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ECONOMIC GEOLOGY OF THE ISLA DE MONA QUADRANGLE, PUERTO RICO,

~~GEOLOGIC SETTING AND EVALUATION OF CAVE-PHOSPHORITE~~

~~DEPOSITS ISLA DE MONA QUADRANGLE, PUERTO RICO~~,

~~WITH NOTES ON OTHER RESOURCES~~

by

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Prepared in cooperation with the

Commonwealth of Puerto Rico, Department of Natural Resources

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GEOLOGIC SETTING AND EVALUATION OF CAVE-PHOSPHORITE DEPOSITS ISLA DE MONA QUADRANGLE, PUERTO RICO, WITH NOTES ON OTHER RESOURCES

by

Reginald P. Briggs

Abstract

The Isla de Mona quadrangle contains two islands, Isla de Mona (area 54.7 km^2) and Isla Monito (area 0.16 km^2), in the south-central part of the Mona Passage, about midway between the Greater Antilles islands of Puerto Rico and Hispaniola.

The very thick and thick-bedded Isla de Mona Dolomite of middle Tertiary age is the oldest bedrock unit in the area; its base is concealed by the sea, but a thickness of more than 80 m is exposed on Isla de Mona. Resting on the Isla de Mona Dolomite is the generally very thick bedded Lirio Limestone which locally may be 40 m thick. The age of the Isla de Mona Dolomite probably is Miocene throughout, and its top is middle Miocene in age. The Lirio Limestone also probably is Miocene in age. On Isla de Mona these two units underlie a rather flat and rocky upland surface that has a very rough micro-relief and sparse small patches of lateritic red earth.

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Limiting this tableland in the northern part of Isla de Mona are sheer sea cliffs chiefly exposing the Isla de Mona Dolomite. Around the southern part of the island are irregular cliffs and steep slopes that chiefly expose the Lirio Limestone.

The structure of Isla de Mona consists of two gentle complex folds--a broad anticline that trends and plunges gently south-southeast through the central and western parts of Isla de Mona, and a parallel syncline through the eastern part of the island that also has a chiefly south-southeast plunge. A near-vertical fault that strikes northwest, then north from the central part to the north coast of Isla de Mona displaces bedrock of the eastern block downward about 10 m.

Many caves, including one cave system more than 100,000 m^2 in total area, are localized in the lower 10 m of the Lirio Limestone, adjacent to the cliffs peripheral to the upland surface, and numerous small caves occur higher in the Lirio. A few small caves also are found in the Isla de Mona Dolomite. However, the total floor area of all caves on Isla de Mona probably is less than 1 percent of the area of the island.

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Almost all caves on Isla de Mona contain phosphorite, which was mined extensively during the late 19th and early 20th centuries. Phosphorite accumulation locally may have exceeded 3.5 m in thickness, but probably averaged less than 1.5 m thick. A fair estimate of original reserves of phosphorite in 12 surveyed caves is about 151,000 m^3 of which about 125,500 m^3 probably has been removed in mining. Original reserves in the entire island are estimated to have been in the range 158,000 to 235,500 m^3. Converted to metric tons, remaining reserves of cave phosphorite probably are considerably less than 50,000.

The very pure limestone and calcitic dolomite that form the bedrock of Isla de Mona are abundant industrial-mineral resources. In addition, these carbonate rocks and the beach deposits are sources of construction materials for some classes of engineering works.

The structure of Isla de Mona suggests some possibility of favorable zones for accumulation of oil and gas, but no source rocks are known, and there are no confirmed reports of oil and gas from any nearby area.

Known supplies of fresh water on Isla de Mona are very small, but wells dug in coastal lowlands or drilled in the upland surface might yield moderate quantities of groundwater.

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Introduction

The Isla de Mona 7 1/2-minute quadrangle contains the large carbonate island named Isla de Mona and a small companion island, Isla Monito, about 4.8 km to the northwest. From a distance, Isla de Mona appears flat and cliff-girt (fig. 1) and Isla Monito

---

Figure 1 near here

---

is a small replica. Isla de Mona has an area of 54.7 km^2; Isla Monito, about 0.16 km^2. Isla de Mona is centered approximately in the southern part of Mona Passage, which separates the Greater Antilles islands of Puerto Rico and Hispaniola; it is about 71 km due west of Puerto Real, P. R. and 67 km nearly due east of Isla Saona, Dominican Republic (fig. 2). Politically, the islands

---

Figure 2 near here

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are part of the Municipio (municipality of) Mayagüez, P. R. The Isla de Mona quadrangle is bounded by long. 67°50' W. and 67°57'30" W., and by lat. 18°02'30" N. and 18°10' N.

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Figure 1.--Isla de Mona from the east-northeast. Line near top of figure is the horizon. Punta Este and light station are in left foreground. Punta Arenas is in center background. Note the sheer cliffs from Punta Este around the north coast of the island and the flatness of the upland surface. Photographed by F. H. Wadsworth from altitude of 1,850 m.

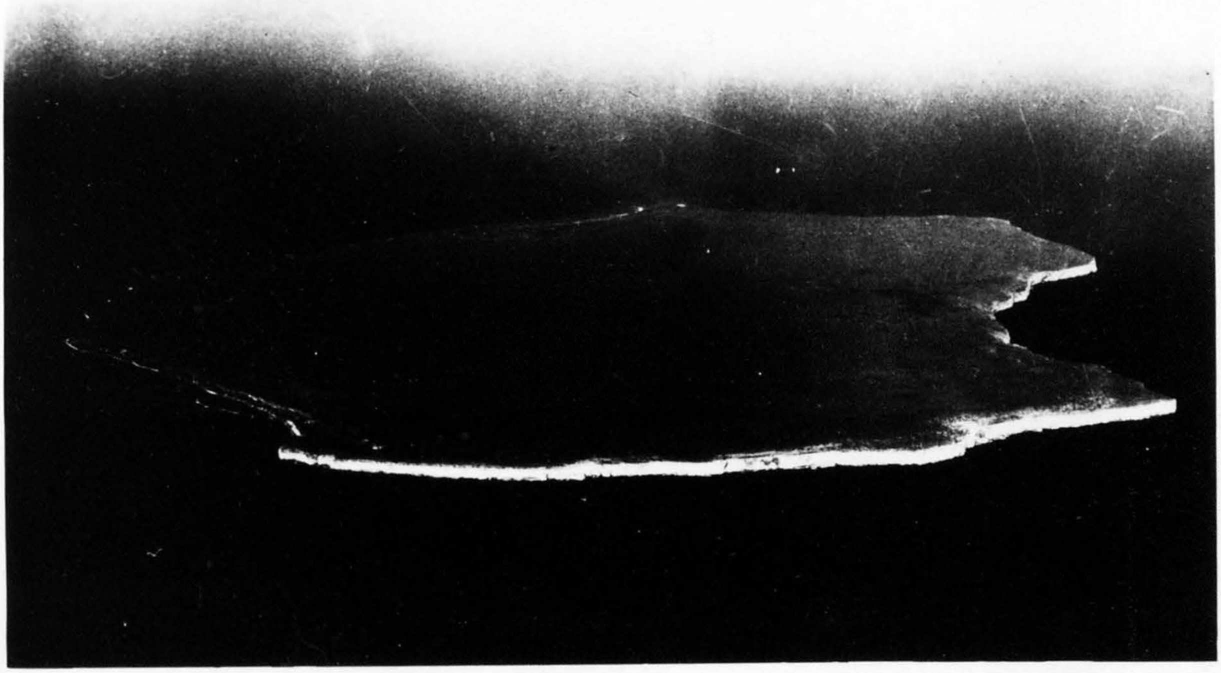

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Figure 2.--Map of Mona Passage showing location of the Isla de Mona quadrangle.

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The geology of the quadrangle is represented on a small-scale geologic map (fig. 3) in this report; a large-scale (1:20,000)

Figure 3 near here

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geologic map of this area has been published separately as U. S. Geological Survey Miscellaneous Geologic Investigations Map I-718 (Briggs and Seiders, 1972). In addition, an earlier intermediate-scale geologic map (Kaye, 1959, plate 12) shows some features not included on the large-scale map. It is recommended that the reader obtain these two maps for reference while reading this report.

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Figure 3.--Generalized geologic map of the Isla de Mona quadrangle.

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Purpose and scope of report

Since the mid-1940's, the U. S. Geological Survey has maintained several cooperative resource programs with the Government of Puerto Rico. In 1955 a program of detailed geologic mapping was begun in cooperation with the Puerto Rico Economic Development Administration (PREDA). Although the chief emphasis of this mapping program has been on the main island of Puerto Rico, in 1964 a situation arose which directed attention toward Isla de Mona. Between 1960 and 1964, two studies were made of the cave phosphorites of the island. The report of one study indicated a very large reserve of phosphorite, whereas the other investigators reported that Isla de Mona contained essentially no economically recoverable phosphorite.

To resolve these conflicting estimates, PREDA requested that the U. S. Geological Survey reappraise the mineral resources of Isla de Mona, paying particular attention to the phosphorites. In response to this request, V. M. Seiders and the present writer spent 32-1/2 days on Isla de Mona between July 29 and September 8, 1964.

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Seiders is co-author, with the present writer, of the large-scale geologic map of the Isla de Mona quadrangle (Briggs and Seiders, 1972). He was reassigned to other work before the present report was done, so unfortunately he was not able to take part in its preparation. To indicate the extent of his participation in the field work, the second person plural is used widely in the text for joint experiences and observations. The present writer, of course, bears sole responsibility for conclusions and interpretations.

We found that stratigraphy and structure were of greater influence on the locations of phosphorite-bearing caves than had been reported previously, so it was necessary to engage in a more general study than originally planned in order to arrive at a meaningful estimate of phosphorite reserves. One reflection of this expanded investigation is the large-scale geologic map, and another is in the scope of the present report. Herein emphasis is on the stratigraphy, on the caves the development of which was controlled by stratigraphy, and on the formerly economic phosphorite deposits in the caves. However, in order to accommodate new data not reported elsewhere and to give the reader a better idea of the setting, some other facets of the general geology also are dealt with. In addition, the potential for mineral resources other than phosphorite is described briefly, and the problem of water supply is considered.

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Aspects of the geology that were treated in detail by Kaye (1959) are touched on only briefly, except where new data is involved or where there is a direct bearing on the cave-phosphorite deposits. For these aspects the reader is referred to his report. The present report therefore may be considered a sequel to that of Kaye (1959).

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Acknowledgments

Many organizations and individuals facilitated our field work in the Isla de Mona quadrangle. Carlos Vincenty, Director, and Leovigildo Vázquez, Geologist of the Department of Industrial Research, PREDA, arranged for the transportation of a vehicle to Isla de Mona; F. S. Nishwitz of the U. S. General Services Administration made a suitable vehicle available; the late Lieutenant Armando Hernández and Officer Luis A. Ramírez of the Police of Puerto Rico were helpful in many ways on Isla de Mona, especially in assisting in the search for correct geographic names; kind permission to reside at the Mona Island (Isla de Mona) Light Station was granted by Captain Robert Wilcox, Commander, Greater Antilles Section, U. S. Coast Guard; and U. S. Coastguardsmen Buenaventura Vélez, Víctor González, Fernando Plá, and Paul Ruel were gracious hosts and lent assistance in other ways.

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Major E. H. Speaks, and Captains Conrow and Cate, Antilles Aviation Section, U. S. Army, flew us to and from Isla de Mona on four occasions; and the U. S. Coast Guard cutter Point Slocum, Chief Horace J. Smith commanding, twice transported us and our equipment between Puerto Rico and Isla de Mona. Frank H. Wadsworth, U. S. Forest Service, assisted us with geographic names and the phosphorite mining history. In addition, Dr. Wadsworth kindly granted permission to use some of his photographs, reproduced herein as figures 1, 6, 7, 10, and 13. W. H. Monroe, U. S. Geological Survey, made many useful suggestions concerning interpretation of karst features on Isla de Mona.

Many other people were helpful, too many to credit individually. In short, the present study of the resources of the Isla de Mona quadrangle depended upon the cooperation of many, and this aid is gratefully acknowledged.

Previous work

Recent geologic studies on Isla de Mona were undertaken by C. A. Kaye of the U. S. Geological Survey, who made four trips to Isla de Mona between 1949 and 1952 (see Kaye, 1959); J. F. Cadilla and Leovigildo Vázquez of PREDA, who spent two weeks on Isla de Mona in September and October, 1960; J. D. Weaver, of the University of Puerto Rico-Mayagüez, who briefly visited Isla de Mona in 1960; and A. D. Fraser and W. R. Bergey, representing private interests, who visited the island in early 1964 expressly for the purpose of examining the phosphorite deposits.

Earlier descriptions of caves, the phosphorites, phosphate minerals, and other features of Isla de Mona and Isla Monito were by Monclova (1879), Nuñez Zuloaga (1879), Tejada (1880), Shepard (1882), Kuhfal (1892), Hübener (1898), Domenech (1899), Klein (1901), Gile and Carrero (1918), Lobeck (1922), and Frondel (1943). The observations of some of these were discussed by Kaye (1959), and others are referred to herein.

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Kaye's report (1959) includes a petrographic study of the phosphorites by Z. S. Altschuler, and a brief history of the mining operations. He estimated that total shipments of phosphorite from Isla de Mona did not exceed 50,000 tons and that "only a small percentage of the cave phosphorite" had been mined (Kaye, 1959, p. 156). J. F. Cadilla and Leovigildo Vázquez in an unpublished report to PREDA (written commun., 1961) reported that about 1 million short tons of phosphorite remained on Isla de Mona. Weaver (1961; written commun., 1962) made no specific comments on the remaining phosphorite deposits. No written report was prepared by A. D. Fraser and W. R. Bergey, but they concluded that Isla de Mona contained insufficient phosphorite for economical extraction, probably less than 50,000 tons (oral commun., W. R. Bergey, 1965). In an historical sketch of Isla de Mona, Wadsworth (1954) quoted records which indicate that more than 90,000 metric tons of phosphorite was removed.

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Methods of study

In preparation for our work on Isla de Mona we studied the available literature and the excellent 1963 aerial photographs (approximate scale 1:20,000) of the U. S. Department of Agriculture, Soil Conservation Service.

Other preparatory work included arranging for local accommodations and for the transportation of supplies, equipment, vehicle, and ourselves to the island. These arrangements required more than the usual effort, for Isla de Mona is virtually a desert isle; water is scarce, and all food must be brought in. At the time of the investigation the only persons living on the island were there on government tours of duty, three men at all times at the Mona Island Light Station and a small varying group of representatives of the Puerto Rican government at Playa Sardinera (fig. 3).

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In the field hard hats and flashlights were carried at all times so that we could reconnoiter any caves encountered on surface traverses. This procedure allowed us to eliminate many small caves from our plans for underground traverses. Detailed investigation of large caves normally was assigned to the morning of a following day, when we could return more completely equipped. Because we had been warned of the strong possibility of attack by feral boars, wild remnants of a former domestic pig colony, we also carried firearms. In our Isla de Mona experience, these proved unnecessary, and unwelcome burdens in the field.

In addition to dilute hydrochloric acid, the following reagents were carried:

1. a solution of 0.002 g of rho-nitrophenyl-azoresorcinal in 100 ml of 2N sodium hydroxide,
2. an ammonium molybdate solution,
3. a benzidine solution.

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Reagent 1 is used in a spot test for magnesium. Dilute HCl is first applied to the rock to be tested. After the acid reaction is completed, reagent 1 is applied. Initially pale purple, reagent 1 changes to a distinctive blue in the presence of magnesium ions. The rapidity of this reaction and the resulting shade of blue is dependent on the magnesium ion concentration. This spot test is a modification of the test described by Mann (1955); the modification (by Celeste Pérez, PREDA, and Zaida Rosado, Central Concessions, Ltd.) consists of the substitution of rho-nitrophenyl-azoresorcinal for rho-nitrobenzene-azoresorcinal. This spot test was used very often in the early stages of investigation, but less frequently later on as we became more familiar with the carbonate rocks of the island.

The other two reagents were intended to be used in a spot test for phosphates, but they proved of no value. The test, abbreviated by the present writer from that of Feigl (1954, p. 305-306) on the basis of laboratory experiments, was a failure in the field, yielding results not borne out by later analyses.

About two-thirds of the working time on Isla de Mona was spent in mapping on the surface, the remainder underground, investigating the caves. For the most part we worked together, but some one-man traverses of moderate length were undertaken.

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Surface traverses totalling more than 60 km were made on foot around the whole periphery of Isla de Mona, up and down the cliffs of the southern part of the island at several places, into the island's interior to Bajura de los Cerezos, Cuevas del Centro (fig. 4), and a

Figure 4 near here

few other areas, and across the coastal lowlands and boulder deposits at several places. The only inland place not reached that looked promising for caves on the basis of aerial photographic studies was Los Corrales de los Indios (fig. 4). Two attempts to reach this feature from the south and east were abandoned because dense thornbush and cactus slowed our movements drastically. A third attempt, an approach from the north, was planned but not made because the aircraft coming to pick us up the final time arrived a day earlier than was expected. A. D. Fraser and W. R. Bergey did reach Los Corrales de los Indios, however, and Bergey (oral commun., 1965) was able to describe the area to the present writer in some detail.

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Figure 4.--Map of Isla de Mona showing areas pictured stereoscopically in figures 5, 8, 9, 12, and 14 and locations of caves and features of the upland surface. Roman numerals identify surveyed caves: I, Cueva de las Losetas; II, Cueva al lado del Faro; III, Cueva del Lirio; IV, Cueva de los Pájaros; V, Cueva de la Casa de Erickson; VI, Cueva de la Playa Brava; VII, Cueva de Doña Geña arriba; VIII, Cueva Negra; IX, Cueva del Diamante; X, Cueva del Esqueleto; XI, Cueva del Capitán; XII, Cueva de la Esperanza.

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Low-level air reconnaissance on five occasions during approaches to and departures from Isla de Mona afforded the only relatively close-up first-hand views of Los Corrales de los Indios and Isla Monito.

Through the kindness of the U. S. Coast Guard personnel at the light station, we were able to circumnavigate Isla de Mona at close range in a small boat, approaching the sea cliffs as closely as 5 m at one point. There was danger in going closer because waves reflected from the cliffs reinforced those approaching, producing a dangerous short-wave-length, high-wave-height chop. This boat trip was especially valuable in gaining some insight into the nature of the lower Isla de Mona Dolomite, which was otherwise inaccessible.

Cave surveys were accomplished chiefly by compass and tape, supplemented by compass-and-pace or other approximate methods. Compass-and-tape cave traverses totalled about 5 km in length, and approximate and reconnaissance traverses probably were double this figure. Many cave-survey stations were marked with aluminum foil. Stations so marked in less accessible parts of caves may be recoverable for some time into the future.

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Early in the cave surveys it was concluded that the time available precluded detailed mapping of all passages, pillars, columns, walls, pits, rubble piles, and other features. The method generally adopted therefore included firstly a rapid but thorough reconnaissance of each cave to discover its general plan and maximum extent in all directions, in particular attempting to go inland from the cliffs of the island as far as possible. Then these extremes were surveyed in conjunction with examination of cave deposits and extent of mining. The resulting maps, some of which are included in figure 16, thus show only the maximum limits of cave development; the details of passages, columns, and other features are omitted.

The Isla de Mona caves are safe to work in if moderate caution is used. The few abrupt changes in the level of the cave floor are primarily where phosphorite had been mined. Except for the passages that are most remote from the sea cliffs, headroom commonly is sufficient for a man to walk upright. A few bats and one scorpion were seen, but in general animal life in the caves is sparse. Ropes were found unnecessary. Battery-powered head lamps, hand flashlights, extra batteries, and, for possible emergencies, candles and matches were carried for illumination during the cave surveys. A cumbersome gasoline lantern carried at first proved unnecessary, as there is at least some slight light in most Isla de Mona caves.

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Special climbing gear and climbing experience would be necessary to investigate the northern sea cliffs closely, but we had neither of these. In any case, the information gained from such work would not have repaid the cost in time and effort, in view of the limited time available for the present study.

Because of the extensive sampling done by previous workers and the thorough petrography done by Altschuler (in Kaye, 1959, p. 157-162), no general sampling program was planned; rather, we concentrated on making a good estimate of the original and present reserves of phosphorite. The final estimates are based on the cave surveys and on thickness determinations, which were obtained by measuring exposed sections of phosphorite, measuring phosphorite stains on walls and phosphorite remnants in mined-out areas, and by driving probes.

Aerial photographic interpretation was used to supplement field data, because no consistent geologic contrasts were found during traverses in the interior part of the upland surface (except in Bajura de los Cerezos) owing to the general homogeneity of the rocks and to the dense vegetation. The aerial photographs, however, showed sinuous features on the upland, in addition to lineaments interpreted as joints or faults. Interpretation of the sinuous features as less vegetated outcrops of continuous beds was consistent with field data and was used in elucidating the structural geology.

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Definitions

Geological terms used herein are those in customary usage for the most part, and most require no redefinition. However, terminology related to karst topography is various and sometimes inconsistent. Terms used herein such as cave, cave system, and karren follow the first definition listed by Monroe (1970), unless otherwise noted.

Layering thicknesses are classified as suggested by Ingram (1954). In centimeters: 100 = very thick; 30 to 100 = thick; 10 to 30 = medium; 3 to 10 = thin; 1 to 3 = very thin; 0.3 to 1 = thickly laminated; 0.3 = thinly laminated.

Color designations are based on the "Rock Color Chart" of the National Research Council (Goddard, 1948).

