Geology of Puerto Rico

by
Richard D. Krushensky
U.S. Geological Survey, Reston, Virginia
and
Johannes H. Schellekens
Department of Geology
University of Puerto Rico, Mayagüez, Puerto Rico

INTRODUCTION

U.S. Geological Survey scientists and others have studied the geology of Puerto Rico for decades, and, as a result, the USGS has published geologic maps and reports that illustrate the geology of most of the island. But, even with decades of work, Puerto Rico is not yet completely mapped at a scale of 1:20,000. Because different workers initiated their work in different areas and at different times, stratigraphic names proliferated to the point that they now may be thought to obscure the understanding of the geology of the island. This compilation and interpretation is intended as an introduction to the geology of Puerto Rico. For detailed information, the reader is referred to the original works cited. The purpose of this discussion and the digitized geologic map of the island is to draw some of this work together and to make it more comprehensible to those who are not expert in the geology of the island.

TECTONIC SETTING OF PUERTO RICO

Puerto Rico, the easternmost island of the Greater Antilles, is a volcanic island-arc terrane in which the geologic record spans about 150 million years. The island consists of volcaniclastic and epiclastic rocks of volcanic origin as well as other sedimentary rocks of Late Jurassic to Paleocene and Eocene age and intrusive mafic and felsic plutonic rocks of Late Cretaceous and early Tertiary age. These rocks are overlain unconformably by Oligocene and younger sedimentary rocks and sediments (Monroe, 1972). Puerto Rico is bounded on the north by the Puerto Rico Trench, on the south by the Muertos Trough, on the east by the Anegada Passage and on the west by the Mona Canyon.

The microplate of which Puerto Rico and the Virgin Islands are the subaerial expression lies within the seismically active Caribbean-North American plate boundary zone. A well-defined southward-dipping Benioff zone lies beneath the east half of the island but is absent in the west half (Schell and Tarr, 1978; Sykes and others, 1982; McCann and Sykes, 1984). Extension, as a result of left-lateral relative motion between the Caribbean and North American plates, created the Puerto Rico Trench. Left-lateral motion between the two plates may have been in part taken up by counter-clockwise rotation of the Puerto Rican microplate in the boundary zone (Speed and Larue, 1991). The left-lateral transpressive movement between the plates and counter-clockwise rotation of the island resulted in pervasive left-lateral wrench faults throughout the island. Left-lateral wrench faults also appear to be illustrated in off-sets in the Puerto Rico Trench (EEZ-SCAN Scientific Staff, 1987). Rotation of the microplate has caused thrusting in the Muertos Trough (Byrne and others, 1985) and extension in the Anegada Passage (Larue and others, 1990). Extension in the Mona Canyon (Gardner and others, 1980) may have been caused by differences in the rates of rotation between the eastern and western ends of the microplate (Speed and Larue, 1991).

Paleomagnetic study of Puerto Rico indicates that it, probably together with Cuba and Hispaniola, was originally deposited as part of an island-arc off the west coast of South America, initially located at about the present latitude of the Peru-Ecuador border. Beginning at some time in the Eocene, throughout the Oligocene, and part of the Miocene the island-arc was rafted northward and then eastward between the North and South American plates (Elston and Krushensky, 1983; Krushensky and Elston, 1983).

Ubiquitous closely spaced strike-slip and normal faults, the generally massive nature of the volcanic and volcaniclastic rocks, the very local nature of many lithofacies, the irregular interbedding of most volcanic and volcaniclastic rock types, and the lack of reported fossils from all but a few stratigraphic units severely inhibits demonstration of the structural nature of the island.

Prior to the completion of mapping of the western and southwestern parts of the island, earlier workers had subdivided Puerto Rico into northeast, central, and southwest structural-stratigraphic blocks on the basis of the perceived presence of major strike slip faults or fault zones and the lack of continuation of stratigraphic units across these faults. Detailed mapping in the eastern part of Puerto Rico indicates that the Cerro Mula-Quebrada San Francisco Fault, a left-lateral wrench fault, does indeed separate distinctive formations in the northeast block from those in the remainder of the island. A southwest Puerto Rico fault zone that was conjectured to separate central and southwest blocks was placed at various locations (Glover, 1971, Briggs, 1973; Cox and Briggs, 1973), but its presence and function in the separation of lithologically unlike blocks was not demonstrated. The presence of oceanic plate rocks in the southwestern part of the island might be thought to characterize a southwestern block, but the detailed delineation of the block is not possible because of the widespread cover by younger Cretaceous and Tertiary rocks and the presence of pervasive normal and strike-slip faults. Nevertheless, division of the island into blocks for purposes of description and discussion helps in simplifying a complex stratigraphic picture, and that scheme will be followed here.

GEOLOGIC DESCRIPTIONS BY REGION

GEOLOGY OF SOUTHWESTERN PUERTO RICO

The oldest rocks in Puerto Rico, the Bermeja Complex (Mattson, 1960a) constitute an ophiolitic suite that was, at least in part, emplaced as a nappe (Mattson, 1973a). The Bermeja consists of serpentinite, serpentinite-enclosed amphibolite or metabasalt, and spilitized basalt, the Las Mesas Greenstone (Schellekens and others, 1990), which, at least locally, intrudes serpentinite (Mattson, 1960; Krushensky and Monroe, 1978a, Volckmann, 1984a, b, c; and Curet, 1986), unconformably overlain by the Mariquita Chert, which is locally interbedded with basalt, possibly the Cajul Basalt (Mattson, 1973a; Volckmann, 1984a, b). Foraminifers in the Mariquita range in age from Jurassic to Late Cretaceous, that is, early Tithonian (Mattson and Pessagno, 1979). Because epiclastic-appearing serpentinite breccia and conglomerate crop out beneath rocks of the younger volcaniclastic sequence in the Mayagues quadrangle (Curet, 1986), serpentinite may have been exposed at the surface prior to deposition of the overlying volcaniclastic formations. Determination of the relative age of serpentinite as pre- or post-volcaniclastic sequence is difficult because serpentinite also has been emplaced as a "cold" intrusion into overlying volcaniclastic rocks (Curet, 1986). Gneissic and massive amphibolite probably have an ocean-floor origin, and spilitized basalts and dikes probably share an island arc origin (Schellekens and others, 1990).

