

MINERAL RESOURCE ASSESSMENT OF PUERTO RICO

FIELD TRIP
June 25, 1992

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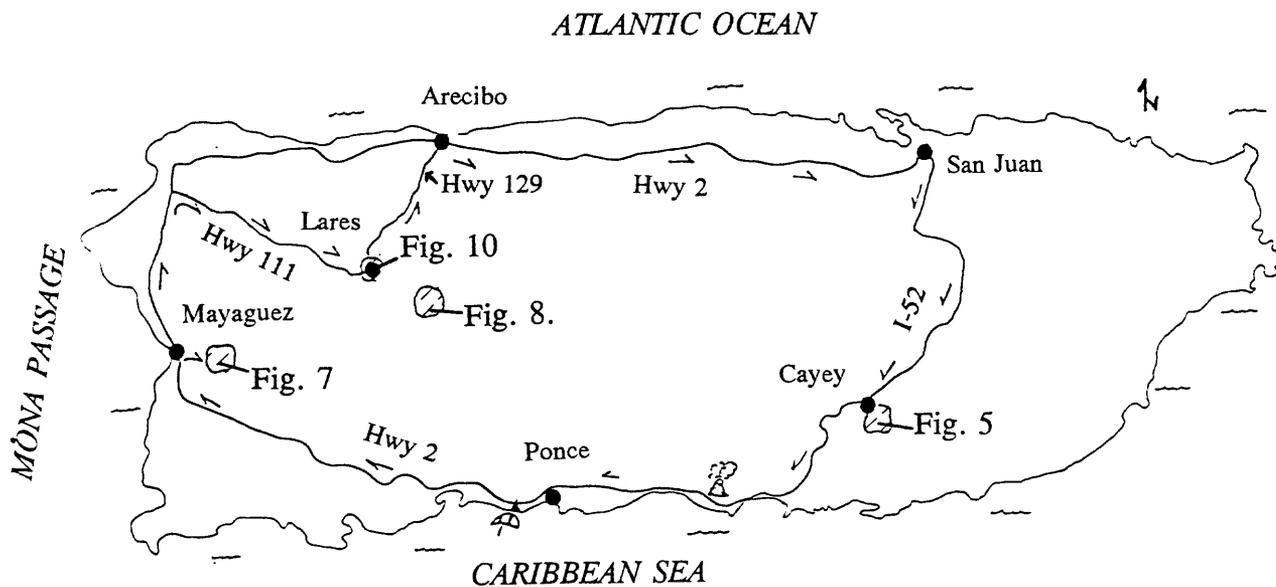
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ACKNOWLEDGMENTS

This trip and guidebook would not have been possible without the assistance from numerous geologists who have worked extensively in Puerto Rico for the past several decades. Particular appreciation is extended to the faculty of the Department of Geology at the University of Puerto Rico in Mayaguez (UPR), the Department of Natural Resources in Puerto Rico (DNR), along with geologists from the United States Geological Survey's Water Resources Division (WRD) in San Juan. Individuals such as Johannes H. Schellekens (UPR), Ramon A. Harris (DNR), Greg McKelvey (Phelps Dodge Mining Company), and Joseph Troester (WRD) deserve our thanks for their assistance in this field trip.



Puerto Rico showing the route of the field trip and location of the stops. An unscheduled stop occurred just east of Ponce where pillow lavas are nicely exposed (sketch of volcano). Lunch was at El Tuque park west of Ponce (sketch of umbrella). Location of Figure 8 was included but the site was not visited due to time constraints.

Cover Photo:

A view to the north from a hill 2.5 km southeast of Angeles, Puerto Rico. The surface in the foreground is a remnant of an erosional plane developed in early Oligocene time (around 35 million years ago). The Tanama porphyry copper deposit (about 40 million years old) is situated 1 km south of this point. Oligocene sedimentary rocks, including the Lares Limestone which forms the irregular karst topography in the distance, were deposited on this erosional plane and, at one time, probably covered the viewpoint as well as the partially eroded copper deposit to the south. (Caption by D.P. Cox, USGS; photo by J.N. Weaver, USGS).

Introduction

This field trip, brief in duration, is designed to introduce participants to a few of the outcrops and mineral deposits addressed during the previous two days of lectures. Due to time constraints only a few stops will be possible, but the trip should permit the participants to get a good feel of the overall geology of the island.

Itinerary

The trip will start and end at the Condado Beach Hotel in San Juan. The bus will head south along Interstate 52 and stop just east of Cayey at the Cerro Avispa deposit. Following a few brief stops, we will continue south on I-52, through Ponce and head west (along Hwy. 2) to Mayaguez, where we will head east a short distance to the Las Mesas nickel laterite deposits. Schedule permitting, we will return to San Juan via the town of Lares where a brief stop will be made at the San Sebastian Formation to examine one of the coal outcrops. The trip back to San Juan will take us through the heart of quite spectacular karst topography.

A brief discussion of the porphyry copper of the Tanamá and Helecho deposits has been included in the back of this report because of its potential importance. The outcrops in this deposit are difficult to reach by bus and will not be included on this field trip. Figures 1 and 2, respectively, show a schematic sketch of the geology of the island and stratigraphic nomenclature of the north coast middle Tertiary basin, Puerto Rico. A columnar section of the Middle Tertiary rocks in the northern part of the island is shown on figure 3.

GEOLOGY OF PUERTO RICO

Extracted from

J.H. Schellekens, J. Joyce, A.L. Smith, and D.K. Larue
1991

Puerto Rico is the easternmost island of the Greater Antilles and is a translational island-arc terrane with a geologic record of 140 million years. The island lies within the seismically active Caribbean-North American Plate boundary zone. The relative motion between the two plates is on the order of 2 cm per year and is taken up mainly by strong oblique underthrusting and left-lateral faulting in the Puerto Rico trench. A well defined southward dipping Benioff zone occurs under the eastern half of the island but is missing under the west side (McCann and Sykes, 1984; Schell and Tarr, 1978). Some plate motion and underthrusting also occur south of Puerto Rico in the Muertos Trough.