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Geographic names

Early in the present study of Isla de Mona, we discovered that many of the place names shown on the published Isla Mona 7 1/2-minute topographic map are either unfamiliar to persons well acquainted with the area, or are in an unfamiliar form. In addition, places or features for which there are well known names were not labelled on the map. An effort was made therefore to seek geographic names information from several people--notably Lt. Hernández, Officer Ramírez, Coastguardsman González (whose father was keeper of the Mona Island Light Station for more than 17 years), Mr. Vázquez, and Dr. Wadsworth. Geographic names in which these men concurred are given on the geologic and location maps (figs. 3 and 4) accompanying this report and on the large-scale geologic map (Briggs and Seiders, 1972); features for which there was no strong consensus as to names have been left unlabelled.

One surprising result of this collateral study was that the Isla de Mona itself was found to be incorrectly labelled on the topographic map. There was essentially complete agreement that Isla de Mona is the correct form (Junta de Planificación, Urbanización y Zonificación de Puerto Rico, 1948); this name will be used in this report.

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Translations

Place names on the large-scale geologic map (Briggs and Seiders, 1972) and used herein are in Spanish, with the exception of the Mona Island Light Station. The following is a list of these names with their English translations:

Bajura de los Cerezos ---------Lowland of the cherry trees

Cabo Barrionuevo --------------Cape Barrionuevo (named for an early explorer)

Cabo el Toro ------------------Bull cape

Cabo Noroeste -----------------Northwest cape

Camino los Cerezos ------------Cherry-tree trail

Cueva al lado del Faro --------Cave beside the lighthouse

Cueva de Doña Geña arriba -----Upper cave of Doña Geña (a former resident)

Cueva de Frío -----------------Cold cave

Cueva de la Casa de Erickson --Erickson's house cave

Cueva de la Esperanza ---------Hope cave

Cueva de las Losetas ----------Cave of the snares or traps

Cueva del Capitán -------------Captain's cave

Cueva del Diamante ------------Diamond cave

Cueva del Esqueleto -----------Skeleton cave

Cueva del Lirio ---------------Lily cave

Cueva de los Pájaros ----------Cave of the birds

Cueva del Rifle ---------------Rifle cave

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Cueva Negra ----------------------Black cave

Cuevas del Centro ---------------Caves of the center or middle

Isla de Mona --------------------Mona Island (name probably of indian derivation)

Isla Monito ---------------------Little Mona Island

Los Corrales de los Indios ------Indians' corrals

Piedra del Carabinero -----------Customs man's rock

Playa del Uvero -----------------Grape beach

Playa de Pájaros ----------------Birds beach

Playa Sardinera -----------------Beach of the sardines

Punta Arenas --------------------Sands point

Punta Brava ---------------------Heavy seas point

Punta Caigo o no Caigo ----------Point I fall or I don't fall (named for a balanced boulder thereon)

Punta el Capitán ----------------Captain's point

Punta Este ----------------------East point

Punta los Ingleses --------------Englishmen's point

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Locations

In the present report, specific locations are referred to the Puerto Rico rectangular coordinate system, in meters. Reference marks for this system appear on the borders of accompanying small-scale maps and on the detailed large-scale geologic map (Briggs and Seiders, 1972). Cave maps in the present report are located with reference to metric grids based on the Puerto Rico system. Careful attention must be paid to coordinate directions, because the zero east-west datum of this system passes through eastern Isla de Mona.

The two topographic maps of the Isla Mona quadrangle published by the U. S. Geological Survey and the Army Map Service bear reference marks to Zone 19 of the unrelated Universal Transverse Mercator coordinate system, creating a possible source of confusion.

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Stratigraphy of bedrock

Introduction

Kaye (1959, p. 146-147) considered that the Isla Mona Limestone (redefined herein as the Isla de Mona Dolomite) made up most of Isla de Mona and that the overlying Lirio Limestone was only a thin sporadic limestone cap on the Isla Mona Limestone. He stated (Kaye, 1959, p. 147):

"In hand specimen, the Lirio Limestone is indistinguishable from the Isla Mona Limestone. No positive way 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."

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At the start of field work, we first visited Cueva del Lirio (fig. 4, cave III), the type area of the Lirio Limestone (Kaye, 1959, p. 147), to become familiar with rocks typical of that unit; next we went to Playa de Pájaros (fig. 3) where the entire exposed section was included by Kaye in the Isla Mona Limestone. Bedrock in both areas is limestone, and specimens from one area cannot be distinguished from those from the other. The foot of the sea cliff near Punta Este (fig. 3) then was visited, and here, as stated by Kaye, we found calcitic dolomite, in hand specimen different in color, hardness, crystallinity, and in reaction to reagents from rocks at the two localities visited earlier.

This reconnaissance resulted in the tentative conclusion that the identical limestones at Cueva del Lirio and Playa de Pájaros represent one lithostratigraphic unit, whereas the dolomite at the base of the Punta Este cliff is a separate underlying unit. This hypothesis was tested during subsequent traverses.

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Observations over the more accessible parts of Isla de Mona largely were in accord with those of Kaye: Cueva del Lirio-type limestone was found underlying much of the upland surface of the island, in the cliffs at Playa Sardinera (fig. 3), and elsewhere. However, owing to the greater time available for the present study than was available to Kaye, it was possible to cover the island more extensively than he did. New findings include a large outcrop area of calcitic dolomite in Bajura de los Cerezos (fig. 4) and many dolomite outcrops sporadically distributed on the periphery of the island (Briggs and Seiders, 1972).

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Accessible outcrops of the peripheral dolomite are of two chief types--thin anticlinal zones of dolomite in the base of cliffs chiefly composed of limestone between Punta los Ingleses and Playa del Uvero (fig. 3), and small areas of dolomite exposed on the upland surface adjacent to the cliffs of the northern and northeastern coasts (fig. 5).

Figure 5 near here

In addition, we were able to work our way north along the west coast to the base of the sea cliff south of Punta el Capitán, where calcitic dolomite also crops out. In a sense this locality is a mirror image of the Punta Este site, for cavernous limestone is exposed in the upper part of the cliff at both places. Although the northern sea cliffs were inaccessible for sampling purposes, the continuity of bedding and general aspect of the cliffs from Punta Este north around the coast to near Punta el Capitán are plain; with the exception of the thin almost continuous limestone capping at the top, these northern cliffs chiefly expose calcitic dolomite.

In short, island-wide observations of field relations confirm the presence of two distinguishable bedrock units, a pure limestone unit resting on a unit largely composed of calcitic dolomite.

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Figure 5. Stereogram showing Punta Este and Mona Island Light Station. Top is North. Scale approximately 1:20,000. Isla de Mona Dolomite crops out in the cliffs and in the sparsely vegetated light-colored area near the north edge. Remainder of upland surface shown is underlain by Lirio Limestone. Note sheer cliffs, collapse sink in Cueva del Lirio cave system just west of Punta Este, collapse area southeast of the light station, and boulders in the sea north of the light station. U. S. Department of Agriculture Soil Conservation Service photographs ELT-4DD-163 and -164. Location shown on figure 4.

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Kaye (1959) named the Lirio Limestone at Cueva del Lirio. In the present report this name is extended to include all limestone of the Cueva del Lirio type on Isla de Mona, much of which formerly was included in the Isla Mona Limestone by Kaye (1959) along with the calcitic dolomite at Punta Este. The name Isla de Mona Dolomite is used in this report for all of the calcitic dolomite on the island as distinct from the overlying limestones of the Lirio Limestone.

The two bedrock units are not separated on the accompanying small scale geologic map (fig. 3), because the chief Isla de Mona Dolomite outcrops, with the exception of those in the Bajura de los Cerezos (fig. 4), are in the peripheral cliffs of the island and thus cannot be shown at the scale of the map. The units are separated on the large-scale geologic map (Briggs and Seiders, 1972) and in the geologic sections accompanying that map.

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Tertiary System

Miocene Series

Isla de Mona Dolomite

The Isla Mona Limestone, first described by Kaye (1959, p. 146), is here redescribed and renamed the Isla de Mona Dolomite.

The change in locality name results from the study of geographic names referred to earlier. The lithologic term is changed because the formation is composed largely of dolomite rather than limestone.

Kaye designated no type locality. The type locality is here defined as the point sampled by Kaye (1959, p. 146, table 1, sample 1) at the base of the cliff 300 m west of Punta Este (28,300 m N; 2,600 m E), the farthest east one can go dry-shod long the base of the cliff. Samples M-8A and M-8B (table 1), which were collected at this

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Table 1 near here

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locality proved to be calcitic dolomite of the classification of Pettijohn (1949, p. 312).

Two limestone samples collected by Kaye (1959, p. 146, table 1, samples 2, 3) from localities near Playa de Pájaros were included by him in the Isla Mona Limestone, but strata at these localities are included in the Lirio Limestone of the present report.

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Most of the Isla de Mona Dolomite is composed of hard, but locally chalky, finely crystalline calcitic dolomite (table 1, all samples except M-14), which is slightly to moderately fossiliferous, very pale orange to moderate orange pink, and apparently impermeable. Locally near its upper contact, the Isla de Mona Dolomite contains dolomitic limestone (table 1, sample M-14), and two apparently continuous 2 m to 5 m thick stratigraphic intervals approximately 15 m and 50 m stratigraphically below the upper contact also are less dolomitic. These two intervals contain virtually all the caves formed by solution of Isla de Mona Dolomite strata.

The calcitic dolomite norms in table 1 may be misleading as to the actual calcite content of this rock. Dolomites from northern Puerto Rico that contain 18.0 percent MgO contain no calcite according to X-ray studies; the excess CaO probably is included in the dolomite mineral lattice (W. H. Monroe, written commun., 1969). Similarly, calcitic dolomite of the Isla de Mona Dolomite may contain no calcite or less calcite than is indicated by the norms; certainly, effervescence from dilute hydrochloric acid was minor in many parts of the formation, and some rocks from the Isla de Mona Dolomite did not effervesce.

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As noted by Kaye (1959, p. 146, table 5) the insoluble fraction of Isla de Mona Dolomite rocks is very small. Nine of the 14 samples analyzed for the present report contained no detectable SiO_2, Al_2O_3, or Fe oxides; the other five samples ranged from 0.16 to 1.29 percent SiO_2+Al_2O_3+Fe oxides, averaging only 0.52 percent (table 1). The average for 14 samples of the Isla de Mona Dolomite is only 0.19 percent SiO_2+Al_2O_3+Fe oxides.

The sulfur content of these samples (table 1) yielded values of normative gypsum from 0.24 to 4.3 percent, averaging 1.3 percent. The significance of this sulfur content is not known; available analyses indicate only that the Isla de Mona Dolomite contains appreciably more sulfur than does the Lirio Limestone. No iron sulfides were observed in the Isla de Mona Dolomite.

Semiquantitative analyses detected only six minor elements. No significant differences were noted from sample to sample (table 1).

Beds in the Isla de Mona Dolomite commonly are 3 to 5 m thick and locally are as much as 10 m thick. In the lower Isla de Mona Dolomite in the northern sea cliffs, cross beds about 10 to 20 cm thick were observed dipping west and southwest at angles steeper than the thicker beds of which they are a part (Briggs and Seiders, 1972).

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At Punta Este, thick and very thick beds that dip southwestward away from the Lirio Limestone-Isla de Mona Dolomite contact at small angles were interpreted by Kaye (1959, p. 147, pl. 13A) as an angular unconformity. An alternative interpretation of this relation is that these southwest dipping beds are large scale crossbeds, for they dip in the same direction as the smaller scale crossbeds just described, and the contact may be essentially conformable. Close examination did not resolve this question, because sedimentary relations at the contact generally are obscured by fine-grained recrystallization that most likely is the result of surface casehardening and the action of waters migrating along the Lirio Limestone-Isla de Mona Dolomite interface.

Where the contact is discontinuously exposed in the cliffs on the western and southeastern shores of Isla de Mona, examination from a distance yields the impression that the lower few meters of the Lirio Limestone of the present report may grade laterally in a generally northeastward direction into the upper Isla de Mona Dolomite. Where the contact was accessible for close examination, no lateral gradation was seen, though such a relation remains a possibility.

The full thickness of the Isla de Mona Dolomite is not known because its base is concealed by the sea. The maximum exposed thickness of slightly more than 80 m is on the west side of the fault just east of Cabo Noroeste (fig. 3).

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Age.--The fossils on which Kaye (1959, p. 146) based a probable Miocene age for his Isla Mona Limestone came from a locality placed within the Lirio Limestone of the present report. Kaye (1959, p. 157) did not report any fossil identifications from his sole dolomite sample; and, of the localities we sampled, only two in the Isla de Mona Dolomite have yielded identifiable fossils.

Locality M-14 is 1 m below the Lirio Limestone-Isla de Mona Dolomite contact on the south-central coast of the island (25,560 m N; 530 m W). The analysis of a part of the sample from this locality (table 1) classifies the rock as dolomitic limestone rather than the more common calcitic dolomite. During thin-section studies for a collateral sedimentological study, John M. Aaron (oral commun., 1970) discovered that the sample contains unrecrystallized microfossils, and referred the thin section for fossil identification to Emile A. Pessagno, Jr., of the University of Texas at Austin. Pessagno identified the following fauna:

Foraminifera

Globorotalia foshi s.l. Bolli

Orbulina universa d'Orbigny

Biorbulina bilobata d'Orbigny

Orbulina suturalis Bronniman

He assigned this assemblage to the middle middle Miocene (E. A. Pessagno, Jr., written commun., 1970).

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The other fossil-bearing locality found in the Isla de Mona Dolomite is on the west coast (locality M-22B: 30,870 m N; 6,590 m W), about 40 m below the Lirio Limestone-Isla de Mona Dolomite contact. A collection from this locality (USGS fossil collection 24634) was examined by Druid Wilson, U. S. Geological Survey. He found it to contain:

Pelecypoda

- *Barbatia* (*Acar*) sp.
- "*Pecten*" sp.
- codakiid (?)
- cardiid
- venerid
- tellinid

Gastropoda

- *Astraea* sp.
- *Turritella* sp.
- *Vexillum* sp.
- *Bulla* sp.
- marginellid
- fissurellid
- cerithiid

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He concluded that the collection afforded no basis for precise age designation; all the listed forms except Vexillum sp. might well be identified with species living in the Caribbean Sea today (Druid Wilson, written commun., 1969).

In summary, of two fossil collections from the Isla de Mona Dolomite, as defined herein, one from the top is firmly dated as middle middle Miocene whereas the other is described only as having a youthful aspect. Because the exposed Isla de Mona Dolomite is only moderately thick, it is reasonable to conclude that all the exposed rocks of this formation are entirely Miocene in age, and possibly all may be middle Miocene in age.

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Lirio Limestone

The Lirio Limestone was named by Kaye (1959, p. 147) for Cueva del Lirio near Punta Este. Cueva del Lirio-type limestone underlies most of the upland surface, forms most of the southern cliffs, and crops out as a thin layer at the top of most of the northern cliffs (figs. 6, and 7). In the northern cliffs from the

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Figures 6, and 7 near here

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chief fault (fig. 3) east to Cabo El Toro, for example, the Lirio is continuous but ranges in thickness from about 1 to 10 m. In the present report, all Cueva del Lirio-type limestone on the Isla de Mona is included in the Lirio Limestone.

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Figure 6. Cliff face on northwest coast. Cliff here is about 60 m high. Base of line of cave mouths near top of cliff marks contact of Lirio Limestone and underlying Isla de Mona Dolomite. Such expression is common from Punta Este around the north coast to Cabo Barrionuevo. Planar upland surface is slightly modified by gentle undulations to left, north of Bajura de los Cerezos. Note well-developed sea-level nip and, in the right center of scene, suggestions of a slightly higher nip (6 m?). Photographs by F. H. Wadsworth.

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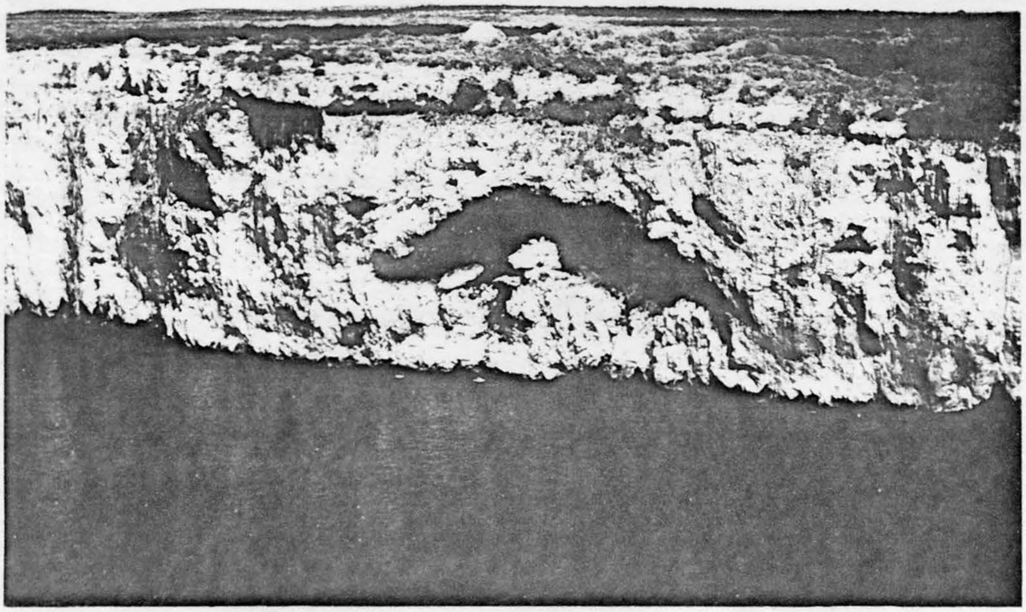

Figure 7. Collapse area in Lirio Limestone just north of Punta Este. Mona Island Light Station to right. Isla de Mona Dolomite cliff rises vertically more than 40 m. Essentially horizontal Lirio Limestone, in place, forms rim of collapse area. Chief access to Cueva del Lirio is through large cave mouth at left (a). One entrance to Cueva al lado del Faro is the large, partly brush-concealed, cave mouth to the right on the path from the light station to the collapse area (b). Note well-formed nip at sea level. Isla Monito visible in upper right corner. Photography by F. H. Wadsworth.

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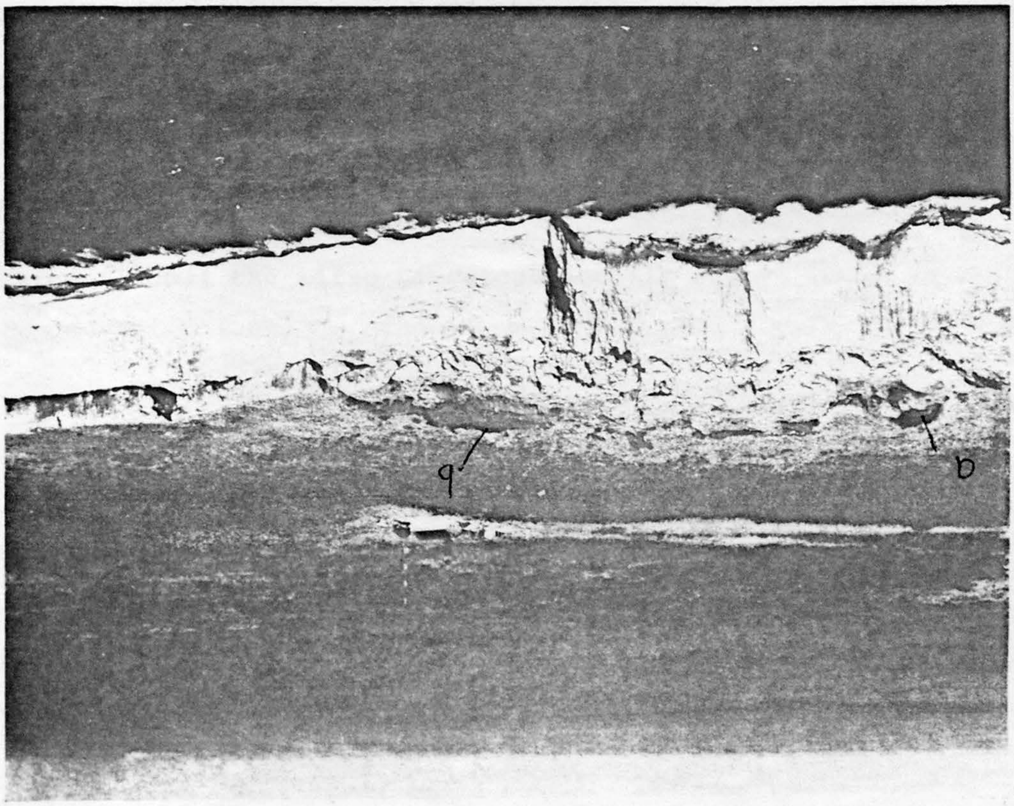

According to the classification of Pettijohn (1949, p. 312) the Lirio Limestone ranges in composition from limestone to magnesian limestone (table 2). In most outcrops the Lirio is a hard fine-

Table 2 near here

grained rock that is very pale orange to grayish orange pink on fresh surfaces but light to medium gray on weathered surfaces. The hardness of the limestone may be deceptive, for at a few localities in irregular cliffs well below the upland surface the Lirio was found to be somewhat chalky. It is very possible that the hardness is only surficial, as discussed by Kaye (1959, p. 151), and is due to recrystallization (casehardening) of the upper few meters such as described in the Aymamón Limestone of northern Puerto Rico by Monroe (1966); the Lirio Limestone locally may be chalk at depth.

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According to Kaye (1959, table 1, samples 2, 3; p. 169, table 5, samples 1, 3-7), the Lirio is essentially pure-limestone--insoluble residues ranging from 0.02 to 0.33 percent--and the new analyses in table 2 are in agreement. The sulfur content contrasts with that in the Isla de Mona Dolomite; expressed as normative gypsum, three samples of Lirio Limestone average only 0.52 percent, whereas samples of Isla de Mona Dolomite average 1.3 percent. No iron sulfides were observed in any Lirio Limestone sample. No significant contrast was found between the minor-element content of Lirio Limestone and that of the Isla de Mona Dolomite, except for the somewhat higher strontium content of the Lirio. Probably this higher strontium content simply reflects the higher calcium content of the Lirio (table 1, 2).

