one good exposure of the Parguera Limestone and because of the lateral variations within its units, no type section for the whole formation is formally established. Rather, for each unit (member or major facies in a member) described below a type section is presented.
Possibly the following traverses across the Parguera hills would form good type sections: 1) north from Isla Cueva, 2) north-northeast from Isla Cueva, and 3) north from Isla Magueyes. The rocks are rarely well exposed except as patchy outcrops.

The vertical sequence in the type area is summarized here and on Figure 14 as follows:

1. The basal unit, the Bahía Fosforescente Member, is a volcaniclastic calcareous sandstone in its lower part which grades upwards into a medium-grained glauconitic calcarenite with a marker zone rich in glauconite near the upper contact.

2. The basal unit thickens eastward, and a thick, massive bedded, coarse-grained, bioclastic limestone appears near Ensenada. Likewise the mudstone becomes coarser-grained and tuffaceous. Lenses of the massive limestone occur in the type area.

3. A calcareous, foraminiferal mudstone, the Punta Papayo Member, overlies the basal unit in gradational contact with it. At the lower and upper (where present) boundaries of the mudstone a zone of coarse-grained, bioclastic limestone occurs interbedded with the mudstone.

4. A calcareous, fossiliferous, volcanic conglomerate, the Isla Magueyes Member, overlies the mudstone unit with erosional unconformity. The conglomerate grades
FIGURE 14
GENERALIZED STRATIGRAPHIC SECTION, PARGUERA LIMESTONE

TYPE OF AREA, NORTHWEST OF PUERTO RICO

TAKEN FROM N-S TRAVERSES ACROSS THE PARGUERA HILLS WEST OF CERRO PARGUERA
upwards into a very coarse-grained pure bioclastic limestone.

5. Augite-hypersthene andesite flows occur within the volcanic conglomerate, near its change to the bioclastic limestone.

6. The Melones Limestone overlies the mudstone unit of the Parguera Limestone with erosional unconformity in the Sierra Melones. It is locally a bioclastic limestone that changes upwards to calcareous, volcanic sandstones and tuffs. It may be the equivalent of the volcanic conglomerate of the Isla Magueyes Member in the Parguera area.

The internal unconformity has rocks dated as Upper Campanian above and below it and has coarse-grained rocks immediately adjacent to it on both sides. It is suggested that the time break and change of regimen is too insignificant to warrant erecting a new formation at this point. Instead, the boundary between members is placed here.

A diagrammatic east-west cross-section of the Parguera Limestone is presented in Figure 15.

**Unit I: Bahía Fosforescente Member**

The Bahía Fosforescente Member is named for the excellent outcrop of tan calcarenite in the low cliffs on the west side of the entrance to Bahía Fosforescente. The bay is east of the village of La Parguera on the south coast.
FIGURE 15
DIAGRAMMATIC SECTION, MEMBERS OF THE PARGUERA LIMESTONE
The rocks exposed here are typical of the basal Parguera in the following ways: the rocks are tan, well sorted, well rounded, medium-grained, non-carbonate clastic-rich calcarenites; they contain much glauconite in the upper portion; there is a thin glauconite marker bed in the upper part of the member; the lower contact is sharp; and the upper contact is gradational. The section is thinner at Bahía Fosforescente than at most other places, and there is no coarse-grained gray bioclastic limestone present.

The Bahía Fosforescente Member is present at the base of the Parguera Limestone wherever this formation crops out, except along fault or where covered by younger deposits. Its occurrence is outlined on Plate I. However, its character changes along its outcrop belt. Generally the glauconitic tan calcarenites of the type section are present, but they may be modified in the following ways: the section is thin at Punta Melones on the west coast, but thickens eastward; a thick section of coarse bioclastic limestone appears eastward at Cerro Verterro and Ensenada; the tan calcarenite becomes a thin sandstone or conglomerate at the base at Ensenada, and a thick volcaniclastic calcarenite appears above the bioclastic limestone to the east at Cerro Lajara. The well-sorted, well-rounded nature of the grains, both carbonate and non-carbonate, and the presence of glauconite are persistent features of the unit. The pure bioclastic limestone
within the section is characteristic of the eastern section; whereas the appearance of large gastropods and a decrease in coarse-grained volcanic material characterizes the western outcrop.

The contacts have a consistent and characteristic appearance throughout the area. The lower contact marks an erosional unconformity. A thin calcite-cemented sandstone or conglomerate, rarely fossiliferous, immediately overlies the pre-Parguera surface and grades sharply upwards into the tan calcarenite. Commonly near Ensenada, this sandstone or conglomerate grades sharply into the overlying massive bioclastic limestone and little or no tan calcarenite is present near the contact. Generally, the rocks immediately above the contact contain pieces of the rocks immediately below the surface of unconformity.

In certain areas, such as the north side of Cerro de Abra at Ensenada, the sandstone overlies a volcanic flow. It belongs to the lowest part of the Parguera Limestone because of its sharp lower contact, its gradational upper contact with the limestone, and its calcite cement.

In other areas, such as the north side of the Sierra Melones, a conglomerate is found between the Bermeja Complex and the overlying silicified tan Parguera Limestone. The contacts bounding the conglomerate are sharp, and there is no indication of its relationship to either the serpentine
or the limestone. Likewise at Bahía Fosforescente there are volcanic conglomerates beneath the basal tan calcarenite. They do not seem to be gradational into the limestone, but they do seem to mark the unconformity. In these cases, where a definite inclusion in the period of Parguera deposition is not demonstrable, the underlying rocks have been excluded from the Parguera. The volcanic conglomerates have been placed with the underlying volcanic unit, and the conglomerate in the Sierra Melones is mapped separately.

The upper contact is everywhere gradational with the overlying foraminiferal mudstones by interbedding of thin beds of fine-grained bioclastic calcarenites and the foraminiferal mudstones. Discrete beds of calcarenite alternate with the mudstones, become thinner upwards, and decrease in number upwards until the rock is entirely medium-bedded mudstone. Rarely, in the western Parguera hills for example, is this type of gradational contact replaced by a gentle upwards gradational decrease in grain size and increase in the components forming the mudstone. Little interbedding of sharply contrasting lithologies is seen. The glauconite present in the lower unit disappears with the appearance of the first few mudstone interbeds.

The upper contact of the Bahía Fosforescente Member is placed at the base of the first true foraminiferal mudstone above the glauconite-rich marker zone. Accepted field
practice generally places the contact of an interbedded sequence of sandstones and shales (Weller, 1960) at the top of the sequence. The reverse procedure is justified here by the disappearance of the glauconite from the lower unit, the appearance of the mudstones, and change in the nature of the calcarenite from medium-bedded, medium-grained, beige, bioclastic limestone with well-rounded grains to a finer-grained, thin-bedded, gray, bioclastic limestone with sub-angular grains. These changes in character of the calcarenite, together with the position of the glauconitic zone, are distinctive enough to closely locate the contact. Furthermore, such a location of the contact more nearly correlates with the change in sedimentary environment indicated by the stratigraphic section.

**Sierra Melones:** At Punta Melones on the west coast the Bahía Posforescente Member is represented by a medium-bedded, medium-grained, dolomitized, silicified limestone and a glauconitic, medium-grained, bioclastic calcarenite with minor non-carbonate clastic grains. The section here is only 108 feet thick.

The Bahía Posforescente Member overlies a thin, brown, siliceous conglomerate which rests upon the serpentine of the Bermeja Complex, which represents the possible soil zone of Mattson (1960, p. 335) and which is correlated here with the thick conglomerate found a short distance to the east.
Above the glauconitic horizon are the foraminiferal mudstones interbedded with more calcarenite containing little glauconite.

The contact between the Bahía Fosforescente Member and the overlying mudstones is placed below the first very fine-grained mudstone above the glauconite calcarenite. This glauconitic calcarenite is considered equivalent to the glauconitic marker bed at Bahía Fosforescente.

To the east the section thickens, especially the tan, silicified, dolomitized calcarenite. This tan, silicified limestone attains a thickness of 325 feet, and the glauconitic zone reaches 130 feet.

The tan calcarenite resembles the tan limestone at locality 186 (Figure 16) in the western Parguera hills except for the silification and lack of abundant non-carbonate clastic grains. The large gastropods, medium-grained bioclastic debris, tan color, and the presence of clay are characteristic of the basal unit at locality 765, as they are at 186. The occurrence of this same rock at locality 793 and elsewhere in the Sierra Melones was one of the factors in showing the faulted Melones syncline.

The silification and dolomitization are secondary and post-depositional as suggested by the partial obliteration of fossil grains and the decrease of silica upwards away from its probable source.
The glauconitic calcarenite overlying the tan limestone occurs in continuous outcrops in the western half of the Melones area and occurs as small erosional remnants to the east. It is generally medium- to thick-bedded with rare, thin marly partings. The rocks are coarser grained and lighter colored than the ones in the western Parguera hills, they do not contain as much glauconite as the marker zone at Bahía Fosforescente, and they contain less volcaniclastic material.

In the western Sierra Melones above the glauconitic limestones are thin lenses of the upper calcarenite that are the same as those of locality 137 in the Parguera hills. Above these beds lie the foraminiferal mudstones.

East of Sierra Melones on the southwest side of the Sierra Bermeja, there is an outcrop of Parguera Limestone in a small synclinal nose. On the north limb a zone of the glauconitic calcarenite overlies a silicified tan rock that may be the tan limestone. On the southern limb, the tan limestones are found not silicified, but the glauconitic beds are very poorly developed. The total section is thin and poorly exposed. The thinness possibly is caused by depositional onlap onto a topographically positive Bermeja block.

**Parguera area:** The basal part of the Bahía Fosforescente Member at the type section is a thick-bedded, tan, medium-grained calcarenite (Figure 17). It contains thirty per cent
Figure 16: Basal Bahía Fosforescente Member, Western Half of Area, Locality 186.

Figure 17: Tan Calcarenite, Bahía Fosforescente Member, Locality 577.
non-carbonate clastic grains, most of which are volcanioclastic. Rare chert and minor glauconite are also present. Ovoid pellets are distinctive of this member, especially the lower part, in this area. Skeletal grains form nearly thirty percent of the rock and are represented mostly by mollusk, echinoid, and algae fragments. Coiled, biserial, and uniserial Foraminifera are minor constituents. All grains are well rounded and of nearly equal size. Skeletal grains are almost always rimmed with a darker rind of cryptoocrystalline calcite, and the interior is partially or wholly recrystallized to coarse calcite spar.

Upwards in the section the bedding changes character to medium-beded, alternating tan calcarenites and marly calcarenites. The bedding planes are wavy, and the marly beds are recessed by weathering between the purer limestones. The constituents remain approximately the same throughout the section although the percentage of clay is higher in the marls and glauconite content increases upward towards the glauconitic bed.

The glauconite bed (sample locality 584b) is ten feet thick, 280 feet above the base of the unit, dark brown to red, silicified, and thick bedded. Glaucnite-rich marls occur immediately above and below it. The glauconite occurs as medium-sand-sized sub-angular to rounded, commonly irregular grains. It can be seen replacing rare foraminiferal tests.
Commonly it occurs as internal molds. The rock at this locality is silicified, intensely iron-stained, and re-crystallized (Figure 18). One shark's tooth was found.

The calcarenite continues above the glauconite bed for thirty feet more with the glauconite decreasing away from the marker horizon. At this point the first thick zone of mudstone appears and the upper contact is drawn here. The non-carbonate clastic component is considerably reduced above the glauconitic zone.

On Isla Matei east of Bahía Posforescente, the marker bed itself was not seen, but a glauconite-rich zone was found at the southeastern end of the island. The section here has thickened a little, and contains slightly less, but coarser, non-carbonate material. The upper calcarenites are slightly coarser grained also.

West of Bahía Posforescente, in the hills north of La Parguera, the section is still thin. The glauconitic marker bed is absent and is represented only by a thin zone of glauconitic limestone near the crest of the hills. The tan calcarenite makes up the rest of the section. It is possible that the thinning of the section in this area represents slightly higher topography on the pre-Parguera surface.

Westward at Cerro Parguera the Bahía Posforescente Member thickens to 1100 feet, the glauconitic marker bed reappears, the upper calcarenite thickens a great deal, and a
Figure 18: Glaucotic Zone, Bahía Fosforescente Member, Locality 433c.

Figure 19: Gray Limestone Facies, Bahía Fosforescente Member, Parguera Hills, Locality 133.
pure gray, coarse-grained bioclastic limestone occupies the lower thirty feet of the section. These alterations in the section continued westward to the west-northwest nose of the Parguera syncline near locality 171. However, at locality 135 the bioclastic limestone thins and disappears except for a lens at 171.

The large lens of bioclastic limestone at Cerro Parguera (Figure 19) and westward represents the same limestone that forms the hills near Ensenada. It is very similar to Mattson's Brujo Limestone in the hills southwest of San Germán. The rock contains sixty per cent skeletal material, more than thirty per cent spar cement, and minor non-skeletal carbonate grains. Non-carbonate clastic material is very rare or absent. Thin beds of similar rock are found between Bahía Fosforescente and Cerro Parguera, but they are too small to map. This rock is not found in the basal Parguera Member to the west in the Melones area.

