Geology of Isla Mona Puerto Rico, and Notes on Age of Mona Passage

GEOLOGICAL SURVEY PROFESSIONAL PAPER 317-C

Prepared in cooperation with the Puerto Rico Water Resources Authority, Puerto Rico Economic Development Administration, Puerto Rico Aqueduct and Sewer Authority, and Puerto Rico Department of the Interior

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By CLIFFORD A. KAYE

With a section on THE PETROGRAPHY OF THE PHOSPHORITES

By ZALMAN S. ALTSCHULER

COASTAL GEOLOGY OF PUERTO RICO

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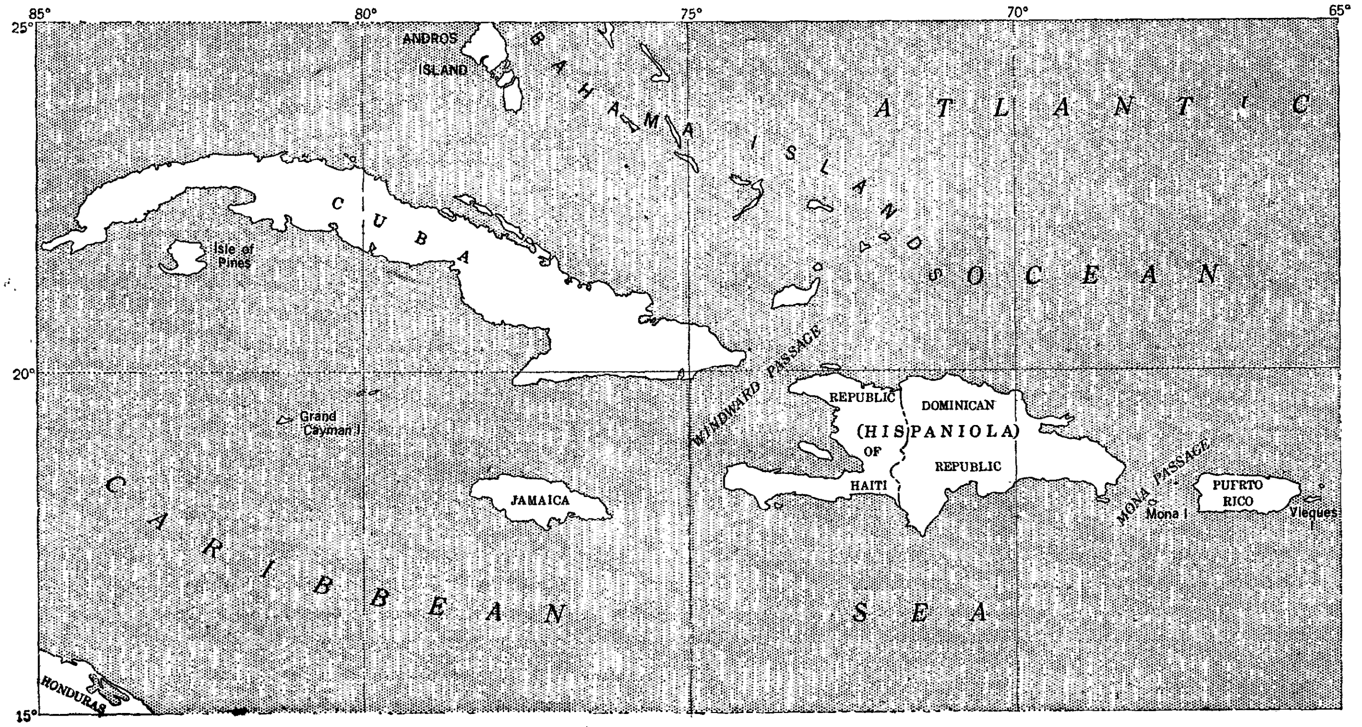

MAP OF THE GREATER ANTILLES

GEOLOGY OF ISLA MONA AND NOTES ON AGE OF MONA PASSAGE

By Clifford A. Kaye

ABSTRACT

Isla Mona and the nearby rock of Monito are situated in Mona Passage, about midway between Puerto Rico and the Dominican Republic. Isla Mona has an area of about 21 square miles and Monito less than a quarter of a square mile. Isla Mona is a limestone tableland, bounded by steep to vertical cliffs and fringed about its southern perimeter by a narrow low-lying coastal terrace. The climate of the island is semiarid; its mean annual rainfall is 38.1 inches. The flora is xerophytic and consists mostly of cactus, leguminous plants, shrubs, and dwarfed trees. The density of the brush is surprising considering the sparse nature of the soil, and most of the larger plants seem to be rooted in narrow, soil-filled crevices in the limestone. The island was discovered by Columbus in 1494 during his second voyage. In early colonial times the island was a watering and provisioning station. At the present time its only inhabitants are the lighthouse crew. In the late 19th century the caverns with which the island abounds were extensively worked for their deposits of leached guano.

Except for the thin soil of the tableland, Isla Mona consists entirely of limestone and dolomite. The Isla Mona limestone forms most of the mass of both islands and is probably early or middle Miocene in age. One sample of rock when tested in the laboratory proved to be dolomite. Unfortunately, it is not known how much of the rock exposed in the vertical sea cliffs of the north coast is dolomite nor whether the dolomite is confined to specific beds or represents irregular-shaped alterations of the limestone. The Isla Mona limestone is essentially flat lying, although apparent dips up to 3½° are visible in the cliffs. No faults were noted. In places a relatively thin cavernous limestone, the Lirio limestone, overlies the Isla Mona limestone. At Punta Este the two formations are separated by a slight angular unconformity. Only one fossil, a coral was found in the Lirio limestone, and from it the formation appears to be either Pliocene or Pleistocene in age. The low coastal terrace surrounding the south side of the island is mostly an elevated reef of Pleistocene age, thinly veneered with sand. Lineations on the plateau suface (best seen from the air) presumably reflect jointing. These have roughly a radial pattern, which suggests that the island has undergone a slight doming deformation since Lirio time.

The scant reddish-brown residual soil of the tableland is a nonplastic, granular aggregate whose inorganic component consists mostly of a mixture of hematite, carbonaceous and amorphous substances (iron oxide?), boehmite, kaolinite, and mica. The soil is rich in phosphorous and nitrogen. Veins and vermicular structures of reddish impure limestone are common throughout the white limestones and probably represent soil washed into solution openings and later cemented by calcium carbonate. The cemented red residuum, as it is called, contains tests of land snails that point to a probable Pleistocene age for the deposit. The plateau surface is everywhere etched into a microrelief of about 1 foot of sharp serrations, pits, and enlarged joints. The plateau surface is very gently domed and is broken by several outward-facing low scarps, a few areas of large sinkholes, and low marginal limestone rims and ramparts. Both the residual soil (cemented and uncemented) and the rims and ramparts indicate that a considerable thickness (roughly estimated to have been about 85 feet) of limestone has been dissolved from the surface of the plateau without having formed a pronounced relief. This points to the importance of surface reduction without dissection in at least the earlier stages of the geomorphic cycle in horizontally bedded pure limestones. The plateau is bounded by steep cliffs on the south and by vertical sea cliffs on the north coast. These sea cliffs plunge to depths estimated to be 16 to 22 fathoms. In the face of evidence of active cliff recession, the plunging nature of these cliffs provides an interesting geomorphic problem. The hypothesis that seems most consistent is that the Isla Mona limestone is actually very friable, although it has a deceptive, casehardened shell where exposed subaerially. Turbulent surf working on the friable rock below sea level is deeply undermining the sea cliffs to a considerable depth, in consequence of which, cliff failure has not produced a platform at or close to present sea level. Hydrographic charts suggest that submarine levels and terraces mark the bank surrounding Isla Mona. There is probably a level of 22 fathoms close to the island on the east side, and a terrace at 7 fathoms is indicated just outside the small barrier reef off the south coast. Behind the reef the lagoon is about 2 fathoms deep. The narrow barrier reef, which for the most part lies only a few hundred yards offshore, merges with a fringing reef along part of the shore.

Both the Isla Mona and the Lirio limestones are cavernous, although the latter formation seems to be more so. Most caverns in the Isla Mona limestone on the south coast are single storied, seem to be level, and have floors that seem to lie about 20 to 25 feet above sea level. Caverns opening out onto cliffs on the windward (east) side of the island generally have very much enlarged mouths, possibly due to solution by direct rainfall. Leached guano (a brown to white powdery material) occurs beneath the dripstone crust on the floors of all caverns. These deposits are no longer being mined although they are far from exhausted. The principal phosphate mineral is hydroxylapatite, with less crandallite, brushite, martinite, and monetite. In addition to the cave phosphorites, phosphatic limestone occurs at Punta Este at the unconformity between the Isla

Mona and Lirio limestones. The replacement of limestone by hydroxylapatite is well illustrated by a petrographic study of this rock. The cave phosphorites are very probably bat guanos. They cannot be ascribed to birds, mainly because they occur deep within the caves in places where birds would not be able to fly because of the total darkness. A small part of the phosphate was probably derived from surface guano deposits, leached and carried down to cavern level by infiltrating water. In addition to phosphatic minerals, deposits of finely pulverulent calcite were noted at several places about the island and may have formed by the disintegration of limestone, perhaps through the activity of an organic agent (algae?).

Mona Passage was probably already in existence in the Miocene and Pliocene (or early Pleistocene), when the Isla Mona and Lirio limestones were deposited. This is evident from the great purity (in terms of insoluble content) of these rocks as compared with limestones of Puerto Rico of early Miocene age. The great purity of the rocks of Isla Mona points to an oceanic-reef environment far from a source of land-derived sediment. The site of Isla Mona today fulfills this requirement because of the essentially oceanic nature of the currents that flow to the north across the center of the strait. If this strait had not existed in the Miocene (that is, if Puerto Rico and Hispaniola had been a continuous landmass), the site of Isla Mona would have been traversed by west-flowing coastal currents similar to those off the south coast of Puerto Rico today, and presumably also off the south coast of Puerto Rico in the early Miocene. The Isla Mona limestone was probably deposited in relatively shallow waters not too remote from reefs. The nature of the unconformity between the Isla Mona and Lirio limestones suggests marine planation within the wave zone. The thin layer of phosphatic limestone at the unconformity at Punta Este also points to the possibility of a preceding interval of subaerial reduction and guano accumulation. At the close of deposition of the Lirio limestone, the island possibly corresponded in dimension to the submarine bank that now surrounds Isla Mona. This means that since that time the shores of Isla Mona have receded as much as a mile while Isla Monito has been reduced by as much as two miles. A sequence of Quaternary climatic changes is indicated by various data.

The cemented red residuum possibly represents a transition from humid to less humid climate. The formation of the many large caverns by solution probably followed the cementation of the red residuum and possibly occurred during a period of very humid climate and high water table; the position of the water table may have been controlled by a higher sea level. The caverns were then drained, possibly as a result of a fall in sea level, and then were occupied by large colonies of bats. The climate may have been more humid than that of today. The interval of guano deposition was abruptly terminated and was followed by the deposition of dripstone in the caverns. This was possibly a response to a climate shift towards greater aridity, and it is speculated that this may have followed the postglacial warm interval. Historical records indicate that the climate of Isla Mona may have been more humid 300 to 450 years ago than it is today.

GEOLOGY OF ISLA MONA

INTRODUCTION

Isla Mona is a little visited and sparsely populated limestone island lying in Mona Passage, about midway between Puerto Rico and the Dominican Republic (fig. 1). Politically it is part of Puerto Rico, and together with Puerto Rico it was ceded to the United States by Spain in the Treaty of Paris of 1898. In the early colonial period the island was important as a provisioning station and pirate hideout. In the last century the guano deposits that are found on the floor of the island's many caves were worked. Since then the island's economic importance has languished, until today it is merely the site of a lighthouse and the hunting ground of an occasional sportsman.

Besides its quiet charm and salubrious climate, Isla Mona offers the geologist varied geological problems. Its isolated position in the middle of one of the principal straits across the Greater Antillean island arc makes it something of a key to the integration of the geology on both sides of Mona Passage and, in fact, to the history of Mona Passage itself. In addition, there are the questions that are posed by every island: How did it originate? What vicissitudes have molded it? What light does it throw on oceanic changes and what evidence does it yield of the interrelation between sea and land, which is so important in the history and morphology of all islands?

The writer first visited Isla Mona in 1949, at the request of the Commissioner of Agriculture and Commerce of Puerto Rico, to examine the guano deposits. Two additional trips were made in 1950 to study the general geology; and a fourth, brief trip was made in the summer of 1952. Field work was hampered by the brush that covers much of the island, and movements were restricted to the several badly overgrown trails that cross the upland. The sea cliffs, which constitute the best rock exposure on the island, were viewed from a 37-foot Coast Guard vessel. The small island of Monito, about 4 miles to the northwest, was inspected from the sea and air, inasmuch as the deep rip and the vertical rock walls above it make a landing on Monito hazardous without special equipment.

LOCATION AND TOPOGRAPHIC DESCRIPTION

Isla Mona lies in Mona Passage about 39 nautical miles (45 statute miles) due west of Puerto Rico (pl. 12; chap. A. pl. 1). This is at latitude 18°05′ north, longitude 67°53′ west, or about midway between Puerto Rico and the Dominican Republic. In plan, the island is a bean-shaped polygon, suggestive of the shape of Australia rotated 180° on the map. Its maximum dimensions are about 6½ miles from east to west and about 4½ miles from north to south, and its area is about 21.3 square miles. About 3½ statute miles to the northwest of Cabo Barrionuevo is the rocky islet of Monito, less than a quarter of a square mile in area. For the sake of brevity in describing the coastal perimeter of Isla Mona, the term "north coast" will be used to designate the northern coastline lying between Punta Este (Cabo Este on many maps and charts) and Cabo Barrionuevo (pl. 12). The remaining coast will be referred to as the "south coast."

Isla Mona is a limestone tableland, bounded by steep to vertical cliffs and fringed about its southern perimeter by a narrow, low-lying coastal terrace (pl. 14*B*). Deep water extends to the foot of the cliff on the north and east sides of the island, but the south coast is protected by shoal water and in places by a barrier reef several hundred yards offshore. Behind the barrier reef the shore of the island consists of sandy to rocky beaches. Access to the island is had by several narrow passes through the reef—one off Playa Pájaro on the southeast, leading to a small pier used by the U. S. Coast Guard, and one on the west at "La Sardinera," the site of a former Civilian Conservation Corps camp, whose buildings, airstrip, and various installations still stand.

Seen from the sea, the surface of the tableland seems perfectly flat, although in reality it is gently undulating and tilted, attaining its maximum altitude of about 90 meters (295 feet) on the north and an altitude of about 25 meters (82 feet) on the south. Moreover, there are fairly gross to minor surface irregularities that are evident from the air and the ground. The more notable topographic features include a series of low but persistant escarpments, for the most part arranged roughly concentrically about the center of the island and facing seaward (pl. 12). In addition, there are several shallow grooves, or "valleys," the largest and best formed of which is rather straight and trends northwest in the central part of the island. The broad sinkhole in the deepest part of this groove is called the Bajura de los Cerezos. Several other areas of large sinkholes occur on the plateau, though they are surprisingly few for a limestone terrain. The large sinkholes are given some local prominence because of the comparatively luxuriant vegetation which their unusually thick soils support. The sinkholes of El Corral and Cuevas del Centro connect in several places to underlying caverns.

The limestone surface of the plateau is everywhere weathered by solution into a karrenfels type of microrelief with sharp limestone points, ridges, and pinnacles. In places these solution features have a decided lineation, which is probably due mostly to finely spaced jointing (pl. 12). The soil on the surface of the plateau is scant and spotty, and consists of thin pockets of red loam occupying solution pits and enlarged joints in the limestone. There is no runoff and practically all precipitation is absorbed by the many rock openings.

At the edge of the tableland the surface is generally slightly downwarped and in places broken by gaping tension joints that are roughly parallel to the cliff edge. This is the zone of active spalling of the cliffs and shows clearly the continuous nature of sea-cliff recession.

The tableland is everywhere bordered by steep cliffs (pl. 13*A*). The north coast of the island is a vertical to slightly overhanging cliff, rising from water estimated to be about 22 fathoms (132 feet) deep to a maximum altitude of 85 meters (279 feet) above sea level. The sea cliff is lowest at Punta Este, where it is about 45 meters (148 feet) high.

The cliffs of the south side of the island are steep, though not everywhere vertical, and are fringed by a narrow coastal plain. On this side of the island the cliffs are conspicuously broken by the mouths of many caves, and reposing on the coastal terrace and piled up against the cliff are large talus blocks of limestone (pl. 14*B*).

The coastal terrace that fringes the plateau on the south side is mostly underlain by reef limestone and represents a recently "raised" reef platform. The altitude of this platform probably does not exceed 12 feet. It is widest in the southwest, between Punta Oeste and Desembarcadero Uvero, where it attains a maximum width of 0.6 miles and a length of 3½ miles. This terrace is covered in many places by a thin sandy soil, which in the past has sustained some agriculture. From the air, the sandy part of the terrace is seen to be lightly marked by a lunate pattern (pl. 12). These lines are very low fossil beach ridges, which show that the sand accumulated as a succession of beaches during a period of higher sea level. The coastal terrace continues around the southern tip of the island, where it shrinks to a very narrow ledge. It widens slightly at Playa Pájaro and just west of Punta Este. Where the terrace is narrowest, it is completely buried by large talus blocks detached from the cliff above.

CLIMATE

The climate of Isla Mona is semiarid. The island is exposed to the full sweep of the trade winds; in consequence, the winds are prevailingly from the east and northeast the year around, occasionally from the southeast, and rarely from the west. Although the island has a mean annual rainfall of 38.1 inches, the general aspect is severely semiarid. This is due not only to the high evaporation rate, but also to the high permeability of the limestone tableland which absorbs all rainfall rapidly. Tables of climatic data for Isla Mona, obtained from the U. S. Weather Bureau, San Juan, P. R., appear below.

Greatest 24-hour rainfall on record, by month, for Isla Mona

	Jan.	Feb.	Mar.	Apr.	May	June	July
Precipitation inches	3.0	2.1	5.7	5.0	8.9	6.0	4.6
Year	1935	1924	1933	1931	1945	1935	1931

	Aug.	Sept.	Oct.	Nov.	Dec.	Record
Precipitation inches	5.6	5.3	4.6	5.4	8.1	8.9
Year	1935	1931	1937	1931	1945	1945

Number of days with rainfall in a year, by selected years, for Isla Mona

	1942	1945	1947	1949
Minimum rainfall (inches)—				
0.1	103	129	125	105
0.25	41	48	33	29
1.00	5	19	5	4

Mean monthly and annual rainfall, for Isla Mona

	Jan.	Feb.	Mar.	Apr.	May	June	July
Mean rainfall inches	1.5	1.8	2.2	2.8	4.3	2.7	3.2
Number of years of record	30	33	33	33	32	31	31

	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
Mean rainfall inches	3.3	4.5	4.8	4.0	3.0	38.1
Number of years of record	32	30	31	31	31	

FLORA AND FAUNA

The flora of Isla Mona is xerophytic and consists conspicuously of cactus, leguminous plants, shrubs, and dwarfed trees that on the tableland rarely exceed a height of 12 feet. The density of the brush is surprising considering the sparse soil, and most of the larger plants seem to be rooted in narrow crevices in the limestone.

Britton (1915) recognized 233 species of flowering plants on Isla Mona, including 8 introduced species and 4 endemic species. More recently J. I. Otero (personal communication) has identified 317 species of flowering plants on the island, 6 of which he considers endemic. Wadsworth and Gilormini (1945) were able to recognize 4 distinct types of vegetation on the tableland and 2 on the coastal lowland.

Among the more conspicuous plants are: *Elaphrium simaruba*, the West Indian birch or almácigo; *Metopium toxiferum*, the papayo; *Tabebuia lucida*, Isla Mona oak; *Capparis indica*, linguán; *Amyris elemifera*, tea; *Hypelate trifoliata*, cigua; *Canella winterana*, barbasco; *Eugenia monticola*, birijí; *Dipholis salicifolia*, sabina; *Plumiera obtusa*, alhelí de la Mona; *Bouerreria suculenta*, palo de vaca; *Krugiodendrum ferreum*, palo de hierro; *Exostema caibaeum*, albarillo.