At most localities, the Lirio Limestone beds are 2 to 3 m thick, but in some areas, particularly in the lower part of the formation, beds are more than 5 m thick. Locally within the very thick beds, crossbeds 2 to 3 cm thick were observed, most notably in the vicinity of Playa Sardinera (fig. 3) where the crossbeds dip as much as 22° to the west.

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A large-scale textural feature of the Lirio Limestone well illustrated by Kaye (1959, plate 13B) is otherwise normal Lirio Limestone bearing a vermicular structure, wherein tubelike features penetrate the limestone with apparent random orientations. These tubules are about 1 to 2 cm in diameter and may be more than 15 cm in length. Commonly the tubules contain reddish-brown to moderate-red clayey material that ranges from essentially uncemented to completely cemented by calcite. During the present investigation, coral remnants were seen in vermicular limestone tubules near the west end of Cueva del Lirio, so it is likely that all vermicular limestone result from replacement of corals. In addition to these corals, the Lirio was found to be moderately fossiliferous elsewhere; sporadic accumulations of large coral heads that suggest patch reefs were observed in exposures of Lirio Limestone near Cueva del Capitán and Cuevas del Centro (fig. 4; Briggs and Seiders, 1972) and along the northwest coast.

The maximum exposed thickness of the Lirio Limestone of the present report is about 40 m near Playa Sardinera (fig. 3); locally the Lirio may have been somewhat thicker than this, but at some localities it may never have reached 40 m in thickness. Kaye (1959, p. 151) suggested that the limestone of the upland surface, the Lirio Limestone of the present report, may have been at least 26 m thicker than it is now on the basis of a theory of soil genesis discussed in a following section. The Lirio is overlain unconformably by younger deposits.

Caves are a conspicuous feature of the lower part of the Lirio Limestone adjacent to the cliffs, and small caves and solution passages are common throughout the unit; the Lirio is distinctly more cavernous than the Isla de Mona Dolomite, as was noted by Kaye (1959, p. 147). Unlike the Isla de Mona Dolomite which forms relatively smooth sheer to overhanging cliffs around the northern periphery of the island (figs. 6, 7), cliffs in the Lirio tend to be irregular with indentations formed by cave entrances and by solution along bedding planes (Kaye, 1959, pl. 14B). Average slopes of Lirio cliffs approach verticality but overhang only above the more readily weathered beds, cave mouths (Kaye, 1959, pl. 14A), and at some points at cliff tops where the uppermost 2 m or more of hard limestone projects out over friable, or less competent, limestone beds.

Age.--Kaye (1959, p. 147) considered the Lirio Limestone to be no older than Pliocene in age, on the basis of the presence of Monastrea annularis. Since the publication of Kaye's report, however, the age range of this species has been extended; and both J. W. Wells and Druid Wilson (written communs., 1969) now discount Monastrea annularis as a good diagnostic fossil--for example, the Bowden Beds of Jamaica are Miocene in age and contain this species.

The fossils on which Kaye (1959, p. 146, 147) based the age of his Isla Mona Limestone came from Cueva Negra (fig. 4, cave VIII), which is now considered to be in the Lirio Limestone of the present report. Thus, the Miocene age represented by that faunal assemblage is now transferred to the Lirio. Kaye (1959, p. 147) further limited the age of the Cueva Negra rocks to "probably early or middle Miocene," but Druid Wilson (written commun., 1969) now considers that there is no basis for assigning an age older than middle Miocene to this faunal assemblage.

No collections of Lirio Limestone made during the present study have yielded diagnostic fossils or faunal assemblages.

Taking into consideration the firm middle Miocene age of the uppermost Isla de Mona Dolomite, the sparse diagnostic paleontological data from the Lirio itself, and the relative thinness of the unit, the Lirio probably is wholly Miocene in age--no older than middle Miocene, perhaps ranging into the late Miocene.

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Structure of bedrock

In broad perspective, Isla de Mona may be described as a southwest dipping monocline shallowly folded along axes that trend and plunge gently south-southeast; the rocks are well jointed, and two near-vertical faults were mapped. Structure contours drawn on the Lirio Limestone-Isla de Mona Dolomite contact are shown on the large-scale geologic map (Briggs and Seiders, 1972).

Folds.--The chief folds are a broad gently plunging, complex anticline and a subparallel, similarly complex syncline (fig. 3). The anticline trends from the north coast between Cabo Noroeste and Cabo Barrionuevo to the south coast between Punta los Ingleses and Playa del Uvero. In figure 3 this complex anticline is indicated by two continuous anticlinal axes, with minor fold axes between. The southwest flank of the anticline dips moderately; the top of the Isla de Mona Dolomite has an elevation of about 55 m in the area 2 km southeast of Cabo Barrionuevo and an elevation of perhaps 10 m below sea level at Playa Sardinera, an average slope of about 25 m per km. The syncline trends from the north coast between Cabo Noroeste and Cabo el Toro to the Playa de Pájaros area on the southeast coast. The relief from the trough of the syncline to the crest of the anticline is somewhat irregular and complicated by faulting but is on the order of 30 m, or a slope of about 10 m per km. The northeast limb of the syncline rises about 20 m per km to the northeast coast of Isla de Mona.

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Over much of the island the axes of the folds that form the complex anticline and syncline appear to have a plunge of 5 to 15 m per km, chiefly south-southeast; however, no axial plunge is apparent in the northwestern part of Isla de Mona, and the plunge may be slightly reversed in the vicinity of Punta Este.

Faults and joints.--Only two faults were seen on Isla de Mona. The chief fault is vertical and is very well exposed in the sea cliff about 800 m east of Cabo Noroeste (fig. 3). On the east side of the fault, medium and thick beds of the Isla de Mona Dolomite are warped upward against the fault, and the Lirio Limestone occurs as a layer less than 10 m thick at the top of the cliff. As seen from the sea, no Lirio Limestone was observed at the cliff top on the west side of the fault. This observation was confirmed during a foot traverse around the north coast of Isla de Mona. The rock on the east side of the fault zone was found to be limestone (table 2, sample M-33A); that on the west was dolomite (table 1, sample M-33B). Because the fault was inaccessible in the sheer cliff, its displacement could not be measured directly. As estimated from seaward and from the outcrop distribution on the upland surface, the eastern block was displaced downward at least 5 to 10 m relative to the western block.

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This fault could not be traced across the upland surface on foot with any degree of certainty because just a short distance south of the cliff-side exposure the brush is almost impenetrable and the fault apparently cuts only Lirio Limestone, so the rocks on both sides are similar. The trace of the fault, though, can readily be seen as a lineament on aerial photographs, extending southward almost to the western end of the Bajura de los Cerezos (figs. 3, 4, 8). From this

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Figure 8 near here

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point, lineaments on aerial photographs (Kaye, 1959, pl. 12) and joints found on the ground indicate that the fault bends southeastward along the southwest side of Bajura de los Cerezos. Whether there was appreciable movement along this southeastward extension is not surely known, but there probably was at least some displacement, perhaps as much as 10 m down to the northeast. Other lineaments near the point where the fault bends are interpretable as splays off the main fault (fig. 3).

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Figure 8. Stereogram showing trace of chief Isla de Mona fault and northern cliff face. Top is North. Scale approximately 1:20,000. Note low escarpments trending westerly across the fault zone (Kaye, 1959, pl. 12). U. S. Department of Agriculture Soil Conservation Service photographs ELT-4DD-152 and 153. Location shown on figure 4.

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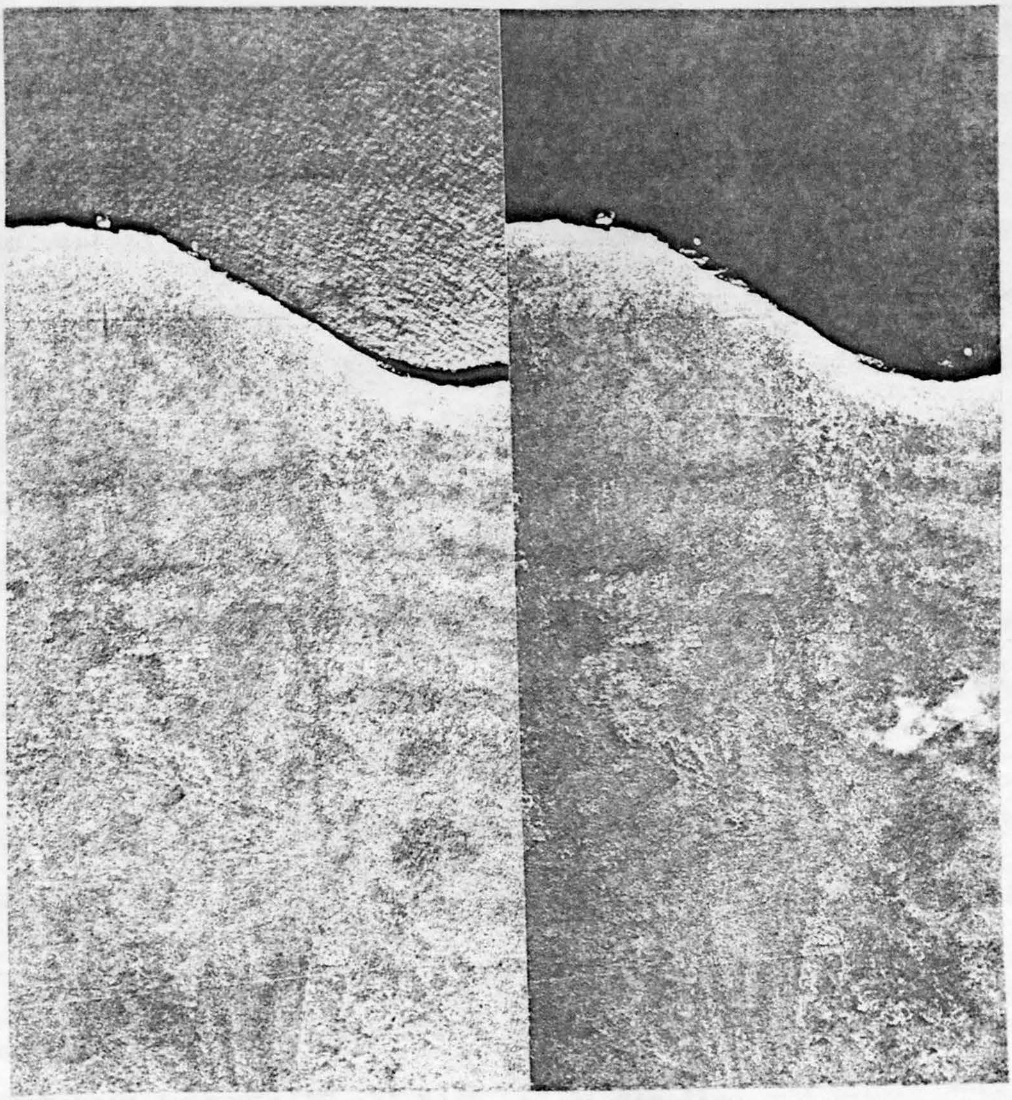

The other fault is at Cabo el Toro (fig. 3); it strikes essentially east-west, apparently is vertical, and has a displacement of less than 1 m, down to the north. The fault plane may not go to depth, but rather it may curve slightly northward to the bedrock-water interface beneath sea level, in effect a joint plane along which a block adjacent to the coast has slipped downward. Although this was the only such fracture in which offset was seen, it may be that this is one method by which Isla de Mona has been reduced to its present size, for joint systems parallel to the cliffs are common features.

A series of vertical joints with spacing of about 1 m is well exposed in the sea cliff between the exposure of the chief fault and Cabo Noroeste; these joints probably were formed in response to the stresses that resulted in the nearby fault. In addition, many cave systems form linear and intersecting patterns, and joints were seen to intersect at a few sink-caves; zanjones (Monroe, 1964), linear zones of alternating bare bedrock and soil-bearing intervening hollows, are moderately common (fig. 9; Kaye, 1959, pl. 12); and joints were seen

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Figure 9 near here

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in bare bedrock at many places. In short, the surface of Isla de Mona is well-jointed terrain, and the joints promote infiltration of rainwater and the solution of limestone.

Figure 9. Stereogram showing Cabo Barrionuevo. Top is North. Scale approximately 1:20,000. Collapse area at Cueva la Esperanza is outlined by semicircular trail segment at north end of north-northeast trending part of trail. Note well-formed northwest-trending zanjones at east edge of picture. U. S. Department of Agriculture Soil Conservation Service photographs ELT-4DD-154 and 155. Location shown on figure 4.

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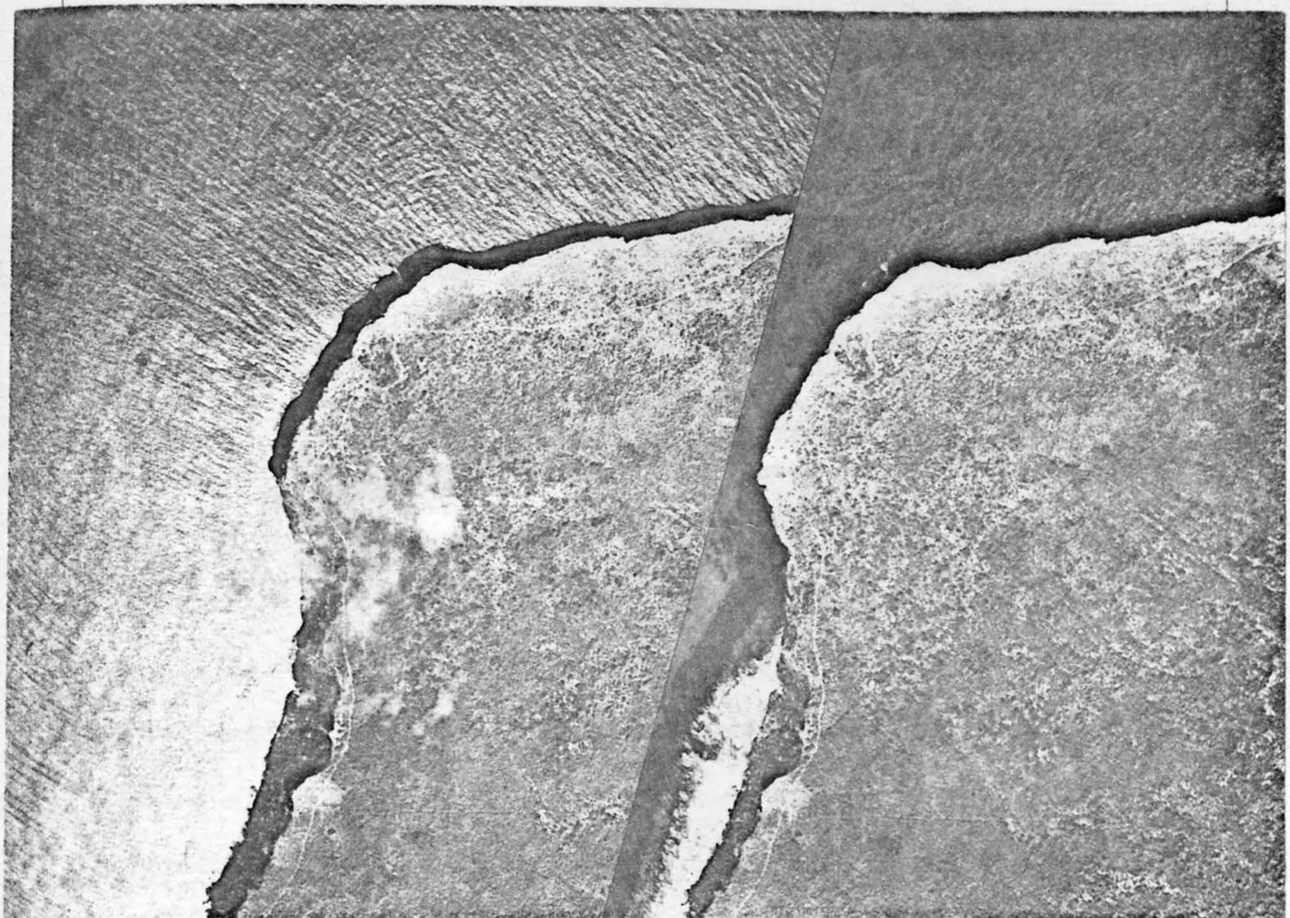

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Provisional Geology of Isla Monito

Isla Monito (fig. 10), northwest of Isla de Mona, is surrounded

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Figure 10 near here

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by sheer cliffs or steep irregular slopes on all sides. Only in the calmest seas may a boat landing be attempted without considerable hazard, so no plans were made to visit Isla Monito during the present study. Our closest view was obtained from an aircraft during a slow circle of the island at a low altitude, and it also was examined through 8X binoculars from several points along the northwest coast of Isla de Mona. From this distant acquaintance, Isla Monito appears to be composed of two units, a lower massive noncavernous unit, forming steep slopes and sheer cliffs to the sea, overlain by a cavernous unit that has an irregular, yet broadly planar, surface sloping gently, then precipitously, southwestward. From the air the Isla Monito rocks appear to strike generally northwest and to dip gently southwest. From Isla de Mona their apparent dip was measured and found to be approximately 3° west-southwest.

A sea-level nip was observed around the periphery of Isla Monito. The nip was exceptionally well-developed on the northeastern point of the islet, where the base of the cliff appeared to be incised as much as 10 m in from the cliff face.

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Figure 10. Isla Monito with Isla de Mona in background; viewed from the northwest. Cliff on left of Isla Monito is about 60 m high. Lower 45 to 50 m is tentatively identified as Isla de Mona Dolomite; upper rubbly cave-forming part (10-15 m), as Lirio Limestone. Dip of contact estimated as 3° to the west-southwest. Note relative size of sailboat in lower right corner. Photograph by F. H. Wadsworth.

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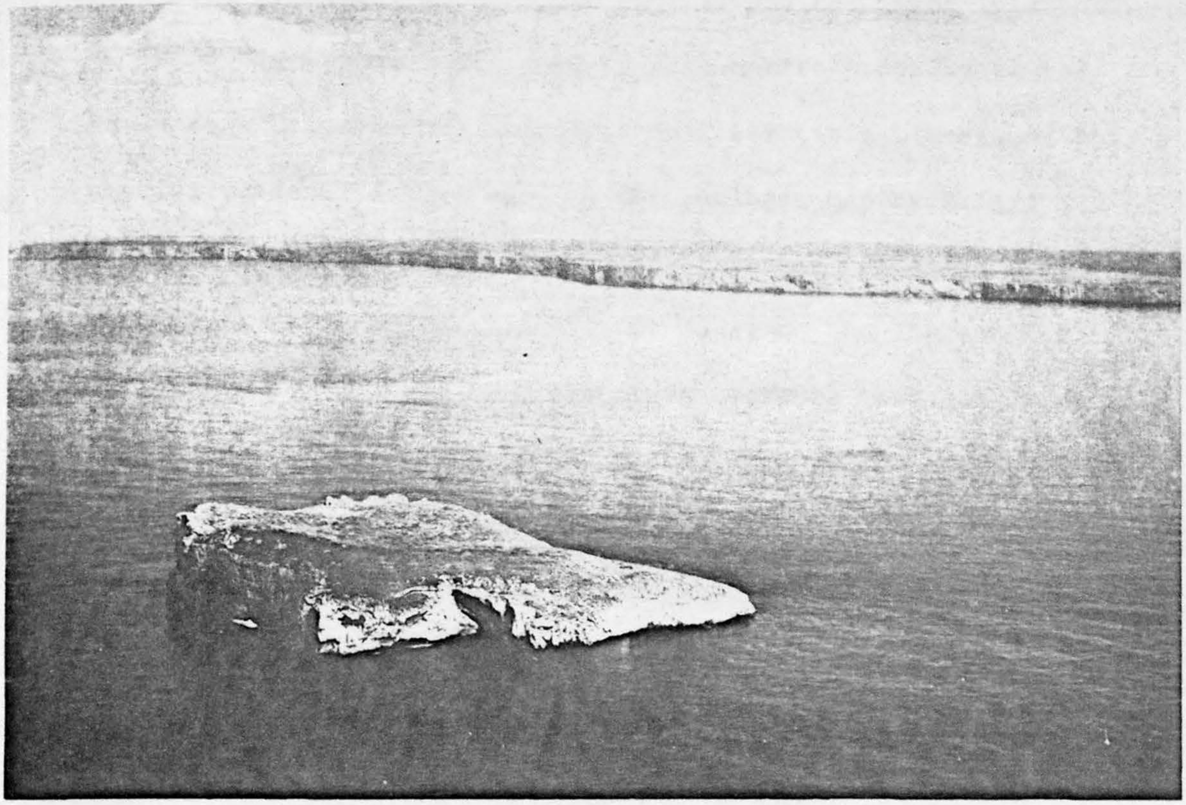

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All the above observations are in essential accord with those of Kaye (1959, p. 142, 146-147), who went around the islet in a boat. The noncavernous lower unit on Isla Monito probably is the Isla de Mona Dolomite and the upper unit the Lirio Limestone; they are tentatively identified as such on the geologic map by Briggs and Seiders (1972). The impression of the structure of Isla Monito matches well the structure of Isla de Mona; on the large-scale geologic map the 40- and 50-m structure contours tentatively are extended toward Isla Monito from Isla de Mona on the basis of this apparent congruence. However, no strong reliance should be placed on this interpretation, for Isla de Mona and Isla Monito are separated by a channel more than 100 fathoms (perhaps as much as 200 m) deep and by a horizontal distance of about 4.8 km.