From locality 135 to 171 the tan calcarenite below the marker bed becomes darker and fine-grained. Also the overlying glauconite marker bed thins and becomes a glauconitic zone. Often patches of glauconite occur as fillings of worm burrows on bedding planes. This part of the section now seems to thin westward.

At locality 433c (between 135 and 171) the glauconitic marker bed is fresh and unsilicified (Figure 18). In this
section it is seen to be composed of fine-grained calcarenite with minor clay, much glauconite, and an important fraction of small subangular volcanic fragments. The high sand-sized fraction of insoluble residue from this zone indicates that these volcanic fragments probably are important throughout its extent. In the Ensenada area, the volcanic fragments can be easily seen in hand specimen. Possibly this glauconitic zone is not only a lithologic marker, but a time horizon as well.

The calcarenite beds (Figure 20) above the glauconite zone thicken from Cerro Parguera to locality 137. Westward from this point they change laterally to a dark-gray, very fine-grained bioclastic sand with rare glauconite grains. The bioclastic sand acquires a greater foraminiferal component and a greater clay component westward to the synclinal nose. Here the calcarenite is represented by dark gray-brown laminated fine-grained limestones. The laminae stand out on the weathered surface. Because of the fine-grained nature and the high foraminiferal and mud content, these rocks are placed in the overlying mudstone unit. Although the upper calcarenite grades laterally as well as vertically into the mudstone, the contact is based on lithology and the calcarenite as defined at Bahía Posforescente and at locality 137 pinches out westward underneath the mudstone member.

At locality 171 the general strike, although erratic
over the nose of the syncline has changed from a westerly to a southerly trend. South of this point to 186 the basal unit is obscured. Also the bed orientations seem to be affected possibly by faulting.

At locality 186, at the southwest end of the Parguera hills, the Bahía Posforescente Member is represented by a tan clay-rich very coarse-grained bioclastic limestone (Figure 16). The limestone is particularly distinctive because of the abundant, large, biconical to obconical gastropods contained within it. Volcanic and possibly Bermeja Complex sand-sized grains are minor constituents. This same lithology is found to the west at the base of the Parguera Limestone in the Sierra Melones.

The absence of a glauconitic zone above the tan limestone, the disturbed strike and dips, and the lateral discontinuity of the unit were used as indications of the minor faulting shown on Plate I near locality 186.

South of 186, at 471 across the southern end of the Parguera hills on the coast, are calcarenites similar to those at locality 137. These may be within the overlying mudstone unit; no definitive outcrops were seen. The position relative to the syncline and the bedding orientation warrant placing these beds in the upper part of the Bahía Posforescente Member.

**Vertero hills:** North of Bahía Posforescente at Cerro Covanas at the west end of the Vertero hills, the Bahía
Fosforescente Member shows the same stratigraphic sequence as is found in the type section. The section is thicker (475 feet compared to 320 feet at Bahía Fosforescente) and the basal part of the tan calcarenite is richer in non-carbonate clastic material. Lenses of the gray coarse-grained bioclastic limestone of locality 133 are found on the north side of Cerro Covanas. The glauconite marker bed is present in the float and rarely found on outcrop. It is less than three feet thick and is overlain by the upper calcarenite.

The lower contact is exposed in a small quarry at locality 217. The rock quarried is the underlying Sabana Grande Andesite. The contact is sharp and the volcanics are altered and weathered along the contact. The overlying tan limestone is massive or poorly bedded, it lies on a gently undulating surface of the volcanic material as if filling the irregularities in the erosional surface, and this contact is considered depositional. Coarse-grained volcanic material is a minor inclusion in the tan limestone immediately above the contact.

The upper contact is gradational by interbedding with the overlying mudstones.

Eastward along the line of the Vertero hills the gray bioclastic limestone increases sharply in thickness. The first continuous beds occur between Cerro Covanas and the west end of Cerro Vertero and they are a major part of the section at Cerro Vertero.
Faulting and folding have confused the stratigraphy in the large rounded hill north of the western peak of Cerro Vertero, but the following sequence can be established. On the south side a thin sequence of tan calcarenite overlies a volcanic-derived sediment. Above the tan limestone is a thin zone of gray limestone, followed in turn by tan calcarenite and the mudstones. On the north side the gray bioclastic limestone is very thick and is overlain by thin tan limestone, and the mudstones interbedded with thin layers of calcarenite. The latter are silicified. The glauconitic zone is not present although rare glauconite grains are seen in the tan calcarenites. Rare fine-grained, dark calcarenites with minor volcanic debris and rare glauconite are present in the float on the hill top but no outcrop was observed.

To the south the buried chert block (or hill) crops out. It has been described above, but it should be restated that the lithologies of the lower part of the tan calcarenite and the rocks surrounding the chert block are similar except for the higher insoluble residue of the latter. Likewise the massive gray, bioclastic limestone resembles that to the north and east. Because of lithologic similarity to the Bahía Fosforescente Member, the rocks around the chert block are included in the Bahía Fosforescente Member.

Eastward along the central part of the ridge of Cerro Vertero, a thin zone of tan calcarenite with much non-carbonate clastic debris overlies the volcanic rocks. The gray, massive,
bioclastic limestone overlies thin, tan calcarenite and is overlain in turn on the south side of the ridge by patches of similar tan calcarenite. On the south side of the down-faulted block of gray limestone north of the main ridge, the glauconitic marker is found in the float on the upper tan limestone. At Ensenada this sequence is confirmed in the outcrop.

At locality 369 (Figure 21) good exposures show the tan calcarenite to be in erosional contact with the augite-hornblende variety of Sabana Grande type andesite. The section of tan calcarenite is approximately ten to fifteen feet thick. The content of volcanic material decreases in amount and grain-size upwards. Near the top are rare local patches of coral in place.

The gray massive limestone overlies this tan calcarenite with fairly sharp contact and consists in its basal part, of great numbers of round "heads" of Archaeolithothamnion sp. up to five centimeters in diameter. These algae are also seen elsewhere (locality 552 to the west for example) in the gray limestone, especially near the base (Figure 22).

On the traverse through locality 479 the basal tan calcarenite is not exposed. The gray limestone is well exposed and is overlain by the tan calcarenite. This upper tan calcarenite contains lenses of the foraminiferal mudstone and several discontinuous thin glauconitic zones. Above this tan
Figure 20: Upper Calcarenite, Bahia Fosforescente Member, Locality 137.

Figure 21: Typical Basal Bahia Fosforescente Sequence, Eastern Half of Area, Locality 369.
calcarenite, in sharp contact with it, is a calcareous, bioclastic-rich volcanic conglomerate. Gray bioclastic lenses occur in the upper portion of the conglomerate. The foraminiferal mudstones crop out above the conglomerate. No dates more specific than Campanian were obtained for any of the units.

Somewhat similar sequences are developed at Cerro Lajara and in the low ridge south of it. There the glauconite marker bed is well developed above thin lenses of the mudstones. In turn, a conglomerate lies above the marker and then the foraminiferal mudstones appear as continuous beds. The date on these continuous mudstone beds is Lower Campanian and agrees well with the age of the lower part of the mudstone sequence in the Parguera area. On the basis of the similar sequence at Cerro Lajara to the east, the contact between the Bahía Fosforescente Member and the overlying mudstones is placed at the top of the volcanic conglomerates in the eastern Verterro hills.

The gray, very coarse-grained, pure bioclastic limestone is an important rock type in the Bahía Fosforescente Member, especially in the eastern part of the area. Further work may prove it to be equivalent to the Brujo Limestone of Mattson (1960, p. 337), but until this is done it is informally designated in this report as the "gray limestone facies" of the Bahía Fosforescente Member. It is most typically developed in the east-west ridge north-northwest of Ensenada that has the knob El Peñón at its east end.
Ensenada area: The thickening of the Bahía Fosforecente Member that began in the Verterro hills is well developed to the east in the Ensenada area. The thickening occurs primarily in the gray limestone facies and secondarily in the tan calcarenite. The grain size of the non-carbonate clastic components of these rocks also noticeably increases throughout the section, and locally the non-carbonate clastic part of the unit is thicker than in the rocks to the west. For example at Cerro Lajara several beds of conglomerate have been introduced into the section.

On the north side of the low hill at the intersection of Highway 116 and Road 326 (locality 505), a basal volcanic conglomerate is found underlying the gray limestone facies and overlying the volcanic rock of the augite-hornblende type. The fragments are rounded to sub-angular and cobble-sized, with a matrix of calcite and finer volcanic debris. Some silification has taken place. This unit is a gray to dark gray-red and is poorly bedded. It grades sharply upwards through a thin bed of tan volcaniclastic-rich limestone into the gray limestone facies.

At this point the gray limestone facies is not much thicker than to the west in the Verterro hills. The gray limestone is overlain by a dark brown, fine-grained limestone, a tan calcarenite and the glauconite marker bed.
Eastward towards El Peñón, the gray limestone facies becomes very thick and is divided indistinctly by a zone of light tan calcarenite with rare glauconite and a higher non-carbonate clastic component compared to the gray limestone facies. Above the upper gray limestones is a dark brown volcaniclastic-rich calcarenite with minor glauconite. This sequence is best developed in the hill between El Peñón north of Highway 116 and locality 505. This section lies upon the same conglomerate found at locality 505, and it extends eastward to just west of road 331 (on the eastern boundary of the area) where the Tertiary (Eocene) Jicara formation unconformably covers it. The section has been thinned to the east by pre-Tertiary and present-day erosion. West of El Peñón its thickness is 1700 feet.

Small knobs stand out above the flat plain south of El Peñón. They are composed of various types of andesites, andesitic conglomerates and silicified volcanic rocks. They seem to comprise a sequence of mappable flow units, but they were not mapped for this report except to note that the lower slopes contain primarily the augite andesite while the augite-hornblende andesite was found locally near the top of the hills. The rocks capping the largest hill, between El Peñón and Cerro de Abra, consisted of a thick sequence of volcanic sandstones and conglomerates similar to the conglomerate at 505. One small hill south of El Peñón was capped
by a thin brown limestone, rich in sand-sized non-carbonate clastic material, and an overlying bed of the gray limestone facies.

The high, sharp, east-west trending ridge of Cerro de Abra, just north of Ensenada, is composed of steeply dipping, massive- to thick-bedded rocks of the gray limestone facies (Figure 23). The gray limestone facies overlies a thin, coarse-grained, calcite-cemented, reddish-brown sandstone composed of reworked grains derived from the immediately underlying augite-hornblende andesite. The contact is exposed just below the cliff of gray, massive, **Durania**-bearing (rudistid) limestone on the north side of Cerro de Abra (localities 675, 687; Figure 24). On the south side of the ridge the limestones are overlain by a dark brown, non-carbonate clastic-rich calcarenite, a bed of coarse-grained volcanic sandstone, and a thick sequence of medium-grained glauconitic calcarenites. Within the glauconitic zone is a band of glauconite green-sand (locality 682). The green sand is correlated with the glauconite marker bed of Bahía Fosforescente.

The above sequence has been complicated by faulting as shown on Plate I. The offset in the western end of Cerro de Abra and the sudden thinning of the gray limestone suggest additional faults. Their trace was not seen in the field, and the gray limestone is somewhat lenticular. The
Figure 22: Algal Growth, Basal Gray Limestone Facies, Bahía Fosforescente Member, Locality 553a.

Figure 23: Typical Outcrop, Gray Limestone Facies, Bahía Fosforescente Member, Locality 676 North of Ensenada
Figure 24: Typical Gray Limestone Facies, Bahía Fosforescente Member, Locality 885a, West of Ensenada.
additional faults were not placed on the map, but their presence is considered probable.

The most fully developed section of the Bahía Fosforescente Member in the area about Ensenada is exposed in the steeply dipping beds that form Cerro Lajara, the high steep hill immediately west of Ensenada. A north-to-south traverse across the crest of the hill reveals the following section in the Bahía Fosforescente Member:

1. At the base of the hill are exposed andesites typical of the augite andesites.

2. A thin zone of fossiliferous, calcite-cemented, volcanic conglomerates lie upon the volcanic rocks and is overlain by a gray limestone rich in volcanioclastic sand-sized material. This whole zone is 120 feet thick.

3. The gray limestone facies, 800 feet thick, overlies the volcanioclastic-rich limestone and forms the resistant crest of the hill. Although mapped by Slodowski (1956, Pl. I), no Tertiary rocks were found in place on the crest. Pieces of Tertiary rock were seen in the float, and they are possibly erosional remnants. However, they may have been introduced through the intensive reworking of the land for ranching purposes.

4. South of the crest, a calcarenite with minor non-carbonate clastic material appears. Within it is a
volcaniclastic-rich limestone. The volcanic fragments are cobble- to pebble-sized. This rock is medium- bedded and 100 feet thick. The total thickness of the calcarenite is 430 feet.