Calc-alkaline and dacitic epiclastic volcanic rocks and volcaniclastic rocks, generally deposited in a marine environment, cover much of the Bermeja, and crop out from the southwestern corner of the island to the Ponce, Jayuya, and Adjuntas quadrangles in the east and in the Rincon, Central La Plata, and San Sebastian quadrangles to the north, beyond the boundaries of the ophiolite sequence. Where they overlie the ophiolite, these rocks may have been rafted into position along with the underlying oceanic rocks.

Marine siltstone, sandstone, and conglomerate of the Yauco Formation unconformably overlie the Mariquita and crop out from the Mayaguez and Rosario quadrangles in the southwest corner of Puerto Rico (Curet, 1986) east to the Ponce quadrangle in the central southern part of the island (Krushensky and Monroe, 1975). Graded siltstone of the Yauco hundreds of meters thick crops out over wide areas, but examination of the stratigraphic section in many areas in the western part of the island also reveals extensive interbedding of the Yauco with marine volcaniclastic breccia of the Sabana Grande Formation of Turonian to Maastrichtian age (Volckmann, 1984d; Krushensky, unpub. data, 1982), with trachybasalt breccia, the Maricao Formation, andesitic breccia and lava of the Lago Garzas Formation. Trachybasalt breccia, first mapped as the Maricao Formation in the Maricao quadrangle (McIntyre, 1975), crops out to the east in the Monte Guilarte (Krushensky and Curet, 1984) and the Mayaguez and Rosario quadrangles (Curet, 1986). Outcrops of the Maricao in the Adjuntas and Jayuya quadrangles were originally mapped as the Robles Formation (Mattson, 1968a, b). Andesitic lava and breccia mapped as the Lago Garzas Formation, and locally as the Rio Blanco Formation (Hubbard, 1923; Slodowski, 1956; Mattson, 1960; and Pessagno, 1960), crop out in the Adjuntas, Central La Plata, Jayuya, Maricao, Monte Guilarte, Penuelas, Ponce, Rosario, San Sebastian, and Yauco quadrangles (Mattson, 1968a, b; McIntyre, 1971; 1975; Tobisch and Turner, 1971; Krushensky and Monroe, 1975; 1978a; Krushensky and Curet, 1984; Curet, 1986) in the central-western and western parts of the island. Although individual lithofacies may be hundreds to more than 1,000 m thick in a single fault block, they are also present as interbedded sequences in which single lithic types may be only a few to tens of centimeters thick. Foraminifers in this interbedded sequence of disparate lithofacies indicate a generally Late Cretaceous through Paleocene age, with a range of Cenomanian through Paleocene (Krushensky and Monroe, 1978; Krushensky and Curet, 1984; Volckmann, 1984d; and Curet, 1986).

Locally, calc-alkaline lithofacies equivalent to the Boqueron Basalt and lava and tuff of the Lajas Formation are interbedded within the Yauco lithofacies in southwestern Puerto Rico (Volckmann, 1984a, b, c, d). The Boqueron and Lajas do not show pillow structures and were assumed to have been deposited under subaerial conditions. However, limestone lenses within the Boqueron and the presence of the Cotui Limestone immediately overlying the Lajas suggest near-shore marine to subaerial conditions of deposition for these basaltic rocks. The El Rayo Formation, a marine unit of pillowed basaltic lava, breccia, and limestone lies within and conformably overlies the Yauco

Formation in the San German (Volckmann, 1984b) Sabana Grande (Krushensky, unpub. data, 1982) and Punta Verraco (Krushensky and Monroe, 1978b) quadrangles.

Carbonate banks, composed chiefly of rudist debris, occur sporadically throughout the Yauco and in the Lago Garzas and Sabana Grande Formations in southwestern Puerto Rico, locally in masses sufficiently large so as to allow their mapping as separate stratigraphic units. Examples are the Parguera Limestone of late Santonian to early Maastrichtian age, which unconformably overlies the Bermeja Complex (Almy, 1965b); the Cotui Limestone of early Campanian to early Maastrichtian age, which is overlain by the Sabana Grande and overlies the Lajas Formation; the Melones Limestone of late Campanian to middle Maastrichtian age (Volckmann, 1984a,d), and the Peñones Limestone of Maastrichtian age (Curet, 1986).