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Cave phosphorite

All caves examined during the present study contain phosphorite. Locations of most caves that have been given names are shown on the large-scale geologic map (Briggs and Seiders, 1972); some are shown in figure 4.

Distribution and description of caves.--Around the periphery of Isla de Mona moderately large caves are common in the Lirio Limestone. Relatively few caves, all apparently small, were seen in the Isla de Mona Dolomite. Most solution caves formed in the Isla de Mona Dolomite appear to be in one of two stratigraphic zones, about 15 m and about 50 m below the Lirio Limestone-Isla de Mona Dolomite contact. Other caves in the Isla de Mona Dolomite were formed by large blocks slipping out of the sea cliffs along joint planes. The mouths of these cavities are large, but they narrow rapidly inward, and from the sea one can see their terminations (for example, fig. 6).

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Perhaps typical of solution caves in the Isla de Mona Dolomite, and perhaps the largest, is Cueva de Frío southeast of Cabo el Toro (fig. 4; Briggs and Seiders, 1972, cave B). As seen from the sea, the entrance to this cave is in the cliff face about 10 m above sea level and 50 m below the upper contact of the formation. The entrance is about 2 m high at its highest point, and a few smaller openings are seen at the same stratigraphic position on either side of the chief entrance. The cave extends only a few tens of meters parallel to the cliff, as judged by cave openings. If the Isla de Mona Dolomite caves share characteristics with caves surveyed in the Lirio Limestone, its extent normal to the cliff face probably is less than its lateral extent. Thus its total area may be rather small. The state of the sea and lack of climbing equipment and experience made it imprudent to attempt entering Cueva de Frío or other caves in the sea cliffs.

Only one cave in the Isla de Mona Dolomite was entered. This very small cave and a few even smaller ones are about 15 m below the limestone-dolomite contact, just west of Punta Este (fig. 3). The mouth of this cave is oval and about 1 m high. One may penetrate about 3 m into the cave before it becomes too constricted for further passage. Owing to turning of the narrow solution channelway which forms the cave, no end of the cave was seen. A thin cover of phosphorite is on the floor of this cave.

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The most favorable locale for the formation of caves on Isla de Mona was in the lower approximately 10 m of the Lirio Limestone where the Lirio intersects the peripheral cliffs (figs. 6 and 7). During the present investigations, we entered probably all the major cave systems at this level in the Lirio Limestone, many less important caves at the same level, and a few caves higher in the Lirio. Two broad classes of cave systems can be defined in the lower Lirio, but boundaries between the classes are not sharp and some caves have features of both classes.

The first class is typified by Cueva de las Losetas and Cueva al lado del Faro (figs. 4, 7, 11, caves I, II). The floor of these caves

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Figure 11 near here

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is most commonly at the Lirio Limestone-Isla de Mona Dolomite contact, and a bedrock wall of Lirio Limestone separates the caves from the cliff face. Perforating this wall are numerous windows that extend upward from the floor of the cave to heights that average somewhat less than 3 m but locally are much higher. The windows commonly are as much as 5 m wide, and the walls through which the windows penetrate are more than 5 m thick at many places.

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Figure 11. Maps of representative caves in Lirio Limestone on Isla de Mona. Locations of these caves are shown on figure 4 and on the large-scale geologic map of the Isla de Mona quadrangle (Briggs and Seiders, 1972). Inland boundaries of caves represent limits of cave development; a man probably cannot penetrate farther inland than these limits. Cave areas represented here are not strictly floor plans; they contain probably about one-half open rooms and passages and one-half rock walls and pillars, and large secondary calcite features (dripstone and flowstone).

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Continuing into the caves on a line perpendicular to the cliff face, no more bedrock walls or pillars are found for a considerable distance, locally as much as 40 m. In effect, long irregular halls (as much as 40 m wide and perhaps 100 m long) parallel the coast and are separated from it only by the perforated bedrock wall. The ceilings of these halls may exceed 8 m in height, but in most caves they are lower. Most of the halls, however, are not actually empty rooms, though they almost surely were at one time. Rather, they have been subdivided, festooned, and columned by deposits of reprecipitated calcite. Flowstone accumulations even bar passage through many parts of the halls so that one must detour around them, either farther inland or out through one of the windows.

Inland from the halls, the ceilings become lower, and bedrock pillars become more abundant and larger until the aspect of the cave changes from moderately large pillared-and-walled rooms to discrete passages through bedrock. Concomitant with this changing aspect, flowstone features become less common, and at the inland termination of the caves, flowstone features are minor and locally absent. The inward termination in most places is a concave bedrock wall, commonly of vermicular limestone, in a small room about 2 m high.

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Cueva de las Losetas and Cueva al lado del Faro are single storeyed for the most part. Locally, horizontal septas of bedrock chiefly less than 1 m thick form a two storeyed situation, with the lower storey rarely more than 1 m high. Elsewhere an impression of horizontal separation into two storeys is gained where phosphorite has been mined from under flowstone accumulations.

The second broad class of cave is typified by Cueva de los Pájaros (figs. 4, 11, cave IV). This cave has a broad mouth, essentially an antechamber (Kaye, 1959, pl. 14A, lefthand cave), in comparison with the rather small windows of the first cave class. Inward from the broad mouth are several large domed rooms, locally more than 100 m long and 15 to 20 m across. The ceilings of the rooms are arched and commonly are more than 8 m high in the center of rooms. These rooms are oriented subparallel to the cliff face, as in the first class of cave system, but they are separated from it by massive pillars and walls of bedrock. As one continues inland, the rooms become smaller and the intervening pillars larger until the limit of penetration is reached. Secondary calcite deposits are relatively minor features of the large entryways or antechambers of this second class of cave system, but are common as flowstone columns and walls, stalagmites, and stalactites a short distance in, and are moderately common as far as one can penetrate. Locally, Cueva de los Pájaros is two-storeyed, the storeys being separated by essentially horizontal septas of bedrock as much as 3 m thick.

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Of the other caves in the lower part of the Lirio Limestone, the Cueva del Lirio (figs. 4, 7, 11, cave III) is chiefly similar to the first class of cave system but contains more bedrock pillars and walls near the edge of the cliff and fewer flowstone features than do the other caves in this class. The small Cueva de la Casa de Erickson (fig. 4, cave V) is related to Cueva de los Pájaros and may even be connected to that cave by devious passages not investigated. Cueva de la Playa Brava on the southeast coast (fig. 4, cave VI) was not surveyed in detail, but it appears generally similar to Cueva de los Pájaros, except that it is smaller and has a smaller entrance. Cueva del Diamante and Cueva del Esqueleto on the west coast (fig. 4, caves IX, X; fig. 12) are generally similar to, but smaller

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Figure 12 near here

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than Cueva de los Pájaros, although Cueva del Esqueleto takes on more of the aspects of the first class of cave in its northern part. Cueva del Capitán (figs. 4, 11, cave XI; fig. 12) is smaller than but otherwise generally similar to the first class of cave, whereas Cueva de la Esperanza (fig. 4, cave XII) and an adjacent large collapsed zone (fig. 9) must have been identical in all but size to the first class of cave.

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Figure 12. Stereotriplet showing Punta Arenas and cliffs in Lirio Limestone. Top is North. Scale approximately 1:20,000. Cueva del Diamante and Cueva del Esqueleto (a) may be entered from the grove of trees at the point where the cliffside trail detours inland for a short distance. Cueva del Capitán (b) is located at the north edge of the view. The entrance to Cueva Negra (c) is due southeast from the cleared area on the lowland southwest of the pier (d). Note reef development and forereef grooves. U. S. Department of Agriculture Soil Conservation Service photographs ELT-4DD-157, 158, and 159. Location shown on figure 4.

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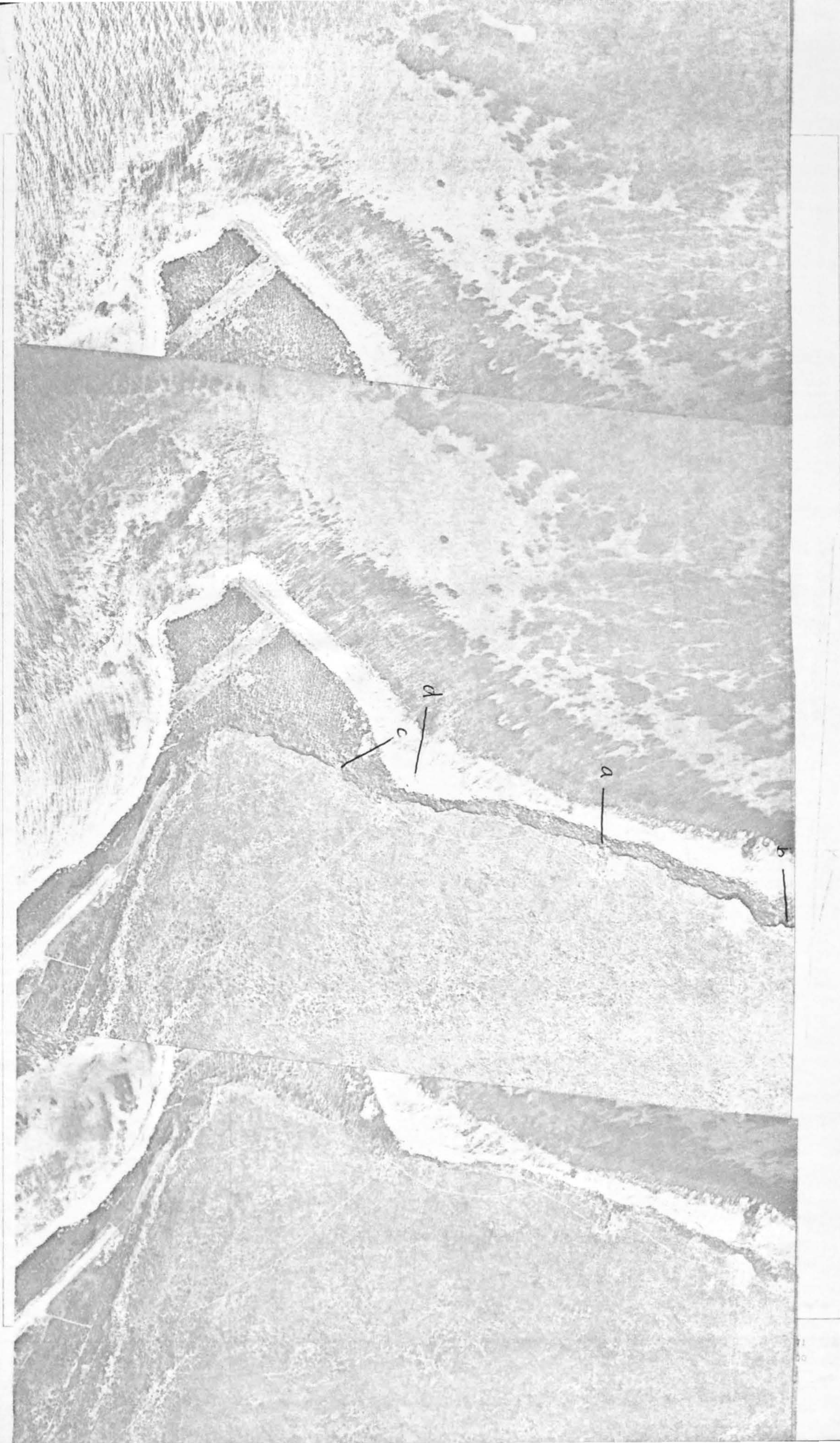

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The two-storeyed Doña Geña arriba (figs. 4, 11, cave VII) cave is too small to classify under either class of cave described. Its lowest point is probably at the Lirio Limestone-Isla de Mona Dolomite contact. The floor of Cueva Negra (figs. 4 and 11, cave VIII; figs. 12, 13) is estimated to be about 15 to 20 m stratigraphically

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Figure 13 near here

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above the base of the Lirio Limestone. This small cave consists of little more than several moderate-sized rooms with low ceilings and many dripstone and flowstone features.

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Figure 13. Interior of Cueva Negra, Isla de Mona. Lirio Limestone strata dip approximately 15 degrees westward. At the base of the column on the right, unsupported flowstone apron is an indication of the thickness of phosphorite mined from this fairly small cave. Photograph by F. H. Wadsworth.

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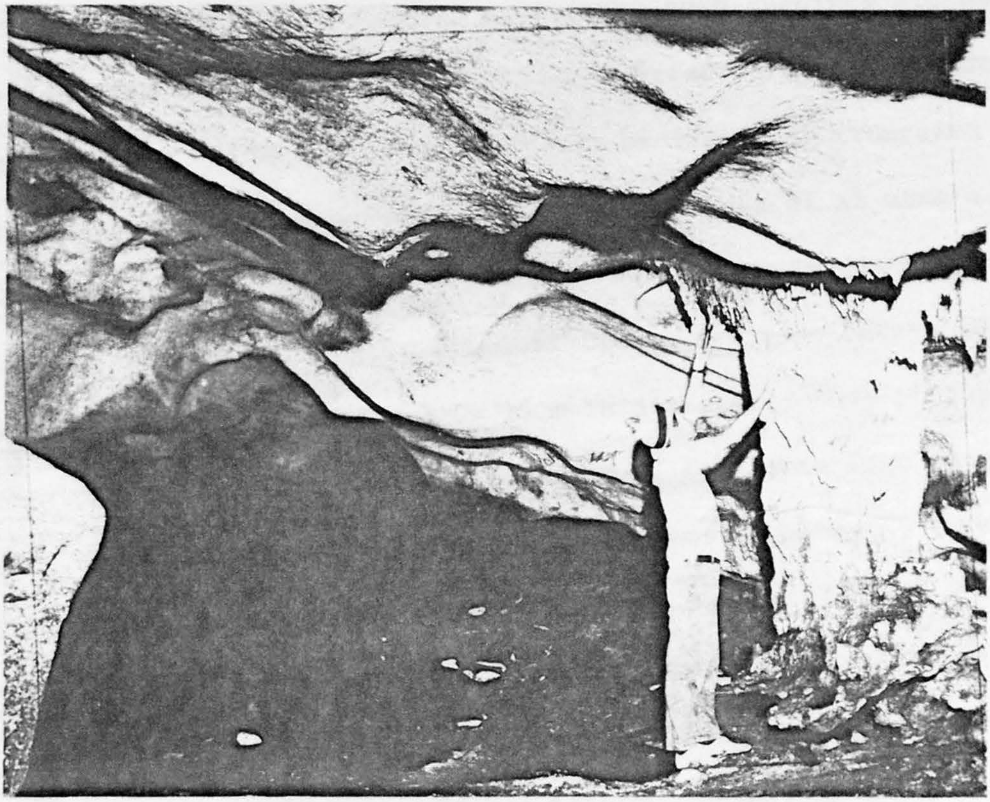

A feature common to all caves with roofs near the upland surface are openings to that surface. Caves with such openings are here called sink caves, for want of a common karst term that is adequately descriptive. Sink caves have the form of irregular truncated cones that rise and narrow through a vertical distance of as much as 10 m, from a base (the cave floor) commonly 40 to 60 m in diameter to a surface opening ranging in diameter from a few centimeters to 40 m. Most surface openings are 3 to 15 m in diameter. Some of the larger openings are visible on the stereogram of the Punta Este area (fig. 5). The floor of each sink cave almost invariably contains a rubble heap in the center, resulting from roof collapse. Flowstone commonly mantles the rubble. Passages ramify from sink caves to adjacent rooms. Of the sink caves seen, the most perfect in form is at the south end of Cueva de las Losetas, centering around the opening shown about 45 m north of the boundary between cave systems (fig. 11, cave I).

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Because the lower Lirio Limestone contains many large caves adjacent to the cliffs of the island, this same stratigraphic interval might be expected to contain many caves in areas away from the cliffs. Little evidence was found to sustain this belief. We found few deep steep-sided sinkholes on the upland surface outside of the peripheral areas underlain by caves. We found none in the Bajura de los Cerezos, and none are found in Los Corrales de los Indios (only a large rock shelter, fig. 14; W. R. Bergey, oral commun., 1965). A few sinkholes

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Figure 14 near here

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were found in the triangle limited by Punta los Ingleses, Punta Este, and the Cuevas del Centro (fig. 14), and a few were found along the trail called Camino los Cerezos, 800 to 1,600 m north of Playa del Uvero (figs. 3, 4).

The nonperipheral sinkholes commonly are subround and 10 to 30 m in diameter. They have steep to sheer sides; most are 2 to 8 m deep, but some are 15 m deep; and they almost invariably have a large bedrock rubble pile in the centers of their bottoms. Most appear to have originated by the collapse of isolated caverns, for no passages were found leading laterally from most nonperipheral sinkholes.

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Figure 14. Stereogram of east-central Isla de Mona. Top is North. Scale approximately 1:20,000. Northeast facing scarp with one collapsed reentrant in the northern part marks Los Corrales de los Indios. Three depressions near west edge are Cuevas del Centro. Note sinkhole in the easternmost of these depressions. Playa de Pájaros at south edge. Grid is survey net for a defense installation intended for this site but cancelled. U. S. Department of Agriculture Soil Conservation Service photographs ELT-4DD-162 and 163. Location shown on figure 4.

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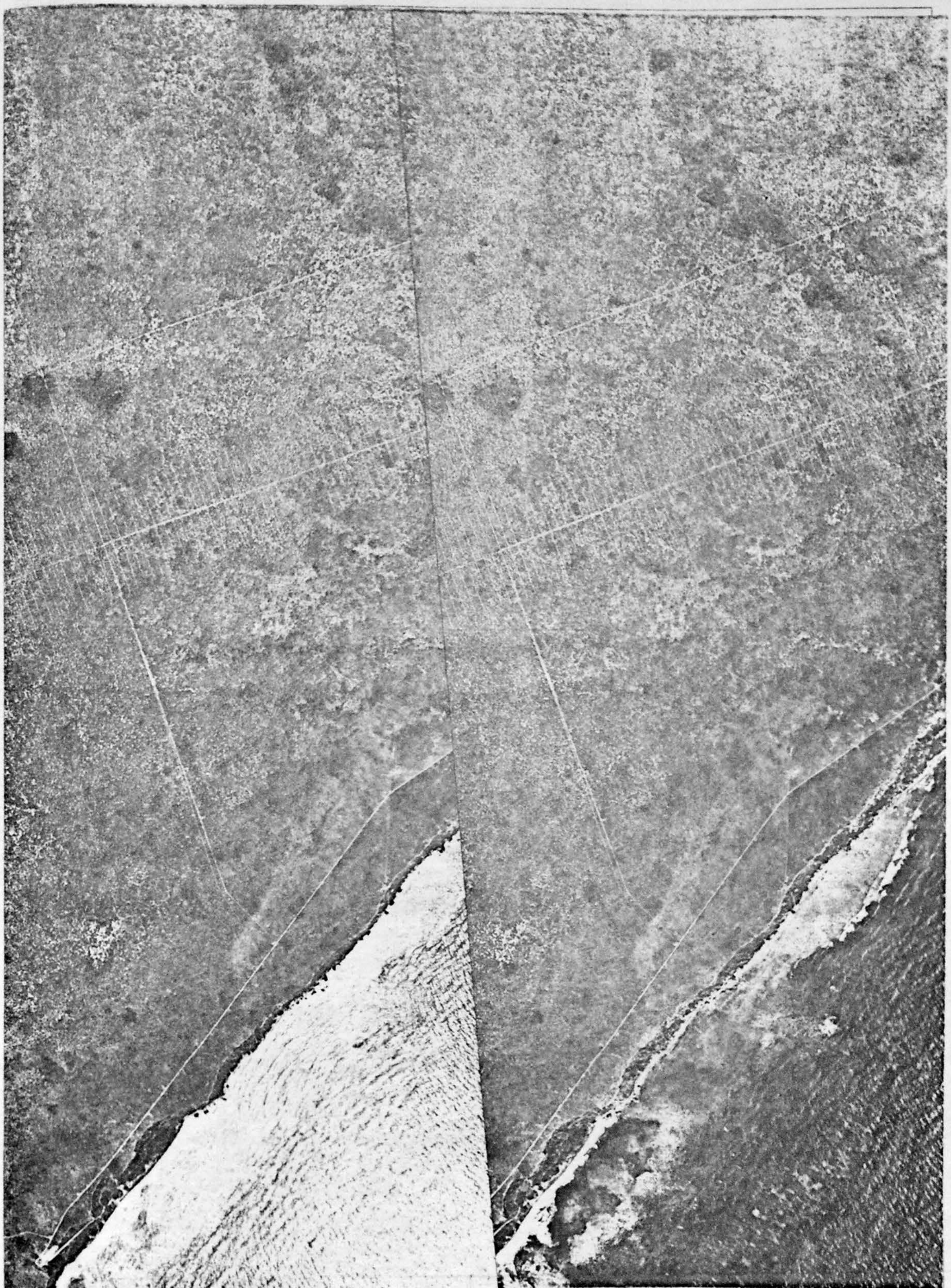

Only the nonperipheral sinkholes along the Camino los Cerezos have openings leading laterally from their bottoms, and these passages, though apparently low and narrow, may connect to form a sizable cave system in the area. Unfortunately, the bottoms of the Camino los Cerezos sinkholes were inaccessible with the equipment we had at hand.

No evidence was found to support the popular idea that one can travel underground for great distances inland from the cliffs of the island; for instance, frequently it is stated that one can go underground from Cuevas del Centro to a cliffside cave near Playa de Pájaros (figs. 3, 4). Our investigation showed this to be impossible; we found that the farthest we could penetrate from the cliffs inland under the upland surface was 240 m airline (fig. 11, cave IV). In most caves, inland movement is not simply limited by narrowing of passages or lowering of the ceiling; rather it is more common to come up against a rock wall that denies passage to anything no matter how small. Another belief is that one can walk underground beneath the Mona Island Light Station. This misconception probably originates in the fact that the diesel generators of the light station are audible in much of Cueva al lado del Faro (figs. 7 and 11, cave II).

