Cretaceous and Lower Tertiary Stratigraphy of The Naranjito and Aguas Buenas Quadrangles and Adjacent Areas Puerto Rico

GEOLOGICAL SURVEY BULLETIN 1253

Work done in cooperation with the Department of Industrial Research Puerto Rico Economic Development Commission

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By MAURICE H. PEASE, JR.

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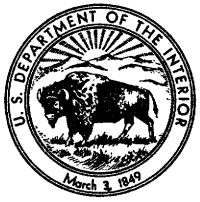

UNITED STATES GOVERNMENT PRINTING OFFICE, WASHINGTON : 1968

UNITED STATES DEPARTMENT OF THE INTERIOR

STEWART L. UDALL, *Secretary*

GEOLOGICAL SURVEY

William T. Pecora, *Director*

Library of Congress catalog-card No. GS 68-182

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402

CONTENTS

ILLUSTRATIONS

TABLE

CRETACEOUS AND LOWER TERTIARY STRATIGRAPHY OF THE NARANJITO AND AGUAS BUENAS QUADRANGLES AND ADJACENT AREAS, PUERTO RICO

By MAURICE H. PEASE, JR.

ABSTRACT

Cretaceous and lower Tertiary stratigraphic units exposed in the Naranjito-Aguas Buenas area of Puerto Rico consist mostly of submarine lava, lava breccia, volcanic breccia, and well-stratified volcaniclastic deposits. Shallow-water marine sedimentary rocks and limestone are present, and nonmarine deposits of volcanic material occur at two or possibly more stratigraphic horizons. The stratified rocks are cut by hypabyssal dikes and stocks, chiefly of diorite and quartz diorite; the stratigraphic sequence has been dismembered by wrench faulting.

The oldest rocks in the mapped area are volcanic rocks exposed locally in the southern part of the area and believed to be of Early Cretaceous age. They are in fault contact with rocks of the Río Orocovis Group which range in age from Albian to Santonian. These strata are structurally isolated from other stratigraphic units to the north by the east-west-trending Cerro Mula fault.

Within the sequence of rocks exposed north of the Cerro Mula fault, three unconformities are recognized: early Cenomanian, pre-Maestrichtian, and pre-Oligocene. Strata exposed above the pre-Oligocene unconformity are not considered in this report.

Formations below the early Cenomanian unconformity form a regularly layered sequence, but those between it and the pre-Maestrichtian unconformity display a complex interfingering and interlayering of facies.

Dikes and stocks of quartz diorite and related intrusive rocks are widely distributed, and the intruded country rock is commonly altered to greenstone. Quartz diorite and associated country rock exposed along several major wrench faults have been altered by hydrothermal solutions. Large-scale igneous intrusion and hydrothermal activity probably took place during the Campanian, but minor intrusive activity evidently continued into the Paleocene.

INTRODUCTION

The area of this investigation lies in north-central Puerto Rico immediately south of the capital city, San Juan (fig. 1). The area represented by the geologic map (pl. 1) comprises the Naranjito and Aguas Buenas quadrangles and parts of the Gurabo, Bayamon, San Juan, and Carolina quadrangles, but within this area only those Cre-

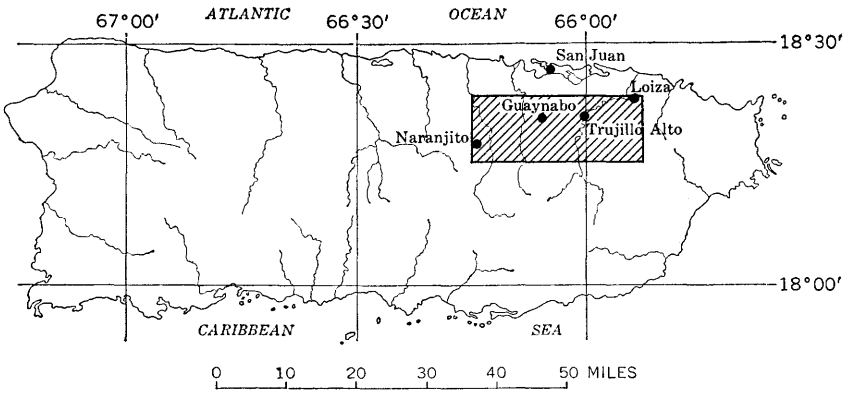

FIGURE 1.—Index map of Puerto Rico showing area of this report.

taceous and lower Tertiary units that crop out in the Naranjito and Aguas Buenas quadrangles are of specific importance to this report. Adjacent areas are included to clarify the stratigraphic interpretation. A sequence of limestone, marl, and calcareous sedimentary rocks of middle Tertiary age that unconformably overlies the older rocks along much of the northern border of the mapped area has not been shown on the geologic map, and contacts between older formations have been extrapolated where they extend beneath this middle Tertiary cover. The map is a partly generalized compilation of the geology; its scale has been reduced from 1:20,000 to approximately 1:120,000.

The purpose of this report is, first, to name or redefine and describe the stratigraphic units that are exposed in the Naranjito and Aguas Buenas quadrangles and, second, to present a regional interpretation of the volcanic-facies complex. The report is intended to supplement the brief texts that accompany the geologic maps of these two quadrangles (Pease, 1968a, b). The reader is referred to these published maps for details described in the text, for locations according to the Puerto Rico Meter Grid Coordinate System, and for geographic names and planimetric detail not shown on the small-scale map accompanying this stratigraphic report.

The first detailed geologic investigation of the area was made by Kaye (1959). Previous research had been carried out by several other workers, notably those sponsored by the New York Academy of Sciences in the early part of the century. A summary of this earlier work can be found in Kaye's report. The area mapped by Kaye is in the north-central part of the area described in the present report—chiefly the San Juan quadrangle and the northern part of the Aguas

Buenas quadrangle. His work served as an excellent framework on which to base the present studies. The lithologic units described in his report correspond in general to those of this report, but several formation names have been changed, and the pre-middle Tertiary geology of this area has been reinterpreted in the light of new stratigraphic, paleontologic, and structural data.

The formation names Cerro Gordo Lava, Santa Olaya Lava, and Río de la Plata Sandstone were first used by Lidiak (1965) in anticipation of detailed descriptions in this report.

The present report is based chiefly on work done for the U.S. Geological Survey in cooperation with the Commonwealth of Puerto Rico Economic Development Administration between 1957 and 1963. Results of this work include geologic maps of the Bayamón (Monroe and Pease, 1962), Naranjito (Pease, 1968b), and Aguas Buenas (Pease, 1968a) quadrangles and an unpublished geologic map of the Carolina quadrangle prepared in 1963 in collaboration with W. H. Monroe. The author has mapped the geology along the northern border of the Gurabo quadrangle in considerable detail and has made a reconnaissance investigation of the geology of the remainder of that quadrangle. Since the author left Puerto Rico, V. M. Seiders of the U.S. Geological Survey has completed mapping in this quadrangle; his detailed work has not been incorporated in this report, but information given by him has led to a clearer understanding of the stratigraphic relations in this part of the area shown on plate 1.

ACKNOWLEDGMENTS

The writer wishes to acknowledge his indebtedness to R. P. Briggs and Lynn Glover, 3d, U.S. Geological Survey, and to W. R. Bergey, Central Concessions, Ltd., Puerto Rico, for their helpful suggestions while the mapping was in progress. The earlier work by C. A. Kaye (1959) is acknowledged above; his descriptions of the lithic character of the units were especially useful. A. E. Nelson, U.S. Geological Survey, assisted in the mapping of part of the Naranjito quadrangle.

Of particular assistance in the formulation of the paleontologic section of this report were N. F. Sohl of the U.S. Geological Survey and E. G. Kauffman of the U.S. National Museum who, in addition to identifying fossils collected by others, visited the area and made collections in the field. Eighteen of the 31 diagnostic fossil collections are microfaunal assemblages found by V. M. Seiders, U.S. Geological Survey, chiefly in the Gurabo quadrangle and identified by E. A. Pessagno, Jr., University of California, Davis, Calif., from thin sections.

GEOLOGIC SETTING

Most of north-central Puerto Rico is underlain by marine lava, lava breccia, volcanic breccia, and volcaniclastic deposits of Cretaceous and early Tertiary age. Three classes of breccia are distinguished in this report: lava breccia composed almost exclusively of lava fragments, volcanic breccia composed mostly of lava fragments but with an appreciable tuffaceous matrix, and tuff breccia composed chiefly of pyroclastic debris, much of the fragmental material being greater than lapilli size. Massive accumulations of pillow lava and lava breccia interfinger with crudely bedded volcanic breccia and well-stratified tuffaceous sedimentary rocks. In a broad sense, the fragmental rocks become progressively more common upward in the stratigraphic section and laterally away from volcanic centers, but lavas and volcaniclastic rocks are intertongued over long distances, and zones of alternating facies commonly characterize transitions from one volcaniclastic facies to another. Consequently, contacts between mappable lithologic units may be indefinite over appreciable thicknesses of section, even though the total character of each mappable unit may be quite distinctive.

Nonmarine deposits of volcanic material occur at two or possibly more stratigraphic intervals; their nonmarine and shallow-water marine counterparts of reddish- to purplish-gray mudstone and conglomerate are also represented. Discontinuous deposits of limestone are commonly associated stratigraphically with these deposits.

The offshore marine deposits show little or no angular discordance between units, but in areas of massive lava accumulation, volcaniclastic deposits and limestone occur as thin discontinuous units, and contacts between stratigraphic units locally are discordant.

This complex of interfingering volcanic facies has been further confounded by intense wrench-fault deformation that apparently shortened the stratigraphic section in an east-west direction and extended the section in a north-south direction. The rocks were severely shattered, and faulted segments, which in some cases originally had been separated by more than 20 km, were juxtaposed. Owing to this fragmentation of the complex sequence of volcanic rocks, it has not been possible to extend the correlation of stratigraphic units between major fault segments with confidence, and a proliferation of stratigraphic names has resulted.

SUMMARY OF PALEONTOLOGIC DATA

Fossil faunas sufficiently diagnostic to aid in stratigraphic correlation have been collected from 31 localities (see pl. 1). The faunas range in age from early Late Cretaceous to Paleocene.

The biostratigraphic divisions in the Cretaceous sequence of this report are listed below according to the standard European stages.

Upper Cretaceous:
- Maestrichtian
- Campanian
- Santonian
- Coniacian
- Turonian
- Cenomanian

Lower Cretaceous:
- Albian
- Aptian

Fossil localities are listed in table 1.

No identifiable fossils were found in the Naranjito quadrangle or in the southern third of the Aguas Buenas quadrangle, and only three localities occur in the southern half of the Gurabo quadrangle. No stratigraphically diagnostic fossils have been obtained from the Santa Olaya Lava, the Río de la Plata Sandstone, or the Camarones Sandstone, and none were found in strata beneath the Santa Olaya.

The relative biostratigraphic positions assigned to fossil collections from the mapped area are in general accord with the stratigraphic interpretation of this report. There seems to be, however, a disparity between megafossil and microfossil age assignments in the middle Late Cretaceous: microfossils are assigned a slightly younger age than megafossils at the same stratigraphic position. A similar discrepancy may be present at the Cretaceous-Tertiary boundary. According to N. F. Sohl (oral commun., 1965), it is entirely possible that megafossil and microfossil correlations with the standard European divisions of the Cretaceous do not coincide exactly. This disparity is particularly conceivable because E. A. Pessagno, Jr. (oral commun., 1965), has correlated the microfossil assemblages with the Gulf Coast section and has not firmly committed himself to correlation with the European section. Specific discrepancies will be described in later sections of the text.

283-187—68——2

TABLE 1.—*List of fossil localities shown on geologic map (pl. 1)*

[Locations by Puerto Rico Meter Grid Coordinate System, shown by marginal ticks on topographic maps of Puerto Rico. SG, collection from Gurabo quadrangle by V. M. Seiders, U.S. Geol. Survey. Pab, collection from Aguas Buenas quadrangle by M. H. Pease, Jr. SAB, collection from Aguas Buenas quadrangle, by V. M. Seiders. The five-digit numbers are U.S. Natl. Museum numbers; prefix "f," Foraminifera catalogue. *, age assignment by E. A. Pessagno, Jr., Univ. of California, based on Foraminifera examined in thin section. **, age assignment by N. F. Sohl, U.S. Geol. Survey, except inoceramids identified by E. G. Kauffman, U.S. Natl. Museum, and echinoids identified by P. M. Kier, U.S. Geol. Survey. +, collections by C. A. Kaye, U.S. Geol. Survey, originally examined by J. B. Reeside, Jr., U.S. Geol. Survey, but reexamined by Sohl and colleagues. ***, age assignment of Foraminifera, by J. Reiskind, Yale University]

Locality		Reference No.	Age	Formation	Fossils	Remarks
No.	Coordinates					
1	53,125 m N., 204,490 m E.	SG–722	*Cenomanian	Unknown	Poorly preserved Foraminifera.	From unknown strata exposed northeast of Leprocomio fault.
2	56,630 m N., 210,580 m E.	SG–638	*Late Cenomanian	----do	Diagnostic Foraminifera	See loc. 1.
3	55,870 m N., 199,680 m E.	SG–258	----do	----do	----do	Do.
4	56,230 m N., 202,100 m E.	SG–114	----do	Guaynabo	----do	From strata in Gurabo quadrangle equivalent to Guaynabo Formation.
5	59,010 m N., 205,165 m E.	SG–202	----do	----do	----do	See loc. 4.
6	59,050 m N., 210,570 m E.	SG–564	----do	----do	----do	Do.
7	52,860 m N., 199,160 m E.	SG–480	*Turonian	Unknown	Poorly preserved Foraminifera.	From area of uncertain structure and stratigraphy south of Leprocomio fault in Gurabo quadrangle.
8	51,410 m N., 204,760 m E.	SG–331	*Turonian or younger	----do	----do	See loc. 7.
9	59,265 m N., 210,465 m E.	SG–566	*Coniacian to early Santonian.	Guaynabo	Diagnostic Foraminifera	See loc. 4.
10	54,290 m N., 188,455 m E.	Pab–1051	**Coniacian	Tortugas Andesite(?)	Single poorly preserved but diagnostic *Inoceramus*.	From limestone boulder.
11	59,270 m N., 210,285 m E.	SG–853	*Santonian	Guaynabo	Diagnostic Foraminifera	See loc. 4.
12	53,480 m N., 188,732 m E.	+23582	**Early Santonian to Early Campanian.	Tortugas Andesite(?)	Inoceramids; also rudistids and *Texanites* sp.	From friable boulder of tuffaceous rock; not in place.
13	58,263 m N., 188,860 m E.	+23193	**Late Santonian to Early Campanian.	Guaynabo	Inoceramids	Kaye's El Minao locality.
14	58,885 m N., 208,465 m E.	SG–620	*Early Campanian	----do	Diagnostic Foraminifera	See loc. 4.
15	59,250 m N., 200,425 m E.	SG–678	----do	----do	----do	Do.

16	58,785 m N., 197,475 m E	SAB-526	*Late Campanian	Leprocomio Siltsone Member of Guaynabo Formation.	----do	
17	58,705 m N., 197,200 m E	SAB-520	----do	----do	----do	
18	59,960 m N., 198,560 m E	SG-466	----do	----do	----do	
19	59,250 m N., 197,270 m E	26849	**Post-Turonian	----do	*Inoceramus*	
20	59,625 m N., 196,375 m E	28613	**Post-Cenomanian	Trujillo Alto Limestone Member of Monacillo Formation.	Echinoids and other megafossils; not specifically diagnostic.	
21	53,745 m N., 189,025 m E	28603	**Maestrichtian	La Muda	Diagnostic rudistids	
22	54,080 m N., 188,860 m E	28602	**Late Cretaceous	----do	Rudistid fragments and echinoids; not specifically diagnostic.	
23	53,480 m N., 188,740 m E	28601	----do	----do	Rudistid fragments	
24	55,680 m N., 188,970 m E	28606	**Maestrichtian	La Muda	Diagnostic rudistids	
25	56,350 m N., 188,515 m E	28863	**Campanian to Maestrichtian.	----do	Diagnostic *Vaccinites*	
26	59,265 m N., 194,740 m E	SAB-851	*Paleocene	Guaracanal Andesite(?)	Diagnostic Foraminifera	From Trujillo Alto Limestone Member of Monocillo as mapped; believed to be lens in base of Guaracanal.
27	59,800 m N., 196,380 m E	SAB-850	----do	----do	----do	Light-gray miliolid limestone like limestone resting on Trujillo Alto Limestone at locality 20.
28	58,820 m N., 185,595 m E 58,265 m N., 185,470 m E 57,170 m N., 185,640 m E	Pab-969 Pab-967 Pab-962	**Paleocene(?)	----do	External impressions of possible venericardia; Foraminifera probably Tertiary, according to Ruth Todd, U.S. Geol. Survey.	Light-gray miliolid limestone at or near base of formation.
29	60,315 m N., 207,060 m E	f35148	Paleocene	Limestone of Guaracanal Andesite(?).	Large Foraminifera	Original collection identified by W. Storrs Cole, Cornell Univ. Recollection by Pease identified by K. N. Sachs, Jr., U.S. Geol. Survey.
30	61,885 m N., 201,220 m E	----------	Probably post-Cretaceous.	----do	Foraminifera	Inadequate fauna for positive identification, according to Ruth Todd.
31	60,000 m N., 185,790 m E	Pab-965	***Late Paleocene	Río Piedras Siltstone	Foraminifera from base of formation.	Tentative assignment.

