Cretaceous and Lower Tertiary Stratigraphy of the Gurabo and El Yunque Quadrangles, Puerto Rico

GEOLOGICAL SURVEY BULLETIN 1294-F

Prepared in cooperation with the Commonwealth of Puerto Rico Economic Development Administration, Industrial Research Department

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By VICTOR M. SEIDERS

CONTRIBUTIONS TO STRATIGRAPHY

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A description of the largely marine-deposited volcaniclastic rocks and subordinate lava flows and pelagic mudstones that underlie this part of eastern Puerto Rico

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CRETACEOUS AND LOWER TERTIARY STRATIGRAPHY OF THE GURABO AND EL YUNQUE QUADRANGLES, PUERTO RICO

By Victor M. Seiders

ABSTRACT

Cretaceous and lower Tertiary volcaniclastic rocks and less abundant lava flows underlie most of the area of the Gurabo and El Yunque quadrangles in eastern Puerto Rico.

The stratigraphic sequence is much fragmented by high-angle faults with vertical and (or) transcurrent displacements. Two faults, the Leprocomio and Cerro Mula faults, separate three areas of differing stratigraphy.

North of the Leprocomio fault, a stratigraphic sequence about 7,500 meters thick consists chiefly of volcaniclastic rocks of Albian to Campanian Age. The volcaniclastic debris was derived from active volcanoes standing near sea level. The debris was transported to moderately deep water by submarine slides, turbidity currents, and pyroclastic ash flows and falls. Moderately high rates of deposition resulted from very rapid volcaniclastic deposition alternating with very slow pelagic sedimentation. A disconformity of probable Maestrichtian Age is overlain by lower Tertiary shallow-water limestone and lava.

Between the Leprocomio and Cerro Mula faults are volcaniclastic rocks of Cenomanian and Turonian Age that are similar to those to the north. The Turonian rocks also include abundant lavas. Other volcaniclastic rocks and lavas in the area between these faults cannot be correlated with certainty. They appear to have been deposited in shallow-water or subaerial environments.

South of the Cerro Mula fault, a small area is underlain by volcaniclastic rocks of possible Turonian to Santonian Age.

Stocks of quartz diorite and abundant diabase dikes, at least in part of early Tertiary age, probably mark the last phase of igneous activity in the area.

INTRODUCTION

This report describes the stratigraphy of volcanic rocks in the Gurabo and El Yunque quadrangles of northeastern Puerto Rico (fig. 1). The geologic mapping was part of a program by the U.S. Geological Survey in cooperation with the Commonwealth of Puerto Rico Economic Development Administration. The geologic map

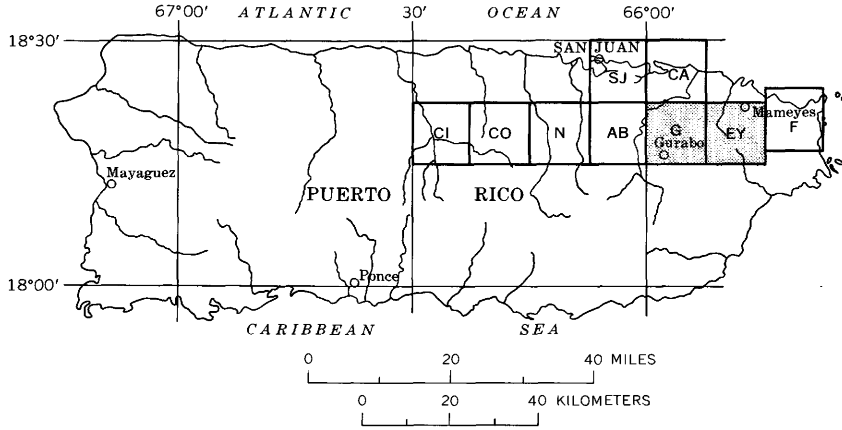

FIGURE 1.—Location of the Gurabo (G) and El Yunque (EY) quadrangles. Other quadrangles referred to in text are: AB, Aguas Buenas; CA, Carolina; CI, Ciales; CO, Corozal; F, Fajardo; N, Naranjito; SJ, San Juan.

(pl. 1) is a generalized version of two quadrangle maps which have been published separately (Seiders, 1971 a, b). The reader with a detailed interest in the study area should have these maps at hand while perusing this report.

The area is southeast of the San Juan metropolitan area (fig. 1). The largest town is Gurabo. Much of the area has a dense rural population, and a good network of secondary roads provides easy access. Access is limited, however, in uninhabited parts of the Caribbean National Forest in the southeastern half of El Yunque quadrangle, where rainfall is heavy and relief is moderately high.

Place names used in the text appear on the quadrangle maps (Seiders, 1971 a, b) but generally not on the simplified geologic map (pl. 1). The locations of places are also given by reference to coordinates of the Puerto Rico coordinate system, in meters (for example, 57,670 N. × 211,810 E.); these coordinates are shown on plate 1 and on the quadrangle maps.

The following Spanish nouns are used with geographic names in the text: Barrio, a political subdivision of a municipality; cerro, hill; pico, peak; quebrada, stream; río, river; sierra, mountain range.

Fieldwork for this report occupied about 28 months in 1964–68.

The first systematic study of the geology of the area was a reconnaissance survey of northeastern Puerto Rico by Meyerhoff and Smith (1931). The presence of lower Tertiary strata was reported by Kaye (1956), who also presented a geologic map of a small area in the Gurabo quadrangle. Berryhill, Briggs, and Glover (1960) published a generalized geologic map of eastern Puerto Rico and proposed regional correlations of stratigraphic units. Pease (1968a) studied parts of the Gurabo quadrangle in some detail and published a generalized geologic map including that quadrangle. The detailed studies of Kaye (1959) and Pease (1968a, b, c) west of the present map area are pertinent to the stratigraphy of the area.

I thank Emile A. Pessagno, Jr., University of Texas, Dallas, Tex., for providing nearly 50 biostratigraphical determinations based on Foraminifera (table 2) and for examining many other barren collections. His data were invaluable in working out the complex stratigraphy and ultimately will provide the most firm basis for the integration of this stratigraphy on a regional basis. Likewise, the examination of four collections of rudistids by N. F. Sohl, U.S. Geological Survey, and two collections of ammonites by W. A. Cobban, U.S. Geological Survey, are gratefully acknowledged. W. R. Bergey generously supplied unpublished geological data on the Pico La Mina area, El Yunque quadrangle. E. Aguilar-Cortez, Puerto Rico Economic Development Administration, Industrial Research Department, ably assisted in the field.

NOMENCLATURE

The age determinations from planktonic Foraminifera given by E. A. Pessagno, Jr., were reported primarily in terms of the standard North American (Gulf Coast) Cretaceous stages. In this report, following the general usage in the Caribbean region, they are presented in terms of the European stage names. Pessagno's (written commun., 1965) tentative correlation of the Cretaceous stages referred to in this report is shown in figure 2.

The nomenclature of volcaniclastic rocks proposed by Fisher (1961) is used here. In descriptive parts of the text, only the nongenetic terms are used. This procedure has been followed chiefly because of the inherent difficulty in rigorously distinguishing between marine-deposited pyroclastic and epiclastic volcanic debris. Possibly the only unequivocal evidence of a primary pyroclastic origin of marine-deposited volcaniclastic rocks is the presence of a doubly graded sequence of beds (Fiske and Matsuda, 1964). Where such sequences are not observed, as in the study area, the criteria of angularity and lithologic homogeneity of fragments may serve as guides in distinguishing either primary or reworked pyroclastic debris from epiclastic volcanic debris. However, these criteria rarely are completely conclusive. For example, a volcaniclastic rock composed of angular lithologically homogeneous volcanic-rock fragments is probably of pyroclastic origin, but it could have formed by rapid erosion and deposition of fully lithified rock from a coeval or even older volcanic terrain of uniform lithology. Likewise, a volcaniclastic rock composed of somewhat rounded fragments of diverse lithologic type is probably of epiclastic origin, but it could have formed by reworking of lithologically diverse debris produced by phreatic explosions. In any case, the use of genetic terminology adds nothing to the description of a rock and in this report is reserved for interpretive statements.

In accordance with Fisher's (1961) nomenclature, the grain-size limit between volcanic sandstone and volcanic breccia (or between tuff and lapillistone) is 2 mm (millimeters). Volcanic breccia and conglomerate are modified by the terms "fine," "medium," and "coarse," corresponding to the standard size limits of pebbles, cobbles, and boulders.

The classification of bedding thickness is that of Ingram (1954); 100 cm (centimeters), 30 cm, 10 cm, 3 cm, 1 cm, and 0.3 cm separate very thick, thick, medium, thin, very thin, thickly laminated, and thinly laminated beds.

GEOLOGIC SETTING

The Gurabo and El Yunque quadrangles (pl. 1) are underlain by a complexly faulted and folded terrain composed chiefly of Cretaceous volcanic rocks and of subordinate Cretaceous and (or) Tertiary intrusive bodies and minor lower Tertiary volcanic and sedimentary rocks.

High-angle faults showing both vertical and transcurrent movement are present, but in most places the two types of movement cannot be distinguished clearly. Faulting is most pronounced in the southwestern half of the Gurabo quadrangle in an area between two major faults. The southern fault is the Cerro Mula fault, which trends slightly north of west through the Gurabo valley in the southwestern corner of the map area. This is probably the major fault in the area and is associated with a broad zone of shear. Although direct evidence of the sense of movement is lacking in the Gurabo quadrangle, Pease (1968c) suggested left-lateral transcurrent movement exceeding 20 km (kilometers). The second major fault is the Leprocomio fault, which trends N. 55° W. across the Gurabo quadrangle. About 2 km of right-lateral movement on this fault is suggested by offset of stratigraphic units in the Aguas Buenas quadrangle (Pease, 1968b) to the west. Many of the numerous faults between the Cerro Mula and Leprocomio faults may be second-order shears related to the larger faults, but other large faults may also be present. Faulting is less intense northeast of the Leprocomio fault.

Almost everywhere folding is rather gentle. Dips of beds rarely exceed 60° and most commonly are less than 30°. The attitudes of bedding and of fold axes have a wide range and cannot be resolved into any pattern consistent with a single lateral compressive stress orientation. The observed structures at the surface probably are tilted fault blocks and strata that are draped over fault blocks at depth. This is most strongly suggested in the central and north-central parts of the area (pl. 1), where a broad north-northeast-trending syncline ends abruptly against a fault. North of the fault is a homocline dipping north-northwest. The geometry of the fault and fold pattern shows that the syncline and homocline could not have been juxtaposed by large-scale transcurrent faulting, and there is no indication of thrust faulting. Instead, the two structures probably formed side by side in response to different vertical movements at depth.

The major deformation took place in late Eocene or possibly early Oligocene time, because elsewhere in Puerto Rico strongly deformed middle or upper Eocene beds are overlain by little deformed lower Oligocene strata (Mattson, 1967, p. B32).

The volcanic rocks of the area are cut by numerous vertical dikes and by less common gently inclined sheets. Most of these bodies are diabase and diabase porphyry (table 1, sample 1). In large part they are of early Tertiary age and were emplaced after the major faulting and folding.

Dikes and small stocks of quartz diorite and diorite occur in the southern part of the area. The largest body, with an area of about 25 sq km (10 sq mi), is the Río Blanco stock in the southeastern part of El Yunque quadrangle (pl. 1). This sharply discordant stock is composed chiefly of quartz diorite (table 1, sample 2), with subordinate diorite. A smaller unexposed stock is probably present in the west-central part of El Yunque quadrangle. Its presence is indicated by an area of contact metamorphism with abundant dikes. These stocks are emplaced in strata of Albian and Cenomanian Age, but they cut faults which in turn offset beds of Paleocene or Eocene(?) age; therefore, the stocks are probably of early Tertiary age. Other bodies of diorite and quartz diorite occur along the Río Gurabo valley in the southern part of the Gurabo quadrangle.

Zeolites and other low-grade metamorphic minerals occur widely in the stratified rocks of the area. Mineral assemblages of hornblende hornfels facies are found in the aureoles of the granitic bodies. The rocks are unfoliated, except in major fault zones.

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TABLE 1.—*Chemical analyses*

[Analysts: Paul Elmore, L. Artis, S. Botts, G. Chloe, J. Glenn,

	1	1*	2	2*	3	3*	4	4*	5
Major oxides									
SiO_2	52.2	53.5	67.1	68.0	45.9	48.8	56.2	57.4	52.4
Al_2O_3	16.6	17.0	15.8	16.0	18.6	19.8	14.6	14.9	19.2
Fe_2O_3	2.4	2.5	2.2	2.2	4.4	4.7	2.5	2.6	2.7
FeO	6.7	6.9	2.1	2.1	6.0	6.4	2.8	2.9	4.9
MgO	5.2	5.3	1.7	1.7	6.0	6.4	1.3	1.3	3.8
CaO	9.7	9.9	5.1	5.2	7.8	8.3	8.4	8.6	8.5
Na_2O	3.2	3.3	3.3	3.3	3.5	3.7	5.7	5.8	3.0
K_2O	.91	.93	.92	.93	.13	.14	1.2	1.2	2.0
H_2O-	.30	--	.04	--	.77	--	.32	--	.34
H_2O+	2.2	--	1.2	--	5.1	--	1.6	--	2.2
TiO_2	.34	.35	.25	.25	1.3	1.4	.98	1.0	.81
P_2O_5	.07	.07	.07	.07	.21	.22	.79	.81	.00
MnO	.11	.11	.12	.12	.18	.19	.20	.20	.14
CO_2	.11	.11	<.05	--	<.05	--	3.3	3.4	<.05
Total	100		100		100		100		100
Minor elements[1]									
Ba	0.01		0.03		0.01		0.15		0.05
Be	--		--		--		--		--
Co	.0015		.001		.001		.0015		.002
Cr	.005		.0005		--		--		.002
Cu	.015		.0015		.015		.003		.05
Ga	.0015		.001		.001		.0015		.001
Mo	--		--		--		.0003		--
Nb	--		--		--		.0005		--
Ni	.003		--		<.003		--		--
Pb	--		.0007		.015		.02		--
Sc	.002		.001		.001		.002		.003
Sn	--		--		.0015		--		--
Sr	.03		.03		.05		.07		.07
V	.01		.007		.01		.02		.015
Y	.0015		.0015		.001		.003		.0015
Yb	.0002		.00015		.0001		.0003		.00015
Zr	.007		.007		.0003		.007		.007
Norms									
Q	1.6		30.7		--		10.2		2.9
C	--		.3		--		--		--
or	5.5		5.5		.8		7.2		12.1
ab	27.8		28.3		31.5		49.2		26.0
an	29.0		25.2		36.9		10.9		33.9
di {wo	8.0		--		1.2		2.1		3.9
di {en	4.4		--		.8		1.3		2.3
di {fs	3.4		--		.3		.7		1.4
hy {en	8.9		4.3		9.6		2.0		7.4
hy {fs	6.9		1.9		3.6		1.1		4.4
ol {fo	--		--		3.8		--		--
ol {fa	--		--		1.6		--		--
mt	3.6		3.2		6.8		3.7		4.0
il	.7		.5		2.6		1.9		1.6
hm	--		--		--		--		--
ap	.2		.2		.5		1.9		--
cc	.3		--		--		7.7		--
Total	100.3		100.1		100.0		99.9		99.9

* Analysis recalculated to 100 percent water free.

[1] Analysts: J. L. Harris and W. B. Crandell. Also looked for but not found: Ag, As, Au, B, Bi, Cd, Ce, Ge, Hf, Hg, In, La, Li, Pt, Re, Sb, Ta, Te, Th, Tl, U, W, Zn, and Eu.