Thick sequences of rhyodacitic and dacitic tuff, breccia, and lava mapped as the Anon Formation crop out in the Ponce, Jayuya, and Adjuntas quadrangles (Mattson, 1968a, b; Krushensky and Monroe, 1975). The Rio Culebrinas Formation, in the San Sebastian, Central La Plata, and Rincon quadrangles (McIntrye and others, 1970; McIntrye, 1971; Tobisch and Turner, 1971), is lithologically identical to marine facies of the Anon in the Monte Guilarte Quadrangle (Krushensky and Curet, 1984). These rhyodacitic and dacitic rocks interbed widely with characteristic lithofacies of the Lago Garzas (McIntrye, 1975), and were mapped as the Palma Escrita and Mal Paso Formations in the Central La Plata, Maricao, Aguadilla, and Rincon quadrangles (Monroe, 1969; McIntyre, 1971; 1974, 1975) and as the Milagros and Matilde Formations in the Bayaney quadrangle (Nelson and Tobisch 1967, 1968). The Anon, Yauco, and Maricao also interbed vo, and Bayaney quadrangles (Nelson and Tobisch, 1968; Krushensky and Monroe, 1978; and Krushensky and Curet, 1984). Foraminifers in the interbedded lithofacies of the Anon and Lago Garzas range from late Paleocene to early middle Eocene (Nelson and Tobisch, 1967; McIntyre and others, 1970; Krushensky and Monroe, 1975; McIntyre, 1975, Krushensky and Curet, 1984). Farther east in the Ponce, Jayuya, and Adjuntas quadrangles (Mattson, 1968a,b; Krushensky and Monroe, 1975) the Anon interbeds with, and is underlain by, a generally graded sequence of dacitic siltstone and sandstone, that contains minor tuff and conglomerate, chert, and bioclastic limestone, of the Monserrate Formation, of middle Eocene age. The

Monserrate is the equivalent of the Rio Descalabrado Formation in the Rio Descalabrado quadrangle (Glover and Mattson, 1973) to the east. The Monserrate conformably overlies the Cuevas Limestone, a bioclastic limestone of early to middle Eocene age in the Ponce and Jayuya quadrangles (Mattson, 1968b; Krushensky and Monroe, 1975).

The Cuevas Limestone, and locally the stratigraphically overlying Monserrate and Anon Formations, constitute an allochthonous plate that overlies the Maravillas Formation or the Achiote Conglomerate everywhere the Cuevas is exposed in the Jayuya and Ponce quadrangles (Mattson, 1968b, Krushensky and Monroe, 1975), or the Coamo Formation in the Rio Descalabrado quadrangle (Glover and Mattson, 1973). The Cuevas in these quadrangles is widely underlain by a fault gouge, the so-called Miramar Formation (Pessagno, 1960), which consists of clasts of whatever formation immediately underlies the Cuevas and clasts of the Cuevas Limestone in a hematite red, slickenside-riddled clayey gouge matrix (Krushensky and Monroe, 1975; Krushensky, 1978).

Although fossils of Tertiary age have not been reported to be present in the Yauco lithofacies, the presence of foraminifers of Tertiary age in interbedded lithofacies of the Anon and Lago Garzas and of the Anon, Lago Garzas, and Maricao and the fact that the Yauco, Anon, and Lago Garzas, and the Maricao interbed conformably over wide areas, strongly suggests that the Yauco may also be Cretaceous and Tertiary in age. The conformable interbedding of these lithofacies over wide areas also indicates that there was no demonstrable break in sedimentation between the Cretaceous and the Tertiary in what is now western Puerto Rico (Krushensky, 1978).

The youngest volcaniclastic rocks in the southwestern part of the island, the Jicara Formation, consist of siliceous mudstone and siltstone of early Eocene age, which crop out over limestone of the El Rayo Formation in the San German quadrangle (Volckmann, 1984c), and in adjacent areas of the Sabana Grande quadrangle the Jicara overlies the Sabana Grande Formation (Krushensky, unpub. data, 1982). Contact of the Jicara and underlying rocks is disconformable.

The western part of the island is intruded by porphyritic trachybasalt mineralogically and texturally identical to the lava flows and breccia clasts of the Maricao Formation, andesite-diorite lithologically identical to the Lago Garzas lithofacies, two-pyroxene olivine basalt like the Rio Loco Formation (Krushensky and

Curet, 1984), hornblende diorite, and andesitic diorite (Krushensky and Monroe, 1975, 1978,; Volckmann, 1984a, b, c; Krushensky and Curet, 1984; Curet, 1986). Subvolcanic and possibly even partly extrusive, abundantly vesicular and amygdaloidal, aphyric to sparsely porphyritic dacite intrudes the interbedded lithofacies of the Yauco, Lago Garzas, and Anon in the Penuelas quadrangle (Krushensky and Monroe, 1978).

Delineation of the margins of the obducted oceanic plate in southwestern Puerto Rico, as noted above, is not possible because of masking by overlying younger rocks and because of pervasive normal and strike-slip faulting. We suggest that the last stage of the emplacement of the oceanic plate was responsible for the formation of a well developed and closely spaced series of west-northwest-striking folds in the middle Eocene Rio Culebrinas Formation and for for the formation of a reverse fault that dips northward beneath the Rio Culebrinas sequence in the Central La Plata quadrangle (McIntyre, 1971). The vertical attitude of the Jicara Formation (Krushensky, unpub. data, 1982) of early Eocene age, on the eastern edge of the Guanica quadrangle was also produced by the emplacement of the oceanic plate. Faulting and folding of middle Eocene rocks by the obducting plate suggests that the age of emplacement is middle Eocene but probably even younger.

GEOLOGY OF CENTRAL PUERTO RICO

The oldest rocks in central Puerto Rico were mapped prior to working out the complex stratigraphy of the region. As a result, they were designated by letter rather than formation names; but with the mapping of broader areas, some of these letter designations were abandoned and formation names were adopted.