CRETACEOUS SYSTEM

UNDIVIDED VOLCANIC ROCKS

Poorly exposed greenstone occurs in the extreme southeast corner of the Aguas Buenas quadrangle on the south side of a prominent shear zone that terminates westward against a cross fault trending north-northwest. The greenstones seem to be related to rocks exposed on the south side of the Quebrada Vicente fault that lies south of the map area, and thus the greenstones are probably the oldest rocks in the area of this report.

RÍO OROCOVIS GROUP

A sequence of submarine lava and volcaniclastic rocks about 4,500 m thick exposed in the southeastern part of the Ciales quadrangle along and adjacent to the valley of the Río Orocovis was named the Río Orocovis by Berryhill (1965). Later work in the Corozal quadrangle by A. E. Nelson (1967) has established the Río Orocovis Group. The Perchas and Los Negros Formations of the Río Orocovis Group extend from the Corozal quadrangle into the area of this report. The Río Orocovis Group is structurally isolated from the rest of the rocks in the area by the Cerro Mula fault, along which strata may have been displaced more than 20 km right laterally.

PERCHAS FORMATION

The upper part of the Perchas Formation is exposed along the southern border of the Naranjito quadrangle, chiefly south of of the Apostoles de Cristo fault, and a thin sliver of this formation extends into the southwest corner of the Aguas Buenas quadrangle where most of it has been hydrothermally altered. Its maximum exposed thickness in the Naranjito quadrangle is about 650 m; however, more than 1,000 m of pillow lavas that was included in Formation K in the adjacent Comerío quadrangle (Pease and Briggs, 1960) is now recognized as part of the Perchas Formation. These lavas, which are highly sheared and in part hydrothermally altered along a major west-trending shear zone, underlie the entire area north of the Quebrada Vicente fault in the Comerío quadrangle.

The Perchas is composed chiefly of massive dark-greenish-gray basaltic lava, but it contains thin lenses of bedded tuff and of bedded volcanic wacke. The lava is characterized by the presence of abundant stubby pyroxene phenocrysts and the near absence of plagioclase phenocrysts. Much of the lava is pillowed and vesiculated. Amygdules are composed of celadonite (?) and calcite. A few isolated outcrops of andesitic lava containing plagioclase phenocrysts were observed

within this formation, but these occurrences could not be correlated; there may be several andesitic lavas within the Perchas. The tuffs are characterized by pyroxene crystals and by fragments of lava similar to the flows.

LOS NEGROS FORMATION

A thick sequence of pyroxene-bearing basaltic tuff and intercalated lava and volcanic wacke is exposed in a broad belt south of the Cerro Mula fault in the Naranjito and Aguas Buenas quadrangles. The tuffs are contiguous with tuffs exposed in the adjacent Corozal quadrangle to the west, which have been named the Los Negros Formation (Nelson, 1967). In the Corozal quadrangle north of the Apostoles de Cristo fault, the Los Negros rests on the Avispa Formation of the Río Orocovis Group, but in the Naranjito quadrangle the Avispa Formation is absent, and the Los Negros Formation rests conformably on the Perchas.

In the Naranjito quadrangle, the Los Negros consists mostly of dark greenish-gray massive to poorly bedded, somewhat friable pyroxene-crystal lithic tuff and lapilli tuff. Units of fine-grained to very fine grained laminated tuff a few centimeters to a few meters thick, are interstratified with the more massive coarser grained tuff. These laminated tuff units, which are common in the western part of the Naranjito quadrangle, are more resistant than the more porous coarser grained tuffs and consequently are conspicuous features in outcrop. The massive tuff also grades locally into units of bedded tuffaceous wacke which are progressively more abundant eastward and which form a large part of the formation in the Aguas Buenas quadrangle.

A siltstone member about 400 m thick has been mapped in the southwest corner of the Aguas Buenas quadrangle where it is exposed in an eastward-plunging anticline between the Anones and Apostoles de Cristo faults. The member consists of thin-bedded tuffaceous siltstone and fine-grained tuffaceous wacke.

The massive tuff and lapilli tuff of the Los Negros are composed of greenish-gray scoriaceous lava fragments and pyroxene crystals in a vitreous matrix mostly altered to chlorite. Plagioclase crystals are rarely present. The fine-grained laminated tuff and bedded volcanic wacke also are rich in pyroxene.

Lenses of pyroxene-rich basaltic lava, similar lithologically to the underlying Perchas Formation, occur at intervals throughout the Los Negros Formation. One such lava was mapped across the valley of the Río de la Plata near the base of the formation. A thin andesite flow about 25 m thick along the Anones fault in the western part of the Naranjito quadrangle is distinguished by the presence of feldspar

phenocrysts rather than pyroxene and resembles the Avispa Formation.

The maximum exposed thickness of the Los Negros Formation is estimated to be about 1,800 m near the western edge of the Naranjito quadrangle on the north flank of a faulted syncline whose axial trace has been obliterated by the Anones fault. Although the top of the formation is cut out by faults in the Naranjito quadrangle, the base is exposed in two areas along the Apostoles de Cristo fault where Los Negros tuffs appear to rest conformably on Perchas lavas.

AGE AND CORRELATION

The Río Orocovis Group, according to R. P. Briggs (written commun., 1965), ranges in age from early Cretaceous (Albian) to Late Cretaceous (probably Santonian) and embraces about the same biostratigraphic interval as the Robles Formation (Pease and Briggs, 1960). No fossils have been found in the Perchas or Los Negros Formations of the Río Orocovis Group in the area described in this report.

PRE-SANTA OLAYA STRATA NORTH OF THE CERRO MULA FAULT

A conformable sequence of rocks exposed in the northern part of the Naranjito quadrangle has been divided into four new formations. These are—from oldest to youngest—the Pájaros Tuff, the Cerro Gordo Lava, El Ocho Formation, and the Cancel Breccia. This is the oldest sequence of rocks exposed north of the Cerro Mula fault; it is overlain unconformably by the Santa Olaya Lava.

PÁJAROS TUFF

Thin-bedded tuffaceous siltstone, coarse-grained tuff, and tuffaceous wacke exposed near the northern edge of the Naranjito quadrangle are here named the Pájaros Tuff for exposures in barrio Pájaros, a political geographic subdivision. Exposures in Quebrada Escarcha about 600 m south of the quadrangle border and southward for about 500 m (Puerto Rico Meter-Grid Coordinate System: 59,390 m N., 177,620 m E. to 58,940 m N., 177,630 m E.) are designated the type section. Good exposures also occur in a stream that parallels the west side of Highway 167 in barrio Pájaros.

The Pájaros Tuff is chiefly thin-bedded fine-grained tuff with interbeds of massive tuffaceous wacke and coarse-grained tuff to lapilli tuff. The tuff is composed of plagioclase and pyroxene crystals and pumice in a greenish-gray chloritic matrix. The lithologic character of this formation is similar to that of the Robles Formation (Pease and Briggs, 1960). Much of this formation has been partly altered to hard jasperoid which contains pyrite.

The maximum exposed thickness of this formation is about 580 m, but the base is concealed everywhere by unconformably overlying strata of Oligocene age or younger. These younger strata are not shown on the geologic map (pl. 1.)

CERRO GORDO LAVA

The Cerro Gordo Formation of Lidiak (1965) is herein adopted as the Cerro Gordo Lava. It consists of lava, flow breccia, and minor tuff and tuff breccia exposed in barrio Cerro Gordo in the Naranjito quadrangle. Exposures in roadcuts along Highway 830 (57,520 m N., 179,330 m E. to 57,020 m N., 179, 510 m E.) are designated the type section. Although the formation generally is poorly exposed, good outcrops also occur in the valley of Quebrada Piña about 720 m S. 18° W. of the Piña road intersection (58,550 m N., 174, 200 m E.). The Cerro Gordo rests with apparent conformity on the Pájaros Tuff.

The characteristic lava of this formation is porphyritic basaltic andesite having a bluish-gray to greenish-gray groundmass. Phenocrysts are randomly oriented plagioclase laths 1–3 mm long, accompanied by more conspicuous but less abundant stubby pyroxene crystals. Phenocrysts commonly amount to more than 50 percent of the rock, and in places the rock is so crowded with phenocrysts that it appears almost holocrystalline. Dikes of microcrystalline basaltic andesite as much as 1 cm wide locally traverse the coarser, grained lava. More sparsely porphyritic lava near the base of the formation contains plagioclase phenocrysts which commonly exhibit cruciform twinning. This lava is very similar to the Lapa Lava Member of the Robles Formation (Berryhill and Glover, 1960).

Lava locally interfingers with and is interstratified with coarse-grained breccia and massive tuff. East of the Río Minillas the Cerro Gordo has been chloritized, silicified, and pyritized where it is closely associated with tongues and dikes of intrusive rock.

A bedded tuff member, about 180 m thick, is well exposed in the valley of the Río Minillas but apparently is absent to the west where the formation is thinner. The tuff is composed mostly of lava and red pumice fragments and pyroxene in a chloritic calcareous matrix. The lava fragments are commonly finely amygdaloidal and sparsely porphyritic.

The maximum exposed thickness of the Cerro Gordo Lava is about 1,100 m in barrio Cerro Gordo. A large part of this formation is unconformably overlapped by younger Oligocene and Quaternary strata.

EL OCHO FORMATION

El Ocho Formation is here named for a coarsely stratified sequence of fine tuff, lapilli tuff, and tuff breccia exposed near the settlement of El Ocho in barrio Buena Vista in the Naranjito quadrangle. This formation is exposed in a complexly faulted belt across the northern part of the quadrangle. The quarry north of El Ocho (56,870 m N., 177,210 m E.) is designated the type section; it includes stratified coarse-grained tuff, lapilli tuff, and a breccia member.

Most of El Ocho Formation is composed of massive to thick-bedded volcanic breccia and coarse-grained tuff with andesitic lava flows and flow breccias near the base. Lava and lava fragments characteristically have a reddish-gray aphanitic groundmass; phenocrysts of plagioclase and pyroxene amount to as much as 30 percent of the rock. Tuffs have a greenish-gray chloritic matrix. Lenticular bodies of bedded tuffaceous wacke and siltstone are interstratified with more massive rock.

A basal siltstone member, about 180 m thick, is here named the Piña Siltstone Member for exposures in the valley of Quebrada Piña; roadcuts on Highway 827 (57,990 m N., 174,430 m E. to 57,743 m N., 174,314 m E.) are designated as the type section. An apparently conformable contact is exposed at the northernmost of these roadcuts where massive lava saprolite overlain by a few meters of coarsely stratified weathered tuff of the Cerro Gordo underlies thin-bedded siltstone of the Piña. This basal member consists of thin-bedded to laminated highly calcareous siltstone interstratified with fine-grained volcanic wacke. Locally the siltstone grades into impure limestone, colored dark gray by carbonaceous material; in places the siltstone is siliceous rather than calcareous. Near the western edge of the Naranjito quadrangle, a limestone lens less than 10 m thick was mapped at the base of the siltstone. The siltstone typically weathers to yellowish-gray finely porous rock.

A breccia member about 20 m thick and distinguished by an abundance of limestone fragments was mapped in El Ocho Formation (Pease, 1968 b), but it has not been shown on the geologic map (pl. 1.) In the type section of El Ocho, this distinctive breccia overlies about 500 m of thick-bedded to massive tuff and tuff breccia above the Piña Siltstone Member, but at the western edge of the Naranjito quadrangle it seems to rest directly on the Piña.

El Ocho Formation attains a maximum exposed thickness of about 825 m in the vicinity of Van Scoy, but because of faults, nowhere is the formation completely exposed. El Ocho Formation thins westward from Van Scoy by the disappearnce of the massive tuff and tuff

breccia above the basal Piña Siltstone Member; most of its apparent thinning eastward is attributed to faulting.

CANCEL BRECCIA

A heterogeneous assemblage of generally massive nonmarine volcanic rocks underlies most of the drainage basin of the Quebrada Cancel in the Naranjito quadrangle and is here named the Cancel Breccia. The type section is east of this area in the valley of the Río Bayamón; it includes outcrops in the river and adjacent roadcuts and quarries extending from a quarry on the west side of the river in barrio Guaraguao (56,600 m N., 183,475 m E.) southward to outcrops in the river below a quarry that exposes basal pillow lava of the overlying formation (55,540 m N., 183,590 m E.).

The base of the Cancel Breccia is exposed only in a few small fault blocks in the Naranjito quadrangle; elsewhere it is cut out by faults. The best exposure occurs on the west bank of the Río de la Plata where coarse-grained flow breccia of the Cancel rests comformably on interbedded siltstone and silty limestone of El Ocho Formation. The Cancel Breccia is almost entirely confined to the Naranjito quadrangle. Westward in the Corozal quadrangle, the Cancel is overlapped by middle Tertiary rocks, and the formation cannot be traced eastward into the Aguas Buenas quadrangle.

A pervasive reddish-gray to purplish-gray color in both tuff and lava of the Cancel Breccia suggests an oxidizing environment and subaerial deposition for these rocks. This environment of origin is indicated further by an extremely irregular distribution of rock types and by the absence of such sedimentary structures as crossbedding and graded bedding. The formation is composed mostly of tuff breccia and coarse-grained lapilli tuff; reddish-gray flow breccia and lavas are present in the lower part of the formation, and lenses of stratified tuff occur throughout. A bedded tuff member about 265 m thick was mapped near the middle of the formation in the western part of the quadrangle; units of bedded tuff are also common near the middle of the formation toward the east, but none are mappable units. These bedded tuffs may represent episodes of marine deposition within this predominantly nonmarine formation.

The lava flows and lava fragments of the Cancel Breccia are fairly homogeneous porphyritic andesite, which is characterized by a reddish-gray to greenish-gray aphanitic groundmass crowded with stubby plagioclase phenocrysts about 2 mm long. Pyroxene is less common and occurs as large, almost equidimensional crystals as much as 4 mm in diameter. Locally the lavas contain abundant irregularly shaped amygdules of calcite and green chloritic material. Tuffs within the

283-187—68——3

Cancel Breccia are purplish greenish gray and composed of oxidized lava fragments and reddish-brown pumice fragments with plagioclase and vitreous dark-green pyroxene fragments. Banded reddish-purple welded tuff containing green compressed altered glass shards was observed in one outcrop. Relatively small exposures of lava and breccia having the characteristic reddish color, but being quite strongly silicified and bleached, have been correlated with the Cancel in the area between the Quebrada la Yegua and Cerro Mula faults. These have been assigned to the Cancel Breccia chiefly on the basis of color and stratigraphic position relative to younger rocks.

The maximum exposed thickness of the Cancel Breccia is probably more than 2,000 m in barrio Buena Vista in the Naranjito quadrangle, but no continuous section is exposed.

AGE AND CORRELATION

No diagnostic fossils have been found in the pre-Santa Olaya formations. Correlation of this part of the statigraphic sequence with the Robles Formation is suggested however, because of the presence of cruciform plagioclase lava in the Cerro Gordo Lava, similar to plagioclase occurrences in the Lapa Lava Member of the Robles, and because of the lithologic similarity between well-bedded fine-grained strata of the underlying Pájaros Tuff and tuffaceous strata of the Robles Formation exposed in the northwestern corner of the Comerío quadrangle. It is conceivable that the lava containing cruciform plagioclase phenocrysts extruded near the base of the Cerro Gordo Lava was derived from the same magma as the Lapa Lava which it so closely resembles and that both were extruded contemporaneously.