SAMPLE DESCRIPTIONS

1. SG-171. Diabase dike, 57,640 N. × 198,250 E., Gurabo quadrangle.
2. SY-988. Quartz diorite, Río Blanco stock, 48,150 N. × 219,200 E., El Yunque quadrangle.
3. SC-969. Basaltic lava, Guaracanal Formation, 60,040 N. × 206,660 E., Carolina quadrangle.
4. SG-1669-B. Altered andesitic lava, Frailes Formation, 59,870 N. × 207,650 E., Gurabo quadrangle.
5. SG-8. Basaltic andesite, Martín González Lava, 58,840 N. × 202,120 E., Gurabo quadrangle.
6. SY-1809. Undevitrified sample of Toma de Agua Vitrophyre Member of Cambalache Formation, 59,420 N. × 212,400 E., El Yunque quadrangle.

TABLE 1.—*Chemical analyses*—Continued

J. Kelsey, N. Smith, and D. Taylor. Results are in percent]

5*	6	6*	7	7*	8	8*	9	9*	10	10*	11	11*
Major oxides—Continued												
53.8	59.0	63.3	56.1	63.8	49.2	51.1	47.9	49.8	52.1	54.4	68.1	70.0
19.7	15.4	16.5	14.3	16.3	17.2	17.9	17.0	17.7	15.0	15.7	12.5	12.8
2.8	2.1	2.2	1.5	1.7	4.5	4.7	8.0	8.3	2.2	2.3	.51	.52
5.0	4.2	4.5	5.2	5.9	5.4	5.6	3.8	3.9	6.4	6.7	5.9	6.1
3.9	1.5	1.6	2.2	2.5	7.5	7.8	6.7	7.0	7.2	7.5	3.0	3.1
8.7	6.6	7.1	5.9	6.7	8.4	8.7	8.1	8.4	8.0	8.3	3.5	3.6
3.1	2.0	2.1	1.0	1.1	2.9	3.0	3.3	3.4	3.0	3.1	.85	.87
2.0	1.0	1.1	.37	.42	.12	.12	.31	.32	.91	.95	2.1	2.2
---	2.0	---	5.9	---	.74	---	.75	---	.40	---	.04	---
---	4.7	---	5.4	---	2.8	---	3.0	---	3.4	---	2.3	---
.83	.93	1.0	.76	.86	.78	.81	.75	.78	.68	.71	.57	.59
.00	.37	.40	.20	.23	.09	.09	.09	.09	.14	.15	.18	.18
.14	.16	.17	.15	.17	.10	.10	.17	.18	.16	.17	.11	.11
---	<.05	---	.21	.24	<.05	---	<.05	---	<.05	---	<.05	---
	100		99		100		100		100		100	
Minor elements [1]—Continued												
	0.15		0.05		0.007		0.007		0.05		0.05	
	.0001		---		---		---		---		---	
	.001		.0007		.003		.003		.005		.0015	
	---		.0005		.005		.007		.01		.003	
	.002		.05		.015		.005		.005		.005	
	.002		.001		.001		.0015		.0015		.0015	
	.0005		---		---		---		.0005		.0005	
	.0005		---		---		---		---		.0005	
	---		---		.003		.003		.01		.002	
	.02		.07		---		.002		.02		.03	
	.0015		.001		.003		.003		.005		.002	
	---		.005		---		.001		---		---	
	.1		.1		.05		.05		.07		.02	
	.007		.007		.015		.02		.03		.01	
	.005		.0015		.002		.002		.002		.003	
	.0005		.00015		.0002		.0002		.0002		.0003	
	.015		.007		.005		.005		.005		.01	
Norms—Continued												
	28.0		35.0		2.3		2.5		2.7		---	
	---		2.8		---		---		---		---	
	6.3		2.5		.7		1.9		5.6		---	
	18.1		9.6		25.5		29.1		26.5		---	
	32.3		30.3		34.9		31.9		25.9		---	
	.1		---		3.3		3.9		6.1		---	
	.0		---		2.3		3.4		3.8		---	
	.1		---		.6		---		1.9		---	
	4.0		6.2		17.1		14.0		14.9		---	
	5.0		8.3		4.7		---		7.6		---	
	---		---		---		---		---		---	
	---		---		---		---		---		---	
	3.3		2.5		6.8		11.1		3.3		---	
	1.9		1.6		1.5		1.5		1.3		---	
	---		---		---		.7		---		---	
	.9		.5		.2		.2		.3		---	
	---		.5		---		---		---		---	
	100.0		99.8		99.9		100.2		99.9		---	

SAMPLE DESCRIPTIONS—Continued

7. SG–603. Zeolitized pumiceous fine volcanic breccia, Cambalache Formation, 57,330 N. × 209,880 E., Gurabo quadrangle.
8. SG–1383–A. Greenish-gray fragment from basaltic vent breccia, Hato Puerco Formation, 58,030 N. × 203,320 E., Gurabo quadrangle.
9. SG–1383–C. Oxidized fragment from basaltic vent breccia, Hato Puerco Formation, same locality as sample 8.
10. SG–1912. Basaltic andesite, Lomas Formation, 48,540 N. × 210,150 E., Gurabo quadrangle.
11. SF–1944. Siliceous volcanic mudstone, unnamed volcaniclastic rocks, 52,400 N. × 226,700 E., Fajardo quadrangle.

The distribution of low-grade metamorphic minerals is very complex and is not yet known in detail. The kind and abundance of low-grade minerals seem to have been influenced more strongly by such factors as proximity to intrusive bodies and the chemical and mineralogical composition of the host rock than by depth of burial. The occurrence of epidote is most closely related to proximity to intrusive bodies. Laumontite is the most widespread zeolite and occurs in all but the youngest stratigraphic units. Analcite, prehnite, and secondary albite occur widely but sporadically. Pumpellyite is uncommon. Heulandite is found only in the Cambalache Formation, in zeolitized vitric siliceous andesitic volcaniclastic rocks. The Cambalache and overlying and underlying formations also contain laumontite. Thompsonite is known only from basalt in the highest exposed formation.

Stratigraphic units of the Gurabo and El Yunque quadrangles are described below. Their nomenclature and stratigraphic relationships are shown in figure 2.

STRATIFIED ROCKS NORTH OF THE LEPROCOMIO FAULT

UNNAMED VOLCANICLASTIC ROCKS

The oldest stratified rocks in the area are in the southeast part of El Yunque quadrangle. These strata consist chiefly of noncalcareous thick to very thick bedded volcanic sandstone and fine volcanic breccia with subordinate noncalcareous thin- to thick-bedded mudstone. Volcanic sandstone and breccia are composed of angular volcanic-rock fragments and grains of plagioclase and clinopyroxene. Locally, the volcaniclastic rocks contain moderately abundant altered perlite and pumice and rare volcanic quartz grains. A chemical analysis of a siliceous mudstone is given in table 1 (sample 11).

Within the mapped area, these rocks are poorly exposed and most are contact metamorphosed. They are better exposed in areas to the east and therefore are not formally described or named in this report.

About 1,500 m (meters) of strata is exposed in El Yunque quadrangle, where the base of the sequence is not reached. The sequence is overlain conformably by the Tabonuco Formation.

TABONUCO FORMATION

DEFINITION AND STRATIGRAPHIC RELATIONSHIPS

Along the highway that rises into the Sierra de Luquillo from the town of Mameyes are conspicuous exposures of dark-gray chiefly medium-bedded mudstones and less well exposed volcanic sandstones. These rocks and minor volcanic breccia and conglomerate are here named the Tabonuco Formation after the Quebrada Tabonuco, 3 km

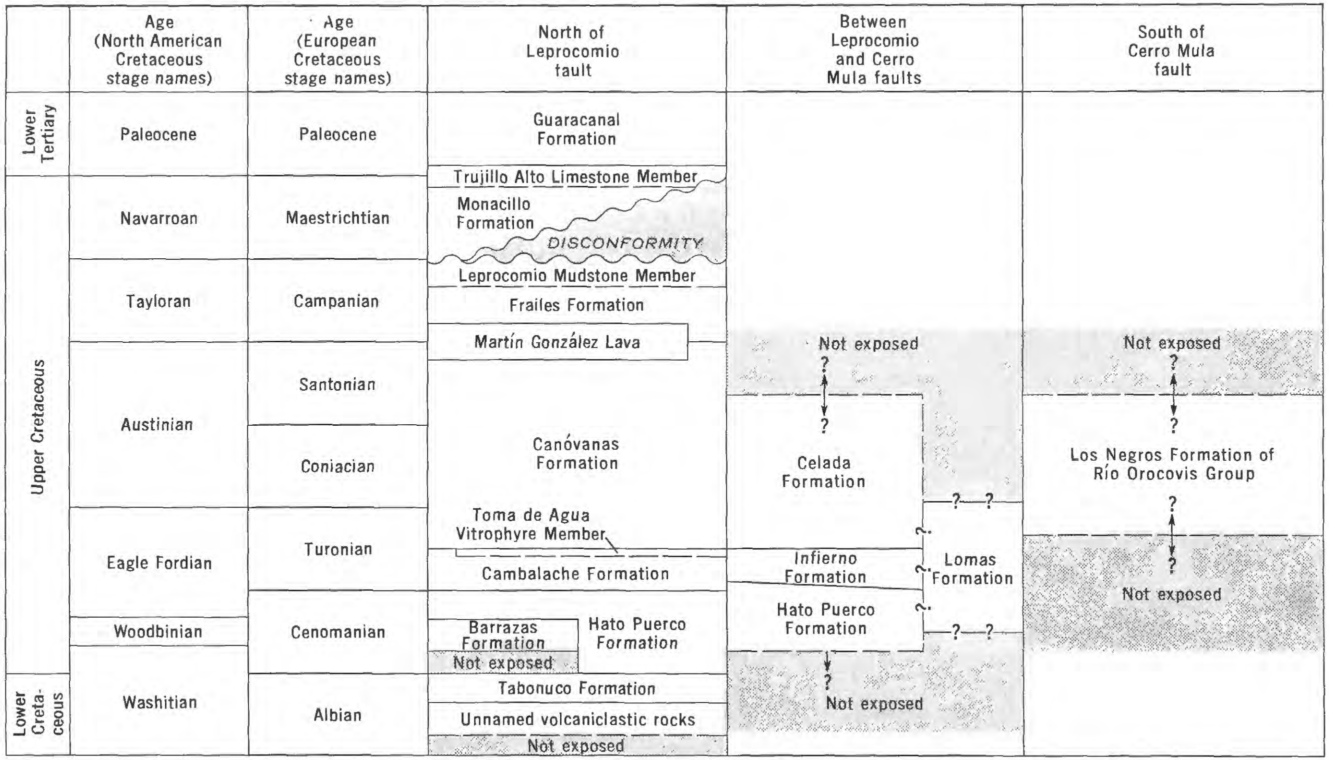

FIGURE 2.—Stratigraphic units in the Gurabo and El Yunque quadrangles. Tentative correlation of North American and European Cretaceous stages from E. A. Pessagno, Jr. (written commun., 1965).

south of Mameyes. The type section is in a tributary of the Río Mameyes, 6 km south of Mameyes (pl. 1). The section extends upstream from a point 300 m west of the river (53,880 N. × 223,330 E.) to above the high cascade (Coco Falls) at the highway (54,110 N. × 222,290 E.).

The Tabonuco Formation conformably overlies the unnamed sequence of volcaniclastic rocks described above. The Tabonuco contains proportionately more mudstone and less very thick bedded sandstone and breccia than the underlying sequence. The base of the Tabonuco is defined by an abrupt upward increase in the relative abundance of thinner bedded finer grained rocks. An additional distinction between the Tabonuco Formation and the underlying sequence is that the Tabonuco rocks are generally calcareous, whereas those of the underlying sequence are noncalcareous. This distinction is not everywhere applicable. In the lower part of the Tabonuco, some mudstones are noncalcareous, and other slightly calcareous beds are extensively leached upon weathering.

The Tabonuco is conformably overlain by the Hato Puerco Formation. The formation is about 1,000 m thick.

LITHOLOGY

About 60 percent of the Tabonuco Formation consists of medium to very thick bedded volcanic sandstone. Most sandstones are calcareous, medium gray, fine to very coarse grained, and moderately sorted. Less common standstones are grayish green and noncalcareous. Many sandstone beds are laminated, and the thinner beds have small-scale crossbedding. Graded bedding is probably common but is difficult to detect and is conspicuous only in rare exposures.

Volcanic sandstones are probably andesitic and are composed chiefly of angular volcanic-rock fragments with less abundant plagioclase and clinopyroxene grains and rare volcanic quartz crystals. In some beds, the clinopyroxene grains are relatively large and are the coarsest grains present. Volcanic-rock fragments are nonvesicular to highly vesicular with hyalopilitic to pilotaxitic textures and, in part, with phenocrysts of plagioclase and clinopyroxene.

Mudstones make up about 30 percent of the formation and are dark gray, thin to rarely thick bedded (mostly commonly medium bedded), and laminated. Most mudstones are slightly to highly calcareous, and some beds are impure aphanitic limestones. Planktonic Foraminifera and Radiolaria are generally abundant. Uncommon mudstones are noncalareous and hard and break with a poorly developed conchoidal fracture. Finely disseminated pyrite is a common constituent of the mudstones.

With an increase in grain size, the volcanic sandstones uncommonly grade into moderately sorted fine volcanic breccias and rare coarse breccias. Some mudstones and sandstones are pebbly to bouldery and grade into poorly sorted fine to coarse breccia-conglomerates. These beds, probably submarine slide deposits, form a distinctive zone about 25 to 100 m thick near the middle of the formation. The coarse fragments locally have an intact framework, but more commonly they float in a matrix of calcareous mudstone or calcareous to noncalcareous sandstone. Some very thick beds have a crude internal stratification defined by slight variations in pebble size. Locally, some thick pebbly beds are graded. Fragments consist of angular chips and blocks of mudstone that reach a size of more than 1 m and of angular to well-rounded fragments of lava nearly as large as 1 m. In some exposures, slabs of mudstone in the breccia-conglomerates tend to be oriented parallel to bedding; elsewhere the orientation is random. The proportions of coarse fragments and of different kinds of fragments vary widely.

In the contact zone of the Río Blanco quartz diorite stock, strata of the Tabonuco Formation have been metamorphosed. Near the contact, calcareous beds have been converted to calc-silicate hornfels composed of wollastonite, garnet, diopside, vesuvianite, and, locally, clinozoisite. At greater distances from the stock, scapolite-bearing hornfels is common.

On Pico La Mina, beds of calcareous conglomerate and conglomeratic mudstone have been altered to a massive skarn which contains irregularly distributed locally massive pyrrhotite and chalcopyrite. Many years ago this skarn was worked on a small scale for copper. Recent drilling by private interests did not lead to further exploitation. In the same area, generally farther from the intrusive contact, the conglomeratic beds are represented by a light-gray finely crystalline actinolitic limestone containing pebbles, cobbles, and boulders of volcanic rock and mudstone.

AGE AND CORRELATION

E. A. Pessagno, Jr. (written commun., 1966, 1967), identified planktonic Foraminifera in thin sections from four localities in the Tabonuco Formation. Two of the localities (locs. 49, 50, pl. 1; table 2) yielded faunas indicative of an Albian Age, and the other two localities (locs. 48, 51) yielded faunas that suggested broader ranges in age, including the Albian. Four genera of ammonites from another locality (loc. 47) were tentatively identified by W. A. Cobban (written commun., 1966), who suggested an Albian Age. The Albian Age of the Tabonuco Formation indicates that it is equivalent to the lower part of the Robles Formation (defined by Pease and Briggs, 1960) and possibly to pre-Robles rocks of central Puerto Rico. The pre-Robles rocks contain Albian fossils (Glover, 1971) and the Robles Formation ranges from Albian to Santonian in age (Briggs, 1967).