Puerto Rico and the Virgin Islands appear to be a separate tectonic block within the plate boundary zone. Puerto Rico is separated from Hispaniola on the west by a zone of active extension, which runs from the Mona Canyon through the southwestern quarter of the

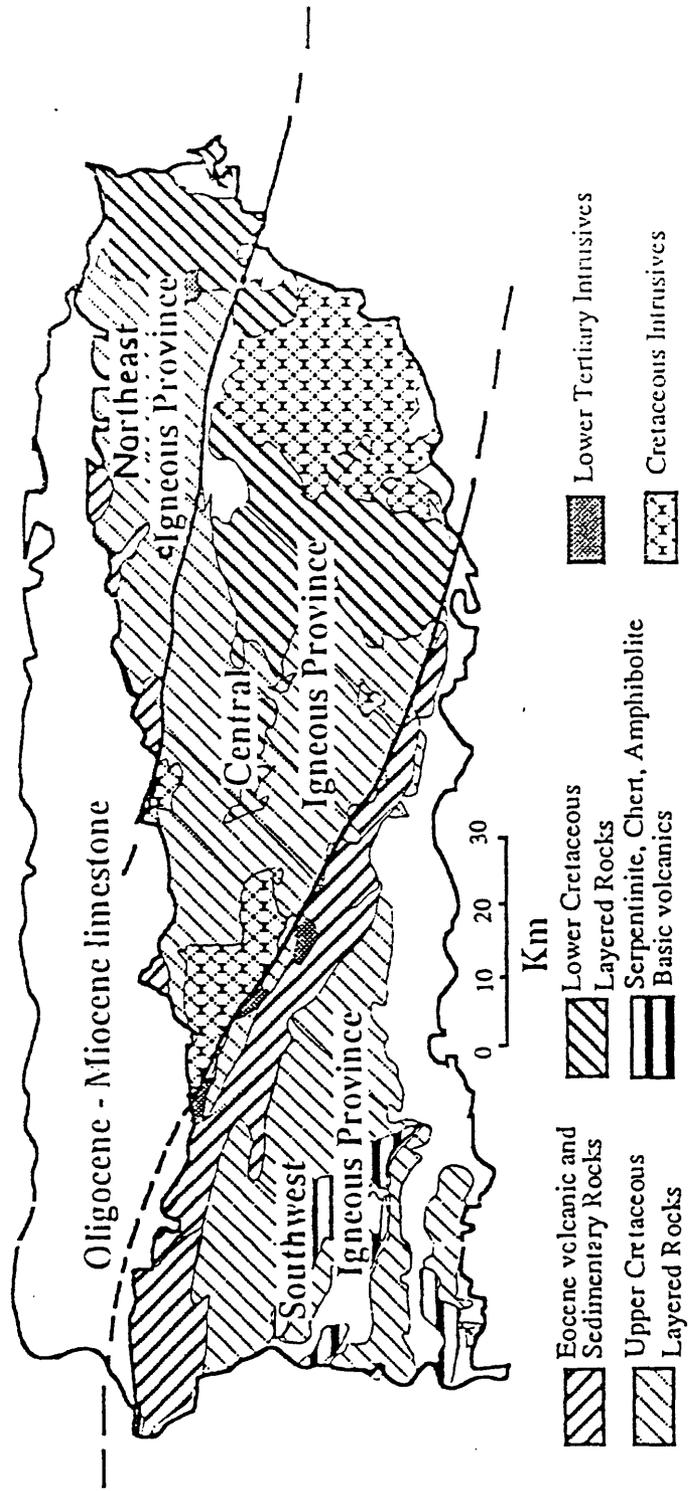


Figure 1. Schematic geologic map of Puerto Rico (Schellekens and others, 1991). The northern Oligocene-Miocene limestone belt also denotes the North Coast Tertiary Basin which comprises the coal-bearing San Sebastian Formation.