The age of the Robles in the northwest corner of the Comerío quadrangle is established as Early Cretaceous (Albian) on the basis of an ammonite identified by N. F. Sohl (written commun., 1961). However, Foraminifera collected from immediately below the Lapa Lava Member of the Robles Formation in the Barranquitas quadrangle have been designated by E. A. Passagno, Jr. (written commun., 1965), as middle or late Cenomanian. Thus, the Pájaros Tuff probably ranges from late Early Cretaceous to early Late Cretaceous, but biostratigraphic evidence in the area of this report provides only a minimum age of Coniacian or Santonian. This evidence is discussed in the following section concerning the age of the Santa Olaya Lava.

SANTA OLAYA LAVA, RÍO DE LA PLATA SANDSTONE AND CAMARONES SANDSTONE

Formational names are here assigned to, or adopted for, a thick sequence of lava breccia and tuff, the Santa Olaya Lava, and to sepa-

rate sequences of volcaniclastic material, the Río de la Plata Sandstone and Camarones Sandstone, that apparently intertongue with the Santa Olaya on the west and on the northeast, respectively. The two sedimentary formations are lithologically similar and are in similar stratigraphic positions relative to the Santa Olaya. Although they may have been contiguous before large-scale faulting, this cannot be demonstrated, so they have been described as separate formations.

SANTA OLAYA LAVA

A generally massive sequence of basaltic and andesitic lava, breccia, and tuff has been named the Santa Olaya Formation by Lidiak (1965) for extensive exposures in the valley of Quebrada Santa Olaya in the Naranjito quadrangle. This sequence is herein adopted as the Santa Olaya Lava. The type section of the Santa Olaya extends from the junction of Quebrada Collores with Quebrada Santa Olaya (54,250 m N., 181,600 m E.) southward through Cerro de Vergara to Quebrada Bello Gallón (51, 865 m N., 182, 035 m E.). Typical pillow lava of the Santa Olaya is well exposed in the quarry on the east bank of the Río Bayamón about 450 m southwest of the intersection of Highways 833 and 837 (55,565 m N., 183,645 m E.). The pillow lava exposed in this area was included by Kaye (1959, fig. 12) in the Hato Puerco Tuff.

The Santa Olaya is overlapped by middle Tertiary rocks in the Corozal quadrangle west of the mapped area; it extends eastward into the Gurabo quadrangle. The Santa Olaya is composed chiefly of massive submarine lava flows, lava breccia, and volcanic breccia, but toward the east the upper part of the formation consists mostly of volcanic breccia; bedded fine- to coarse-grained tuff and tuffaceous wacke are increasingly common. It is apparently as much as 2,600 m thick in the east-central part of the Naranjito quadrangle but thins rapidly toward the west. Between the Quebrada la Yegua and Quebrada Cruz faults in barrio Ortíz, the Santa Olaya consists of a single flow of pillow lava less than 120 m thick. This flow is well exposed in a roadcut on the northwest side of the highway just southwest of the mouth of the Quebrada Ortíz. The Santa Olaya Formation exposed south of the Quebrada la Yegua fault and in the area north of the Quebrada Cruz fault apparently has been offset several kilometers right laterally along the Quebrada la Yegua fault.

The Santa Olaya Lava is a marine sequence and is believed to lie unconformably on the Cancel Breccia, an essentially nonmarine sequence, because basal pillow lava of the Santa Olaya appears to rest on progressively younger strata of the Cancel toward the west, and clasts evidently derived from the Cancel are found in conglomerates

of formations that interfinger with the Santa Olaya. However, nowhere is the basal contact clearly exposed.

Dark-gray to greenish-gray somewhat chloritized pillow lavas form the base of the Santa Olaya where it is exposed in the Naranjito quadrangle. Pillows are commonly well defined, generally ellipsoidal, and of uniform size, averaging about one-half meter in largest dimension. The lava is porphyritic, containing light-greenish-gray plagioclase laths about 2 mm long and vitreous green stubby pyroxene crystals. Abundance of phenocrysts ranges from sparse to crowded, and plagioclase is everywhere predominant. Amygdules are common and of two varieties: coarse irregular amygdules of calcite and of quartz, or both, and smaller commonly spherical dark-green amygdules of chlorite and celadonite.

Lava flows higher in the section are interstratified with breccias and tuffs. These flows generally are not pillowed; they are relatively thin and commonly exhibit a platy jointing essentially parallel to layering. They are dark gray and aphanitic. They contain, however, sparse plagioclase phenocrysts less than 1 mm long, a few pyroxene phenocrysts, and rare calcite amygdules and are locally finely scoriaceous or pumiceous with pores filled by chlorite. A characteristic yellowish-brown rind about 2 mm thick forms on weathered surfaces of this lava. A lava flow about 75 m thick distinguished by prominent pyroxene phenocrysts occurs near the top of these platy flows in the central part of the Naranjito quadrangle and is shown separately on the geologic map.

A unit of massive tuff breccia interbedded with lava was mapped within the Santa Olaya Lava in the central and western parts of the Naranjito quadrangle. In its western area of exposure, it is relatively thin and rests directly on the basal pillow lava. Eastward, as the formation thickens, the breccia unit is found higher in the section with a maximum thickness of about 310 m. In the central part of the Naranjito quadrangle, the unit rests directly on the pyroxene-lava member; farther northeast, increasing amounts of lava are included with the breccia.

The breccia unit terminates abruptly to the northeast against the westward-trending Guaraguao fault. On the north side of the fault, only a basal segment of the breccia is exposed; its upper part has been cut out along a north-northeast-trending fault on which there has been nearly 300 m of apparent stratigraphic displacement.

The tuff-breccia member is composed of highly scoriaceous and amygdaloidal lava fragments in a matrix of greenish-gray and reddish-brown pumice fragments and plagioclase- and pyroxene-crystal fragments. The lava fragments are spherical or broken spheres with

extremely irregular borders; cores are similar texturally and mineralogically to the fine platy lava of the Santa Olaya. Fragments and matrix are identical in composition, and there seems to be a complete gradation in size from fragments to matrix with no evidence of sorting. Fragments do not exhibit the distinctive teardrop shapes and chilled rinds characteristic of airborne volcanic bombs.

This breccia closely resembles the pillow breccia with aquagene tuff matrix described by Carlisle (1963). It is interlayered with marine lavas, many of which are pillowed, but no gradation from pillow lava to pillow breccia was observed.

Most of the rocks exposed in the belt between the Quebrada la Yegua and Cerro Mula faults are much altered hydrothermally; nevertheless, the least altered lava within this belt closely resembles the Santa Olaya Lava north of the belt, and it was possible to distinguish massive flow and flow breccia of the Santa Olaya from the Cancel Breccia and from the bedded rocks of the Río de la Plata Sandstone. The Santa Olaya also has been altered to greenstone in exposures north of the Quebrada la Yegua fault along the eastern border of the Naranjito quadrangle and throughout the Aquas Buenas quadrangle owing to pervasive intrusion by plutonic dikes and stocks.

Massive volcanic breccia is a conspicuous constituent of the partly silicified and chloritized Santa Olaya exposed in the fault block on the south side of the Carraízo fault. This breccia characteristically contains abundant greenish-gray pumice and scoriaceous lava fragments. It is similar to the breccia member exposed in the Naranjito quadrangle.

Most bedrock exposures in the area of uncertain structure and stratigraphy in the Gurabo quadrangle south of the Leprocomio fault also consist of massive breccia intercalated with lavas, and their lithologic character is very like that of the Santa Olaya; they may be in part correlative.

RÍO DE LA PLATA SANDSTONE

The Río de la Plata Formation, named by Lidiak (1965) is herein adopted as the Río de la Plata Sandstone for well-bedded tuffaceous sedimentary rocks exposed in the valley of the Río de la Plata between barrios Quebrada Cruz and Guadiana in the Naranjito quadrangle. These are not the same rocks as those named the Río de la Plata series by Hodge (1920). Nearly continuous exposures of the Río de la Plata Sandstone in the valley of the Río Cañas, extending from its mouth (55,470 m N.; 172,425 m E.) to the Quebrada la Yegua fault (55,470 m N.; 172,425 m E.), are designated the type section, but here only the upper part of the formation is exposed. The lower part of the formation is exposed in discontinuous outcrop in the valley of the Río

de la Plata beginning 340 m downstream from the mouth of Quebrada Ortíz (5,350 m N.; 174,625 m E.) to the mouth of Quebrada Abarca (54,465 m N.; 173,580 m E.).

The Río de la Plata Sandstone consists of thin-bedded to laminated highly calcareous volcanic wacke and siltstone interstratified with thick-bedded coarse-grained wacke and volcanic conglomerate. The volcanic wacke is composed mostly of subangular lava and feldspar fragments but also includes reddish-brown oxidized pumice fragments and vitreous green pyroxene. Interstices are filled with chlorite and related minerals and calcite. Thin lava flows petrographically similar to the platy lavas of the Santa Olaya are mapped at several stratigraphic positions within the Río de la Plata.

A conglomerate member about 190 m thick occurs near the middle of the formation and is best exposed in the valley of the Río de la Plata immediately upstream from Quebrada Abarca. Clasts in this conglomerate are pebbles, cobbles, and rare boulders chiefly of porphyritic andesite. Cobbles of a hornblende phanerite were also found at a few localities.

The Río de la Plata Sandstone reaches its maximum thickness in the zone of partly altered rocks along the north side of the Cerro Mula fault. Here aphanitic lava flows apparently compose a large part of the formation although textures are somewhat obscured by alteration. The conglomerate member was not exposed in that area.

The Río de la Plata Sandstone rests on pillow lava of the relatively thin westward extension of the Santa Olaya in barrio Dajaos. Near the center of the Naranjito quadrangle, the Río de la Plata Sandstone is cut out along the north side of the Quebrada la Yegua fault; south of this fault, the formation extends across the entire width of the Naranjito quadrangle where it rests on much higher strata of the Santa Olaya. It crops out in the Aguas Buenas quadrangle in fault slivers along the north side of the Cerro Mula fault where it is mostly altered to greenstone.

Lithologic similarity of the lavas in the Río de la Plata to platy lava in the Santa Olaya and the eastward onlapping relation of the Río de la Plata Sandstone to the Santa Olaya Lava north of the Quebrada la Yegua fault suggest that the Río de la Plata is stratigraphically equivalent to part of the Santa Olaya. South of the fault, however, sedimentary rocks of the Río de la Plata overlie the youngest Santa Olaya strata, a condition indicating final overlap across the marine lava and breccia pile. The top of the Río de la Plata is everywhere cut out by faults, and the nature of the upper contact and the relation of this formation to younger rocks are not known. The maximum exposed thickness of this formation is estimated to be about 1,100 m.

CAMARONES SANDSTONE

Well-stratified tuff and tuffaceous wacke are here named the Camarones Sandstone for exposures in the valley of Quebrada Camarones in the Aguas Buenas quadrangle. Exposures near the top of the formation along a road and in the adjacent creeks near the northwestern edge of barrio Mamey east of Quebrada Camarones (55,205 m N.; 187,180 m E. to 54,480 m N.; 187,720 m E.) are designated the type section. Previous writers had included most of this formation in the Hato Puerco Tuff.

The Camarones Sandstone consists mostly of well-bedded dark-gray calcareous, possibly carbonaceous, thin-bedded tuffaceous siltstone interstratified with bedded fine- to coarse-grained tuffaceous wacke and minor amounts of volcanic pebble to cobble conglomerate. These rocks have been altered partly to greenstone where they are closely associated with intrusive rocks.

The Camarones appears to interfinger with the Santa Olaya Lava in exposures along the border between the Naranjito and Aguas Buenas quadrangles, and tongues of lava that resemble lava of the Santa Olaya are interlayered with bedded strata of the Camarones. These tongues are commonly finely scoriaceous or pumiceous greenish-gray lavas. At least two flows of this type have been mapped in the lower part of the formation. Lava of this type is at least 150 m thick in an exposure on hill 254 about 1.3 km east-southeast of the La Muda road intersection (Pease, 1968a). Structural dislocation has prevented specific correlation of exposures of these lavas.

The base of the Camarones Sandstone is indeterminate owing to fault dislocation and interfingering relations with the Santa Olaya Lava. The Camarones is conformably overlain by the Tortugas Andesite in barrio Mamey, where a maximum thickness of about 680 m in unfaulted sequence has been measured between this contact and the La Muda fault to the north. It is not unlikely that the total maximum thickness of the formation is considerably greater, particularly in the area where the Mamey Lava Member reaches its maximum thickness.

MAMEY LAVA MEMBER

The Mamey Lava Member of the Camarones Sandstone is here named for exposures of lava in barrio Mamey in the east-central part of the Aguas Buenas quadrangle. The type section is in the upper valley of the Río Piedras (54,000 m N.; 192,040 m E. to 54,800 m N.; 192,020 m E.).

This lava was originally mapped by Kaye (1959) as intrusive andesite porphyry, but recent more detailed mapping and petrographic

studies of this porphyry indicate that it is an extrusive rock and may have been originally basaltic in composition.

Most commonly, the basalt is dark gray and so crowded with coarse-grained plagioclase phenocrysts that it appears almost holocrystalline. Phenocrysts of clinopyrozene and less common pseudomorphs after orthopyroxene, which are generally much smaller than the plagioclase phenocrysts, occur interstitially in a microcrystalline groundmass. This groundmass consists mostly of stubby plagioclase and granular clinopyroxene in a mesostasis of chlorite and clay minerals. Coarse crystals and grains of magnetite are abundant. Amygdules consist of chlorite, prehnite, and possibly celadonite. These same secondary minerals apparently replace the orthopyroxene phenocrysts. Plagioclase phenocrysts have been sericitized and partly albitized; their composition ranges from An_{35} to An_{54} on the basis of extinction angles. This lava is about 50 m thick in barrio Mamey and locally appears to bifurcate. Farther east, the lava attains a maximum exposed thickness of about 350 m.

The upper surface of the Mamey is exposed in an outcrop (54,000 m N., 192,040 m E., Pease 1968a) in a small stream in the area where the lava is thickest and trends northeastward between La Muda and Carráizo faults. Here the lava is finely sparsely porphyritic with an aphanitic chilled groundmass and is coarsely scoriaceous. Fine-grained clastic rock less than a centimeter above the lava surface shows no evidence of baking, but silt and fine sand in the scoriaceous surface appear to be bleached by baking. Evidently fine sediments filtered into cavities on the surface of the lava before it had entirely cooled.

In an outcrop of the Mamey in the bed of the Río Guaynabo on the south side of La Muda fault (54,580 m N., 187,890 m E., Pease, 1968a), the lava contains contorted lenses of thinly stratified siltstone as much as 10 cm thick. Bedding in the siltstone and crystallization foliation in the lava conform to the configuration of these lenses which indicates that both lava and sediment were in a plastic or semifluid state when the lava was extruded.

AGE AND CORRELATION

No fossils were obtained from the Santa Olaya Lava, Río de la Plata Sandstone, or Camarones Sandstone, but the Santa Olaya rests with apparent unconformity on conglomerate of the Cancel Breccia, and the Río de la Plata and Camarones evidently are stratigraphically equivalent. As the pre-Santa Olaya formations are believed to extend into the Cenomanian or even higher, on the basis of correlation with the dated Lapa Lava Member of the Robles Formation, the Santa Olaya and its interfingering formations should be no older than Cenomanian.

The minimum age for these formations cannot be determined with certainty. The Camarones is overlain by the Tortugas Andesite that appears to contain Coniacian fossils, but it is entirely possible that the top of the Santa Olaya is biostratigraphically higher than the Camarones and that the upper part of the Río de la Plata Sandstone, which appears to overlap the Santa Olaya south of the Quebrada la Yegua fault, is younger than the Tortugas Andesite of Coniacian age. It is conceivable that the Santa Olaya Lava and stratigraphically equivalent rocks span most of the Upper Cretaceous.

GUAYNABO FORMATION

The Guaynabo Formation, named originally by Meyerhoff and Smith (1931) and modified by Kaye (1959), is herein redefined. As now defined, the Guaynabo Formation consists mostly of well-bedded rhythmically bedded volcanic wacke and tuffaceous siltstone interstratified with volcanic conglomerate; it is exposed chiefly in the north-central part of the Aguas Buenas quadrangle and in a broad band astride the boundary between the Carolina and Gurabo quadrangles. Extensive outcrops of the Guaynabo in the valley of the Río Piedras in the Aguas Buenas quadrangle (56,130 m N., 191,000 m E., to 59,400 m N., 191,500 m E.) are here designated the type section.