Formations A, B, C, and J crop out in the Cayey, Patillas, Comerio, Caguas, Central Aguirre, and Yabucoa quadrangles in eastern and east-central Puerto Rico (Berryhill, 1960; Berryhill and Glover, 1960; Pease and Briggs, 1960; Rogers, 1979; Rogers and others, 1979; and Glover, 1982). They are equivalent and consist of andesitic and basaltic volcaniclastic breccia, lava, and generally lesser quantities of tuff, sandstone, and minor limestone. Bedding in the sequence is either not discernable or generally poorly developed over broad areas, pillow structure is absent in lava flows, and breccias were described as autoclastic (Berryhill and Glover, 1960; Pease and Briggs, 1960; Rogers, 1979; Rogers and others, 1979). The presence of limestone that contains fossil rudists (Sohl, 1976), the apparent lack of pillow structure in the basaltic and andesitic lavas, and the local lens-like interbedding of breccia, lava, tuff, sandstone, and limestone suggest that the sequence may have been deposited under near-shore and shallow-water conditions, possibly in part under subaerial conditions and probably near volcanic centers. Although limestone has been described in a number of areas, fossils other than the rudists have not been reported. The sequence is thought to be Lower Cretaceous because it underlies the Torrecilla Breccia of early Albian age (Douglass, 1961; Sohl, 1976). Although, M'Gonigle (1978) considers Formation A and its equivalents to be lithologically like the Rio Abajo Formation, which crops out east of the San Lorenzo batholith in the Humacao quadrangle, the Rio Abajo there contains variable amounts of bipyramidal quartz crystals and quartz crystal fragments (Krushensky, unpublished data, 1983), which are unknown in Formation A and its equivalents.

A sequence of autoclastic breccia, lava, sandstone, siltstone, and conglomerate, much like Formation A and its equivalents, is mapped as the Torrecilla Breccia in the Barranquitas, Orocovis, Comerio, Aguas Buenas, and Cayey quadrangles (Berryhill and Glover, 1960; Pease and Briggs, 1960; Briggs and Gelabert, 1962; Pease, 1968b; and

Briggs, 1969a; 1971a). It consists at the base, of the Aguas Buenas Limestone Member of early Albian age (Sohl, 1976). The Torrecilla is equivalent to Formation D in the Cayey quadrangle (Berryhill and Glover, 1960) and to Formation K in the Comerio quadrangle (Pease and Briggs, 1960; Briggs, 1969a). M'Gonigle (1977; 1978) has correlated the Torrecilla with the lithologically similar Pitahaya Formation in the Humacao quadrangle.

The Robles Formation, a sequence of volcanic sandstone and siltstone that contains minor pillowed lava and limestone overlies and is in part equivalent to the Torrecilla, and crops out in the Coamo, Juncos, Cayey, Caguas, Orocovis, and Comerio quadrangles (Berryhill and Glover, 1960; Pease and Briggs, 1960; Glover, 1961a; 1971; Briggs and Gelabert, 1962). The type section of the base of the Robles was described as the Rio Maton Limestone Member in the Cayey quadrangle (Berryhill he Rio Maton type section are of early Albian age. However, limestone thought to be the base of the Robles and mapped as Rio Maton in the Comerio quadrangle (Pease and Briggs, 1960) contains fossils of middle Albian age (Sohl, personal communication, 1982). Because confusion in the identification and mapping of the Rio Maton and Aguas Buenas was never resolved, the Robles as mapped in broad areas encompasses the Torrecilla. Areas mapped as Torrecilla may also include Robles.

Berryhill (1965) mapped a sequence of lava, clastic rocks, and limestone in the Ciales quadrangle, named it the Rio Orocovis Formation, and suggested that it was equivalent to the Robles as mapped in eastern Puerto Rico. Nelson (1967a), mapped similar lithofacies in the Corozal quadrangle, described them as the Rio Orocovis Group, and subdivided them into the Los Negros, Avispa, Perchas, and Magueyes Formations. Similar interbedded lava, sandstone and tuff lithofacies were mapped in the Barranquitas, Aguas Buenas, Naranjito, Comerio, Jayuya, Florida, Caguas, Gurabo, and Juncos quadrangles (Pease and Briggs, 1960; Briggs and Gelabert, 1962; Nelson and Monroe, 1966; Mattson, 1968b; Pease, 1968a, b; Seiders, 1971a; and Rogers, 1979). Nelson (1967a) mapped the Rio Orocovis Group as continuous with Formation L in the Barranquitas quadrangle (Briggs and Gelabert, 1962). Briggs (1969a) abandoned the term Formation L and substituted stratigraphic names from the Rio Orocovis Group. The Barrancas Limestone Member, the base of the Magueyes Formation which is the base of the Rio Orocovis Group correlates with the middle Albian Rio Maton Limestone at the base of the Robles in the Comerio quadrangle (Sohl, oral communication, 1982). The Manicaboa Formation, a sequence of volcanic breccia, conglomerate, and tuff may be equivalent to the Avispa (Berryhill, 1965) in the Ciales quadrangle.

Recurrent change in facies both vertically and laterally suggests that the Torrecilla Breccia, Robles Formation, and Rio Oroted near volcanic centers, chiefly under submarine conditions, over wide areas, probably from multiple volcanic centers, and in shallow to deep water.