TABLE 2.—*List of age*

[X, present, abundance not specified; A, abundant;

Stratigraphic unit and age	Locality No.	Sample No.	Location (Puerto Rico meter grid)
Guaracanal Formation:			
Paleocene-early Eocene	1	SG-762	59,990 N.×206,225 E.
Late Paleocene-Eocene	2	SG-761	59,745 N.×206,150 E.
Frailes Formation, Leprocomio Mudstone Member:			
Late Campanian-early Maestrichtian, probably late Campanian.	3	SG-1853	59,590 N.×206,350 E.
Late Campanian-early Maestrichtian, probably late Campanian.	4	SG-466	59,960 N.×198,560 E.
Latest Campanian	5	SAB-526-D	58,975 N.×197,730 E.
Late Campanian	6	SAB-526-A,B,C	58,950 N.×197,730 E.
Late Campanian	7	SAB-525-A,B,C	58,690 N.×197,150 E.
Frailes Formation:			
Early Campanian	8	SG-678	59,250 N.×200,425 E.
Early Campanian	9	SG-620	58,885 N.×208,465 E.
Early Campanian or younger	10	SAB-951	58,020 N.×196,970 E.
Canóvanas Formation:			
Early Santonian	11	SG-853	59,270 N.×210,285 E.
Late Turonian-early Santonian	12	SG-1390	59,640 N.×205,450 E.
Coniacian-early Santonian	13	SG-566	59,265 N.×210,465 E.
Coniacian-early Santonian	14	SG-565	59,195 N. ×210,530 E.
Coniacian	15	SG-1783	59,670 N.×211,000 E.
Late Turonian	16	SG-2230	59,590 N.×205,720 E.
Late Turonian	17	SG-564	59,050 N.×210,550 E.
Cambalache Formation:			
Turonian	18	SY-1602	57,670 N.×211,810 E.
Infierno Formation:			
Turonian or younger	19	SG-331	51,410 N.×204,760 E.
Turonian	20	SG-480	52,870 N.×199,170 E.
Hato Puerco Formation (north of Leprocomio fault):			
Possibly Albian (reworked fragment)	21	SG-1768	57,400 N.×210,475 E.
Late Cenomanian	22	SG-960	59,270 N.×203,385 E.
Late Cenomanian	23	SG-202	58,690 N.×204,780 E.
Late Cenomanian	24	SG-1388	58,650 N.×204,060 E.
Late Cenomanian	25	SY-1246	57,750 N.×215,730 E.
Albian-early Cenomanian (reworked fragment)	26	SG-1820	56,150 N.×208,040 E.
Late Cenomanian	27	SG-3	52,100 N.×209,870 E.
Middle Cenomanian (reworked fragment)	28	SY-1587-B	55,340 N.×212,515 E.
Late Cenomanian	29	SG-638	55,630 N.×210,580 E.
Probably Cenomanian (reworked fragments)	30	SG-640	54,860 N.×208,880 E.
Possibly Cenomanian	31	SY-1148	58,465 N.×219,050 E.
Possibly Albian	32	SY-1672	60,070 N.×220,140 E.
Cenomanian, probably middle Cenomanian	33	SY-1498-B	58,890 N.×219,900 E.
Possibly Albian	34	SY-1219	59,850 N.×221,960 E.
Possibly Albian	35	SY-1465	59,100 N.×221,550 E.
Cenomanian (reworked fragment)	36	SG-722	53,100 N.×204,500 E.
Early Cenomanian	37	SY-1684	59,880 N.×224,200 E.
Early Cenomanian	38	SY-1683	59,750 N.×224,370 E.
Possibly Albian	39	SY-1626	54,820 N.×220,230 E.
Hato Puerco Formation (south of Leprocomio fault):			
Turonian	40	SAB-1979	51,890 N.×198,075 E.
Cenomanian, probably late Cenomanian	41	SG-1087	55,050 N.×199,210 E.
Cenomanian, probably middle to late Cenomanian	42	SG-1086	54,980 N.×199,180 E.
Middle to late Cenomanian	43	SG-457	54,620 N.×199,140 E.
Probably Cenomanian (reworked fragments)	44	SAB-836	56,125 N.×198,160 E.
Barrazas Formation:			
Probably late Cenomanian	45	SG-114	56,260 N.×202,090 E.
Late Cenomanian	46	SG-258	55,880 N.×199,680 E.
Tabonuco Formation:			
Probably Albian	47	SY-1112	57,760 N.×222,835 E.
Albian-middle or late Cenomanian	48	SY-1006	57,665 N.×222,885 E.
Probably Albian	49	SY-1453	57,340 N.×223,665 E.
Albian	50	SY-1450	57,165 N.×223,950 E.
Possibly Aptian to middle Cenomanian	51	SY-1019	54,115 N.×223,365 E.
Lomas Formation (?):			
Late Cenomanian	52	SG-1026	54,500 N.×200,230 E.

determinations and fossils

C, common; R, rare; ?, uncertain identification]

Foraminifera																													
Heterohelix sp.	*H. globulosa*	*H. moremani*	*H. reussi*	*Globigerinelloides* sp.	*G. barri*	*G. caseyi*	*G. yaucoensis*	*Shackoina* sp.	*Hedbergella* sp.	*H. amabilis*	*H. brittonensis*	*H. delrioensis*	*H. planispira*	*H. washitensis*	*Clavihedbergella* sp.	*C. simplex*	*Praeglobotruncana delrioensis*	*P. stephani*	*Loeblichella hessi*	*Rotalipora appenninica*	*R. cushmani*	*R. evoluta*	*R. greenhornensis*	*Whiteinella archeocretacea*	*W. inornata*	*Marginotruncana* sp. (double keeled)	*M. angusticarenata*	*M. canaliculata*	*M. concavata*
A	Cf			A																									
X							Cf																						
X				X																									
C																													
																											A		R
			Aff																							C	C		
																			A								C		
			Cf.																								A		?
			A																								A		
			Aff																								C		
			Cf													R		R						R	R		C	X	
																									X				
			X									X						??											
X									X															Cf					
								—				C																	
									X			X								C	R		C						
X						Cf			A			A				R				R	C		A						
				X						X					X			X		X			X						
											R	A								A	C		R						
												A	C																
										C		A				R				R	R		R						
												A				R		C		A			C						
												A	R			C				A			C						
									C												?								
												X																	
				C				R				A						C		C	R	?	X						
				C								A																	
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		R				?		X				A	R					R		C		C							
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												?				R				R	?		R						
									X												R								
		Cf		X								A								C	C								
									A			A																	
									A			A				R		R	C	R									
												A																	
				X								A					C												
					C							A	C																
				X								X																	
									X											C			C						

TABLE 2.—*List of age determinations*

Stratigraphic unit and age	Locality No.	Foraminifera													
		M. coronata	*M. difformis*	*M. helvetica*	*M. indica*	*M. marginata*	*M. pseudolinneiana*	*M. renzi*	*M. sigali*	*Pseudoguembelina costulata*	*Pseudotextularia* sp.	*P. elegans*	*Archaeoglobigerina* sp.	*A. blowi*	*Rugoglobigerina* sp.
Guaracanal Formation:															
Paleocene–early Eocene	1														
Late Paleocene–Eocene	2														
Frailes Formation, Leprocomio Mudstone Member:															
Late Campanian–early Maestrichtian, probably late Campanian	3									?		A	X		X
Late Campanian–early Maestrichtian, probably late Campanian	4											C			
Latest Campanian	5											X			?
Late Campanian	6											X			
Late Campanian	7											X		Cf	
Frailes Formation:															
Early Campanian	8													Cf	
Early Campanian	9													C	
Early Campanian or younger	10														
Canóvanas Formation:															
Early Santonian	11	C				?	R	R							
Late Turonian–early Santonian	12														
Coniacian–early Santonian	13	C						A							
Coniacian–early Santonian	14	C					R	C			?				
Coniacian	15	?			X			C							
Late Turonian	16		R	?					C						
Late Turonian	17		R	R					R						
Cambalache Formation:															
Turonian	18			X											
Infierno Formation:															
Turonian or younger	19														
Turonian	20			X		X	Cf		?						
Hato Puerco Formation (north of Leprocomio fault):															
Possibly Albian (reworked fragment)	21														
Late Cenomanian	22														
Late Cenomanian	23														
Late Cenomanian	24														
Late Cenomanian	25														
Albian–early Cenomanian (reworked fragment)	26														
Late Cenomanian	27														
Middle Cenomanian (reworked fragment)	28														
Late Cenomanian	29														
Probably Cenomanian (reworked fragments)	30														
Possibly Cenomanian	31														
Possibly Albian	32														
Cenomanian, probably middle Cenomanian	33														
Possibly Albian	34														
Possibly Albian	35														
Cenomanian (reworked fragment)	36														
Early Cenomanian	37														
Early Cenomanian	38														
Possibly Albian	39														
Hato Puerco Formation (south of Leprocomio fault):															
Turonian	40			X					X						
Cenomanian, probably late Cenomanian	41														
Cenomanian, probably middle to late Cenomanian	42														
Middle to late Cenomanian	43														
Probably Cenomanian (reworked fragments)	44														
Barrazas Formation:															
Probably late Cenomanian	45														
Late Cenomanian	46														
Tabonuco Formation:															
Probably Albian	47														
Albian–middle or late Cenomanian	48														
Probably Albian	49														
Albian	50														
Possibly Aptian to middle Cenomanian	51														
Lomas Formation(?):															
Late Cenomanian	52														

and fossils—Continued

Foraminifera—Continued																			Mollusca											Algae
Globotruncana arca	*G. austinensis*	*G. bulloides*	*G. elevata*	*G. fornicata*	*G. lapparenti* s.s.	*G. linneiana*	*G. plummerae*	*G. rosetta*	*G. stephensoni*	*G. stuartiformis*	*G. ventricosa*	*Planomalina buxtorfi*	*Globorotalia* (s.s.) sp. (keeled)	*Globigerina* sp.	*Pseudorbitoides* sp.	*Discocyclina* sp.	*D. barkeri*	*Operculinodes bermudezi*	*Mortoniceras* s.l. sp.	*Hypacanthoplites* sp.	*Flickia* sp.	*Lechites gaudini*	*Immanites* sp.	*Caprinuloidea* sp.	*Coalcomana* sp.	*Plesioptocus* sp.	*Parastoma* sp.	*Antillocaprina* sp.	*Actaeonella* sp.	*Archaeolithothamnion*
																X	C	A												Cf
													X	X																
R			R	A	C	A	?			C																				
		R	C	A		C				A																				
		X	X	X	X	X	X		X	X	X				X															
		X	X	X	X	X				X																				
		X	X	X	X	X		X		X																				
R	R			C	A				?	A	R																			
		R		C	C	R	?	R		R	R																			
																											X	?	X	
		C		?																										
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											Cf																			
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											C																			
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																		?	?	?	?									
											C																			

BARRAZAS FORMATION

DEFINITION AND STRATIGRAPHIC RELATIONSHIPS

A sequence of marine-deposited calcareous volcanic sandstone and less abundant volcanic breccia and calcareous mudstone is here named the Barrazas Formation after barrio Barrazas, Gurabo quadrangle. The type locality is in the Quebrada Maracuto (55,390 N.×204,500 E.), 1 km west-southwest of Cerro Gordo (pl. 1).

The Barrazas Formation is known to crop out only in the northwestern part of the Gurabo quadrangle on the west limb of the broad Río Canóvanas syncline (pl. 1). Here the Barrazas is overlain with apparent conformity by the Hato Puerco Formation, and both formations contain late Cenomanian fossils. On the east limb of the Río Canóvanas syncline, the Hato Puerco ranges down into the lower Cenomanian. Thus, the Barrazas is equivalent in age to part of the Hato Puerco to the east. The two formations probably interfinger in the subsurface of the Río Canóvanas syncline.

On the east limb of the syncline, the Hato Puerco is underlain by the Tabonuco Formation. In spite of broadly similar lithologies and the same stratigraphic position with respect to the Hato Puerco, the Tabonuco (Albian) is older than any exposed part of the Barrazas Formation (upper Cenomanian). The base of the Barrazas is cut out by faults, and the lower contact and maximum age of the formation are not known. Contacts of the Barrazas with the Tabonuco, if present at all, are concealed in the subsurface of the Río Canóvanas syncline.

The maximum exposed thickness of the Barrazas Formation is about 1,100 m.

LITHOLOGY

Rock types in the Barrazas Formation are similar to those in the Hato Puerco Formation. The Barrazas differs from the Hato Puerco chiefly in its greater proportion of mudstone and thin- to medium-bedded sandstone and in its smaller proportion of volcanic breccia. In addition, volcanic sandstones of the Barrazas are typically gray and calcareous, whereas those of the Hato Puerco are most commonly green and include fewer calcareous beds.

Volcanic sandstones of the Barrazas Formation are medium gray to dark gray, thin to very thick bedded, and fine to coarse grained. Most beds are laminated, and small-scale crossbedding is common in the thinner beds. Graded bedding can be detected in some beds. Chips and small slabs of mudstone are included in some very thick sandstone beds. Most sandstones are moderately sorted; less commonly they are poorly sorted. They are composed of angular grains of nonvesicular to sparsely vesicular volcanic-rock fragments of andesitic to basaltic(?) composition with less abundant plagioclase, clinopyroxene, and sparse hornblende grains. Most sandstones contain a small percentage of thick-shelled calcareous fossil debris and some calcite cement.

Volcanic breccias are very thick bedded, fine to medium grained (less commonly coarse grained), and composed chiefly of angular volcanic-rock fragments. Light-gray shallow-water limestone occurs as sparse fragments and locally makes up as much as 10 percent of the clasts. Rounded fragments are locally present.

Mudstones are medium to dark gray and thin to medium bedded. Nearly all the mudstones are calcareous and are composed of variable amounts of very fine volcanic ash, calcite, planktonic Foraminifera, Radiolaria, and carbonaceous matter. Some mudstones contain a small percentage of pyrite.

AGE AND CORRELATION

Pessagno (written commun., 1965) identified late Cenomanian Foraminifera from fossil localities 45 and 46 (pl. 1; table 2) in the Barrazas Formation.

The Barrazas Formation on the western border of the Gurabo quadrangle is a continuation along strike of part of the Guaynabo Formation as redefined by Pease (1968a). The Guaynabo Formation also includes rocks younger than the Barrazas.

HATO PUERCO FORMATION

DEFINITION AND STRATIGRAPHIC RELATIONSHIPS

The name "Hato Puerco tuffs" was introduced by Meyerhoff and Smith (1931, p. 272–275) to describe a very thick sequence of dominantly massive tuffs and volcanic breccias widely exposed in northeastern Puerto Rico. A poorly exposed sequence of similar breccias believed to underlie the Hato Puerco was named the "Guzmân formation" (Meyerhoff and Smith, 1931, p. 267). The Guzmân was distinguished from the Hato Puerco by the presence of subordinate calcareous beds and better stratification. Because of very limited access to the supposed area of exposure of the Guzmân, Meyerhoff and Smith (1931, p. 279–271) expressed reservations on the stratigraphic position and extent of the formation. However, they (p. 270) believed that the type locality of the Guzmân, along the Río Canóvanas 9 km south of the town of Canóvanas, was on the crest of an anticline, and that beds of the Guzmân dipped beneath the Hato Puerco. The present study has shown that this locality is, in fact, in the trough of a syncline. The beds assigned by Meyerhoff and Smith to the Guzmán now are included within the Hato Puerco.

In this report, new formations are defined both above and below the Hato Puerco, and the stratigraphic position of the Hato Puerco is redefined. The type locality designated by Meyerhoff and Smith, barrio Hato Puerco[1] (northeast Gurabo quadrangle), is retained.

The Hato Puerco Formation is exposed over large areas of the Gurabo and El Yunque quadrangles. The largest area of exposure is in the trough and broad flanks of the Río Canóvanas syncline. On the east limb of this syncline, the Hato Puerco rests on the Tabonuco Formation. To the west the Hato Puerco overlies the Barrazas Formation. Both contacts are marked by an abrupt upward increase in the proportions of volcanic breccia and very thick bedded, grayish-green volcanic sandstone.

In the northern parts of the Gurabo and El Yunque quadrangles, the Hato Puerco is overlain conformably by the Cambalache Formation.