The Guaynabo Formation was defined by Meyerhoff and Smith (1931) as a "succession of sediments which lie below the La Muda limestone and above the Hato Puerco tuffs * * *" Kaye (1959, p. 13) redefined the formation as follows: "the limits of the Guaynabo * * * include only the section of non-carbonate sediments overlying the Hato Puerco tuff and underlying the Tortugas andesite or, where the latter horizon is missing, the Frailes formation." Kaye (1959, p. 16) further stated that "the Frailes consists of sedimentary and pyroclastic rocks (particularly a massive lapilli tuff) with prominent limestone in the upper and lower parts." He indicated that the Frailes in most places overlies his Guaynabo Formation but that locally it unconformably overlaps the Tortugas Andesite.

The coarse-grained lapilli tuff described by Kaye was also recognized by the writer in much of the area mapped as Frailes by Kaye; however, numerous exposures observed by the writer that had not been available to Kaye have revealed that the pyroclastic material is intimately interlayered with volcaniclastic deposits typical of the Guaynabo. No consistent contact can be found, so the Frailes Formation was not recognized as a mappable unit during the present investigation, and the older term, Guaynabo Formation, was retained to include both the Guaynabo and Frailes of Kaye's usage. The part of Kaye's Frailes

283-187—68——4

that overlaps the Tortugas Andesite is here considered part of the Tortugas.

Kaye (1959) included La Muda Limestone Member at the base of his Frailes and the Leprocomio Limestone Member at the top. New stratigraphic and paleontologic data have shown that La Muda belongs higher in the stratigraphic section; it is therefore described later. Kaye's Leprocomio Limestone Member represents the same stratigraphic interval as the Leprocomio Siltstone Member of the Guaynabo Formation in this report. The term siltstone is used in preference to limestone because most of the member consists of highly calcareous tuffaceous siltstone and includes only a few lenses of true limestone.

The oldest rocks assigned to the Guaynabo Formation in the Aguas Buenas quadrangle are lava exposed at the base of the type section. This is a greenish-gray pillowed lava remarkably similar to pillowed lava in the Santa Olaya. However, the Guaynabo type section is too far removed structurally from the Santa Olaya for reliable correlation, so this lava is here included in the Guaynabo. The base of the Guaynabo in this area is cut out by faulting.

The lava is overlain by rhythmically interbedded tuffaceous calcareous siltstone and volcanic wacke interlayered with numerous pebble- to cobble-conglomerate beds. Clasts in these conglomerates are mostly a heterogeneous assortment of lavas, but limestone cobbles, some of which contain rudistids, are typically abundant. A few traces of quartz, chert(?), and hornblende (?) were also observed in the matrix. At a single locality near the base of the section, a limestone lens less than 2 m thick was observed.

The lithologic and bedding characteristics of the basal part of the Guaynabo in the Aguas Buenas quadrangle are not unlike those of the Camarones. In places where the Guaynabo and Camarones are separated from each other only by a fault, they are distinguished principally by the fact that the Camarones is a more indurated, somewhat altered rock. Because of its tongues of scoriaceous lava, it is more closely allied to the Santa Olaya.

The upper part of the type section of the Guaynabo Formation is well bedded and contains fewer conglomerate beds. Laminated calcareous siltstone is interlayered with the coarser volcanic wacke, and a gradational contact separates these strata from the overlying Leprocomio Siltstone Member, which lies at the top of the formation in this area. The thickness of Guaynabo strata in the type section between the basal lava and the Leprocomio Siltstone Member is at least 1,200 m and may be as much as 1,600 m.

In the westernmost area of exposure of the Guaynabo near the top of the formation, tongues of the Tortugas Andesite are interlayered

with Guaynabo strata, and Guaynabo strata contain a large pyroclastic component. In this area coarse-grained lapilli-tuff beds form conspicuous ridges strewn with large spheroidal boulders of the tuff, and blocky lava fragments with baked vitreous selvages are sparsely distributed in the finer grained volcaniclastic strata. The pyroclastic debris generally is coarser and more abundant toward exposures of the Tortugas Andesite, which is believed to be the source of this material. Most of these strata were mapped as Frailes by Kaye, but their distribution in most of the Aguas Buenas quadrangle is not sufficiently uniform to constitute a mappable stratigraphic unit; no key was found by which to map a contact between the rocks containing pyroclastic interbeds and the volcaniclastic deposits typical of the Guaynabo. Near the eastern edge of the Aguas Buenas quadrangle, however, and in the Gurabo quadrangle, there is a mappable distinction between Kaye's Frailes and Guaynabo.

In the Gurabo quadrangle V. M. Seiders (written commun., 1965) has divided strata that have been included in the Guaynabo Formation of this report into the Frailes Formation and several as yet unnamed formations. He apparently finds no formational contact at the stratigraphic position of the base of the Guaynabo as shown on the geologic map of this report. This contact has been placed beneath a conspicuous thin-bedded unit that seems to mark a transition from mostly well-bedded volcanic wacke above and mostly more massive volcanic breccia below. Bedded strata, however, appear to be interstratified with more massive breccia through a wide transitional interval in this area, and the detailed work by Seiders may have resulted in a more accurate interpretation of the stratigraphy.

The breccia units in this transitional interval and, according to Seiders, at several lower stratigraphic levels in the Gurabo quadrangle, characteristically contain abundant reddish- and greenish-gray scoriaceous lava fragments. This breccia is lithologically similar to the Hato Puerco tuffs named by Meyerhoff and Smith (1931) for exposures in barrio Hato Puerco in the east-central part of the Gurabo quadrangle.

MARTÍN GONZÁLEZ LAVA MEMBER

The Martín González Lava Member of the Guaynabo Formation is here named for exposure of thick basaltic lava in barrio Martín González in the northeast corner of the Gurabo quadrangle. A large quarry in this barrio (59,040 m N., 120,230 m E. to 59,090 m N., 120,240 m E.) is designated the type locality.

The Martín González Lava Member lies about midway stratigraphically between the base of the formation and the Leprocomio Siltstone Member; it is well exposed in the area of its type locality in

the northwestern part of the Gurabo quadrangle where it is about 400 m thick. The lava is exposed in almost continuous outcrop from the type locality westward to another quarry in the Aguas Buenas quadrangle just east of the town of Trujillo Alto (fig. 1). It is cut out by faults just west of this town but is exposed again in fault blocks and slivers along the central part of the boundary between the Aguas Buenas and San Juan quadrangles. The lava lies about 700 m stratigraphically below the Leprocomio Siltstone Member, but west of the Leprocomio fault; nowhere is it observed in the same fault block as the siltstone. The intermittent occurrence of the Mamey Lava Member of the Camarones Sandstone in this area suggests that the westward-advancing flow had a deeply lobate form. Exposures of the lava also extend from the type section eastward in faulted segments to the extreme northeast corner of the mapped area; they seem to be contiguous with a thick sill exposed in a broad area about 10 km east of the town of Loiza (fig. 1).

The Martín González Lava Member is very similar in texture and composition to the Mamey Lava Member of the Camarones Sandstone. It is typically a greenish-gray coarsely porphyritic lava in which prominent plagioclase phenocrysts 2–5 mm long compose more than 40 percent of the rock, and the groundmass is microcrystalline.

Plagioclase is the coarsest and most abundant phenocryst and has been largely altered to sericite and clay minerals. Extinction angles measured on unaltered parts of a few phenocrysts suggest a composition that ranges from An_{34} to An_{44}. The rock contains interstitial clinopyroxene and much less abundant calcite and olive-green chlorite pseudomorphs after orthopyroxene. Magnetite is ubiquitous and occurs either as fine evenly distributed grains or as coarser more sporadically distributed crystals and anhedra. The groundmass contains relatively sparse stubby plagioclase microlites and rare clinopyroxene anhedra in a peculiar vitreous mesostasis that appears to be a fibrous matte of albite(?) and brown turbid crystallites. Amygdules are scattered throughout the rock. Calcite is the most common filling, but rosettes of olive-green chlorite occur, and radial chlorite commonly forms a border around a calcite center. Prehnite is rarely present. According to V. M. Seiders (written commun., 1966), the chemical composition of this lava is that of andesite, but plagioclase extinction angles and the presence of pseudomorphs after orthopyroxene suggest that this partly altered lava was originally basalt.

At the northern end of the large quarry at the type locality in the northwestern part of the Gurabo quadrangle (59,090 m N., 20,240 m E.) near the top of the lava, a lens of bedded tuff about 2 m thick is intercalated with the lava; on the north wall of the quarry, lava

and sedimentary rock are intimately intermixed throughout an interval more than 5 m thick. Fine-grained silt penetrates the lava in a branching pattern. Flow structures in lava and sediment are parallel to irregular contacts.

The anastomosing pattern and convolute borders of these included sediments indicate that the lava was still a fluid or crystal mush when the sediments were introduced, but phenocrysts in the lava are randomly oriented. Fluidal structures in siltstone, shown by color variations from dark gray to greenish gray and by abrupt variations in grain size, indicate that the sediment also was essentially a fluid. Some plagioclase crystals are broken at the sediment interface; others protrude into the sediment. Crystals and bits of lava locally are caught up in the sediment. Conversely, stringers of sediment seem to be pulled out and caught up in the lava.

Thin sections show that phenocrysts are not alined parallel to sediment contacts and that many phenocrysts are broken at the interface. However, turbid brown hairlike crystallites, which are prominent in the groundmass, exhibit a plumose to trachitic texture that is also alined parallel to contacts. The sediment stringers normally are marked by a thin brown baked selvage, and silt grains at the borders are alined parallel to contacts. It thus appears that the Martín González Lava Member, in the form of a coarse-grained plagioclase-crystal mush, invaded unconsolidated sediments of the Guaynabo Formation.

In the eastern part of the Gurabo quadrangle the Martín González Lava Member is thinner and apparently more basaltic than where exposed in the quarry; it is locally pillowed and contains algal limestone incorporated between pillows. The upper part of this pillow lava is greenish-black olivine basalt containing pseudomorphs after olivine and a greater concentration of clinopyroxene than elsewhere in the lava.

The top of the Martín González Lava Member is exposed near the western border of the Guaynabo quadrangle in the low hills just east of Trujillo Alto. The lava grades upward from typical coarse-grained crowded plagioclase-crystal lava into a greenish-gray variolitic lava containing abundant coarse-grained irregularly shaped amygdules of quartz, chlorite, and celadonite(?). The uppermost part is bleached light gray, probably by fumarolic autometamorphism.

LEPROCOMIO SILTSTONE MEMBER

The Leprocomio Siltstone Member (formerly the Leprocomio Limestone Member of the Frailes Formation) lies at the top of the Guaynabo Formation throughout most of its exposure in the Aguas Buenas quadrangle and is overlain disconformably by the Monacillo Forma-

tion. In the Carolina quadrangle and in the extreme northeast corner of the Aguas Buenas quadrangle, a thin sequence of volcanic wacke and pebble conglomerate tentatively assigned to the Guaynabo lies between the Leprocomio and the Monacillo.

The Leprocomio consists of thin-bedded and laminated tuffaceous calcareous siltstone and fine-grained volcanic sandstone. It attains a maximum thickness of about 250 m and seems to thin westward, perhaps because of erosion along the disconformable upper surface. The fresh rock is dark gray and well indurated, but it weathers to a punky porous rock. Small lenses of massive dark-gray limestone containing comminuted shell fragments occur locally and at different stratigraphic levels in this member.

AGE AND CORRELATION

Diagnostic fossils have been obtained from 12 localities in the Guaynabo Formation (table 1). Localities 4–6, 9, and 11 are from below the Martín González Lava Member; 13 is from below the Leprocomio in a fault block where the Martín González is not present; 14 and 15 are from between the Martín González and Leprocomio Members; and 16–19 are from the Leprocomio Member. These megafossil and microfossil assemblages range in age from late Cenomanian to late Campanian.

All but localities 13 and 19 are foraminiferal assemblages collected by V. M. Seiders from the Gurabo quadrangle and the northeast corner of the Aguas Buenas quadrangle. Foraminifera also were collected in the Gurabo quadrangle from strata believed to be stratigraphically below the base of the Guaynabo at localities 1–3.

According to E. A. Pessagno's (written commun., 1965) identifications, strata in the unmapped rocks northeast of the Leprocomio fault and stratigraphically beneath the Guaynabo are upper Cenomanian, and strata of the Guaynabo Formation to within about 230 m of the base of the Martín González Lava Member are also upper Cenomanian; in the 230-m thick interval below the lava, no Turonian assemblages have been found. Apparently rocks of Turonian age are very thin or absent, but Coniacian and Santonian rocks are present. Strata above the lava, up to and including the lower part of the Leprocomio Siltstone Member, are lower Campanian; the upper part of Leprocomio is upper Campanian.

Kaye's El Minao collection (loc. 13) contains several inoceramids, which, according to E. G. Kauffman (written commun., 1965), range from late Santonian to early Campanian in age. The stratigraphic position of El Minao locality is the approximate position of the Martín González Lava Member, which is absent in the fault block that contains

the fauna. This correlation is in general agreement with Pessagno's (written commun., 1965) Santonian age assignment for fossils from locality 11, less than 35 m below the lava, and his lower Campanian assignment for locality 14, a few hundred meters above the lava.

A fauna from locality 19 at the top of the Leprocomio Siltstone Member yielded an *Inoceramus* which E. G. Kauffman assigned to the upper Campanian. This is in agreement with E. A. Pessagno's (written commun., 1965) upper Campanian assignment for the Leprocomio.

The stratified volcaniclastic deposits of the Guaynabo Formation seem to interfinger in part with the Santa Olaya Lava, the Camarones Sandstone, and the Carraízo Breccia (see below). The evidence, however, is only inferred owing to large fault dislocations and insufficient paleontologic information. The interpretation of the stratigraphic succession is largely based on the correlation between the Mamey Lava Member of the Camarones Sandstone and the Martín González Lava Member of the Guaynabo Formation.

The evidence for this correlation is summarized as follows:

1. The Mamey and Martín Gonzáles Lava Members, characterized by the presence of pseudomorphs after orthopyroxene, are more calcic than other lavas in north-central Puerto Rico. As typically developed, they are coarsely porphyritic and contain abundant coarse plagioclase phenocrysts in a microcrystalline groundmass. Clinopyroxene phenocrysts, notably smaller than the plagioclase, occur interstitially as intermediate-sized phenocrysts.
2. Each lava seems to represent a single outpouring of lava of unusual thickness that can be traced laterally for long distances; each thins westward.
3. Both lavas are interlayered with well-bedded volcaniclastic sedimentary rocks which are much alike, except for a difference in their degree of alteration.
4. Both lavas were apparently a relatively cool crystal mush that flowed over and incorporated poorly consolidated water-saturated sediments.

The correlation is also supported by lithologic similarities of other stratigraphic units below the Mamey and Martín González Members—pillow lava that occurs at the base of the type section of the Guaynabo is similar to pillow lava in the lower part of the Santa Olaya Lava, and volcaniclastic deposits that overlie the Santa Olaya-like lavas in the type section of the Guaynabo are similar to the Camarones strata that are separated from the Guaynabo Formation by faults.

If this correlation is correct, at least part of the Guaynabo Formation must be stratigraphically equivalent to part of the Santa Olaya Lava because the Camarones Sandstone is known to interfinger with

the Santa Olaya. The Carraízo Breccia and its relations to these formations are described in a following section of this report.

Paleontologic data do not entirely support correlation of the Mamey with the Martín González because the Martín González Lava Member of the Guaynabo is Santonian or younger, according to E. A. Pessagno (written commun., 1965), yet an *Inoceramus* collected from locality 10 in the Tortugas Andesite, which overlies the Mamey Lava Member of the Camerones, was identified by E. G. Kauffman (written commun., 1965) as Coniacian. The biostratigraphic correlation of megafossil faunas with microfossil faunas appears to be at variance. This conflict is discussed in greater detail in the following section concerned with the Tortugas Andesite.

The stratigraphic proximity of the Campanian fauna at locality 14 to the Cenomanian fauna at locality 6 leaves only a small interval for the Turonian, Coniacian, and Santonian Stages in the northeast corner of the Gurabo quadrangle. This proximity suggests an interval of nondeposition, but there is no apparent evidence of an unconformity or hiatus. Perhaps deposition was slow but continuous.