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In summary, the most favorable site for cave development on Isla de Mona was in the lower 10 m of the Lirio Limestone on the periphery of the island. Caves in the Isla de Mona Dolomite are few and small. The only nonperipheral cave development of any extent in the Lirio Limestone may be along Camino los Cerezos, and isolated Lirio Limestone caverns not yet exhumed may be present in the structurally low synclinal zone in the southeastern part of the island, as is suggested by the sparse sinkholes found in that area. The total floor area of caves accessible to man in Isla de Mona probably is considerably less than 0.5 km^2, less than 1 percent of the total area of the island. The commonly held belief that Isla de Mona is a honeycomb of caves throughout is without basis.

The extensive peripheral caves may have formed at levels of the sea appreciably higher than present, when the cave sites were in the zone of mixing where salt water met fresh groundwater and conditions were optimum for solution of limestone. Here differences in carbon dioxide partial pressure may have resulted in "Mischungskorrosion" (mixture-dissolving) as described by Bögli (1963, p. 65). Another factor affecting the development of the largest cave system, Cueva de los Pájaros (fig. 11, cave IV), is suggested by its down-dip location in the trough of a syncline (fig. 3; Briggs and Seiders, 1972) and by its perennial freshwater pool, described in a following section on water resources. This structural setting probably funnels more groundwater through the Cueva de los Pájaros site than passes through other peripheral zones on the island. Further discussion on development of caves is in the report by Kaye (1959, p. 151-153).

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Description of phosphorite.--In view of the excellent mineralogical and petrographic work done by Z. S. Altschuler and R. C. Erd (in Kaye, 1959, p. 157-164), detailed mineralogic examination of cave samples collected during the present study was unnecessary. Altschuler determined that the chief phosphate mineral is hydroxylapatite [$(Ca_5(PO_4)_3(OH)$]; crandallite [$CaAl_3(PO_4)_2(OH)_5.H_2O$], brushite [$CaHPO_4.2H_2O$], monetite [$CaHPO_4$], and martinite [hydrous and carbonate-bearing whitlockite=β-$Ca_3(PO_4)_2$] also were recognized. The question of the genesis of the phosphorite on Isla de Mona was discussed thoroughly by Kaye (1959, p. 164-167), who concluded that the phosphorite largely is the result of diagenetic alteration of guano from fish-eating bats.

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Phosphorite is a characteristic deposit of all the caves visited on Isla de Mona, but its distribution and thickness vary greatly. We found that only about 1/2 of the floor area (1/4 of the total area) of the average cave system contained appreciable thicknesses of phosphorite; the remainder of the cave floor was covered with reprecipitated calcite features, rock rubble, and nothing but perhaps a very few centimeters of phosphorite and(or) calcite dust. The thickness of phosphorite in undisturbed areas of appreciable accumulation was estimated to be very irregular and to range from 20 cm to 2 m, averaging 1 to 1.5 m. In the mined-out areas the phosphorite apparently was thicker, ranging from about 30 cm to 3.5 m in thickness and averaging about 1.5 m, as estimated from unmined remnants, wall stains, and other features. In many areas, the phosphorite was found to have been concealed by flowstone layers 1 to 4 cm or more in thickness (fig. 13).

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Most phosphorite on Isla de Mona is a loose to moderately cohesive silty material that is moderate yellowish brown to dark yellowish orange and pale reddish brown; it commonly is moderately well to well stratified. In the face shown in figure 15, the stratification

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Figure 15 near here

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consists of alternating lighter and darker layers ranging from 2 mm to about 3 cm in thickness. Locally, pieces of white gypsiferous phosphorite as much as 5 cm in diameter disturb the bedding (fig. 16);

Figure 16 near here

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these white inclusions probably are altered limestone fragments. Sample G-3 (table 3) is a channel sample of the phosphorite (fig. 10)

Table 3 near here

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that proved to be gypsiferous phosphorite, the composition of which corresponds chiefly to normative apatite and gypsum. Sample G-4 (table 3), picked from white inclusions (fig. 11), contains appreciably more normative gypsum than does sample G-3; they average about 50 percent.

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Figure 15. Well-stratified phosphorite in remnant mining face in Cueva del Lirio. Apparent cycloidal irregularities in bedding caused by tool used in scraping outcrop. Dark beds are pale reddish brown; light beds are yellowish brown. Sample G-3 (table 3) is composite of the exposed section. Sampled site is located on figure 11. Exposed tape segment is 1.16 m long.

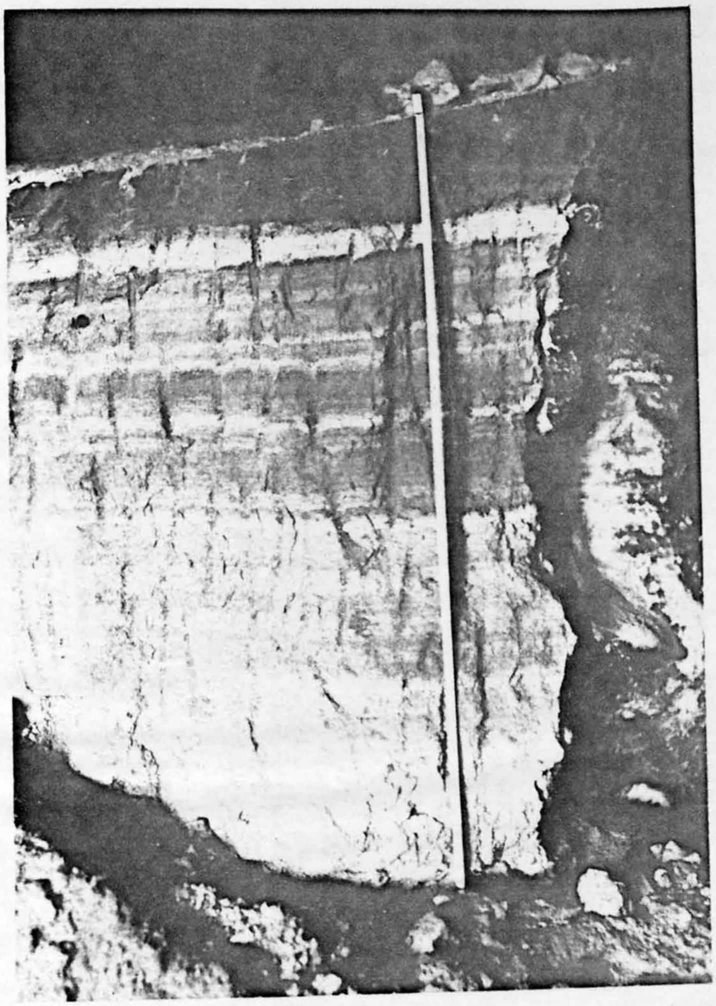

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Figure 16. Somewhat irregularly stratified phosphorite in remnant mining face in Cueva del Lirio. Apparent cycloidal irregularities and colors of bedding as in figure 15. White inclusions are gypsiferous phosphorite that probably formed from alteration of limestone fragments; sample G-4 (table 3) was collected by picking inclusions in the field of view of the photograph. Sampled site is located on figure 11. Exposed tape segment is 1.02 m long. The left edge of this figure is about 50 cm from the right edge of figure 15.

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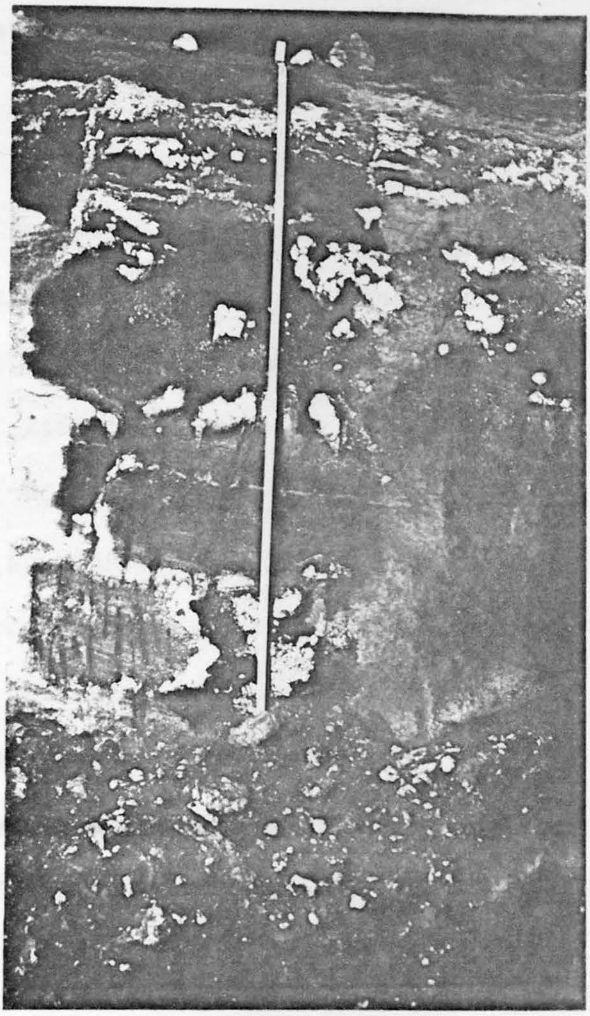

In addition to its intimate association with some of the phosphorite, gypsum also occurs as an encrustation on the roofs of some caves (Kaye, 1959, p. 163). Sample I-12 (table 3; fig. 11, Cave III) demonstrates the considerable purity of gypsum in this mode of occurrence.

Some phosphorite is well indurated, as was noted by Altschuler (in Kaye, 1959, p. 157-8, samples M-4 and M-7A). Sample M-23B (table 3), for example, was hard, yellowish-brown, and pisolitic in texture. It was collected during the present study from an exposed platform in the cliff face northeast of the Mona Island Light Station, where the phosphorite formed a 10-cm-thick layer at the contact of the Lirio Limestone and the Isla de Mona Dolomite (fig. 11, cave II). Although collected from a different site, sample M-23B is similar in description to the Kaye's (1959) sample M-7A. Altschuler reported that sample M-7A was almost wholly hydroxylapatite, which is borne out by its 37.1 percent content of P_2O_5 (Kaye, 1959, p. 158, 159, table 2), whereas sample M-23B contains appreciable normative calcite and dolomite (table 3).

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The P_2O_5 content of the three phosphorite samples analyzed for the present study averages 18.7 percent (table 3). All these samples were collected from caves in the vicinity of Punta Este (fig. 3), as were the samples of Cadilla and Vázquez (written commun., 1961), which averaged 19.52 percent P_2O_5. The samples of phosphorite collected by Kaye, however, are somewhat better distributed geographically; they range from 26.3 to 41.4 percent P_2O_5 and average 35.8 percent. The appreciably greater average P_2O_5 content of Kaye's samples is an indication that samples M-23B, G-3, and G-4 (and perhaps those of Cadilla and Vázquez) may not be representative, even of Punta Este phosphorites. Kaye's samples from the Punta Este area average 37.6 percent P_2O_5 (Kaye, 1959, p. 159, table 2, samples M-7A and M-8).

Tejada (1880, p. 87) estimated the average density of undisturbed Isla de Mona "guano" as "un pie cúbico pesa 63,5 libras" (63.5 pounds/ft^3). The Spanish units he used were the Castillian pound (1.014 English pounds or 460 grams) and the Castillian foot (0.92 English foot or 27.9 cm). Converted to the metric system, the density of undisturbed phosphorite, after Tejada, is 1.34 g/cc (grams per cubic centimeter). Cadilla and Vázquez (written commun., 1961) considered that phosphorite in place in the Punta Este area had a density of 1.17 g/cc.

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Columns, stalactites, stalagmites, curtains, and sheets of reprecipitated calcite are very common in the caves of Isla de Mona. They were deposited before, during, and after deposition of the principal phosphorite deposits. Locally, columns of secondary calcite appear to be the only support for some cave roofs. In Cueva del Lirio in a dry trough formed of flowstone were found abundant homogeneous spheres ("cave pearls") 1 to 2 cm in diameter. These proved to be slightly phosphatic, magnesian limestone (table 3, sample I-11; fig. 11, cave III).

Age of caves and cave deposits.--Kaye (1959, p. 173) concluded on the basis of climatic analysis that the Isla de Mona caves probably reached their full development before the close of Pleistocene time. Several other lines of evidence also indicate that the caves are Pleistocene: (1) they are best developed in the Miocene, perhaps upper Miocene, Lirio Limestone, so they almost surely are post-Miocene; (2) they have preferred cliff-side locations, so they must have formed after Isla de Mona reached a close approximation of its present size and shape, implying a long interval of erosion after Miocene time to reduce the original, probably quite extensive carbonate blanket; and (3) they probably formed at levels of the sea tens of meters higher than present, but there is no evidence that such high stands took place after the deposition of the Pleistocene, perhaps early Holocene raised reef of Isla de Mona.

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Plainly the cave deposits are almost entirely younger than the time of chief cave development, for the deposits coat the floors, walls, and ceilings of caves. However, the advanced degree of diagenesis in the phosphorite deposits suggests that they are at least of moderate antiquity, and most of the dripstone and flowstone accumulations must be of similar antiquity for they are intimately related to the phosphorite deposits. Moreover, if bats were the initial source of the phosphorite, then too few bats are now present to supply the necessary quantity of raw material (Kaye, 1959, p. 166). It appears reasonable to suggest that accumulation of the cave deposits began before the Holocene Epoch, but substantial deposition may have continued into the Holocene.

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Evaluation of phosphorite resources

Exploration and mining history.--It is not known who first discovered potentially exploitable phosphorite in the caves of Isla de Mona or when the discovery was made, but their "value and abundance were certainly recognized there as early as 1790. After 1850*** the shipment of phosphates from the island began, at first on a limited scale using small boats" (Wadsworth, 1954).

The first recorded detailed prospecting of the cave phosphorites took place in 1856, when Captain José Tejada of the Spanish Military Engineers inspected 16 caves (Tejada, 1880). His report contains no general map, and the written descriptions are inadequate to identify with assurance the caves he investigated; however one in which he estimated that 5,561 toneladas (1 tonelada=2,032.2 English pounds= 921.6 kilograms) of phosphorite were present may have been Cueva de los Pájaros (figs. 4, 11, cave IV) and another in which he estimated 1,038 toneladas may have been Cueva del Capitán (figs. 4, 11, cave XI). In the caves he investigated, Tejada estimated that there was a total of 23,545 toneladas or about 21,700 mT (metric tons) of phosphorite (Tejada, 1880).

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Wadsworth (1954) records that "in 1858 an official survey was made and thirty tons (of phosphorite) were sent to Cadiz and London for assay". Probably, the 1858 test shipments were made as a result of Tejada's work in 1856. A man named Acosta may have been involved in the removal of the test samples, for Acosta visited Isla de Mona in 1858 according to Nuñez Zuloaga (1879, p. 227).

In 1874, the Government of Puerto Rico granted what appears to have been the first exclusive concession for mining the cave phosphorites to Manuel Homedes y Cabrera, and 2 years later the franchise was transferred to Miguel Porrata Doria of Fajardo, Puerto Rico, and Juan Contreras of Madrid (Wadsworth, 1954). There is no record that any mining was done by Homedes y Cabrera, but the Sociedad Porrata Doria, Contreras Y Cía. actively exploited the cave phosphorites from 1877 to 1887; during which time, according to Wadsworth (1954), 32 ships carried a total of 7,830 mT (metric tons) to England, France, the United States, and other countries. Wadsworth (1954) further reported that "at one time during 1883 about 40 tons were mined daily at Playa de Pájaros, using 76 laborers brought from Guadaloupe." If this rate of mining had continued for as much as a year, the total reported for the entire period of 1877-1887 would have been exceeded. Probably the records of shipments are incomplete. For reasons not known this first period of phosphorite mining came to a close, and by 1888 "there was no continuous colony" on Isla de Mona (Wadsworth, 1954).

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The second, and greatest, period of mining activity began in 1890. According to Wadsworth (1954) the concession was sublet then to Anton Mobins, a German. On the other hand, in the introduction to the report by Kuhfal (1892), Theodor Schmidt of Hamburg is referred to as the man "whose family for years has leased, and has been permitted to exploit by the Spanish government, the guano deposits existing on" Isla de Mona (freely translated from the German by the present writer). The relation of Schmidt to Mobins is uncertain, but in any case, the second period of mining was controlled by Germans, and, according to Wadsworth (1954), between 1890 and 1892 they mined and dispatched at least 50 shiploads. In 1894, twelve ships were laden with a total of about 4,500 mT of phosphorite (Wadsworth, 1954). Competition from other worldwide sources of phosphates brought mining on Isla de Mona to a halt in 1896. Wadsworth (1954) reported that the total of phosphorite mined between 1890 and 1896 was no more than 50,000 mT, and that shipments were made to France, Norway, England, Denmark, and Germany.

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The third and last period of phosphorite mining began after the turn of the century, when, according to Wadsworth (1954), exploration in 1901 revealed that 460,000 mT of phosphorite remained in 22 caves. A mining concession granted to Percy Saint in 1903 was transferred to the Mona Island Phosphate Company in 1905, and operations were begun using some of the equipment abandoned by the Germans (Wadsworth, 1954). Operations continued sporadically from 1905 to 1924. Production levels were lower than those maintained by the Germans, and the quantities removed dwindled with time, as the more accessible deposits were worked out. Wadsworth (1954) states that records of royalty payments show that fewer than 36,000 mT were shipped during this 20-year period.

From 1924 to the present there has been no mining on Isla de Mona, and only recently has interest in the Isla de Mona phosphorite deposits been revived.

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Concerning the mining itself, one of the ships transporting phosphorite from Isla de Mona during the second mining period was the General Contreras. Captain Kuhfal of this ship wrote the following description of the phosphorite mining:

"The removal of the guano from the caves is accomplished easily. The entrance to the cave to be exploited is enlarged and, where necessary, supported. Gangways or paths are prepared, and frequently tracks are laid down. The guano, which commonly is found in layers thicker than a meter, frequently also must be freed from overlying rock by blasting. It then is shovelled into pushcarts or tramcars and taken to the cave exit where it is poured through screens into tramcars waiting beneath. These then carry the guano to the drying ovens.

"Following drying in the ovens, the guano goes through a mixing mill which produces an homogeneous guano mixture. A small part of the guano is dried in the sun and then mixed. Guano thus prepared for shipping has a very low moisture content. The guano then is put in sacks and loaded onto lighters which are pulled by a small tugboat to ships lying in the roadstead***. The lighters hold 5 to 6 tons, and they can deliver as much as 120 tons on board each day.

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"For the working of the guano of the island, aside from large machines and horses there are 300 to 400 workers busy daily. Supervision is in the hands of Germans stationed there." (Kuhfal, 1892, p. 305; freely translated from the German by the present writer).

The guano of Kuhfal (1892) is the phosphorite. The overlying rock he referred to was no doubt flowstone. The screens probably were only to remove pieces of rock, as the phosphorite is mostly fine grained. The part of the statement not included deals with safe shipboard stowage.

During the present investigation, many relics of mining were seen--including the walls of the drying house at Playa de Pájaros (fig. 14), remnants of rain catchment and cistern systems, rusted-out tramcars in Cueva del Lirio (which thus may have been the last cave mined), overgrown but well-built wagon roads on the southeast and southern coasts that led from below cave openings to what probably were lighter-loading points, and tramways from which most tracks since have been removed. Tramway systems in caves were found to have been most extensive in the eastern part of Isla de Mona, but surface tramways were common in both east- and west-coast mining areas. The fact that some wagon roads and tramways terminated at points where the phosphorite must have been loaded directly into lighters suggests that some of the guano may have been shipped without drying and mixing. Or it was carried in lighters to the drying house.

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Little evidence was seen of the enlargement or supporting of cave entrances reported by Kuhfal (1892). He may have seen an unusual operation, or rather than enlarged (erweitert) perhaps one should read instead cleared. Supports locally may have been present at one time, since rotted away or removed for firewood.

Some idea of the sort of work that was done with the low cost of labor of the time can be gained from the facts that some rooms from which phosphorite was mined have roofs less than a meter high after removal of the ore, and remaining patches of phosphorite in such areas indicate that the phosphorite thickness can have been little more than 20 or 30 cm.

To summarize known production: at least 7,830 mT of phosphorite were mined and shipped during the first period of mining, perhaps appreciably more, as indicated by the daily production estimate; during the second period, production may have been no more than 50,000 mT; and in the third period, apparently less than 36,000 mT was shipped. These figures are quoted from Wadsworth (1954) and total about 94,000 mT. Wadsworth (oral commun., 1967) has stated that he believes the records available to him were incomplete, so the actual total of phosphorite mined and shipped probably was somewhat greater.

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Reserves.--Known estimates of original or remaining phosphorite reserves include 21,700 mT estimated by Tejada (1880); 460,000 mT estimated as remaining in 1901 (Wadsworth, 1954); 1,000,000 T (short tons) estimated to remain in 1961 by Cadilla and Vázquez (written commun., 1961); and less than 50,000 T estimated remaining in 1964 by Fraser and Bergey (W. R. Bergey, oral commun., 1965).

Estimates of original and remaining phosphorite reserves in the 12 caves that we surveyed during the present investigation are given in table 4. Of these caves, only eight underlie more than 10,000 m^2

Table 4 near here

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each of the upland surface and only one, Cueva de los Pájaros (figs. 4, 11, cave IV), exceeds 100,000 m^2 in area of chief development. Only one of the surveyed caves, Cueva de las Losetas (figs. 4, 11, cave I), has not been mined out, though a few tons of phosphorite have been removed from pits in this cave. The total original phosphorite reserves indicated in the 12 caves is 151,000 m^3, of which 125,500 m^3 has been removed, 14,000 m^3 is considered as mining loss, and 11,500 m^3 are the remaining reserves. Converted to weight, the indicated remaining reserves in the 12 caves are 13,500 mT if the 1.17 g/cc density reported by Cadilla and Vázquez (written commun., 1961) is used. If the density of 1.34 g/cc derived by Tejada (1880, p. 87) is used, the indicated remaining reserves are about 15,500 mT.