The Hato Puerco is also exposed in the west-central part of the Gurabo quadrangle between the Leprocomio and Cerro Mula faults. The formation in this area is not significantly different from the formation to the north and is described here along with rocks north of the Leprocomio fault. Between the Leprocomio and Cerro Mula faults, the Hato Puerco is overlain conformably by lavas and volcaniclastic rocks of the Infierno Formation.

In most areas, the full thickness of the Hato Puerco cannot be measured because the section is interrupted by faults or because the top has been removed by erosion. In the north-central part of the Gurabo quadrangle, the complete section between the Barrazas and Cambalache Formations is present and measures about 1,100 m. The formation thickens to the east and south. Between the top of the Barrazas Formation in barrio Barrazas and the axis of the Río Canóvanas syncline to the east, about 1,500 m. is exposed, and the top is not reached. On the east limb of the Río Canóvanas syncline, about 1,900 m. is exposed above the Tabonuco Formation, and the top of the Hato Puerco has been removed by erosion. In the west-central part of the Gurabo quadrangle, about 500 m. of the Hato Puerco is exposed below the Infierno Formation. The Hato Puerco here is continuous with underlying beds in the Aguas Buenas quadrangle mapped by Pease (1968b) as the Carraízo Breccia. The Carraízo is very similar to the Hato Puerco, and the two formations are probably correlative. The combined thickness of the two units, scaled from the Aguas

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[1] The name of this barrio was recently changed from Hato Puerco (meaning "pig farm") to Campo Rico ("rich countryside").

Buenas and Gurabo maps, is about 2,600 m., and the base of the Carraízo is cut out by a fault.

LITHOLOGY

The Hato Puerco Formation consists chiefly of very thick bedded volcanic standstone and breccia of andesitic to basaltic composition. Subordinate rock types include medium- to thick-bedded volcanic sandstone, volcanic and calcareous mudstone, conglomerate, and lava flows.

Fine to coarse volcanic breccias make up about 30 to 40 percent of the Hato Puerco Formation. Most of the breccias are probably the products of the explosive disruption of fully consolidated volcanic rock. Nearly all fragments are angular to subrounded pieces of dense to moderately vesicular augite andesite or basalt without the crusts or rounded forms of volcanic bombs. Appreciable mixing and redistribution of the debris both during ejection and by marine processes is indicated. In any bed, a variety of textural modifications is commonly present. Generally, a small percentage of fragments is oxidized. Angular to rounded fragments of limestone containing rudistids, corals, algae, and other shallow-water forms occur as scattered clasts in some beds and rarely make up as much as 30 percent of the breccia. Locally, scattered fragments of calcareous mudstone are present. Some beds contain a few well-rounded volcanic pebbles, and rare beds of conglomerate consist chiefly of rounded pebbles. In most breccias, the coarser fragments have an intact framework with interstices filled with sand and small pebbles. Sorting ranges from moderate to poor, and some breccias have disrupted frameworks. Some fine breccia beds are graded.

Much less common breccias probably represent the near-vent fragmentation of solid lava with little redistribution of fragments. These breccias contain many fragments larger than 1 m, all of uniform texture, and locally associated with massive lava. Some blocks contain open fractures filled with fine angular fragments of volcanic rock. Material in and adjacent to the fractures is commonly oxidized grayish red, and in some areas the oxidation is pervasive over outcrop areas of at least several square meters. It is interesting to note that this oxidation probably occurred in or below fairly deep marine waters, as indicated by the occurrence of graded bedding and planktonic faunas in underlying and overlying strata. Chemical analyses of unoxidized and oxidized breccia fragments are given in table 1 (samples 8, 9).

In the Gurabo quadrangle (Seiders, 1971a), an informal member composed chiefly of breccia has been mapped at the base of the Hato Puerto Formation. This member increases in thickness from about

200 m at the west border of the quadrangle to about 700 m in the central part of the quadrangle. Farther south in the Gurabo quadrangle, as well as in El Yunque quadrangle, breccias in the lower part of the Hato Puerco are interbedded with more abundant volcanic sandstone. In these areas, the breccia member is not recognized as a distinct unit.

More than half of the Hato Puerco consists of very thick bedded volcanic sandstone and less abundant medium- to thick-bedded volcanic sandstone. Graded bedding is common in beds as much as about 1 m thick; some beds as thick as 4 m are graded. Where sandstone is interbedded with mudstone, sole markings occur at the base of graded beds, and chips and slabs of mudstone are moderately common in the sandstone beds. Some of the thinner sandstone beds are laminated and locally show small-scale crossbedding. Many sandstones are evenly bedded; graded bedding, if present at all, is too poorly developed to be readily detected.

Most sandstones of the Hato Puerco Formation are grayish-green to dusky-green moderately sorted rocks composed chiefly of angular fragments of dense to moderately vesicular volcanic rock. Plagioclase, clinopyroxene, and minor hornblende occur as phenocrysts and separate clastic grains. Typically 10 to 20 percent of the volcanic rock grains are oxidized, but some beds, especially in the lower part of the formation in El Yunque quadrangle, lack oxidized grains. Scattered fragments of calcareous fossils are common. Rare beds of sandstone and fine breccia are rich in pumice.

Mudstones of the Hato Puerco Formation are chiefly medium to dark gray and thin to medium bedded. Most mudstones are calcareous and contain planktonic Foraminifera and Radiolaria.

Andesitic to basaltic lava flows occur as thin discontinuous lenses and make up a minor part of the Hato Puerco Formation. Both pillowed lava and massive lava are present, and the texture is variable. Plagioclase occurs in the groundmass and as sparse to abundant phenocrysts. Less abundant clinopyroxene is a groundmass mineral and locally occurs as phenocrysts. Some lavas contain phyllosilicate pseudomorphs after phenocrysts of orthopyroxene or olivine. The groundmass texture is generally intersertal; less commonly it is pilotaxitic. Amygdules are common and locally are partly filled with chilled lava.

The Hato Puerco Formation was affected by low-grade metamorphism, but no foliation formed. Secondary minerals include analcite, laumontite, prehnite, pumpellyite, epidote, chlorite, and celadonite. In some rocks, the plagioclase is albitized, but commonly it is of intermediate composition; secondary calcium-aluminum silicates are only present in minor amounts or are absent. Actinolite and hornblende are present near intrusive bodies.

The widespread occurrence of marine fossils in the Hato Puerco indicates that it was deposited in a marine environment. Much of the volcaniclastic debris originated near sea level, as is shown by the clasts of shallow-water fossils included in the volcaniclastic rocks. However, the presence of graded bedding in the sandstones and the exclusively planktonic character of the fauna of the mudstones indicate that much of the formation was deposited in at least moderately deep water.

AGE AND CORRELATION

Identifiable fossils were obtained from 24 localities (pl. 1; table 2) in the Hato Puerco Formation. Abundant planktonic Foraminifera were identified by E. A. Pessagno, Jr.; three collections of rudistids were identified by N. F. Sohl. The biostratigraphic determinations give ages ranging from possibly Albian to Turonian. The stratigraphically lowest diagnostic faunas (locs. 37, 38) are of early Cenomanian Age and occur about 300 m above the base of the formation in the northeast corner of El Yunque quadrangle. Foraminifera of probable middle Cenomanian Age occur in the middle part of the formation in the northern part of El Yunque quadrangle (loc. 33) and in the upper part of the formation where it underlies the Infierno Formation southwest of the Leprocomio fault (locs. 42, 43). Late Cenomanian fossils occur higher in the Hato Puerco below the Infierno (loc. 41) and at six localities in the trough of the Río Canóvanas syncline (locs. 27, 29, 30) and in the upper part of the formation in the northern part of the Gurabo quadrangle (locs. 22, 23, 24). Turonian fossils occur at one locality (loc. 40) in the Quebrada Infierno just west of the mapped area, near the top of the formation.

Three collections of Foraminifera of possible Albian Age (locs. 32, 34, 35) came from beds stratigraphically above the diagnostic early Cenomanian faunas. Pessagno (written commun., 1966) pointed out that the Albian Age is suggested only by the absence of certain forms, and the faunas could be younger but impoverished in species. Three other collections (21, 26, 28) from the upper part of the Hato Puerco are anomalously old (possibly Albian to middle Cenomanian) with respect to other determinations. Each of these collections was made from blocks of mudstone included in sandstone and breccia and suggests that the blocks were reworked from older beds.

According to Sohl (written commun., 1965), the three rudistid collections (22, 30, 44) are probably of Cenomanian Age although related forms are known as low as the late Albian.

In summary, the fossil determinations show that the Hato Puerco Formation is largely of Cenomanian Age. The basal part could be as old as Albian, and the uppermost beds, at least locally, are Turonian.

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The age of the Hato Puerco Formation indicates that it is equivalent to part of the Robles Formation (defined by Pease and Briggs, 1960) of Albian to Santonian Age of central Puerto Rico. It is probably also equivalent to part of the Río Orocovis Group (Berryhill, 1965, p. 45) of north-central Puerto Rico. Stratigraphic position and lithologic similarity suggest that the Hato Puerco is equivalent to at least part of a sequence of formations defined by Pease (1968a) which underlies the Santa Olaya Lava in the Naranjito quadrangle, north-central Puerto Rico. From top to bottom these formations are the Cancel Breccia, El Ocho Formation, Cerro Gordo Lava, and Pajaros Tuff. According to Pessagno (written commun., 1966), poorly preserved Forminifera in a sample of mudstone collected from the Piña Siltstone Member of the El Ocho Formation (57,730 N. × 174,330 E.) may indicate a late Cenomanian age.

Along the northern part of the western border of the Gurabo quadrangle, the Hato Puerco Formation is continuous with part of the Guaynabo Formation of Pease (1968a), which also includes beds above and below the Hato Puerco.

CAMBALACHE FORMATION

DEFINITION AND STRATIGRAPHIC RELATIONSHIPS

A sequence of andesitic volcanic breccias, sandstones, and mudstones characterized by abundant altered pumice and perlite is here named the Cambalache Formation for exposures near the upper part of the Quebrada Cambalache, northeastern Gurabo quadrangle. A roadcut on an unpaved road in the southeast corner of barrio Canóvanas (57,450 N. ×210,975 E.) is designated the type locality (pl. 1). A thin vitrophyric lava flow at the top of the formation is here named the Toma de Agua Vitrophyre Member for exposures near the settlement of that name in barrio Canóvanas (58,040 N. ×208,630 E.).

The Cambalache Formation conformably overlies the Hato Puerco Formation with a gradational contact. Near the contact, some fine volcanic breccias of the Hato Puerco contain altered vitric debris like that characteristic of the Cambalache, and many breccias of the Cambalache contain lithic volcanic fragments like those in the Hato Puerco. A consistent contact between the two formations is drawn at the top of the highest lithic volcanic sandstone of the Hato Puerco, generally easily recognized by the presence of oxidized grains. The Cambalache Formation is conformably overlain with a sharp contact by the Canóvanas Formation.

The Cambalache Formation crops out in small areas in the northwestern part of the Gurabo quadrangle, where either the base or the top of the formation is cut out by faulting. The full thickness of the formation is exposed in the north-central part of the report area. The formation averages 350 to 450 m thick but locally is about 600 m thick in the northwestern part of El Yunque quadrangle.

LITHOLOGY

The Cambalache Formation consists of about 60 percent volcanic breccia, 30 percent volcanic sandstone, and 10 percent volcanic and calcareous mudstone. Various rock types occur throughout the formation, commonly interbedded on a scale of a few meters to a few tens of meters. Locally fine volcanic breccia and mudstone are interbedded on a scale of a few centimeters.

Most rocks of the Cambalache Formation weather very deeply. Even rocks exposed in fast-flowing streams are generally slightly weathered. The degree of weathering is in part a function of the amount of altered vitric material present; the highly zeolitized vitric material weathers more readily than unaltered lithic volcanic debris. The light weathering colors (grayish orange to yellowish gray) of many of the vitric Cambalache rocks aids in their recognition in the field.

VOLCANIC BRECCIA

Volcanic breccias are the most variable rock type in the formation. Breccias occur in beds from a few centimeters to at least 10 m thick. Bedding is commonly even, but some very thick beds, probably submarine slide deposits, thin markedly over distances of 5 to 10 m. Some fine breccias grade upward into thick well-graded sandstone beds, and some beds of fine to medium breccia are indistinctly graded. Most breccias, however, show no graded bedding.

The breccias are typically mixtures of lithic and altered vitric material with subordinate crystals of plagioclase and clinopyroxene. The relative abundance of lithic to vitric debris varies through nearly all proportions. Least common but most distinctive breccias are composed chiefly of altered vitric material. These rocks, when completely unweathered, are a distinctive pale green to grayish blue green, mottled with dark gray and grayish green. Grain size is rarely coarser than 2 cm. The vitric breccias are moderately sorted and contain very little material finer than medium sand. Some rocks contain as much as 95 percent altered vitric fragments and about 5 percent mineral grains, chiefly fresh or slightly altered plagioclase, and less abundant fresh clinopyroxene. Most of the altered vitric fragments are pumiceous and have both globular and attenuated vesicles. The long-tube pumice fragments show a moderate tendency to be oriented in the plane of bedding. The pumice-rich rocks from east-central Puerto Rico, described and photographed by Fiske (1969), are from the Cambalache

Formation. Less abundant altered vitric grains are nonvesicular and have well-preserved perlitic cracks. Uncommon beds are rich in altered perlite. These rocks consist of abundant angular fragments of perlite as much as 2 cm in diameter floating in an unsorted matrix of smaller pumice fragments, crystals, and abundant very fine mud. Some beds of altered vitric breccia contain abundant strongly flattened blebs of dense microcrystalline zeolite. The blebs superficially resemble the collapsed pumice fragments of welded tuffs but more probably were formed by compaction and alteration of vitric material during diagenesis.

Volcanic breccias of mixed lithic and vitric components have a wide range of sorting. In part, these rocks are moderately sorted; grain sizes range from fine pebbles mixed with medium and coarse sand to fragments chiefly 0.5 to 4 cm in diameter. Uncommon breccias are composed chiefly of 4- to 30-cm fragments. Most of the fragments in these breccias are volcanic rock with microtrachytic texture, sparse vesicles, and sparse plagioclase phenocrysts. Some lithic volcanic fragments contain abundant vesicles, and some are rich in plagioclase phenocrysts or have sparse clinopyroxene phenocrysts. Commonly, a small percentage of the grains are oxidized. Less abundant constituents include globular and long-tube pumice, perlite, plagioclase, and clinopyroxene. Most grains are angular to subrounded, but many rocks contain a small percentage of well-rounded mudstone fragments.

Some of these otherwise moderately sorted fine breccias contain scattered larger clasts of volcanic rock reaching a size of as much as 2 m but more commonly 10 cm to 1 m. In some exposures, they are very widely scattered and are separated from each other by several meters, but locally they make up as much as 25 percent of the breccia. The are commonly rounded to subrounded. Most of these larger fragments are of a rather uniform lithology similar to that of devitrified parts of the Toma de Agua Vitrophyre Member. They are medium gray to medium dark gray and nonamygdaloidal to sparsely amygdaloidal; they have a very fine grained felted to microtrachytic groundmass and sparse to moderately abundant small phenocrysts of plagioclase and subordinate clinopyroxene commonly in glomeroporphyritic clusters. Many of the large lava fragments have a well-developed flow banding.

Other volcanic breccias are composed of a thoroughly unsorted mixture of sand, pebbles, cobbles, and, rarely, small boulders. Fragments include lithic volcanic rock, pumice, calcareous and volcanic mudstone, and uncommon very light gray limestone containing corals and other thick-shelled fossils. Most of the fragments are angular although many mudstone and limestone fragments are rounded. These breccias commonly occur in very thick beds, but in a rare example a 17-cm limestone cobble was recovered from a bed only about 20 cm thick.