Agriculture has been carried on sporadically on the coastal lowlands, but recent attempts have met with indifferent success. Some fruits and vegetables have been raised, and sea-island cotton was cultivated for a time. There is a small mahogany grove southeast of Anclaje Isabel that was planted by the Civilian Conservation Corps in the 1930's.

The land snails of Isla Mona were described by W. J. Clench (1950, 1951), who recorded 16 species, 4 of which were new though closely allied to known species. He considers the fauna as probably fortuitous in origin and more closely related to the faunas of the islands lying to the east than to that of Hispañola (Dominican Republic and Haiti), lying to the west of Isla Mona.

Ramos (1946) has listed 526 species of insects, 24 of which are endemic. He attributes the poverty of this insect fauna to the general aridity of the place.

Stejneger (1902) and Schmidt (1926, 1928) have described the amphibians and reptiles of Isla Mona. Schmidt listed 1 tree frog—*Eleutherodactylus monensis;* 5 lizards—*Spaerodactylus macrolepis*, *Anolis cristatellus*, *Cyclura stejnegeri*, *Ameiva alboguttata*, and *Maybuya sloanii;* and 3 snakes—*Typhlops monensis*, *Epicrates monensis*, and *Alsophis variegatus*. Five of these species are endemic, including the curiously archaic Mona iguana, *Cyclura stejnegeri*.

Of the several descriptions of Isla Mona birds, the more comprehensive works include those of A. Wetmore (1927), and V. Barnés (1946). Barnés lists 52 species and subspecies, 11 of which are land birds, 4 of which are migrants, and 1 of which—the Isla Mona blackbird—is endemic. Conspicuous among the land birds are: the white-crowned pigeon, which migrates to the island in great flocks every year and is highly valued as a game bird; the Zenaida dove; the Isla Mona ground dove; the gray kingbird; and the yellow-billed cuckoo. The marine birds include such species as: Audubon's shearwater, yellow-billed tropic-bird, West Indian brown pelican, white-bellied booby, and the Caribbean man-o'war bird.

H. E. Anthony (1918) lists two species of bats, *Noctilio leporinus mastivus* and *Mormoops blainvilli*, as the only indigenous mammals on the island. Both species are widely distributed in the greater Antilles.

In addition to these mammals, a large number of feral animals live on Isla Mona. Officials of the Puerto Rico Bureau of Fish and Game estimate the wild goat population to be about 3,000, for the most part descendants, according to Dr. F. H. Wadsworth (written communication), of a 16th-century herd. In addition to wild goats there are wild pigs, cats, and even a few burros. All these animals subsist precariously on a very meager and uncertain water supply.

FAUNAL ORIGIN

Opinions differ among the specialists as to the origin of the various components of the Isla Mona flora and fauna. For those writers who favor a derived origin there has been, of necessity, a strong reliance on geologic interpretations of the island's history. Data presented in this paper will show that in all probability Isla Mona was submerged during a part of the Pliocene or Pleistocene. It would follow that the entire terrestrial biota must postdate this event. It is possible, though unlikely, that a former extension of Isla Mona, now eroded away, might have remained emergent during the Pleistocene and thus provided a sanctuary for the late Tertiary plants and animals.

HISTORY

The name Mona, or Amona, seems to have been the Indian name for the island and was accordingly adopted by Columbus, who discovered the place on September 24, 1494. There seems no reason to speculate, as did Fra Bartolomé de las Casas (1875) in the 16th century, that the Admiral was influenced by the ancient Celtic name for Anglesey, Mona,[1] in naming this obscure island.

The discovery of Isla Mona in the course of Columbus' second journey is recounted by his chroniclers, De las Casas and Fernando Colón. De las Casas (1875) described the island as being exceedingly rocky and marked by many holes containing a very fertile red soil (presumably sinkholes and solution pits on the plateau). The Indians living there (Taino Indians, according to Rouse, 1952) raised yucca, from the roots of which they made cassava bread. Furthermore, De las Casas reported that the roots grew so large in some of these soil-filled holes that an Indian could carry only two of them on his back. Other crops included melons ("melones de España") as large as a gallon and a half jug of olive oil ("botijas de las de media arroba de aceite"). De las Casas speculated that this exceptional fertility was the result of the rocks of the island yielding up moisture to the surrounding soil![2] This fertility of Isla Mona, so at variance with the visitor's impression today, was also emphasized by the observant Gonzalo Fernandes de Orviedo who, writing in the middle of the 16th century, tells of the fine melons, cassava bread, succulent red crabs, and good fresh water found on Isla Mona. The curious fact that fresh water could be had on Isla Mona is further indicated by nautical charts of the period, which, even as late as De la Rochette's "General Chart of the West India Islands," published in 17?6 in London, shows Isla Mona as a watering port. Juan de Laët (1640), writing in the early 17th century, tells further of the excellent fruits and particularly of the sweet oranges that are grown on the island. This productivity, in fact, was responsible for the island becoming a source of provisions for the precariously situated Spanish colony on nearby Puerto Rico, founded by Ponce de León about 14 years after the discovery of Isla Mona. The Indians living on Isla Mona were apparently friendly and provided the Spanish ships with the food that could not be wrested from the natives of the very much larger and more fertile island of Puerto Rico. Later on, the Isla Mona Indians provided the mainland with hammocks and cotton shirts (Rouse, 1952).

The last record of Indians existing on Isla Mona was in 1584 (Rouse, 1952). According to Rouse, the natives had a closer cultural affinity to the Dominican Indian cultures at the west than to the Indian culture on Puerto Rico. Professor R. Ramírez, University of Puerto Rico, reported (oral communication) that an Indian colony was imported in the 17th century from Yucatán (?) in an unsuccessful attempt to start up agricultural production on Isla Mona again, although this event was not mentioned by Rouse in his account of the Indian history of the island.

On April 11, 1591, Sir Christopher Newport (Hakluyt, 1904, v. 10, p. 185) visited Isla Mona, where he found "19 soules, the children of an olde Portugall and his wife who offoured us such fruits as their island yielded, viz. swine's flesh, potato rootes, etc." This gentleman privateer was later captain of one of the three ships of the Jamestown expedition, and Captain John Smith (1624) tells us how that historic fleet, on its way to Virginia in the spring of 1607, put into Isla Mona for several days in order to take on fresh water and provisions.

But the role of Isla Mona in Caribbean history was not always agricultural or peaceful. On many occasions it provided shelter for buccaneers and others living outside the law. In 1528 the French corsairs who burned the early Puerto Rican town of San Germán fled to Mona, and in 1554 a French force collected on Isla Mona to launch an attack against the Spanish colony of Puerto Rico. The Puerto Rican pirate Cofresí made his head-

[1] "In hoc medio cursu est insula, quae appellatur Mona."—Julius Caesar, "Gallic Wars" 5, 13, 3. Here, according to commentaries, Caesar meant the Isle of Man rather than Anglesey.

"Nor on the shaggy top of Mona high."—John Milton, "Lycidas."

[2] "Aridity follows the plow," a somewhat related idea, died hard. For example, Sir Charles Lyell (1840, v. 3, p. 253) wrote "The felling of forests has been attended, in many countries, by a diminution of rain, as in Barbados and Jamaica." The Rev. Gilbert White ("Natural History of Selborne") stated the case admirably in his letter of Feb. 7, 1776: "In some of our smaller islands in the West Indies, if I mistake not, there are no springs or rivers; but the people are supplied with that necessary element, water, merely by the dripping of some large tall trees, which, standing in the bosom of a mountain, keep their heads constantly enveloped with fogs and clouds, from which they dispense their kindly, never-ceasing moisture; and so render those districts habitable by condensation alone."

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quarters on Isla Mona in the first part of the 19th century.

Mining of the guano deposits in the island's many caves began in 1872 and, according to record, lasted until about 1922, although the greatest mining activity antedated the present century.

In the early part of this century a few hardy people still farmed the thin sandy soil of the coastal terrace around Desembarcadero Uvero, raising fruits, vegetables, and seaisland cotton, which they marketed on the mainland. In 1937 a Civil Conservation Corps camp was established at La Sardinera, on Punta Oeste. A landing strip was cleared, a concrete pier built, and an unpaved "road" blazed across the tableland to Playa Pájaro. At the time the writer visited Isla Mona, its only steady inhabitants were the lighthouse crew. Sportsmen in search of the varied game that abounds make periodic trips from Puerto Rico. But during much of its history the island was as sparsely populated as now.

ROCKS

Except for the thin soil of the tableland, Isla Mona consists entirely of limestone and dolomite. The Isla Mona limestone (one sample of which proved to be dolomite when tested in the laboratory) forms the main mass of Islas Mona and Monito and is early or middle Miocene in age. A fragmentary capping of Pliocene or Pleistocene reef limestone, here called the Lirio limestone, occurs on Isla Mona and probably on Monito. In addition, a low elevated reef deposit forms a terrace about 10 to 12 feet above sea level around the southern perimeter of the island.

It is notable that in hand specimens all the limestones are similar. The typical rock is a dense white pure limestone, apparently detrital. Except in the elevated reef rock, fossils are rare and poorly preserved.

ISLA MONA LIMESTONE

The thick-bedded, dense, and finely crystalline limestone and dolomite that makes up most of Islas Mona and Monito is here named the Isla Mona limestone. The rock has a clear metallic ring when struck with a hammer. It is white on the fresh surface, but in the cliffs it is stained a light yellow. It is an exceptionally pure carbonate rock; the greatest insoluble residue of any sample tested (table 5) was 0.33 percent, and the average insoluble content was considerably less. Macrofossils are scarce, but thin sections reveal that the rock contains well-preserved shell fragments and Foraminifera tests. The limestone is probably largely if not entirely of detrital origin and was originally a calcareous sand made up of debris of lime-secreting marine organisms.

One sample, from the foot of the cliff at Punta Este, of what appeared to be a typical limestone proved on semiquantitative spectroscopic analysis to be a pure dolomite. It is not known whether this sample came from a local development of dolomite, whether it represents an isolated dolomite bed, or whether much of the Isla Mona limestone that is exposed in the inaccessible sea cliffs of the north coast is actually dolomite. No dolomite was identified by use of the Stevens and Carron (1948) abrasion pH method among the many samples of rock collected from the south side of the island. Moreover, two samples of the Isla Mona limestone from the Playa Pájaro area were chemically analyzed (table 1) and yielded a very low MgO content. A thin section of the dolomite showed that it consists mostly of the tests of Foraminifera and finely comminuted shell and algal material. The excellent state of preservation of the microscopic structures of these organisms is outstanding, considering the alteration of the original shell material to dolomite.

Age.—Identifiable fossils were found at only one locality in the Isla Mona limestone. These were collected from loose blocks on the floor of Cueva Negra, not far from the mouth of the cavern. The rock is a rather friable finely crystalline, white limestone. The mollusks, which were poorly preserved molds that did not permit specific identification, were studied by Mr. W. P. Woodring, who listed *Cypraea* sp., *Conus* sp., and *Spondylus* sp., and suggested that this meager fauna might be of any age from Miocene to Recent. The corals, examined by Mr. J. W. Wells, consisted of *Acropora* sp., *Antillia gregorii* Vaughan, *Manicia areolata* (Linné), *Stylophora granulata* Duncan, and *Thysanus excentricus* Duncan, and appear to be a Miocene assemblage.

TABLE 1.—*Analyses of samples of Isla Mona limestone*

Percent CaO, MgO, P_2O_5, N, *and* U

[Quantitative chemical analyses. Analysts: sample 1, A. Caemmerer; samples 2 and 3, H. F. Phillips]

Sample	Location	CaO	MgO	P_2O_5	N	U	Acid-insoluble residue
1	Punta Este near base of cliff	------	------	0.37	0.03	0.001	0.04
2	Playa Pájaro, surface of plateau.	55.0	.16	.00	------	------	.17
3	Playa Pájaro, base of cliff	52.4	1.9	.00	------	------	.10

Percent concentration of minor elements

[Semiquantitative spectroscopic analysis, by Charles Annell. See table 4 for threshold values]

Sample	Location	>10	10–1	1.0–0.1	0.1–0.01	0.01–0.001	0.001–0.0001
1	Punta Este, near base of cliff.	Mg	Ca	Fe, Pb, Si.	Al, Na, V, Sr, Mn, Ti.	Mo, Cu, Cr.	Ba.

A VERTICAL SEA CLIFFS, EAST COAST OF ISLA MONA, SHOWING LIRIO LIMESTONE CAP

Note angular unconformity between cavernous Lirio limestone and underlying Isla Mona limestone; also large slumped block (right) and deep sea-level nip

B CEMENTED RED RESIDUUM IN WHITE LIRIO LIMESTONE, SHOWING TYPICAL VERMICULAR STRUCTURE

A ENLARGED CAVERN MOUTHS, PLAYA PÁJARO

B VIEW TO SOUTHWEST FROM PUNTA ESTE, ISLA MONA

Shows general undissected nature of the plateau surface, large talus blocks at foot of cliff, 12-foot elevated reef platform (foreground), and living barrier reef (background)

In addition to the fossils collected by the writer, Hubbard (1920, 1923) lists the following fossils as having been collected on Isla Mona by A. K. Lobeck: *Strombus proximus* Sowerby (?), *Bullaria* cf. *paupercula* Sowerby, *Turritella* cf. *gatunensis* Conrad, and *Lucina* cf. *chrysostoma* (Meuschen). Exact collecting localities are not given, but it is presumed the fossils came from the Isla Mona limestone and not from the overlying Lirio limestone.

The age of the Isla Mona limestone appears on the basis of the corals to be Miocene, probably early or middle Miocene. Hubbard (1923) assumed that the Isla Mona limestone is the equivalent of the early Miocene Ponce limestone of the south coast of Puerto Rico. It seems, however, that the known fauna is too meager to permit a satisfactory comparison with any of the Miocene sections of Puerto Rico or the Dominican Republic. There is no more reason at this stage of our knowledge to correlate the Isla Mona limestone with the lower Miocene of Puerto Rico than to correlate it with the lower or middle Miocene rocks of the eastern part of the Dominican Republic.

LIRIO LIMESTONE

Islas Mona and Monito are in places capped by a thin limestone that overlies the Isla Mona limestone unconformably. This formation is here called the Lirio limestone after Cueva del Lirio, at Punta Este, which lies entirely within it. The unconformity separating the Lirio limestone from the Isla Mona limestone is best seen in the sea cliffs at Punta Este, where the underlying Isla Mona limestone dips about 3° S. and the Lirio limestone is practically horizontal (pl. 13*A*).

In hand specimen, the Lirio limestone is indistinguishable from the Isla Mona limestone. No positive method was found to recognize the two formations on the surface of the plateau. Where exposed, however, in the sea cliff at Punta Este they are readily distinguished by the unconformity and the darker weathered surface of the Lirio limestone, and by the fact that the Lirio limestone is much the more cavernous of the two formations. No attempt has been made to separate the formations on the plateau surface on the accompanying geologic map (pl. 12), and only those places where the Lirio limestone was clearly identifiable in the sea cliffs are shown.

Besides Punta Este, the Lirio limestone was noted at four other stretches of the sea cliffs of the north coast but at no place with certainty in the cliffs of the south coast. It is possible that this limestone, which seems to occur only as isolated fragments at the cliff edge, is present as a broad blanket over the higher central part of the plateau. This is suggested by the shallow caverns at El Corral and Cuevas del Centro—caverns that resemble the thin-roofed Cueva del Lirio at Punta Este, which is developed entirely within the Lirio limestone. The Lirio limestone is thickest at Punta Este, where it is about 50 feet thick. In other places where it can be identified in the sea cliff, it commonly attains a thickness of only 10 to 15 feet.

The scarcity of fossils in the Lirio limestone indicates deposition somewhat removed from active reef growth, as at the center of a broad lagoon or at moderate depths associated with the outer reef slopes. In both these environments thick calcareous sands, much like those that originally composed the Lirio limestone, can accumulate.

Age.—The Lirio limestone is particularly lacking in macrofossils. Only one fossil was found—the coral *Monastrea annularis* (Ellis and Solander), a widespread existing reef species whose earliest record is from the Pliocene. From the meager fossil evidence the age of this formation is therefore taken to be either Pliocene or Pleistocene.

There is, however, another method, albeit a speculative one, of estimating the age of the Lirio limestone. It is estimated (p. 151) that between 80 and 100 feet of Lirio limestone may have been dissolved from the top of the island. Recently published studies of J. P. Miller (1952), based on controlled laboratory experiments of limestone solubility, indicate that the reduction of a soilless limestone surface proceeds at the rate of 1 foot in 11,100 years where the annual rainfall is 40 inches (which is approximately that of Isla Mona today), provided equilibrium in the system $CaCO_3$–CO_2–H_2O is attained, and provided the $CaCO_3$, once dissolved, is not reprecipitated.

Assuming that Isla Mona has been exposed throughout Quaternary time to the same average climate as at present, and that the conditions of equilibrium were met with, it would have taken approximately 940,000 years to dissolve 85 feet of the dense Lirio limestone. Although there are good reasons to think that climatic fluctuations occurred at Isla Mona during the Pleistocene, varying from climates more humid to climates more arid than that of today (p. 173), the average rainfall may have been close to the present rainfall of 40 inches per annum. It should be assumed, moreover, that equilibrium between rainfall and the surface limestone rarely occurs and that influent seepage is undersaturated with $Ca(HCO_3)_2$. Viewed broadly, therefore, the implication seems to be that the Lirio limestone has been exposed to subaerial erosion for about a million years. It would follow from this that the age is a million or more years, and hence that the formation dates from the Pliocene or perhaps the very early Pleistocene.

REEF LIMESTONE

The low coastal terrace lying off the south side of the island is for the most part an "elevated" coral reef thinly veneered with sand. In a few places, such as just west of Punta Este, the sand cover is absent (pl. 14*B*). The reef limestone is a moderately dense white rock, slightly more friable than the older limestones already described, and contains a great abundance of coral heads ranging up to 5 or more feet across but averaging a little under 1 foot. Fossil mollusks, which are of living species, are not particularly common.

The following fossil corals were collected along the road between "La Sardinera" and Desembarcadero Uvero and were identified by Mr. Wells: *Diploria strigosa* (Dana), *Diploria clivosa* (Ellis and Solander), *Monastrea annularis* (Ellis and Solander), *Monastrea cavernosa* (Linné), *Porites* sp., *Siderastrea siderea* (Ellis and Solander). Corals collected on the platform just west of Punta Este, also identified by Mr. Wells, included: *Acropora palmata* (Lamarck), *Agaricia agaricites* (Linné), *Dendrogyra cylindrus* Ehrenberg, *Diploria labyrinthiformis* (Linné), *Diploria strigosa* (Dana), *Meandrina meandrites* (Linné), *Monastrea annularis* (Ellis and Solander), *Porites porites* (Pallas). All these forms are typical surface reef species of Pleistocene to Recent age.

This low terrace of reef limestone, standing about 12 feet above the present sea level, is found on many other islands in the Caribbean and is generally considered to be of late Pleistocene or Recent age. A very close parallel to the Isla Mona occurrence is furnished by the morphologically similar Cayman Islands in the western Caribbean, south of Cuba, where Matley (1926) describes an identical "elevated" reef platform under the name of Ironshore formation. Also of note is the island of Anegada, in the British Virgin Islands, which, according to Earle (1924), is made up entirely of a 12- to 15-foot terrace of reef rock. A similar terrace and deposit occur extensively on the south coast of the Dominican Republic and at several places on the north coast of Puerto Rico (chap. B).

STRUCTURE

The Isla Mona limestone, as exposed in the cliffs of the island, is essentially flat lying; here and there are local undulations, which apparently dip as much as 3½°. These undulations are not well-defined folds but have more of the character of local warps or monoclinal flexures. The longest exposure of dipping beds is in the sea cliff at Punta Este, where, for a distance of about 0.7 mile to the north, the Isla Mona limestone has a southerly component of dip as great as 3° (pl. 13*A*). The true dip here is probably southwest and may amount to about 4°. In addition, pronounced local thickening of beds and what appear to be either large-scale crossbedding or local unconformities within the section of Isla Mona limestone can be seen at several places in the sea cliffs, notably near Cabo Norte.