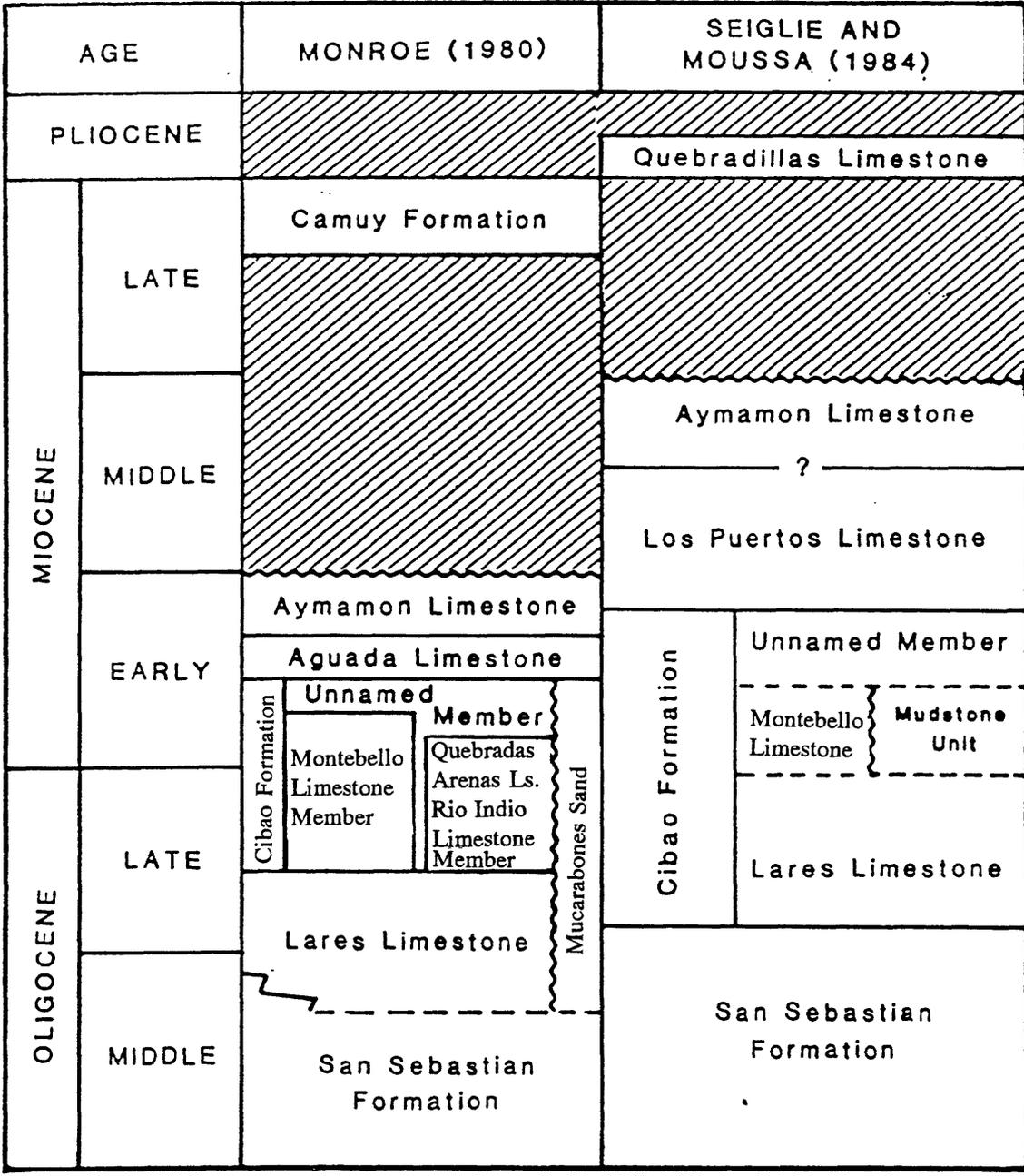
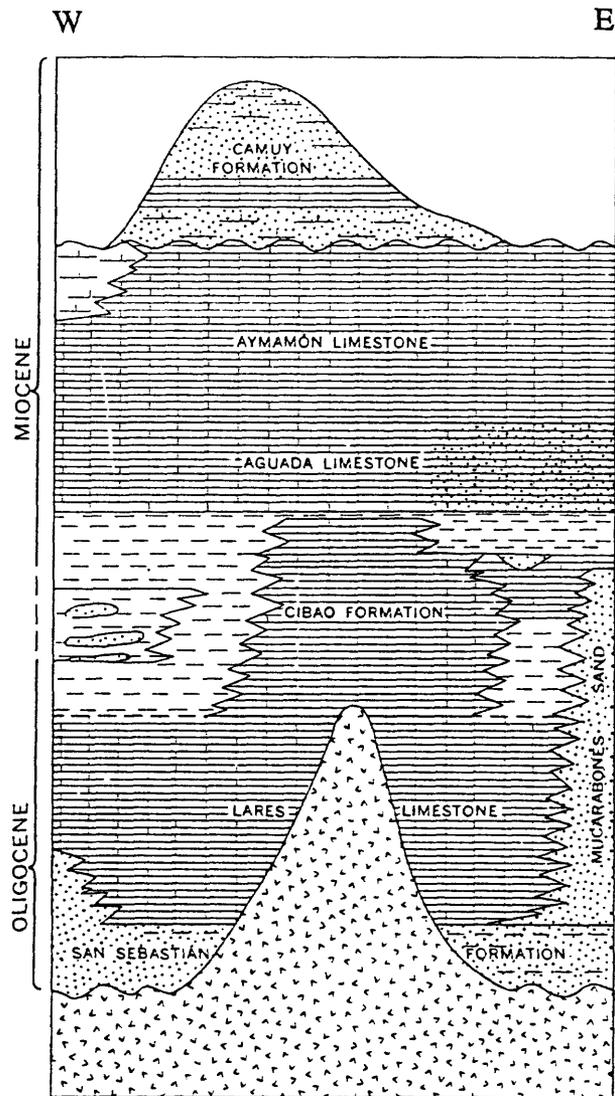
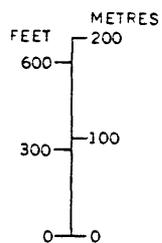


Figure 2. Stratigraphic nomenclature of the north coast Middle Tertiary basin, Puerto Rico. (Modified from Ward et al., in press).



EXPLANATION



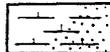
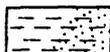
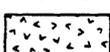
-  LIMESTONE, SANDY LIMESTONE
-  CHALK, SANDY CHALK
-  CALCAREOUS CLAY, SANDY CLAY
-  SAND, SAND AND GRAVEL
-  CRETACEOUS TO EOCENE ROCKS (MAINLY VOLCANIC)

Figure 3. Columnar section of Middle Tertiary rocks in northern Puerto Rico. (Monroe, 1976)

island. On-land extensional faulting has produced the distinctive ridge and valley topography and generally low elevations of southwestern Puerto Rico. Eastern Puerto Rico and the northern Virgin Islands are separated from St. Croix and the Lesser Antilles by another active zone of extension, which formed the Whiting Basin (south of Puerto Rico), the Virgin Islands Basin, and the Anegada Passage.

Puerto Rico consists of volcanic, volcanoclastic, and sedimentary rocks of Late Jurassic to Early Tertiary age, which were intruded by felsic plutonic rocks during the Late Cretaceous and Early Tertiary, and are overlain by slightly tilted Oligocene and younger sedimentary rocks and sediments (Briggs and Akers, 1965).

Island-wide lithostratigraphic correlation within the basement rocks is difficult because individual units appear to have limited original lateral extent and the rocks have been strongly deformed and faulted. To overcome these correlation problems, earlier workers divided the island into structural blocks (Cox and Briggs, 1973) or subprovinces (Barabas, 1977). Here the island is divided into three igneous provinces, the southwestern igneous province (SIP), the central igneous province (CIP), and the northeastern igneous province (NIP) based on differences in stratigraphy, lithology, petrology and geochemistry (fig. 1).

Each igneous province contains a number of volcano-stratigraphic associations, identified as packets of volcanic and interstratified sedimentary rocks, where the age of the association is defined based on fossils in the sedimentary rocks. The boundaries of a volcano-stratigraphic association may be disconformities or unconformities (Schellekens, 1991).