Phosphorite remaining in caves not surveyed can be estimated in a general way, based on historical records and on the familiarity with Isla de Mona caves and phosphorite gained during the present study.

At least 44 names of caves have been reported from Isla de Mona, most of which have been associated with the mining of phosphorite. These caves are listed in tables accompanying the large-scale geologic map (Briggs and Seiders, 1972), and definite locations of the 12 surveyed caves (table 4) and probable identifications of 13 others are shown thereon. The remaining names probably refer to parts of, or rooms in identified caves. In addition, it is possible that a large cave system underlies the vicinity of the sinkholes along Camino los Cerezos (fig. 4; Briggs and Seiders, 1972, table 2, cave N).

In the tables with the geologic map (Briggs and Seiders, 1972) ranges of areas of unsurveyed cave systems also are shown, estimated from reports of earlier investigators, by analogy to caves that were surveyed, by the stratigraphic position of the caves, by the thickness of limestone present in which caves might be developed, by geomorphic relations, and by the presence or absence of evidence of mining or prospecting. By these means, the total area of cave systems not surveyed during the present study is estimated to be in the range 18,500 m^2 to 225,000 m^2 (Briggs and Seiders, 1972, table 2). It is the present writer's opinion that surveying would demonstrate that the true total area of these cave systems is in the lower part of this range.

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Assuming that the same general rules used in the computations for the surveyed caves (table 4) are applicable to unsurveyed caves (that is, 25 percent of the area of each cave system bears phosphorite with an average thickness of 1.5 m), then the possible volume of original reserves of phosphorite in unsurveyed caves was in the range 7,000 m^3 to 84,500 m^3.

During the present study, we found that virtually all caves surveyed or reconnoitered, no matter how insignificant or apparently poor of access, showed evidence of prospecting for or mining of phosphorite. Even out-of-the-way caves such as Cueva del Rifle in the northern cliffs of Isla de Mona (fig. 4; Briggs and Seiders, 197_, cave L) have recorded production (Wadsworth, 1954). Thus, a large proportion, perhaps most, of the phosphorite in caves not visited probably has been mined.

For the purposes of the present evaluation, no estimates are made of phosphorite in concealed isolated caverns that may exist beneath the upland surface. There is no basis for estimating the area of such caverns or for speculation on the thickness of phosphorite present. In any case, the rewards for prospecting for such caves probably would not repay the investment. In addition, no estimate is made for the phosphorite probably present in the caves of Isla Monito. In view of the small size of that island and its poor accessibility, it is unlikely that any phosphorite present could be of economic interest.

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In summary, original indicated phosphorite reserves in surveyed and unsurveyed cave systems on Isla de Mona probably were in the range 158,000 m^3 to 235,500 m^3. With a 10 percent mining-loss provision, the original minable reserves ranged from 142,000 m^3 to 212,000 m^3 in volume and 166,000 mT to 248,000 mT in weight. Incomplete records show about 94,000 mT shipped, and it now is estimated that about 147,000 mT (table 4; 125,500 m^3 X 1.17 g/cc) were mined from the surveyed caves. Thus, if no phosphorite at all has been removed from unsurveyed caves, the remaining phosphorite on Isla de Mona probably is in the approximate range 19,000 mT to 101,000 mT. Because mining is known to have been widespread, the present writer considers it highly unlikely that more than 50,000 mT of phosphorite remains, and probably there is considerably less.

This estimate is in strong contrast to the 460,000 mT estimated as remaining in 1901 and the 1,000,000 T estimated to remain in 1961. At a guess, the 1901 estimate may have been the result of a misprint; an estimate of 46,000 mT would have been more realistic. The 1,000,000 T estimated by Cadilla and Vázquez (written commun., 1961) probably chiefly was due to inadequate surveying that resulted in a vastly exaggerated idea of the extent of caves. The 1964 estimate of Fraser and Bergey is in essential agreement with the present estimate of remaining phosphorite; in short, in terms of modern conditions, there are no economically valuable phosphorite deposits in Isla de Mona.

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Surficial deposits

Lateritic soil

Lateritic soil mantles about 5 percent of the upland surface of Isla de Mona, forming a few large patches as long as 400 m and myriad minor patches far too small to show at the scale of the large-scale geologic map (Briggs and Seiders, 197_). This soil is composed chiefly of dark-reddish-brown clay. It contains few constituents larger than silt size, and the larger constituents are organic debris --chiefly rootlets, wood fragments, and snail shells. According to Kaye (1959, p. 149), F. A. Hildebrand and his coworkers found that the minus 140 mesh (U.S. Standard sieve) fraction of a sample contained "a mixture of hematite, carbonaceous and amorphous substance (probably iron oxide), boehmite, kaolinite, and mica" with lesser amounts of other minerals including quartz. Microscopic examination of soil samples collected during the present study, however, revealed no quartz grains.

Most of the soil is moderately friable to loose, but locally it has been cemented thoroughly by calcite. Its general thickness ranges from 0 to perhaps 1 m, but the thickness of even the large patches is extremely variable, and limestone cupolas 1 m or so in diameter are common, surrounded by soil. The soil locally has worked downward through joints and solution passages, forming columnar and tabular calcite-cemented bodies (solution pipes or sand pipes) in the walls of caves (Kaye, 1959, p. 149-150) and filling the tubules in the vermicular parts of the Lirio Limestone.

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Kaye (1959, p. 148, 149, 151) considered the soils of Isla de Mona to be residuum from dissolution of the Lirio Limestone, estimating that the minimum thickness of Lirio Limestone required to yield the Isla de Mona soils as residue is 85 feet (26 m). However, no evidence was found during the present study to support the suggestion that the Lirio was ever much thicker than it is today.

An alternative hypothesis for the derivation of the Isla de Mona soils is suggested by the soil composition (table 3, sample M-32) and by its distribution. Sample M-32 (table 3) was collected from a patch of soil about 10 m by 20 m in area at Cuevas del Centro (fig. 4; Briggs and Seiders, 1972). The $SiO_2:Al_2O_3$ ratio of the analysis of sample M-32 is 1.25, the $SiO_2:R_2O_3$ ($Al_2O_3+Fe_2O_3$) ratio is 0.97, and the $Al_2O_3:Fe_2O_3$ ratio is 3.47. In comparison, four lateritic red earths from Puerto Rico (Briggs, 1966, p. 63, table 1, analyses I, II, IV, V) range as follows: $SiO_2:Al_2O_3 = 1.14$ to 1.69; $SiO_2:R_2O_3 = 0.70$ to 0.96; $Al_2O_3:Fe_2O_3 = 1.31$ to 2.27. Clearly then, sample M-32 is similar, except that it has proportionately much less Fe_2O_3; it probably can be best described as aluminous lateritic red earth.

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A source of this silica-and alumina-rich soil is suggested by its minor-element content (table 3, sample M-32), which resembles that of beach sands in western Puerto Rico (Guillou and Glass, 1957, p. 296-297, table 5, samples RI-2, MY-5, AG-4), especially with respect to rather high trace quantities of chromium, nickel, cobalt, and copper. There is no reason to assume that there have been substantial changes in the easterly direction of prevailing winds since Miocene time, so the parent material of the Isla de Mona soils could have come from Puerto Rico, borne to the area that is now Isla de Mona by the wind, as suggested by F. A. Hildebrand (in Kaye, 1959, p. 149). The very sparseness of the Isla de Mona soils suggests that the mode of transport was not capable of carrying large volumes. Indeed, transport from an external source by marine currents would appear to be ruled out by Kaye's reasoned argument that the Mona Passage may predate the deposition of the Isla de Mona carbonate rocks (Kaye, 1959, p. 172).

The lateritic soil rests on Miocene limestone. Most soil accumulation probably took place well in the past, but development continues today, in the sense of continuing laterization and probably minor transportation and accumulation. The lateritic soil may be considered Miocene(?) to Holocene in age.

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Raised reef

Areas of raised reef are distributed sporadically along the east, south, and west shores from Punta Este to near Punta el Capitán (fig. 3). This raised limestone reef, composed largely of coral fragments, is locally somewhat chalky but commonly is casehardened; the reef corals are in growth position at many localities, most notably between Playa del Uvero and Piedra del Carabinero (fig. 3). Like the Lirio Limestone, this reef rock normally has a medium-gray to light-gray weathered surface, whereas fresh surfaces are grayish orange pink.

The seaward edge of the raised reef 1 km west-southwest of Punta Este has been eroded to an irregular scarp that rises about 2 m above sea level. From the scarp the rather smooth surface of the reef rises inland at an angle of about 5°. At the foot of the cliffs in this area, the reef surface is at an elevation of about 10 m and apparently incorporates boulder rubble from the Lirio Limestone (Kaye, 1959, pl. 14B).

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No raised reef is exposed from about 600 m northeast of Playa de Pájaros southwestward to about 700 m northwest of Punta Caigo o no Caigo. From this latter point, however, the raised reef is extensively exposed for a distance of about 4 km northwest. Unlike the raised reef near Punta Este, the reef surface in this area has no appreciable upward slant inland; it is essentially horizontal and planar and is strewn with rubble chiefly composed of coral fragments. At the shore near Playa del Uvero the eroded scarp in the raised reef is about 3 m high. From here the reef surface dips almost imperceptibly northwestward along the coast to the northwesternmost point of this reef flat area, where the reef remnant is at sea level (Briggs and Seiders, 1972). A small remnant of the raised reef is found adjacent to the cliffs 2 m above sea level about 600 m south of Punta el Capitán.

Boulders of reef material as much as 6 m long containing coral heads as large as 2 m in diameter locally rest on the raised reef flat west of Playa del Uvero. It is not clear how these boulders reached their present positions; they may have been eroded from the edge of the raised reef and thrown up on the flat by prehistoric hurricane or seismic sea waves.

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The base of the raised reefs was not seen, so the maximum thickness is not known. Locally, however, the raised reefs must exceed 3 m in thickness and may be as much as 10 m thick. The raised reefs probably rest unconformably on both Lirio Limestone and Isla de Mona Dolomite, and perhaps on boulders and other concealed deposits.

Druid Wilson (written commun., 1969) identified the following fossil mollusks collected from the eroding seaward edge of the raised reef, west-northwest of Punta Caigo o no Caigo (USGS fossil collection 24632, from 25,540 m N.; 3,020 m W.):

Pelecypoda

Barbatia (*Acar*) *domingensis* (Lamarck)

Gastropoda

Cittarium pica (Linne)

Strombus gigas (Linne)

Wilson concluded that the raised reefs probably are Pleistocene in age, although the individual species have greater ranges than the Pleistocene. This age is within the Pleistocene to Holocene age range deduced by Kaye (1959, p. 148) on the basis of corals collected from the surface of the raised reef flat near Punta Este (fig. 3) and near the southwest coast.

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Boulder deposits

Deposits of boulders, blocks, and finer material derived chiefly from the Lirio Limestone are thickest and most extensive adjacent to the cliffs from Playa de Pájaros northeast to Punta Este and from Playa Sardinera north to Punta el Capitán. These deposits form laterally continuous, highly irregular slopes that locally rise to within a few meters of the upland surface. Some of the boulders are as much as 50 m long (Kaye, 1959, pl. 14B). Boulder deposits also are present locally from the vicinity of Playa de Pájaros to Playa Sardinera.

At a few places adjacent to the sheer cliffs of Isla de Mona Dolomite from Punta Este north and west to Punta el Capitán, very large blocks of dolomite protrude above sea level at the base of the cliffs (figs. 4). The sea floor nearby is 15 to 22 fathoms (28 to 40 m) deep. Thus, some blocks may be 40 m or more high, unless they rest on submerged boulder piles. These partly drowned blocks were examined from a small boat, and all but one of them were found to have a sea-level nip similar in elevation and form to the nip along the base of the cliffs (fig. 7). No nip was formed in the single exception, and no block bore any evidence of a nip higher than that commensurate with present sea level. Thus, almost all the presently exposed, partly drowned blocks must have fallen before or during the early stages of the present stand of the sea.

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Some boulders of Lirio Limestone were observed to have been incorporated within the raised reefs, whereas others rest on the raised reef flats. The boulder deposits probably range from Pleistocene to Holocene in age, and from time to time are still forming.

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Beach deposits

Beach deposits shown on the large-scale geologic map of Briggs and Seiders (1972), represent the sands of present beaches, beach rock, reef rubble accumulations, and windblown sand deposits of recent origin. The largest sandy areas extend from Playa Sardinera southeastward to the vicinity of Playa del Uvero and from Punta los Ingleses northeastward to a point about 300 m northeast of Playa de Pájaros (fig. 3). Narrow sand beaches also are found sporadically along the remainder of the southeast, south, and west coasts.

The beach sands are fine to medium sands composed entirely of grayish-pink calcite and aragonite grains, chiefly fragments of shells of marine organisms; no quartz or heavy mineral grains were seen. A 300-m stretch of beach largely composed of reef rubble and beach rock is just northwest of the northwesternmost raised reef occurrence between Playa del Uvero and Playa Sardinera (Briggs and Seiders, 1972), and shorter lengths of rubble beach are found elsewhere. Windblown beach sand mantles a large part of the raised reefs between Playa del Uvero and Playa Sardinera, but such sand was mapped by Briggs and Seiders (1972) only where it is more than just a few centimeters thick.

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Beach rock, calcium carbonate-cemented beach sand, forms layers a few centimeters thick approximately parallel to present beach surfaces and commonly is exposed in beaches from the vicinity of Playa del Uvero to Punta Arenas and Playa Sardinera (fig. 3, 12; Briggs and Seiders, 1972). None was seen north of Playa Sardinera or east of Playa del Uvero. All the beach-rock occurrences are at levels compatible with present sea level; thus, their exposure probably is due only to normal shore processes and not changes in sea level.

The beach deposits are all considered to be Holocene in age.

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Resources other than phosphorite

Limestone and dolomite

The Lirio Limestone is composed of very pure limestone and magnesian limestone that generally contain less than 1 percent insoluble residues (table 2). Over much of the Isla de Mona the Lirio is rather thin, averaging somewhat more than 10 m thick (Briggs and Seiders, 1972, sections A-A', B-B'). Thus, large quarries for limestone extraction probably could be opened economically only in the thickest parts--at the southeast end of the syncline near Playa de Pájaros and in the southwestern Lirio exposures near Playa Sardinera (figs. 3, 12, 14). In the former area, though, cave systems are extensive and would make quarrying somewhat difficult. In the latter area caves are rather small, and quarrying would be less of a problem. In either area, the volume of limestone is sufficient to support large-scale quarrying operations for many years.

The raised reef also is composed of very pure limestone, but it is not considered a significant resource because it probably averages appreciably less than 10 m thick.

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The Isla de Mona Dolomite is composed largely of calcitic dolomite. The normative concentration of the mineral dolomite in 12 samples averages 81.8 percent (table 1, excluding samples M-9 and M-14). Rocks that have lower concentrations of the mineral dolomite occur locally in the top of the unit and in rather thin zones 15 m and 50 m stratigraphically below the top.

Present data suggest that the Isla de Mona Dolomite underlies the entire island, because it crops out in sea cliffs of the northern half of the island, sporadically on the south coast, and in Bajura de los Cerezos. At most places, the dolomite is covered by a Lirio Limestone cap several meters thick (Briggs and Seiders, 1972); only in Bajura de los Cerezos (fig. 4) is there little or no limestone overburden.

If both pure limestone and dolomite were desired, the most promising sites for two-commodity quarries would be on the west coast between Punta el Capitán and Playa Sardinera, on the southeast coast between Punta Este and Playa de Pájaros, or on the south coast in the vicinity of Punta Caigo o no Caigo. In the first two localities thick boulder deposits would have to be removed before quarrying operations could begin.

Both limestone and dolomite are moderately valuable industrial and construction-material resources.

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Construction materials

Fine aggregate.--Beach sand is a restricted but significant source of fine aggregate on Isla de Mona, and it has been used in concrete for limited local construction. For this purpose the sand is adequate, even though the strength of the calcite and aragonite sand grains is relatively low, and washing of sand is a problem owing to very limited fresh-water supplies. However, if any extensive concrete construction were undertaken on the island, large quantities of better fine aggregate would have to be brought in from elsewhere. Characteristics of the hard limestone and dolomite of the island probably are such that insufficient quantities of sand-sized material would be produced by crushing to contribute significantly to the fine-aggregate supply.

Coarse aggregate.--There are no deposits of durable gravel on Isla de Mona. Hard dolomite, and perhaps hard limestone, probably would crush to sizes adequate for coarse concrete aggregate and base and surface course material for roads or airstrips. Their strengths probably would be sufficient for low-rise construction and for relatively light land and air traffic.

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Riprap.--Hard Isla de Mona Dolomite probably would prove adequate as riprap. It would last well in shore works owing to the special condition that mineral grains harder than calcite and dolomite are lacking along the Isla de Mona coast, so abrasion potential is low. Blocks large enough readily could be quarried, as is shown by the blocks presently exposed along the northern and northeastern coasts of the island.

Clay.--Lateritic red earth soils are the only deposits on the island bearing significant proportions of clay minerals. They constitute a restricted source of raw material for the manufacture of common brick for local construction. Because the soils are so limited in area and volume, they offer no attractive targets for bauxite prospecting, despite their moderately promising chemistry (table 3) and mineralogy (Kaye, 1959, p. 149).

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Oil and gas possibilities

The discovery of folds and faults on Isla de Mona suggests that favorable sites for the accumulation of petroleum and natural gas could be found in this part of the Mona Passage. The rather impermeable Isla de Mona Dolomite shows no promise as a reservoir rock, but it could serve as an entrapping layer if it were underlain by permeable rocks. However, there have been no confirmed reports of oil or gas from Isla de Mona or any nearby area, and no rock units are known that might serve as source rocks. The closest area where oil has been produced from rocks of Tertiary age is in the southern Dominican Republic, 350 km due west of Isla de Mona (Blesch, 1967).

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Water resources

J. P. Akers, U. S. Geological Survey, was on Isla de Mona for 2 days of the overall period of investigations, reconnoitering the island for water resources. Four water samples were collected for analysis (table 5). The following section is based in part on

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observations made by Akers.

The apparent absence of large quantities of potable water is the chief barrier to more than the most modest development of any sort on Isla de Mona. During the Columbian era, however, and possibly as late as the early part of the 19th Century, Isla de Mona was a well-known port-of-call for water and other provisions (Wadsworth, 1954, p. 145), so the quantity of water available seems to have decreased over the last century or two. Moreover, the quality of water in the southwestern coastal lowlands must have deteriorated in relatively recent times, for in the lowlands are a number of shallow wells that once supplied fresh (or at least fresher) water for livestock and the small farming population that was present in decreasing numbers until about 1943. These wells yielded brackish water or water of marginal quality in 1964 (table 5, samples I-III).

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As of 1968, almost all fresh water used on Isla de Mona was collected by rain catchment from roofs at the light station and at Playa Sardinera, and relics of other catchment and cistern systems are found at Playa de Pájaros and between Playa de Pájaros and the light station. There is no surface drainage on Isla de Mona except during and immediately after heavy rain showers.

In Cueva de los Pájaros is a small perennial pool of fresh water that has been used by fishermen visiting Playa de Pájaros for as long as anyone can remember (table 5, sample IV; fig. 11, cave IV). The pool is cylindrical and is about 1 m in diameter and less than 1 m deep. The water level is about 2.5 m higher than the cave entrance some 130 m to the southeast. The rim of the pool is flowstone, but the bottom may be in bedrock. The mode of replenishment of this pool is not clear; it almost surely is not maintained by water dripping from the ceiling of the cave (for the cave ceiling here is irregularly concave), nor by run-off along the surface of the cave floor. Rather, replenishment must occur by some form of lateral or vertical-upward water migration through flowstone or through the basal Lirio Limestone, perhaps controlled by the gently southeast-plunging syncline (fig. 3). According to J. P. Akers (written commun., 1964), the nitrate content of the water in the pool (table 5, sample IV) is more than is desirable for human consumption. He suggested that the nitrate may have come from the phosphorite deposits.

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No other perennial sources of water were reported from or found in any of the caves, although both fresh and salty water drip from stalactites for long periods after rains.

On the west coast of Isla de Mona in the boulder deposit below the south end of the Cueva del Capitán is a seep, evidenced by the presence of a patch of muddy ground in otherwise dry terrain.

The Cueva de los Pájaros pool and the west-coast seep, point toward the presence of perennially migrating ground water within the island, maintained by infiltration of much of the 960-mm (38-inch) annual rainfall (Kaye, 1959, p. 144). Wells drilled on the upland in the structurally favorable synclinal areas might encounter quantities of fresh water at or near the contact between the permeable Lirio Limestone and the relatively impermeable Isla de Mona Dolomite. The structure contours shown on the large-scale geologic map (Briggs and Seiders, 1972) thus may be an aid in the search for fresh water. If water is not found by this means, Akers (oral commun., 1964) suggests that drilling to sea level in the center of Isla de Mona might find a water supply, for a fresh-water lens probably exists at or near sea level, as is the case in carbonate islands and atolls elsewhere in the world.

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Akers also considers that, despite the brackishness of the water in present wells (table 5), there is a good chance of getting small supplies of fresh water by digging wells in the coastal lowlands as far from the sea as possible. The wells should be 2 m or more in diameter and should be dug to sea level, but no further, for maximum yield of fresh water.

Thus, despite the poor water supply situation at the time of the present study, it is likely that fresh ground-water supplies can be obtained from Isla de Mona. Studies to date, however, are inadequate to predict just how much fresh water might be obtained. For relatively small-scale development of facilities on the island, collection of water in catchment and cistern systems probably will continue to be the more economical method of water supply.