VOLCANIC SANDSTONE AND MUDSTONE

Volcanic sandstones of the Cambalache Formation are grayish blue green to dusky blue green, fine to coarse grained, and moderately sorted. They occur in thin to very thick beds. Many sandstones are laminated and some good exposures show graded bedding. Small-scale crossbedding occurs in some thin to medium beds. The volcanic sandstones are composed of pumiceous and lithic volcanic grains similar to those in the volcanic breccias and less abundant plagioclase and clinopyroxene crystals. Some sandstones contain sparse Radiolaria and planktonic Foraminifera. Oxidized fragments are very rare. Thin sections made from three levels of a graded sandstone bed show a good gradation in size but little or no sorting according to density.

Mudstones are medium gray to dark gray, thin bedded, and aphanitic to silty. They are composed of widely varying proportions of very fine volcanic debris and planktonic microfossils. Some volcanic mudstones are almost completely replaced by 1-mm grains of granoblastic laumonite. Small penecontemporaneous slump structures occur in some mudstones. These structures commonly involve laminae within a thin bed but not the bed itself. Some small slump folds are nearly isoclinal.

MUDSTONE SLABS

Discoidal and irregular slabs of mudstone are commonly found in the fine breccias and coarse sandstone of the Cambalache Formation. The slabs are less than a centimeter to more than 4 m in diameter and have ratios of diameter to thickness ranging from about 4 to about 20. The slabs are very commonly oriented parallel or nearly parallel to the bedding of the beds that contain them. Only in the coarse very poorly sorted breccias do the slabs have random orientations. Individual slabs commonly consist of a single bed of mudstone; rarely do they consist of several beds. The edges are generally tapered and rounded; rarely are they irregular and angular. The mudstone slabs are most common in very thick beds but also occur in thin and medium beds. In some beds, the slabs are distributed randomly throughout, and in others they are concentrated at definite levels in the middle part of the bed. Most beds containing mudstone slabs are not graded, but sparse slabs occur in some graded beds.

The mudstone slabs that occur in graded beds clearly were transported by the turbidity currents that deposited the graded beds. However, most of the mudstone slabs in the Cambalache Formation, especially the larger ones, probably formed by postdepositional flow of unconsolidated sand and gravel when the semiconsolidated mudstone interbeds broke apart. The mobility of the unconsolidated volcaniclastic debris is also shown in rare exposures where sandstone and fine breccia crosscut mudstone and form clastic sills and dikes within mudstone. Such sills and dikes are probably common, but the critical crosscutting relationships are seldom exposed in the generally small outcrops of the Cambalache Formation. Probably many of the thin but coarse clastic units containing mudstone slabs are clastic sills rather than true beds.

TOMA DE AGUA VITROPHYRE MEMBER

The Toma de Agua Vitrophyre Member of the Cambalache Formation ranges from 0 to about 50 m in thickness. It occurs at the top of the Cambalache Formation in the northwestern El Yunque and northeastern Gurabo quadrangles but is absent in the northwestern part of the Gurabo quadrangle. The rock has well-developed platy jointing and locally has columnar jointing. (See Meyerhoff and Smith, 1931, fig. 20.) The unaltered rock is black, has a vitreous luster, and breaks with a hackly to conchoidal fracture. In thin section, the rock consists of about 65 percent light-brown glass containing many crystallites. The glass locally has perlitic cracks and in part shows flow layering. Very fresh intermediate plagioclase and less abundant augite occur as microlites and as sparse phenocrysts, typically in glomeroporphyritic clusters. An undetermined but probably large part of the Toma de Agua Vitrophyre Member is devitrified. The groundmass of the devitrified rock has a felted texture and consists chiefly of plagioclase, chlorite, minor quartz, and calcite. Much of the plagioclase of the devitrified rock is altered to albite.

The restricted occurrence of the Toma de Agua Vitrophyre Member at the same stratigraphic horizon at the top of the Cambalache Formation suggests that it is a lava flow. However, the upper contact is not well enough exposed to preclude the possibility that it is an intrusive sheet. Consanguinity of the vitrophyre with the volcaniclastic rocks of the Cambalache is suggested by the strong textural similarity of the Toma de Agua to blocks of lava included in the volcaniclastic rocks and by the close chemical similarity of the vitrophyre to the zeolitized volcaniclastic rocks (table 1, samples 6, 7).

SECONDARY MINERALS

Undevitrified volcanic glass is preserved only in the Toma de Agua Vitrophyre Member of the Cambalache Foundation. Secondary minerals are common in the volcaniclastic rocks of the Cambalache and are most abundant in rocks originally rich in vitric material. Secondary minerals include analcite, heulandite, laumontite, albite, quartz, calcite and phyllosilicates.

AGE AND CORRELATION

A single locality very near the base of the Cambalache Formation (loc. 18, pl. 1; table 2) has yielded a sparse foraminiferal fauna of Turonian Age (E. A. Pessagno, Jr., written commun., 1968). The overlying Canóvanas Formation also contains Turonian fossils, and the Cambalache, therefore, is largely or entirely Turonian.

The Cambalache Formation is correlative with the Infierno Formation (Turonian) of the southwestern part of the Guarabo quadrangle. It is equivalent in age to part of the Robles Formation (Albian to Santonian) and Río Orocovis Group of central Puerto Rico. It is probably equivalent to parts of the Guaynabo Formation and Santa Olaya Lava (defined by Pease, 1968a) of north-central Puerto Rico.

CANÓVANAS FORMATION

DEFINITION AND STRATIGRAPHIC RELATIONSHIPS

The Canóvanas Formation is here named for a sequence of mudstones and volcanic sandstones exposed in barrio Canóvanas in the northeastern corner of the Gurabo quadrangle. Exposures along a stretch of the Quebrada Cambalache extending about 700 m upstream from the point where the stream leaves the Gurabo quadrangle (59,120 N. ×211,420 E. to 58,540 N. ×211,390 E.) are designated the type locality (pl. 1). A good reference section in the western part of the area is exposed on the north bank of the Río Grande de Loíza 1.5 km east of the western border of the Gurabo quadrangle (58,520 N. ×199,670 E.).

The Canóvanas Formation consists of about 75 percent volcanic sandstone and 25 percent calcareous mudstone. The sandstones are commonly pebbly and probably formed from a mixture of reworked pyroclastic and epiclastic debris chiefly of basaltic composition. A few beds of hornblende andesite composition are present locally in the upper part.

The Canóvanas Formation rests conformably on the Cambalache Formation. In general, the contact between the Canóvanas and Cambalache is sharp, but rarely the lower beds of the Canóvanas contain small amounts of the long-tube pumice that is characteristic of the Cambalache. The Canóvanas is conformably overlain by the Martín González Lava.

Near the border between the Gurabo and El Yunque quadrangles, the Canóvanas Formation is about 450 m thick. In this area, mudstones are more abundant in the upper one-third and sandstones in the lower two-thirds of the formation. In the northwestern part of the Gurabo quadrangle, the Canóvanas ranges from about 100 to 200 m in thickness.

LITHOLOGY

Volcanic sandstones of the Canóvanas Formation are medium to dark gray and medium to coarse grained. They most commonly occur in thick beds, but some beds are only a few centimeters thick and others are at least 2 m thick. Sedimentary structures are rarely well shown, but graded bedding is locally well developed. Most of the sandstones are slightly calcareous, and in some areas flattened ellipsoidal and irregular concretions of calcareous mudstone as much as 20 cm in diameter occur in the sandstone.

Many of the volcanic sandstones contain a few percent to a maximum of about 40 percent of well-rounded sand, pebbles, and, rarely, small cobbles. The rounded clasts are rather poorly sorted and have a disrupted framework and a matrix of moderately sorted angular sand grains.

Textures are moderately well preserved although most of the primary constituents of the sandstones are replaced by zeolites and phyllosilicates. Typical sandstones contain about 45 percent grains recognizable as volcanic-rock fragments. About half these grains are nonvesicular and consist of a very fine grained moderately turbid, felted to pilotaxitic groundmass with sparse phenocrysts of plagioclase and clinopyroxene and rare hornblende phenocrysts. Other volcanic-rock grains are largely to completely replaced by a green and brown finely to coarsely crystalline phyllosilicate having low to moderately high birefringence, probably nontronite. Some of these grains have cellular structure, and some approach pumice of the globular variety. Recognizable plagioclase grains, almost completely replaced by zeolite, make up about 13 percent of of the rock, and fresh clinopyroxene constitutes about 11 percent. A few green hornblende grains are present. Well-rounded grains are chiefly of volcanic rock with the same textures as the angular volcanic-rock grains but locally fragments of fine- to medium-grained diabase are included. In the western part of the area, a common type of rounded fragment is a basalt with a pilotaxitic groundmass containing abundant stubby clinopyroxene grains and plagioclase microlites with phenocrysts of fresh clinopyroxene and probable olivine completely replaced by phyllosilicate. A small percentage of rounded mudstone fragments is present everywhere.

A few beds of hornblende andesitic volcanic sandstone occur interbedded with basaltic sandstone about 50 m below the top of the Canóvanas Formation on the north bank of the Río Grande de Loíza 1.5 km east of the western border of the Gurabo quadrangle.

The andesitic sandstone contains about 10 percent euhedral and broken grains of hornblende with a pleochroic formula of X=pale yellow, Y=pale brown, and Z=reddish brown, rarely pale olive. Plagioclase grains, in part replaced by calcite, zeolite, and phyllosilicate, are an abundant constituent. Angular fragments of aphanitic volcanic rock with sparse phenocrysts of plagioclase, clinopyroxene, and hornblende are slightly less abundant. Clastic clinopyroxene crystals make up 1 or 2 percent of the rock. Small euhedral crystals of apatite are a common accessory. There are no rounded grains.

Mudstones of the Canóvanas Formation are medium gray to medium dark gray and thin to medium bedded, uncommonly thick bedded. The mudstones are calcareous, aphanitic to finely sandy, and in part laminated with siltstone and fine sandstone. They occur as thin units interbedded with the volcanc sandstones throughout the formation but are more abundant in the upper part of the formation near the type locality. Radiolaria and planktonic Foraminifera occur abundantly in the mudstones and are the only fossils found in the Canóvanas Formation.

AGE AND CORRELATION

Planktonic Foraminifera identified by E. A. Pessagno, Jr., from seven localities in the Canóvanas Formation indicate that the formation ranges from Turonian to Santonian in age. Five of these localities are in the upper part of the formation northwest of the type locality in barrio Canóvanas (pl. 1; table 2). The stratigraphically lowest determination comes from beds about 320 m above the base of the formation and is late Turonian (loc. 17).[2] On the basis of this determination and the fact that the underlying Cambalache Formation is Turonian in age, the lower 320 m of the Canóvanas is also Turonian. Beds about 40 m higher in the Canóvanas section have a Coniacian fauna (loc. 15). Foraminifera with ranges of Coniacian to early Santonian occur in overlying beds (locs. 13, 14), and a diagnostic early Santonian fauna is found near the top (loc. 11). Fossil assemblages with ages of late Turonian and late Turonian–early Santonian occur at localities 16 and 12 in the north-central part of the Gurabo quadrangle.

The Turonian to Santonian Age of the Canóvanas Formation indicates that it is correlative with the upper part of the Robles Forma-

[2] Pease (1968a, table 1, loc. 6) reported a Cenomanian Age supplied by me from this locality. A new collection yielded the Turonian determination. The earlier age may have resulted from a mixed sample number.

tion (Pease and Briggs, 1960) of Albian to Santonian Age of central Puerto Rico. The basaltic Cotorra Tuff is equivalent to the uppermost Robles (Briggs, 1967, p. A28) and therefore, is probably correlative with the Canóvanas. Likewise, the Tetuán Formation (Nelson and Monroe, 1966) is in part equivalent to the Cotorra (Briggs, 1967, p. A25, fig. 3) and is probably correlative with the Canóvanas. In the type area, the Tetuán has yielded an ammonite with a Santonian to Campanian range (Nelson and Monroe, 1966, p. C8). The basaltic Los Negros Formation (Nelson, 1966) of the Río Orocovis Group of north-central Puerto Rico is considered by Briggs (1967, p. A8) to be correlative in a general way with the Cotorra. A similar correlation of the Los Negros with the Canóvanas is likely.

The distinctive hornblende andesitic volcanic sandstones of the upper part of the Canóvanas in its western exposures are probably correlative with similar rocks in the Cariblanco Formation (Santonian) of Glover (1961, 1971) or, possibly, with similar beds in the Maravillas Formation (Mattson, 1967) of Santonian-Campanian Age. These formations are known only from central and southern Puerto Rico. In northern Puerto Rico, hornblende andesitic rocks of equivalent age have not been described until now. Here they must be absent or, as in the Gurabo quadrangle, very thin.

Strata here assigned to the Canóvanas Formation previously were mapped by Pease (1968a, b) in the middle part of the Guaynabo Formation in the Gurabo and Aguas Buenas quadrangles. The Canóvanas Formation is equivalent to beds in the upper part of the Guaynabo Formation as defined by Kaye (1959).

The Canóvanas is probably correlative with the Celada Formation in the southern part of the Gurabo quadrangle.

MARTÍN GONZÁLEZ LAVA

DEFINITION AND THICKNESS

The Martín González Lava was defined by Pease (1968a, p. 23) as a member of the Guaynabo Formation. Pease designated a large quarry in barrio Martín González, Gurabo quadrangle, as the type locality.

In the present report, strata mapped by Pease (1968a) as the Guaynabo Formation in the Gurabo quadrangle are, however, divided into several formations, and the name Guaynabo Formation is not used. The Martín González Lava is one of these formations; it is here raised to formational rank.

The Martín González crops out in the northern part of the Gurabo quadrangle and northwestern part of El Yunque quadrangle. The lava forms a discontinuous sheet between the underlying Canóvanas Formation and the overlying Frailes Formation. The lava varies widely in thickness, and abrupt changes in thickness take place across northwest-trending faults cutting the lava. In the northwestern corner of the Gurabo quadrangle, the Martín González is about 200 m thick. Near the type locality just east of a northwest-trending fault, the lava is about 700 m thick. In the north-central part of the Gurabo quadrangle, east of another fault, the Martín González is absent. In barrio Canóvanas, east of another fault, it is about 200 m thick. It is about 50 m thick in the northwestern part of El Yunque quadrangle east of another fault.

LITHOLOGY

Typically, the Martín González Lava is grayish green to dusky green with abundant 2- to 5-mm nearly equant plagioclase phenocrysts in a very fine grained groundmass. Plagioclase phenocrysts commonly make up more than 40 percent of the rock and locally are tightly packed, the groundmass being restricted to small intergranular spaces. Sparse clinopyroxene phenocrysts are present locally. At one locality, the rock also contains phenocrysts of orthopyroxene largely replaced by antigorite. The turbid groundmass has intersertal to hyalopilitic textures and consists of plagioclase, clinopyroxene, iron oxides, and greenish clorite. Amygdules are generally common but locally are absent. At least some of the plagioclase is generally turbid and albitized. Secondard minerals in amygdules and less abundantly in the groundmass and phenocrysts include calcite, laumontite, prehnite, and chlorite.

A chemical analysis of the Martín González Lava is given in table 1 (sample 5). The composition is that of a mafic andesite or basalt. Possibly the rock is best termed a "basaltic andesite."

STRATIGRAPHIC RELATIONSHIPS AND ORIGIN

The Martín González at the western border of the Gurabo quadrangle is continuous with rocks mapped by Kaye (1959) in the San Juan area as augite andesite porphyry. Kaye (p. 30) considered the possibility of an extrusive origin of the porphyry but interpreted it as an intrusive sill. Later, Pease (1968a, p. 24–25) described pillow structures in the Martín González. He also reported contacts between the Martín González and an included lens of bedded tuff, indicating that the bedded rock was unconsolidated at the time of emplacement of the lava. Similar contact relationships have since been exposed at the base of the Martín González just east of the village of Trujillo Bajo in the Gurabo quadrangle. Here the porphyry rests on thin-bedded mudstones of the Canóvanas Formation. Although the lava is not obviously pillowed, broad 20-cm to 1-m mammillary bulges press into the underlying mudstone, and wedges of mudstone rise as much as 1 m into the overlying lava. The mudstone is not baked at the contact with the lava.