Cerro Avispa Gold-Silver-Copper Prospect

Geology

The Cerro Avispa deposit occurs at the northwestern end of a large area of hydrothermally altered rocks southeast of the town of Cayey and is about 8 km long and 0.5 to 2 km wide running WNW-ESE. The alteration is superimposed on a sequence of WNW dipping volcanic flows and flow breccias ranging in composition from basaltic andesite to andesite. To the NE and SW, the flows are interstratified with volcanic siltstones and sandstones (Berryhill and Glover, 1960). The spatial arrangements of these lithologies suggest an association of proximal volcanic rocks flanked by more distal volcanoclastic rocks. The volcanic rocks typically contain abundant pyrite. Along a NW striking deformation zone the pyrite has oxidized, bleaching the rocks and leaving pyrite casts and Fe-hydroxides on fracture planes (Schellekens, 1987). Mineralized rocks occur at the top of this pile of volcanic rocks at the northwestern end of the hydrothermally altered zone, in intensely altered volcanic breccia.

The mineralized area consists of sulfide-bearing quartz veins in an area of generally silicified and pyritized rocks. Reconnaissance sampling by Bergey (1960) had contents ranging from 1 to 17 oz/ton Au and 0.1 to 14 oz/ton Ag. The highest gold and silver values were found in samples with visible chalcopyrite and sphalerite (Bergey, 1960). Chip samples of quartz veins with abundant sulfides yielded 2.1 percent Cu, 1.2 percent Zn, and 15.1 percent Pb (Ludden, 1961a). Ludden (1961a) reports that samples from the NW striking altered zone showed Cu contents of 80 to 420 ppm, but no Au and Ag.

History

In 1956, a mineral exploration program was initiated by A.D. Fraser from Kingston, Jamaica (Ludden, 1961a; Bergey, 1963). In 1957 Mr. Fraser was granted a number of Exclusive Prospecting Permits by the Mining Commission of the Commonwealth of Puerto Rico. One of these permit areas was the Cayey permit area of about 206 sq. miles (527 km). In June 1960, quartz veins were discovered with Au, Ag, and Cu values in the Cerro Avispa area, southeast of Cayey in the Cayey permit area.

Prospecting and sampling of the prospect area indicated a large number of mineralized veins in an area of about 2 by 1 miles. About 1 mile to the west of the first discovery numerous excavations were noted, including an open cut of more than 200 ft (30 m) long and at least 10 ft (3 m) deep. According to the local farmers, this mining activity was carried out around 1860 by the Spaniards. Based on this first reconnaissance, a map delineating areas of interest was produced in which the gold contents were displayed. Gold contents ranged from 3 to 434 ppm, silver values from 31 to 527 ppm.

In August 1960, R.B. Ludden carried out a preliminary investigation and based on his recommendation, Phelps Dodge acquired an option on the Fraser prospects, and in November 1960 started a program of geologic reconnaissance and geochemical sampling (Ludden, 1961a). The study of the Cerro Avispa gold-silver-copper vein prospect by this company revealed a fairly large area of narrow, widespread, steeply dipping quartz veins varying in strike from N-S to NW-SE. In the quartz veins and the adjacent country rock, varying amounts of pyrite, chalcopyrite, sphalerite, and supergene chalcocite were reported (Ludden, 1961a).

Following the initial exploration, a detailed proposal for intensive exploration was submitted. Within the prospect, four vein systems were selected which contained high grade Au-Ag quartz veins, sometimes with Cu, in the central and eastern part of the Cerro Avispa area. The company proposed to undertake 1,800 ft (550 m) of drilling; drive an exploratory adit of 1,250 ft (380 m) and carry out 40 days of trenching. As far as is known, these exploration activities were never carried out.

About 1983, COMINCO American Resources Inc. initiated a new exploration program in Puerto Rico. One of the prospects of interest was the Cerro Avispa deposit. COMINCO carried out an initial geological and geochemical investigation and applied for an exploration permit. To date, no gold has been extracted.

Origin of the Deposits

Pease (1976) suggested that the sulfide deposits at Cerro Avispa may have formed from hydrothermal fluids carried along NW-SE fault zones from late magmatic differentiates of the San Lorenzo Batholith at Punta Tuna near Puerto Maunabo. Schellekens (1987) proposed that the sulfide deposits were the result of emanations near a volcanic center on top of the Early Cretaceous volcanic pile (fig. 4). The subaerial environment for the volcanics as suggested by Berryhill and Glover (1960), combined with precious metal bearing quartz vein-system, suggests an epithermal vein deposit.

STOP 1: To reach Cerro Avispa (fig. 5):

Take I-52 south from San Juan and exit at Cayey. Follow Hwy. 1 south, turn left under I-52 and then right on 7736. From kilometer marker 0.6, the road goes through outcrops with hydrothermally altered volcanic rocks on the flanks of Monte El Gato. The rocks probably were feldspar porphyry flows. Now the feldspars are altered to white clay occurring in a red clay groundmass. Numerous small veinlets cut across the outcrop.

ROAD LOG FROM STOP 1 TO STOP 2:

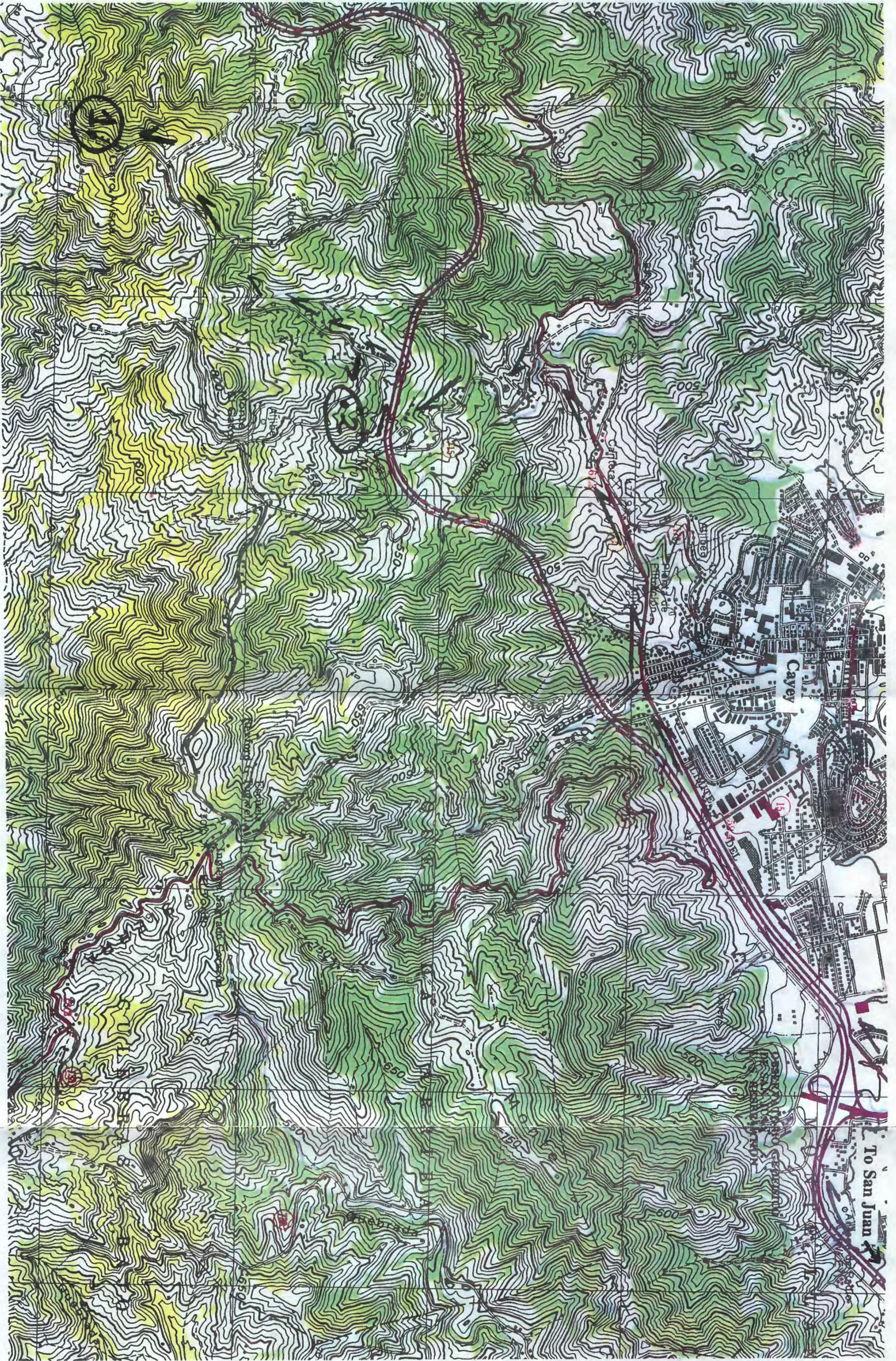
From kilometer markers 2.9 to 3.1, the rocks appear to be intensely altered. The groundmass now consists of bleached white clay and veins with white clay cutting the rock. Abundant iron oxide casts are present.

At kilometer marker 3.4 turn left on Hwy. 715 to the Cerro Avispa deposit. Stop 1 is an outcrop of argillically altered andesite with crosscutting quartz veins. Stop 2 shows boulders of ferricrete. The field trip only stopped at Stop 1. Buses were unable to travel the road between Stop 2 and Stop 1. Figure 4 locates the Cerro Avispa deposit in relation to the hydrothermally altered zone and pre-Robles Formation. The pre-Robles Formation refers to the geologic units which are older than the Albian-Santonian units of the Robles Formation.

Return on route 715, cross under I-52 to route 1. Turn right on route 1 north, towards Cayey. In Cayey, take I-52 towards Ponce (south).

At kilometer marker 44.2, I-52 intersects the hydrothermally altered zone related to the Cerro Avispa deposit.

Jibaro Monument: I-52, Km 49.7: this monument is dedicated to all the people in the country who work the land. The monument is on the right side of the road with good parking.



10

Figure 5. Location of Cerro Avispa Gold-Silver-Copper Deposits. Stops 1 and 2 are marked. Cayey 1:20,000 scale topographic sheet.

Figure 4. Geologic map of the hydrothermally altered zone and pre-Robles formations along Route 15 from Guyama to Cayey with location of Cerro Avispa deposit.

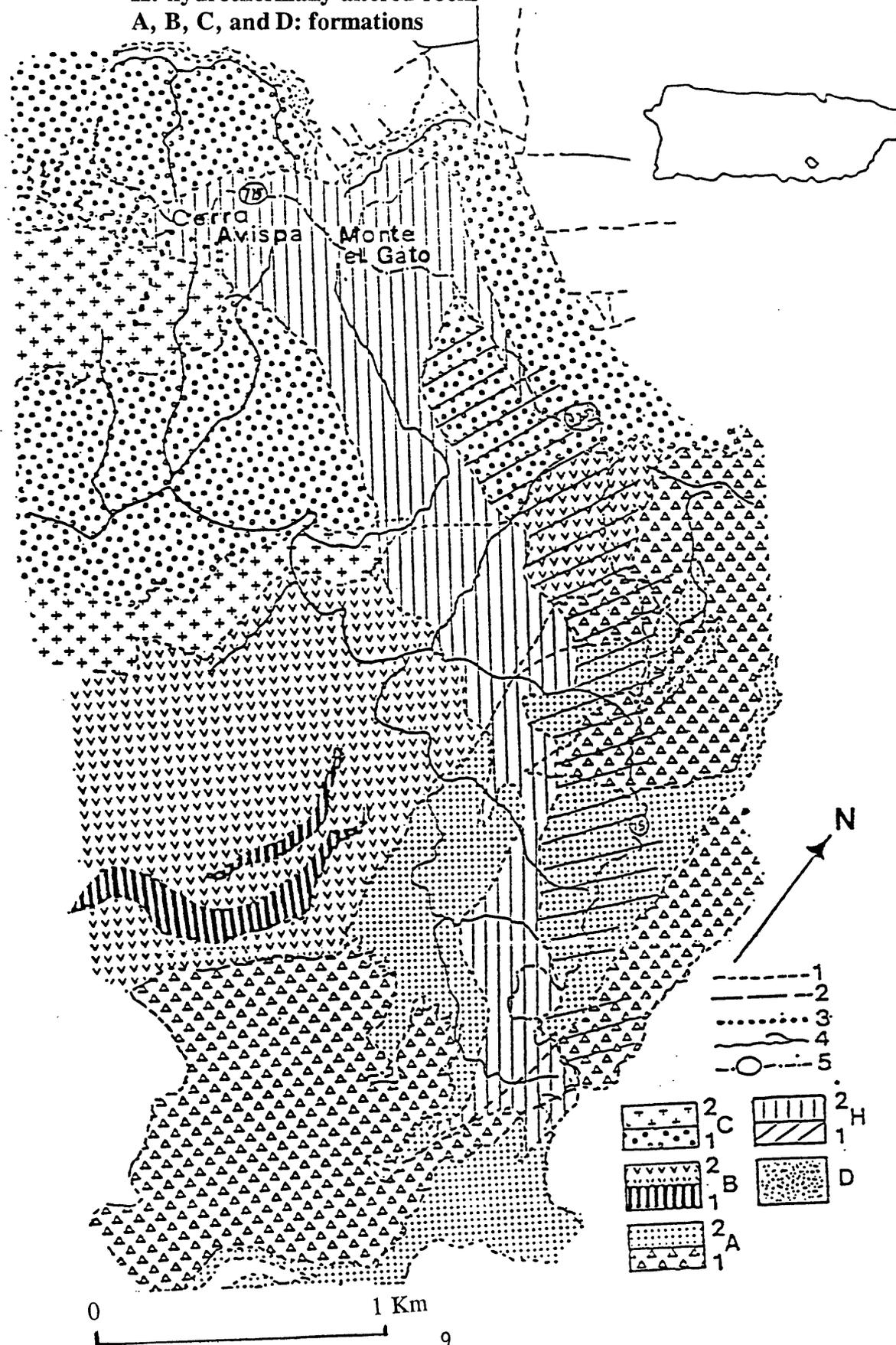
Geology: Berryhill and Glover (1960) (Schellekens, 1987)