The only other places where deviations from the horizontal were seen are in the cliff behind the Desembarcadero Uvera, where there is a low northerly component of dip; just southeast of Cabo Noroeste, where there is a curious steep local downwarp to the south; and within Cueva Negra, behind La Sardinera, where west dips as great as 5° were noticed locally. In the eastern part of Monito the limestone beds dip very gently to the west but flatten out in the western part of the island.

The bedding of the Lirio limestone is not apparent in the cliff exposures, but the base of the formation shows signs of gentle undulations. It dips to the south at an angle of less than 1° at Punta Este. Strike and dips could not be determined on the surface of the plateau because bedding was not discernible.

No faults were noticed in the cliffs.

Jointing is thought to be expressed by pronounced linear features on the plateau surface, which are best seen from the air. The general radial pattern of these joints (pl. 12) about the center of the island suggests strain resulting from a fairly simple doming stress. T. J. Parker and A. N. McDowell (1951) show photographs of model domes produced on a laboratory scale by the deformation of heavy mud over an asphalt layer. The pattern of fractures in Parker's and McDowell's models 68 and 72 is suggestive of the joint pattern of Isla Mona. In the models, the fractures were interpreted as faults. There is no evidence that there has been fault displacement across any of the linear fractures on Isla Mona, and the jointing is possibly a strain effect resulting from stresses of a low intensity that with increased deformation might have developed into faults.

At Punta Este the lineations are partly in the Lirio limestone, suggesting thereby that the age of the inferred doming deformation is Lirio or post-Lirio in age and pointing to the possibility that the crudely domed form of the present surface of the island (pl. 12) actually reflects this crustal deformation.

SOIL

The dark reddish-brown lateritic soil of the tableland is presumably a residual deposit left from the dissolution of the Isla Mona and Lirio limestones. The high purity in terms of carbonate content of these limestones (table 5) suggests that an appreciable thickness of rock has been dissolved to produce even the existing thin and patchy cover. Fred A. Hildebrand has suggested (written communication) that much of the soil may have originally been airborne dust, possibly volcanic in origin. It seems likely to the writer, however, that atmospheric dust has contributed only a small part of the soil matter.

The soil is a nonplastic loose aggregate of reddish-brown floccules of clay and iron oxide mixed with organic material. Texturally it could be called a fine sandy loam, because of the fine sand-sized floccules. The soil is azonal and occurs as thin patches in depressions and fractures in the limestone. In one sample studied, the coarse (>80 mesh) organic component of the soil consituted approximately 30 percent by weight of the sample and consisted mainly of wood fragments, rootlets, spines, seeds, spores, seed capsules, shells and shell fragments of land snails, small fecal pellets, and an abundance of very small bones and bone fragments (probably mostly lizards). Analysis of one sample of soil for phosphate by the Soil Laboratory of the Insular Agricultural Experiment Station, Río Piedras, showed a total P_2O_5 content of 1.43 percent by weight. Two samples of soil were analyzed for nitrogen by the same laboratory and yielded the unusually high figure of 1.06 percent and 0.94 percent. It was thought that chitin, bones, fecal pellets, and other organic matter are responsible for this concentration.

The small flocculated aggregates are isotropic and have an index of refraction of 1.59. They resemble a "clay" from Bermuda described by Foreman (1951). Foreman thought the Bermuda clay was halloysite. Analysis of the "clay" floccules of Isla Mona, made by Mr. Hildebrand with the cooperation of other members of the U. S. Geological Survey, indicate a much more complex composition. A minus-140 mesh (U. S. Standard) fraction of this soil was studied by X-ray diffraction, spectrographic, electron microscope, differential thermal, and petrographic methods. The results indicate a mixture of hematite, carbonaceous and amorphous substance (probably iron oxide), boehmite, kaolinite, and mica, with lesser amount of calcite, quartz, anatase, magnetite, goethite(?), halloysite(?), and attapulgite(??). The relative abundance of the components could not be determined because of the large amount of carbonaceous and amorphous substance present. In view of the presence of boehmite, the content of Al_2O_3 was determined by quantitative spectrographic analysis (Janet D. Fletcher, analyst) and found to be only 8 percent. The sample, however, had previously been treated with concentrated HCl and 30 percent H_2O_2 in preparation for an X-ray diffraction picture, so that the percentage of Al_2O_3 in the raw soil is very probably even less than this low figure. A very high percentage of amorphous(?) iron oxide is therefore indicated.

The thin, patchy nature of the soil cover of Isla Mona is similar to that of many other limestone regions, including the classic Dalmatian karst region. This is not surprising when it is remembered that the weathering of pure limestone yields little or no soil. There is therefore no compelling reason to think, as did Davis (1930, p. 530) concerning the Dalmatian karst, that the soil cover of Isla Mona was ever more complete than today and that today's surface has been denuded of soil.

CEMENTED RED RESIDUUM

The white Isla Mona and Lirio limestones are marked in many places by conspicuous veinations, mottlings, and vermicular structure (pl. 13*B*) of a red to reddish-brown argillaceous limestone, not uncommonly of about the same density as the enclosing rock. These veinations are found not only on the surface of the tableland but also in the cliff face and in walls of caverns 70 feet or more below the plateau surface. It seems evident from the shapes of the mottlings and veinations that the red limestone constitutes the epigenetic fillings of fractures and minor solution openings in the white limestones. The common occurrence of the shells of land snails in these structures suggests that they represent mostly cemented residual soil, most of which may have been washed down from the surface. Petrographic and X-ray examination (p. 157) of the insoluble residue of the red impure limestone supports the impression that it is essentially a residual soil, although it is noteworthy that it differs from the present soils on the plateau surface by lacking high alumina clay and therefore signs of extensive lateritization. Perhaps by having been cemented at a relatively early age these soils were spared the long course of alteration that has resulted in the lateritic composition of the surface material.

Somewhat similar occurrences of cemented red residuum are found widely in the dense limestones of Tertiary age of the West Indies. Woodring and Brown (Woodring and others 1924, p. 109) describe, under the term "solution breccia," recemented red limestone residuum from Haiti. More recently Shrock (1946) discussed these breccias and their probable origin. Although the term "breccia" may properly be applied to occurrences in which angular fragments of wallrock limestone are enclosed in the red limestone, it seems inappropriate for the Isla Mona occurrence, where the brecciated texture is relatively unimportant. The feature is therefore called simply cemented red residuum in this report, although the term leaves much to be desired.

Age.—The cemented red residuum has yielded the following species of land snails, identified by Dr. W. J. Clench: *Lucidella umbonata* (Shuttleworth), *Chondropoma turnerae* Clench, *Bulimulus diaphanus* (Pfeiffer), *Cerion monaense* Clench, *Suavitas* (*Euclastaria*) cf. *krugiana* (von Martens), *Lacteoluna selenina* (Gould). Of these six species the last two have not been found living on Isla Mona (Clench 1950, 1951) but are known from Puerto Rico. Three (*Chondropoma turnerae*, *Bulimulus diaphanus*, and *Cerion monaense*) of the six species have larger mean shell sizes than the living fauna. The significance of this difference in shell size is not known, although one can conjecture that it is an environmental response. Dr. H. A. Rehder and Dr. R. T. Abbott, U. S. National Museum, who examined the shells, suggested that the fossil fauna indicate that "the present xerophytic conditions are of more-or-less recent origin" (written communication). Not much can be told as to the age of the fossil land snails except that the fauna is sufficiently different from the existing fauna to indicate Pleistocene age.

GEOMORPHOLOGY

PLATEAU SURFACE

Viewed from the ground, with the restricted view permitted by the brush, the plateau surface seems to be a monotonous flat expanse (pl. 14*B*) everywhere etched into a microrelief, with a general relief of about 1 foot, of sharp serrations, pits, and enlarged joints. Here and there one encounters a sinkhole, and the few large sinkholes that occur—such as the Bajura de los Cerezos, Cuevas del Centro, and El Corral—offer some variety to the scene by the comparatively rank vegetation that springs from the thick soil in the bottoms of these depressions.

The plateau surface has a variety of features that deserve special attention, some of which are best appreciated when viewed from the air. According to the topographic map[3] prepared photogrammetrically by the U. S. Army Map Service, the plateau surface is in reality somewhat dome shaped, the high point being a little less than 1 mile south of Cabo Noroeste (pl. 12). From this point, which is approximately 90 meters above sea level, the surface slopes off in all directions to the plateau rim. This slope is most pronounced to the west and south, and the plateau edge at Punta Caigo o no Caigo is approximately 20 meters above sea level. Cutting across the eastern part of the dome is a gentle swale that has a general northwest bearing and contains the sinkholes of El Corral and Cuevas del Centro. An alinement of rather shallow sinkholes, bearing west-northwest, occurs in the central part of the island. There is a somewhat concentric festoon of low outward-facing scarps in the northern and eastern part of the island, and from the air one perceives, here and there, well-defined sets of parallel to subparallel striae.

[3] Although this map has not been checked in the field by the Army Map Service and has been found by the author to be in significant error in several places in the delineation of the coast and in some of the topographic details, its general hypsometry is the best available.

TERRACES, SCARPS, RIMS, AND RAMPARTS

A pronounced low scarp, which ranges generally between 10 and 30 feet in height, occurs on the surface of the plateau (pl. 12) and extends more or less continuously in a crescent-shaped arc roughly concentric with the outline of the island. It is absent on the west side of the plateau. The scarp faces outward and both scarp and terrace are warped and conform to the general domed shape of the plateau surface. In the area of Cabo Noroeste a second low scarp closely parallels the first but is shorter and apparently disappears in an area of sinkholes and topographic irregularities. A third low scarp extends northwestward for about 1½ miles in the eastern part of the island. There are several sinkholes and a cavern opening at its base.

Close to the north edge of the plateau several elongate, low limestone walls, or ramparts, occur roughly parallel to the present coast; and at Cabo Norte a low limestone rim, estimated to be about 6 feet high, forms the edge of the plateau. Both rim and limestone rampart are best developed at Cabo Norte. These features were not seen in the field and data concerning them are interpreted from aerial photographs. The rampart appears to rise between 10 and 15 feet and roughly parallels the edge of the plateau for a distance of about 3 miles. It is situated between 300 and 1,000 feet from the plateau edge.

Terraces, rims, and ramparts are common features of limestone islands in both the Atlantic and the Pacific. Hoffmeister and Ladd (1945) have described this group of topographic forms on several islands of the southwest Pacific. Following the explanation used by Smith and Albritton (1941) for certain solution basins in limestone, they suggest that the rim and ramparts are the result of differential solutional attack by rain water on gently tilted limestone surfaces. The rim is supposed to develop on the uptilted edge. Hoffmeister's and Ladd's explanation for limestone rims and ramparts is given some support on Isla Mona by the distribution of these features, for it is true that they are found on the north, or high, side of the plateau.

More recently, Flint and others (1953) and McNeil (1954) have questioned this interpretation and from their work on Okinawa have advanced the explanation that limestone rims and ramparts are the result of differential erosion on porous limestone whose exposed surfaces have been densified (casehardened). The casehardening of porous, poorly indurated limestone takes place, according to these authors, on vertical or steeply dipping surfaces in climates particularly characterized by alternate wetting and drying. Indurated faces of terrace and cliff are then raised into relief by subsequent reduction of the plateau surface.

However, the porous, poorly indurated limestone with densified crust that Flint and others described from the Pacific Islands has not been observed on Isla Mona. With the possible exception of blocks of porous, friable fossiliferous limestone found on the floor of Cueva Negra at Punta Oeste, all rock seen by the writer—whether in cavern, cliff, or plateau—was very dense. Moreover, the large detached blocks of limestone at the foot of the sea cliffs would seem to indicate that coherent, dense limestone is not simply a thin surface veneer. It may be, however, that these blocks represent the effect of casehardening of joint surfaces, and that in actuality each block consists of a poorly indurated interior surrounded by a casehardened crust. Deep blasting, or even a drill hole in the tableland of Isla Mona, would prove particularly informative in this matter.

REDUCTION OF LIMESTONE SURFACES WITHOUT DISSECTION

Isla Mona—with its relatively undissected plateau surface, marred only here and there by low scarps and sinkholes—is in the youthful stage of the limestone erosion cycle, in the context of the term established by Cvijić (1925) and Davis (1930). The presence of residual soil on the plateau brings up the question, however, of whether or not this soil represents the solution of an appreciable thickness of limestone, for if it does, interesting light is thrown on the nature of geomorphic development in limestones.

The best estimate, based on many assumptions, that the writer is able to make of the amount of the detrital mineral component of the loose and cemented soils on and under the plateau is that it represents a soil blanket about 1 inch thick over the entire surface of the plateau. This estimate was made by assuming a typical cross section of the plateau showing the distribution of loose surface soil and the cemented red residuum. Because the variable and uncertain nature of the distribution of the soil in and under the plateau makes meaningful measurements almost impossible, this cross section represents only the writer's judgment of a normal distribution. The loose soil was then assumed to contain 50 percent organic material and the cemented older soil 60 percent secondary calcite and organic material. To correct for the difference between the specific gravity of the mineralogic components of the soil (assumed to be 2.8) and the bulk density of the loose soil (assumed to be 85 pounds per cubic foot), a factor of 0.48 was used.

The insoluble content of 7 samples of Isla Mona and Lirio limestones (table 5) averaged 0.13 percent. The single sample of Lirio limestone tested contained only 0.02 percent insoluble residue. Assuming, then, that the limestone that yielded the residual soil contained an average of 0.1 percent insoluble material (this figure may be too high if much of the rock was the Lirio limestone), the total thickness of dissolved rock represented by the 1-inch blanket of soil is of the order of 85 feet. This figure is a minimum, for the process of lateritization has probably reduced the mass of the residual blanket.

The process of topographic reduction of limestone surfaces without dissection is indicated by other limestone islands that possess rims and ramparts. The undissected terraces whence these features rise have been interpreted as reduced to their present levels below the rim (or rampart) crest by weathering. Hoffmeister and Ladd (1945) tell of a rampart that rises 100 feet above a terrace on the island of Tuvuthá in Eastern Fiji. The implication here is that at least 100 feet of limestone has been dissolved off the top of this terrace without appreciable dissection.

These interpretations point to the importance—at least in the earlier stages of the geomorphic cycle in limestone terrains—of surface reduction without dissection. Vermeij (1937, p. 59) came to the same conclusion from his study of some of the limestone regions of southern France. From the geomorphic point of view, therefore, a level limestone surface need not represent an old-age base level.

CAVERNS

It has been reported by Lobeck (1922, p. 372), and also by others acquainted with the place, that Isla Mona is literally honeycombed with caverns. The reconnaissance study of the caverns made by the writer indicates, however, that the distribution of caverns differs somewhat in different parts of the island. Shallow, thin-roofed caverns underlie parts of the plateau and can be entered through some of the sinkholes or via mouths high up on the sea cliffs. These caverns are possibly confined to the Lirio limestone.

Caverns in the Isla Mona limestone are best developed in the south coastal area where their enlarged mouths pierce the cliffs in scores of places. These caverns are mostly single-storied and seem to be level. At their mouths, the floors of many of these caverns are 20 to 25 feet above sea level. None of the caverns were surveyed and it is not known therefore how far under the tableland the cave system penetrates. It is reported by several persons that some caverns interconnect and extend far under the island, permitting underground passage between widely separated coastal areas. The writer has the impression from the several caverns he explored that he was able to penetrate a distance of about a quarter of a mile under the tableland, although in all cases at this distance the caverns were much reduced in size and complexity and showed evidence of pinching out.

The caverns consist typically of ramifying and somewhat winding corridors with chambers tending to develop at corridor intersections. The corridor ramifications seem more complex near the mouths.

The caverns on the south side of the island, and particularly those letting out on the windward southeast coast in the vicinity of Playa Pájaro, have very much enlarged mouths (pl. 14*A*). These enlargements are not very deep and form a sort of antechamber or foyer at the entrance of the cavern proper. They were attributed by Hübener (1898) to marine erosion at a former sea level. Although there is a possibility that a higher sea level might have controlled the levelness of the cavern, the enlarged mouths are probably the result of solution by rainfall on normal cavern openings. A contributing factor may be the solution work of organic agents, like the black, green, and yellow slimes (algae) that are so colorfully conspicuous at the mouths of the caverns.

The cavern entrances showing the greatest enlargement are those facing to the windward (east). A good though small-scale example of direct solution by rainwater, that is probably comparable to the enlargement of cavern mouths, occurs in Cueva del Lirio at Punta Este, in the Lirio limestone. Here one of the cavern corridors is separated from the steep sea cliff by a thin limestone septum into which windows, commanding a striking view of the sea, have been corroded. At one place stalagmites, rising from the cave floor about 10 feet behind the window, have been neatly bisected longitudinally. The sides of the stalagmites facing the windows have been dissolved, exposing the internal accretionary structure of the dripstone. It seems clear that the solution was brought about by rain driven at low angles through the windows. The relatively high wind velocity required for this indicates that most of the solution is the result of precipitation during squalls and storms.

The pitted floors of the caverns are covered with a deposit of brown earthy phosphorite (guano). Overlying the earthy phosphorite is nonphosphatic dripstone, which forms a general crust 1 or 2 inches thick. The earthy phosphorite therefore seems to take the place, spatially at least, of the red clay cave filling that is so common in limestone caverns and that Bretz (1942) described as suggesting a phreatic origin of caves.

Large dripstone and flowstone deposits are found only locally. They are moderately spectacular where major joints intersect the caverns, but for the most part they are absent entirely or are relatively thin and inconspicuous. Besides normal calcium carbonate dripstone, thin crusts and efflorescences of colorless gypsum are found on the roofs of many caverns.

Except after heavy rains, the caverns are dry. No permanent pools of water were seen; and although some slow dripping was noticed, most dripstone was only slightly moist or dry.

The active deposition of dripstone is clearly displayed, however, by the presence of newly formed stalagmite butts on the well-worn paths used by the guano miners, probably as recently as the early part of this century. Quite a few of these embryonic stalagmites, spreading 8 to 10 inches across at their base and rising to a peak about 1 inch high, were seen in a cave just southwest of Playa Pájaro and also in Cueva Negra.

Isla Mona caves are examples of what Davis (1930) called two-cycle caverns—that is, limestone caverns that contain dripstone, thereby indicating an early period of corrosion followed by a period of cavern filling (dripstone formation).[4] In addition to this, the intermediate period of red-clay filling, described from a number of caverns by J H. Bretz (1942)[5] is represented on Isla Mona by the phosphorite, although the origins of these two types of deposits are undoubtedly different.

Hübener (1898) thought the Isla Mona caverns were sea caves, dissolved by marine waters at some relatively higher sea level. The fact that the floors of many of the caverns of the Isla Mona limestone on the south coast are about at the same level might point to a causal connection between sea level and cavern formation. It is, however, extremely unlikely that marine

[4] The term two-cycle cavern was used by Davis in two senses. First he applied it simply to caverns containing dripstone and therefore indicating a radical change in environment (1930, p. 477). Later in the same work (p. 561 etc.) he implied by the term that an uplift, inaugurating a second erosion cycle, separates the solutional from the depositional period.

[5] Bretz (1942, p. 773–777) suggests that red-clay fills are deposited in chambers filled with stagnant water. The clay is thought to be surface derived.

waters are capable of the extended solution required in an explanation of the deep Isla Mona caverns. It seems more reasonable to suppose that the caverns were dissolved by meteoric waters, although some type of control might have been provided by a higher sea level.

The levelness of many south-coast caverns may be due to the cavernous nature of a particularly soluble bed, as was suggested by Lobeck (1922, p. 373). Here again there is some question, because in at least one place on the south coast (behind Desembarcadero Uvero), a slight structural undulation in the prevailingly horizontal attitude brings different strata to cave level. Some control therefore other than the solubility of a particular bed or beds may have regulated cavern formation. This may have been a higher sea level that formed a base level for underground stream erosion (Davis, 1930), or it may have been a higher water table under the island ("water-table streams" of Davis, 1930; "phreatic streams" of Swinnerton, 1932), possibly also controlled by a higher sea level. Detailed field work is needed, however, to trace the continuity of the strata of the thick-bedded Isla Mona limestone and to determine the levels of the many caverns before the question can be decided conclusively.