The contact relationships, the local occurrence of pillows, and the common occurrence of amygdules strongly suggest that the Martín González is a submarine lava flow or series of flows. The lava locally sank into the soft sediments upon which it was extruded, but it is unlikely that the bulk of the unit was emplaced as a sill under any great thickness of rock.

Near Buenaventura, in the north-central part of the Gurabo quadrangle, the typical Martín González Lava is absent between the Canóvanas and Frailes Formations. Instead, an unnamed sheet of diabase porphyry and diabase occurs at this horizon. To the east, this sheet is above the base of the Frailes Formation. In the western part of barrio Canóvanas, the base of the sheet is generally about 100 m above the top of the Martín González. East of the Río Canóvanas, however, the base of the sheet is in contact with the underlying Canóvanas Formation, and the Martín González does not appear at the surface. In this area, the top of the diabase porphyry is exposed in a small excavation in the southeastern part of the Carolina quadrangle. The top of the sheet is nearly horizontal and shows a sharply discordant contact with more steeply dipping mudstone beds above.

Pease (1968a) mapped the diabase porphyry and diabase of this area as part of the Martín González. If this is correct, the Martín González everywhere must be an intrusive sheet rather than an extrusive lava. The discordant top of the sheet is about 800 m stratigraphically above the base, which is at nearly the same horizon as the base of the Martín González to the west. If the two rocks are the same, the base of the Martín González must have been emplaced under a cover of at least about 800 m of rock. This conclusion conflicts with the evidence suggesting that the Martín González is largely extrusive.

In spite of the superficial lithologic similarity and close association in the field, other differences indicate that the Martín González and the diabase porphyry are distinct and unrelated bodies. (1) Plagioclase phenocrysts in the diabase porphyry are only moderately abundant and are lath shaped, whereas those of the Martín González are quite abundant and more nearly equant. (2) The diabase porphyry contains abundant accessory apatite, which is absent in the Martín González. (3) Unlike the Martín González, the diabase porphyry varies to a medium-grained diabase with subophitic to intergranular texture and sparse hornblende grains. (4) Amygdules and, locally, pillows are present in the Martín González but are absent in the diabase. (5) Contact relationships of the Martín González indicate emplacement on unconsolidated sediments, whereas the straight upper contact of the diabase sheet suggests emplacement in fully lithified rock.

AGE

No identifiable fossils have been found within the Martín González Lava. However, early Santonian fossils occur near the top of the underlying Canóvanas Formation (loc. 11, table 2), and early Campanian fossils occur near the base of the overlying Frailes Formation (loc. 9). The Martín González, therefore, is Santonian to early Campanian in age.

FRAILES FORMATION

DEFINITION AND STRATIGRAPHIC RELATIONSHIPS

The Frailes Formation was defined by Kaye (1959, p. 16) to describe a sequence of "sedimentary and pyroclastic rocks (particularly a massive lapilli tuff) with prominent limestones in the upper and lower parts." Kaye (1959, p. 13) indicated that the Frailes Formation overlies the Tortugas Andesite (defined by Kaye, 1959) or, where that formation is absent, the Guaynabo Formation (defined by Meyerhoff and Smith, 1931, and redefined by Kaye, 1959). Later, Pease (1968a, p. 21) discovered that a consistent contact between the Guaynabo and Frailes Formation could not be found in much of the Aguas Buenas quadrangle; apparently, the chief rock types were intercalated over a thick sequence of rocks. He therefore (p. 21) redefined the Guaynabo Formation to include both the Guaynabo and Frailes of Kaye's usage. The part of Kaye's Frailes that overlies the Tortugas Andesite was considered by Pease (p. 21–22) as part of the Tortugas. Pease (p. 23) indicated that near the eastern edge of the Aguas Buenas quadrangle and in the Gurabo quadrangle Kaye's Frailes and Guaynabo can be distinguished.

The name Frailes was taken from barrio Frailes in the western part of the Aguas Buenas quadrangle, but Kaye (1959, p. 16, 19) designated exposures near the eastern edge of that quadrangle, along Highways 175 and 23,[3] as the type locality. The rocks exposed at the type locality are continuous with beds in the Gurabo quadrangle, and the name Frailes is here retained to describe these beds.

Kaye (1959, p. 16) indicated that at the type locality the Frailes Formation overlies an andesite porphyry sill. This andesite porphyry was interpreted by Pease (1968a) as a lava and was named the Martín González Lava Member of the Guaynabo Formation. In the present report, the Martín González Lava Member is raised to formational status, and the base of the Frailes Formation is redefined as the top of the Martín González Lava. Where the Martín González is absent in the Gurabo quadrangle, the base of the Frailes is defined as

[3] The number of Highway 23 has since been changed to 181.

the base of the lowest volcanic breccia overlying the volcanic sandstones and mudstones of the Canóvanas Formation.

Kaye (1959, p. 18–19) included the La Muda Limestone as a member in the lower part of the Frailes Formation. This unit was redefined as the La Muda Formation by Pease (1968a, p. 34). The two thin beds in the type section of the Frailes that Kaye referred to the La Muda Limestone Member do not continue into the Gurabo quadrangle.

Kaye (1959, p. 19) named the Leprocomio Limestone Member of the Frailes Formation for exposures near Leprocomio in the northeastern part of the Aguas Buenas quadrangle. Pease (1968a, p. 22) changed the name to Leprocomio Siltstone and made it a member of the Guaynabo Formation. The Leprocomio is here retained as the Leprocomio Mudstone Member at the top of the Frailes Formation.

The Frailes Formation ranges in thickness from about 900 m in the northwestern part of the Gurabo quadrangle to about 1,100 m in the northeastern part of the quadrangle, including about 220 m of the Leprocomio Mudstone Member.

LITHOLOGY

Kaye (1959, p. 16) stressed the diversity of rock types found in the type area of the Frailes Formation, and this is also characteristic of the Frailes in the present area. Calcareous foraminiferal mudstones are most abundant near the base of the formation and in the Leprocomio Mudstone Member at the top. The thick, middle part of the Frailes consists of interbedded grayish-green andesitic to dacitic volcanic sandstone, pebbly volcanic sandstone, fine volcanic breccia, fine to medium breccia-conglomerates, and less abundant volcanic mudstones. In the eastern exposures of the formation, two units of pillow lava are present.

LOWER PART

In most exposures, the base of the Frailes is marked by a thin unit of very poorly sorted fine to medium volcanic breccia. The breccia is composed chiefly of nonvesicular to sparsely vesicular greenish volcanic-rock fragments and spare rounded fragments of mudstone and volcanic sandstone. Commonly, a small percentage of grains are oxidized. Most of the volcanic fragments have a turbid cryptocrystalline texture. Less commonly, the texture is felted to pilotaxitic with sparse plagioclase phenocrysts. A few wisps of phyllosilicate resemble compressed pumice fragments. The breccia locally has a highly calcareous matrix.

In most areas, the overlying 100 m of the Frailes consist chiefly of dark-gray thin- to medium-bedded calcareous mudstone containing abundant planktonic Foraminifera.

MIDDLE PART

Volcaniclastic rocks of the middle part of the Frailes are chiefly thick to very thick bedded sandstones and fine breccias and less abundant thin- to medium-bedded sandstones and mudstones. These rocks are chiefly grayish green and only locally contain sparse oxidized grains. Many beds are composed of angular moderately sorted grains, but not uncommonly the sandstones are pebbly to cobbly and locally grade into poorly sorted breccia-conglomerates.

The volcaniclastic rocks are composed chiefly of angular and rounded fragments of volcanic rock with turbid cryptocrystalline, felted, and microtrachytic textures. Less than half the fragments have plagioclase phenocrysts. Pyroxene phenocrysts, replaced by phyllosilicate or calcite, are uncommon. Embayed volcanic quartz crystals are a minor but nearly ubiquitous constituent. Accessory minerals in the volcanic-rock fragments and in the matrix include apatite and stubby zircon crystals. Scattered grains of mudstone and radiolarian chert commonly are present.

A few rounded grains are composed chiefly of fine- to medium-grained granoblastic quartz and feldspar, in part with sparse epidote grains. These fragments resemble some of the hydrothermally altered rocks from the southern part of the Gurabo quadrangle. Rounded detrital grains of epidote are also present in some rocks. These fragments mark the first appearance in the stratigraphic section of detritus from previously altered or metamorphosed rock. However, the general lack of diversity in the kinds of volcanic-rock fragments in the Frailes suggests that the altered fragments were derived from small areas, perhaps by the erosion of an island or islands in which the aureole of a small high-level pluton was exposed. No widespread interval of deep denudation is indicated.

Just below the Leprocomio Mudstone Member in the western exposures and just below the upper lava member in the east, the Frailes volcaniclastic rocks generally lack rounded volcanic-rock fragments but contain abundant large scattered fragments of mudstone. These beds are probably equivalent to the thick sequence of massive lapilli tuff described by Kaye (1959, p. 16) at the type locality of the Frailes. The rocks consist of 0.5- to 10-m beds of coarse volcanic sandstone to fine volcanic breccia with thin units of interbedded thin- to medium-bedded standstone and mudstone. Some very thick beds are graded. Some beds are rich in pumice fragments, commonly much altered and compressed in the plane of bedding. Other rocks are composed chiefly of angular fragments of dense cryptocrystalline volcanic rock with less abundant plagioclase grains and very sparse quartz crystals. Some volcanic fragments show poorly preserved perlitic cracks. Angular and rounded fragments of volcanic and calcareous mudstone are from sand size to as large as 2 m. Locally, the mudstone fragments are roughly disk shaped and are oriented parallel to bedding, but more commonly the orientation is random.

LAVA MEMBERS

The lower of the two lava members of the Frailes Formation is evidenced only by float in barrio Canóvanas, Gurabo quadrangle. The rock, probably a basalt, consists of abundant 1- to 2-mm clinopyroxene phenocrysts in fine-grained intersertal groundmass of turbid plagioclase, clinopyroxene, and secondary minerals. Sparse phenocrysts of olivine or orthopyroxene are entirely replaced by phyllosilicate. Secondary prehnite occurs in sparse amygdules and in the groundmass. Although there are no outcrops of the lava, the presence of pillow structures is suggested by the occurrence of float fragments of cherty material similar to that which occurs in the interpillow spaces of many pillow lavas.

The upper lava member of the Frailes was temporarily well exposed in an area of housing construction in barrio Canóvanas. The lava is about 85 to 125 m thick. In the upper part, it is pillowed and contains moderate blue-green cherty interpillow material. The lava is medium bluish gray to dark greenish gray and consists of abundant small (0.5–1 mm) plagioclase phenocrysts in a fine-grained intersertal groundmass of plagioclase, calcite, chlorite, laumontite, iron oxides, sparse clinopyroxene, and minor prehnite and apatite. The albitic plagioclase is highly turbid and is in part replaced by calcite and laumontite. Abundant small irregular amygdules and sparse larger (2–5 mm) ovoid amygdules are present. The altered nature of the lava, originally of basaltic to andesitic composition, is shown in the chemical analysis (table 1, sample 4).

The upper lava member is overlain by about 20 m of medium to very thick bedded poorly sorted fine breccia-conglomerate and less abundant volcanic sandstone, in part pebbly. Pillows are well developed at the top of the lava, and the overlying breccia-conglomerate fills depressions between the pillows. The breccia-conglomerate is conformably overlain by the Leprocomio Mudstone Member.

LEPROCOMIO MUDSTONE MEMBER

The Leprocomio Mudstone Member consists chiefly of thin- to medium-bedded, rarely thick-bedded, calcareous mudstone and much less abundant volcanic mudstone and sandstone. The calcareous mudstone is medium light gray to medium dark gray and weathers light gray. It contains abundant planktonic Foraminifera. The calcareous mudstone locally grades into pale-green volcanic mudstone. Grayish-green volcanic sandstone, rarely showing graded bedding, makes up a very small part of the member.

CONDITIONS OF DEPOSITION

Deposition of the Frailes in at least moderately deep water is indicated by the occurrence of graded beds and by the almost exclusively planktonic character of the fossils of the mudstone. Just west of the mapped area, in the type locality of the Frailes, rudistids and algae occur near the base of the formation and indicate a shallower environment there.

AGE AND CORRELATION

Identifiable fossils were collected from eight localities in the Frailes Formation (pl. 1; table 2). Rudistids collected from the lower part of the formation at the type locality (loc. 10) were examined by N. F. Sohl, who suggested an early Campanian or younger age (written commun., 1965). Planktonic Foraminfera identified by E. A. Pessagno, Jr. (written commun., 1965), from the lower mudstones of the formation in barrios Martín González and Canóvanas (locs. 8 and 9, respectively, about 100 m and 50 m above the base of the formation) indicated an early Campanian Age. Foraminifera identified by Pessagno (written commun., 1965) from three localities in the Leprocomio Mudstone Member in the Aguas Buenas quadrangle (locs. 5, 6, 7) indicated late Campanian Age. Collections from two localities in the upper part of the Leprocomio (loc. 4 in barrio Cuevas and loc. 3 in barrio Canovanillas) yielded Foraminifera of probably late Campanian, or possibly early Maestrichtian Age (Pessagno, written commun. 1965, 1967). Pease (1968a, p. 27) reported a late Campanian *Inoceramus* identified by E. G. Kauffman from the top of the Leprocomio in the Aguas Buenas quadrangle. The Frailes Formation, therefore, ranges from early to late Campanian in age.

The Frailes Formation is equivalent to that part of the Guaynabo Formation, as defined by Pease (1968a), stratigraphically above the Martín González Lava. Pease (1968a, p. 27–28) correlated the Martín González with the Mamey Lava Member of the Camarones Sandstone. If this correlation is correct, then the Frailes is equivalent to that part of the Camarones which overlies the Mamey and to the overlying Tortugas Andesite. However, Pease (1968a, p. 28, 30, 31) reported that a boulder of limestone probably derived from the Tortugas contained a single poorly preserved fragment of *Inoceramus* of Coniacian Age, in apparent conflict with the Campanian Age obtained from Foraminifera in seemingly equivalent beds in the Gurabo quadrangle. Pease (1968a, p. 31) accepted the stratigraphic evidence favoring the correlation and suggested that the conflict results from divergent ages determined from microfossils and macrofossils. However, the fragmental nature of the *Inoceramus* and the presence of conglomerates elsewhere in the Tortugas (Pease, 1968a, p. 29) present the distinct possibility that this fossil was reworked. If the Mamey and Martín González lavas are equivalent, as seems probable, there is no reason to doubt the correlation and Campanian Age of the Tortugas and Frailes Formations.

In north-central Puerto Rico, the lithologically similar Manicaboa Formation and at least part of the overlying Pozas Formation (Berryhill, 1965) are probably correlative with the Frailes. Recent paleontological data are consistent with a Campanian Age for the Manicaboa and show that part of the Pozas is definitely Campanian. According to Briggs (1969), the Río Bauta Member of the Pozas Formation contains fossils of probable late Santonian to early Campanian Age; the Río Bauta is probably correlative with the upper part of the Manicaboa. The stratigraphically higher Flor de Alba Limestone Lentil of the Pozas contains Campanian-Maestrichtian fossils (Nelson and Monroe, 1966, p. C12; late Campanian to early Maestrichtian, according to Sohl, written commun., 1965). The Coamo Formation (Glover, 1961) of south-central Puerto Rico contains Campanian or Maestrichtian fossils (Mattson, 1967, p. B20) and is probably in part correlative with the Frailes.