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Table 2.--Major oxides, minor elements, partial norms, and rock classes of samples from Lirio Limestone, Isla de Mona, P. R.

[Chemical analyses for major oxides by U. S. Geological Survey laboratories; analysts P. Elmore, H. Smith, L. Artis, S. Botts, and J. Glenn. N. R. = not reported. Semiquantitative spectrographic analyses for minor elements by U. S. Geological Survey laboratories; analysts J. L. Harris and W. B. Crandall. Elements looked for but not detected: Ag, As, Au, B, Be, Bi, Cd, Ce, Co, Eu, Ga, Ge, Hf, Hg, In, La, Li, Mo, Nb, Ni, Pb, Pd, Pt, Re, Sb, Sc, Sn, Ta, Te, Th, Tl, U, V, W, Y, Yb, Zn, Zr. 0 = not detected.]

Field number----------	M-7	M-31	M-33A	[2] 2	[2] 3
Laboratory number-----	W167668	W167671	W167672	----------------	----------------
Location coordinates[1]--	28,430 N.; 2,850 E.	29,200 N.; 600 E.	32,220 N.; 3,210 W.	----------------	----------------
Location description----	Cueva del Lirio	Cuevas del Centro, bottom of sink-hole	East of Cabo Noroeste, just east of fault, 10 m in from cliff edge	Playa de Pájaros, upland surface	Playa de Pájaros, base of cliff
Major oxides (percent)					
SiO_2 ----------------	0.00	0.16	0.00	N.R.	N.R.
Al_2O_3 ----------------	.00	.10	.00	N.R.	N.R.
Fe_2O_3 ----------------	.00	.00	.00	N.R.	N.R.
FeO ----------------	.00	.04	.00	N.R.	N.R.
MgO ----------------	.95	.70	1.1	.16	1.9
CaO ----------------	54.1	54.1	54.2	55.0	52.4
Na_2O ----------------	.30	.02	.07	N.R.	N.R.
K_2O ----------------	.10	.20	.04	N.R.	N.R.
H_2O- ----------------	.45	.18	.10	N.R.	N.R.
H_2O^+ ----------------	.30	.42	.58	N.R.	N.R.
TiO_2 ----------------	.00	.00	.00	N.R.	N.R.
P_2O_5 ----------------	.12	.13	.09	.00	.00
MnO ----------------	.00	.03	.03	N.R.	N.R.
CO_2 ----------------	43.3	43.4	43.8	N.R.	N.R.
HCl-soluble S as SO_3 ----	.65	.00	.08	N.R.	N.R.
Sum ----------------	100	99	100	——	——
Minor elements (percent)					
Ba ----------------	0.0003	0.0003	0.0003	[3]	[3]
Cr ----------------	0	0	.0003		
Cu ----------------	.0005	.0007	.0003		
Sr ----------------	.02	.015	.05		
Partial norms					
Calcite ----------------	93.0	94.4	93.8	[4] 98	[4] 88
Dolomite ----------------	4.3	3.2	5.0	[4] 1	[4] 9
Gypsum ----------------	1.4	0	.17	Unknown	Unknown
Apatite ----------------	.28	.30	.21	0	0
Rock classification (of Pettijohn, 1949, p. 312)					
	Limestone	Limestone	Magnesian limestone	Limestone	Magnesian limestone

[1] Coordinates are those of the Puerto Rico rectangular coordinate system; locations are reported to the nearest 10 m.

[2] Sample from Kaye (1959, table 1).

[3] Not analyzed spectrographically.

[4] Approximate.

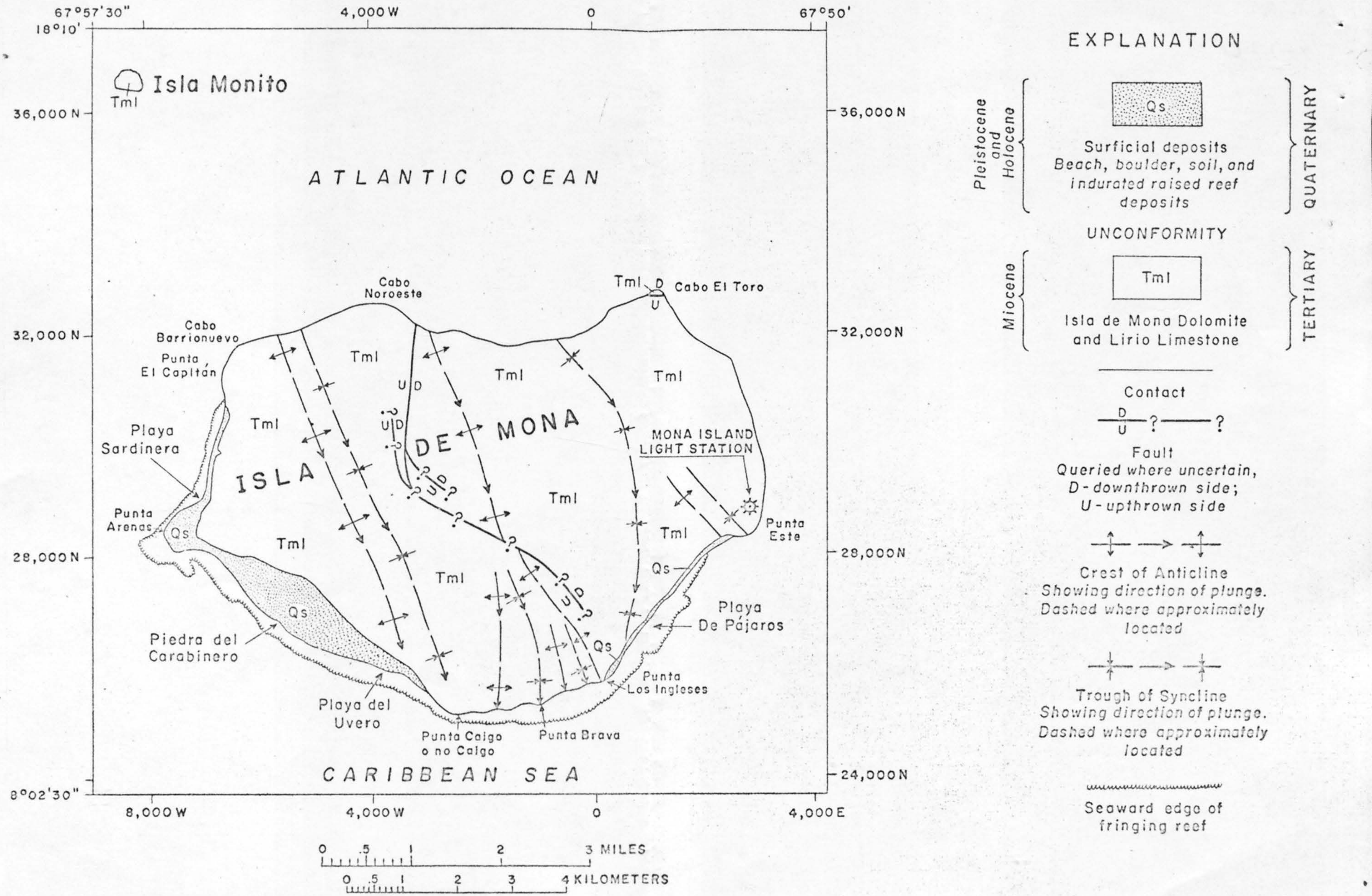

Figure 3. Generalized geologic map of the Isla de Mona quadrangle.

Table 4.--Indicated original and remaining phosphorite reserves in surveyed caves on Isla de Mona, P. R.

[Areas, volumes and weights are rounded to the nearest 500. Locations are shown on figure 4 and in Briggs and Seiders (1972).]

Cave name	Map reference symbol	Total area 1/ (m 2/)	Proportion of cave area covered by phosphorite deposits	Average original thickness of phosphorite deposits (m)	Indicated original reserves of phosphorite (m 3/)	Quantity 4/ removed (m 3/)	Quantity remaining (m 3/)	Mining loss 5/ (m 3/)	Indicated remaining recoverable phosphorite reserves 7/ Volume (m 3/)	Weight 8/ (mT)
Cueva de las Losetas	I	43,500	0.25	1	11,000	0	11,000	6/ 1,000	10,000	11,500
Cueva al Lado del Faro	II	61,500	.25	1	15,500	14,000	1,500	1,500	0	0
Cueva del Lirio	III	97,000	.25	1.5	36,500	33,000	3,500	3,500	0	0
Cueva de los Pájaros	IV	128,000	.25	1.5	48,000	43,000	5,000	5,000	0	0
Cueva de la Casa de Erickson	V	5,000	.25	1	1,500	1,500	0	0	0	0
Cueva de la Playa Brava(?)	VI	13,000	.25	1.5	5,000	4,500	500	500	0	0
Cueva de Doña Geña arriba	VII	2,500	.25	1.5	1,000	1,000	0	0	0	0
Cueva Negra	VIII	5,000	.20	1	1,000	1,000	0	0	0	0
Cueva del Diamante	IX	18,000	.25	1.5	7,000	6,500	500	500	0	0
Cueva del Esqueleto	X	20,500	.25	1.5	7,500	7,000	500	500	0	0
Cueva del Capitán	XI	41,000	.25	1.5	15,500	14,000	1,500	1,500	0	0
Cueva de la Esperanza	XII	5,000	.25	1	1,500	0	1,500	6/ 0	1,500	2,000
Totals	---	440,000	---	---	151,000	125,500	25,500	14,000	11,500	13,500

1/ Includes areas occupied by pillars and walls between passages and rooms. Areas of passages and rooms probably average about half the total area of each system. Areas measured by polar planimetry of maps based on compass-and-tape and compass-and-pace surveys.

2/ Rest of cave area consists of pillars, columns, walls, thick rock rubble, or essentially phosphorite-free rock floor.

3/ Based on thicknesses measured in exposed sections, thicknesses apparently removed during mining, and estimates of remaining thicknesses determined by driving probes.

4/ In each mined-out cave, the quantity is estimated as about 90% of the original reserves of that cave.

5/ Thickness and distribution of remaining phosphorite in mined-out caves is such that removal most likely would not prove economic.

6/ Potential 10 percent mining loss in areas not yet mined.

7/ Recoverable assuming the economic conditions surrounding mining are the same as those that existed during the era of active mining (1877-1924).

8/ mT=metric tons. Conversion based on density of 1.17 g/cc (Cadilla, J. F., and Vázquez, Leovigildo, written commun., 1961).

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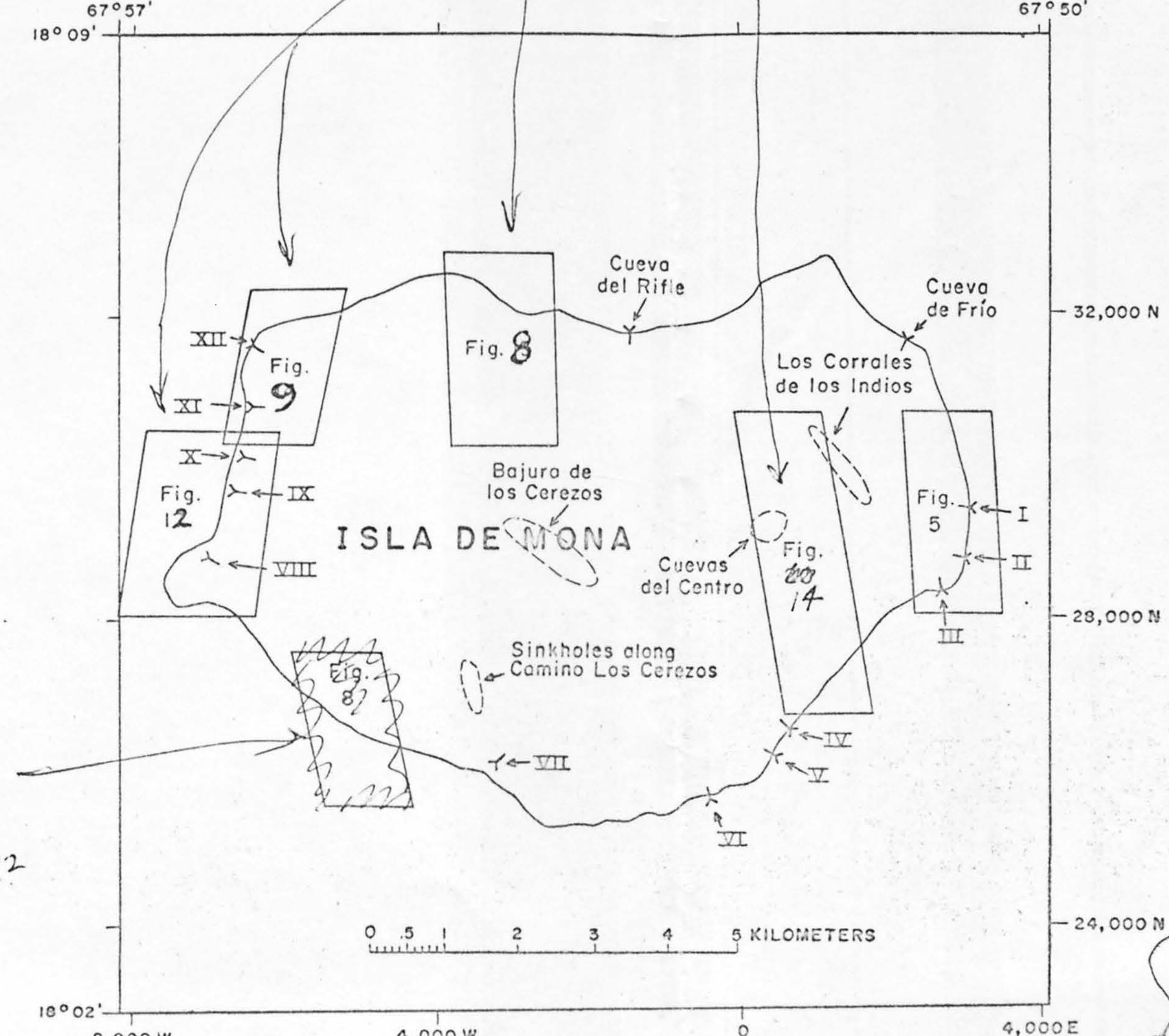

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5, 8, 9, 12, and 14

~~5, 8, 10, 11, 18, and 19~~.

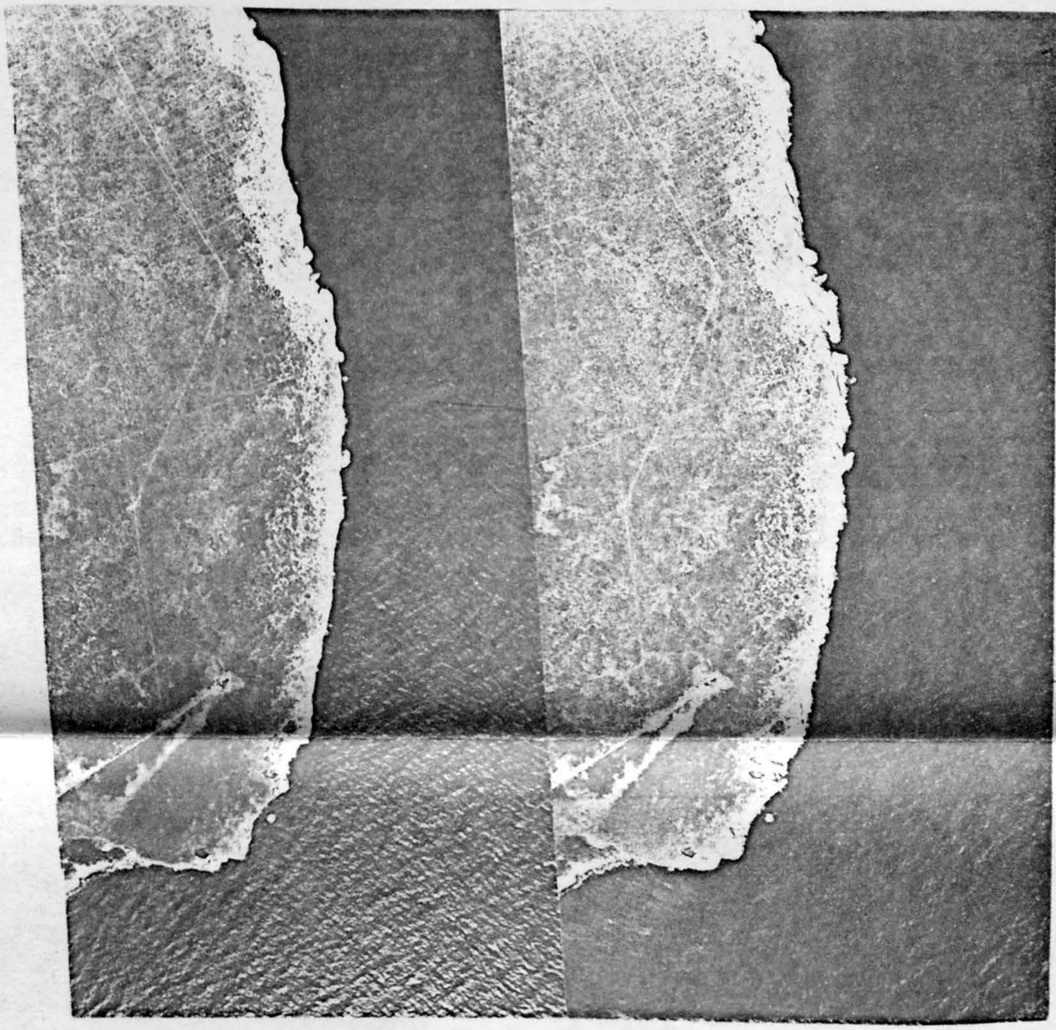
Figure 4 Map showing areas pictured stereoscopically in figures, ~~5, 8, 10, 11, 15, and 20~~ and locations of caves and features of the upland surface. Roman numerals identify survey caves listed in table 4.

Table 5. --Chemical analyses of water supplies, Isla de Mona, P. R.

Analyses by U. S. Geological Survey laboratories
Samples I, II, and IV collected by R. P. Briggs and V. M. Seiders, 1964.
Sample III collected by J. P. Akers, 1964.
n. a. = not applicable; n. r. = not reported.

Sample, Source	Location[1]	Date of collection	Meters			Milligrams per liter														
			Approximate elevation of land surface	Water level (below land surface)	Depth of well	Silica (SiO_2)	Iron (Fe)	Calcium (Ca)	Magnesium (Mg)	Bicarbonate (HCO_3)	Phosphate (PO_4)	Chloride (Cl)	Fluoride (F)	Nitrate (NO_3)	Dissolved solids	Hardness as $CaCO_3$: Calcium, magnesium	Hardness as $CaCO_3$: Noncarbonate	Specific conductance (micromhos at 25°C)	pH
I. --"Pozo del Portugués" well	28,620 N.; 7,200 W.	7-30-64	1	0.9	1.8	2.5	0.00	78	66	240	0.26	695	0.1	0.2	n. r.	466	269	2,600	8.0
II. --Well at aerodromo	27,780 N.; 6,300 W.	7-30-64	2.5	2.3	3.3	3.5	.00	118	110	496	.06	1,090	.5	.2	n. r.	747	340	4,050	8.1
III. --Well at Playa del Uvero	25,940 N.; 3,400 W.	8-31-64	2	1.5	2.4	7.5	.04	122	130	330	2.3	1,890	.8	.6	3,900	839	568	6,090	7.8
IV. --Pool in Cueva de los Pájaros	26,660 N.; 560 E.	7-31-64	n. a.	n. a.	n. a.	14	.00	36	126	8	3.0	190	.0	86	n. r.	608	601	1,560	6.6

[1] Coordinates are those of the Puerto Rico rectangular coordinate system locations are reported to the nearest 10 m.