5. Within the calcarenite occur lenses of foraminiferal mudstone. They are slightly coarser than the foraminiferal mudstones overlying the Bahía Fosforescente Member and show laminae standing out as small ridges on the weathered surface.

6. Within the calcarenite at approximately 375 feet above its base, a glauconitic zone is found. The glauconitic marker bed is not present, but this zone is taken to be its equivalent. The rocks resemble the glauconitic limestones on the south side of Cerro de Abra at locality 699 or near the greensands of locality 682.

7. The calcarenites grade by interbedding into the overlying mudstone. The mudstones are slightly more tuffaceous at Cerro Lajara than to the west. This section is 1350 feet thick and thins eastward.

The section at Cerro Lajara is repeated in the low east-west ridge south of Cerro Lajara by the fault between it and Cerro Lajara. Outcrops are found at the east end of the low ridge on Bahía de Guánica. The mudstones are likewise exposed here, and these rocks are the one named Ensenada shales by Mitchell (1922, p. 252). In general the exposures
south of the fault are poor and covered by the overlying Juana Díaz and Ponce Limestones of the Middle Tertiary.

**Insoluble residues:** Insoluble residue data for the Bahía Fosforescente Member are summarized in Figures 10 and 11. The data are presented for four lithologic units: the tan calcarenite below the glauconitic zone, the gray limestone facies, the glauconitic zone, and the calcarenite above the glauconitic zone. Both total residue and the percent of residue that is less than 62 μ (clay-silt fraction) is presented.

The following variations should be noted:

1. For the tan calcarenite, the total insoluble residue and the percentage of the residue that is clay-silt sized decreases from west to east.

2. For the gray limestone facies, the insoluble residue decreases eastward, but the percentage of residue that is clay-silt increases eastward.

3. For the glauconitic zone, the total residue is approximately the same throughout the area, but the percentage of clay-silt decreases markedly eastward, especially in the Parguera hills.

4. For the upper calcarenite, the total residue increases markedly eastward, but the percentage of clay-silt material may decrease eastward.
Variations in the insoluble residues of these limestones depend upon the differences in the effectiveness of current and wave action in the different areas in sorting a supply of terrigenous sediments that have a large range in grain size. Minor effects upon the current-wave sorting are produced by variations in the grain-size range of material supplied and the type or location of the source. The source could be a point, i.e., one river; or it could be linear, i.e., a series of rivers or an eroding coast line.

As indicated by the variations in the insoluble residue data outlined above, current and wave action winnowed out the clay in the Ensenada area and moved it westward, except in the gray limestone facies.

For the tan calcarenite facies the sediment supplied was clay-rich, and the currents and waves moved the clay and finer sand westward, concentrating a smaller, but coarser, fraction in the east.

The whole rudistids present in the gray limestone facies and the somewhat lenticular nature of this facies may indicate a reef-like deposit. If so, it may have acted as a trap for clay-sized material, or the currents may have been so affected during the growth of this mass that they locally moved from west to east. The position of the reef with respect to open sea and the source is not certain. The sediments may have had to enter the area from the central part, instead from the east, and then be distributed westward.
Non-carbonate clastic supply for the rocks of the glauconitic zone may have been a little coarser-grained on the average than for the tan calcarenite, and probably a coarser component was additionally introduced from the east. The current and wave action still moved the finer material westward.

In the upper calcarenite, the sediment was supplied from the east, and most was somewhat coarser than clay-silt-sized material. Current and wave action sorted the sediment and moved the finer material westward.

The period of greatest non-carbonate clastic influx relative to the rate of carbonate sedimentation was during the deposition of the beds of the glauconitic zone. However, the rate of supply of both components may have been low. The period of most rapid deposition for the non-carbonate material was the time of accumulation of the various conglomerate lenses at the base and within the section. The gray limestone facies marks the time of greatest rate of carbonate clastic deposition. The balance of rates of supply during the deposition of the tan calcarenite, whether divided by the gray limestone facies or not, were little different from those of the glauconitic zone. The gray limestone facies received very little non-carbonate material.

As suggested in the structural geology section of this report, the Salinas Fortuna anticline may have been a positive area during part or all of the period of Parguera
Limestone deposition. Variations in the pattern of insoluble residue distribution would then be solely local variations, especially in the $>62 \mu$ fraction. The conglomerate lenses in the Bahía Fosforescente Member and in the overlying Punta Papayo Member support such a suggestion, at least in the eastern part of the area. The clay-silt fraction could easily be supplied on a regional basis by currents from the north entering the area from the east.

Whether the non-carbonate clastic component of the Parguera rocks is solely locally supplied, solely regionally supplied, or supplied from both sources in varying amounts and sizes is not yet known, but the possibility of a local source for some of the coarser material should not be ignored.

**Clay mineralogy:** The variations in the clay components of the Bahía Fosforescente Member are summarized in Figure 12. Mixed-layer clays are the most important in this member; chlorite and kaolinite are important; montmorillonite is a minor constituent; and illite is rare. The most important mixed-layer type is montmorillonite-illite. Glaucnite, having a 10Å spacing, is included with illite **sensu strictu** under the broad class "illite" in this report. The lack of illite actually means the lack of any mica-clay or 10Å material in the clay-silt fraction of the rocks. The abundant glauconite seen in the field must therefore be restricted to
sand-sized or larger grains and it probably is diagenetic. The low illite content reflects the low content of 10Å material being supplied to the Bahía Fosforescente sediments.

From the west to the east, the following clay mineral changes in the Bahía Fosforescente Member as a whole are suggested:

1. Chlorite content is relatively constant.
2. Kaolinite content increases sharply in the western Parguera area and then decreases.
3. Illite content decreases and then disappears in eastern Parguera.
4. Montmorillonite content is more or less constant.
5. Quantity of mixed-layer clays increases noticeably eastward. This increase correlates well with clay data on the gray limestone facies as well as with its outcrop pattern.

Considered unit by unit the clay data show the following:

1. Chlorite is slightly more abundant in the tan calcarenite below the glauconite marker.
2. Kaolinite and montmorillonite are roughly constant vertically.
3. Mixed-layer clays are much more important in the gray limestone facies than in the other rock types.
4. Illite is more important in the glauconitic zone.

The variations in the clay data, although apparently real
because of their fairly consistent pattern, do not simply fit the detrital sorting hypothesis of Whitehouse (1960) as supported by Griffin (1960) and others.

This hypothesis suggests that lateral clay variations in a sedimentary unit can be described in terms of mechanical sorting by waves and currents because of the difference in settling velocity of floccules of different clay types, e.g., montmorillonite settles more slowly than kaolinite or illite and so will be found farther from its terrigenous source. Diagenesis is considered to play an unimportant part in producing the clay mineral suite.

The addition of material as pyroclastic debris, diagenesis, and the possibly complex interaction of current pattern and sedimentary supply indicated by the insoluble data may combine with the qualitative nature of the clay data to confound any simple proposition describing the distribution of the clays.

**Paleontology and age:** Abundant rudistid fauna is restricted to the gray limestone facies generally, although large fragments are found in the other lithologies, and well rounded fragments of the same size as the other associated carbonate grains are common throughout the Bahía Fosforescente Member. *Archaeolithothamnion* is commonly associated with the basal part of the gray limestone facies. Foraminifera, echinoids, and mollusks are common throughout.
Pessagno (personal communication) gives a maximum age range for the rocks in the Bahía Fosforescente Member of Santonian - Maestrichtian, but he dates the overlying mudstones as Lower or Lowermost Campanian in their lower part (Table 4). Most of his dates restrict the upper date to Campanian and the lower to possibly Upper Santonian. In Mattson's work (1960, Pl. 6), the maximum range for dates from this unit were Turonian - Campanian. Rarely early Campanian was noted.

Perkins' work with the rudistids (personal communication) gives a date of no-older-than-Campanian to Maestrichtian. The dates all come from the gray limestone facies which is near the base of the unit at Ensenada.

On the basis of this data the Bahía Fosforescente Member is considered to range from Upper Santonian to Lower Campanian in age.

**Depositional environment:** The rocks of the Bahía Fosforescente Member were all deposited under normal marine conditions. A basal conglomerate or sandstone marks the transgression of the sea over the pre-Parguera land surface and the ubiquity of the tan calcarenite indicates the generally widespread nature of the environment. The gray limestone facies indicates a reef or near-reef deposit, possibly a rudistid reef as indicated by the abundance of these animals in the eastern part of this facies. The glauconitic zone may
indicate a time of slow clastic sedimentation, both carbonate and non-carbonate. The restricting influence is not known. The upper calcarenite marks a lessening of the non-carbonate clastic supply and, through its interbedded nature with the mudstones, a gradual deepening of the Parguera basin.

Wave and current action were effective throughout the area but were stronger to the east. Likewise the presence of algae, especially at the base of the gray limestone facies, indicate deposition within the photic zone and thus in a zone subject to wave action, i.e., shallow water.

Uniformity and ubiquity of the various units between the Melones and Parguera areas indicate the Sierra Bermeja, although possibly exposed in lower Parguera time, was no restrictive barrier to the sedimentary environment.

**Unit II: Punta Papayo Member**

The Punta Papayo Member is named for the exposures of foraminiferal mudstone and interbedded gray calcarenites exposed in the sea cliffs east of Parguera at Punta Papayo. Other excellent exposures are found farther east along the shore, such as the entrance to Bahía Fosforescente and the south side of Isla Matei. The south side of the Parguera hills west of Parguera has a more complete, but less well exposed, section of the Punta Papayo Member.

Two reference sections are also established: the first is the west side of the entrance to Bahía Fosforescente and
shows the nature of the lower contact; the second reference section is exposed on the west side of Highway 304 at the foot of the hill in a small pit where the upper contact is exposed (locality 113).

The Punta Papayo Member includes the foraminiferal mudstones and interbedded tuffs and limestones for which G. J. Mitchell (1922, p. 252) established the Ensenada Shales. Slodowski (1957, p. 32) redefined both the unit and the type locality, and Mattson (1960, p. 333) revised the section once again. Because of the above revisions, because of the inclusion of part of Mitchell's Ensenada Shale and his San Germán Limestone (1922, p. 253) in the Bahía Fosforescente Member, and because of the better exposures and more complete section and more typical lithologies developed near Parguera, designation of Punta Papayo as the type section for this unit is considered proper.

The rocks exposed at Punta Papayo are typical of the member in the following ways: the interbedded nature of the mudstones and the calcarenites is demonstrated; the even-bedded, medium-bedded nature of the mudstones is shown; the two types of mudstones, the evenly laminated type and the type with the "wisps" of Mattson (1957, p. 44) are present; and the penecontemporaneous slump structures are well developed.

The exposures are atypical as follows: the thickness shown is only a part of the total thickness of the unit;
the amount of calcarenite present is too high; the minor to rare beds of volcanic tuff are not present; the zone of silicified, very evenly laminated, tan to yellow or red mudstone (now chert) is not seen; and neither of the contacts are clearly seen.

Where it has not been removed by post-Cretaceous erosion, the Punta Papayo Member is present above the Bahía Fosforescente Member throughout the area. It has not been found directly in contact with the pre-Parguera surface except possibly on the south side of the Sierra Melones on the northwest end of Sierra Bermeja. It has not been found totally absent with some younger member of the Parguera Limestone resting upon the Bahía Fosforescente Member. The distribution of the Punta Papayo Member is shown on Plate I. It should be noted that the member is present primarily along the south coast or where protected by overlying deposits as in the Sierra Melones. Along the Verterro hills it is rare, and north of Ensenada it is absent because of erosion.

The true thickness of the Punta Papayo Member is unknown because of an erosional unconformity at the upper contact. Other than its variation in thickness, the unit is marked by its characteristic foraminiferal mudstone throughout the area of outcrop. This mudstone shows little variation in its lithology except for the introduction of minor tuffaceous material in the Ensenada area. The interbedded calcarenites are generally found at the lower contact and
near the upper contact where most of the section has been preserved. Rare beds of calcarenite are found throughout the section. Rare beds of volcanic debris occur in the section, e.g., near the lower contact at Punta Melones and at Cerro Lajara. At locality 106 north of La Parguera a sequence of graded beds shows a volcanic sand fraction in the coarser bottom part of the graded beds. Similar graded beds are uncommon, but present throughout the section.

The lower contact of the Punta Papayo Member with the Bahía Fosforescente Member consists of interbedded calcarenite and mudstone as discussed previously. The mudstone increases in thickness and amount upwards and the calcarenite decreases. The upper calcarenite of the Bahía Fosforescente Member changes from slightly glauconitic, tan, fine- to medium-grained calcarenite to a non-glauconitic, gray, slightly coarser grained calcarenite with slightly irregular bedding surfaces. Interbedded with the gray calcarenite is a tan-gray, clay-rich, calcareous, fossiliferous, evenly laminated to non-laminated mudstone. Commonly both the mudstone and the associated calcarenites show slight silification. The interbeds of calcarenite decrease in number upwards, but in an irregular fashion. The distinctive characters of the lower contact are the appearance of the mudstones, the loss of glauconite upwards and the change from beige calcarenite to gray, medium-grained calcarenite.
In the western Parguera hills and locally elsewhere, the gray calcarenite beds thin and disappear laterally into a dark gray to brown fine-grained calcarenite that grades vertically into a coarse-grained laminated dark mudstone with rare glauconite. This change takes place above the glauconitic zone. The contact here is placed at the disappearance of common glauconite and the loss of any sand-sized bioclástic component. The beds above grade upwards into the very fine-grained foraminiferal mudstones typical of the Punta Papayo Member.