MONACILLO FORMATION

DEFINITION AND STRATIGRAPHIC RELATIONSHIPS

The Monacillo Formation was named by Kaye (1959, p. 19–20) to describe beds ranging from siltstone to conglomerate that are between the Frailes Formation and the Trujillo Alto Limestone. Later, Pease (1968a, p. 36–38) redefined the Monacillo to include the Trujillo Alto Limestone of Kaye, making that limestone a member in the upper part of the Monacillo. Some beds of limestone, possibly considered the uppermost part of the Trujillo Alto by Kaye, were included by Pease (1968a, p. 42) in the base of the overlying Guaracanal Andesite. Pease (1968a, p. 26, 38; 1968b) took the top of the Leprocomio Siltstone Member of the Guaynabo Formation as the base of the Monacillo in most areas. However, in the northeast corner of the Aguas Buenas quadrangle and adjacent areas of the Carolina and Gurabo quadrangles, Pease assigned beds overlying the Leprocomio to the Guaynabo Formation. The top of these beds, described as volcanic wacke, pebble conglomerate, and a discontinuous basalt lava, was taken as the base of the Monacillo. However, the contrast between these rocks of the Guaynabo and similar rock types in the Monacillo is not great. In the present report, following the original usage of Kaye, the base of the Monacillo is drawn at the top of the distinctive Leprocomio Mudstone Member of the Frailes Formation.

In the Gurabo quadrangle, Monacillo exposures are very limited. In the extreme northwestern corner, the lowest 80 m is present; in the north-central part, the Monacillo apparently is represented by the Trujillo Alto Limestone Member only. The Monacillo does not appear in El Yunque quadrangle.

LITHOLOGY

LOWER PART

In the northwestern corner of the Gurabo quadrangle, the lower 80 m of the Monacillo is very poorly exposed but includes volcanic mudstone, sandstone, and, in the upper part, a thin basaltic lava. The lava has a fine-grained intersertal groundmass and contains sparse plagioclase phenocrysts and amygdules of laumontite and chlorite.

TRUJILLO ALTO LIMESTONE MEMBER

Rocks tentatively correlated with the Trujillo Alto Limestone Member of the Monacillo Formation are exposed in a very small area on the northern border of the Gurabo quadrangle, about 2 km west of the town of Loíza (Canóvanas) and 1½ km east of the village of Buenaventura. This locality was mentioned by Pease (1968a, p. 42) and was described in detail by Kaye (1956). At this locality, about 10 m of very thick bedded light-gray fine-grained limestone is exposed; it contains abundant miliolid Foraminifera and less common fragments of hexacorals, coralline algae, and echinoids. The lower contact of this limestone, with the Leprocomio Mudstone Member of the Frailes Formation, here is covered by alluvium, and about 50 m of section is concealed. The limestone is overlain by mudstone of the Guaracanal Formation lower Tertiary.

CRETACEOUS–TERTIARY DISCONFORMITY

Although there is no distinct structural discordance between the Frailes and the Guaracanal, stratigraphic relationships suggest that an important disconformity is present. In the Aguas Buenas quadrangle to the west, the Trujillo Alto Limestone Member of the Monacillo is separated from the Leprocomio Mudstone Member of the Frailes by about 450 m of Cretaceous clastic rocks. According to Pease (1968a, p. 38), these clastic rocks contain pebbles and cobbles derived from older formations and indicate a widespread interval of erosion. At the Loíza locality, if such beds are present at all, they constitute no more than about 50 m in the interval that is covered by alluvium. The shallow-water miliolid limestone may represent the basal transgressive deposit laid down after the interval of erosion. Alternatively, it may have been deposited during a temporary episode of submergence that was both preceded and followed by erosion or nondeposition. Diagnostic fossils that would fix the age of the limestone in the interval between the Frailes Campanian and the Guaracanal Paleocene are lacking.

CORRELATION AND AGE

Both Kaye (1956), p. 111, 113; 1959, p. 22) and Pease (1968a, p. 42) correlated the Gurabo quadrange limestone with the Trujillo Alto Limestone at its type locality in the northeastern part of the Aguas Buenas quadrangle. However, because of its light-gray color and rich content of miliolid Foraminifera, it more closely corresponds to Pease's (1968a, p. 42) description of the limestone included by him in the base of the overlying Guaracanal Andesite. At the Loíza locality, both Kaye and Pease correlated overlying beds containing orbitoid-bearing limestone with the Guaracanal. Pease's meaning, however, is somewhat unclear in that he (p. 42) described this upper limestone as containing miliolids rather than orbitoids and does not mention the miliolids in the underlying Truijillo Alto Limestone Member. According to Kaye (1959, p. 21–22), the massive Trujillo Alto Limestone at the type locality is overlain by thin- to medium-bedded calcareous tuff. At the Loíza locality, similar rocks overlie the miliolid limestone and occur below the orbitoid limestone. In the present report, the usage of Kaye is followed, and the top of the tentative Trujillo Alto is drawn at the base of the overlying thinner bedded rocks. In this usage, the limestone near Loíza may be in part equivalent to the basal limestone of the Guaracanal mapped by Pease near the type locality of the Trujillo Alto.

No diagnostic fossils have been found in the Monacillo Formation in the mapped area. An earlier age limit is set by the late Campanian Age of the underlying Leprocomio Mudstone Member of the Frailes Formation. The Trujillo Alto Limestone Member in the type area has yielded several collections of Late Cretaceous (Kaye, 1959) and possibly early Tertiary fossils (Pease, 1968a, p. 39). The formation, therefore, is Campanian or Maestrichtian, possibly lower Tertiary in the upper part.

GUARACANAL FORMATION

DEFINITION AND STRATIGRAPHIC RELATIONSHIPS

The Guaracanal Andesite was named by Pease (1968a, p. 40) to describe a volcanic sequence of hornblende andesitic composition exposed near the Quebrada Guaracanal, San Juan and Aguas Buenas quadrangles. The name is nearly synonymous with the Figuera Volcanics mapped in the San Juan area by Kaye (1959). Pease (1968a, p. 40, 44) indicated that paleontological data show that these lower Tertiary volcanic rocks are not equivalent to the type Figuera of eastern Puerto Rico, now known to be of Cretaceous age. Pease (p. 40) abandoned the term "Figuera Volcanics."

The Guaracanal Formation overlies the Trujillo Alto Limestone Member of the Monacillo Formation in a small area in the north-central part of the Gurabo quadrangle. This is the Loíza locality described by Kaye (1956). Only a small part of the section here is volcanic, and that part is of basaltic rather than andesitic composition. Therefore, the name Guaracanal Formation rather than Guaracanal Andesite is used here.

LITHOLOGY

In the Gurabo quadrangle, the Guaracanal Formation is exposed in a low northeast-trending hill just north of the Quebrada Cambute. The lowest beds are thin- to medium-bedded volcanic and calcareous mudstones, in part containing planktonic Foraminifera. Near the top of the hill, these mudstones are overlain by a conspicuous medium to very thick bedded medium-light-gray coarse-grained to conglomeratic limestone. The surface of the limestone weathers out in relief showing abundant algal fragments, orbitoid Foraminifera, and less abundant volcaniclastic debris. The stratigraphically highest rock exposed in the Gurabo quadrangle, about 125 m above the base is, an amygdaloidal basaltic lava. This rather unusual rock has a fine-grained pilotaxitic groundmass composed of altered plagioclase, stubby to moderately elongate clinopyroxene, chlorite, iron oxides, and sparse fine-grained biotite. Sparse phenocrysts include plagioclase, clinopyroxene, and brown hornblende. Thompsonite, in Puerto Rico a very uncommon zeolite, was reported by Kaye (1956, p. 111) in amygdules of this rock. Other amygdule minerals include analcite, chlorite, and sparse calcite. A chemical analysis of the rock is given in table 1 (sample 3). Although the rock is basaltic, affinities with the andesites described from other localities of the Guaracanal (Kaye, 1959, p. 23, 25) are indicated by the presence of hornblende phenocrysts, biotite, and thompsonite. According to Kaye (1956, p. 111), the lava is about 43 m thick, and in the Carolina quadrangle it is overlain by another limestone rich in algae and orbitoid Foraminifera.

AGE

Foraminifera in the orbitoid limestone exposed in the Gurabo quadrangle are of late Paleocene to early Eocene age (Kaye, 1956; Pease, 1968a; E. A. Pessagno, Jr., written commun., 1965). Planktonic Foraminifera in the lower mudstones (loc. 2, pl. 1; table 2) were identified by Pessagno (written commun., 1965) as late Paleocene to Eocene. Pease (1968a, p. 46) reported a probable late Paleocene age for the overlying Río Piedras Siltstone. The Guaracanal Formation, therefore, is probably also Paleocene in age.

STRATIFIED ROCKS BETWEEN THE LEPROCOMIO AND CERRO MULA FAULTS

HATO PUERCO FORMATION

The Hato Puerco Formation occurs both north and south of the Leprocomio fault. It is described in the section dealing with the stratified rocks exposed north of the Leprocomio fault.

INFIERNO FORMATION

DEFINITION AND STRATIGRAPHIC RELATIONSHIPS

A sequence of andesitic to basaltic lavas, volcaniclastic rocks, and mudstones overlying the Hato Puerco Formation south of the Leprocomio fault is here named the Infierno Formation after a stream of that name in the west-central part of the Gurabo quadrangle. The Infierno is overlain by the basaltic Celada Formation. Because of extensive faulting, the only complete section through the formation is exposed in and near barrio Quebrada Infierno. For this reason, the type locality is designated in exposures along the Quebrada Infierno from the western border of the Gurabo quadrangle to about 900 m upstream (51,850 N. × 198,200 E. to 51,520 N. × 199,010 E.). An excellent reference section, including both lava and pumice-rich volcanic sandstone, is exposed along a small stream 2 km to the east-northeast, extending from above the conspicuous waterfall (52,040 N. × 200,450 E.) downstream to the Quebrada Grande fault (52,800 N. × 201,300 E.).

In barrio Quebrada Infierno, the formation is about 600 to 900 m thick. Here, and in barrio Quebrada Negrito to the north, the lower part of the formation consists chiefly of lava and less abundant volcanic breccia. The upper part of the formation in the type area is composed of volcanic breccia, sandstone, and mudstone. Just to the northeast, however, pillow lava occurs at the top of the formation. Elsewhere, the Infierno occurs only in fault blocks isolated from other formations. Because of rapid facies changes, the rocks exposed in individual fault blocks cannot be correlated with specific parts of the type section. In some fault blocks east of the Quebrada Grande fault, the formation consists chiefly of mudstone and well-bedded volcanic sandstone without lava. Locally, these rocks compose nearly 400 m of section, far greater than the thickness of similar rocks to the west. Nevertheless, the distinctive pumice-rich sandstones are identical with sandstones intercalated with the lavas, leaving little doubt as to their correlation.

LITHOLOGY

Typical lavas of the Infierno vary from shades of gray to green and in most exposures are pillowed. Some breccias may be flow breccias. Plagioclase phenocrysts are nearly ubiquitous and vary widely in size and abundance. Sparse clinopyroxene phenocrysts are present in addition to plagioclase in a few exposures. The intersertal to hyaloophitic groundmass consists of plagioclase lathes, granular clinopyroxenes, iron oxides, and secondary minerals. Most plagioclase is at least partly altered, but rarely it is quite fresh. Amygdules are common and locally are partly filled with chilled lava.

Locally, a thin basal lava flow of the formation is rich in clinopyroxene phenocrysts but has only sparse to moderately abundant plagioclase phenocrysts. This rock crops out in barrio Quebrada Negrito along the Quebrada Infierno and one-half kilometer west of Ramón Colon. Higher in the formation, one lava flow consists, exclusive of amygdules, of about 30 percent clinopyroxene. Such rocks, however, are subordinate to the typical plagioclase-phenocryst lavas.

Volcaniclastic rocks of the Infierno Formation range from mudstone to breccia, are in thin to very thick beds, and vary from moderately to poorly sorted. The sandstone and finer breccia contain abundant altered pumice with bold globular and attenuated vesicles and less abundant altered perlite, lithic volcanic-rock fragments, plagioclase and clinopyroxene grains. In all respects, these rocks are quite similar to the volcaniclastic rocks of the Cambalache Formation. Some large scattered clasts included in finer breccias are texturally identical with the Toma de Agua Vitrophyre Member of the Cambalache Formation and to clasts in breccias in the Cambalache.

Greenish volcanic mudstones grade into dark-gray calcareous and noncalcareous mudstones containing Radiolaria and planktonic Foraminifera. Characteristically, the Foraminifera are poorly preserved.

Secondary minerals in the Infierno Formation include phyllosilicates, calcite, albite, analcite, laumontite, less common prehnite and pumpellyite, and rare epidote.

AGE AND CORRELATION

Examination of many mudstones of the Infierno yielded only two collections with identifiable Foraminifera. Diagnostic Foraminifera of Turonian Age were identified by E. A. Pessagno, Jr. (written commun., 1965), from a roadcut 500 m north-northwest of La Silla, barrio Masa (loc. 20, pl. 1; table 2). A locality in the thick mudstone sequence to the east (loc. 19) yielded fossils of Turonian or younger age (Pessagno, written commun., 1965). Turonian fossils from the top of the underlying Hato Puerco Formation show that the base of the Infierno is also Turonian.

Direct evidence bearing on the younger age limit of the Infierno is lacking because no fossils have been found near the top of the Infierno nor in the overlying basaltic Celada Formation. However, the Infierno is correlative with the Cambalache Formation north of the Leprocomio fault. The Cambalache is overlain by the basaltic Canóvanas Formation, and fossils in each of these formations show that both the Cambalache and the lower part of the Canóvanas are Turonian. If the advent of basaltic volcanism was contemporaneous north and south of the Leprocomio fault, which seems likely, then the top of the Infierno is probably also Turonian.

Pease (1968a) mapped rocks in the Gurabo quadrangle here assigned to the Infierno and Celada Formations as part of the Santa Olaya Lava. However, the type locality of the Santa Olaya in the Naranjito quadrangle is remote, and rocks assigned to the Santa Olaya in intervening areas are largely greenstones strongly affected by hydrothermal alteration (Pease, 1968a, p. 17). Because of the uncertainty in correlation and in order to distinguish the pyroxene-poor Infierno from the pyroxene-rich Celada, new formations have been defined. Nevertheless, the Infierno is probably correlative to at least part of the type Santa Olaya. The thick units of mudstone and sandstone in the Infierno are lithologically similar to the Camarones Sandstone which, according to Pease (1968a, p. 19), interfingers with the Santa Olaya.

CELADA FORMATION

DEFINITION AND STRATIGRAPHIC RELATIONSHIPS

Basaltic pillow lavas and breccias exposed in the southwestern part of the Gurabo quadrangle are here named the Celada Formation after the village of Celada, north of Gurabo. A roadcut in pillow lava on Highway 181, 2 km northwest of Celada (50,350 N.×200,700 E.) is designated the type locality.

The Celada Formation conformably overlies the Infierno Formation. The top of the formation is cut out by faults and is indeterminant. At least 600 m of the formation is exposed.

LITHOLOGY

The Celada consists of pillow lavas, fine to coarse volcanic breccias, and subordinate volcanic sandstone and siliceous mudstone. The lavas and volcaniclastic rocks are charcterized by the presence of abundant clinopyroxene.

The typical lava of the Celada Formation is grayish green and contains abundant calcareous amygdules and common phenocrysts of clinopyroxene reaching a maximum size of 4 mm. Some rocks also have plagioclase phenocrysts. Rarely, plagioclase is the dominant phenocryst, and the rock is identical with lava of the underlying Infierno Formation. The groundmass contains abundant granular clinopyroxene, iron oxides, chlorite, and minute randomly oriented plagioclase microlites. In addition to calcite, amygdules contain chilled lava, chlorite, quartz, and various calcium-aluminum silicates.

Most exposures of Celada lava show well-formed ellipsoidal pillows and either calcareous or cherty interpillow material. Locally, the pillow lava grades into coarse breccia composed of angular and crudely ellipsoidal blocks of lava and less common angular fragments and matrix of calcareous mudstone like that found between pillows. Some blocks are broken and their component parts only slightly displaced. There is little tuffaceous matrix such as that described by Carlisle (1963) from broken-pillow breccia associated with aquagene tuffs.