scale 1:20,000

Legend: 1: Boundary; 2: fault; 3: veins; 4: river; 5: road

H: hydrothermally altered rocks

A, B, C, and D: formations



The surrounding rocks are Early Cretaceous volcanoclastic rocks. The Las Tetas Lava Member of the Robles Formation (Albian to Santonian) crop out to the northwest, in a conspicuous pair of bald knobs bearing the same name.

Between kilometer markers 54.4 and 59, we see volcanic and volcanoclastic rocks mapped as the Early Cretaceous "pre-Robles Formations" (Berryhill and Glover, 1960). The low ridges in the valley below are the eastern extension of the Eocene Belt.

On I-52, between kilometer markers 59.8 and 60.9: Lapa Lava Member of the Robles Formation (Albian-Santonian) is well exposed. The outcrop exposes spectacular pillows and other submarine lava-flow features. The basaltic rocks are pyroxene and porphyries, with typical characteristic cruciform texture of the feldspars (Jolly, 1971). These calc-alkaline lavas with high K_2O contents are more or less contemporaneous with the tholeiitic low K_2O Las Tetas lavas.

At kilometer marker 68.3, we saw an outcrop consisting of folded limestone in the northeast and a melange of limestone and purple volcanoclastic blocks in a bedded sandy matrix in the southern part. The section is mapped as Cuevas Limestone (Eocene) and Coamo Formation (late Cretaceous). The section is part of the Eocene Belt and the Great Southern Puerto Rico Fault zone (Glover, 1971; Glover and Mattson, 1973).

LUNCH at El Tuque park just west of Ponce.

At kilometer marker 82.9, the highway intersects outcrops of the nearly vertical beds of interbedded sandstones and mudstones containing sedimentary structures of typical turbidite deposits. The rocks probably belong to the Eocene Raspaldo Formation.

Between kilometer markers 87.3 and 86.8, outcrops on both sides of the highway contain coarse conglomerate interlayered with red-colored finer-grained sediments. Bottom contacts of the conglomerates are scoured and often show reverse grading. The unit is mapped as part of the lower clastic member of the Oligocene Juana Diaz Formation (Krushensky and Monroe, 1975).

On I-52 at kilometer marker 97.3: Juana Diaz Formation is visible consisting of a limestone mass about 115 m wide and 15 m thick occurring within the pelagic claystones of the Juana Diaz Formation. The limestone is made up entirely of biogenic material, predominantly calcareous tests and skeletal fragments of shallow-water organisms. The limestone mass has been interpreted as a dislodged block of an algal bank that had slid into a deep-water environment (Moussa, 1977).

Geology of the Area: Southwest Igneous Province

Extracted and modified from
J.H. Schellekens, J. Joyce, A.L. Smith, and D.K. Larue
1991

The Southwest Igneous Province of Puerto Rico is distinct from the rest of Puerto Rico in the occurrence of outcrops of three serpentinite belts. These serpentinites contain rafts of metavolcanic rocks and cherts that are dated as being the oldest rocks of Puerto Rico and were mapped as the Bermeja Complex (Mattson, 1960). Cherts as old as Kimmeridgian (Montgomery, 1990; Schellekens and others, 1990) and amphibolites dated at 126 Ma (Cox and others, 1977) occur in the Sierra Bermeja. These rocks are overlain by Cenomanian to Eocene, basic to intermediate volcanic and volcanoclastic rocks, and limestones that are intruded by small, probably shallow, plutonic rocks (fig. 3).

Of the three serpentinite belts that crop out in southwest Puerto Rico (Mattson, 1960) the two northern belts are locally capped by laterite deposits (fig. 6). These have been studied in the past to assess their potential as a source for nickel, cobalt, iron, and chromium. The two largest deposits, Las Mesas (figs. 6 and 7) and the Guanajibo-Punta Guanajibo (fig. 7), were extensively drilled; the other small deposits were tested with only a few holes at readily accessible sites. A total of 10,856.5 ft (3,250 m) in 279 holes was drilled. Based on a cutoff of 0.6 percent Ni, the reserves were inferred to be 90.5 million short tons with an average nickel content of 0.88 percent. The enriched zones average in thickness from 10.5 ft (3.2 m) to 51 ft (15.4 m), with a mean of about 19.5 feet (6 m) (Heidenreich and Reynolds, 1959). A restudy of the Guanajibo deposit by the "Comisión de Minería" of Puerto Rico, that put in 12 drill holes with a total length of 545.1 ft (170 m), came up with more accurate figures than previous estimates (Cram, 1972).