In the Parguera area, the upper contact is very sharp with a volcanic conglomerate or very coarse-grained volcaniclastic-rich limestone overlying the very fine-grained mudstones or pure gray, medium-grained calcarenites of the Punta Papayo Member. The section varies in thickness, but the lower interbedded part is always present and so is a zone of very fine-grained irregularly laminated mudstones containing a distinctive radiolarian fauna. These lower units are very continuous and constant in character. Other distinctive zones higher in the section are commonly absent in the thinner sections. The implication is that the upper part of the section is missing by erosion prior to deposition of the overlying volcanic conglomerates, and the upper contact is an erosional disconformity.

From dates by Pessagno (personal communication), the upper part of the mudstone section, in the more complete
sections, is Upper Campanian or Upper Campanian – Lower Maestrictian (e.g., localities 157, 445, 144). In the overlying fossiliferous conglomerates the dates obtained are consistently Upper Campanian – Maestrictian (e.g., 1946c, 201, A-44). These dates indicate that the time gap between the Punta Papayo Member and the Isla Magueyes Member is very small. The increase in calcarenite in upper part of the section indicates possibly a water depth decreasing with time, so that the transition from one sedimentary environment to the other across the disconformity is also small. The disconformity, although marked, is considered to be relatively unimportant.

On the south side of the Melones syncline, the massive bioclastic limestone that forms the basal Melones Limestone (Mattson, 1960, p. 335) lies upon the mudstones. The contact itself was not seen. Mattson (1960, p. 337) reports that it is possibly disconformable. Fragments possibly of the mudstone were seen by the writer in the tuffaceous rocks above the massive limestone, but none within it. It is possible that this massive limestone is a well-developed calcarenite belonging to the Parguera Limestone and that the erosional disconformity is above this massive limestone. Paleontologic dates do not dispute this interpretation, and an erosional contact above the bioclastic limestone might explain the apparent lenticularity of the bioclastic limestone.
At the east end of the Sierra Melones the volcanioclastic limestones of the Melones Limestone are found in sharp, possibly disconformable contact over the mudstone.

**Sierra Melones:** On the west coast the Punta Papayo Member is exposed in a thin and incomplete section. The calcarenites within it are thicker-bedded than those near the base in the type area. There is also present a clay-rich, brown, very weathered, thick-bedded volcanioclastic sandstone. The mudstones on the coast do not show well-developed wisp structure, and are not always laminated.

Eastward at locality 813 the characteristic mudstone with wisps crops out. Beneath it is the non-wispy mudstone which grades, through a thin zone of interbedding, into the calcarenites of the Bahía Fosforescente Member.

The mudstones are only locally exposed to the east in the Melones syncline. On the south side they occur in the float, and at the east end of Sierra Melones a thin section of mudstones occurs in thin, silicified beds.

On the southwest flank of the Sierra Bermeja the small, shallow syncline has rocks typical of the exposures of the Punta Papayo Member in the western Parguera hills. A thin zone of the non-laminated rocks overlie the glauconitic zone. Above these are typical mudstones with wisps. The exposures are poor and the contacts are not clear.

Small disconnected outcrops of laminated silicified
rock similar to the silicified zones in the mudstones are found on the north side of the Sierra Bermeja. The basal unit was not seen.

**Parguera area:** The calcarenites of the Punta Papayo Member are thin- to thick-bedded with somewhat irregular bedding surfaces. The carbonate skeletal grains forming them are coarse-grained and stand out slightly on the weathered surface. These grains are angular and well sorted.

In thin-section the contacts with the mudstones are sharp. The grains of the calcarenite are current-worked and aligned (Figure 25). Such grains as echinoid plates or pelecypod fragments form much of the sediment and commonly are imbricated.

These calcarenites commonly show peculiar structures on the bedding planes that resemble worm burrows filled with fine clay-rich gray mud, but the structures are straight and cigar-shaped. Furthermore, in many cases they assume a somewhat parallel orientation. Although the structures may well represent organic activity of some sort, they may also represent a mechanical disruption of the sediment and later filling by finer-grained material.

From the structures developed along the contacts between the calcarenites and mudstones, it is evident that the sediments were soft and plastic at the time of the deposition of the respective beds.
The mudstones in the zone of interbedding are clay-rich (some show forty to fifty per cent insoluble residue), very fine grained, evenly laminated or poorly laminated, and rich in Foraminifera, sponge spicules, and echinoid spines (Figure 26). Carbonate mud may also be an important constituent of the matrix. Commonly the mudstones are silicified. They are generally cream or beige, but may be tan. They occur as thin- to medium-bedded rocks from one to four inches thick, rarely more. The laminae within the beds represent a minor concentration of iron and either an absence or a concentration of microfossil debris. There is a noticeable correlation between the increase of silification of the mudstones and the increase in the development of very fine, even laminae.

Within and above the zone of interbedding, olive to cream to blue-gray very fine-grained foraminiferal mudstones with abundant radiolarians and sponge spicules characterize the section (Figure 27). The rock is medium-bedded and evenly bedded. Its most distinctive feature, however, are the "wisps" (Mattson, 1957, p. 44) or irregular lenticular laminae that criss-cross any fresh, fractured surface not parallel to the bedding plane.

These wisps were discussed by Mattson (1957, p. 44) with respect to the structures in the fine-grained mudstones of the Yauco mudstone, and they were also noticed by Berkey (1915, pp. 21-22). The wisps are not linear but planar or
Figure 25: Calcarenite, Punta Papayo Member, Locality 591.

Figure 26: Microfossil-rich Mudstone, Lower Punta Papayo Member, Locality 891.
commonly show a curved or contorted surface. They are internally finely laminated and at their extremities in a vertical exposure commonly exhibit fine dark lines that parallel the shape of the end of the wisp.

Several origins have been proposed for them. Mattson proposed disturbance of the unconsolidated sediment or introduction of slightly different material by currents. Donnelly (personal communication) suggested they were compacted flattened mud-balls that had rolled down a sloping surface of deposition.

The writer proposes two hypotheses. First, burrowing by any animal having a planar dimension, such as a gastropod, instead of the normally pictured linearly dimensional animals such as worms, would produce a planar burrow. The animals burrowing the sediments need not inhabit the burrows, rather they were working the sediments for organic detritus. Pyrite was not found in these rocks, and there was no other indication of an anaerobic environment. The lack of preserved shells need only mean the burrowing animals were entirely soft-bodied.

The second suggestion is that the laminae are current produced, but not necessarily by introduction of new or different material. Only faint sorting of the sediment, distributing mud-sized components in slight depressions on the bottom and leaving the slightly coarser microfossil debris
on faint ridges would be necessary. The areas sorted would be irregular and indistinct because the currents would be weak as indicated by the very fine-grained material involved.

Two features favor a burrowing hypothesis for at least some of the wisp structures. First, the wisps can be seen to cross each other in many cases. Second, in certain mudstones, such as at locality 163, the wisp structures are profusely developed giving the rock a mottled appearance that very closely resembles the burrowed textures found in other carbonate rocks (Behrens, 1963; Pusey, 1964; Moore and Scruton, 1957).

The origin of the wisps is not considered restricted to any one of the ideas given above, nor are any considered eliminated. However, the burrowing hypothesis is considered to be a definite contributor to the existence of some of the wisps.

The rock types described briefly above can be found at Punta Papayo or at Bahía Fosforescente. Some of the silicified mudstones at Bahía Fosforescente should more properly be considered cherts. They probably should be considered as secondary, but the writer feels a possible argument might be pressed for a primary origin.

In western Parguera area the lower part of the section contains mudstones similar to those with the wisps, except they have no wisps, are faintly laminated, are darker, and
show slightly more coarsely crystalline calcite on the weathered surface. These are the mudstones that grade downwards into the thin upper calcarenite of the Bahía Fosforescente Member. Commonly they show the mottled structures mentioned above. Localities 161 and 163 are illustrative. These rocks form lenses of mudstone within the Bahía Fosforescente Member in certain localities (479, 719).

An altered red to yellow fine-grained mudstone zone occurs in western Parguera where the strike swings around the nose of the Parguera syncline. The beds are porous and partly silicified. This zone is locally traceable laterally, is conformable with the bedding, and seems to be strati-graphically controlled. It is possibly caused indirectly by some primary property in the rock that is slightly different from the surrounding rock.

Higher in the section, wherever preserved, a thin zone of evenly laminated, tan to reddish, thin-bedded cherts appear that are similar to those seen at Bahía Fosforescente. These have a typical exposure at locality 532.

The mudstones with wisps continue upwards in the section, and a calcarenite component, similar to that at the base of the unit, reappears. It is generally not as common as inter-beds as at the base, but it commonly is somewhat more thickly bedded.

Above this is the volcanic conglomerate at the sharp upper contact discussed above.
From east to west the section generally thickens. North of La Parguera the complete section is present and is 850 feet thick. To the west it thickens to 2250 feet (locality 530-545) and then thins somewhat over the synclinal nose to a thickness of 1870 feet.

Although there is certainly some variation laterally within the section, no marked changes were seen other than those described above. Certain lithologies appear in the section, and at the level at which they appear, their characters remain very constant laterally.

**Vertero hills:** At the western end of the Vertero syncline on Cerro Covanas, the Punta Papayo Member shows the interbedding of calcarenite and mudstone similar to the section in the eastern Parguera hills. The mudstone with wisps lies in the center of the syncline. Slightly east of Cerro Covanas, Punta Papayo rocks occur in the float. The next outcrops eastward are patches on the crest of the large hill north of Cerro Vértaro, e.g., at locality 225a.

Near the eastern end of the Vertero hills at locality 485 is another outcrop of the lower Punta Papayo Member. The section here lies upon a volcanic conglomerate with bioclastic limestone lenses. The lower contact is probably sharp. Although not actually exposed here nor on the neighboring knob to the west (locality 387), the contact is restricted to a zone not more than ten feet thick.
Lenses of the non-wispy mudstone occur at locality 478 within the underlying rocks of the Bahía Fosforescente Member. However, similarity of this section with that at Cerro Lajara places the contact above the volcanic conglomerate. Furthermore, at locality 485 the calcarenite-mudstone interbedding is seen. Above this is the foraminiferal mudstone with wisps. In some places (locality 487) the Foraminifera content is so high the rock becomes a foraminiferal sand (Figure 28).

In general no changes in the lithology of the Punta Papayo Member take place eastward in the Vertero hills.

**Ensenada area:** The only exposures of the Punta Papayo Member in the Ensenada area are west of Ensenada on Cerro Lajara and in the low ridge immediately south of the town where G. J. Mitchell first described the Ensenada Shales. The most complete section, although not the best exposed one, is found in north-south traverses across Cerro Lajara.

On the south side of Cerro Lajara on the southward extending nose just south of locality 716, a thin zone of interbedding of calcarenite and mudstone is found and then the foraminiferal mudstones appear. Rarely the mudstones will show minor tuffaceous material within the rock. A lens of volcanic conglomerate is present in the section, and near the fault at localities 713 and 712, the fine-grained material of the mudstone becomes a matrix for a very
Figure 27: Typical foraminiferal Mudstone with Wisps, Punta Papayo Member, Locality 157.

Figure 28: Foraminiferal Mudstone, Punta Papayo Member, Showing Local Concentration of Foraminifera, Locality 487.
tuffaceous sediment. The same sequence is found eastward in other traverses crossing Cerro Lajara.

These same tuffs and conglomerates are exposed within the mudstones on the south side of the low ridge south of Ensenada. To the west along this ridge, the Cretaceous rocks are covered by the gently dipping Middle Tertiary beds.

There is a minimum of 870 feet of section exposed on Cerro Lajara. The volcanic conglomerate is 100 feet thick and appears at 580 feet above the lower contact.

**Insoluble residues:** Insoluble residue data from the Punta Papayo Member is presented in Figures 10 and 11. The total residue and the percentage of residue less than 62μ is presented for samples of the mudstones and the calcarenites. Only total residue data were available for the volcaniclastic-rich beds. The data indicate the following:

1. For the calcarenites both total residue and clay percentage of the residue decrease to the east, i.e., the residue decreases but coarsens eastward.

2. For the mudstones the total residue increases from Sierra Melones to eastern Parguera and then decreases, but the percentage of clay within the residue changes in an opposite manner.