Volcaniclastic sandstone and siltstone, tuff, and minor pillowed basaltic and andesitic lava flows of the Vista Alegre Formation, conformably underlie and interbed with lithologically similar pillowed basaltic and andesitic lava flows and intercalated sandstone and siltstone of the Mameyes Formation. These lithofacies crop out in the Florida, Jayuya, Utuado, Adjuntas, and Orocovis quadrangles (Nelson and Monroe, 1966; Nelson, 1967b; Mattson, 1968a, b; Briggs, 1971a). The Vista Alegre and Mameyes are distinguished from one another only because the Mameyes contains more lava flows (Nelson and Monroe, 1966). The Vista Alegre is separated from the conformably underlying Robles Formation because the latter is finer grained and thinner bedded (Mattson, in Nelson and Monroe, 1966). Pumiceous and crystal-lithic tuff and pillowed basaltic and andesitic lava flows of the Tetuan Formation interbed with the Mameyes and are overlain by welded and non-welded ash flow tuff of the Alonso Formation in the Florida, Utuado, and Bayaney quadrangles (Nelson and Monroe, 1966a, b; Nelson, 1967b, Nelson and Tobisch, 1968). The tuffaceous facies of the Mameyes are lithologically identical with those of the Vista Alegre (Nelson and Monroe 1966a, b) and with the Cotorra (Mattson, 1967). The Tetuan also crops out in the Jayuya quadrangle. Vista Alegre and Tetuan lithofacies probably are differently mapped aspects of the same sequence; and the Mameyes represents only a local increase in number and thickness of basaltic and andesitic lava flows also present in the Vista Alegre and the Tetuan. The Malo Breccia, a hyaloclastite breccia that contains subordinate volcanic sandstone, is probably a lithofacies of the Mameyes. It interbeds with the top of the Robles and interbeds laterally with the Vista Alegre and the Tetuan. The Malo crops out in the Orocovis, Jayuya, and Barranquitas quadrangles (Briggs and Gelabert, 1962; Mattson, 1968b; Briggs, 1971a). The lithologically similar Cotorra Tuff, a hyaloclastite breccia and pillowed lava, interbeds with the top of the Malo and pinches out to the east between the Robles and overlying Cariblanco Formation. The Alonso Formation, welded and partially welded ash-flow tuff and related breccia conformably overlies the Tetuan Formation. It was probably erupted and deposited, at least in part, under subaerial conditions and in close proximity to eruptive centers; however, the proximity of related units to eruptive centers is not established. The abundance of volcanic sandstone and siltstone in the Vista Alegre indicate only a time of erosion of the volcanic pile. Tuff in the Tetuan does indicate the presence of eruptive centers but their proximity is unknown. Lava flows of the Mameyes, Cotorra, and Malo, and to a lesser degree, the Vista Alegre and Tetuan were probably submarine or submarine extensions of subaerial eruptions. One ammonite specimen indicates a possible Late Cretaceous age for the Tetuan (Nelson and Monroe, 1966).

A thick sequence of graded, massive conglomerate, the Achiote Conglomerate, and the Cariblanco Formation, a contemporaneous and interbedded sequence of conglomerate, sandstone, lava, and limestone, overlie the Robles Formation and the Rio Orocovis Group. The Achiote and Cariblanco sequence indicates erosion of the volcanic pile accompanied by sporadic but minor contributions from volcanic eruptions. The Achiote, because of grading in the finer grained clastic sequences and the lack of sorting in major parts of the conglomerate facies, suggests deposition from high-concentration turbidity currents, and may indicate a farther off-shore environment of deposition; carbonate banks in the Cariblanco suggest deposition nearer to the shore. Marine pelecypods and gastropods from the upper part of the Achiote are of Santonian to Maastrichtian age (Sohl, in Mattson, 1967); and foraminifera from the limestone units of the Cariblanco are Santonian to early Campanian in age (Pessagno, 1962). The Achiote and Cariblanco are overlain and possibly interbedded with the Maravillas, Pozas, and Coamo Formations. The Maravillas consists of graded volcaniclastic sandstone and siltstone that contains minor pillowed lava and conglomerate like that in the Cariblanco. Carbonate banks locally present at the base and sporadically throughout the Maravillas contain rudists of late Campanian to Maastrichtian age (N.F. Sohl, oral communication, 1982). The Pozas Formation, a sequence of volcanic breccia, conglomerate, tuff, volcanic sandstone, limestone, and welded ash-flow tuff, ranges from marine at the base to probably subaerial in the largely welded ash-flow tuff of the Blacho Member (Berryhill, 1965). Calcarenite in the basal member of the Pozas and at higher stratigraphic levels that crop out in the Florida (Nelson and Monroe, 1966) and Barranquitas (Briggs and Gelabert, 1962) quadrangles indicates a largely submarine, but near-shore, environment of deposition. Rudists from the Pozas range in age from early Campanian to late Maastrichtian (Sohl and Kollmann, 1985).

The Coamo Formation of south-central Puerto Rico, a time and lithologic equivalent of the Maravillas and Pozas Formations, consists of generally unsorted, massive tuff, volcanic breccia, local lava flows, and carbonate banks. Included foraminifera are of late Santonian to early Maastrichtian age (Pessagno, 1962). Carbonate banks indicate that the Coamo was deposited under marine and probably near-shore conditions. Massive tuff beds were deposited as high- concentration debris flows, also in a marine environment.

The Los Puertos and Raspaldo Formations are very local in outcrop, intergrade laterally, and are isolated by faults from all other units. They are distinguished from the Coamo only by the presence of quartz-bearing dacitic tuff and lithic clasts. Foraminifers in the Los Puertos are of early Paleocene age (Glover, 1971), and foraminifers reported from the Raspaldo are latest Paleocene to early Eocene age (Reiskind, in Glover, 1971). According to Glover (1971), they are disconformably overlain by the Cuevas Limestone. However, bedding in the Raspaldo dips at low angles into a vertical contact with the Cuevas. The contact is a fault, as are all other contacts between the Raspaldo and the Cuevas in the Coamo quadrangle.