The high-level Lirio limestone caverns were probably formed by what Davis (1930) called vadose streams—that is, by concentrations of ground water above the main zone of saturation flowing laterally in solution channels after rainstorms (a type of temporary perched water body). Localization of vadose drainage along the unconformity separating the Isla Mona limestone and the Lirio limestone was probably due to differences in the relative permeability of the two formations. The absence today of a perched water table at that level emphasizes the humidity of the climate that must have existed when these caverns were formed.

SEA CLIFFS

The origin of the vertical sea cliffs forming the north coast of Isla Mona poses a particularly difficult geomorphologic problem. These cliffs differ from the talus-encumbered cliffs of the south coast by dropping off into deep reefless water (pl. 13*A*). The depth of water at the foot of the cliffs is not known, but soundings on U. S. Coast and Geodetic Survey Chart 901 (fig. 64) indicate that off the east and northeast coasts a 22-fathom level exists at least as close as 300 yards from shore, whereas off the coast between Cabo Noroeste and Cabo Barrionuevo the bottom close to shore is about 16 fathoms deep. Lead-line soundings taken by the writer north of Punta Este, about 40 yards offshore (the choppy seas made a closer approach to the cliffs hazardous), showed depths ranging from 20 to 22 fathoms. Deep water at the cliff edge is also indicated by the fact that the bottom cannot be seen from the top of the sea cliff even in clear weather and relatively calm sea; whereas, off the south coast the bottom at 9 fathoms can readily be seen from the air.

Because the open, reefless coastline is on the windward side of the island, the impression is conveyed that the difference between north and south coasts is primarily that of exposure to or protection from the trade winds and to waves generated by them. Indeed there is ample evidence of the active erosion of the north-coast sea cliffs. In many places large prisms of limestone rise out of the sea at the foot of the cliff (pl. 13*A*); their fresh angularity gives the impression that they have broken off the cliff in relatively recent time. On the surface of the plateau, close to the cliff edge, there are gaping tension fractures parallel to the cliff that show incipient movement preparatory to the final rupture of the cliff edge; and in one place, northeast of the lighthouse, a prism forming part of the cliff face is already entirely isolated from the plateau surface by fractures several feet in width. Moreover, there is a well-developed sea-level nip at the base of the cliff, which in places is estimated to be 15 feet deep. It has an uneven upper surface (pl. 13*A*), apparently caused by the caving of blocks of rock from the ceiling of the nip. The development of this nip certainly represents effective undermining of the cliff.

In spite of all these signs of cliff recession there is no erosional platform at or close to the present sea level. Assuming active cliff recession, the implication is that the base of erosion is well below sea level.

Cotton (1949) discusses some aspects of this type of coastline under the term "plunging cliffs", but he assumes that it is relict of negative glacioeustatic sea levels. Unless one were to concede that the 22-fathom eustatic level was the most recent negative sea level (chap. B) and that not enough time has elapsed since then for any cliff recession to have occurred, the explanation of the origin of the Isla Mona sea cliffs appears unattractive in light of the evidence of active cliff recession.

The absence of a sea-level erosion platform becomes additionally puzzling when the active undercutting so clearly expressed by the nip is considered. Cliff recession due to undercutting by the nip should result in a well-defined sea-level platform. Apparently, however, if there has been any cliff recession due to this process it has been entirely effaced by cliff recession to a greater depth.

In considering, then, the origin of the Isla Mona sea cliffs, the following hypotheses are suggested: (1) The

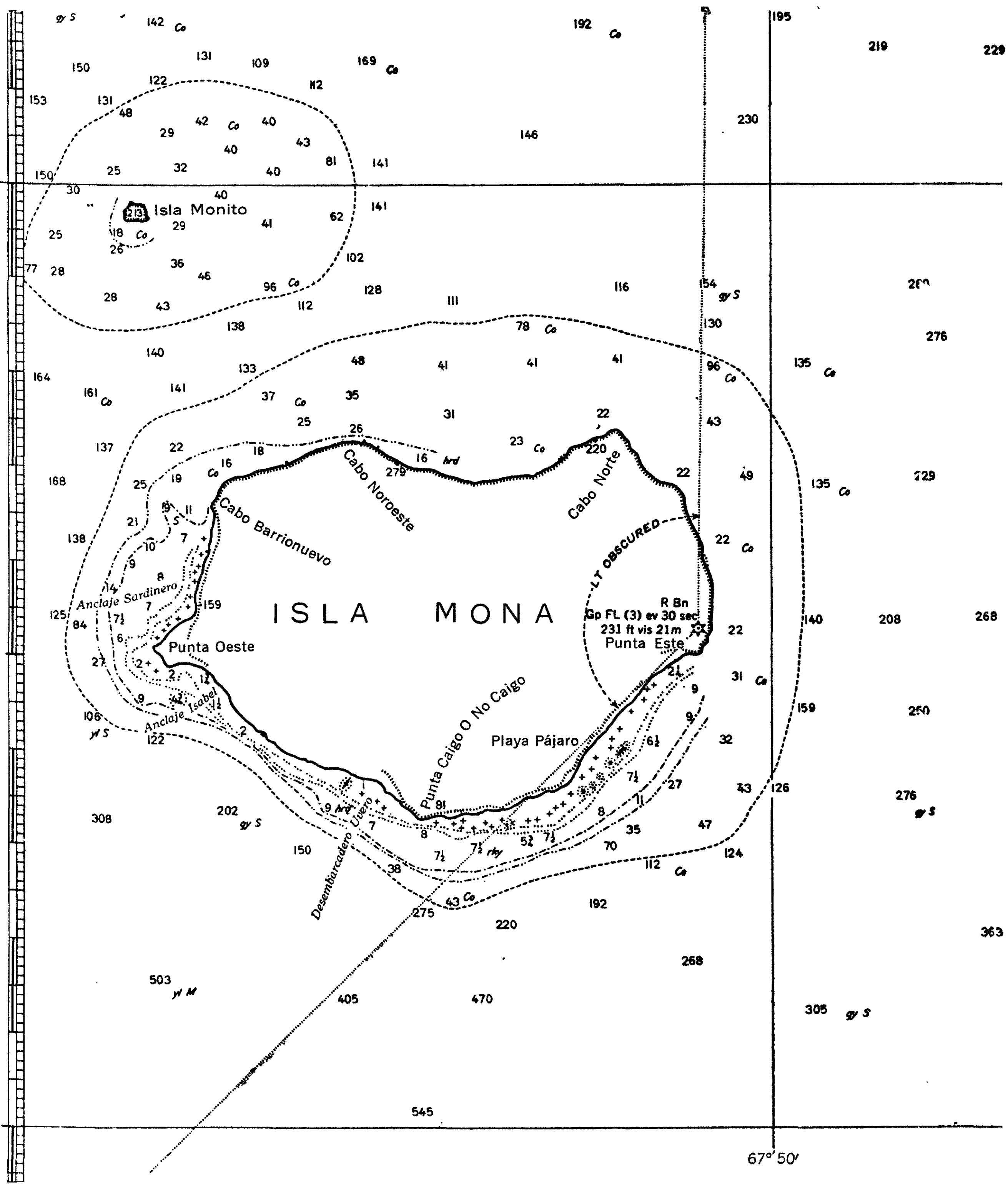


FIGURE 64.—Chart of Isla Mona and Isla Monito. Depth of fathoms. Quality of bottom: Co, coral; M, mud; S, sand; gy, gray; hrd, hard; rky, rocky; yl, yellow. From U. S. Coast and Geodetic Survey Chart 901.

base of wave erosion of the sea cliffs is well below sea level; (2) the energy of wave impact is great enough to induce rock fall by shearing off and dislodging prisms of the well-jointed limestone to an appreciable depth below sea level; (3) the present cliffs constitute an essentially unaltered fault scarp; and (4) the island has very recently subsided about 132 feet (22 fathoms) and there has been no significant erosion since then. Each of these hypotheses will be discussed in turn.

1. Although it is true that the Isla Mona sea cliffs

receive the full force of the sea and, moreover, that strong wave action has been noted at depths considerably greater than 22 fathoms (Kuenen, 1950, p. 228),[6] it is nevertheless doubtful that wave abrasion could be an important erosive process of these cliffs if the rock below sea level is as dense as the limestone exposed above sea level. The ineffectiveness of wave abrasion on dense pure limestone is shown by the solutional sea-level nip, which possesses a median tidal terrace, or *Lithothamnium* shelf (chap. B; Kaye, 1957). If the nip were carved by wave abrasion, the *Lithothamnium* shelf would probably also have been destroyed.

As already discussed (p. 151) there is the possibility that the dense Isla Mona limestone is only a deceptive casehardened shell that has formed on exposed surfaces of an essentially poorly indurated rock. If Flint and others (1953) are correct in attributing the casehardening of poorly indurated limestone to repeated wetting and drying, it follows that submerged rock does not caseharden. Assuming—for want of certainty as to the true nature of the Isla Mona limestone—that beneath sea level the sea cliffs lose their familiar lithologic characteristic and become friable, we might expect considerable erosion by the turbulence of the choppy seas and the removal of much soft rock from beneath the cliffs. This undercutting, or sapping, of the cliff by the removal of soft foundation rock would produce collapse of the casehardened cliff face, which would then fail en bloc. Moreover, the erosion of the friable rock might reach a considerable depth below sea level, owing to the turbulent eddies set up by the continuous and vigorous wave action confined within the undercut.

2. Wave impact, alone, might possibly develop sufficient energy to dislodge large prisms of the well-jointed limestone to a considerable depth below sea level. The details of this process remain vague, however, for it is difficult to explain how the large masses of rock are finally displaced and toppled over by wave impact alone, and it is uncertain that such a process would be capable of producing a bottom of fairly uniform depth.

3. No faults have been observed in the cliffs or, for that matter, elsewhere on the island, and therefore there is little reason to think that faulting has recently affected the island. Moreover, nautical charts (fig. 64) do not indicate the extension of such a scarp across the bank surrounding the island.

4. There likewise seems little reason to think that the island has very recently subsided by about 132 feet (22 fathoms). The levels of both the submarine terraces and the elevated coral platform on Isla Mona are closely duplicated in other islands of the Caribbean as well as in more distant places (chap. B). G. F. Jordan (1952), moreover, has called attention to the importance of the 22-fathom level off the west coast of Florida. It is widely thought that these represent former sea levels and date, for the most part, from the Pleistocene. The inference seems to be that comparatively little crustal movement has occurred at Isla Mona in the course of late Quaternary time.

Although these four hypotheses for the origin of the plunging cliffs of Isla Mona have to remain conjectural until one can be confirmed, the first—or the undermining and removal of friable rock by wave erosion—is the easiest to reconcile with the known facts.

[6] The problem of the effective depth of surface-wave abrasion has recently been reviewed by Dietz and Menard (1951), who show that the depth of vigorous abrasion is probably limited to 5 fathoms for exceptionally large breakers.

SHOAL-WATER FEATURES

SUBMARINE TERRACING

The soundings on U. S. Coast and Geodetic Survey Chart 901 (fig. 64) indicate that the submarine platform surrounding Isla Mona is characterized in places by terraces or levels. A level at about 22 fathoms seems to lie close to the east and northeast coasts of the island. Soundings off the south coast suggest a terrace, just outside the reef, that has a mean depth of about 7 fathoms. The occurrence of several 41-fathom soundings near the northern edge of the Isla Mona marine platform suggests that a terrace level may also exist at this depth.

The terracing off the south coast can be identified on aerial photographs and on clear days can be seen from the air. The shoalest level is that of the lagoon within the barrier reef, which, for the most part, is about 2 fathoms deep. On the seaward side of the reef, off Playa Pájaro, there is a steep scarp that flattens somewhat at about 5 fathoms and then drops off again abruptly to a broad sandy-floored terrace, which is represented by soundings of about 7 fathoms on the chart.

REEFS

A narrow barrier reef lies between 100 and 200 yards offshore along most of the southeast coast of the island. This reef touches shore at Punta Caigo o no Caigo and southeast of Punta Este, where it continues for about half a mile as a fringing reef. Another reef connects Punta Oeste and Cabo Barrionuevo. This reef is a narrow barrier reef for much of its length and for the most part lies about 100 yards offshore. Behind both reefs are lagoons, about 2 fathoms deep, floored in places with white calcareous sand and in others with reef rock. The crest of the reef lies at about mean tide level.

PARALLEL GROOVES

Off Playa Pájaro the submarine slopes outside the reef are incised with parallel grooves that trend approximately normal to the reef and to the slope (pl. 12). Similar grooves score the terrace scarp outside the barrier reef north of Punta Oeste, although the latter grooves trend north northwest and are therefore oblique to the reef and to the coast. As measured on the aerial photographs, the grooves are spaced at intervals of less than 5 yards to as much as 40 yards apart.

Identical submarine grooves associated with coral reefs have recently been discussed by Munk and Sargent (1948); Ladd and others (1950, p. 412); Newell and others (1951, p. 24); and Cloud (1954). Munk and Sargent have shown that the distribution of grooves on Bikini Atoll is adjusted to areas of heavy surf and the grooves play an important role in dissipating wave energies. Ladd and others suggest that the grooves are largely if not entirely formed by the growth of the intervening buttresses, which are built up by crustose coralline algae. Newell and others, however, describe grooves from Andros Island, Bahamas, which are incised in the oolite bedrock and which in places support only a sparse growth of encrusting organisms. The last authors conclude, therefore, that the Andros Island grooves are erosional and are formed by strong undercurrents generated during storms by the high surf. Cloud (1954) supports this theory from his study of Pacific atolls. The composition of the walls of the Isla Mona grooves was not ascertained, so it is not possible to attribute their origin to either erosion or deposition. The morphologic similarity of these features the world over would suggest a common origin, however, whether erosional or constructional.

PHOSPHORITE DEPOSITS

HISTORY OF MINING

According to F. H. Wadsworth (written communication), there is documentary evidence that the value of the cave phosphorite deposits on Isla Mona was recognized as early as 1790. It was not until 1858, however, that a reconnaissance of the deposits was made by the Puerto Rican government with a view to their exploitation. In 1874 the Puerto Rican government granted a private franchise to extract guano from Isla Mona. In 1890 the mining concession was subleased to a German national; and from that date to 1896, when the competitive opening of phosphate deposits in Peru, Curaçao, and Florida brought mining to an abrupt halt, the deposits underwent their most intensive period of exploitation. After the transfer of Isla Mona's sovereignty from Spain to the United States, a new franchise was granted by the local authorities in 1903 and reassigned in 1905 to the Mona Island Phosphate Company. The mining franchise remained in force until 1921, although during this period mining was carried on irregularly and shipments were few. There has been no mining of the phosphate deposits since 1921.

The total shipments of phosphorite from Isla Mona is estimated not to have exceeded 50,000 tons.

There is little reliable information concerning mining methods, although much can be inferred about this from the nature of the deposits and the equipment, and signs of working which still are in evidence in the caves. The deposits were probably worked by painstaking hand labor. The pockets of phosphorite on the floor of the caves had to be felt out through the dripstone crust, presumably by prodding with picks. The dripstone crust was then stripped and the underlying pockets of ore excavated by hand. Much digging was done in close quarters, where men must have felt their way along bent nearly double beneath the low roof. From the litter of narrow-necked bottles in many caves it is evident that mining lamps consisted of bottles of kerosene provided with thick wicks.

A single-track rail line was laid along the main trunk chambers of the cave. Ore was probably hauled from the many small diggings to the rail line by hand, either in sacks or by drags. The ore was then hauled by rail to the mouth of the caves, where there are signs that it was temporarily stockpiled. There are ruins of what resembles a small drying plant at Playa Pájaro, and it seems evident that some of the ore was thus treated.

The gathering of the ore from the many caves probably presented a particularly difficult problem and apparently was done by various means, depending on the location and setting of the cave. In some places wagons were used, in others rail; and in some caves, such as Cueva del Gato at Cabo Barrionuevo, ore was loaded directly onto ships precariously tied up against the unprotected sea cliffs. The rusted remains of several rail lines associated with the mining are to be seen today about the island.

There were signs of exploration and some mining in all the caves visited by the writer, and it is probable that most of the caves on the island have been explored to some degree. It is estimated, however, that only a small percentage of the cave phosphorite has actually been mined.

DESCRIPTION OF DEPOSITS

The phosphorite deposits occur in the caverns of both the Isla Mona and Lirio limestones and consist mostly of friable to loose, granular material that has a silty to sandy texture, and is brown to reddish brown when moist and very light tan when dry. In some places oolitic to pisolitic grains are conspicuous. A crude stratification of the deposit was seen in a few places.

Not uncommonly there are thin crusts and interspersed layers of opaline dark-brown phosphorite and friable layers of slightly cemented granular ore. Somewhat intermixed with the typical brownish ore, but occurring mostly at the base of the deposits, are concentrations of white fine-grained calcium phosphate minerals, and in places a quantity of fine-grained calcite and gypsum is mixed with the phosphate minerals. Bones or other identifiable organic remains were found in the phosphorite at only one place.

The phosphorite deposits apparently cover the floors of all the limestone caverns on the island, and in several places they were noted in narrow crevasses in the walls and in the ceiling of Cueva del Lirio adhering to the sides of a small cupola. As a floor cover the deposits are generally thin, a matter of 3 or 4 inches, except where the material fills enlarged joints, pits, and crevices in the floor. It is these pockets of ore that formed the basis of most of the mining. It was observed that pits rarely attained the depth of 6 feet and generally were only big enough to accomodate one digger at a time.

Where undisturbed by mining activity the phosphorite deposit is generally covered by a deposit of nonphosphatic dripstone, which forms a protective crust about 1 to 2 inches thick but thickens locally under stalagmites. The contact between the phosphorite and the dripstone is generally sharp. Comparatively little dripstone is interbedded with the phosphorites and this is generally altered to phosphorite (see description of "pyroclasite" by Shepard, 1882).

Besides cave phosphorites, there is a 6-inch layer of hard phosphatic rock at the unconformity between the Isla Mona and Lirio limestones at Punta Este. The rock phosphate is dense, light yellow tan, and somewhat oolitic. A few small bone fragments, possibly of birds, were embedded in the phosphorite. It is not known how extensive this deposit is, because the unconformity is generally inaccessible in the sea cliff and the phosphatic layer is difficult to detect from a distance.

PETROGRAPHY OF THE PHOSPHORITES

By Zalman S. Altschuler, U. S. Geological Survey

This section describes chemical and petrographic investigations of cave phosphorites and related calcareous and argillaceous rocks from Isla Mona, Puerto Rico. It is based on samples collected by Mr. C. A. Kaye of the Geological Survey. The work discussed here had two aims—(a) the determinative mineralogy of the rocks, and (b) a study of the compositional and petrographic characteristics reflecting the origin of the phosphorites.

Description of samples.—The samples studied are described below and located by number on plate 12.

Sample	Description
M–1	Limestone, ferruginous, clayey; orange-brown, earthy. This is a composite sample of the cemented red residuum collected in three different localities. Sample M–1 A consists of red clayey limestone with angular, 1-inch insets of white unweathered limestone. Sample M–1 B is red clayey limestone with angular cavities and many small calcite vugs. Sample M–1 C is a red clayey limestone without white limestone inclusions or obvious cavities. All three samples are virtually identical mineralogically and contain the following suite of major minerals (>5 percent), identified by X-ray and optical methods and listed in order of importance: calcite, kaolinite, montmorillonite, and limonite. Goethite is present in addition to limonite in sample M–1 A. No phosphate minerals are present. The proportion of limonitic clay is about the same as that of calcite and the samples could be classified as calcareous ferruginous clays as readily as limestones.
M–2	Dolomite, white, pure; contains many fossil molds, casts, and fillings. This sample is from the Isla Mona limestone at the base of Punta Este and probably represents an atypical zone of dolomitization. The secondary nature of the dolomite is evident from the abundance of dolomitized fossils. The dolomite is similar in appearance to all outcrops of Isla Mona limestone that were inspected by Kaye. However, tests by Kaye for MgO on two other samples of limestone from the island gave 0.16 and 1.9 percent (table 1). This sample was selected, because of its apparent purity and the absence of red vein alteration, in the belief that it was a typical limestone.
M–3	Phosphorite, white, earthy, almost pure hydroxylapatite. Traces (<1.0 percent) of calcite, quartz, and clay are present. The rock specimen is porous and moderately indurated, and has secondary crusts of brown hydroxylapatite, more coarsely crystallized than the isotropic matrix. The sample comes from the floor deposit in Cueva Negra.
M–4	Phosphorite, brown, aphanitic, hard. The rock contains major hydroxylapatite. Crandallite, $CaAl_3(PO_4)_2(OH)_5.H_2O$, and montmorillonite are also important constituents, and brushite, $CaHPO_4 \cdot 2H_2O$, is present in minor (<5 percent) amounts. The crandallite occurs as rims and patches of alteration related to cavities in the rock. The phosphorite occurs as a crudely stratified material consisting of irregular quarter- to half-inch porous seams of lightly cemented globular aggregates alternating with dense massive layers. Associated with this material is a tan loose earthy mixture of montmorillonite clay, fine-grained calcite and gypsum, globular white aggregates of needlelike brushite, and brown nodular hydroxylapatite. The sample comes from the floor deposit of Cueva de los Pájaros and is described as typical phosphorite.