3. The total residue of the rare volcaniclastic units within the mudstones decreases eastward. Although there are no clay data, the insoluble residue probably becomes coarser-grained eastward as suggested by the
presence of the volcanic conglomerates on Cerro Lajara and not elsewhere in the section.

The clay-silt variation in the calcarenite may be explained by a clay-rich supply being introduced from the east and the finer material being moved westward. A like solution may be postulated for the volcanioclastic rocks, although the data for these rocks is not considered as reliable as that for the rest of the section. The cause of the clay distribution shown for the mudstone is uncertain. Possibly a weak, but consistent current swept this area and was periodically swamped by coarser material brought from the east by more competent currents. Thus the sudden increases in grain size as well as different sorting patterns could be superimposed upon the more continuously present conditions.

As discussed under the Bahía Fosforescente Member, some of the variations in the insoluble residues may exist because their source was local and not regional.

Clay mineralogy: The clay mineral data for the Punta Papayo Member is summarized in Figure 12.

The clay suite of this member is very similar to that of the Bahía Fosforescente Member, except that mixed-layer clays are more important and montmorillonite less so. Montmorillonite-illite is the most important mixed layer clay by far.

Concerning the lateral variation in the clay components,
the following suggestions may be made:

1. Chlorite generally decreases eastward, but increases slightly in the Ensenada area in the east.

2. Kaolinite shows an inverse relation to chlorite.

3. Illite and montmorillonite are uncommon and disappear eastward.

4. Mixed-layer clays are important and fairly constant in the west and increase sharply in importance east of Parguera.

Mixed-layer clays are more important in the calcarenites and volcanic conglomerates than in the mudstones, but chlorite is more important in the mudstones. Kaolinite is equally important in the mudstones and the volcanic conglomerates, but it is more important in the calcarenites. Montmorillonite is present in the calcarenites, and illite is important only in the mudstones.

**Paleontology and age**: Macrofauna present in the calcarenite are detrital fragments only, as shown by their sorting. The important fauna for this member are the microfauna, especially the Foraminifera.

The dates given by Pessagno (personal communication) indicate the lower part of the section is Lower to Lowermost Campanian and the upper limit is Upper Campanian - Maestrichtian (Table 4). A range of Lower Campanian to Upper Campanian, possibly Lower Maestrichtian, is considered the most likely range for this unit.
The fauna is indicative of fairly deep water, or rather, of open-ocean waters over the depositional area. The water may have been only shelf depth or, as suggested by the penecontemporaneous slump structures, on a shallow slope. Open-ocean waters may come quite close to islands far from continental masses without being affected by run-off or sediment supply (Phleger, 1960). Possibly a fairly deep (300 feet?) trough existed locally and a tongue of open-ocean water approached quite closely to what is now the center of the island. Thus the planktonic Foraminifera and Radiolaria typical of open-ocean faunas could be deposited in fairly shallow water close to land, and the Punta Papayo Member and the similar Yauco Mudstone to the north could have the aspects of both deep and shallow water deposition.

**Depositional environment:** The sediments and the microfauna indicate slightly deeper basins that permitted open-ocean waters to penetrate close to the island's present-day center. Upon these general conditions were superimposed periodic introductions of coarser material from the east, both of carbonate skeletal material (many times) and volcaniclastic material (rarely). Possibly a period of tectonic and/or volcanic quiescence existed from Lower to Upper Campanian time. The change from the shallow water agitated conditions existing while the Bahía Fosforescente Member was deposited to the quieter water conditions marked
by this deposit was gradational and of short duration. The same seems to be true also of the changes in the upper part of the section.

As in the case of the Bahía Fosforescente Member, the ubiquity of uniform lithologies indicate no major barriers, such as an uplifted Sierra Bermeja block, were effective in restricting the deposition of the Punta Papayo Member in this area.

Unit III: Isla Magueyes Member

The Isla Magueyes Member is named for the exposures of volcanic conglomerate and volcaniclastic limestone exposed on a north-northeast traverse from Isla Magueyes to the south flanks of the hills north of La Parguera. The lower boundary of the member and the nature of its lowermost beds are well exposed at localities 113 and 462 north of La Parguera. Its upper part is well exposed on Isla Magueyes. The above may be considered a type section for the formation; however, its middle portion is covered by alluvium and the town of La Parguera. A reference section showing some of these details is established at localities 546 and 550 in the western Parguera hills.

The type section is typical of the member in the following ways: the lower contact is exposed as a sharp contact overlying the Punta Papayo Member; the basal unit is almost entirely volcaniclastic material with little or no calcite
cement; the upper part of the unit is a gray, coarse-grained, bioclastic limestone with larger Foraminifera and much coarse-grained bioclastic debris; an andesitic flow lies near the top of the section; and the uppermost rocks are nearly pure bioclastic limestones with abundant whole specimens of the rudist *Barrettia monilifera*.

The type section is atypical as follows: the poor exposures of the middle part of the section, the vesicular nature of the flow, the lack of locally important macrofossils such as the sponges found to the west, and the absence of two pyroxenes in the flow (the mafic minerals are entirely altered to opaque minerals in the flow in the type section). The reference section demonstrates the characters of this member not found in the type section.

The lower contact with the underlying Punta Papayo Member is sharp. Although no fragments found in the Isla Magueyes Member could be definitely assigned to the Punta Papayo Member, the variations in thickness of the Punta Papayo Member suggest an erosional contact. The basal bed of the Isla Magueyes Member is generally a non-calcareous poorly sorted volcanic conglomerate. To the west some calcite is present. It is not derived directly from bioclastic material, but rather is secondarily introduced as cement.

The upper contact has been removed by erosion.

The Isla Magueyes Member is exposed only south of the
Parguera hills. It may possibly represent a deposit contemporaneous with and environmentally similar to the tuffaceous part of the Melones Limestone. If so, the local areas were sufficiently restricted to produce slightly different deposits. The ages of the units are the same. However, the units are not equated as one geologic formation.

The exposures of this member occur along the southern base of the Parguera hills as residual remnants plastered onto the mudstones. They also occur as the low rises and small knobs dotting the low coastal plain west of the town. Usually the volcanic flow, or a slightly silicified zone or the upper, pure, massive limestone cap these knobs or rises. East of the type section, the Parguera hills come down to the coast (at Punta Papayo) and only a short narrow strip of low land extends east of La Parguera. The volcanic conglomerates occupy this strip eastward to Punta Papayo.

At locality 462 the basal beds are coarse sands to pebble-sized conglomerates. The presence of clay-sized material indicates the rock is not very well sorted. Calcite is a minor cement. The grains are derived from andesitic material, but no particular type could be discerned. The rock is greenish-tan to reddish-tan, depending on the degree of weathering, the bedding is medium, and individual beds are not always distinct.

Above the basal sandstone and conglomerate is a coarse-to fine-grained bioclastic limestone rich in volcanic cobble-
to clay-sized material (Figure 29). The limestones are gray
to greenish gray. Bedding thickness varies and is somewhat
lenticular and rarely wavy. The mollusk fragments are bored
by algae, possibly *Pithonella* sp. Both types of Foraminifera
and the possible encrusting bryozoan found on one cobble are
not bored. The sponges are hexactinellids. The rudistid
fragments are radiolitids, probably related to *Sauvagesia.*
Commonly much lime mud is present.

Rounded rudist and other mollusk (pelecypod?) fragments,
algae fragments, rounded echinoid plates, whole larger
Foraminifera, encrusting Foraminifera bound to volcanic
fragments, and rare whole sponges in growth position (locality
549) form the bioclastic component of the rock.

The volcanic material is andesite lava and is very well
rounded. There are two types of rock fragments, and both
have their mafic phenocrysts altered to chlorite and opaque
minerals. The first shows fine-grained plagioclase laths and
needles set in brownish altered glass. Commonly the needles
are aligned. The second shows a similar groundmass with
large plagioclase laths as phenocrysts and relict mafic grains
of a larger size than those in the first rock type. The
fine plagioclase needles in the groundmass of the second type
are generally aligned in flow textures.

The content and grain size of the volcanic component of
these limestones decreases upwards in the section, but un-
evenly and with reversals. Thick beds appear rarely within
the rock type. The carbonate component increases in grain size and angularity upwards. Within this volcaniclastic limestone occur the flows of dark gray to black Río Loco type augite-hypersthene andesites described earlier. These volcaniclastic-rich limestones and the associated flows are best exposed in the western Parguera hills, at locality 549 for example and at locality 44 on Isla Magueyes.

Above these flows the volcanic component in the limestone decreases and the uppermost limestones become pure, light gray to white, massive bioclastic limestones with rare volcanic cobbles and sand-sized grains scattered through the rock (Figure 30). Rudist fragments become plentiful and large, and echinoid fragments are abundant. Mollusk fragments, generally pelecypod pieces, are commonly bored by other macrofauna as well as microfauna and flora. Whole Barrettia monilifera are commonly found in the float associated with this unit, and rarely in the outcrop. Algal fragments are common, Archaeolithothamnion sp. being the most abundant and Halimeda-like fragments occurring rarely. The most typical outcrops are found capping the hill on Isla Magueyes (locality 46) and to the west of La Parguera at localities 905, T-3, 198, and 200.

Two variations occur in the section from east to west. First, the basal sandstone or conglomerates are slightly more carbonate-rich with a very minor bioclastic component west
Figure 29: Volcaniclastic-rich Limestone, Isla Magueyes Member, Locality 146c.

Figure 30: Coarse-grained Bioclastic Limestone, Isla Magueyes Member, Locality 905.
of La Parguera. Second, the volcanic flows of Río Loco type lava are not found east of Cerro Parguera. The only flow seen to the east is the vesicular andesite on Isla Magueyes. Its overall composition with regard to groundmass-to-phenocryst and plagioclase phenocryst to total mafic phenocryst compares favorably with similar parameters of the lavas to the west. However, the western lavas are thicker, more resistant to weathering, and not vesicular.

The thickness of the volcaniclastic-rich limestones and volcanic conglomerates, with the included flows, is approximately 1000 feet. This figure is very inexact because the unit occupies the center of the syncline and because its outcrops are generally poor and scattered. This is the existing thickness, as the upper part is not present but eroded away.

**Insoluble residues:** The insoluble residues within the volcaniclastic limestone increase slightly eastward within the Parguera area and the less than 62 µ fraction decreases eastward. Current or wave action, which is more effective to the east, is indicated. Possibly the poor sorting indicates rapid deposition in this area, and the well-rounded fragments indicate reworking elsewhere before final deposition. The insoluble residue decreases markedly upwards in the section.

**Clay mineralogy:** Within the unit, the following
relationships are noted:

1. Chlorite, mixed-layer clays, and kaolinite remain constant, and first two are important constituents while the last is a rare constituent.

2. Illite is important in the volcaniclastic limestone and absent in the bioclastic limestone.

3. Montmorillonite is important in the bioclastic limestone and absent in the volcaniclastic limestone.

4. The important mixed-layer clay in the volcaniclastic limestone is illite-chlorite-montmorillonite, and montmorillonite-illite is important in the bioclastic limestone.

Compared to the lower members of the Parguera Limestone, the clay mineralogy of the Isla Magueyes Member shows the following characteristics:

1. Chlorite is equally important.

2. Kaolinite is much less important.

3. Illite is much more important in the volcaniclastic limestone only.

4. Montmorillonite is much more important in the bioclastic limestone only.

5. Mixed-layer clays are equally important.

Paleontology and age: The most interesting aspect of the fauna is perhaps not its composition, but its persistence throughout the volcaniclastic limestone, as if the volcanic
material were simply superimposed on a normally carbonate-producing, normal marine environment. The fauna of the lower part of the member evidently are those tolerant to the introduction of clastic material, while the upward change in the fauna, especially the introduction of the abundant rudists indicate the change to organisms that flourish in a clastic-free environment. The larger Foraminifera and the whole *Barrettia monilifera* are characteristic of this formation, although they are not necessarily restricted to it. Similar associations of the larger Foraminifera with volcaniclastic limestones were also noted in the Bahía Fosforescente Member.

The ages assigned by Pessagno (personal communication) are uniformly restricted to no older than Upper Campanian and range upwards to Lower Maastrichtian, Maastrichtian or Upper Maastrichtian (Table 4). The volcaniclastic limestones were given a slightly older designation of Upper Campanian to Maastrichtian, probably Upper Campanian (locality 201). The bioclastic limestones were similarly given as slightly younger designation of Upper Campanian to Maastrichtian, probably Maastrichtian. As in the other members of the Parguera Limestone no noticeable time transgression by any unit is present.

**Depositional environment:** The volcaniclastic limestones apparently were deposited with variable and minimal reworking.
The sorting and grain size of the volcaniclastic material varies from bed to bed in the lower part of the section. Possibly much of the material was introduced relatively rapidly after brief uplift and erosion of the upper Punta Papayo Member. This uplift, the introduction of volcanic material, and the andesitic flows may indicate a brief renewal of volcanic activity in the surrounding area, or the peak activity of such a renewal. Possibly the direction of the source has an easterly component.