The Cibuco Formation, structurally isolated at its base, consists in the Corozal quadrangle, of massive conglomerate, sandstone, siltstone, and tuff. It is interbedded with and conformably overlain by siltstone and tuff of the Carreras Siltstone (Nelson, 1966a; 1967a). The Yunes Formation, a sequence of marine volcanic sandstone, siltstone, limestone, and conglomerate is structurally isolated by faults from older rocks (Nelson and Monroe, 1966; Nelson, 1967b). The Yunes in the Utuado quadrangle is overlain by volcanic breccia, conglomerate, sandstone, and lava of the Jobos Formation (Nelson, 1967b). Lithologically, the Yunes and Jobos resemble the Anon lithofacies to the south and west. The Yunes may be late Paleocene to middle Eocene (Nelson and Monroe, 1966).

Intrusive rocks in the central part of the island range from gabbro to diorite, diorite-hornblendite, quartz diorite, granodiorite, quartz-hornblende dacite, and porphyritic augite-andesite. Potassium-argon ages for the San Lorenzo-Punta Guayanes intrusive complexes (Cox and others, 1977) range within the Campanian-Maastrichtian to the very early Paleocene (78 to about 65 Ma), some younger ages obtained were discounted by the original workers because of possible resetting or alteration. Similarly, potassium-argon dates from quartz diorite and quartz monzonite Utuado batholith range from Maastrichtian to early Paleocene (73 to 65 Ma) (Cox and others, 1977).

GEOLOGY OF NORTHEASTERN PUERTO RICO

The left-lateral Quebrada San Francisco-Cerro Mula fault separates stratigraphic units in northeastern Puerto Rico from those in the central part of the island. Because no direct correlation of stratigraphic units is possible across this fault, the total exposed length of the fault, about 35 km, was considered by Briggs and Pease (1968) as the minimum displacement along the fault. Volcanic rocks in northeastern Puerto Rico of Early Cretaceous and Neogene age range from basalt to rhyolite; intrusive rocks reflect this compositional range.

Massive, andesitic breccia, lava, hyaloclastite breccia, and fine-grained volcaniclastic rocks make up the Daguao Formation, the oldest mapped sequence, in the Humacao, Naguabo, and Punta Puerca quadrangles in the northeast block (M'Gonigle, 1978, 1979). Although the age of the Daguao is not documented, it is assumed to be Early Cretaceous (M'Gonigle, 1977b, 1979) because of its position in the general stratigraphic succession in the region. The Daguao is overlain by and interbedded with the Figuera Lava (M'Gonigle, 1978, 1979), a sequence of pillowed andesitic lava flows. Fossils have not been reported to be present in the Figuera, but it is also assumed to be of Early Cretaceous age because of its stratigraphic relationship to the conformably overlying tuffaceous sandstone-siltstone and tuff breccia of the Fajardo Formation (Briggs and Aguillar, 1980). Ammonites identified as of late middle Albian age have been reported as collected from the (Cobban, in Briggs, 1973). Pillowed lava present throughout the Fajardo is lithologically like the underlying Figuera Lava (M'Gonigle, 1979).

Calcareous and tuffaceous sandstone-siltstone and volcanic breccia of the Tabonuco Formation overlie and interbed with the Fajardo Formation and include foraminifera of Aptian to late Cenomanian age, and ammonites of Albian age (Seiders, 1971a). The Tabonuco crops out in the El Yunque, Cayo Icacos, and Fajardo quadrangles.

To the west, in the Gurabo quadrangle, calcareous volcanic sandstone and breccia, lithologically like the Tabonuco but mapped as the Barrazas Formation, also contain late Cenomanian foraminifera (Seiders, 1971c). The Barrazas is mapped as continuous with the Guaynabo Formation in the Aguas Buenas quadrangle adjacent to the west of the Guynabo quadrangle (Pease, 1968b). The Barrazas probably interbeds with and is a lithofacies of the overlying Hato Puerco Formation (Seiders, 1971a), a sequence of andesitic to basaltic volcanic sandstone, breccia, conglomerate, and basaltic lava flows (Seiders, 1971a, c) in the Gurabo and El Yunque, Rio Grande, Fajardo, and Cayo Icacos quadrangles. Foraminifera reported to be present in the Hato Puerco are of middle Cenomanian to Turonian age (Seiders, 1971b). Conformably overlying the Hato Puerco in the northern part of the Gurabo quadrangle, and in the El Yunque and Rio Grande quadrangles, is a sequence of pumiceous breccia, volcanic sandstone and mudstone, and welded ash-flow tuff of the Cambalache Formation. The Infierno Formation, lithologically like the Cambalache (Seiders, 1971b, c), is locally mapped as overlying the Hato Puerco in the western Gurabo quadrangle; both the Infierno and the Cambalache contain fossils of Turonian age (Pessagno, in Seiders, 1971c). The Hato Puerco and the Infierno in the Gurabo quadrangle are mapped as continuous with the sequence mapped as Carraizo Breccia in the Aguas Buenas quadrangle (Pease, 1968b; Seiders, 1971c).

The sequence of Hato Puerco through Cambalache rocks in the Gurabo and El Yunque quadrangles is conformably overlain by the Canóvanas Formation, a sequence of basaltic volcanic sandstone, and calcareous mudstone (Seiders, 1971b, c). The Canóvanas is conformably overlain by a locally pillowed basaltic andesite, the Martin Gonzales Lava, which was mapped as a member of the Guynabo Formation in the Aguas Buenas quadrangle (Pease, 1968b). A structurally isolated sequence of pillowed lava, volcanic breccia, and volcanic sandstone mapped as the Celada Formation conformably overlies the Infierno Formation in the Gurabo quadrangle (Seiders, 1971c) and may be partly or completely equivalent to the Canóvanas Seiders, 1971b, c). The Lomas, also structurally isolated (Seiders, 1971b, c), consists of basaltic to andesitic lava, volcanic breccia and sandstone. It is lithologically like the Celada and the Infierno, but its age and correlatives have not been established.