Sample	*Description*
M–5	Phosphorite, brown, loose, and earthy. The sample consists mainly of coarse sand and granule-sized nodules of hydroxylapatite. Minor amounts of calcite and trace amounts of an unisolated, unidentified mineral are present. In X-ray patterns of the rock the few reflections of this unidentified mineral matched the strongest lines of martinite, the hydrous and carbonate-bearing variety of whitlockite, β-$Ca_3(PO_4)_2$. The sample comes from the floor deposit in the north branch of Cueva Negra.
M–6	Phosphorite, orange-brown, highly porous; consists essentially of nodular encrustations of hydroxylapatite rich in dispersed limonite and clay but containing no crystalline iron oxides. Irregular microscopic inclusions of calcite occur in hydroxylapatite nodules. Martinite is a minor constituent, occurring as isolated globular aggregates of fibrous crystals and platy crystals of rhombohedral outline, and also as cavity fillings with the same crystal habit. The rock is cemented by minor amounts of secondary calcite, which encrusts cavities and nodules. Thin milky-white films of recent and poorly crystallized hydroxylapatite coat all materials in the rock. Sample M–6 comes from the floor deposit of Cueva Negra.
M–7A	Phosphorite, brown, hard, with waxy luster; consists of about 30 percent of nodules in a massive groundmass. The rock is almost entirely hydroxylapatite, which composes the nodules and the matrix and is present also as accretions on the surfaces. The rock is vesicular and appears leached. It occurs on the surface (not in a cavern) together with phosphatic limestone (M–7B) in a 6-inch layer underlying the Lirio limestone at Punta Este.
M–7B	Limestone, phosphatic, white to cream-colored, nodular, fossiliferous, slightly leached, vesicular. The sand-sized nodules dispersed through the calcite matrix are composed of calcite partly replaced by hydroxylapatite. These nodules are somewhat more concentrated on the irregular leached surfaces of the rock. A late coarsely crystalline calcite druse lines cavities and coats all exposed surfaces. Figure 65 is a sketch of the rock portraying the above relations. This sample like M–7A, comes from the 6-inch layer at the base of the Lirio limestone at Punta Este. Owing to the "caliche sealing of bedding planes it is not clear whether this layer is an integral part of the Lirio limestone, or separate from it" (Kaye, written communication). The field relations between 7A and 7B are equally unclear. However, in view of the textural similarity of the two, and the fact that both were collected from the same 6-inch layer, it seems evident that 7A is equivalent to 7B but in a more advanced state of replacement of apatite.

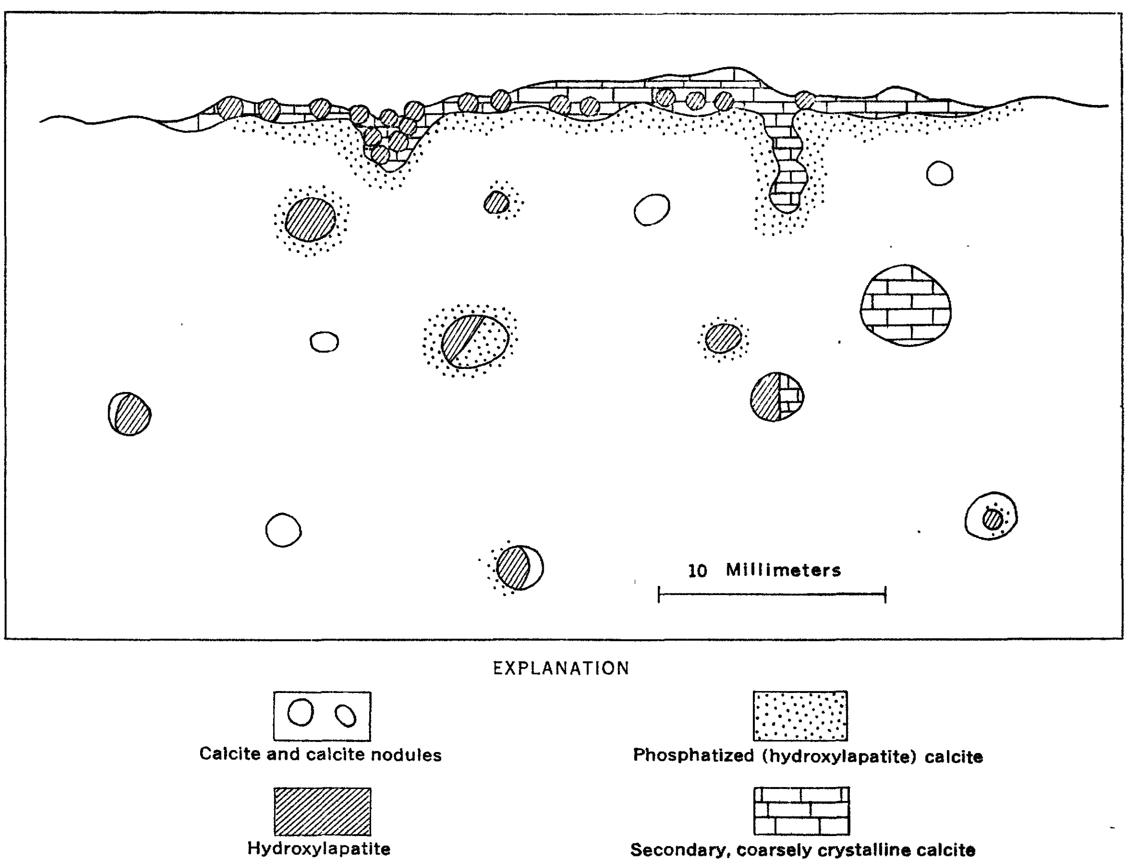


FIGURE 65.—Diagrammatic sketch of phosphatic limestone, Punta Este, Isla Mona.

Sample	*Description*
M–8	Phosphorite, tan, loose; consists almost entirely of hydroxylapatite nodules ranging in size from fine sand to small pebble. The nodules, as in all the other samples, are massive and contain no evident internal textures or structures. They are aggregates of oriented submicroscopic fibers, however, as can be inferred from the sweeping pattern of the isogyres upon rotation of the microscope stage between crossed nicols. The sample was taken in Cueva del Lirio. Besides minute amounts of limonite, clay, and quartz silt, no other minerals were identified.

ANALYTICAL DATA

All of the samples were analyzed for P_2O_5, uranium, and total nitrogen, and the two samples highest in P_2O_5 content were analyzed for fluorine. The results are tabulated below.

TABLE 2.—*Percent U, P_2O_5, N, and F in phosphorites and associated rocks from Isla Mona, P. R.*

[Partial quantitative chemical analyses. Analysts: For U and P_2O_5, A. Caemmerer; for N, W. Tucker; for F, A. Sherwood]

Sample	U	P_2O_5	N	F
1A	0.001	0.52	0.03	(a)
B	.001	.15	.03	(a)
C	.001	.17	.01	(a)
2	.001	.37	.03	(a)
3	.002	41.4	.03	0.13
4	.002	32.4	.08	(a)
5	.002	39.8	.07	.54
6	.001	26.3	.06	(a)
7A	.002	37.1	.06	(a)
B	.001	15.8	.02	(a)
8	.003	38.0	.06	(a)

a Not determined.

Because it had been established by petrographic and X-ray study that, with the exception of the cemented red residuum, these rocks were composed dominantly of one or two minerals, it was considered unnecessary to obtain complete chemical analyses. Instead, semiquantitative spectrographic analyses were made of all samples to obtain more complete data on composition. The data are given in table 3 and the elements determined and their limits of detection in this analysis are given in table 4. The method of analysis is described in Waring and Annell (1953).

TABLE 4.—*Threshold values, in percent, of sensitivity to elements analyzed by semiquantitative spectrographic method*

[Utilized in analyses of tables 1 and 3]

Element	Sensitivity	Element	Sensitivity	Element	Sensitivity
Ag	0.001	Ga	0.01	Rb	10.0
Al	.0001	Gd	.01	Re	.1
As	.1	Ge	.001	Sb	.001
B	.001	Hf	.1	Sc	.1
Ba	.001	Hg	.1	Si	.0001
Be	.001	In	.001	Sm	.1
Bi	.001	K [2]	.0001 (0.1)	Sn	.01
Ca	.0001	La	.01	Sr	.01
Cb	.01	Li [2]	.0001 (0.1)	Ta	.1
Cd	.01	Mg	.0001	Tb	.1
Ce	.1	Mn	.001	Th	.1
Co	.001	Mo	.001	Ti	.001
Cr	.001	Na [2]	.0001 (0.1)	Tl	.1
Cs	1.0	Nd	.01	U	.1
Cu	.0001	Ni	.001	V	.01
Dy	.01	P	.1	W	.1
Er	.01	Pb	.01	Y	.001
F [1]	.1	Pr	.01	Zn	.001
Fe	.001	Pt	.01	Zr	.001

[1] Fluorine is estimated at the later reading when a second exposure is required for K, Li, Na.
[2] A second exposure is required for the high sensitivity listed.

PETROGRAPHY AND ORIGIN

Several mineralogical features bearing on the origin of these rocks are apparent from the analyses of tables 2 and 3. The predominant phosphate mineral is apatite. This was clearly established by X-ray study. It is possible to distinguish fluorapatite, hydroxylapatite, and carbonatefluorapatite from one another by X-ray (Altschuler and others, 1952). The apatite from Isla Mona, however, does not always yield clear patterns. It was therefore desirable to supplement the tenuous X-ray identification of the hydroxyl variety of apatite by analyses for fluorine on samples M–3 and M–5, the two samples of highest P_2O_5 content and both virtually pure apatite. The resulting low contents of fluorine provide proof that hydroxylapatite is the phase dealt with.

Students of bone mineralogy (Dallemagne and others, 1949) have suggested the existence of alpha-tricalcium phosphate, a low-temperature hydrate, $Ca_9(PO_4)_6H_2OH$, whose X-ray pattern is presumably identical with that of hydroxylapatite. Compounds having the CA: PO_4 ratio of 1.5 can be converted to whitlockite, the beta-tricalcium phosphate, when heated

TABLE 3.—*Percent concentration of minor elements in cave phosphorites and associated rocks from Isla Mona, P. R.*

[Semiquantitative spectrographic analyses, by Charles Annell. For threshold values see table 4]

Sample	Description	>10	10–1	1.0–0.1	0.1–0.01	0.01–0.001	0.001–0.0001
M–1A	Clayey limestone	Al	Ca, Si, Fe, K	Mg, Mn, Ti, P	Na, Sr, V, Pb, Cr, Ga	Ni, Zr, Cu, Ba, B, In	
B	do	Al	Ca, Si, Fe, K	Mg, Mn, Ti	Na, V, Sr, Pb, Cr, Ga	Ni, Zr, Cu, Ba, In, B	
C	do	Al, Si	Ca, Fe, K	Mn, Na, Ti, Mg	V, Sr, Cr, Pb, Ga	Ni, Zr, Ba, Cu, B, In	
2	Dolomite	Mg	Ca	Fe, Pb, Si	Al, Na, V, Sr, Mn, Ti	Mo, Cu, Cr	B.
3	Phosphorite	Ca, P		Fe, Mg, Mn, Na	Si, Sr, Pb, Al, V, Zn	Cu, Cr, Ti	In, Ba.
4	do	Al, P	Ca, Fe	Si, Mg, Sr, Mn, Na, Ti	V, Pb, Cu, Cr, Zn, Ga	Cd, Zr, Ba, B	In.
5	do	Ca, P		Fe, Al, Mg, Mn, Na, Si.	Sr, Pb, V, Ti, Cu, Cd, Cr, Zn.	In, Ba	
6	do	P, Al, Ca	Si, Fe	K, Mg, Mn, Na	Sr, V, Ti, Pb, Cr	Ga, Cu, Ni, Ba, In, B	
7A	do	P, Ca	Mg, Fe	K, Al, Na, Si, Mn, Sr	V, Pb, Ti, Cr, Cd, Cu	Zn, Ba, B	In.
B	Limestone, phosphatized	Ca	P, Mg	Fe, Al, Na, Si, Mn	Sr, Ti, Pb, V	Cu, Cr, Ba	B, In.
8	Phosphorite	Ca, P	Al, Fe	Mg, Na, Sr, Mn, Si	V, Ti, Cu, Cd, Pb, Cr, Zn.	Ga, Ba, B	In.

above 900°C. A mixture of hydroxylapatite and other phosphate, with a Ca:PO_4 ratio of 1.50 or slightly lower, will also change to whitlockite on heating at 900°C. (Posner and Stephanson, 1951.) Pure hydroxylapatite treated in this manner remains the same (Hodge and others, 1938).

In view of the occurrence of martinite (hydrous and carbonate-bearing whitlockite) in the cave phosphorites from Isla Mona, it was of interest to test the hydroxylapatite by heating it to 900°C and then X-raying the ignited product. This establishes whether the hydroxylapatite present could be alpha-tricalcium phosphate or, what would be more probable, a mixture of hydroxylapatite and another, more acid phosphate. Accordingly, homogeneous hydroxylapatite nodules from samples M–3 and M–5 were heated for three hours at 925°C, allowed to cool, and X-rayed. The materials continued to give the hydroxylapatite patterns. We may thus safely assume that the apatite dealt with is relatively homogeneous and pure and that if alpha-tricalcium phosphate is a valid mineral it is not present in the phosphorites from Isla Mona.

Sedimentary hydroxylapatite is indicative of continental origin. It commonly originates as a replacement of limestone by guano solutions or as a residual product of leached guano deposits. In the presence of fluorine, fluorapatite is the stable variety and precipitates as such (Kazakov, 1950) or replaces hydroxylapatite. In fact, marine phosphorites are generally overfluorinated (Jacob and others, 1933).

In addition to excess fluorine, marine phosphorites generally contain uranium (McKelvey and Nelson, 1950), typically in the order of 0.006–0.008 percent and even higher (U. S. Geol. Survey, unpublished analyses) if they are as rich in P_2O_5 as the phosphorites from Isla Mona. A uranium content of 0.001–0.003 for pure marine apatite is abnormal.

The nitrogen contents of these samples do not differ significantly from the nitrogen content of average sediment (Hutchinson, 1944). However, it is notable that the samples with the highest nitrogen content are, with one exception, those with the greatest P_2O_5 content.

The low uranium contents, the hydroxylapatite nature of the phosphate, the minor occurrences of martinite and brushite, and the general although not universal association of high nitrogen with high phosphate—all suggest a guano source for the cave phosphorites.

The phosphorites would thus represent leached guano, or limestone altered by leached guano, inasmuch as they do not, for the most part, contain the more soluble acid calcium phosphates like brushite or monetite. Kaye, in describing (written communication) the occurrence of the phosphorites, notes that several of them were underlain by white crumbly material, which in turn was underlain by the limestone of the cave floor. The acid calcium phosphates are almost all incongruently soluble (Eisenberg and others, 1940) and yield more P_2O_5 to solution than CaO. Thus it is to be expected that leached phosphate deposits, which originated from the guano alteration of limestone, should consist of vertical succession of basic calcium phosphates like hydroxylapatite and martinite, underlain by reprecipitated or residual acid calcium phosphates like brushite—the entire deposit underlain by unaltered host rock. This sequence does not necessarily imply that the alteration occurred in place or that the paragenesis is invariable. Thus, the calcium phosphates may have derived from overlying limestones that were dissolved by the acid guano solutions percolating through the jointed limestone cave walls. Also, assuming an earlier acid calcium phosphate deposit, or a mixed deposit of acid and basic calcium phosphates such as brushite and martinite, or brushite, martinite, and hydroxylapatite, continuous leaching by ground water would tend to remove the acid phosphates. Acid calcium phosphates could reprecipitate, however, under conditions of discontinuous leaching, particularly as the minerals which would contribute to the ground waters are incongruently soluble and the ratio of P_2O_5 to CaO in solution would be greater than that characterizing the basic calcium phosphates such as martinite and hydroxylapatite. Thus, secondary druses of brushite could coat normally later phases like apatite or monetite in phosphorites derived from leached guano. It is also probable that basic calcium phosphates could precipitate in like manner, owing to the fact that ground water flowing through a limestone terrain would be enriched in calcium. Similarly, apatite could form as a direct alteration of limestone by guano solutions.

Samples 7A and 7B illustrate the progressive replacement of limestone by hydroxylapatite. In sample 7B the actual manner of replacement can be studied. Apatite is seen to occur in nodules and encrusting surfaces (fig. 65). Nodules of pure calcite and of both calcite and apatite are also present. The carbonate in 7B is entirely calcite. Almost all of the calcite occurs as irregular crystals of subequant shape with anhedral plane boundaries. The crystals are generally interlocking but not in optical continuity and their sizes and mutual relations can be determined. In thin-section study four modes of occurrence can be discerned—the calcite of entirely calcitic nodules (*e*, fig. 66), the calcite of the groundmass (*d*, fig. 66), the obviously late calcite encrusting vugs and open surfaces (*a*, fig. 66), and the calcite occurring adjacent to phosphatic nodules and surfaces and also as inclusions in the phosphate nodules (*c*, fig. 66). The groundmass calcite is clear and ranges in size from 0.005 to 0.01 mm, except where it adjoins phosphatic material. Nearer the phosphatic material, the calcite is finer grained and brown, and in places it contains cavities and tiny fragments of dispersed phosphate. The contact between phosphate nodule and fine-grained calcite is irregular in detail, although apparently smooth and continuous in the hand specimen. Similar fine-grained brown calcite occurs as irregular embayments into and inclusions within phosphate nodules. The fine-grained calcite is typically 0.001–0.002 mm in size. The crystals making up the calcitic nodules are, like the groundmass calcite, unoriented, anhedral, and subequant, with interlocking plane boundaries. The crystal size is somewhat larger, however, being typically 0.01 to 0.02 mm. The groundmass calcite adjoining the calcitic nodules is not finer grained, unclear, discolored, or porous. The vug calcite is clear, coarsely crystalline (0.05–0.1 mm), subhedral, and oriented with its c-axis normal to the surface of growth. Adjoining crystals are parallel to subparallel in orientation, and optical continuity is common. This vug calcite is unquestionably the last mineral to form in the rock, as it coats equally the phosphate encrustations, phosphate nodules, and the other varieties of calcite on the surfaces which it overlies.

It is apparent from the above facts that the hydroxylapatite occurs as a replacement of calcite and that both nodules and groundmass have been so replaced. The replacement origin is evident from the border zones of fine-grained altered calcite, the inclusions of such fine-grained altered calcite in the phosphate nodules, and the lack of similar material at the borders of calcitic nodules. The calcitic nodules are a primary feature of the rock. They probably represent reworked particles of slightly coarser limestone that were deposited as detritus during the precipitation of the groundmass limestone. This is evident from the lack of orientation in the coarser crystals composing them, and their equigranular interlocking texture.

Thus sample 7B represents a clastic limestone that has been partly replaced, preferentially along cracks and in nodules, by dilute guano solutions under subaerial conditions. The replacement proceeds by dissolving and altering first the individual calcite crystals and eventually the entire rock, with some loss in volume as evidenced by the greater porosity and nodule content of sample 7A (see under description of sample, above). Probably owing to the location of the samples on the cliff face, which is exposed to rain and sea spray, acid calcium phosphates were never developed or, if formed, were soon washed out. Subsequent to the period of guano alteration, further leaching and precipitation has coated parts of the rock with drusy calcite.