The fauna, the spar cement, and very coarse-grained nature of the bioclastic grains and the absence of clay indicate that a shallow-water, wave-agitated, normal marine, carbonate-producing environment existed during the deposition of the upper bioclastic limestone.

An effective barrier possibly existed between the Sierra Melones and the Parguera areas during the time of deposition of the Isla Magueyes Member and the Melones Limestones. These units are slightly different in lithology (Figure 31), but are similar in age and similarly indicate a period of renewed volcanic activity. The barrier may be only distance from the source or current directions. More likely the emplacement of the Sierra Bermeja block between the two areas brought about the brief period of erosion of the Punta Papayo Member and formed the sedimentary barrier between Sierra Melones and Parguera in Isla Magueyes time.
Figure 31: Dark Argillaceous Limestone, Melones Limestone, Locality 761e.
Correlation With Nearby Areas

Each of the members has certain of its various lithologies present elsewhere in the Yauco and Mayagüez areas. Where the discussion of the unit has revealed certain possible correlations elsewhere that may affect the stratigraphic interpretation as now understood, a brief description of these points is presented. No revision of the existing stratigraphy in these areas is intended, nor can it be made without detailed field work. Areas of future study are merely pointed out. The discussion is presented in stratigraphic order by units, beginning with the basal Parguera unit.

Bahía Fosforescente Member: The rocks of these areas are briefly considered: Hormigueros syncline north of the Valle de Guanajibo, the major area of outcrop of the San Germán Formation south of Valle de Guanajibo, and the Susúa basin on the north side of the Valle de Lajas.

A large area of outcrop of the Parguera Limestone occupies the center of the Hormigueros syncline (Mattson, 1960, p. 334; pl. I). The section outlined by Mattson (1960, p. 334; 1957, p. 76) generally is similar to that in the Parguera area. Mudstones (calcilutites of Mattson) are found above massive glauconitic bioclastic limestones similar to the Bahía Fosforescente Member. In turn, volcaniclastic rocks occur above the mudstones. These features are pointed
out to indicate the relatively consistent nature of the members of the Parguera Limestone. Furthermore, the age range for the Parguera Limestones in the Hormigueros syncline is Campanian to Lower Maestrichtian; thus little or no time transgression is indicated for the Parguera Limestone south of the Cordillera Central. Conditions controlling deposition of the carbonate component of the Parguera Limestone must have been regional in extent and must have varied simultaneously. The lack of carbonate rock in some unit of the same age therefore becomes a matter of non-carbonate clastic flooding primarily.

The Brujo Limestone and its underlying volcanic rocks match the gray limestone facies and the underlying volcanic rocks of the Ensenada area, according to descriptions by Mattson (1960, p. 337). Likewise some samples of the Cotui Limestone and the underlying rocks are very much like the gray limestone facies and corresponding volcanic rocks north of Ensenada. Mattson correlates the Brujo with the basal Parguera and says that the underlying volcanic rocks (Sabana Grande Andesite) are indistinguishable from those of the San Germán Formation in the area south of the Valle de Guanajibo.

The rudist fauna of the Cotui Limestone is similar to that of the Parguera area, and dates from the Cotui Limestone give a range Campanian to Maestrichtian. Two dates from the Cotui Limestone give Upper Maestrichtian dates, one is
from the Yauco area (PR814) and the other is from the Rosario allochthonous block (Mattson, 1960, Pl. VI, pp. 343-344).

Some parts of the Cotui Limestone may prove to be equivalent to the lower Parguera Limestone and some of the Parguera slide blocks may actually be in place above the massive limestones. Detailed work, first within the San Germán Formation itself, and second in comparing the various units involved, must be carried out before such a suggestion may have any validity at all. Mattson (1960, pp. 340-344 and pp. 354-356) develops very strong arguments for his interpretation. Only the striking similarity between certain Cotui Limestone outcrops (Road 314, sample 707a-d) and those in the Cerro de Abra north of Ensenada has prompted the questioning of Mattson's interpretation for parts of the San Germán Formation.

North of Susúa in the high hills at Cerro La Torre, are gray bioclastic limestones containing calcite cemented, partly bioclastic volcanic conglomerates with rounded cobble-to boulder-sized fragments. These volcanic conglomerates are interbedded with coarse-grained limestones and limestone conglomerates. Thin beds of foraminiferal mudstones, some with the internal structures like the mudstones of the Punta Papayo Member are associated with the coarser-grained rocks. These beds have been correlated with the Parguera Limestone by Mattson (1957, p. 124) and the writer agrees. The determination of their precise stratigraphic position
will require some detailed work. One other feature about this outcrop is that the Parguera beds overlie the Sabana Grande Formation of Slodowski by deposition.

South of Susúa the tan calcarenite with large gastropods, the glauconitic horizon, and the gray limestone facies of the Bahía Fosforescente Member of the Parguera Limestone crop out above the Ensenada volcanic rocks of Slodowski. These volcanic rocks possibly correlate with one of the Sabana Grande rock types.

Above these limestones of the basal Parguera Limestones lie the mudstones typical of the lower part of the Punta Papayo Member. As in Cerro Lajara to the south, these mudstones are overlain or interbedded with a volcanic conglomerate. The conglomerate is similar to that at Cerro La Torre to the north, but much thinner.

Deposition of the lower Parguera Limestones close to the volcanic center would provide a possible environmental interpretation. The structural interpretation may again consists of upthrown blocks tilted southward.

Again it must be stressed that, although the writer visited the areas, detailed field work is essential to proving any of the above suggestions. The alterations of the Susúa correlations were prompted by similar lithologies in Slodowski's "Upper Ensenada Limestones" at Susúa and the basal Parguera rocks at Ensenada.
Punta Papayo Member: Occurrences of mudstones similar to the Punta Papayo Member that are associated with rocks like the Bahía Fosforescente Member have been pointed out in the previous section. Two other possible correlations should be mentioned: first, the mudstones of Punta Papayo may be a more calcareous facies of the Yauco Mudstone extending southward (noted by Mattson and others); second, the calcarenite found near the upper part of the Punta Papayo Member and the basal gray massive limestone of the Melones Limestone may be correlative. This correlation has been mentioned in the discussion of the Punta Papayo Member and the Isla Magueyes Member.

The similarities between the Yauco Mudstones and the mudstones of the Punta Papayo Member are the following:

1. The age of the Yauco Mudstone encompasses that of the Punta Papayo Member (Yauco ranges from Turonian to Maestrichtian; Mattson, 1960, p. 332; Slodowski, 1957, p. 76).

2. The mudstones of both units have a large content of planktonic Foraminifera.

3. The wisps characteristic of certain beds in both units were described by Mattson for the Yauco (1957, p. 44).

4. Both units show evenly bedded and thin- to medium-bedded mudstones.

5. Both have some silicified mudstones.

6. Both contain beds of volcanic tuff or conglomerate.
7. Both have a high clay content. The dissimilarities of the mudstones in each unit are as follows:

1. The Yauco Mudstones are commonly slightly coarser grained or less well sorted.

2. The Yauco contains a considerably greater amount of bedded tuff and conglomerate. The Punta Papayo volcaniclastic beds are well developed only at Ensenada.

3. The Yauco Mudstones contain little or no carbonate, while the Punta Papayo mudstones have an overall average of forty-six per cent insoluble material, most of which is clay. However, many beds of the Punta Papayo Member, not silicified, contain over eighty per cent insoluble material.

The most serious objection to any direct correlation of these not entirely similar lithologies is the great gap in the outcrop caused by the wide alluvially filled Valle de Lajas.

The probability that the Punta Papayo Member represents a southward extension of Yauco-type deposition and sedimentary conditions during middle Campanian time should be given more thought because of its importance in paleogeographic considerations.

The massive, light gray limestones beneath the tuffaceous rocks of the Melones Limestone in the Sierra Melones was
considered by Mattson (1960, p. 335) to be the basal unit of the Melones Limestone. He described the lowest part of the unit as a "massive or thick-bedded dark argillaceous limestone" (ibid.) or as a "massive or wavy-bedded limestone" (ibid, p. 336). This limestone in the Sierra Melones, on the south side, is neither dark nor argillaceous but it is the massive limestone of which Mattson is speaking according to his map (1960, Pl. I).

The importance of considering the position of the limestone lies in reconstructing the history of the area. The whole algal balls of Archaeolithothamnion sp. and the coarse, bioclastic nature of the limestone indicate shallow water, possibly wave-agitated marine conditions. Above this light gray limestone, the bioclastic limestones show a sharp and considerable gain in volcaniclastic components ranging in grain size from clay to pebbles or rarely cobbles. The insoluble residue changed from two per cent for the massive gray limestone to forty-four per cent for the volcaniclastic limestone. Possibly this change occurred at the same time as the similar change in character between the Punta Papayo Member and the Isla Magueyes Member in the Parguera area.

The mudstones directly beneath the massive limestone give a date of Upper Campanian - Lower Maestrichtian (locality 756a), and the immediately overlying tuffaceous
bioclastic Melones Limestone gives a date of Campanian - Lower Maestrichtian (locality 791a; Pessagno, personal communication). The limestone has the same age as the contact between the volcaniclastic and mudstone - calcarenite units in the Parguera area.

Mattson reported only minor reworking of the Parguera rocks near the Melones - Parguera contact in the Sierra Melones (1960, p. 337). The only evidence of erosion seen by the writer were cobbles of fine-grained laminated silicified mudstone in the volcaniclastic rocks that are definitely Melones Limestone and that lie above the massive limestone. The lenticularity of the massive limestone may represent erosion through the massive limestone into the mudstone.

The fauna of the volcaniclastic limestones of the Melones Limestone differ from those of the Isla Magueyes Member, possibly because of differences of environment. The algae and fauna of the massive, light gray limestone are the same, but occur in different proportions than the calcarenites of the Punta Papayo Member. However, the calcarenites are generally somewhat finer grained and better sorted than those of the massive limestone.

The writer suggests that the massive gray limestone forming the southern ridge of the Sierra Melones may possibly belong to the underlying Parguera Limestone and that it marks a shallowing of the sea similar to that seen in the
Punta Papayo Member in the Parguera area. Also possibly the Melones Limestone begins above this massive limestone and marks a change of conditions similar to that indicated by the Isla Magueyes Member of the Parguera Limestone in the Parguera area. The evidence is not considered strong enough to warrant a formal change, but such a change should be investigated further.

**Isla Magueyes Member:** The major correlation problem is the question of the time equivalence of the environmental implications of this unit and of the Melones Limestone in the Sierra Melones. This has been discussed above.

A similar problem is the extension of this question of time equivalence northward to the volcanic conglomerates associated with the Parguera Limestones in the center of the Hormigueros syncline and in the Susúa basin. The significance of the El Rayo Volcanic Rocks and the Melones Limestone lenses in the Tea syncline (Mattson, 1960, pp. 336, 339) may be related to this same problem. Specifically the contemporaneity or the possible transgression of the volcaniclastic limestones over the mudstones of the Parguera Limestone or their equivalents should be determined. Also the reasons for differences in the lithology of the volcaniclastic and bioclastic limestones should be determined. No evidence for discussion of these problems was obtained by the writer, rather these studies were considered to be separate problems for later study.
Summary of the Stratigraphic Succession

The Parguera Limestone on the south coast of western Puerto Rico is divisible into three major units: a basal well-sorted, carbonate and non-carbonate clastic sandstone containing a thick, bioclastic limestone to the east; a middle sequence of mudstones; and an upper coarse, volcaniclastic limestone. The Parguera Limestone represents a normal marine environment throughout its section. The lower and upper units represent shallow water and/or near-shore deposition, the mudstones represent deeper water or isolation from a terrigenous clastic source, except for some clay.

The basal unit is the Bahía Fosforescente Member, named for its type locality at Bahía Fosforescente. It consists of a tan calcarenite with an important non-carbonate clastic component at the base that decreases upwards. Glaucontite appears in the section and increases upwards, commonly being concentrated in a glauconite marker bed near the top. The basal contact is sharp, the upper one is gradational, with the contact drawn at the first mudstone interbed. The gray limestone facies of this unit occurs near the base of the member only in the eastern half of the area of outcrop of the member. This limestone is very coarse-grained, bioclastic, somewhat lenticular, and pure carbonate.

The Punta Papayo Member is distinguished by its medium-
bedded, very fine-grained, foraminiferal mudstones. These rocks may or may not be laminated, and the laminae are regular or locally irregular, because of burrowing. These mudstones are interbedded with medium-grained to fine-grained calcarenites, especially near the upper and lower boundaries of the unit. There is little lateral change in the unit except for an increase in volcanic material eastward. The mudstone fauna indicates an invasion of open-ocean water over the Parguera area which probably was caused by a cessation in volcanic activity and a deepening of the Parguera basin along the vertical faults.