No diagnostic faunas were obtained from the type section of the Guaynabo in the Aguas Buenas quadrangle. Two lines of indirect evidence suggest that basal strata in the type section below the stratigraphic position of fossil locality 13 represent approximately the same Cenomanian biostratigraphic interval as the basal Guaynabo beneath the Martín González Lava Member in the Gurabo quadrangle. First, the thickness of rocks in the type section stratigraphically beneath fossil locality 13, which is believed to lie at the approximate stratigraphic position of the Santonian to early Campanian Martín González Lava Member, is comparable to the thickness beneath the Martín González in the Gurabo quadrangle. Second, the basal pillow lava in the type section is believed to be correlative with the Santa Olaya Lava which has been independently, though tentatively, assigned to the Cenomanian on the basis of stratigraphic correlation to the west.

TORTUGAS ANDESITE

This formation was named by Kaye (1959, p. 13) "after Barrio Tortugas, lying north and east of La Muda, where it is well exposed." He further states, "The formation consists of a non-persistent horizon of flow rock, breccia, and, in places, conglomerate, all of a characteristic augite-andesite composition—lying between the Guaynabo Formation, herein redefined, and the Frailes Formation."

Although the Frailes Formation was not recognized as a mappable stratigraphic unit and has been included with the Guaynabo Formation in this report, the sequence of massive, chiefly nonmarine, andesite

volcanic rocks, named the Tortugas Andesite by Kaye, was observed to intertongue with the upper part of the Guaynabo Formation at the approximate stratigraphic position designated by Kaye.

Kaye (1959) did not assign a type area or type section to the Tortugas Andesite, but he did note (p. 14), "The Tortugas Andesite is particularly well exposed in several of the quarries that lie north of Highway 1 about a mile southeast of La Muda." These quarries have been worked almost continuously since Kaye visited the area, and the workings have been greatly enlarged to form a single quarry. The north face of this quarry (53,800 m N. 188,800 m E. to 53,800 m N. 189,000 m N.), which has been moved at least 50 m northward, is designated the type section for the Tortugas Andesite. Greenish- and reddish-gray mottled lava and lava breccia compose most of this section, but finer fragmental material is sporadically incorporated in the breccia, and thin lenticular reddish-brown conglomerate beds also occur locally. Neither the top nor the bottom of the formation is exposed in this section.

The Tortugas Andesite is chiefly a nonmarine deposit of volcanic breccia with a few intercalated lavas, lenticular beds of poorly stratified volcanic wacke, and lenses of reddish-gray conglomerate. The rock is medium gray to brownish gray, and the lavas exhibit a characteristic reddish tint on slight weathering. Lava and lava fragments are commonly crowded with randomly oriented plagioclase crystals. The mafic mineral is clinopyroxene, occurring as nearly equant fresh phenocrysts generally larger than the plagioclase crystals. Nonmagnetic black grains of hematite(?) are prominent in the lavas. Zeolite minerals, including the salmon-pink laumontite(?), are ubiquitous. They occur in anastomosing veins and between fragments in breccia. Small pods of limestone occur locally mixed with breccia and volcanic wacke. The erratic distribution of this formation does not permit a reliable estimate of overall thickness, but its maximum exposed thickness is probably as much as 700 m.

The base of the Tortugas Andesite is exposed in barrio Mamey in the Aguas Buenas quadrangle, where it rests conformably on well-stratified tuffaceous wacke and siltstone of the Camarones Sandstone. In this area typical massive volcanic breccia of the Tortugas grades laterally westward into crudely stratified purplish-gray tuffaceous wacke and breccia which Kaye correlated with the Frailes Formation and on this basis concluded that the Frailes unconformably overlaps the Tortugas. This crudely stratified material, however, which clearly overlies the Camerones Sandstone as shown by the delineation of the Mamey Lava Member, is a facies common in the Tortugas and is, therefore, included with the Tortugas.

The volcanic breccia consists of mottled greenish-gray to reddish-gray lava fragments in a matrix of smaller lava fragments, reddish-gray pumice, and crystal fragments. Individual lava flows in the Tortugas have limited lateral extents and occur only in the most northwestern exposures where they are interstratified with massive coarse-grained volcanic breccia. Their presence in this area suggests that the Tortugas vents were nearby. The Tortugas Andesite, as previously stated, intertongues toward the northwest with the upper part of the Guaynabo Formation and has contributed pyroclastic debris to much of this part of the Guaynabo as high as the base of the Leprocomio Member, the amount of contamination decreasing away from the Tortugas source. The base of the Tortugas was not observed in this area.

The Tortugas Andesite rests on the Mamey Lava Member or bedded rocks of the Camarones Sandstone toward the southeast where the strata trend northeast and the Mamey Lava Member is thickest. Here the Tortugas has a somewhat different character from that in other areas. It consists almost entirely of massive coarse-grained volcanic breccia containing varicolored greenish- to reddish-gray porphyritic lava fragments in a matrix of volcanic wacke characterized by prominent red and green pumice fragments; its lithology closely resembles that of the Carraízo Breccia which is separated from the Tortugas by the Carraízo fault.

AGE AND CORRELATION

A single poorly preserved fragment of *Inoceramus* of Coniacian age was identified from a large limestone boulder at least a cubic meter in size that was resting on strata of the Tortugas Andesite at the top of a hill (fossil loc. 10). Although no limestone was found in place in this area, the topographic position and size of the boulder suggest that it has not been moved very far. Pods of similar limestone are known to occur in place elsewhere in the Tortugas.

There is a conflict here, as previously stated, between stratigraphic interpretation and faunal evidence. The Coniacian fossil locality 9 in the Gurabo quadrangle underlies Santonian fossil locality 11, which, in turn, lies stratigraphically below the Martín González Lava Member of the Guaynabo, whereas this Coniacian fossil locality 10 in the Tortugas Andesite lies above the Mamey Lava Member of the Camarones.

The lithologic correlation of the two lavas, however, appears to be well established. It is also quite unlikely that the Coniacian limestone boulder came from strata beneath the Mamey because no rocks in the area older than the Tortugas are exposed topographically higher than

this locality, and there is no apparent reason why this large boulder should have been transported any great distance by man.

E. A. Pessagno, Jr., and E. G. Kauffman are each confident of their fossil identifications, but unless further conflicting paleontologic evidence is obtained, it would seem that the conflict is between microfossil and megafossil age assignments and does not represent a stratigraphic inconsistency. However, the variance leaves some question as to the maximum age of the Tortugas.

An abundant fauna was collected by C. A. Kaye from a large weathered boulder of tuffaceous rock (Kaye, oral commun., 1965) in an area underlain by the Tortugas Andesite (fossil loc. 12). J. B. Reeside, Jr., identified the fauna from this boulder as Santonian or Campanian, and N. F. Sohl, who reexamined the museum collection, stated on the basis of the presence of the ammonite *Texanites* that this fauna is at least as old as Santonian (Sohl, written commun. 1963).

Kaye (1959, p. 14) suggested that this locality belongs to the Tortugas Andesite or older rocks. He correlated the fauna from fossil locality 12 with those from a limestone exposed in a small fault wedge at fossil locality 23, which is now believed to be part of La Muda Formation higher in the section. Sohl and the writer attempted unsuccessfully to reestablish fossil locality 12. However, its tuffaceous character, as contrasted with the limestone lithology of fossil locality 23, suggests that fossil locality 12 represents a boulder that rolled downhill from the Tortugas Andesite.

If the tuffaceous boulder of fossil locality 12 is from the Tortugas, the age of part of the Tortugas at least is probably Santonian or younger. A Santonian to Campanian age for the Tortugas Andesite is also indicated by the fact that the Tortugas interfingers with and has contributed pyroclastic debris to the Guaynabo Formation in the stratigraphic interval between fossil locality 13, Santonian or younger, and the Campanian Leprocomio Siltstone Member of the Guaynabo. On the basis of present biostratigraphic information, therefore, Tortugas deposition began in the Coniacian and continued at least into the Santonian. This conclusion is supported by the fact that the Tortugas Andesite intertongues with the Guaynabo at about this biostratigraphic level.

CARRAÍZO BRECCIA

A remarkably uniform sequence of massive volcanic breccia that underlies a large part of the east-central part of the Aguas Buenas quadrangle is herein named the Carraízo Breccia for its exposure in barrio Carraízo. The large quarry just northeast of the dam on the Río Loíza (55,100 m N. 196,20 m E.) is designated the type locality. Massive mottled greenish-gray to reddish-gray volcanic breccia charac-

terized by an abundance of greenish-gray and reddish-gray pumice fragments is well exposed in this quarry.

The lithic character of the Carraízo Breccia is very similar to that of rocks exposed in barrio Hato Puerco in the east-central part of the Gurabo quadrangle and in El Yunque quadrangle east of the mapped area. These rocks were named the Hato Puerco Tuff by Meyerhoff and Smith (1931). Kaye (1959) noted this similarity and redefined the Hato Puerco Tuff to include rocks here assigned to the Carraízo Breccia. He also included in the redefined Hato Puerco a wide variety of other rock types and parts of several other formations in the Aguas Buenas quadrangle. Recent mapping in the Gurabo quadrangle by V. M. Seiders (written commun., 1965) has shown that the Carraízo Breccia in the Aguas Buenas quadrangle is not contiguous with the Hato Puerco Tuff in the barrio of that name and that breccias of similar lithology probably occur at several stratigraphic levels in the Gurabo quadrangle.

The Carraízo Breccia is isolated by the Leprocomio, Carraízo, and other faults from other stratigraphic units in the Aguas Buenas quadrangle. It is chiefly a massive breccia in which lenses of bedded volcanic wacke are widely distributed, but a tuffaceous siltstone member has been mapped in the northwest corner of the Carraízo exposures.

The breccia consists of varicolored greenish-gray to reddish-gray porphyritic lava fragments in a fragmental matrix composed chiefly of the same lava fragments but characterized by an abundance of both reddish-gray and greenish-gray pumice fragments and including fragments of plagioclase and pyroxene. Chloritic material and clay are interstitial. Red pumice fragments generally are more conspicuous than green pumice fragments and serve as one means of distinguishing the Carraízo Breccia from breccia in the Santa Olaya exposed south of the Carraízo fault.

The siltstone member which is exposed in fault slivers in the northwest corner of the area of exposed Carraízo Breccia consists of well-bedded tuffaceous siltstone, volcanic wacke, and some conglomerate. These strata look much like strata of the Guaynabo Formation exposed just north of the Leprocomio fault, but because they are separated from the Guaynabo by faults and because they apparently rest conformably on typical Carraízo, they have been included as a member of the Carraízo Breccia. The exact stratigraphic position of this member in the Carraízo Breccia is uncertain because of lack of stratigraphic and structural control in this formation. Possibly this member represents a tongue of Guaynabo in the Carraízo. Similar less extensive zones of siltstone and bedded volcanic wacke are present but unmapped elsewhere in the Carraízo Breccia.

The maximum thickness of the Carraízo Breccia is very uncertain, but at least 1,400 m of this formation is apparently exposed along the north side of the Carraízo fault west of Lago de Loíza, and as much as 800 m more may occur in this area, assuming that no undiscovered faults have repeated the section.

AGE AND CORRELATION

The stratigraphic relation of the Carraízo Breccia to other rocks exposed in the area cannot be demonstrated because the formation is isolated by faults on the north, west, and east and because the geology southeastward in the Gurabo quadrangle is still uncertain. Therefore, the new name, Carraízo Breccia, is needed to define the massive breccia exposed in the Aguas Buenas quadrangle between the Carraízo and Leprocomio faults.

The conspicuous concentration of reddish-gray lava and pumice fragments in the Carraízo Breccia in the western part of the fault block north of the Carraízo fault and the lithologic similarity of these strata to the Tortugas Andesite exposed south of this fault suggests that much of the Carraízo may be stratigraphically equivalent to or younger than the Tortugas. The presence of Guaynabo-like volcaniclastic strata in northwestern exposures of the Carraízo also suggests a correlation with part of the Guaynabo. If these correlations are correct, the age of the formation probably ranges from Coniacian possibly to Campanian.

Near the eastern border of the Aguas Buenas quadrangle, red pumice fragments typical of the Carraízo to the west are only rarely present, and the breccia more closely resembles breccia assigned to the Santa Olaya south of the Carraízo fault. This breccia is contiguous with volcanic breccia, lava, and stratified rocks exposed in the Gurabo quadrangle, the geology of which, according to V. M. Seiders (written commun., 1965), is still uncertain owing to complexities of structure and stratigraphy. Accordingly, the areal extent of the Carraízo Breccia is restricted to the Aguas Buenas quadrangle.

Fossil localities 7 and 8 (table 1) in the west-central part of the Gurabo quadrangle are from the area of uncertain stratigraphy where the Carraízo Breccia may be in contact with other stratigraphic units as yet unnamed. The fossils are significant to this report as they are the only paleontologic collections from between the Leprocomio and Carraízo faults. The collections contain Foraminifera that are Turonian or younger, according to E. A. Pessagno (written commun., 1965), and thus are younger than fossils collected from beneath the Guaynabo Formation northeast of the Leprocomio fault.

Thus, the Carraízo Breccia, which is arbitrarily restricted to the Aguas Buenas quadrangle for this report, appears to be stratigraph-

ically equivalent to or younger than the Tortugas Andesite and equivalent at least in part to the Guaynabo Formation. It appears to be younger than similar volcanic breccia exposed beneath the Guaynabo Formation on the northeast side of the Leprocomio fault.

However, there is no direct evidence to support this stratigraphic assignment, and the entire Carraízo may be much older. The oxidized material in the Carraízo may have been derived from the Cancel Breccia and may then be as old as Cenomanian. The general attitude of the bedding supports this interpretation.

The volcanic breccia and associated strata exposed in the Gurabo quadrangle southwest of the Leprocomio fault and apparently contiguous with the Carraízo to the west more closely resemble strata of the Santa Olaya Lava southwest of the Carraízo fault than typical Carraízo. It is quite possible that a structural break, not recognized by the writer, exists near the eastern border of the Aguas Buenas quadrangle, and that this break separates the Carraízo from older rocks that include fossil localities 7 and 8.

LA MUDA FORMATION

"La Muda Limestone," originally named by Berkey (1915) and described both by Meyerhoff and Smith (1931) and by Kaye (1959), is herein redefined to include the discontinuous sequence of bedded strata that overlie the Tortugas Andesite in the Aguas Buenas quadrangle. The formation contains conspicuous lenses and pods of limestone, particularly at the base, and in places the entire formation is limestone. The type section of La Muda Formation is in a quarry (53,710 m N., 189,120 m E. to 53,690 m N., 188,970 m E.) just north of Highway 1 and east of the quarry containing the type section of the Tortugas Andesite. A very coarse reddish-gray massive conglomerate member is exposed locally at the base of La Muda as well as in isolated fault blocks.

The strata in La Muda are for the most part well-bedded sandstone and siltstone and lenticular massive limestone. The sandstone is friable and yellowish to brownish gray in weathered outcrop, but where calcite cement has not been leached, the rock is neutral gray and well indurated. The calcium content in these beds is variable and in places is sufficient to term the rock a bedded sandy limestone. Detrital quartz and flakes of biotite are present in this chiefly feldspathic sandstone. Pebble to cobble conglomerate is commonly interlayered with the finer grained rocks. Locally the clasts in these conglomerates are almost exclusively limestone, but generally the principal clasts are a heterogeneous assortment of lava fragments. Quartz, chert, and hydrothermal jasperoid are ubiquitous minor constituents. Locally the

formation consists almost entirely of massive limestone, and pods of limestone occur at several horizons in the stratified rocks. These limestones contain fragments of rudistids, gastropods, and pelecypods as well as coral and algae. A ball-shaped echinoid, about 1 inch in diameter, is a conspicuous fossil in this formation; it has been identified by P. M. Kier (written commun., 1963) as cf. *Conulus* sp. which evidently is found throughout the Upper Cretaceous.

Unlike most of La Muda, the conglomerate member that occurs at the base of La Muda is characteristically reddish gray; the great majority of clasts seems to have been derived from the Tortugas Andesite. This conglomerate rests on the Tortugas Andesite except at one locality where a thin tongue of La Muda sandstone apparently lies between the conglomerate and the Tortugas. Clasts in the conglomerate range from cobbles to boulders as much as a meter in diameter. The conglomerate is not everywhere in contact with other La Muda strata. In several localities it rests alone on the Tortugas, and in most places the top is not exposed, but nowhere have strata other than La Muda strata been observed to rest on top of it. This apparent basal conglomerate, derived from prominent local highs in the Tortugas, rests unconformably on the Tortugas.