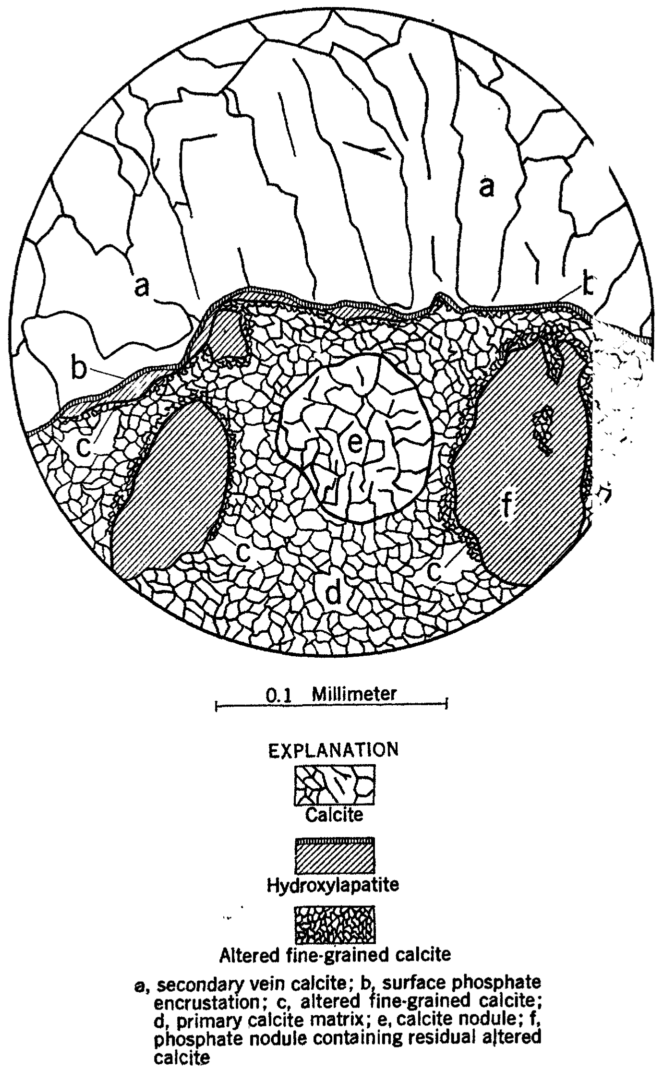


FIGURE 66.—Camera-lucida drawing of microscopic relations between calcite and hydroxylapatite in phosphatic limestone.

The direct precipitation of calcium phosphates from solution is evident from the hydroxylapatite films in sample 6 and also from microscopic study of sample 4, which like sample 7 contains porous, nodular phosphorite. Lining cavities in the nodular phosphorite and in immediate contact with the yellow-brown hydroxylapatite of both groundmass and nodules are multilayered druses of relatively clear, fibrous hydroxylapatite, oriented with prism and optic axes perpendicular to the surface of growth (see fig. 67). The druses are reniform in outline, conforming to the original globular surface of the nodules that protrude into the cavities. Interior to the hydroxylapatite druse in many of the cavities are deposits of clear martinite. The martinite occurs as a massive aggregate of platy, rhomb-shaped crystals; and, as the martinite is the

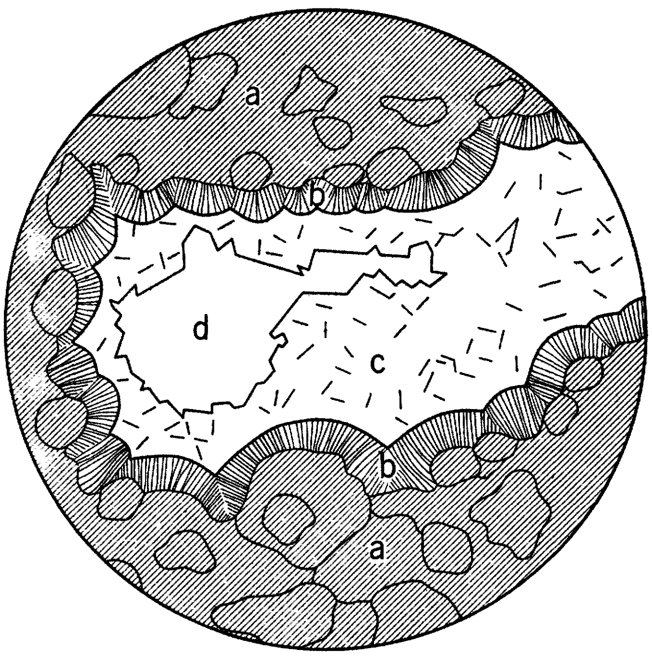


FIGURE 67.—Camera-lucida drawing of microscopic relations between martinite and hydroxylapatite in nodular phosphorite.

last mineral to deposit, it imparts an angular rhombic outline to the present cavities (see fig. 67). There is no evidence of pseudomorphism in the habit of either the hydroxylapatite druse or of the later martinite; and as the martinite is only a minor constituent of the rock, its deposition after the more basic hydroxylapatite, in contrast to the late apatite films of sample 6, is attributed merely to the vagaries of percolation and solution by the phosphatic solutions. Apparently less calcium was carried by the solutions that deposited the martinite. This could signify a locally enhanced guano deposition and a consequent increase in the ratio of P_2O_5 to CaO.

SUPPLEMENTARY NOTES ON THE MINERALOGY OF ISLA MONA

In addition to the mineralogic determinations of Altschuler in his study of the typical phosphorites supplemental mineralogic data are supplied by Mr. R. C. Erd, of the Geological Survey, who identified the minerals in several samples collected by the writer. This material was collected primarily for its possible mineralogic interest rather than for its importance in the study of the paragenesis of the phosphorite, yet its study has also shed light on the paragenesis of the phosphate deposits.

The samples composing this collection consisted of white, friable, finely crystalline to chalky material from the floors of three caverns. This type of material generally underlies the typical brown earthy phosphorites and overlies bedrock, although some interlayering of brown and white occurs. The contact with the underlying limestone is not everywhere clear because the upper surface of the limestone is slightly pulverulent in places. Thus there is evidence that at least some of the friable white material grades into the underlying limestone and is therefore altered floor rock.

Samples of phosphatic dripstone, ceiling encrustations, and an unusual pulverulent calcite deposit found at several places on the island were also examined by Mr. Erd. His report furnishes much of the analytical data given below.

The earliest description of the phosphate minerals of Islas Mona and Monito was by Mr. C. U. Shepard (1882), who recognized monetite, monite, and pyroclasite from material sent to him by a Mr. John G. Miller. The minerals monetite and monite were first described in Shepard's report, whereas pyroclasite was referred to material described earlier by Shepard (1856) from Islas Los Monges, in the Caribbean Sea off the Gulf of Venezuela. According to Shepard, the monetite and monite occurred intermixed in lumps of light-colored material that contained, in addition to these minerals, lesser amounts of gypsum and calcite. Shepard implied that the material came from a cavern on Monito (misspelled by him "Moneta") rather than from Mona, although it is apparent that his unfamiliarity with the locality did not permit him to make an explicit statement as to the provenance of his samples.

In view of the inaccessibility of Monito and the poor development of caverns there, it seems more probable that Shepard's collection came from a cavern on Isla Mona. Both the misspelling of Monito and the confusion regarding the provenance of Shepard's samples have thus left their work on the name of the mineral species monetite, which probably would have been monatite or monite if its author had been in command of all the necessary facts.

Monetite, $CaHPO_4$ (Frondel, 1953), was described by Shepard as a pale yellowish-white mineral in well-formed crystals up to one-twelfth of an inch long, occurring as masses, irregular seams, crusts, and botryoidal shapes associated with lesser amounts of white monite, gypsum, and calcite. Frondel (1943), after a restudy of insular phosphate minerals, considered monetite a valid mineral species.

Monetite occurs in samples, collected by the writer, of friable white material from the cave just southwest of Playa Pájaro and from El Cueva del Lirio. In samples from the former place it occurs as scattered ragged prismatic grains much attacked by solution and possessing a strong yellow fluorescence. In the sample from El Cueva del Lirio, monetite occurs as yellowish lumps of finely crystalline material with a grain size considerably smaller than that reported by Shepard (1882). The lumps have a hardness of 5.5 (Mohs scale) which is at variance with the 3.5 reported by Shepard (1882). The mineral has a strong yellowish-white fluorescence.

Shepard (1882, p. 402) named a massive, amorphous, snow-white calcium phosphatic material monite. This mineral occurred in close association with monetite in his samples. Strunz (1939) and Frondel (1943) have both come to the conclusion that this mineral is probably hydroxylapatite, although neither author was able to study the type material and Frondel's material was markedly different in aspect from the monite described by Shepard. No material agreeing with the original description of monite was represented in the samples collected by the writer on Isla Mona.

Brushite ($CaHPO_4 \cdot 2H_2O$) occurs widely as a disseminated constituent in the white deposits on the cavern floors, locally attaining fairly pure concentrations. This was evident from one random sample, several cubic inches in volume, which on examination proved to be nearly pure brushite. The color and textural similarity, however, between brushite and the other major constituents of the white deposits (predominantly hydroxylapatite, fine-grained calcite, and gypsum) make it difficult to recognize the outline of the brushite concentrations. All brushite collected was very fine grained, the individual crystals being barely discernible under the hand lens.

Two typical samples of the friable, finely crystalline to chalky white material from beneath the brown cave phosphorites are described below by Mr. Erd. Some idea of the nature of this material may be had from these samples. Each description is based on 100 grams of material and minerals present in amounts of less than 5 percent were not sought for; however, all constituents that were determined are mentioned.

Description

Sample 1 (a composite sample of light-colored material from several places in a cavern just west of hairpin curve in the Playa Pájaro–Lighthouse road. For the most part, collection was from within 150 yards of cavern mouth). The sample is composed mostly of angular clear fragments of fine-grained calcite, which in thin section is seen to be porous; secondary growths of coarsely crystalline calcite project into the cavities. Some recognizable fragments of shells [probably land snail, according to Kaye] are present but have been almost obliterated by solution. Surrounding the calcite is a thin crust of light reddish to yellowish-brown "apatite" which is weakly anisotropic. The indices of refraction range (apparently with the amount of the staining material) from about 1.59 to 1.65; some of the material is isotropic with an index of refraction of 1.612. The X-ray pattern most nearly matches that of hydroxylapatite, and since there is no apparent variation from this pattern by the apatites present in the other samples from Mona Island they are considered to be hydroxylapatites. Because no chemical analyses were made, the amount of other members of the apatite series present is unknown, and the material is referred to hereafter only as apatite. The carbonate content, especially in sample 2, seems to be low.

In addition to the above, a small amount of brushite is also present. The X-ray powder pattern of the 100-gram sample is of calcite, apatite, and brushite. Trace amounts of a platy magnetic mineral, probably pyrrhotite, are present. Some kaolinite, stained with iron oxide, and quartz were noted as impurities in the unsorted sample. Water-soluble salts are present but were not determined; strong tests for chloride and sulfate ions and a moderate test for phosphate ion were obtained. Copper-bearing organic matter was leached from the sample with acetone. Iron and zinc are present in minute quantities in the raw sample.

Sample 2a (from floor of Cueva Negra) is composed chiefly of apatite with a very low birefringence, a mean index of 1.638, and spherulitic extinction. A small amount of calcite and possible brushite are present but the sample is relatively homogeneous. In thin section the apatite appears as an extremely porous material in various shades of light and dark brown. Most of the apatite is submicrocrystalline, but interlocking mats of fibrous crystals extend into the pore spaces. Small patches of calcite are scattered throughout. The porosity, homogeneity, and low carbonate content of this sample and the near absence of water-soluble salts suggest that it represents leached material. No lines other than those of hydroxylapatite were found in the X-ray diffraction pattern. The slight amount of water-soluble salts are composed chiefly of an organic compound; a strong test for phosphate ion was obtained, but no chloride or sulfate ions could be detected. Zinc, but no iron, was noted in the raw sample.

Thin encrustations and delicate arborescent growths of light gray to pink gypsum occur in places on the ceilings of the caverns. One of the arborescent masses proved to be a thin crust of gypsum on earlier white brushite and white hydroxylapatite.

Shepard (1882) discussed dark brown, laminated encrustations that resembled dripstone in form under the name "pyroclasite," although he was skeptical as to whether this material constituted a true mineral species. Similar material was collected by the writer and reported on by Erd as follows:

Description

Sample 2b Pyroclasite.—The hard reddish-brown crust is composed of an isotropic brown to yellow-brown material; the indices of refraction range from 1.59 to 1.63. A minor amount of a hard, white, opaline material with a medium birefringence, spherulitic extinction, and a mean index of refraction of 1.63 is present. The X-ray pattern of both materials is of apatite.

Deposits of white to pink finely pulverulent calcite consisting of very fine crystal fragments lightly held together in a friable aggregate were noted in several places. One such deposit occurs in the face of the cliff at Punta Este just below the Lirio limestone. This deposit is stratified, the beds dipping fairly steeply to the south. The deposit forms a large wedge. It is apparently plastered unconformably against the Isla Mona limestone and is overhung by the Lirio limestone cap. A sample of this material was examined by Erd, who reports over 90 percent of minute euhedral rhombs and irregular aggregates of fine-grained calcite. The residue, after solution in monochloracetic acid, is made up of gypsum, brushite, quartz, minor apatite, and plant material. The X-ray pattern of the residue, however, shows only gypsum. Another deposit was noted at the mouth of a cavern about one-half mile southwest of the Playa Pájaro pier. At least seven feet of the white pulverulent calcite, with the same minor constituents as in the deposit at Punta Este, occur in an unstratified deposit on the sill of this cavern. Somewhat similar material was noted under a large overhanging boulder at the foot of the cliff just north of the pier at La Sardinera. Here the color was a light pink and the calcite grains tended to be uneven to spindle-shaped rather than rhomboidal. Besides brushite, and quartz and gypsum as minor constituents, there was some kaolinite and halite.

Little is known about the origin of these deposits of pulverulent calcite. They are possibly derived from the disintegration of the overlying or the underlying limestone. The bedded deposit at Punta Este and the deposit beneath the boulder, by their position and structure, may well have been built by material falling from the overhanging limestone as a light shower of fine calcite fragments. This suggests that the overhanging limestone may be weathering by a disintegration in which the strong intermesh of calcite crystals making up the limestone breaks down and individual crystals and cleavage fragments become free to fall under gravity. Evidence that such a disintegration process may take place is offered by the thin coat of fine calcite dust clinging to the walls and ceilings of most caverns. A notable example of this dust coat is found in a chamber in Cueva Negra, where the ceilings and walls are scored by Indian finger designs made simply by running fingers over the dust-coated wall. The freshness of these designs, which probably are at least 400 years old, is rather remarkable and suggests that the accumulation of this dust is from the base (limestone surface) rather than from the atmosphere.

The conditions necessary for the disintegration of a dense, finely crystalline limestone are, again, matters for conjecture. It seems evident that neither limestone solution nor dripstone deposition can occur on the disintegrating surface. This implies that there must be absolute dryness insofar as ground-water seepage is concerned; humidity in the atmosphere and even occasional wetting by rain water may not necessarily inhibit the process. The mechanism responsible for the actual mechanical breakdown of the limestone is also obscure. Changes in temperature might possibly be effective; but at present the temperature range on the island is slight. Hydration of the impurities in the limestone with an attendant swelling, or dehydration of these impurities with a resulting shrinkage, might shatter the calcite mosaic; but, as stated before, the limestones of the island are remarkably pure.

The possibility of organic activity as a casual agent in the formation of the calcite dust would be worth exploring. The importance of blue-green algae in the solution and deposition of $CaCO_3$ is well known (see Fritsch, 1945, p. 866–869 for a comprehensive summary), and the manufacture of small calcite crystals by these organisms, such that the crystal shapes differ with the specific character of the organism, has been noted (Fritsch, 1945, p. 869). A difference in the algae responsible might perhaps explain the prevailing rhomboidal shape of the crystals in two of the deposits discussed and the spindle-shaped fragments in the third. An alternative hypothesis is that the calcite crystals are isolated and dislodged by the honeycombing of the limestone by boring blue-green algae.

GUANO ORIGIN OF THE PHOSPHORITE DEPOSITS

Hübener (1898) postulated that the cave phosphorites of Isla Mona were due to the decomposition and leaching of marine organic matter deposited in the caves at a time when the island was submerged. He further stated that the marine plants and animals were first leached of their organic content by sea water and later by fresh water to produce the crystalline deposits we see today. This theory of origin seems untenable in consideration of the inferred physiographic development of the caverns and from what is known of the geochemical characteristics of insular phosphate deposits. Altschuler has discussed the latter characteristics and has demonstrated that the deposits lack the chemical properties of typical marine phosphorites. Furthermore, as suggested by Hutchinson (1950), there seems little reason to propose a marine origin when either bats or birds could produce comparable deposits. It was Hübener's contention that the lack of nitrogen in the deposits pointed to a nonguano source. It seems evident however that he was not fully aware of the degree of leaching that guanos can attain, nor of the characteristics of phosphatized limestone derived from leached guanos.

The presence of brushite and hydroxylapatite associated with gypsum encrustations on the ceiling of the caverns (p. 163) indicates that at least some of the calcium phosphate has been brought down to cavern level by descending ground water. The absence, however, of significantly large amounts of phosphate in the tested samples of wall-rock limestone (table 1) or in the cemented red residuum (table 2), and the apparent absence of notable phosphate mineralization on the surface of the island or along joints, points to the probability that supergene enrichment of the cave phosphorites has been of negligible importance. On limestone islands of the West Indies and in the western Pacific (Hutchinson, 1950), most phosphorite deposits that are due to surface accumulations of guano are characterized by calcium phosphate mineralization on the island surface and along joints connecting to the surface. If the phosphorites in the Isla Mona caves were predominantly derived from surface deposits, there seems little doubt that the avenues of seepage—that is, the joints—connecting caves with the surface, would have been extensively altered. The ceiling deposits of Isla Mona may be explained by the descent of phosphate ions derived from any of the following sources: (a) contemporary minor guano deposition on the plateau surface from both the bird and mammal population, (b) cave guanos in higher level caverns, such as those in the Lirio limestone, and (c) the thin phosphorite zone marking the unconformity between the Isla Mona and Lirio limestone (as seen at Punta Este). The relative unimportance of descending phosphate solutions today is further attested by the nonphosphatic dripstone layer which, except for the rare and strictly local "pyroclasite" dripstone, is forming throughout the caverns.

Sometime, therefore, before the advent of the present cycle of dripstone deposition, guano was deposited directly in the caverns and was converted to several calcium phosphate minerals. There has been, however, a difference of opinion as to whether these deposits are of bat or of bird origin. Gile and Carrero (1918, p. 8) refer to Isla Mona guanos as leached bird guanos. K. P. Schmidt (1926) thought they were bat guanos. More recently E. Hutchinson (1950), on reviewing the literature of Isla Mona, expressed the opinion that most of the guano was probably of bird origin. His reasons for this conclusion are that—(a) many sea birds are reported to nest on Mona and Monito Islands, and (b) unless fish-eating bats were exceptionally abundant (which they are not) the bulk of the guano would of necessity be contributed by the island's bird colony. From the importance he allots the present composition of the island's biota in his argument, it is apparent that Hutchinson did not sufficiently appreciate the fossil nature of the Isla Mona deposits.

At the outset it should be said that except for one occurrence (described below) no skeletal remains of either bats or birds were found associated with the guano, and therefore direct proof of origin of this type is lacking. Moreover, well-leached bird and bat guanos are apparently chemically indistinguishable (Gile and Carrero, 1918) so that no clue is provided by chemical analysis.

The only evidences found by the writer that possibly point to a bird origin for the cave guano deposits are the following:

1. Marine birds roost in fairly large numbers in the sea cliffs and in the mouths of caves that let out onto these cliffs. This is particularly true of Monito, which apparently has a much denser bird population than the Isla Mona cliffs. Barnés (1946) has reported many nests of the white-bellied booby (*Sula sula leucogaster*) on the floor and walls of Cueva El Torro on the north side of the island. On the other hand, no large bird colonies were seen by the writer in the cliffs or cavern mouths on the south side of Isla Mona.