The Isla Magueyes Member is a poorly sorted volcanioclastic limestone that grades upwards into a very coarse-grained, well-sorted, bioclastic limestone. The Isla Magueyes Member lies with probable erosional contact upon the Punta Papayo Member. The volcanioclastic portion of the Isla Magueyes Member may be equivalent to the Melones Limestone chronologically. The two may also represent similar environments in separated areas as indicated by the volcanic debris, the larger Foraminifera, the coarse-grained bioclastic material, and the poor sorting in both. The upper bioclastic limestone was deposited in shallow, wave-agitated, marine waters. It contains rare volcanic cobbles and whole *Barrettia monilifera*. 
The whole Parguera Limestone is Campanian, possibly Santonian, to Maestrichtian in age. The Bahía Fosforescente Member is Lower or Lowermost Campanian or possibly Santonian; the Punta Papayo Member is Lower or Lowermost Campanian to Upper Campanian; and the Isla Magueyes Member is Upper Campanian to Maestrichtian.

Lithologic changes in the unit and insoluble residue data indicate a source with an easterly component to its direction from Parguera. This source is a primarily volcanic source, and a source of variable supply and tectonic activity. An alternative or an additional local source for this material may have existed along the axis of the Salinas Fortuna anticline if it were a positive element during Parguera time.
PALEOGEOGRAPHY

Paleogeographic hypotheses derived from a study of the area considered in this report are restricted by two factors: the limits of the basins of deposition lie outside of the area of study for all units, and the east-west belt of outcrop provides only east-west components to any directional features. The paleogeography of this area has three gross features. First, the Sierra Bermeja has had some effect as a positive area throughout Parguera deposition, and has acted as a restrictive barrier during the deposition of the upper Parguera beds. Second, variable influx of non-carbonate clastic material has been superimposed upon a consistently carbonate-producing environment. Third, vertical tectonic movements have affected both source areas and the depositional basin.

Local Paleogeography

Pre-Parguera Surface

The pre-Parguera surface has been described. Its main features consist of a somewhat uneven surface sloping to the east and west away from a low positive area in the area of the Sierra Bermeja. The surface is an erosion surface which represents a successively smaller time interval eastward from the Parguera-Vertero area to Ensenada. The basal Parguera laid down on this surface locally includes
fragments of the various rock types present at any one locality. Probably the Sierra Melones area was separated from the Parguera area by the positive Sierra Bermeja block, but this positive element did not restrict the environmental conditions of sedimentation.

Bahía Fosforescente Member

A broad area existed where bioclastic material could be sufficiently reworked to produce a well-sorted, well-rounded carbonate sand. Glaucine in the upper portions indicates carbonate deposition was slow. Upon this general "background environment," two conditions were imposed. One was a general introduction of non-carbonate clastic material whose rate of introduction decreased upwards. The other was the development of rudist banks in the eastern half of the area.

These banks are represented by the gray, very coarse-grained, massive, bioclastic limestones best developed north of Ensenada. Whether the banks are true organic reefs in that they could maintain themselves against wave action or near the water surface is unknown. Their shape is unknown also, except they have a strong east-west component and they are somewhat lenticular. Their extent is limited northward to a maximum of the north side of the Valle de Lajas by their absence in the Susúa basin.

On the basis of insoluble residue data, an east to west
component for current movement and an easterly direction for the source of non-carbonate clastic material (local or regional) is indicated. The effect of the gray limestone facies on the distribution of sediments is unknown. It may have acted as a barrier to restrict the introduction of material from the north or east.

In the western half of the area sedimentary conditions were not affected by any barriers as indicated by the uniformity of lithologic succession in this area. Possibly there was a small hill north of Punta Melones, as indicated by the westward pinchout of the conglomerate underneath the Parguera Limestone and the westward thinning of the section.

**Punta Papayo Member**

A gradual deepening of the local basin was accompanied by a continuous decrease in non-carbonate clastic supply. The source of the non-carbonate material had an easterly component as indicated by the coarser-grained volcanic tuffs and conglomerates introduced into the mudstones at Ensenada.

The fauna indicate that open-ocean waters invaded the area. Rarely to commonly mudstone deposition was interrupted by the introduction of well-sorted calcarenite. The fauna of the calcarenite are somewhat shallower water forms. This open-ocean influx or initiation of deeper water conditions was possibly permitted by gradual downward movement of the area as a large fault block. Also volcanic activity may have
ceased and the terrigenous source areas become low-lying. Deepening is indicated by the lack of wave or current action affecting the sediments. Sedimentation on or near a slope is indicated by the great amount of penecontemporaneous slump seen in the sedimentary section. Strong currents possibly periodically brought in the calcarenites from the east while continuous weak current activity was centered in the central part of the area. The possible correlation of the Punta Papayo Mudstones with part of the Yauco Mudstones indicate that the invasion of open-ocean conditions was widespread in the Mayagüez and Yauco areas during the Lower to Upper Campanian. No evidence for restrictions between localities within the area was noted.

**Isla Magueyes Member**

Uplift and minor erosion occur just prior to deposition of this unit. The Sierra Bermeja seems to have been a restrictive influence during this time of deposition by isolating the Sierra Melones from the Parguera area. Deposition may have been rapid or current action poor in the areas of deposition as indicated by the poorly sorted sediments. However, areas of shallow, well-agitated water are indicated by the upper part of this unit. Possibly rudistid banks or reefs existed on a shallow platform throughout the area.
Paleogeography Related to Nearby Areas

Mattson (1960, p. 356) believed the Parguera area to be a shallow shelf area south of an area that received the great amount of volcanic material that forms the bulk of the Mayagüez Group. Such an area would indeed act as a trap for the volcanic material and prevent its reaching the Parguera area, providing the direction of the source of volcanic material had a northerly component with respect to the Parguera area, as well as easterly component demonstrated within the area. The easterly component could have been locally superimposed on a regional northern direction of supply.

The northerly component to a direction of volcaniclastic supply is indicated in one instance by the southward decrease in cobble size and bedding thickness for the volcanic conglomerates found at Cerro La Torre, Susúa, and Cerro Lajara.

According to Mattson (1960, p. 356) the Cordillera Central, in the northern part of the Mayagüez area, did not interrupt or restrict sedimentation in western Puerto Rico until Middle Campanian time. After that time the area to the north of the Cordillera Central seems to have developed independently of the area to the south. Throughout the time both before and after the introduction of the Cordillera Central as a barrier, the Parguera area was carbonate-producing while the more northerly areas were being flooded with clastic material.
The outcrops at Susúa and in the Hormigueros syncline indicate shallow areas of carbonate deposition must have existed in a manner similar to those at Parguera and at a similar time. In each area the lithologic changes occur in the same sequence and have the same age.

The presence of the Parguera Limestones to the north indicates that certain areas north of Parguera must also have been shallow carbonate-producing banks not flooded by volcanic debris. The Parguera depositional regime certainly did not extend over the whole area at any one time nor did it occur in different places at different times. Rather it was deposited concomitantly with the rocks of the Yauco Mudstone and with the Sabana Grande Andesite to a lesser degree.

Probably the Parguera area represents a large positive block with a possible northern boundary suggested by the Valle de Lajas. Smaller upthrown blocks might have occurred in a generally slightly down-dropped area to the north. These upthrown blocks could provide suitable platforms for carbonate development. Their relative height above a basin floor and their distance from the source of volcanic material would determine the times and amounts of influx of such material.

In the slightly deeper areas, open-ocean waters could introduce their typical faunas into fine-grained mudstones
as found in the Yauco Mudstone. This deposition would be
interrupted by sudden periodic introduction of volcanic
debris. This material would only rarely invade the areas
of Parguera deposition because of their slightly higher
position.

In the Lower Campanian, a regional change provided
conditions favorable for the invasion of open-ocean waters
over most of the area and the deposition of the resulting
mudstones. Coarser material was still periodically intro-
duced, but the areas of shallow-shelf carbonate deposition
were reduced in size and number or eliminated. This change
was gradual and its subsequent reversal, indicated by the
emergence of much of the region, especially former bank
areas like the Parguera area, was also gradual.

Possible widespread, short-lived, subaerial exposure
took place in the Upper Campanian to Lower Maestrichtian
time. It was followed by local shallow submergence and
renewed igneous and tectonic activity.

The undefined source area, mentioned above, probably
was not just one great land mass, but several small land
masses associated with volcanoes or volcanic centers.
Meyerhoff (1933, p. 50) shows a major center of volcanic
activity occupying the eastern half of Puerto Rico and a
minor one northeast of the Parguera area in the Utuado-
Adjuntas area during the Upper Cretaceous. Mattson (1960,
p. 356) suggests even closer local sources, one possibly
concealed under the San Germán deposits south of the Valle de Guanajibo. Probably local fissures and vents supplied much of the material.

Many of these local vents need not have been land areas, but sites of submarine extrusion. Such extrusion not only can produce volcanic flows, but graded pyroclastic material as well. The work of Fiske and Matsuda (1964) in Japan may show a situation analogous to some of the volcanic deposits within the Yauco Mudstone. In their study, Fiske and Matsuda suggested that submarine pyroclastic extrusions developed a primary grading in the resulting deposits by differential settling through sea water. A secondary grading was provided by turbidity current deposition from overloaded slopes developed immediately after eruption during the period of settling. Thus a coarse fraction, settling first, was regraded by a turbidity current, and a later finer-grained deposit was similarly moved to give a sequence of internally graded beds that among themselves also were graded finer upwards. Between the pyroclastic deposits were mudstones similar to those in the Yauco. However, their rocks were dacites and thus more siliceous than the andesites of this area.

The carbonate material of the shallower bank areas was produced within these areas as primarily skeletal debris by organic activity. Inorganic precipitation of carbonate
material was very minor and only locally and rarely important (coated grains, for example).

The sources of the volcanicleastic debris were probably local and ephemeral. The material was possibly supplied by mud flows in many cases. However, the well-rounded nature of the grains in some of the deposits indicate reworking by waves or currents possibly before final deposition. That is, a briefly stable area or shoreline must have been available some of the time in some areas.

All these events - deposition, erosion, structural movement - took place within the east-west zone of development of the Caribbean island arc. The general outline of today's geography was probably present in Upper Cretaceous time: Caribbean deep-sea areas to the south, the upraised welt of the island arc through present-day Puerto Rico, and the Atlantic Ocean basins to the north and east.

The development of the island arc has been discussed by many. The recent synthesis by Donnelly (1964) has been suggested previously as a model. Its emphasis on vertical movements within the developing arc supplies, in the upper crustal rocks, a rationale for the locally continuous, regionally patchy, but similar, development of the rocks of the Parguera Limestone. Differential vertical movement would provide blocks of slightly different relief on which sedimentary depositions of different types could develop
contemporaneously and adjacently. The Parguera deposits were developed on the generally shallow upraised blocks that acted as carbonate banks, while the slightly deeper basins received the volcanic material and mudstones of the Yauco deposits. The Parguera block seems to have represented an extensive positive element.

Summary

Within the Parguera area, current movement was from east to west and non-carbonate clastic material was introduced from the east. The Sierra Bermeja was the most positive part of a generally positive area and was a restrictive influence on sedimentation in Sierra Melones during Upper Campanian - Lower Maestrichtian time.

Regionally, oceanographic conditions were proper for skeletal carbonate deposition, and locally shallow areas for such deposition were provided by differential vertical movement. One of the larger shallow areas is the Parguera area. The carbonate deposition developing in the interbank areas was overwhelmed by the introduction of volcaniclastic debris. The volcanic source lay northward and eastward from Parguera, or possibly it was partially local. Regional vertical movement restricted or enlarged the general deposition of Yauco Mudstone. Local movement controlled variations within any one block.

For Campanian - Maestrichtian time, the great geographic
regions were distributed similarly to their present-day distribution and their nature - shallow or deep, linear or otherwise - has likewise been constant.
CONCLUSIONS

The following conclusions are made from a detailed study of the Parguera Limestone of southwest Puerto Rico:

1. The pre-Parguera surface is erosional and cuts across the underlying rock units, including Sabana Grande Andesite, Río Loco Formation and the Bermeja Complex. The Sabana Grande Andesite not only underlies the Parguera Limestone but is deposited contemporaneously with it to the north.

2. The Parguera Limestone is divisible into three sedimentary members: the well-sorted glauconitic calcarenites of the Bahía Posforescente Member; the calcareous foraminiferal mudstones of the Punta Papayo Member; and the coarse-grained, volcaniclastic, bioclastic limestones of the Isla Magueyes Member.

3. The Parguera Limestone was deposited entirely under normal marine conditions. Its members represent respectively shallow water with bank and possible reef deposits to the east, open-ocean deeper water deposits, and shallow water, near-shore deposits that become more reef-like upwards.

4. In the Parguera area, non-carbonate clastic sediment was generally supplied from the east, but this represents a directional component locally superimposed upon the regional northerly to northeasterly direction
of supply. In many cases, local vents were the source, but most of these also lay north of the Parguera area.

5. The Sierra Bermeja represents the most positive structural element in the Parguera area, and it became a barrier to sedimentation in the Upper Campanian - Lower Maestrichtian time.