GEOLOGY AND PGE POTENTIAL

By

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Reston, Va.	Mayaguez, PR	Denver, Colo.

The nickel-bearing laterites in Puerto Rico are located on the southwestern end of the island and overlie serpentinitized ultramafic rocks. The laterite deposits are in an area roughly bounded by Mayaguez (NW), Maricao (NE), San German (SE) and Cabo Rojo (SW) (fig. 6). The ultramafic rocks were emplaced over a period of time that probably began in the Late Cretaceous (Mattson, 1960) and ended in the Eocene (R.D. Krushensky, 1991, oral communication). Mattson (1960) believed that the ultramafic rocks were exposed sometime during the Eocene, at which time the present-day laterite began to form. However, Krushensky (1978) presented evidence that deposition in western Puerto Rico had been

continuous from the Cretaceous to the Middle Eocene. In either event, it seems clear that the great majority, if not all, of the laterite formation took place between the Middle Eocene and the present.

Of the several studies of the laterites, the most extensive was by Heidenreich and Reynolds (1959), in which 279 drill holes totaling nearly 9,000 ft (2,700 m) were examined and assayed for Ni, Co, Fe, and Cr. Table 1 summarizes the resources of Ni, Co, Fe, and Cr based upon a 0.6 percent Ni cutoff. Cram (1972) did more drilling in the largest of the deposits, the Guanajibo, and estimated 37 million tons of laterite at 1.2 percent Ni. The other metals were not estimated by Cram. The two estimates are remarkably close in terms of the amount of nickel in the Guanajibo area. Heidenreich and Reynolds' (1959) figures yield about 410,000 tons of nickel whereas Cram's figures yield about 440,000 tons of nickel (to the nearest 10,000 tons in each case).

Here, the results of a reconnaissance sampling of the laterite for platinum group elements (PGE) in several areas are presented. Samples were collected at various locations where a complete, or nearly complete, section of laterite from the serpentinite to the iron cap was present. The samples were analyzed for PGE by Induction-Coupled Plasma-Mass Spectrometry (ICP). The PGE concentrations in the laterites are higher than in the serpentinite directly below by a factor of 4.3 to 11.7 and averaging 7.4. The highest total concentration of PGE is in the Maricao East deposit (about 340 ppb). In almost every profile the content of PGE increases just above the laterite-serpentinite contact and remains high throughout the laterite profile. Only in the upper part of the Las Mesas-1 locality does the PGE content drop back to near serpentinite levels. Preliminary geochemical analysis of other elements indicates a good correlation between PGE and cobalt. However, further detailed study will be necessary in order to determine the relation of the changes in PGE to other chemical changes that have occurred in the laterite. All the samples were also analyzed for gold and none were found to contain more than the detection limit of 0.01 ppm.

Data presented here are not detailed; however, they do show significant increases in PGE concentration in Puerto Rican laterites over that of bedrock. These increases suggest similarities to the laterite developed over some Alaskan-type complexes in New South Wales, Australia (Elliott and Martin, 1991). Detailed exploration and drilling revealed that PGE concentrations in one of them, the Tout complex, has typical grades of platinum of 20 to 50 ppb in dunite and 800 ppb in the overlying laterite, with some assays as high as 16 ppm (Derrick, 1991). If that kind of enhancement is encountered in western Puerto Rico as a result of subsequent, more detailed study, PGE values of hundreds of ppb to perhaps 1 ppm may be encountered. Based on these observations, the Puerto Rican laterites may be considered a speculative resource for platinum group elements.

STOP 2: Nickel laterite deposits (location on fig. 7)

Take Hwy. 2 north to Mayaquez, turn right on Hwy. 106, right on 348 then left to 349. Go past the Hospital Bella Vista and 5 km down the road, on the left is an excellent

Table 1. Summary of Ni-laterite resources from Heidenreich and Reynolds (1959).

(0.6 percent Ni cut-off)

Deposit	Average thickness, feet	Inferred reserves, short dry tons	Metal content, percent			
			Ni	Co	Fe	Cr
Guanajibo	16.0	46,800,000	0.88	0.08	20.54	0.51
Punta Guanajibo	10.5	2,100,000	1.03	0.07	19.03	0.63
Las Mesas	18.5	25,000,000	0.81	0.12	28.39	0.75
Rosario SE group						
North deposit	22.5	4,800,000	0.85	0.07	20.76	0.58
South deposit	15.5	1,100,000	0.71	0.06	12.47	0.34
Maricao SW group						
West deposit	25.0	5,000,000	0.98	0.10	22.05	0.59
East deposit	<u>51.0</u>	<u>5,600,000</u>	<u>1.08</u>	<u>0.11</u>	<u>29.45</u>	<u>0.67</u>
Total and average	19.5	90,500,000	0.88	0.09	23.20	0.59

exposure for the nickel laterite deposit at Las Mesas. This stop is located on the Rosario 1:20,000 scale topographic sheet.

The Tanamá and Helecho Porphyry Copper Deposits

Extracted and modified from
D.P. Cox
1985

The Late Cretaceous to Lower Tertiary volcanogenic rocks (fig. 3) that occur south of the Late Cretaceous Utuado Batholith are intruded by Lower Tertiary plutons, some of which may be hosts for porphyry copper-gold deposits (fig. 3) (Cox, 1972; Cox and others, 1973, 1975b; Barabas, 1977).

Introduction

The Tanamá and Helecho copper deposits (figs. 8 and 9) are situated in west-central Puerto Rico. The area, which includes these deposits and two associated copper prospects, extends 8 mi (13 km) eastward and 4.6 mi (7.5 km) southward of the town of Lares and encompasses the southern third and the northern most part of Bayaney and Monte Guilarte 7½ minute quadrangles.