The Frailes Formation, volcanic mudstone, sandstone-conglomerate, and pillowed lava conformably overlies the Martin Gonzales and is of early Campanian to possibly early Maaestrichtian age (Seiders, 1971a, c). It is also partly equivalent to the Guynabo mapped adjacent to the west in the Aguas Buenas quadrangle (Pease, 1968b). The Frailes is conformably overlain by the Monacillo Formation, a sequence of volcanic mudstone-sandstone, basaltic lava, and, at the top, a miliolid limestone, the Trujillo Alto Limestone Member, (Seiders, 1971b, c). The overlying Guaracanal Andesite in the Aguas Buenas quadrangle consists of purple-gray lava breccia and includes foraminifers of late Paleocene to early Eocene age (Pessagno, in Pease, 1968a ; Pessagno, in Seiders, 1971a). Rocks mapped as Guaracanal in the Gurabo quadrangle consist chiefly of a basal mudstone, limestone, and, at the top, a basalt. It is lithologically unlike the Guaracanal as previously defined.

In the Aguas Buenas and Naranjito quadrangles, a thick sequence of volcaniclastic and volcanic rocks is separated from the previously described formations by high-angle normal faults or covered by younger formations (Pease, 1968a, b, c). This structurally and stratigraphically isolated sequence of rocks has no demonstrable lithologic or depositional relationship to rocks in central or northeastern Puerto Rico. The Pájaros Tuff, at the base of this sequence (Pease, 1968b, c), consists of tuffaceous siltstone, tuff, and tuffaceous volcanic sandstone. The base of the Pájaros is everywhere concealed by younger deposits. It is conformably overlain by the Cerro Gordo Lava, basaltic lava flows, autoclastic flow breccia, and tuffaceous breccia. The El Ocho Formation conformably overlies the Cerro Gordo and consists of volcanic breccia, tuff, andesitic lava flows and siltstone. The Cancel Breccia, a sequence of massive volcanic breccia, autoclastic flow breccia, and lava conformably overlies the El Ocho. The ages of the Pájaros Tuff, Cerro Gordo Lava, El Ocho Formation, and Cancel Breccia are problematic in that fossils have not been reported to be present in them (Pease, 1968a).

A massive sequence of pillowed basaltic and andesitic lava, hyaloclastite breccia, tuff, and volcanic sandstone of the Santa Olaya Lava, crops out in the Corozal, Naranjito, and Aguas Buenas quadrangles (Nelson, 1966a; Pease 1968b, c). The Santa Olaya is laterally interbedded with the Rio de la Plata Sandstone, calcareous sandstone and conglomerate in the western and southern parts of the Naranjito and northeastern Corozal quadrangles, and with the Camarones Sandstone, a sequence lithologically similar to the Rio de la Plata that crops out in the central Aguas Buenas quadrangle (Pease, 1968a, b, c). The Santa Olaya Lava, in the Aguas Buenas quadrangle, is mapped ac continuous with the Celada Formation in the Gurabo quadrangle (Seiders, 1971c). Although the contact of the Santa Olaya with the underlying Cancel Breccia is nowhere well exposed, Pease, (1968a) speculates that the Santa Olaya unconformably overlies the Cancel Breccia. Fossils have not been reportya Lava, Camarones Sandstone, or Rio de la Plata Sandstone, and the age of the formations is problematic. According to Seiders (1971a), volcaniclastic rocks of the Infierno Formation, of Turonian age are lithologically similar to those of the Cambalache Formation.

Volcanic breccia, lava, mudstone-sandstone, and subordinate conglomerate and limestone lenses of the Tortugas Andesite conformably overlie the Camarones Sandstone and are interbedded with the Guynabo Formation (Pease, 1968a, b). Although the Tortugas was described as subaerial by Pease (1968a), the presence of limestone lenses in the breccia and the sandstone-mudstone facies suggests that the rocks were deposited in a marine environment. Volcanic sandstone, limestone and conglomerate of the La Muda Formation overlie the Tortugas Andesite. The contact is described as unconformable because basal conglomerate of the La Muda contains clasts lithologically like the underlying Tortugas (Pease, 1968a). Rudists in the La Muda have been described as Maastrichtian and possibly Campanian (Sohl oral commun., 1990). Tuff, tuffaceous sandstone, conglomerate, and tuffaceous breccia mapped as the Naranjito Formation crop out in the Naranjito (Pease, 1968c) and Corozal (Nelson, 1967a) quadrangles. Interbedded volcanic siltstone and sandstone, mapped as the Palmarejo Formation, crop out in the Naranjito and Corozal quadrangles where the formation conformably overlies the Naranjito Formation (Nelson, 1967a; Pease, 1968c). Foraminifera from the Palmarejo range in age from Paleocene to Eocene (Pessagno, in Nelson, 1966a). The Guaracanal Andesite, a sequence of coarse volcaniclastic breccia, conformably overlies the Monacillo Formation and appears to be lithologically equivalent to part of the Naranjito (Pease, 1968a). Volcanic sandstone, siltstone, and conglomerate of the Rio Piedras Siltstone conformably overlie the Guaracanal in the Aguas Buenas and Naranjito quadrangles (Pease, 1968b, c), but in the San Juan quadrangle, the Guaracanal is absent and the Rio Piedras overlies the Monacillo (Pease and Monroe, 1977). Foraminifers from the Rio Piedras are late Paleocene (Riskind, in Pease, 1968a).