AGE AND CORRELATION

The history of correlation of this formation is complex. Berkey's (1915, p. 22) original description of La Muda as a "rather heavy development of limestone in the vicinity of La Muda * * *" fits the present location of La Muda Formation sufficiently for the name to be retained. Meyerhoff and Smith (1931) described two limestones in the vicinity of La Muda, one of which they correlated with the Trujillo Alto Limestone Member exposed further east. Kaye (1959) also described a La Muda Limestone and a Trujillo Alto Limestone in this vicinity, but his mapped units were different from those of Meyerhoff and Smith. He correlated the Limestone exposed "in the two quarries about 1½ miles southeast of the La Muda road fork and the limestone exposed to the southwest at El Laborinto * * *" (Kaye, 1959, p. 18) with La Muda Limestone of Berkey, and he mapped as Trujillo Alto Limestone that limestone which is overlain by the Guaracanal Andesite along the north side of La Muda fault.

Recent geologic mapping has revealed several previously undiscovered outcrops of limestone and associated sedimentary rocks of La Muda Formation in widely distributed fault blocks. Most of these, including those mapped by Kaye as La Muda and as Trujillo Alto, belong to a single formation that overlies the Tortugas Andesite, the Camarones Sandstone, and the Guaynabo Formation and underlies

the Guaracanal Andesite. Paleontologic data indicate an age corresponding to the biostratigraphic interval of the Trujillo Alto Limestone. Berkey's original term La Muda is retained in preference to Trujillo Alto Limestone because of the great areal and structural separation of this formation from the limestone near Trujillo Alto and because the two calcareous units overlie and are interstratified with quite different lithologic facies.

Five fossil collections from La Muda Formation in isolated fault blocks contain identifiable faunas. Most of these are from limestone in this formation. Their age assignments all include the Maestrichtian Stage, although several are not specifically diagnostic of this stage. Fossil locality 21 contains the rudistid species assignable to the genera *Vaccinites* and *Antillocaprina* and has been assigned by N. F. Sohl (see table 1) quite definitely to the Maestrichtian. Fossil locality 24 contains a fauna similar to that of 21, including *Antillocaprina*, and is also considered by Sohl to be Maestrichtian. Fossil locality 25 contains *Vaccinites* and was assigned by Sohl to the Campanian or Maestrichtian. Faunas from fossil localities 22 and 23 could be identified only as Late Cretaceous in age.

Fossil locality 23 is in a small fault wedge in what appears to be La Muda Formation on the north side of Highway 1 opposite the intersection with Highway 173. An abundant fauna was collected from limestone in this fault block, but both J. B. Reeside, Jr. (Kaye, 1959, p. 19), and N. F. Sohl (written commun., 1963) were able to define its age only as Late Cretaceous. The writer has tentatively assigned this fault block to La Muda Formation because the limestone seems to be associated with friable tuffaceous micaceous sandstone characteristic of La Muda. Kaye, as stated previously, correlated this with the nearby tuffaceous boulder of fossil locality 12, but Sohl (oral commun., 1965) examined both fossil collections and concluded that they probably are not correlative.

MONACILLO FORMATION

The Monacillo Formation was described by Kaye (1959, p. 19) as a "predominantly continental deposit ranging in texture from siltstone to conglomerate, and lying between the Frailes Formation and the Trujillo Alto limestone. The formation has been named from barrio Monacillo, southwest of Río Piedras, where it crops out widely."

The Monacillo Formation as described in this report is approximately the same as that mapped by Kaye, except for minor variations in areal distribution and except for the inclusion of the Trujillo Alto Limestone as a member in the Monacillo. At the time of Kaye's work most of the area underlain by this formation was in pasture lands and

cane fields and, according to Kaye, covered by old alluvial soil. In the past 10 years, however, much of the area has been developed for residential housing. The writer was fortunate to be working in the area at the time of this development and was able to observe broad exposures of the formation cleared by heavy construction equipment.

These same exposures are now covered by houses so that there are few good exposures of the Monacillo remaining. The best are found in the developed area of several square kilometers in barrio Frailes, east of La Esperanza road intersection in the northwestern part of the Aguas Buenas quadrangle; this is designated the type area. The contact between the Monacillo and underlying Leprocomio Siltstone Member of the Guaynabo was at one time exposed in this general area just east of the boundary between barrios Frailes and Monacillo.

The broadest area of exposure of the Monacillo Formation is toward the west. Four hundred meters of strata was measured, but probably at least some of this has been repeated by faults. The formation pinches out eastward in the southwest corner of the Carolina quadrangle. A reddish-gray and purplish-gray color is characteristic of these strata; it is due to hematitic iron oxide coating and manganese staining and indicates that the source material was eroded in an oxidizing environment.

Although mudstone may be more widespread, the conglomerate is the most conspicuous feature of this formation, particularly in the lower part of the formation and toward the southwest. This conglomerate contains a more heterogeneous assortment of clasts than any of the underlying stratigraphic units. Most clasts are a variety of porphyritic lavas chiefly from the Tortugas Andesite. Also recognizable are the brown aphanitic and pumiceous lavas from the Santa Olaya and associated sedimentary formations. Siliceous clasts are common, occurring as quartz, chert, and hydrothermal jasperoid. Welded tuff fragments have been observed. Very light yellowish-brown crumbly clasts are probably phaneritic diorite.

Massive to thick-bedded mudstone is interstratified with the conglomerate but is normally poorly exposed. Quartz grains and biotite flakes are present in the purplish-gray mudstone.

The mudstone and conglomerate alternate with lesser amounts of thin-bedded siltstone and sandstone suggestive of a shallow-water marine environment. Some of the coarser grained beds exhibit the characteristic deep-red and purple coloring, but most are only tinted shades of red and purple; considerable thicknesses of bedded fine-grained strata are gray to olive gray, the characteristic red coloring being entirely absent. These well-bedded strata are increasingly common toward the northeast.

The Monacillo rests directly on the Leprocomio Siltstone Member of the Guaynabo Formation throughout much of its area of exposure, and no angular discordance was noted at this contact; however, an apparent eastward thickening of the Leprocomio and the appearance of volcanic wacke above the Leprocomio in the southwest corner of the Carolina quadrangle suggest that the Monacillo rests unconformably on progressively younger rocks of the Guaynabo toward the east.

The presence of an unconformity at the base of the Monacillo is indicated by the lithic character of the formation, which suggests that the Monacillo was deposited on the slope of an eroding highland. Conglomerate is most common in southwestern exposures of the Monacillo toward areas of exposure of the older Tortugas Andesite and Santa Olaya Lava. Cobbles and pebbles of the Tortugas and to a lesser extent of the Santa Olaya, which are the principal clasts in these conglomerates, are evidence that both formations were exposed to erosion at the time of deposition of the Monacillo. The conspicuous red and purple coloration in most of this formation is indicative of derivation from a subaerial environment, but the presence of unoxidized wacke and siltstone and of the Trujillo Alto Limestone Member interstratified with the oxidized material indicates that deposition was chiefly in a shallow-water marine environment.

TRUJILLO ALTO LIMESTONE MEMBER

Kaye (1959) mapped as the Trujillo Alto Limestone a broad belt of rocks above the Monacillo and below the Figuera Volcanics. Extensive exposures in a recently developed housing area in the St. Just area in the northeast corner of the Aguas Buenas quadrangle have revealed that the Trujillo Alto Limestone is a more restricted unit than Kaye had shown and that it is in most places overlain by bedded mudstone, sandstone, and siltstone of the Monacillo. It is here considered to be a member of the Monacillo Formation. The large limestone quarry on the north side of Route 845 in the valley of Quebrada Cepero (59,250 m N., 194,740 m E.) is designated the type locality of the Trujillo Alto Limestone Member of the Monacillo Formation.

The Trujillo Alto is the thickest and most extensive limestone exposed in the area. Its maximum thickness may be as much as 60 m. Much of its exposure is in large fault slivers along the northeast-trending Leprocomio fault. It pinches out in the northeast corner of the Aguas Buenas quadrangle and is not present in western exposures of the Monacillo Formation. The Trujillo Alto typically pinches and swells; it contains abundant fossil fragments consisting chiefly of algae and corals, which are poorly preserved and not specifically diagnostic. As in La Muda Formation, the echinoid cf. *Conulus* sp. is

a conspicuous fossil at several localities in this limestone. In a quarry at fossil locality 20 in the northeast corner of the Aguas Buenas quadrangle, the Trujillo Alto seems to be at the top of the Monacillo and to be overlain by Tertiary strata. Light-gray limestone, characterized by a light-yellowish-gray weathering rind and by an abundant fauna of algae and miliolid Foraminifera, is exposed above darker gray limestone. This distinctive upper limestone has been separated from the Trujillo Alto and correlated with basal limestone in the Guaracanal Andesite which it closely resembles.

AGE AND CORRELATION

The Trujillo Alto Limestone Member of the Monacillo Formation contains abundant fossils, most of which are fragmental and provide only a broad clue to the age of this formation. Kaye (1959) obtained several collections from the Trujillo Alto, and John B. Reeside, Jr., who identified the fossils, was able to determine only that the limestone is probably Upper Cretaceous (Kaye, 1959, p. 21). N. F. Sohl examined Kaye's collections, recollected from Kaye's localities, as far as possible and made further collections from a few new localities. The most abundant fauna obtained by Kaye and by Sohl was from the quarry at fossil locality 20. Sohl (written commun., 1963) was able to identify the age of the Trujillo Alto Limestone at this locality as Late Cretaceous, post-Cenomanian.

A sample collected by Seiders from fossil locality 27 yielded Foraminifera that have been assigned tentatively to the Paleocene by E. A. Pessagno, Jr. (written commun., 1965). The writer was unable to ascertain the exact stratigraphic position of this locality, but Seiders has indicated that it is from the middle of the dark-gray Trujillo Alto Limestone Member. Thus there again may be a variance between megafossil and microfossil biostratigraphic correlation, but it is possible that the Trujillo Alto is partly Paleocene in age. An alternative possibility is that the limestone of this locality does not represent the middle of the Trujillo Alto and is a younger limestone that rests directly on the Trujillo Alto Limestone member. A relation such as this has been observed at fossil locality 20 where the Trujillo Alto is overlain by light-gray miliolid limestone assigned to basal limestone in the overlying Guaracanal Andesite. If this is the case, a sliver of the limestone member of the Guaracanal Andesite is exposed on the south side of the Leprocomio fault. However, this relation was not observed at fossil locality 27 by the writer and is therefore not shown on the geologic map.

The Monacillo Formation is believed to be stratigraphically equivalent to La Muda Formation and perhaps to have interfingered

with La Muda before structural dislocation. Both formations are probably Maestrichtian in age and rest unconformably on older rocks. The lithologic character of the basal conglomerate member of La Muda is very similar to that of the conglomerates in the Monacillo although the basal conglomerate member of La Muda is much coarser. In both, the predominant lava clasts apparently were derived from the Tortugas Andesite, and the matrix is characteristically reddish gray. Quartz and jasperoid are conspicuous minor constituents in these formations and are rarely present in older rocks.

TERTIARY SYSTEM

PALEOCENE AND EOCENE SERIES

GUARACANAL ANDESITE

A volcanic sequence characterized by conspicuous hornblende phenocrysts is exposed chiefly in the northwestern corner of the Aguas Buenas quadrangle. It is here named the Guaracanal Andesite for exposures on Quebrada Guaracanal which flows along the southern border of the San Juan quadrangle and into the Aguas Buenas quadrangle. Exposures along highway 1 and on adjacent hill slopes between Cerro Magueyes and the alluviated valley north of La Muda (56,320 m N., 188,140 m E. to 44,360 m N., 187,760 m. E.) are designated the type section of the Guaracanal Andesite.

The rocks here called the Guaracanal Andesite were named the Figuera Volcanics by Kaye (1959, p. 22) on the basis of correlation with "a belt of fine-grained andesite flow rocks in the eastern part of the island, south of Fajardo" that Meyerhoff and Smith (1931) had named the "Figuera formation." As discussed below, paleontologic evidence has shown that this correlation is invalid; therefore, the Figuera of Kaye's usage has been renamed, and the term "Figuera Volcanics" is hereby abandoned.

The Guaracanal Andesite is distinguished from older volcanic rocks in the area by ubiquitous black euhedral hornblende and by a distinctive purplish-gray color. In its largest area of exposure, in the northeastern part of the Aguas Buenas quadrangle, it consists almost entirely of massive coarse-grained breccia and has many of the characteristics of a local vent agglomerate. The breccia is in part lava breccia in which an igneous matrix incorporates angular fragments of the same composition and partly volcanic breccia with a distinct pyroclastic component of similar composition. Unbrecciated lava flows are rare in this formation, and the coarse-grained breccia changes abruptly, both vertically and laterally northward into massive to crudely strati-

fied tuff and lapilli tuff in which coarser grained clasts are widely scattered.

The andesite is more silicic than most andesite of the northeastern Puerto Rico volcanic sequence; it is almost a dacite and, judging from the fragmental natural of its deposits, was probably more explosive. The lava contains abundant euhedral white plagioclase phenocrysts which, combined with the black hornblende against a strongly contrasting purplish-gray aphanitic groundmass, give the lava a distinctive spotted aspect.

Lava breccia or vent agglomerate underlies a conical hill on the south side of the Tortugo fault about 1 km east-southeast of Highway 1. At one locality just south of the fault the Guaracanal appears to intrude La Muda Formation. This lava breccia grades northwestward along the south side of this fault into volcanic breccia with a conspicuous tuff matrix. Coarse-grained volcanic breccia composes the lower part of the type section along Highway 1 and underlies Cerro Magueyes. North of Cerro Magueyes, the pyroclastic component is increasingly prominent and the formation is crudely stratified. Finer grained pyroclastic debris and coincident stratification also are increasingly important upward in the section or toward La Muda fault, which forms the southwestern boundary of the formation in the type section.

In a small faulted syncline on the north side of the Tortugo fault about 0.6 km south of the town of Guaynabo, stratified tuff of the Guaracanal, including a lenticular basal limestone member, rests unconformably on beds of the Guaynabo Formation that are stratigraphically well below the Leprocomio Siltstone Member. Farther to the northwest, similar purple-tinted stratified tuffs of the Guaracanal rest on the Monacillo Formation with no apparent disconformity. Lenticular pods of limestone are again present at or near the base of the formation.

The Guaracanal Andesite is also exposed in a narrow arcuate strip that trends along the border between the San Juan and Aguas Buenas quadrangles and includes the valley of the Quebrada Guaracanal for which the formation was named; it pinches out northeastward in the Carolina quadrangle. In this area the formation consists of waterlaid bedded tuffaceous wacke and conglomerate containing well-rounded cobbles and small boulders of lava, but it exhibits the purplish-gray color and contains the abundant black hornblende crystal fragments that are characteristic of the type area.

A thickness of 600 m is estimated for exposures in the type section, but here neither the top nor the bottom is exposed. The same order of maximum thickness is estimated for exposures in the southeast corner of the San Juan quadrangle.

Thin discontinuous lenses of light-gray algal limestone that characteristically weathers light yellowish gray are exposed in several places at or near the base of the Guaracanal. Large miliolid Foraminifera are conspicuous in this limestone at almost all the exposures; these are associated with fragments of pelecypods and other megafossils. The light-gray miliolid and algal limestone that overlies the Trujillo Alto Limestone Member of the Monacillo in the quarry at fossil locality 20 is assigned to the Guaracanal. A similar relation exists in a low hill about 2 km west of the town of Loiza in the Gurabo quadrangle, where massive medium-gray limestone assigned to the Trujillo Alto Limestone Member of the Monacillo is overlain by calcareous beds containing miliolid Foraminifera correlated with the Guaracanal. Kaye (1956) described this locality in detail.

The Guaracanal Andesite apparently rests conformably on the Monacillo Formation throughout most of its extent. Locally it rests on the Trujillo Alto Limestone where this member forms the top of the Monacillo. In the small syncline south of Guaynabo the Guaracanal evidently rests unconformably on the Guaynabo. On the south side of the Tortugo fault vent, agglomerate of the Guaracanal appears to intrude La Muda Formation. About 1.4 km northwest of the type section, the stratified pyroclastic debris of the Guaracanal Andesite is conformably overlain by the Río Piedras Siltstone. This contact is defined by a fairly abrupt change from crudely stratified purplish-gray tuff to well-stratified thin-bedded dark-gray siltstone and volcanic wacke.

Fossil locality 26 lies at about the same stratigraphic position as the light-gray miliolid limestone exposed above the Trujillo Alto at fossil locality 20. Foraminifera collected from this locality have been assigned to the Paleocene by E. A. Pessagno, Jr. (written commun., 1965), as were the Foraminifera from fossil locality 27, the stratigraphic position of which, as previously mentioned, is less certain.