The poorly sorted volcaniclastic rocks of the Celada commonly contain abundant pumice or scoria with globular, but not attenuated, vesicles. Other constituents include amygdaloidal and dense microcrystalline lava fragments, clinopyroxene grains, and, locally, plagioclase grains. Like the lava flows, the volcaniclastic rocks of the Celada are relatively rich in clinopyroxene.

Secondary minerals include calcite, chlorite, quartz, albite, laumontite, prehnite, pumpellyite, and epidote. Epidote is more widespread than in the Infierno Formation. Just east of Celada on the north edge of the Río Gurabo valley, the formation contains metamorphic hornblende, probably the contact metamorphic effect of a plutonic body hidden under the alluvium of the valley.

AGE AND CORRELATION

No fossils have been found in the Celada Formation. Its stratigraphic position above the Infierno Formation and its composition suggest correlation with at least the lower part of the Canóvanas Formation (Turonian to Santonian). It may also be generally correlative with the compositionally similar Los Negros Formation of the Río Orocovis Group, exposed in the Río Gurabo valley to the south.

LOMAS FORMATION

DEFINITION AND STRATIGRAPHIC RELATIONSHIPS

A thick sequence of basaltic to andesitic lava and very poorly sorted volcanic breccia and sandstone exposed chiefly in the south-central part of the mapped area is here named the Lomas Formation. Exposures of volcanic breccia and sandstone in a new roadcut in the southwestern part of barrio Lomas, Gurabo quadrangle, are designated the type locality (48,750 N.×207,890 E.).

The Lomas Formation is restricted to fault blocks, and nowhere is it observed in depositional contact with other formations. In the type area, about 1,500 m of the formation is exposed. Rocks exposed in an isolated fault block at Escuela Negroni, west-central Gurabo quadrangle, and in fault blocks in the southwestern part of El Yunque quadrangle are tentatively assigned to the Lomas Formation. In each of these areas, a few volcanic breccias contain oxidized lava fragments like those of the Hato Puerco Formation, but in other aspects the breccias more closely resemble those of the Lomas Formation.

LITHOLOGY

The most characteristic rock type of the Lomas Formation is a very thick bedded very poorly sorted fine to medium volcanic breccia. The very thick beds typically show an indistinct thin to thick internal stratification produced by variation in the size of the larger clasts. Except in the Lomas Formation, this type of stratification is uncommon within the mapped area. Other volcaniclastic rocks in the Lomas include coarse volcanic breccia, pebbly to cobbly volcanic sandstone, and moderately sorted volcanic sandstone. Mudstone is rare.

Many of the volcaniclastic rocks contain abundant altered vitric volcanic debris, chiefly pumice with globular vesicles and vesicular lava fragments. Most lava fragments have hyalopilitic textures. Some volcaniclastic rocks are rich in relatively large (2–3 mm) grains and phenocrysts of plagioclase but have less abundant clinopyroxene. Other volcaniclastic rocks contain fragments rich in granular clinopyroxene similar to rocks in the Celada Formation. Calcite is locally very abundant in the matrix. In some rocks, the calcite is tinted shades of pink, making a bright contrast with the green volcanic fragments.

A variety of lava types occurs in the Lomas Formation. The lowest exposed part of the formation in the type area is a massive lava without pillow structure or interlayered volcaniclastic rock. The grayish-green lava contains moderately abundant small (1–2 mm) phenocrysts of plagioclase, clinopyroxene, and, locally, phyllosilicate pseudomorphs after olivine or orthopyroxene in an intersertal to hyalopilitic groundmass. Sparse amygdules are locally present. A chemical analysis of this rock is given in table 1 (sample 10).

The two lavas in the upper part of the section exposed in barrio Barrazas are pillowed and contain abundant amygdules. The lower of the two lavas has a hyalopilitic texture and phenocrysts of plagioclase and sparse clinopyroxene. The upper lava has an intersertal texture and only plagioclase phenocrysts. This lava contains conspicuous cherty interpillow material.

Two units of lava without pillows are exposed in a fault block just to the north in barrio Cedro. The lower lava in large part has an integranular to intersertal texture with inconspicuous greenish plagioclase and clinopyroxene phenocrysts. The upper lava contains light-gray plagioclase phenocrysts in a pilotaxitic to intersertal groundmass.

Lavas exposed near Escuela Negroni are pillowed and sparsely amygdaloidal. The rock contains abundant 2- to 5-mm plagioclase phenocrysts in an integranular groundmass. In fresh exposures, the greenish plagioclase phenocrysts are inconspicuous and are strikingly accentuated by weathering.

Secondary minerals in the Lomas Formation include albite, chlorite, calcite, prehnite, analcite, and laumontite. Pumpellyite, epidote, and quartz occur in some areas. Plagioclase is almost everywhere highly turbid and albitized.

AGE AND CORRELATION

The age and correlation of the Lomas Formation are uncertain. One collection of Foraminifera of late Cenomanian Age (Pessagno, written commun., 1965) was obtained from a small outcrop of dark-gray calcareous mudstone in barrio Quebrada Negrito 1¾ km northwest of Escuela Negroni (loc. 52, pl. 1; table 2). The locality, however, is close to a major fault, and the rock type is rare in the Lomas Formation. The outcrop could be part of a fault block of another formation, perhaps the Hato Puerco. The clinopyroxene-rich volcaniclastic rocks of the Lomas are similar to rocks in the Celada Formation, and some lavas are similar to Infierno lavas. Other lavas and the volcaniclastic rocks rich in large plagioclase grains, however, are unlike rocks in other formations. The Lomas could be in part equivalent to both the Celada and Infierno Formations, but there is nothing to preclude an entirely older age, possibly equivalent to that of the Hato Puerco Formation.

STRATIFIED ROCKS SOUTH OF THE CERRO MULA FAULT

RÍO OROCOVIS GROUP—LOS NEGROS FORMATION

DEFINITION AND STRATIGRAPHIC RELATIONSHIPS

The Río Orocovis Formation was defined by Berryhill (1965) in the Ciales quadrangle, north-central Puerto Rico. To the east in the Corozal quadrangle, Nelson (1966) raised the formation to group status. An unnamed basaltic tuff member described by Berryhill was defined by Nelson as the Los Negros Formation. Pease (1968 a, b, c) traced the Los Negros eastward through the Naranjito and Aguas Buenas quadrangles to the southwestern corner of the Gurabo quadrangle. The Los Negros is as much as 1,800 m thick in the Naranjito quadrangle (Pease, 1968a, p. 10). Because of intensive shearing, its thickness cannot be accurately estimated in the Gurabo quadrangle.

LITHOLOGY

Relatively unaltered rocks of the Los Negros are restricted to a small hill in the Río Gurabo valley just northwest of the town of Gurabo. Here the formation consists of thick-bedded volcanic sandstone and mudstone and very thick bedded moderately to poorly sorted volcanic breccia and conglomerate. A thin section of the volcanic sandstone shows abundant highly angular fragments of scoria and less abundant dense lava fragments. Clinopyroxene, slightly altered to green amphibole, is moderately abundant as clastic grains, as phenocrysts in the scoria and dense lava, and in the groundmass of some of the lava fragments. The scoria is altered to chlorite and sparse epidote, and the groundmass consists of granoblastic albite.

On the south side of the Río Gurabo valley, rocks tentatively correlated with the Los Negros are highly sheared, metamorphosed, and, locally, hydrothermally altered. Some rocks are recognizable as fine volcanic breccias rich in clinopyroxene. New roadcuts just southeast of Gurabo expose a moderately foliated rock containing recognizable pumiceous fragments and little altered clinopyroxene crystals. The bulk of this rock has been altered to fibrous amphibole and a low birefringent phyllosilicate.

AGE AND CORRELATION

No fossils have been found in the Los Negros Formation. Its stratigraphic position in the upper part of the Río Orocovis Group of probable Albian to Santonian Age (Pease, 1968a, p. 10) and its pyroxene-rich character suggest that it may be generally correlative with the Canóvanas and Celada Formations.

STRATIGRAPHIC SUMMARY AND CONCLUSIONS

The stratigraphic sequence in the Gurabo and El Yunque quadrangles consists chiefly of volcanic rocks ranging in age from Early Cretaceous (Albian) to Paleocene. The more complete sequence exposed north of the Leprocomio fault is about 7,500 m thick and consists largely of volcaniclastic rocks and very subordinate lava flows. The less widely exposed and highly faulted sequence south of the Leprocomico fault probably is largely of Cenomanian and Turonian Age but could be in part as young as Santonian. The Turonian to possibly Santonian parts of this sequence contain appreciable thicknesses of lava, but probably less than half of the total thickness of the internal is lava. The age of the Lomas Formation of the southern part of the area is not clearly known but possibly is Cenomanian and Turonian.

The Cretaceous to lower Tertiary sequence is interrupted by only one important disconformity. This occurs within the Monacillo Formation of probable Maestrichtian Age. This formation is very poorly exposed in the mapped area, but Pease (1968a, p. 37) reported that to the west the Monacillo contains numerous fragments derived from older rocks. In the north-central part of the Gurabo quandrangle, the Monacillo, including the Trujillo Alto Limestone Member, is represented by at most about 60 m of beds between the Frailes Formation (upper Campanian) and the Guaracanal Formation (probably upper Paleocene). Less than 10 km to the west, the same interval is more than 400 m thick, and the overlying beds contain possible early Paleocene fossils (Pessagno, written commun., 1965).

The sequence of formations exposed below this unconformity records continuous deposition from the late Campanian back to the Albian. North of the Leprocomio fault, all these formations are remarkably similar in many respects. Each is composed chiefly of volcaniclastic rocks which commonly show moderately good sorting, contain graded beds, and are interbedded with mudstones that contain exclusively planktonic faunas. All these formations were probably deposited largely in at least moderately deep marine waters below effective wave base. Yet almost all contain evidence that at least part of their debris originated on land or in shallow water. Each formation contains some well-rounded fragments of volcanic rock, and the Hato Puerco, Barrazas, and Cambalache Formations also contain detrital fragments of shallow-water marine limestone. Only the unnamed volcaniclastic rocks below the Tabonuco Formation (Albian) have so far failed to yield rounded detritus, and in the mapped area these rocks are poorly exposed and in large part highly metamorphosed. Slump structures and (or) submarine slide deposits occur in nearly all the formations and attest to the presence of steep submarine slopes.

Most of the volcaniclastic debris is angular, and within individual formations it shows little lithologic variation. Most is probably of primary and reworked pyroclastic origin. The rocks are largely tuffs and lapillistones and less abundant pyroclastic and autoclastic breccias. Rounded volcanic fragments are less abundant and everywhere are compositionally similar to the angular debris in the same rocks. The rounded debris, therefore, was derived from coeval volcanoes rather than from much older volcanic rocks. During deposition of the Frailes Formation (Campanian), some aureoles of high-level plutons may have been eroded to contribute detrital epidote and fragments of hydrothermally altered rock. However, there probably was no widespread uplift because the volcaniclastic debris of the Frailes shows little lithologic diversity.

During the Albian to Campanian interval, volcanoes standing near sea level produced pyroclastic and epiclastic volcanic debris. This debris, in part mixed with fragments of limestone from fringing reefs, was transported to deeper waters by submarine slides, turbidity currents, and pyroclastic ash flows and ash falls. Some volcanic eruptions probably also occured in the deeper parts of the depositional basin, but the lack of doubly graded sequences of pyroclastic beds suggests that very thick columns of water did not exist over the erupting volcanoes (Fiske and Matsuda, 1964).

South of the Leprocomio fault, the Hato Puerco and Infierno Formations probably formed under conditions similar to those of the formations to the north. The Lomas Formation, however, consists largely of very poorly sorted volcaniclastic debris and lacks graded beds. This formation was probably deposited in relatively shallow water, and some parts could be subaerial deposits.

Table 3 shows estimates of the maximum thicknesses and rates of deposition of the strata assigned to the Cenomanian through Campanian Stages of the Cretaceous. A large thickness of Albian strata is probably also present, but the base of the Albian sequence has not yet been determined. These data apply only to the sequence exposed north of the Leprocomio fault, where sufficient paleontological data are available.

Some errors are probably introduced into these data in interpolating between paleontologically determined horizons and in estimating thicknesses. These errors probably are not large. More serious errors arise from uncertainties in the Cretaceous time scale (Casey, 1964) and can be seen in table 3 in the different durations of the stages suggested by Kulp (1961) and Casey (1964). The rates of deposition calculated for the individual stages, therefore, could well be in error by a factor of four. The error for the total interval undoubtedly is much less.

TABLE 3.—*Thicknesses and rates of deposition of Cenomanian through Campanian rocks north of the Leprocomio fault*

Formation	Age	Maximum thickness, in meters, excluding lava flows	Duration, in 10^6 years (Kulp, 1961)	Rate of deposition ($m/10^6$ yr) from Kulp's duration	Duration, in 10^6 years (Casey) (1964)	Rate of deposition ($m/10^6$ yr) from Casey's duration
Frailes	Campanian	900	9	100	6	150
Canóvanas	Santonian	50	3	17	6	8
	Coniacian	75	4	19	6	12
Cambalache	Turonian	930	2	465	6	155
Hato Puerco	Cenomanian	2,500	20	125	6	417
Total		4,455	38	117	30	149
Total, including lava flows		4,865	38	128	30	162

The exclusion of lava flows from these data does not greatly affect the results except in the case of the Martín González Lava. The Martín González occurs between Santonian and Campanian strata and ranges in thickness from 0 to 700 m. Inclusion of the maximum thickness in either the Santonian or Campanian would greatly alter the calculated rate of deposition. An average thickness of 200 m for the Martín González is included in the total thickness of the interval including lavas.

The rates of deposition indicated from these data for the total interval and for individual stages are not great when compared with rates calculated for many geosynclinal sequences. The rates of deposition are quite similar to the rates reported by Kay (1955) for 85 geosynclinal sequences throughout the world, many of which contain no volcanic rocks. In the Cretaceous sequence of Puerto Rico, the very rapid deposition accompanying volcanic eruptions was balanced by very slow pelagic deposition between eruptions, a consequence of the absence of any large source area for terrigenous detritus. This is most clearly reflected in the small thicknesses and relatively slow rates of deposition of the Coniacian and Santonian rocks, which consist in large part of pelagic mudstones. Similar rocks occur throughout the sequence, interlayered with the volcaniclastic rocks, and contribute greatly to lower average rates of deposition.

A very small thickness of strata above the Maestrichtian unconformity is exposed within the present mapped area. These rocks include shallow-water marine limestone and basaltic lava. Just west of the mapped area, Pease (1968a) described a sequence of lower Tertiary volcaniclastic rocks nearly 2,000 m thick.

Few chemical analyses are available, but the volcanic rocks of the area probably range in composition from basalts to siliceous andesites or, possibly, dacites. Clear trends of magmatic evolution are not evident.

The most common volcanic rock of the area is probably a rather mafic clinopyroxene-bearing andesite. Balsaltic rocks occur in minor volume at many stratigraphic levels throughout the sequence and are dominant in the Los Negros, Celada, and Canóvanas Formations of Turonian to, in part, Santonian Age. More siliceous andesites, possibly in part dacites, are represented by deposits containing long-tube pumice and, locally, sparse quartz crystals. These rocks occur in small volume in the Albian volcaniclastic rocks and in the Hato Puerco Formation (Cenomanian). They are more abundant in the Cambalache and Infierno Formations (Turonian) and the Frailes Formation (Campanian). Hornblende andesites occur in very small volume in the Santonian of the Canóvanas Formation and, just outside the area, abundantly in the Guaracanal Andesite (Paleocene) (Pease, 1968a; Kaye, 1959).

Regional correlations are possible, at least in a general way, for most stratigraphic units in the area. However, paleogeographic reconstructions are still very uncertain chiefly because of the presence of transcurrent faults with probable large, but uncertain, displacements.

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