The Corozal Limestone, a sequence of massive limestone and limestone breccia, calcareous sandstone, siltstone, and bentonitic clay (Nelson, 1966a, 1967a) conformably overlies the Palmarejo Formation and is conformably overlain by the Ortiz Formation. Foraminifera from the Corozal range in age from Paleocene to early or middle Eocene (Applin, in Kaye, 1956; Todd, in Kaye, 1956). The Ortiz consists of interbedded volcanic sandstone, linconformably overlain by middle Tertiary rocks (Nelson, 1966a, 1967a).

INTRUSIVE ROCKS

The northeastern block is intruded by Late Cretaceous and Tertiary rocks that include granodiorite, hornblende quartz diorite, quartz diorite, granodiorite, augite andesite porphyry, diorite, gabbro, and quartz keratophyre. Biotite and hornblende from quartz diorite of the Rio Blanco stock (Seiders, 1971b) have ages of 46.2 Ma and 45.7 Ma respectively (Cox and others, 1977).

MIDDLE TERTIARY SEDIMENTARY ROCKS

Rocks of Oligocene and Miocene age overlie the Jurassic to Eocene core of the island with a profound unconformity along the south-central and southwestern and north coasts of the island. Although the north- and south-coast sequences are both Oligocene and Miocene in age, they cannot be directly correlated (Monroe, 1980c).

On the south coast, middle Tertiary formations crop out from the village of Descalabrado in the east to Guanica Bay in the west. The Juana Diaz Formation, the oldest middle Tertiary formation in this area, consists of basal gravel overlain by a thin-bedded to very thick-bedded coralline limestone, and locally a channel fill of sand and gravel (Monroe, 1980c). Because the Juana Diaz is separated from the overlying Ponce Limestone by an erosional unconformity, Moussa and Seiglie (1970, 1975), include these channel-fill deposits with the overlying Ponce Limestone.

Middle Tertiary rocks on the north coast crop out from the Rio Grande quadrangle in the east to the west coast of the island. The middle Tertiary sequence there consists, from the base up, of sand, gravel, and locally clayey limestone of the San Sebastian Formation, which is conformably overlain by, and interbedded with, limestone of the Lares Limestone. Overlying limestone and sand-gravel beds of the Cibao Formation grade laterally to the east into sand and gravel of the Mucarabones Sand. The Mucarabones overlies the San Sebastian from the Ciales to the San Juan quadrangle (Monroe, 1980c). The conformably overlying Aguada Limestone grades into limy and clastic phases indistinguishable from the Cibao (Monroe, 1980c). Limestone unmixed with other clastic rocks is distinguished as the Aymamón Limestone. The Aymamón is unconformably overlain by sandy lime and chalk of the Camuy Formation, the youngest middle Tertiary rock on the north coast of Puerto Rico (Monroe, 1980c).

SEDIMENTATION MODEL FOR PUERTO RICO

Puerto Rico consists of complexly interfingering shallow- to deep-water, marine alluvial-fan and well-bedded turbidity-flow deposits, as well as hyaloclastite breccia, autoclastic flow-breccia, and pillowed lava flows, and carbonate bank deposits. The alluvial fan deposits accumulated from submarine debris flows characterized by high particle concentrations; sandstone-tuff that show partial or complete Bouma cycles were produced by turbidity flows having low particle concentrations. Lava flows preserved as hyaloclastite breccia, autoclastic flow breccia, and pillow lava. Carbonate banks are preserved as formed in the original near-shore environment or as talus and debris flow materials admixed with volcaniclastic debris originally deposited in deeper water. Volcaniclastic rocks, breccias, and tuff, were derived directly from pyroclastic eruptions and indirectly from alluvium composed of pyroclastic debris as well as epiclastic debris. Materials of pyroclastic and epiclastic origin are mixed to varying degrees, they are seldom, if ever, present as pure unmixed end-members. Subaerial deposition is probably evidenced by welded ash-flow tuff, however Kokelaar and Busby (1992) suggest that even submarine eruptions may give rise to rocks that resemble subaerial welded ash-flow tuff deposits. Subaerial deposition is not otherwise unequivocally demonstrated. Although formations that consist of red and green rocks were described by the original mappers as of subaerial origin, the presence throughout their vertical and lateral extent of foraminifera as well as other fossils of marine origin, and in many cases coarse calcarenite derived from carbonate banks, suggests that they were in reality deposited under marine conditions. Coarse well-rounded cobble and boulder conglomerate were generally deposited under marine conditions and are not indicative of unconformities or disconformities in the rock sequence, although they may suggest subaerial erosion in the source area. Sediments were probably derived chiefly from local volcanic centers, including some, commonly subordinate, materials received from explosive eruptions of ash from more distant subaerial volcanic centers. Subvolcanic intrusive igneous rocks were emplaced at about the same time as eruptions were in progress. Coarse crystalline batholithic masses in the San Lorenzo and Utuado areas were emplaced at greater depth. The whole of the volcanic-intrusive pile was deeply eroded and locally covered by epiclastic rocks and carbonate bank deposits. In the southwest, oceanic rocks largely covered by rocks identical to those in the island-arc proper, were thrust over the island-arc volcanic pile. The initiation of this thrusting may postdate the Kimmeridgian; it continued to some unknown time after the early Eocene. The volcanic pile was eroded deeply enough to expose rocks of the San Lorenzo and Utuado batholiths. Margins of the eroded pile were submerged and covered with basal clastic debris as well as mixtures of epiclastic and carbonate deposits.