Three collections were made from a thin discontinuous algal limestone at and just above the base of the Guaracanal Andesite in the northwest corner of the Aguas Buenas quadrangle (fossil loc. 28). This limestone contains the miliolid foraminiferal fauna which appears to be nondiagnostic but characteristic of the Paleocene in this area. It also contains external impressions of a possible Venericardia, which, according to N. F. Sohl (written commun., 1963), suggests a Tertiary rather than Cretaceous age.

Kaye (1956) collected a sample from fossil locality 29 from the north side of the low hill west of Loiza. This sample contains large Foraminifera identified by W. Storrs Cole (Kaye 1959, p. 25) as uppermost Paleocene or lower Eocene. The writer recollected this fauna from outcrops in the field a few tens of meters to the north. These were identi-

fied by K. N. Sachs (written commun., 1963), who also assigned them to the upper Paleocene or lower Eocene.

Fossil locality 30, which is in Quebrada Blasina in the Carolina quadrangle, has also been correlated with the limestone of the Guaracanal. The limestone is light buff colored and contains abundant miliolid Foraminifera as well as fragments of small pelecypods. Ruth Todd (written commun., 1965) assigned a probable post-Cretaceous age to this fauna.

NARANJITO FORMATION

The Naranjito Formation is here named for pale-reddish-gray to reddish-brown, commonly speckled light-gray poorly sorted pyroclastic and epiclastic deposits exposed near the town of Naranjito in the west-central part of the Naranjito quadrangle. Exposures in roadcuts on Highway 825 and in the adjacent streambanks just north of the town at the western border of the quadrangle (52,350 m N., 172,160 m E. to 52,070 m N., 172,050 m E.) are designated the type section. The Naranjito Formation is believed to be correlative with the Guaracanal Andesite, but as it is widely separated both structurally and spatially it requires a different name.

The formation crops out in a narrow faulted graben extending from the town of Naranjito to the valley of the Río de la Plata. It consists mostly of thickly bedded tuff and tuffaceous mudstone, coarse-grained volcanic conglomerate, and tuff breccia; lava may be the principal component toward the east in the valley of the Río de la Plata. Clastic rocks are moderately friable and break around grains. Plagioclase crystals are abundant in tuffs and lavas; characteristic mafic minerals are hornblende and pseudomorphs of biotite and chlorite after hornblende, which are coated with black opaque dust. The Naranjito Formation shows no evidence of the alteration to greenstone that is characteristic of older rocks in this area. The formation weathers locally to soft friable rock in which clasts as well as matrix may be cut with a knife. The soil overlying the Naranjito is grayish red, grayish purple, or yellowish gray.

Approximately 300 m of the Naranjito Formation is exposed in the Naranjito quadrangle, but both top and bottom have been cut out by faults. In the Corozal quadrangle to the west, the base is also faulted, but the upper contact is clearly exposed; the Naranjito is conformably overlain by well-stratified siltstone of the Palmarejo Formation (Nelson, 1967).

No fossils have been obtained from the Naranjito Formation, but the formation bears a striking lithologic resemblance to the waterlaid deposits of the Guaracanal Andesite in the Aguas Buenas and San Juan quadrangles. On this basis, the Naranjito Formation is believed

to be stratigraphically equivalent to the Guaracanal Andesite and is therefore considered Paleocene in age. The two formations evidently are exposed on opposite sides of a major anticline that has been intensely distorted by faulting. This correlation is partly corroborated by the stratigraphic relation of the Naranjito to overlying units exposed in the Corozal quadrangle. These relations are described in the following section.

PALMAREJO FORMATION

Thin-bedded well-indurated olive-gray siltstone exposed in one small outcrop on the north bank of the river at the town of Naranjito is assigned to the Palmarejo Formation. This formation is named for more extensive exposures in the Corozal quadrangle (Nelson, 1967) where it attains an exposed thickness of approximately 370 m. In the Corozal quadrangle the Palmarejo Formation rests conformably on the Naranjito Formation and conformably underlies the Corozal Limestone of Paleocene or Eocene age (Nelson, 1967).

No fossils have been obtained from the Palmarejo Formation, but the conformable relation of the Palmarejo to the overlying Corozal Limestone suggests that these strata are no older than earliest Tertiary and that the underlying Naranjito Formation falls in about the same biostratigraphic position. A regional unconformity exists at the base of the Maestrichtian, but there is no evidence of a regional unconformity at the Cretaceous-Eocene boundary.

The lithologic character of the Palmarejo is like that of the Río Piedras Siltstone, and its stratigraphic relation to the Naranjito Formation is the same as that of the Río Piedras to the Guaracanal Andesite. The Palmarejo therefore is probably stratigraphically equivalent to the Río Piedras Siltstone and is Paleocene or Eocene in age.

RÍO PIEDRAS SILTSTONE

The Río Piedras Siltstone is here named for a sequence of well-stratified mostly fine-grained tuffaceous epiclastic rocks that are well exposed in the Montes de Hatillo south of the town of Río Piedras in the San Juan quadrangle. The type section of this formation is in a large quarry just west of Highway 181 in the San Juan quadrangle (60,940 m N., 195,360 m E. to 60,360 m N., 195,150 m S.). Kaye (1956) assigned the rocks an early Tertiary age and, because of lithologic similarity, correlated them with the Fajardo Formation of Berkey (1919). However, the discovery of early Late Cretaceous ammonites in the type area of the Fajardo Formation contradicts this lithologic correlation and necessitates a new name for the younger rocks near Río Piedras.

The Río Piedras Siltstone is widely distributed across the northern border of the mapped area, and a prominent lobe extends southeastward into older rocks along the northeast side of La Muda fault. The Río Piedras rests conformably on the Guaracanal Andesite wherever the Guaracanal is exposed, but in the southwest corner of the San Juan quadrangle the Guaracanal Andesite was not recognized, and the Río Piedras rests on the Monacillo Formation. In the southwest corner of the Carolina quadrangle, east of the point where the Guaracanal Andesite pinches out, the Río Piedras apparently rests on a variety of stratigraphic units, but the relations shown on the map are in doubt because most of this area is overlain by a thick blanket of Quaternary terrace deposits.

The Río Piedras Siltstone typically consists of thin-bedded to laminated siltstone interstratified with thick-bedded to massive fine- to coarse-grained volcanic wacke. In fresh outcrops the siltstone is dark gray and generally highly calcareous. In places it appears to contain traces of finely comminuted carbonaceous material, and locally silica is the cementing agent rather than calcite. Structures such as crossbedding and ripple marks are uncommon in the fine-grained strata of this formation. In most outcrops the rock is highly weathered to yellow, red, and green shades of gray and brown and the carbonate cement is leached, leaving a soft flaggy rock that parts readily along lamilar bedding planes. Coarser grained beds weather spheroidally and form dark-greenish-gray boulders in a brown sand.

A large part of the sequence exposed in the southern lobe north of La Muda fault consists of dark-greenish-gray bedded coarse-grained volcanic wacke, but these coarse-grained strata thin abruptly toward the north and are not present in most of the San Juan and Carolina quadrangles, except perhaps for a few beds near the base. The formation in the Naranjito and Aguas Buenas quadrangles is divided into four members—a basal siltstone, a tuffaceous bedded limestone, a coarse-grained wacke, and an upper member composed of interlayered sandstone and siltstone. These members are not shown on the generalized geologic map (pl. 1). The reader is referred to U.S. Geological Survey Miscellaneous Geologic Investigations Maps I–479 and I–508 (Pease, 1968a, b).

The basal siltstone member consists chiefly of laminated siltstone with thin layers of claystone or shale. Its maximum exposed thickness is about 120 m, and where the basal contact is observed, the formation appears to grade downward into the underlying tuffaceous rocks of the Guaracanal Andesite. Locally, pebble conglomerate, which contains clasts of Guaracanal lava and shell fragments, occurs at this contact.

The bedded tuffaceous limestone member is restricted to the Aguas

Buenas quadrangle where it readily is distinguished from the underlying siltstone member because it apparently is more resistant to erosion and tends to form prominent ridges. It also can be recognized in weathered outcrop by its brighter red staining. A maximum thickness of 120 m is estimated for this member, which pinches out to the northwest.

The coarse-grained wacke member is best exposed along the northeast side of La Muda fault in the Aguas Buenas quadrangle where its maximum thickness is about 120 m. It thins to less than 40 m in the extreme northwest corner of the Aguas Buenas quadrangle. This member is composed of massive beds of olive-gray volcanic-pebble conglomerate and coarse-grained volcanic wacke interstratified with thick-bedded coarse-grained volcanic sandstone and siltstone.

The upper member consists of dark-gray to grayish-black thin-bedded to laminated calcareous siltstone and very fine grained calcareous sandstone alternating with thick-bedded to massive coarse volcanic sandstone and pebble conglomerate or pebble breccia. The siltstone weathers to light olive brown and dusky yellow and commonly is leached of carbonate; the coarser rock forms dark olive-gray spheroids in a brownish-gray soil. This upper member is at least 1,000 m thick, but no conformable or moderately unconformable top is exposed; it is overlain with profound unconformity by strata of Oligocene age or younger.

A fauna of small Foraminifera was collected from the base of the Río Piedras Siltstone in the southwest corner of the San Juan quadrangle almost on the border of the Aguas Buenas quadrangle. These were tentatively identified by Jeremy Reiskind (written commun., 1963) as "upper but not uppermost Paleocene." Thus the base of the Río Piedras is Paleocene in age, only slightly younger than the underlying Guaracanal Andesite. The thickness of the Río Piedras suggests that its uppermost beds may be Eocene in age.

INTRUSIVE AND HYDROTHERMALLY ALTERED ROCKS

Plutonic to hypabyssal stocks and dikes, ranging in composition from diorite to quartz diorite and in texture from phanerite to porphyry, have been grouped under the general heading of quartz diorite on the geological map, even though the plagioclase is commonly more albitic than normal diorite. Only the large exposures are shown, and their contacts are highly generalized.

These dikes and stocks are widely distributed but are found in greatest concentration cutting rocks of the Santa Olaya Lava. They also occur in appreciable amounts in the highly fragmented area between the Limones and La Muda fault where they intrude the Camarones

Sandstone and the Tortugas Andesite. A contact exposed at one locality in this area suggests intrusion into La Muda Formation, but the contact is possibly a fault. A fairly large stock is exposed west of La Muda fault between two west-northwest-trending wrench faults. The hook-shaped stock in the north-central part of the Aguas Buenas quadrangle intrudes strata of the Guaynabo Formation.

Most of the quartz diorite is altered in the belt between the Cerro Mula and Quebrada la Yegua faults and along the trace of La Muda fault. In these areas the rock is highly silicified; hornblende is altered to chlorite; feldspar is entirely albite-oligoclase. Pyrite is ubiquitous, and near La Muda fault, base-metal sulfides may be of economic importance.

A system of mafic dikes are conspicuously exposed in the eastern part of the Aguas Buenas quadrangle and in the Gurabo quadrangle. These are too thin to show at the scale of the geologic map (fig. 2), but they are a prominent feature on the published geologic map of the Aguas Buenas quadrangle. The dikes are generally distinguished from the quartz diorite by their darker color and by the presence of pyroxene, but locally they contain large crystals of hornblende and are difficult to distinguish from varieties of the quartz diorite. These mafic dikes are most common in areas of exposure of the Carraízo Breccia and the Guaynabo Formation. In the San Juan quadrangle a mafic dike cuts the Río Piedras Siltstone.

Hydrothermally altered volcanic rocks, now composed chiefly of quartz, jasperoid, sericite, and clay minerals, occur in elongate belts along major zones of shear in the same general areas as do the altered intrusive rocks with which they appear to be genetically related. A few small diorite dikes cut the hydrothermally altered rock and are essentially unaltered.

Intrusive emplacement evidently postdates the Coniacian to Santonian interval because quartz diorite cuts the Tortugas Andesite. The conspicuous occurrence of silicified pebbles and rotten phanerite pebbles and grains of quartz and biotite in La Muda and Monacillo Formations of Maestrichtian age is evidence that, prior to the Maestrichtian, intrusive emplacement and hydrothermal activity had taken place and the affected rocks had been uplifted and exposed to erosion. Thus large-scale igneous intrusion and hydrothermal activity probably commenced and ended during the Campanian and prior to erosion of the Maestrichtian unconformity.

If the previously mentioned contact between quartz diorite and La Muda Formation is an intrusive contact, there is a possibility that intrusive activity continued to the end of the Cretaceous. The fact that a few diorite dikes cut hydrothermally altered rocks related to

earlier intrusive activity supports this possibility. Mafic dikes that may or may not be genetically related to the quartz-diorite magma evidently were emplaced in the Paleocene as they cut basal beds of the Río Piedras Siltstone.

STRATIGRAPHIC INTERPRETATION

An interpretation of stratigraphic relations between the principal formations described in this report is presented graphically on plate 1. Critical points of interpretation are shown by numbered circles and explained on plate 1. The Río Orocovis Group and other units south of the Cerro Mula fault are not included in the interpretation.

Plate 1 is a fence diagram consisting of six schematic facies diagrams arranged to present a three-dimensional interpretation of the stratigraphy. The structure has been removed as well as possible, considering the uncertain amounts of offset on some faults in the area. The illustration shows the general geographic distribution of units but cannot be compared directly with the geologic map (pl. 1).

The Cretaceous and lower Tertiary strata north of the Cerro Mula fault are a thick sequence of interstratified volcanic and volcaniclastic rocks which are separated by two unconformities, A and B (pl. 1). Unconformity A is at the base of the Santa Olaya Lava or correlative strata; unconformity B is beneath La Muda and Monacillo Formations or younger strata where these formations are absent.

STRATA BELOW UNCONFORMITY A

Thin-bedded marine strata of the Pájaros Tuff form the base of the sequence. These are conformably overlain by marine lava and associated volcanic breccia of the Cerro Gordo Lava, which in turn are conformably overlain by the thin-bedded calcareous tuffaceous basal Piñas Siltstone Member of El Ocho Formation. Nonmarine deposits of the Cancel Breccia rest with apparent conformity on well-bedded volcanic wacke of El Ocho.

STRATA BELOW UNCONFORMITY B

Unlike the regularly layered sequence below the unconformity at the base of the Santa Olaya Lava, stratigraphy above it displays widespread interfingering and interlayering of facies so that formations and parts of formations are stratigraphically equivalent to one another. The Santa Olaya is a sequence of marine lava and intercalated volcanic breccia that rests unconformably on the Cancel Breccia and forms a thick accumulation along the southern border of the area. This formation thins markedly toward the west-northwest but shows

no evidence of thinning eastward (section 1, pl. 1) and probably extends well to the east of the mapped area.

Relatively fine-grained well-stratified volcaniclastic strata of the Río de la Plata and Camarones Sandstones interfinger with the Santa Olaya Lava on the west (section 1, p. 1) and north (section 4, pl. 1). The two volcaniclastic formations seem to be stratigraphically equivalent and may once have been continuous. Thin tongues of lava, evidently derived from the Santa Olaya volcanic pile, are interlayered with strata of these two volcaniclastic formations. Thin basal pillow lava of the Santa Olaya extends westward beneath the lowest beds of the Río de la Plata (section 1, pl. 1) and northward beneath basal beds of the Guaynabo.

Lava of the Santa Olaya is interlayered northeastward and probably northward, with increasing amounts of volcanic breccia characteristically containing abundant greenish-gray scoriaceous lava and pumice fragments. The area in the Gurabo quadrangle south of the Leprocomio fault is one of uncertain structure and stratigraphy, but it evidently represents a zone of transition from chiefly lava to chiefly breccia (section 5, pl. 1). The Camarones Sandstone apparently is also exposed in this area of complex geology, but its northeastward extent and its relation to other stratigraphic units in the Gurabo quadrangle is not known.

The Guaynabo Formation exposed in the northern part of the Gurabo quadrangle rests conformably upon unnamed strata (section 6, pl. 1) composed largely of volcanic breccia similar to that of the Hato Puerco Tuff of Meyerhoff's usage. The contact in this area is an arbitrarily chosen horizon in a transitional interval of interlayered volcanic breccia and bedded volcanic wacke and tuffaceous siltstone. Strata of the Guaynabo Formation exposed in the Aguas Buenas quadrangle in the vicinity of the Tortugo fault are stratigraphically equivalent to the Camarones Sandstone (section 3, pl. 1).