2. A deposit containing many bones of Audubon's shearwater (*Puffinus lherminieri*) was found on the floor of a chamber in the cavern known as Cueva Negra. This deposit and the chamber containing it are so unusual that they merit description. The cavern is situated on the west side of the island behind La Sardinera camp. The mouth consists of two separate and rather small openings leading to two separate branches of the cavern. Several hundred feet from the portal, in the south branch of the cavern, is a somewhat rectangular chamber whose floor, walls, and ceilings are streaked with black. This chamber receives only the slightest glimmer of light from the cavern mouth and several minutes of adjustment to the dark are required for the eye to perceive this. The black coloration on the chamber walls is probably due to smoke, and it very probably was this place that Hübener (1898) referred to in his account of a smoke-blackened chamber containing pirate mementos.

The chamber gives evidence of a long occupancy by man. On the floor there are fragments of early Spanish colonial and Indian pottery, old glass, and conch shells (*Strómbus gigas*). The walls contain a great number of signs, initials, names, and dates (the earliest noted by this writer was 1742 although Hübener reports a 1726). Indian finger designs score the ceiling.

The floor deposit is unlike any other found in the caves by the writer and consists of 1 to 6 inches of a slightly plastic yellow silt. The top 1 to 3 inches of this deposit contain many small charcoal fragments and innumerable, somewhat mineralized bones of Audubon's shearwater (no other species was identified among a representative collection of the bones sent to Dr. Alexander Wetmore, Smithsonian Institution).

In a few places, where probings were made, the silt was underlain by thin pockets of the normal cave phosphorite. There was no dripstone crust separating the two deposits. Patches of paper-thin, dark-brown phosphorite encrustations similar to "pyroclasite" were found in several places on the floor.

The question posed by this find is whether or not the bone deposit is due to purely natural agencies or whether it is due to human activity.

If the deposit is a natural one, here at least is an indication that marine birds have occupied the darker recesses of the caves. Dr. Wetmore (written communication) had the following to say about Audubon's shearwater (*Puffinus lherminieri* Lesson):

> Recorded as a breeding species on Mona; these birds nest in the obscurity of rock crevices or holes, so that it is possible that they might enter caves such as the one described.

What Dr. Wetmore apparently did not appreciate is the almost complete darkness of this chamber. It seems doubtful to the writer that the Audubon's shearwater would be able to navigate on wing into this chamber without the aid of greater illumination. It is not known whether this, or any, shearwater possesses any of the peculiar "echo-sounding" navigational powers recently demonstrated (Griffin, 1954) in the oil bird (*Steatornis caripensis* Humboldt). J. Hough, Geological Survey, comments (written communication) on this matter as follows:

> Audubon's shearwater is not nocturnal. It is a marine bird spending its days at sea usually far from shore and returning at night to nest in rocky cliffs or crevices along the coast generally above sea level. They are found in large numbers in such places during the breeding season and are captured by natives with nets. Eight or nine birds are required per man per meal. The remainder of the catch is pressed between hides and stored for future use.

It has been suggested that the birds might have been blown into the cave during a storm. This is possible, although not probable, for the mouth of the cavern is small and rather protected by vegetation and large talus boulders.

Bones of what must be literally thousands of birds are contained in the floor deposit of the chamber and all of them are more or less intimately mixed with small charcoal fragments. The abundance of charcoal well within the cave cannot, it seems to the writer, be ascribed to natural causes. Woody plants do not grow in the caverns away from a light source nor is it clear what natural agency would so effectively break up naturally carbonized wood to small fragments. The conclusion seems inescapable, therefore, that the bird bones constitute a midden built with the refuse of many feasts, probably during Indian occupancy of the cave, and that the charcoal represents scattered ashes from the fires. Why the Audubon's shearwater was exclusively favored in these feasts is not known. Archeologists familiar with the local Indian cultures do not know of any animal fetishism that might explain this preference. Regardless of this difficulty, the Cueva Negra deposit is not thought to support the theory of an avian origin of the cave guano deposits.

Evidence of a bat origin for the cave guanos is, on the other hand, more convincing. Two species of bats inhabit the caves today (Anthony, 1918), one of which, *Noctilio leporinus mastivus*, is a fish-eating bat. Although these bats are apparently not very numerous today, there is no reason to suppose that they were not more numerous in the past. The nonphosphatic dripstone crust over the cave guano shows that the guano is not a contemporary deposit. The bat population of the caves at that time might have greatly exceeded that of today.

But perhaps the most persuasive argument is simply the fact that the caverns, except for short stretches near their mouths, are completely dark and that guano is more or less evenly distributed throughout. This seems clearly to point to bats as the responsible organisms rather than birds, for no Puerto Rican birds are known to fly in complete darkness.

The bat guano of the caves has been extensively transformed. The material we find today on the floor of the caves may represent in part a completely leached guano, from which most of the original carbon and nitrogen has been removed. The residual phosphorus has combined in various proportions with calcium and hydroxyl ions in the leaching ground water to form the characteristic suite of minerals. On the other hand the cave phosphorites, from the spatial point of view, may also represent the limestone floor rock on which the guano rested and which was phosphatized by solutions brought down from the overlying guano. The only indication suggesting that the phosphorites may be separable into either of these two spatial types is the existence of the brown and white material. The white phosphorite, it will be recalled, commonly forms the base of the deposit, though in places there is some interstratification. Except for the presence of very small amounts of montmorillonite clay and iron oxide in several samples of the brown phosphorite examined by Altschuler, the two materials are mineralogically the same. The nitrogen content of the two materials perhaps offers a more substantial clue. The nitrogen contents of the brown phosphorites (table 2, samples

4, 5, 6, and 8) are all higher than the one sample of white phosphorite (sample 3) analyzed. This difference in nitrogen content, which amounts to a factor of about 2, may perhaps be the result of the residual nature of the brown phosphorite and the replaced nature of the white phosphorite. Hübener suggested that the brown phosphate was due to organic matter and that it was less leached and altered than the white material. Tests for carbon were not run in this study; but it is recalled that pure apatite not uncommonly has a brown color, and at Isla Mona we have seen this in the brown hydroxylapatite dripstone ("pyroclasite"). The occurrence in the phosphorites of fine-grained calcite and the physical semblance of the white phosphorites to the pulverulent calcite deposits strongly suggests that the phosphorite, and particularly the white material, represent the alteration of pulverulent calcite deposits rather than limestone floor rock. But here again clues to permit one to refine this distinction seem lacking.

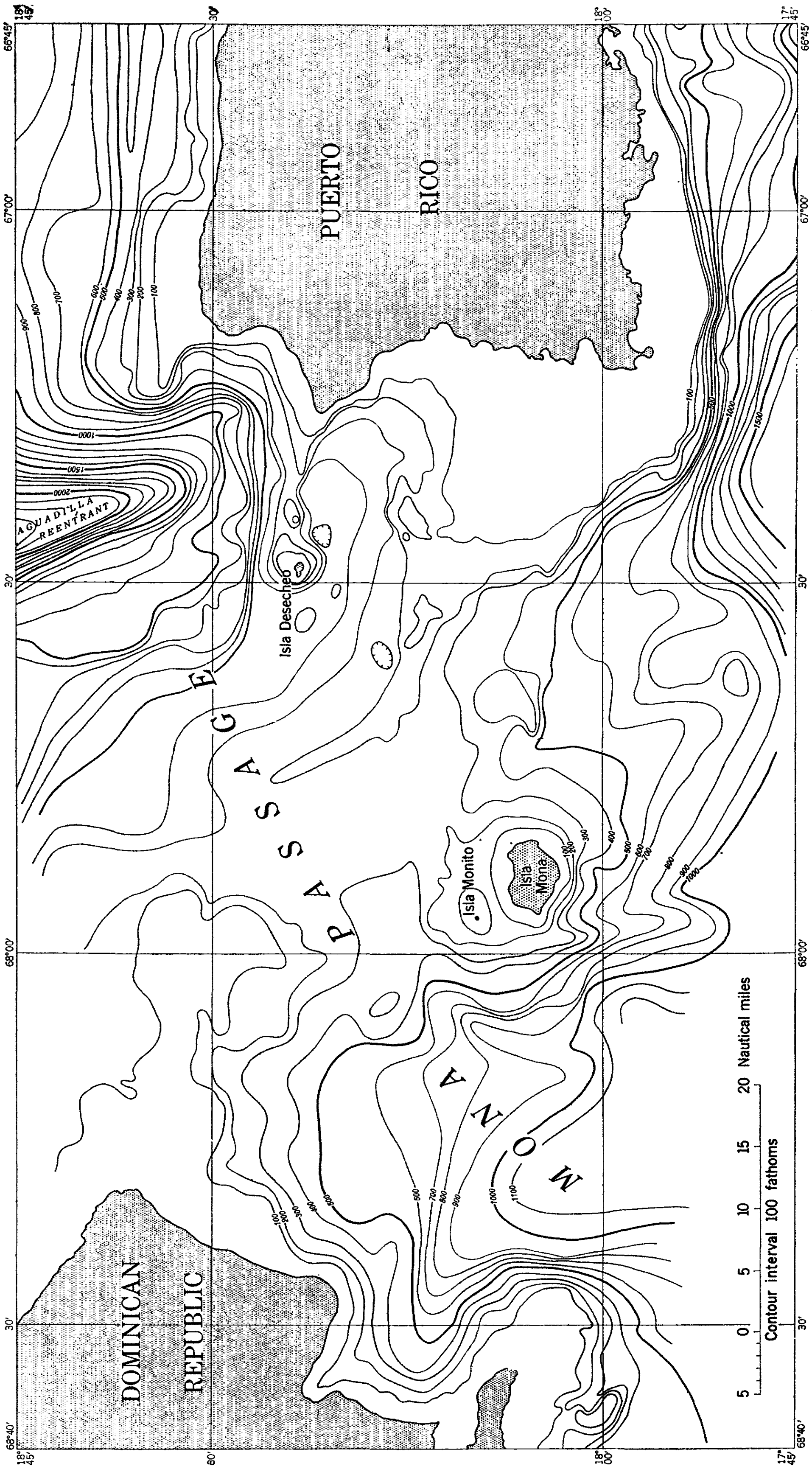
A word remains to be said concerning the significance of the occurrence of brushite and monetite in close environmental association. Frondel (1943) describes brushite, the hydrated form of $CaHPO_4$, as a "low temperature product" and monetite ($CaHPO_4$) as forming at higher temperatures. Hutchinson (1950), referring to the work of Kazakov, refines this remark by stating that brushite is formed below 25°C (71°F) and at a PH below 6.4. In dry air, he continues, finely divided brushite decomposes spontaneously to monetite. As we have seen, both minerals have been found in the floor deposits of the caves, more or less intimately associated with hydroxlapatite and other calcium phosphate species. Although a temperature of 71°F is somewhat lower than the minimum air temperatures recorded at the weather station on the surface of the plateau and also is probably slightly lower than the temperatures prevailing in the caverns today (unfortunately, no temperature measurements were made by the writer), it may have occurred in the past. If 71°F is actually a precise and delicate threshhold separating the formation of the two minerals, we can perhaps ascribe the formation of brushite to a paleoclimate colder than the present and monetite to a climate comparable to or warmer than the present climate. The conversion, however, of the hydrous brushite to the nonhydrous monetite in a dry atmosphere has apparently never taken place on a broad scale, since brushite seems to be the more widespread and abundant of the two minerals. Indeed one would hardly expect a low island in the path of the trade winds to attain the low degree of humidity probably required for this conversion.

Although the temperature differences suggested may have been the critical factor in the determination of which of the two minerals formed, the distribution of the two minerals is not nearly as systematic as one might expect under these circumstances. If atmospheric temperatures provided the only critical factor, one would expect a persistent zoning or stratification throughout the deposits with each of the two minerals confined to its proper time-climate zone. Neither the samples nor the field relations seem to confirm this. Rather, a mixing of the various mineral species making up the calcium phosphate suite by very local concentration seems to characterize the deposit. No solution to this paragenetic problem is apparent other than by resorting to unappreciated microvariations in the local depositional and postdepositional environments.

NOTES ON THE HISTORY OF MONA PASSAGE AND ISLA MONA

TOPOGRAPHY OF MONA PASSAGE

When compared to the deep waters of the Atlantic Ocean to the north and the Caribbean Sea to the south, Mona Passage is a shallow sill. The soundings shown on the western part of the U. S. Coast and Geodetic Survey Chart 920 (edition of December 1942) indicate that a lowering of the sea level by 300 fathoms would permit one to walk dry shod across the passage from Puerto Rico to the Dominican Republic. The bathymetric map (fig. 68), constructed from soundings on this chart, shows that Mona Passage is essentially an arch whose axis is aligned west-northwest, thereby diverging somewhat from the east-west topographic axis of Puerto Rico. On the south, the floor of the passage drops off to the Caribbean at a somewhat more gentle gradient than the adjoining slope on the south side of Puerto Rico. Projecting southward from about the midpoint of the axis of the passage is a broad, somewhat irregular spur on the top of which are Islas Mona and Monito. Rising from the end of a narrow submarine ridge that juts out from the Rincón peninsula, on the west shore of Puerto Rico, is Isla Desecheo. This small conical island on the north side of the passage rises steeply to an elevation of 715 feet above sea level. Immediately to the north of the east-west submarine ridge from which Isla Desecheo rises is a deep reentrant of the Atlantic Ocean, the Aguadilla reentrant, which is a southward projection of the Puerto Rican Trench. This deep, the axis of which lies about 75 nautical miles north of the north coast tip of Puerto Rico, extends east-west for over 200 miles and has a level floor whose depth is about 4,350 fathoms (Northrop, 1954; Ewing and Heezen, 1955).



Bathymetric data from U. S. C. and G. S. chart 920 and H. O. chart 2650. Contoured by C. A. Kaye; the Aguadilla Reentrant modified from Northrop (1954)

FIGURE 68.—Bathymetric map of Mona Passage.

Several broad, shallow banks occur in Mona Passage. One, extending 16 nautical miles into the passage, fringes Puerto Rico on the southwest. The abundant soundings on this bank show that it is no deeper than 18 fathoms and has a shallow rim at its outer edge. The northwestern part of the passage is marked by a bank that projects 25 miles into the passage from Cabo Engaño, the easternmost projection of the Dominican Republic.

The most important conclusion to be drawn from a cursory examination of the topography of Mona Passage (roughly and perhaps deceptively drawn as it is in figure 68) is that it does not constitute a break in the continuity of the Antillean arc. The passage is an arch with about the same span and essentially the same topographic axis as that of adjoining Puerto Rico and the eastern part of the Dominican Republic. In consequence there is no reason to doubt the integrity of the islands and the passage as a single structural unit.

INSOLUBLE RESIDUE OF THE ROCKS OF ISLA MONA

The composition of the rocks of Isla Mona provides evidence that Mona Passage existed during their deposition. All the limestones of this island have exceptionally low insoluble residues, which is probably an indication of remoteness, at the time of deposition, of a source of terrestrially derived sediment. The purity of these limestones in terms of carbonate content can be judged by comparing them to the limestones of early Miocene age cropping out on the north and south coasts of Puerto Rico, which are inferred to have been laid down as shelf deposits marginal to the emergent central axis of the island.

The insoluble residue of ten representative samples of Isla Mona limestone and eight representative samples of the purer Miocene limestones of Puerto Rico were determined, in order to compare these rocks and to see if the impression of exceptional purity, in terms of carbonate content, which the Isla Mona rocks convey to the eye was essentially true. Table 5 gives the result of these analyses. The samples were pulverized, oven-dried at 105°C and then leached in 15 percent hydrochloric acid. The insoluble fraction was filtered, dried, and weighed on an analytical balance. Three separate runs were made for sample 2 in order to check the results. The final run was of a single chunk, surface washed in dilute acid in order to remove all possible organic contamination. The insoluble residue of 0.04 percent is a weighted average of the three runs. The chunk sample yielded only 0.008 percent insoluble residue and it is thought that the first two runs may have contained a certain amount of organic contamination.

The difference in insoluble residue between selected samples of purer limestone from Puerto Rico and random samples of limestone, Isla Mona, as shown in Table 5, is evident without extended comment. The limestones from Puerto Rico contain, with few exceptions, 10 times and more the insoluble residue of the Isla Mona rocks. Five out of six of the Isla Mona samples contain considerably less than one percent insoluble residue. Moreover, part of the residue of several samples is finely divided pyrite and iron(?) oxides that are probably authigenic in origin. The limestones from Isla Mona contain extremely little clay, which is in marked

TABLE 5.—*Insoluble residues, in percent of total weight of sample, of some limestones from Puerto Rico and Isla Mona*

Sample	Location	Stratigraphic horizon	Sample description	Insoluble residue
	Isla Mona:			
1	From floor of Cueva del Lirio	Isla Mona limestone	Dense white limestone	0.19
2	Cliff at Punta Este	do	Dense finely crystalline white dolomite	[1] .04
3	Fossiliferous limestone, Cueva Negra	do	Somewhat porous, fossiliferous white limestone.	.33
4	Lower cliff face, Playa Pájaro	do	Dense white limestone	.10
5	From ceiling of Cueva del Lirio	Lirio limestone	Dense fossiliferous white limestone	.02
6	Side of roadcut above Desembarcadero Uvero	Isla Mona limestone (?)	do	.17
7	From plateau above Playa Pájaro	do	Dense white limestone	.17
8	Large boulder, between Anclaje Isabel and Desembarcadero Uvero.	Pleistocene reef limestone	Dense fossiliferous white limestone	.76
	Puerto Rico:			
9	Yauco quadrangle,[2] Highway 36; 0.6 miles east of Playa de Guayonilla.	Lower member Ponce limestone [3]	Slightly marly limestone	5.28
10	200 yards north of sample 9	Lower member Ponce limestone	Dense cream-colored limestone	3.82
11	Guànica quadrangle, ½ mile north of lighthouse, from roadside.	Upper member Ponce limestone	Dense white limestone	3.02
12	Bayamón quadrangle, quarry north of Military Highway, east of Bayamón.	Aguada limestone	Dense pink limestone	3.34
13	Quebradillas quadrangle, cliffs north of Highway 34, just east of Guajataca dam.	do	Dense yellow limestone	1.29
14	Arecibo quadrangle, Km 70.0 Arecibo-Utuado road	Lares limestone	White slightly chalky limestone	1.89
15	Quebradillas quadrangle, Highway 34, about 2½ miles east of Guajataca dam.	Aymamón limestone	Dense yellow limestone	3.18
16	Camuy quadrangle, Río Camuy valley	do	Dense light-pink limestone	2.27

[1] Weighted average of 3 runs totaling 84 gr of sample.
[2] U. S. Geological Survey topographic quadrangles, scale 1:30,000.
[3] Puerto Rican stratigraphy from Zapp, Bergquist, and Thomas (1948).

contrast with the limestones from Puerto Rico, whose insoluble fraction without exception consists predominantly of clay.

The difference in content of noncarbonate detrital sediment between the limestones of Puerto Rico and those of Isla Mona suggests a significant difference in sedimentary environment. A pure skeletal limestone, like that of Isla Mona, results from either an absence of noncarbonate sediment in the depositional environment or a very rapid rate of carbonate accumulation (which would have the effect of diluting the normal noncarbonate clastic sedimentation). The first facies is normal in an oceanic reef environment, far removed from terrestrial sediment, and the second might conceivably occur anywhere in the tropics though under restricted circumstances. There is no reason, however, to suppose that in comparison with adjoining Puerto Rico, the banks about Isla Mona would have experienced a more-than-usual proliferation of marine organisms and therefore a more-than-normal deposition of shell detritus. It seems likely therefore that the proximity of a source of land-derived sediment—in this instance, the emergent core of Puerto Rico—affected the composition of the limestones of Puerto Rico, while the rocks of Isla Mona were deposited in an oceanic reef environment marked by an absence of land-derived sediment.