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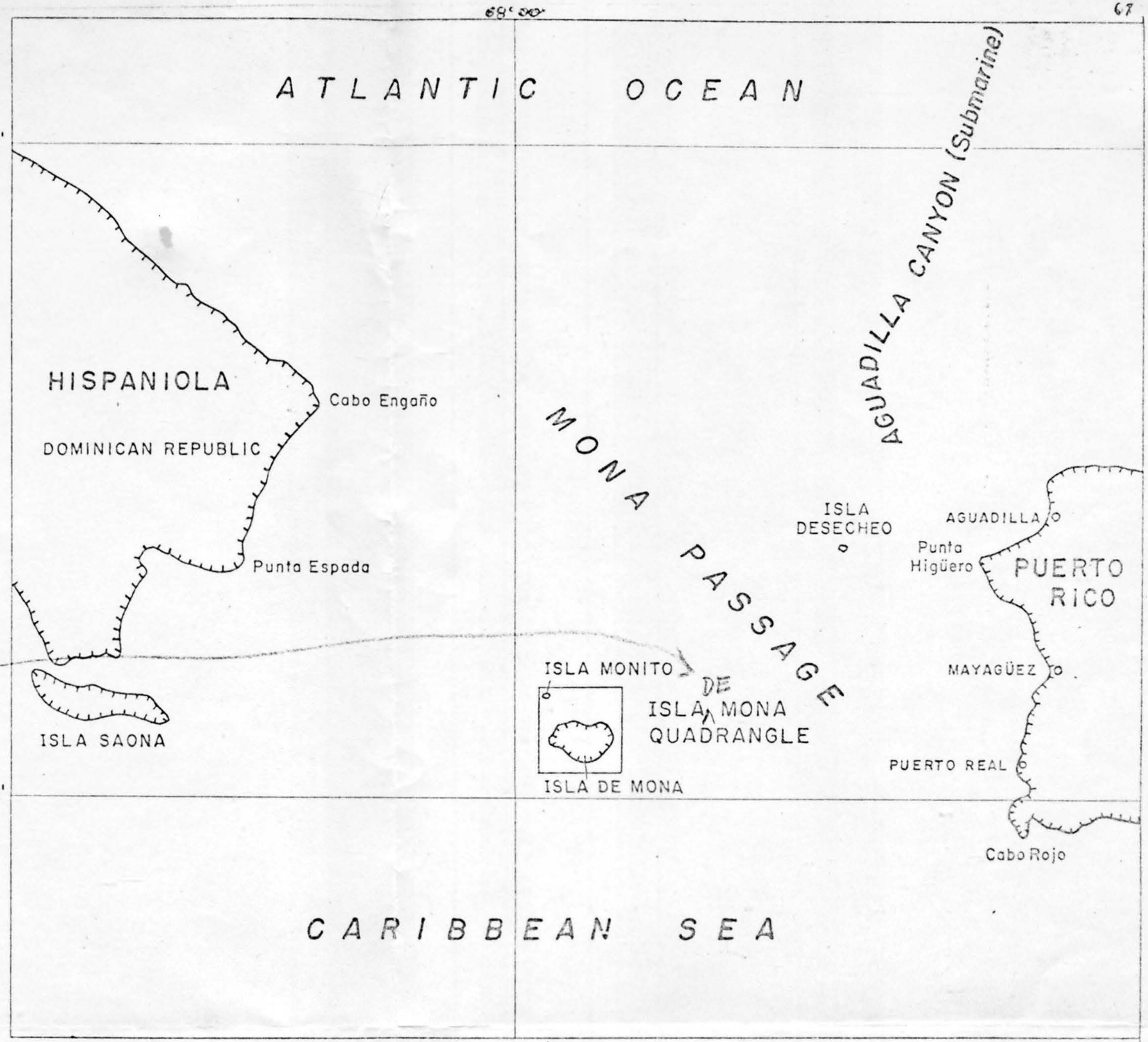

68°00'
67°00'
ATLANTIC OCEAN
AGUADILLA CANYON (Submarine)
19°00'
19°00'
HISPANIOLA
DOMINICAN REPUBLIC
Cabo Engaño
Punta Espada
MONA PASSAGE
ISLA DESECHEO
AGUADILLA
Punta Higüero
PUERTO RICO
MAYAGÜEZ
PUERTO REAL
Cabo Rojo
ISLA SAONA
ISLA MONITO
ISLA DE MONA QUADRANGLE
ISLA DE MONA
18°00'
18°00'
CARIBBEAN SEA
68°00'
67°00'
0 10 20 30 40 50 100 KILOMETERS
0 10 20 30 40 50 60 NAUTICAL MILES

Table 3. --Major oxides, minor elements, and partial norms of samples from cave deposits and soil, Isla de Mona, P. R.

[Chemical analyses for major oxides by U. S. Geological Survey laboratories: analysts P. Elmore, S. Botts, G. Chloe, L. Artis, H. Smith, and J. Glenn. N.R. = not reported. Semiquantitative spectrographic analyses for minor elements by U. S. Geological Survey laboratories: analysts J. L. Harris and W. B. Crandell. Elements looked for in all samples but not detected: Ag, As, Au, Bi, Cd, Eu, Ge, Hf, In, Li, Mo, Nb, Pd, Pt, Re, Sb, Sn, Ta, Te, Th, Tl, U, W, Zn; also looked for in sample M-32 but not detected were Pr, Nd, Sm. 0 = not detected. The first-stated sums for the major oxides are obtained by using the HCl-soluble S figures; sums in parentheses are obtained by using the Aqua regia-soluble S figure (also in parentheses).]

Field number ---------	M-23B	G-3	G-4	I-11	I-12	M-32
Laboratory number ----	W167675	W167678	W167879	W167680	W167681	W167677
Location coordinates 1/	28,370 N.; 3,080 E.	28,370 N.; 2,880 E.	28,370 N.; 2,880 E.	28,390 N.; 2,790 E.	28,410 N.; 2,790 E.	29,230 N.; 330 E.
Location description---	Cueva al Lado del Faro, north end at cliff	Cueva del Lirio	Cueva del Lirio	Cueva del Lirio	Cueva del Lirio	Cuevas del Centro
Major oxides (percent)						
SiO_2 ----------------	0.85	1.6	0.31	1.4	0.30	26.0
Al_2O_3 ----------------	1.2	.32	.10	.40	.00	20.8
Fe_2O_3 ----------------	.83	.07	.00	.14	.00	6.0
FeO ----------------	.08	.10	.00	.04	.04	2.5
MgO ----------------	1.8	.95	.38	1.9	.40	1.1
CaO ----------------	49.0	35.0	32.1	51.3	32.4	6.2
Na_2O ----------------	.65	2.0	.95	.40	.27	.25
K_2O ----------------	.15	.27	.12	.11	.02	1.2
H_2O_- ----------------	1.4	14.9	9.8	.85	19.7	7.6
H_2O_+ ----------------	2.9	3.3	13.8	1.1	1.6	6.4
TiO_2 ----------------	.07	.00	.00	.00	.00	1.1
P_2O_5 ----------------	24.2	17.6	14.2	3.0	.17	.64
MnO ----------------	.00	.00	.04	.10	.10	.28
CO_2 ----------------	15.8	.30	.15	38.7	.10	2.7
Volatiles other than H_2O and CO_2 ---------	N.R.	3.6	5.2	.00	.00	17.2
Aqua regia-soluble S as SO_3 ----------------	N.R.	(19.6)	(29.8)	(.48)	(45.5)	(.12)
HCl-soluble S as SO_3 -----	.52	18.0	26.4	.51	42.6	.10
Sum ----------	99	98(100)	104(107)	100(100)	98(101)	100(100)
Minor elements (percent)						
B --------------------	0.003	0.003	0	0	0	0.005
Ba --------------------	.003	.0007	.0005	.005	.002	.01
Be --------------------	0	0	0	0	0	.00015
Ce --------------------	0	0	0	0	0	.01
Co --------------------	0	0	0	0	0	.0015
Cr --------------------	.005	.0007	0	.001	0	.01
Cu --------------------	.03	.005	.001	.002	.0005	.007
Ga --------------------	0	0	0	0	0	.0015
La --------------------	0	0	0	0	0	.007
Ni --------------------	0	0	0	0	0	.007
Pb --------------------	0	0	0	.0005	0	.001
Sc --------------------	0	0	0	0	0	.001
Sr --------------------	.1	.03	.003	.07	.02	.005
V --------------------	.003	0	0	0	0	.005
Y --------------------	.002	0	0	0	0	.005
Yb --------------------	.0002	0	0	0	0	.0003
Zr --------------------	0	0	0	0	0	.007
Partial norms						
Calcite ----------------	27.1	2/	2/	81.5	2/	3.9
Dolomite ----------------	8.2	2/	2/	8.7	2/	5.0
Gypsum ----------------	1.1	3/ 42	3/ 59	1.0	100	.3
Apatite ----------------	4/ 56.0	5/ 44	5/ 36	3.9	2/	1.5

1/ Coordinates are those of the Puerto Rico rectangular coordinate system; locations are reported to the nearest 10 m.

2/ Minor or trace; not calculated.

3/ Approximate because SO_3 values vary.

4/ Probably largely hydroxylapatite [$Ca_5(PO_4)_3(OH)$] (Kaye, 1959, p. 159).

5/ Approximate because computation of normative gypsum leaves excessive P_2O_5 for computation as hydroxylapatite alone. Probably contains in addition crandallite [$CaAl_3(PO_4)_2(OH)_5 \cdot H_2O$], martinite [hydrous and carbonate-bearing variety of whitlockite $Ca_3(PO_4)_2$], brushite [$CaHPO_4 \cdot 2H_2O$], and(or) other phosphate minerals (Kaye, 1959, p. 157-162).

Sample M-23B. Carbonate-bearing phosphorite. Well indurated.

G-3, G-4. Gypsiferous phosphorite. Friable; volatiles other than H_2O and CO_2 may be contained in nitrates or organic compounds.

I-11. Phosphatic magnesian limestone concretions.

I-12. Gypsum from a roof encrustation. For comparison, pure gypsum [$Ca(SO_4) \cdot 2H_2O$] is composed (in percent) of CaO = 32.5; SO_3 = 46.5; H_2O = 20.93 (Palache and others, 1951, p. 484).

M-32. Aluminous lateritic red earth. Remainder chiefly clay minerals and hydrous iron oxides. Ratio $Al_2O_3+Fe_2O_3:SiO_2$ = 1.03. Volatiles other than H_2O and CO_2 probably chiefly contained in organic compounds.

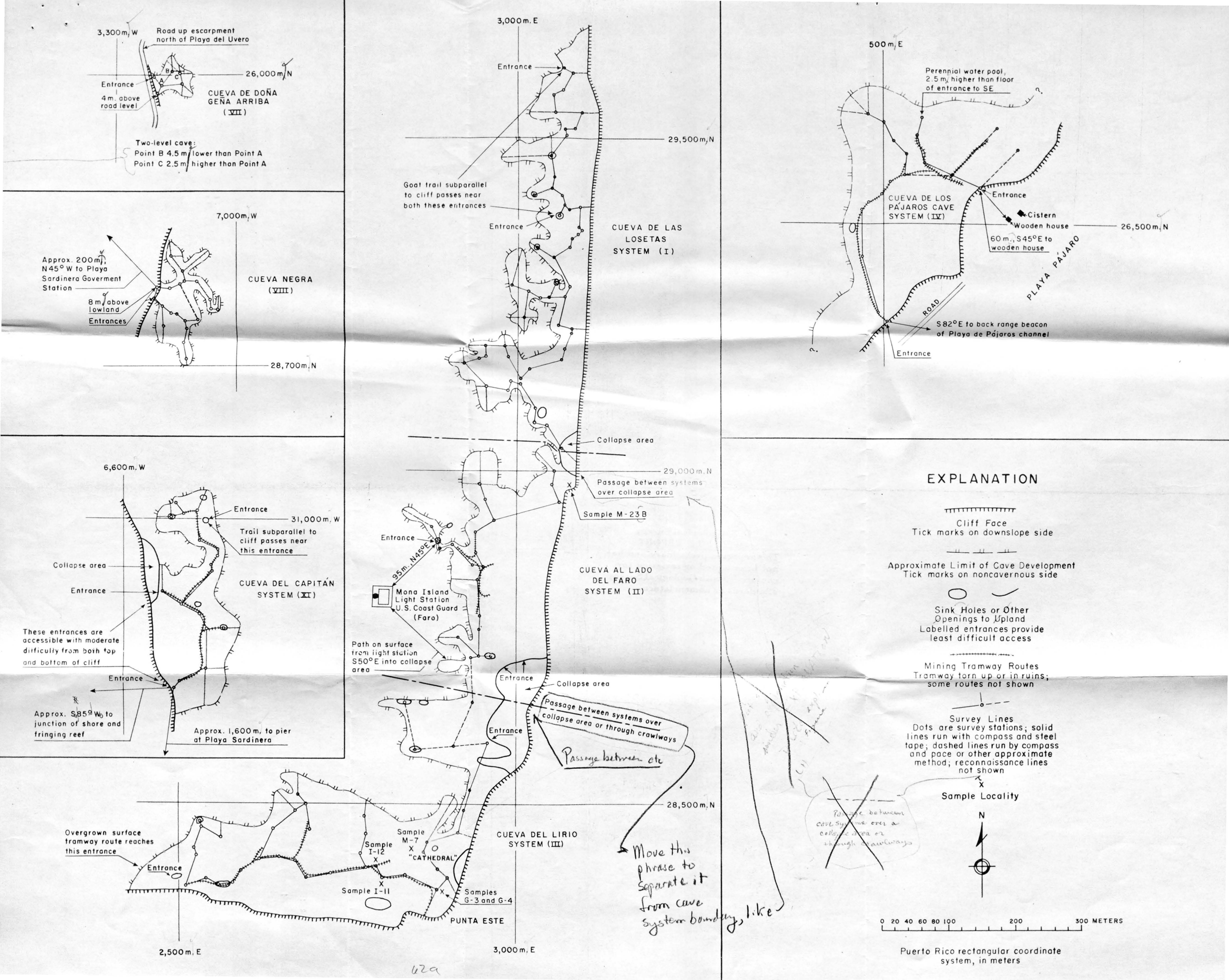
Table 1.--Major oxides, minor elements, partial norms, and rock classes of samples from the Isla de Mona Dolomite, Isla de Mona, P. R.

[Chemical analyses for major oxides by U. S. Geological Survey laboratories; analysts P. Elmore, H. Smith, L. Artis, G. Chloe, S. Botts, and J. Glenn. Semiquantitative spectrographic analyses for minor elements by U. S. Geological Survey laboratories; analysts J. L. Harris and W. B. Crandell. Elements looked for but not detected: Ag, As, Au, Be, Bi, Cd, Ce, Co, Eu, Ga, Ge, Hf, Hg, In, La, Li, Mo, Nb, Ni, Pd, Pt, Re, Sb, Sc, Sn, Ta, Te, Th, Tl, U, V, W, Y, Yb, Zn, Zr. 0 = not detected.]

Field number	M-8A	M-8B	M-9	M-12	M-13A	M-13B
Laboratory number	W167658	W167659	W167664	W167673	W167665	W167674
Location coordinates[1]	28,300 N.; 2,600 E.	28,300 N.; 2,600 E.	28,330 N.; 2,530 E.	26,320 N.; 480 E.	25,710 N.; 130 E.	25,710 N.; 130 E.
Location description	West of Punta Este, 2 m above sea level, type locality	West of Punta Este, 5 m above sea level, type locality	West of Punta Este, and M-8, 20 m above sea level	Between Playa de Pájaros and Punta los Ingleses, base of cliff section	Punta los Ingleses, 3 m above sea level	Punta los Ingleses, 10 m above sea level
Major oxides (percent)						
SiO_2	0.16	0.00	0.00	0.00	0.00	0.16
Al_2O_3	.00	.00	.00	.00	.00	.10
Fe_2O_3	.00	.00	.00	.00	.00	.00
FeO	.00	.00	.00	.00	.00	.00
MgO	18.2	17.5	11.2	17.8	18.3	18.2
CaO	33.7	33.7	41.5	34.4	32.9	33.4
Na_2O	.20	.07	.20	.52	.20	.72
K_2O	.00	.00	.00	.11	.10	.16
H_2O^-	.15	.24	.82	.17	.59	.40
H_2O^+	.45	.36	.28	.40	.41	.70
TiO_2	.00	.00	.00	.00	.00	.00
P_2O_5	.06	.05	.08	.10	.08	.14
MnO	.00	.05	.03	.11	.04	.10
CO_2	46.9	47.1	45.1	46.1	45.9	45.7
HCl-soluble S as SO_3	.20	.48	1.7	.11	1.4	.44
Sum	100	100	101	100	100	100
Minor elements (percent)						
B	0	0	0	0	0.003	0
Ba	.0005	.0003	.0003	.0003	.0003	.0003
Cr	0	0	.001	.0003	.0003	.0003
Cu	.0007	.0005	.0005	.0005	.0005	.0007
Pb	0	0	0	0	.0007	0
Sr	.01	.015	.015	.015	.015	.01
Partial norms						
Calcite	15.3	17.2	45.4	16.9	12.4	13.3
Dolomite	83.3	80.1	51.2	81.4	83.7	83.3
Gypsum	.43	1.0	3.7	.24	3.0	.95
Apatite	.14	.12	.19	.23	.19	.32
Rock classification (of Pettijohn, 1949, p. 312)						
	Calcitic dolomite	Calcitic dolomite	Calcitic dolomite	Calcitic dolomite	Calcitic dolomite	Calcitic dolomite

Field number	M-13C	M-14	M-17	M-22A	M-25	M-27	M-30	M-33B
Laboratory number	W167669	W167666	W167667	W167660	W167661	W167662	W167670	W167663
Location coordinates[1]	25,710 N.; 130 E.	25,560 N.; 530 W.	25,890 N.; 3,220 W.	30,870 N.; 6,600 W.	30,590 N.; 2,780 E.	31,620 N.; 6,500 W.	29,090 N.; 3,080 W.	32,220 N.; 3,210 W.
Location description	Punta los Ingleses, 11 m above sea level	Between Punta los Ingleses and Punta Brava, base of cliff section	North of Playa del Uvero, base of cliff section	South of Punta El Capitán, 5 m above sea level	Between Light Station and Cabo El Toro, top of cliff	Cabo Barrionuevo, just below Lirio Limestone-Isla de Mona Dolomite contact	Bajura de los Cerezos, at point where Camino los Cerezos enters lowland	East of Cabo Noroeste, just west of fault, 10 m in from cliff edge
Major oxides (percent)								
SiO_2	0.31	1.0	0.16	0.00	0.00	0.00	0.00	0.00
Al_2O_3	.10	.18	.17	.00	.00	.00	.00	.00
Fe_2O_3	.04	.05	.04	.00	.00	.00	.00	.00
FeO	.04	.06	.04	.00	.00	.00	.00	.00
MgO	16.6	5.6	17.0	17.7	18.0	18.2	17.9	19.1
CaO	34.1	47.7	34.7	34.5	34.5	33.9	34.6	33.3
Na_2O	.22	.03	.30	.05	.06	.05	.11	.06
K_2O	.12	.04	.10	.00	.00	.00	.12	.00
H_2O^-	1.1	.30	[illegible]	.16	.10	.25	.07	.08
H_2O^+	.70	.90	.10	.42	.46	.47	.46	.19
TiO_2	.00	.00	.00	.00	.00	.00	.00	.00
P_2O_5	.12	.22	.09	.05	.09	.17	.06	.04
MnO	.00	.07	.00	.00	.00	.00	.00	.07
CO_2	44.1	43.3	45.7	47.1	46.6	46.3	46.7	47.2
HCl-soluble S as SO_3	2.0	.25	1.1	.11	.12	.46	.12	.11
Sum	100	100	101	100	100	100	100	100
Minor elements (percent)								
B	0	0.003	0	0	0	0	0	0
Ba	.0003	.0005	.0003	.0003	.0003	.0003	.0003	.0003
Cr	.0007	.001	.002	0	.0005	.0007	.0007	.0003
Cu	.0007	.002	.001	.0005	.0003	.0007	.0002	.0005
Pb	.003	0	0	0	.001	0	.0005	.007
Sr	.015	.03	.015	.015	.015	.015	.01	.015
Partial norms								
Calcite	17.9	70.8	18.9	18.1	16.6	14.7	17.0	11.9
Dolomite	75.9	25.6	77.8	81.0	82.4	83.3	81.9	87.4
Gypsum	4.3	.54	2.4	.24	.26	.99	.26	.24
Apatite	.28	.51	.21	.12	.21	.49	.14	.09
Rock classification (of Pettijohn, 1949, p. 312)								
	Calcitic dolomite	Dolomitic limestone	Calcitic dolomite	Calcitic dolomite	Calcitic dolomite	Calcitic dolomite	Calcitic dolomite	Calcitic dolomite

[1] Coordinates are those of the Puerto Rican rectangular coordinate system; locations are reported to the nearest 10 m.


3,300 m. W
Road up escarpment north of Playa del Uvero
Entrance
26,000 m. N
4 m. above road level
CUEVA DE DOÑA GEÑA ARRIBA (VII)
Two-level cave: Point B 4.5 m. lower than Point A Point C 2.5 m. higher than Point A
7,000 m. W
Approx. 200 m. N45° W to Playa Sardinera Goverment Station
8 m. above lowland
Entrances
CUEVA NEGRA (VIII)
28,700 m. N
6,600 m. W
Entrance
31,000 m. W
Trail subparallel to cliff passes near this entrance
Collapse area
Entrance
CUEVA DEL CAPITÁN SYSTEM (XI)
These entrances are accessible with moderate difficulty from both top and bottom of cliff
Entrance
Approx. S85° W. to junction of shore and fringing reef
Approx. 1,600 m. to pier at Playa Sardinera
3,000 m. E
Entrance
29,500 m. N
Goat trail subparallel to cliff passes near both these entrances
Entrance
CUEVA DE LAS LOSETAS SYSTEM (I)
Collapse area
29,000 m. N
Passage between systems over collapse area
Sample M-23 B
Entrance
95 m. N45° E
Mona Island Light Station U.S. Coast Guard (Faro)
CUEVA AL LADO DEL FARO SYSTEM (II)
Path on surface from light station S50° E into collapse area
Entrance
Collapse area
Passage between systems over collapse area or through crawlways
Entrance
Passage between etc
28,500 m. N
Overgrown surface tramway route reaches this entrance
Entrance
Sample I-12
Sample M-7
"CATHEDRAL"
Sample I-11
Samples G-3 and G-4
CUEVA DEL LIRIO SYSTEM (III)
PUNTA ESTE
Move this phrase to separate it from cave system boundary, like
2,500 m. E
3,000 m. E
500 m. E
Perennial water pool, 2.5 m. higher than floor of entrance to SE
CUEVA DE LOS PÁJAROS CAVE SYSTEM (IV)
Entrance
Cistern
Wooden house
26,500 m. N
60 m., S45° E to wooden house
PLAYA PÁJARO
ROAD
S82° E to back range beacon of Playa de Pájaros channel
Entrance
EXPLANATION
Cliff Face
Tick marks on downslope side
Approximate Limit of Cave Development
Tick marks on noncavernous side
Sink Holes or Other Openings to Upland
Labelled entrances provide least difficult access
Mining Tramway Routes
Tramway torn up or in ruins; some routes not shown
Survey Lines
Dots are survey stations; solid lines run with compass and steel tape; dashed lines run by compass and pace or other approximate method; reconnaissance lines not shown
Sample Locality
N
0 20 40 60 80 100 200 300 METERS
Puerto Rico rectangular coordinate system, in meters
Passage between cave systems over a collapse area or through crawlways
62a