The Martín González Lava Member of the Guaynabo Formation and the Mamey Lava Member of the Camarones Sandstone are believed to be fault-separated segments of one lava (section 4, pl. 1) that was extruded into water-saturated sediments on the sea floor; the lava appears to be comagmatic with a thick basaltic sill exposed in the Río Grande quadrangle east of the mapped area. This lava is thickest to the northeast and thins toward the south and west; its intermittent presence in the north-central part of the Aguas Buenas quadrangle suggests a lobate western margin (section 6, pl. 1); it pinches out westward on the south side of La Muda fault (section 4, pl. 1).

The Tortugas Andesite, composed chiefly of nonmarine volcanic rocks, is exposed in a number of fault blocks in the central and eastern

parts of the Aguas Buenas quadrangle. It rests with apparent conformity on the Camarones Sandstone and interfingers with the upper part of the Guaynabo Formation (section 4, pl. 1). In its eastern area of exposure, south of the northwestern end of the Carraízo fault, the Tortugas Andesite is almost entirely massive relatively coarse-grained breccia in which oxidized reddish-gray scoriaceous lava and pumice fragments characteristic of the Tortugas farther west are mixed with the greenish-gray lava and pumice fragments characteristic of the Santa Olaya.

The Carraízo Breccia is characterized by conspicuous reddish-gray scoriaceous lava and pumice fragments, is lithologically very similar to the eastern facies of the Tortugas Andesite, and is believed to be stratigraphically equivalent to the Tortugas; presumably it is underlain by lava equivalent to the Mamey and Martín González lavas (section 5, pl. 1). However, the apparent thickness of the Carraízo Breccia exposed in the Aguas Buenas quadrangle is considerably greater than is shown in section 5 (pl. 1). It is likely that the Carraízo Breccia, as mapped, includes strata below the level of the Tortugas and is in part equivalent to the Camarones, Santa Olaya, and Guaynabo.

STRATA ABOVE UNCONFORMITY B

Unconformity B lies beneath the Monacillo Formation exposed in the north-central part of the area mapped and beneath the correlative La Muda Formation, which is exposed in small disconnected outcrops in the same general area as the Tortugas Andesite. Isolated deposits of La Muda or its basal conglomerate member rest unconformably on the Tortugas Andesite and on the Camarones Sandstone (section 3, pl. 1). The Monacillo Formation disconformably overlies the Guaynabo Formation and, in western areas of exposure, rests in large part on the Leprocomio Siltstone Member of the Guaynabo (section 6, pl. 1). The Monacillo is not mapped south of the Tortugo fault but is believed to intertongue with strata of La Muda Formation (sectiion 3, pl. 1) and to pinch out southward (section 2, pl. 1). These relations are not demonstrable in the field because of faulting.

The Monacillo rests on progressively younger strata toward the east, and in the southwest corner of the Carolina quadrangle it rests on strata assigned to the Guaynabo Formation that overlie the Leprocomio Siltstone Member of the Guaynabo. The formation also thins northeastward in this quadrangle and evidently pinches out (section 6, pl. 1).

The Trujillo Alto Limestone Member of the Monacillo is overlain by mudstone, sandstone, and conglomerate of this formation throughout most of its exposure. In the northeast corner of the Aguas Buenas

quadrangle, however, the limestone occurs at the top of the Monacillo (section 6, pl. 1); and in the central part of the Gurabo quadrangle near its northern border, east of the point where clastic deposits of the Monacillo pinch out, limestone that has been assigned to the Trujillo Alto rests directly on strata assigned to the Guaynabo Formation (section 6, pl. 1).

The Guaracanal Andesite conformably overlies the Monacillo in the north-central part of the mapped area (section 6, p. 1). In this area the Guaracanal is composed mostly of crudely stratified water-laid deposits of hornblende andesite pyroclastic debris. Lenses of miliolid limestone with characteristic light-yellowish-gray weathered surfaces occur at or near the base of the Guaracanal. In the northeast corner of the Aguas Buenas quadrangle, this basal limestone of the Guaracanal apparently rests directly on the Trujillo Alto Limestone Member of the Monacillo Formation where the Trujillo Alto occurs at the top of the formation (section 6, center pl. 1). Miliolid limestone that has been correlated with the limestone in the Guaracanal is exposed in two isolated outcrops in the Carolina quadrangle and rests directly on the limestone assigned to the Trujillo Alto in exposures near the northern border of the Gurabo quadrangle. The limestone in this area is interstratified with hornblende-rich tuffaceous material that is questionably assigned to the Guaracanal Andesite, a condition indicating a reappearance of this formation here.

In its southeasternmost area of exposure southwest of the Tortugo fault, the Guaracanal Andesite consists chiefly of massive coarse-grained flow breccia where it probably represents a volcanic vent (section 3, pl. 1); it apparently intrudes La Muda Formation on the southwest side of La Muda fault. Northwestward away from the area of the volcanic vent, the Guaracanal becomes crudely stratified and finer grained. Exposures of the Guaracanal on the northeast side of the Tortugo fault are similar to those previously described on the northeast side of the Leprocomio fault.

Most of the stratified tuffaceous rocks of the Guaracanal in the northeast corner of the Aguas Buenas quadrangle rest conformably on the Monacillo and contain lenses of limestone at or near the base. These deposits evidently extended beyond the area of deposition of the Monacillo, however, because in a small syncline just north of the Tortugo fault, stratified tuffs of the Guaracanal with a basal limestone rest unconformably on the Guaynabo Formation stratigraphically below the Leprocomio Siltstone Member (section 4, pl. 1). The Guaracanal Andesite is believed to have overlapped most of the mapped area and to be correlative with the Naranjito Formation (sec-

tion 1, pl. 1), exposed in the southwest part of the mapped area on the north side of the Cerro Mula fault.

The Río Piedras Siltstone rests conformably on the Guaracanal Andesite. In the southwest corner of the San Juan quadrangle the Guaracanal Andesite is not present, and the Río Piedras rests directly on the Monacillo Formation (section 6, pl. 1). Toward the east the Río Piedras evidently overlaps both the Guaracanal and Monacillo and rests directly on the Guaynabo. The Río Piedras, as well as the Guaracanal Andesite, evidently covered a much broader area prior to uplift and erosion. It is believed to be correlative with the Palmarejo Formation that overlies the Naranjito Formation in the southwest part of the mapped area (section 2, pl. 1).

GEOLOGIC HISTORY

The earliest geologic event included in this stratigraphic interpretation is believed to be recorded in the rocks of the Pajaros Tuff. These strata and those of the overlying Cerro Gordo Lava and El Ocho Formation evidently represent marginal facies of a much greater accumulation of basalt and andesite volcanic rocks represented by the Río Orocovis Group exposed south of the Cerro Mula fault and centered several kilometers west and south of the area of this report. These formations are now separated from rocks of the Río Orocovis Group by several wrench faults of large displacement.

These marine volcanic and volcaniclastic deposits, which were laid down in the early part of the Cenomanian Stage of the Late Cretaceous, evidently built a volcanic pile that ultimately extended above sea level. This local landmass, represented by nonmarine strata of the Cancel Breccia, soon began to founder. Well-rounded conglomerate exposed at the top of the Cancel Breccia in its eastern outcrops probably represent coarse gravels deposited along the shore of an encroaching sea.

The extrusion of pillow lavas of the Santa Olaya Lava on the eroded surface of the Cancel Breccia initiated a younger cycle of submarine volcanism whose center probably was in the present position of the east-central part of the Naranjito and west-central Aguas Buenas quadrangles. This volcanic episode, which may have begun in the latter part of the Cenomanian, appears to have provided volcanic debris through most of Late Cretaceous time until the close of the Campanian. Most of the rocks exposed in the mapped area are correlative facies that are associated with this eruptive cycle.

The eruptive cycle evidently began with the formation of an east-southeast-trending submarine rise of Santa Olaya Lava that probably extended well to the southeast of the area represented on the geologic

map (pl. 1). Accumulations of massive volcanic breccia were interstratified with lava and flow breccia on the northern and eastern flanks of this volcanic pile. These are represented by an eastward increment of volcanic breccia within the Santa Olaya, by the presence of similar breccia in the southern part of the Gurabo quadrangle, and perhaps by breccia that has been included in the Carraízo Breccia along the eastern border of the Aguas Buenas quadrangle.

Finer grained volcaniclastic material, derived from the Santa Olaya volcanic eruption, was deposited in a broad marine basin that evidently extended unknown distances in all directions from the volcanic pile. These strata are represented by the Guaynabo Formation on the northeast, the Camarones Sandstone and Guaynabo Formation on the north, and by the Río de la Plata Sandstone on the west and south. Most of the sedimentary basin on the south side of the volcanic pile has been cut out by the Cerro Mula fault.

These volcaniclastic deposits consist mostly of well-stratified coarse-bedded volcanic wacke, minor conglomerate, and thin-bedded tuffaceous siltstone. These strata interfinger laterally and are interlayered vertically with each other, and they evidently intertongue with lava and coarse volcanic debris around the flanks of the volcanic pile. In general, they become finer grained away from the volcanic pile and higher in the stratigraphic sequence although no regular or sequential variation has been demonstrated in detail.

The Camarones Sandstone, the lower part of the Guaynabo Formation, and probably most of the Santa Olaya Lava and Río de la Plata Sandstone were deposited during the biostratigraphic interval from late Cenomanian to Coniacian or Santonian, according to the microfaunal evidence of A. E. Pessagno (written commun., 1965). Evidently most of the deposition in the northeastern part of the marine basin, represented by strata of the Guaynabo Formation in the Gurabo quadrangle below the Coniacian and Santonian Martín González Lava Member, occurred in the Cenomanian; the Turonian apparently is not represented in these strata, and less than 300 m of thickness occurs between sediments deposited in late Cenomanian time and the base of the lava. The occurrence of a Turonian interval in the Gurabo quadrangle in the area of uncertain stratigraphy and structure south of the Leprocomio fault suggests that deposition did occur during the Turonian interval closer to the volcanic pile and perhaps within the Santa Olaya, but no faunal data was obtained from this stratigraphic interval in the Aguas Buenas or Naranjito quadrangles.

The Martín González Lava Member of the Guaynabo Formation and its southwestward extension, the Mamey Lava Member of the Camarones Sandstone, were extruded during the early part of the Coniacian

or possibly as late as the Santonian. They appear to be the extrusive equivalent of a large basaltic sill extensively exposed east of the mapped area and to have flowed westward across the sea floor to the base of the Santa Olaya volcanic pile. Feeder dikes may have added to the Martín González-Mamey magma locally.

Shortly after extrusion of this basaltic lava, subaerial lava and breccia of the Tortugas Andesite were erupted and deposited in the region of the central part of the Aguas Buenas quadrangle. The accumulation of volcanic and volcaniclastic material deposited during the period of marine volcanism evidently had thickened to the extent that these deposits reached sea level; the Tortugas Andesite was then deposited subaerially along the northern flank of the volcanic pile. The Tortugas eruption apparently began during the Coniacian, but deposition of Tortugas debris continued at least into the Santonian Stage of the Late Cretaceous. Subaerial facies of the Tortugas eruption interfingered with and contaminated marine facies of the Guaynabo Formation that presently lie north of the Tortugo fault. Coarse-grained volcanic breccia containing conspicuous oxidized scoriaceous lava and pumice fragments that characterize the easternmost facies of the Tortugas appear to have been contiguous with similar volcanic breccia now exposed north of the Carraízo fault and termed the Carraízo Breccia.

Sedimentation in the northern and northeastern parts of the mapped area was unaffected by the Tortugas eruption, except for the incorporation of oxidized volcanic-ash debris in these sediments. This sedimentation continued uninterrupted through the Campanian Stage of the Late Cretaceous, but the lithologic character of the sediments changed rather abruptly in the late Campanian from volcanic wacke of the Guaynabo Formation to thin-bedded calcareous tuffaceous fine sand and silt of the Leprocomio Siltstone Member of the Guaynabo. Exposures in the Carolina quadrangle indicate that sediments coarsened again before the close of the Campanian, but in the Aguas Buenas quadrangle these coarser sediments apparently had been removed by erosion before Monacillo sediments were deposited unconformably on the Guaynabo.

At about the end of the Campanian interval, volcanic activity had subsided, and the region was warped up, probably as a result of forcible intrusion of quartz-diorite magma, much of which had been emplaced by this time. The Tortugas Andesite and the Santa Olaya Lava and equivalent strata were exposed to erosion in the region south of a general line marked by the present traces of the Tortugo and Leprocomio faults. Quartz diorite that evidently had been emplaced in the

early stages of magmatic intrusion and at relatively shallow depths was also exposed to erosion at this time.

The sedimentary basin to the north, which had probably been filled to near sea level, also was exposed temporarily to erosion by this uplift but rapidly subsided to form the shallow sea in which were deposited conglomerate, mudstone, sandstone, and limestone of the Monacillo and La Muda Formations.

Sea cliffs apparently formed locally along the shoreline, and the very coarse, very thick, but areally restricted basal conglomerate member of the La Muda Formation probably represents talus from these sea cliffs. Massive limestone lenses of La Muda, thick relative to their lateral extent, and associated marine sandstone and conglomerate with limestone clasts probably developed in near-shore embayments as reef and fore-reef deposits. These deposits rest disconformably on an eroded Tortugas surface.

The preponderance of Tortugas Andesite clasts and of reddish-gray hematitic iron oxide coating on grains in the matrix of these coarse-grained deposits indicates that the principal source area was the uplifted Tortugas landmass, but an appreciable component of clasts from the Santa Olaya Lava attests to exposure and erosion of these older rocks as well.

More extensive but finer grained conglomerate and mudstone intercalated with thin-bedded marine sediments of the Monacillo Formation represent offshore extensions of La Muda near-shore complex. The Trujillo Alto Limestone Member of the Monacillo was deposited at a distance from the margin of the sedimentary basin.

The deposits of La Muda and Monacillo Formations contain the earliest appreciable amounts of siliceous pebbles and of quartz and biotite grains observed in the volcanic sequence. Many of the siliceous pebbles appear to be hydrothermal jasperoid, and rotten light-gray phaneritic pebbles are possibly diorite. The presence of this detritus in Maestrichtian deposits strongly suggests that plutonic intrusion and hydrothermal alteration had taken place and that their products had been exposed to erosion by this time.

Hornblende-rich volcanic rocks of the Guaracanal Andesite erupted explosively in earliest Tertiary (Paleocene) time from a volcanic vent in the northwestern part of the Aguas Buenas quadrangle, and large quantities of volcanic ash and lapilli tuff were spread over a broad area. The areal extent of these rocks may have included a large part of north-central Puerto Rico, at least as far west as the north-central part of the Corozal quadrangle, where similar ashy deposits are represented by the Naranjito Formation. Most of these deposits, however, have since been removed by uplift and erosion.

Much of the Guaracanal volcanic debris was dumped into shallow seas and was partly sorted and redistributed by wave action. The deposits rest conformably on strata of the Monacillo Formation, but in places they completely overlap the Monacillo and have been observed to rest on the pre-Maestrichtian unconformity.

Limestone formed at several localities in the lower beds of the Guaracanal but was covered rapidly by thick accumulations of ash and lapilli. It is significant that limestone was deposited, in part, in the same local basins that existed at the close of the Cretaceous. In two localities, Tertiary limestone of the basal Guaracanal rests on the Cretaceous Trujillo Alto Limestone Member with no evidence of a hiatus. Evidently, local topographic highs of the Trujillo Alto Limestone Member deposited in shallow seas were swept clear of clastic and pyroclastic sedimentation, and Guaracanal limestone was deposited on these preexisting highs.

After the Guaracanal eruption, well-layered volcanic silt and sand of the Río Piedras Siltstone were deposited over an area at least as extensive as that of the Guaracanal. The Palmarejo Formation, exposed above the Naranjito Formation at the extreme western edge of the Naranjito quadrangle and in the Corozal quadrangle, is believed to be stratigraphically equivalent to the Río Piedras. Fine volcanic ash, perhaps representing the last of the Guaracanal volcanic episode, undoubtedly composes a large part of these fine sediments, but normal offshore detritus from the receding volcanic landmass to the south probably is of equal importance. The presence of coarse-grained volcanic wacke in the lobe of the Río Piedras that extends southward toward this landmass supports this conclusion.

The diabase dikes, which are not shown on the geologic map (pl. 1), but which are so abundantly distributed through the eastern part of the Aguas Buenas and the Gurabo quadrangles are at least younger than the Río Piedras beds that they cut.

After the Paleocene and probably at least the early Eocene, the volcanic activity ceased, faulting reached a maximum and then died down, and broad upwarping exposed the volcanic terrane to extensive erosion. Gradual subsidence resulted in onlapping deposition of strata of Oligocene age and younger.

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