It is pertinent to note that the limestones of Isla Mona compare in purity with limestones from isolated oceanic localities or from localities removed from a source of land-derived sediment (see Sayles, 1931; and Illing, 1954, table 4). Thorp (1935, table 5) gives the insoluble components of eight sediments from southern Florida and the Bahamas:

Sample	*Material*	*Insoluble residue (percent of total weight of sample)*
1	Beach sand from east side of Sands Key, Florida.	1. 15
2	Great Bahama Bank, between Gun Cay Light and Northwest Passage, Bahamas.	. 13
3	South Bight, Andros Island, Bahamas	. 46
4	Shore material, west side of Andros Island, Bahamas.	. 89
5	Tongue of the Ocean, Bahamas	1. 05
6	do	1. 34
7	Mud Flat, north side Loggerhead Key, east of Sugarloaf Key, Florida.	1. 04
8	Near obstruction buoy at southwest entrance to Fort Jefferson Channel, Tortugas, Florida.	1. 11

F. Foreman (1951), in his study of some Bermuda rocks, gives the following insoluble residues of seven marine limestones:

Sample	*Material*	*Insoluble residue (percent of total weight of sample)*
1	"Cladocora rock"	0. 16–0. 36
2	"Oculina rock"	. 64
3	"Undated old rock"	. 04
4	"Sandstone"	. 054
5	"Shell conglomerate rock"	1. 02
6	"Lampanella clay"	1. 02
7	"Brachydontes rock"	. 85

	Remarks
1	Over 90 percent finely crystalline pyrite.
2	
3	All fine-grained pyrite.
4	Chiefly black carbonaceous particles.
5	All pyrite.
6	Almost all a light-brown clay.

CURRENTS OF MONA PASSAGE

With Puerto Rico and the Dominican Republic both relatively near, the reason for the purity of the Isla Mona rocks is evidently not the remoteness of land. More important to the problem, however, than the distance of the site of deposition from land is the distance from land measured along the prevailing currents that sweep over the point of sedimentation. The explanation for the purity of the Isla Mona sediments should therefore be sought in the currents that have passed over the site of Isla Mona during the island's depositional history.

The best source of surface current information for the Caribbean region is the records compiled by the Navy Hydrographic Office from information cooperatively supplied by all types of vessels sailing these seas. These data have been compiled into a series of regional charts for each month of the year (U. S. Hydrog. Office Misc. No. 10,690) on which the mean direction and force of the surface currents for each degree of latitude and longitude are shown. From these charts a general picture of the major lines of surface circulation can be derived. Figure 69 represents current streamlines interpreted by the writer from the data on currents for the month of August. The configuration of the flow lines differs somewhat from month to month, but the general picture persists throughout the year (see Pritchard, 1948, for a discussion of principles of construction of streamlines).

It will be seen that the equatorial current, with a general northwesterly set, enters the Caribbean Sea from the Atlantic Ocean by way of the broad passages between the islands of the Lesser Antilles. Here, after experiencing minor local deflections, the current continues in a northwesterly direction across the Caribbean. The islands of Puerto Rico and Hispaniola are

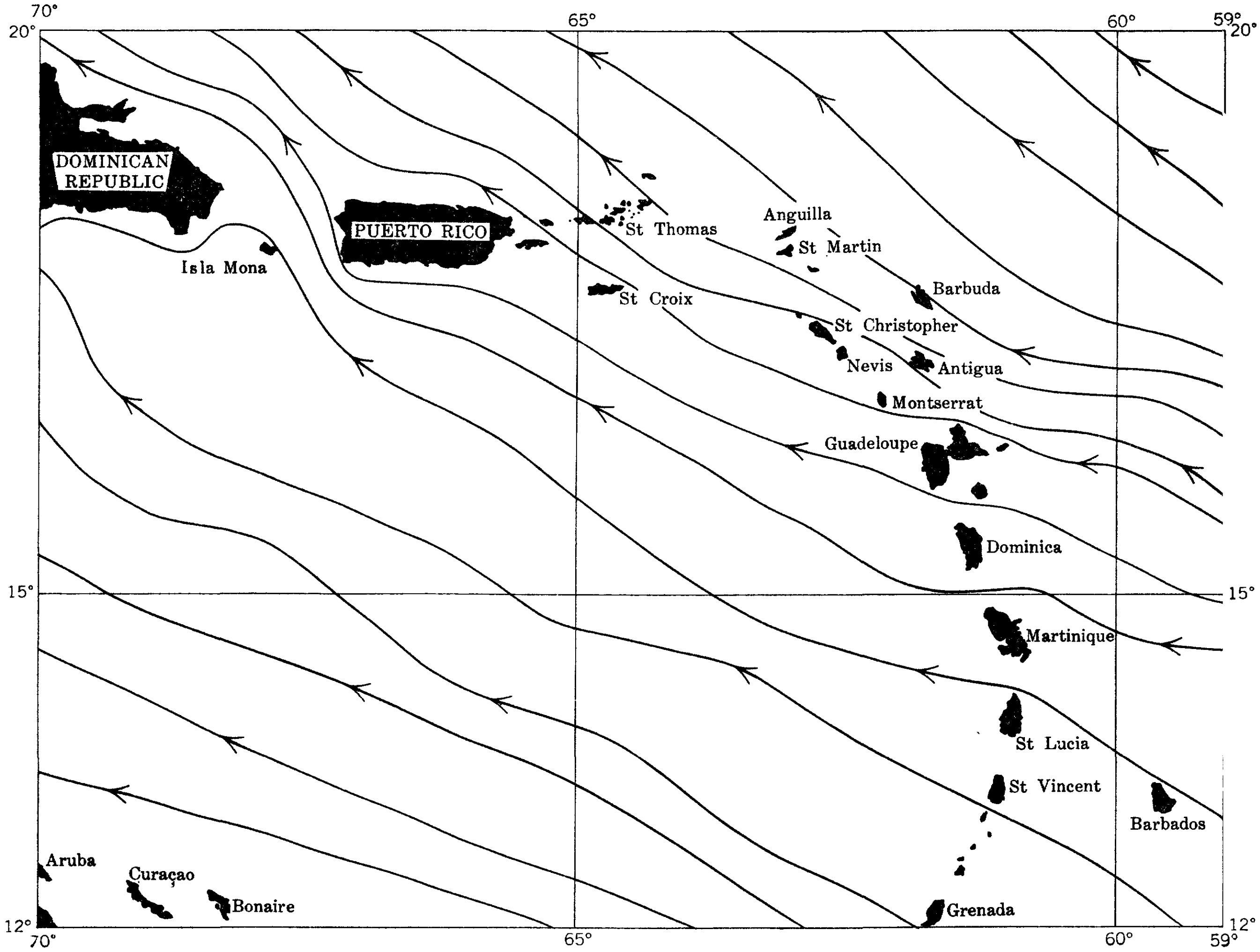


FIGURE 69.—Prevailing surface currents of eastern Caribbean for month of August. From U. S. Coast and Geodetic Survey Misc. No. 10,690–8.

barriers, however, to this west-northwesterly flow, and the current is deflected into westerly coastal currents along the south sides of these islands. Mona Passage, however, provides an outlet from the Caribbean system and permits the escape of some of the Caribbean water into the North Atlantic. A north-flowing current therefore moves along the sides of Mona Passage throughout most of the year. This current deflects northward through the passage the westerly coastal current of the south coast of Puerto Rico, confining it probably [7] to the west shore of Puerto Rico. The main north-flowing Mona Passage current passes somewhat east of the center of the passage, or just east of Isla Mona, and it consists principally of water that enters the Caribbean Sea via the central section of the Lesser Antilles, varying between approximately the latitude of Guadaloupe on the north to St. Vincent on the south, depending on the time of the year. It consists therefore of water that has flowed from the Lesser Antilles to Isla Mona without having been affected by land drainage. Moreover, it is certain that in the course of its journey from the broad passages between the Lesser Antilles to Isla Mona, a matter of over 400 miles and a journey of probably 60 or more days, all or almost all of the sediment derived from the Lesser Antilles is lost by normal settling. The site of Isla Mona today, under the influence of Mona Passage current, is therefore comparable to Bermuda, the Bahamas, and southern Florida in terms of its remoteness from land drainage.

The changes in current that would be brought about at the site of Isla Mona if Mona Passage were closed by a narrow land connection between Puerto Rico and the Dominican Republic, as has been suggested for Miocene time (Meyerhoff, 1933), are pertinent. If it is assumed that the Lesser Antilles provided at that time, as it does today, only a fragmentary barrier to

[7] U. S. Hydrographic Office Misc. No. 10,690 gives no information on this deflected coastal current. However, U. S. Hydrographic Office No. 128, "Sailing Directions for the West Indies, v. 1." notes a 1½ knot north current on the sides of the passage.

the admittance of the northern equatorial current into the Caribbean, it seems certain that the westerly coastal current of the south coast of Puerto Rico would then have continued across the site of Isla Mona (indeed, there would have been nowhere else for it to go) and that sedimentation at the Mona site would in consequence have differed little from that off the south coast of Puerto Rico. The limestones of Isla Mona and Puerto Rico under these conditions would show a comparable content of land-derived sediment instead of the disparity already noted.

If, on the other hand, Woodring's analysis (1928, p. 422) of the geography of the Lesser Antilles in Miocene time is correct and instead of the present island chain there existed a more or less continuous narrow landmass, the surface-current pattern for the eastern Caribbean would have been quite different from that of today. Instead of a modified equatorial current there would have been the complex internal circulation of the land-locked seas. The reconstruction of such a hypothetical system would be hazardous and too charged with unknown factors to be of value to this study. It would seem probable, however, that even in such a system the same coastal currents would have prevailed at the site of Isla Mona as have just been described. The high purity of the limestones of Isla Mona therefore is construed as indicating that approximately the present oceanic current existed in the Miocene and also in the Pliocene or Pleistocene (when the Lirio limestone was probably deposited) and, as a corollary, that Mona Passage existed at that time.

SOME HISTORICAL NOTES ON ISLA MONA

The first event in the history of Isla Mona about which we have evidence is the deposition of the Isla Mona limestone probably in early or middle Miocene time. This formation, if its corals can be taken for a guide, was deposited in relatively shallow water somewhat removed from reef building. According to Yonge (1935) the coral *Manicina areolata* thrives in water less than 12 fathoms deep. The Isla Mona coral assemblage, according to Mr. Wells, are not typical reef species. The most common environment of *Manicina areolata*, for example, is protected flats (Vaughan, 1910.)

The angular unconformity between the Isla Mona and Lirio limestones suggests that the area of Isla Mona was slightly disturbed and then bevelled by erosion following the early or middle Miocene. The dips of the Mona limestones are so low, however, that there is a possibility that they represent, wholly or in part, true initial dips.

The bevelled edges of the Isla Mona limestone, which are very evident at the Lirio limestone unconformity at Punta Este (pl. 13*A*), probably result from marine planation within the wave zone. There is a possibility, however, that they represent a combination of subaerial reduction followed by marine planation, and that the thin phosphatic layer that marks the unconformity at Punta Este is evidence of biochemical activity in the subaerial zone. The unconformity, however, is remarkably smooth and there are none of the solutional irregularities that might be expected of the surface of a dense limestone that has undergone extensive weathering. Moreover, the absence of solution cavities beneath the unconformity which might have developed during weathering in pre-Lirio time provides an additional argument for the importance of marine planation.

The subsequent deposition of the Lirio limestone may have been due either to a subsidence of the shallow marine bank in the Pliocene or very early Pleistocene or else to a rise in sea level. Supporting the possibility of a sea-level rise are the views of Baulig (1935), Wooldridge and Linton (1938), Sprigg (1952) and others who have suggested that the Pliocene was an epoch of high sea level in relation to the present. A sea level 300 feet above the present land could account for the deposition of the Lirio limestone without postulating any post-Miocene crustal movements.

The Lirio limestone is a detrital limestone rather than a true reef limestone. Coral heads, large masses of calcareous algae, and associated reef fauna—all of which form the important part of reef limestone—are conspicuously missing. However, a growing reef was probably in the near vicinity, for the limestone contains a considerable amount of finely comminuted reef detritus.

The island at the close of Lirio limestone deposition possibly corresponded in dimension to the submarine bank that now surrounds Isla Mona. This means that since that time the shores of Isla Mona have receded slightly over a mile in all directions, with the exception of the southwest, or leeward side of the island, where the bank is less than half a mile wide.

Isla Monito seems to have suffered somewhat greater depredation by marine erosion, and its submarine bank indicates a shore recession of about 2 miles. This little island, according to available soundings, is separated from Isla Mona by a trough which descends to a depth of about 150 fathoms, and which is possibly a shallow graben formed during the uplift of the entire island block in Miocene time.

Post-Lirio time has left its mark on the island, principally by the wasting away of the island by subaerial and marine planation, by the excavation of the caverns, and by the building of the submarine banks and reefs. This work was accomplished during a time when there were fluctuations of climate and of sea level, probably in synchronization with the waxing and waning of Pleistocene glaciation in other latitudes. There are some indications on Isla Mona of the nature of these climatic and sea-level fluctuations, though the evidence is delicate and difficult to decipher.

QUATERNARY CLIMATIC CHANGES

CEMENTED RED RESIDUUM

The cemented red residuum containing land snail shells possibly offers some evidence of past climatic conditions on Isla Mona. Additional data are provided by the sequence of cavern solution, guano deposition, and dripstone deposition within the caves, and possibly by the reported fertility of the island in the 16th and 17th centuries.

The cemented red residuum, which veins the Isla Mona and Lirio limestones to a considerable depth and which can be found exposed in the walls of some of the caverns, contains an assemblage of fossil land snail shells that is different from living land snails of Isla Mona in several respects. Two species, *Suavitas* cf. *S. krugiana* (von Martens) and *Lacteoluna selenina* (Gould), have not been found living on the island. The former species is known only from the interior of Puerto Rico and the latter is widespread in Puerto Rico, the West Indies south to Barbados, southern Florida, and Bermuda. Three species, *Chondropoma turnerae* Clench, *Bulimulus diaphanus* (Pfeiffer), and *Cerion monaense* Clench, are significantly larger in size than the living shells. Messrs. Rehder and Abbot, who examined these shells, speculated (written communication) that the larger shell size of the fossil snails might be due to changes in the climatic factor and, specifically, that the larger shell size suggested a more favorable and presumably less arid climate. A dissenting opinion was voiced by Mr. Clench, however, who also examined the shells but did not think that they represented a significant environmental change. The precise age of this fauna is not known, although it is probably sufficiently different from the existing fauna to suggest a Pleistocene age.

The fact that veinations and vermiculations of cemented red residuum are found in cavern walls indicates that they formed at least before the solution of the caverns had attained its present stage. The vein-like form assumed by much of this material suggests further that it represents an early stage of the weathering of the limestone when only local slight widening of joints had been accomplished and solution had not yet advanced to the degree of cavern-sized openings. The almost ubiquitous presence of well-preserved fossil shells in the cemented red residuum further indicates that the solution openings were well connected to the surface of the plateau and that surface material was readily washed into them.

It would seem that the cemented red residuum implies that at any particular point the degree of saturation of the ground water with $Ca(HCO_3)_2$ increased with time. From the undersaturation necessary for wall-rock solution to the saturated state expressed by (a) well-preserved calcareous shells, and (b) cementation of the residual fill, we may well have evidence of climatic change. Undersaturated ground water at depth indicates a relatively rapid rate of recharge, such as normally follows relatively heavy precipitation. On the other hand, the scant rate of recharge provided by small showers is probably characterized by vadose water reaching saturation at shallow depths—and below which lime precipitation can occur. The climatic change indicated by the cemented red residuum is therefore either towards greater aridity or towards a smaller average rate of precipitation.

CAVERN SOLUTION

The excavation (or dissolution) of the caverns of Isla Mona was probably entirely accomplished before the close of the Pleistocene and occurred at a time when a plentiful supply of ground water unsaturated with $Ca(HCO_3)_2$ reached cavern level. This condition does not prevail now when only small amounts of vadose water normally occur in the caverns. The large volume of dissolved limestone represented by the caves therefore probably points to a climate decidedly more humid than today, and probably than that which preceded it. As suggested above, the levelness of the caves may indicate that this humid climate was contemporary with a sea level that stood approximately 20 to 25 feet higher than today.

GUANO ACCUMULATION

The excavation of the caverns was followed by a period during which they were inhabited by bats in large numbers and during which guano accumulated. By this time the water table and sea level had fallen below the level of the cavern floor. The climatic implications of the Isla Mona guano are not clear. It is certain, however, that bats were more abundant in the past than they are today, and we may assume that this was so because living conditions were more favorable. As to what precisely constituted a more favorable environment for the responsible species of bat is a moot question. It may have been a more plentiful food supply, and if a fish-eating bat like *Noctilio* was mainly responsible, it probably was more abundant life in the surrounding waters. It is speculated that the climate might have been somewhat more humid than at present. This is based simply on the fact that the rainfall of most places in which the genus *Noctilio* is found (eastern Caribbean, Central and northern South America) is higher than that of Isla Mona today. Possible support for this hypothesis is the advanced degree to which the deposits have been leached and which points to a fair amount of water having percolated through the guano before the deposition of the overlying nonphosphatic dripstone.

DRIPSTONE DEPOSITION

The interval of guano deposition was apparently terminated rather abruptly throughout the island and was followed by the deposition of dripstone in the caves. Since that time the old guano deposits have been entirely covered by a dripstone pavement and the bats have largely deserted the island. This was possibly brought about by a rather abrupt change in climate to greater aridity (humid caves inhibit evaporation and therefore the formation of dripstone). Just when in the Quaternary this change occurred is of course not known, but the suggestion is offered that it might have been at the close of the postglacial warm interval (the "Hypsithermal" of Deevey and Flint, 1957) about 2,600 years ago. The dripstone interval has apparently continued to the present, though probably with minor fluctuations in climate and, therefore, in rate of dripstone accumulation.

HISTORICAL CLIMATES

Some consideration should be given to the former fertility of Isla Mona as reported by early observers (p. 145), which when taken at face value indicate a more humid climate in the late 15th, 16th, and 17th centuries than at present. The historic facts reflecting on the former fertility of Isla Mona are puzzling and peculiarly provoking to anyone acquainted with Isla Mona today. The island was a provisioning and watering station during earlier centuries, although today no springs capable of providing an ample and reliable source of water are known. The writer knows of no permanent bodies of water in the caves; except for some slow dripping and associated shallow puddles, the caves are rather dry. Exception to this condition is to be expected, however, during and after heavy rains, when much water probably enters the caves (the writer has not witnessed a heavy shower on the island). Even about this there is some uncertainty, for there are few signs of erosion of the soft, earthy phosphorite deposits that are exposed on the floors of many caves as a result of previous mining operations. It is possible, however, that provident Indians and others in the past provided catchments beneath some of the more important seepage points in the caves, and that the water thus accumulated was enough to satisfy the requirements of an occasional ship. Surface water on the tableland exists today as small ephemeral pools, rarely more than a few inches deep, in shallow depressions in unjointed limestone. Small quantities of slightly brackish water can be had from shallow dug wells on the low coastal terrace near Punta Oeste.

As to fertility, the thin sandy, and in places stony, soil of the coastal terrace between Desembaradero Uvero and Anclaje Sardinero was farmed until the first decades of this century but apparently with only modest success. No orange trees grow on Mona Island today as was reported by Johannes de Laët (1640, p.5); and there is little reason to think that they would do well, although according to F. H. Wadsworth (oral communication) melons, which De las Casas tells about, (p. 145) were grown at "La Sardinera" during the life of the Civil Conservation Corps camp. The sparse red soil on the tableland, to which the early chroniclers seemed to refer, may grow yucca, but the writer does not know of any recent attempts at yucca culture.

Brooks (1949, p. 281–359) has summarized what is known about climatic changes during historic time and cites several well-known examples of reported and inferred climatic shifts in both hemispheres. Although it is unfortunate that no data relating to Recent climatic changes have been collected in the Carribbean, the fluctuations of not too distant Yucatan furnish an interesting example of what has taken place in climates of the subtropical latitudes. The climatic fluctuations of Yucatan are known from archeological interpretation of the Mayan civilization. Three wet and three dry periods are thought to have occurred from about 500 B. C. to the present. The last of these, a wet period, began about 1400 A. D.

It is interesting that the Yucatan climatic periods were roughly duplicated in western United States, as revealed in the tree-ring studies of Ellsworth Huntington and others (see Brooks, 1949, and Zeuner, 1950, for a summary of this), but in an opposite sense—that is, a dry period in one place was roughly contemporary with a wet period in the other. This clearly points to the fact that local or regional factors condition the nature of these short-term climatic trends, although their broad outline and periodicity may depend on more far-ranging forces.

As to Isla Mona, all that can be said is that the historical record suggests a climatic change to greater aridity within the last 2 or 3 centuries, although, without supporting data from other parts of the Antillean region, one can not press this interpretation. There is indicated here, however, a fruitful field for further investigation.

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