6. Detailed study shows the Parguera Limestone is neither overturned nor overthrust as formerly believed, but it is either faulted along nearly vertical faults and tilted generally southward or is folded into open asymmetrical folds steeper on the southern anticlinal limb. Such folding possibly may have been formed by the sediments being draped over vertically shifted basement blocks.

7. The Parguera area was a positive area that had carbonate shelf deposits forming on it. Other areas of Parguera deposition also mark relatively positive carbonate shelf areas around which the mudstones and volcanic rocks of the Mayagüez Group, chiefly the Yauco Mudstone and Sabana Grande Andesite, were deposited.

8. Differential movement on vertical fractures permitted carbonate deposits to develop locally in an area generally receiving great amounts of clastic material. Such movement could take place locally, as in the Parguera, or regionally, as during the deposition of the Punta Papayo - Yauco Mudstones.
Tectonic isolation by vertical faulting permitted the semi-independent geologic development of different areas; and the "intra-block" persistence of stratigraphic units, the mild structural deformation, and the thick limestone sequences characteristic of the Parguera unit were able to develop contemporaneously with the great volcanic sequences found elsewhere in Puerto Rico.
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APPENDIX A: DESCRIPTIONS OF REPRESENTATIVE VOLCANIC ROCKS

Modal analyses for these rocks are presented in Tables 1 and 2.

Sample T-5: Augite-hypersthene andesite porphyry (Figure 7).

On fresh surface the rock shows black, glassy to aphanitic groundmass with fine- to medium-grained clear plagioclase phenocrysts barely visible. Matrix weathers brown to show both plagioclase and slightly smaller pyroxene phenocrysts. Faint phenocryst alignment visible.

Groundmass consists of dark, faintly brownish-red devitrified glass containing flow-aligned plagioclase needles, equant subhedral opaque (ore) minerals, and minor fine-grained pyroxene needles.

Phenocrysts are the following: Plagioclase as 1) fresh, twinned laths (3 mm.) with slightly rounded to angular corners and 2) commonly twinned and zoned nearly equant grains with opaque inclusions in the grain interiors and secondary rims or resorption features on the grain margins. Clinopyroxene (augite) is present in fresh twinned equant grains (2 mm.) and laths commonly in glomerocrysts, and it commonly is intergrown, but not necessarily reacting with, plagioclase, opaque minerals and orthopyroxene. Orthopyroxene (hypersthene - parallel extinction and pleochroism) occurs as fresh equant grains (1 mm.), shows rounded corners and minor resorption,
and rarely has a clinopyroxene rim or replacement. Opaque minerals occur as medium-grained equant embedded grains. Flow structure is present.

Sample 217: Augite andesite porphyry (Figure 8).

Fresh surface shows dark blue-gray aphanitic groundmass of altered glass with coarse-grained plagioclase phenocrysts and small pyroxene phenocrysts. Weathers brown.

Groundmass is altered to fine-grained chlorite, calcite, hematite, and low birefringent material. Altered plagioclase needles are somewhat aligned.

Plagioclase occurs as zoned and rimmed equant grains and zoned and twinned laths (5 mm.), all somewhat resorbed. Certain zones are altered or show inclusions of calcite and chlorite, others are only slightly altered. Equant grains are more altered than laths. Pyroxene is clino- pyroxene (2 mm.), probably augite, with two generations possibly indicated. Some pyroxene is fresh, most is altered to calcite, chlorite, and opaque grains. Some apparently primary opaque grains also form phenocrysts. Minor flow structure is present.

Sample 432: Augite-hornblende andesite porphyry (Figure 9).

Dark gray aphanitic groundmass with coarse-grained plagioclase and hornblende(?). Possible flow structure. Short, stubby pyroxene grains. Weathers gray to dark brown
and the phenocrysts stand out on the surface.

Groundmass consists of glass altered to a low birefringent material; plagioclase needles and minor very fine grained pyroxene and opaque minerals are contained in the groundmass.

Plagioclase in large laths (5-10 mm.) and equant grains both twinned and zoned, commonly occurring in glomerocrysts. Plagioclase shows seriate texture. Pyroxene is clinopyroxene (augite), occurring in equant grains and laths (2 mm.). Hornblende is nearly completely altered to plagioclase, calcite, opaque minerals, limonite, biotite and possible chlorite. Grain shape in cross-section and rare remnant hornblende in grain centers are the basis for the identification. Hornblende grains occur as large laths 5-10 mm. in size. Quartz occurs as rounded, resorbed grains and probably is xenolithic, possibly Bermeja chert(?). Rare volcanic xenoliths of similar andesite rock also occur. Minor flow alignment, especially in groundmass needles.
APPENDIX B: DESCRIPTIONS OF REPRESENTATIVE PARGUERA ROCKS

Modal analyses for these rocks are given in Table 3.

Sample 577: Tan calcarenite, Bahía Fosforescente Member
(Figure 17).

Massive- or thick-bedded, changing to medium-bedded, tan, medium-grained, well-sorted bioclastic calcarenite rich in volcaniclastic sand. Glaucónite increase upwards. Commonly the medium beds are interbedded with soft marls. Rare pelecypod pieces, algae, or coral form large grains in the rock.

Matrix is spar cement binding the well-rounded, sand-sized, bioclastic and volcaniclastic grains. Biserial and coiled Foraminifera, echinoid plates, fragments of Archaeolithothamnion, mollusk fragments (rare definitely pelecypod pieces), rare ostracods, ovoid cryptocrystalline fecal pellets, common aggregate grains and volcanic fragments (andesite) or volcanic minerals form the rock. Hematite, limonite and opaque (ore) minerals generally are secondary (weathering). Insoluble residues (31%) contain feldspar, glauconite casts of Foraminifera and small gastropods, pellets, pyroxene(?), quartz, biotite, weathered volcanic grains, sponge spicules.
Sample 133: Gray limestone facies, Bahía Fosforescente Member (Figure 19; see also Figures 22, 23, 24).

Thick- to massive-bedded, very coarse-grained, poorly sorted light gray limestone. Weathered surface is fluted and shows thin zones of silicification especially around fossils. Whole rudists found to east, Durania, Barrettia fragments found here. Lenticular at this locality, much thicker eastward. Rare glauconite and sand-sized volcanoclastic grains. Algae are rare at this locality, common near the base elsewhere.

Matrix is spar cement, except in grain shadows or in algal traps. Large rudistid fragments (radiolitid and possibly caprinid), rare biserial or coiled Foraminifera, echinoid plates, rare rounded glauconite, and mollusk(?) fragments form the rock. Algae are commonly present both as fragments and as possible grain coatings or borings. Fragments rounded and poorly sorted. To the east (e.g., locality 885a, Figure 24), the rock is coarser grained and fragments are angular. Insoluble residue (3%) shows double-ended quartz crystals, glauconite, limonite flakes, rare rounded feldspar and quartz grains, rare volcanic sand grains.

Sample 433c: Glauconitic zone, Bahía Fosforescente Member (Figure 18).

Dark gray-brown to dark red-brown, medium-bedded, fine-
to medium-grained, glauconitic, bioclastic limestone rich in non-carbonate clastic grains. Dark green, coarse-grained (5 mm. or more) glauconite grains are abundant. Thin marly partings occur between beds. The zone is less than 10 feet thick and contains 1 to 5 beds.

Matrix is spar with minor clay and iron oxide stain. Lithoclasts of fine-grained bioclastic limestone and porphyritic andesite, plagioclase, rare chert, glauconite, aggregate grains, coated grains, benthonic and possibly planktonic Foraminifera, echinoid plates, rare radiolitid rudists, mollusk fragments, algal fragments form the rock. The volcaniclastic grains show alteration to chlorite and calcite. Carbonate grains are recrystallized to spar (skeletal) or cryptocrystalline calcite (aggregate grains, Foraminifera). Other examples of this horizon contain much more glauconite than this sample, but they are more recrystallized. Insoluble residue (35%) showed large globular glauconite grains, minor foraminiferal casts, fecal pellets.

**Sample 137**: Upper calcarenite, Bahía Fosforescente Member (Figure 20).

Medium-bedded, light gray to light tan, well-sorted, slightly glauconitic calcarenite occurs above the glauconitic zone and below the mudstone of Punta Papayo Member. Matrix is spar cement.
Unidentifiable recrystallized skeletal grains that are coated with one or two layers of cryptocrystalline calcite and some grains showing alteration of their edges within the original grain outline form most of the rock. All are rounded. Echinoid plates and spines, mollusk fragments, rare Foraminifera, and rare algal grains are identifiable. Glaucobonite is in rounded grains. Minor silicification and rare opaque minerals are present. Insoluble residue (10%) shows glauconite, rare rounded quartz, rare rounded feldspar, rare mica.

Sample 591: Calcarenite, Punta Papayo Member (Figure 25).

Thin- to medium-beded medium- to coarse-grained, light gray, bioclastic limestone is interbedded with fine-grained thin- to medium-beded mudstones. Grains are more angular than in sample 137 and there is only very rare glauconite. Contacts between the mudstone and calcarenite are somewhat irregular. Thin lenses and stringers of mudstone occur within the calcarenite.

Matrix is generally spar with mud in the grain shadows. Mollusk fragments and echinoid plates form the bulk of the rock; they are angular and commonly aligned or even imbricated. Lithoclasts of limestone and rarely of volcanic rock, Foraminifera, and rare sponge material are other grain types present. Skeletal grains commonly show thin
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carings or rinds. Rock recrystallized and rarely silicified
to a minor extent. Insoluble residue (12%) shows rare
glaucnite, rare quartz, rare feldspar, and spicules.

Sample 157: Foraminiferal mudstone, Punta Papayo Member
(Figure 27).

Medium-bedded, evenly bedded, very fine-grained, blue-gray
to cream colored mudstone showing wisp structures on
the fresh surface. The rock weathers into angular blocks
formed on closely spaced joint planes, and it breaks with
conchoidal fracture.

Matrix is cryptocrystalline calcite and clay showing
faint laminations in wisp areas. Laminations and wisps are
areas that show variation in iron oxide content and grain
content (either more or less) relative to the surrounding
matrix. These areas are barely differentiable in thin-section
and show no distinct structure. Planktonic Foraminifera,
radiolaria, sponge spicules, echinoid spines, secondary
opaque grains form the grain constituents. The rock is mud
supported as opposed to the grain supported types described
above. Insoluble residues (34%) show considerable clay,
sponge spicules, alcyonarian spicules, rare foraminiferal
casts, radiolarians.
Sample 146c: Volcaniclastic, bioclastic limestone, Isla Magueyes Member (Figure 29).

Medium- to thick-bedded coarse-grained gray to greenish gray volcaniclastic-rich limestone. Well-rounded cobble- to sand-sized grains of andesite are mixed with large Foraminifera and mollusk fragments and are bound by calcite cement. Rare sponges are seen in growth position at locality 549 to the northeast. Rock is poorly sorted.

Matrix is cryptocrystalline calcite and clay and spar cement. Various volcaniclastic grains are mixed with radiolitid rudists, mollusk fragments, echinoid plates, algal fragments (Solenopora?), sponge spicules, whole sponges, aggregate grains, limestone lithoclasts coated grains, and larger Foraminifera. Bryozoa(?) encrust some of the volcanic fragments as do Foraminifera (locality 446). Insoluble residue (39%) shows much clay to fine sand-sized material, much chlorite, pellets, spines, feldspars, much volcaniclastic cobbles and sand, rare rounded quartz.

Sample 905: Bioclastic limestone, Isla Magueyes Member (Figure 30).

White thick- to massive-bedded, very coarse-grained bioclastic limestone containing rare volcanic cobbles and whole Barrettia monilifera. Larger Foraminifera, mollusk fragments, limestone lithoclasts show on the weathered surface.
Matrix is spar cement. Rare medium sand- to cobble-sized rounded volcanic fragments, rare rounded fine-grained bioclastic limestone lithoclasts, large pelecypod and rudist (radiolitid) fragments, echinoid plates, algal fragments, larger Foraminifera, aggregate grains are present. Skeletal grains are generally angular. Insoluble residue (4%) shows rare detrital quartz, rare volcanic debris, rare plagioclase double-ended quartz crystals, possible sponge(?) fragment. Rock is recrystallized.

Samples 761e: Dark argillaceous fossiliferous limestone, Melones Limestone (Figure 31).

Thin- to medium-bedded, dark gray limestone with fine-grained matrix containing whole pelecypod shells, whole large Foraminifera and a peculiar meandering structure that may be algal(?). Rock weathers tan.

Matrix is dark cryptocrystalline calcite and clay. Larger benthonic Foraminifera, whole thick costate pelecypod shells, whole thin smooth pelecypod shells, volcanic fragments, rare plagioclase, fine-grained detrital quartz form the rock. The rock is divided into segments by thin meandering "tendrils" or "walls" of sparry calcite. These formed at the time of deposition as indicated by the segregation of other detrital grains along the meandering "tendrils." Origin is unknown (algal?). Rock has a poorly sorted bioclastic component, but a fairly well sorted non-carbonate clastic component and is representative of quiet water deposition.