This area is characterized by gently rolling uplands dissected by streams with very steep valley slopes. The uplands rise gently from 1,000 ft (300 m) elevation in the north to a drainage divide in the southern edge of the map area at approximately 2,000 ft (600 m) elevation. The area has an annual rainfall of 80-100 in (200-250 cm) and supports a heavy vegetation cover. The area has been extensively cultivated in the past, and native vegetation has been replaced largely by coffee, banana, and orange groves and intervening areas of pasture.

Copper deposits in this area have been known since 1958. Their discovery by geologists of the Kennecott Copper Corp. was followed by extensive geologic mapping and diamond drilling. Results of this work were summarized in two reports by J.E. Welsh (unpub. data, 1965) and J.C. Wilson (unpub. data, 1966), which were made available to the writer by the Kennecott Copper Corp. and the Puerto Rico Mining Commission. Geologic mapping of the Bayaney quadrangle by Nelson and Tobisch (1968) laid much of the groundwork for the present study, as did later mapping in the Monte Guilarte quadrangle by R.D. Krushensky and A.F. Curet (unpub. data, 1978). Weaver (1958) and Chen (1969) published petrologic studies of the Utuado batholith that underlies part of the area, and Cox and others (1973) published a brief account of porphyry copper mineralization and alteration in Puerto Rico in which the deposits of the map area were described.

The present study was carried out in cooperation with the Department of Natural Resources of the Commonwealth of Puerto Rico. The main objective of this study

was to describe the mineralogic and geochemical characteristics of a porphyry-type deposit in a potassium-deficient geologic environment that differs markedly from that of most porphyry copper deposits in the conterminous United States.

History of the Porphyry Copper Deposits

In 1950, the Kennecott Copper Corp. recognized the possibility of porphyry copper mineralization in Puerto Rico. Following reconnaissance, an exploration concession for west-central Puerto Rico was obtained in 1958. Surface mapping and stream-sediment geochemical analyses were carried out in 1959. The first deposit drilled was Laundry Creek, followed by Copper Creek, Helecho, and Tanamá deposits. By 1965, 155 holes were drilled with a total length of 12,150 ft (44,000 m) (Cox, 1985). Reserves are estimated at about 139 million tons at 0.64 percent copper (Lutjen, 1971). In 1957, W.R. Bergey discovered copper mineralization in the Rio Viví area. Subsequent drilling by American Metals Climax outlined two ore bodies containing more than 100 million tons of ore at 0.8 percent copper (Cox and others, 1975b).

In 1965, Kennecott Copper Corp. and American Metal Climax Corp. (Amex), through their subsidiaries Cobre Caribe S.A. and Ponce Mining Co., Inc., applied for a mining lease but were not successful (Lutjen, 1971).

Mineral Deposits

Of the two main porphyry copper deposits and two porphyry-type prospects, Tanama is the largest with 139 million tons of ore averaging 0.64 weight percent Cu (proved by diamond drilling). The Helecho deposit, 1 mi (1.5 km) to the south, contains a slightly smaller amount of ore of about the same grade. The Laundry Creek prospect appeared to be highly attractive on the basis of limited outcrops and geochemical expression but was found on drilling to have too small a tonnage for economic interest. The Copper Creek prospect is also a small occurrence and shows economic-grade mineralization in only one drill hole.

Regional Environment

The relation of porphyry copper mineralization to the geologic development of Puerto Rico and adjacent areas, as described by Barabas (1971, 1982) and Cox and others (1977), can be summarized as follows:

1. Early sedimentary, volcanic, and tectonic events in southwestern Puerto Rico are recorded in rocks of Bermeja Complex of Mattson (1959, 1960).
2. The Bermeja Complex is overlain by volcanic and sedimentary rocks as old as Cenomanian that are part of a thick sequence of basalt, andesite, and breccia, conglomerate, sandstone, and shale derived from volcanic rocks, which were deposited from Albian time to

the end of the Cretaceous Period. Volcanic activity affected the regional tectonics from Cenomanian to Eocene time.

3. These volcanic rocks were intruded by plutons of tonalitic and granodioritic composition beginning in the Aptian and culminating in the Maestrichtian. Two batholiths were emplaced during Maestrichtian time, the San Lorenzo in the eastern part of Puerto Rico and the Utuado in the west-central part.

4. After emplacement of these batholiths, parts of the region were uplifted and eroded, and during the middle to late Eocene Epoch, basaltic to dacitic lava, tuff, and volcanoclastic sediment were deposited in west-central Puerto Rico, mainly along a northwest-trending trough, 62 mi (100 km) long by 6.2 mi (10 km) wide. This trough may have resulted from rifting.

5. During late Eocene time, small stocks of tonalite were placed along the boundary between the Eocene trough and the Utuado batholith as well as in other parts of central and northeastern Puerto Rico.

6. Uplift, erosion, and formation of extensive areas of low relief followed the termination of igneous activity in Puerto Rico. Clastic sediment with thin coal seams (San Sebastian Formation) of middle Oligocene age was overlain by thick marine limestone deposits during the Oligocene and Miocene (Lares Limestone and overlying units).

7. Renewed erosion followed arching and uplift of the island during Pliocene to Holocene time, and the present topography began to develop.

The most important conclusion that has been reached by a study of the regional development of Puerto Rico relative to the occurrence of copper deposits is that formation of the porphyry copper deposits did not accompany the main pulse of volcanic activity during the Maestrichtian but, instead, accompanied a minor terminal igneous event, possibly associated with rifting in Eocene time.

Tanamá Deposit (fig. 8):

The Tanamá deposit is on the west side of the Rio Tanamá in the Municipio de Utuado, 12 mi (3.2 km) south of the town of Angeles (lat 18°15'30" N., long 66°49'29" W.). The deposit consists of two ore bodies, separated by about 320 ft (100 m) of weakly mineralized rocks. The northern ore body is exposed in a few places, whereas the southern ore body is completely mantled by a thick layer of saprolite. Studies at Tanamá leading to this report were made on drill core provided by the Kennecott Copper Corp.

Geology

Three tonalite porphyry bodies enclosed in metavolcanic rocks of the Cretaceous basaltic sequence are hydrothermally altered and mineralized in the Tanamá area. These porphyry bodies show no textural or compositional features, other than degree of alteration and mineralization, that distinguish them from tonalite porphyry bodies elsewhere in the region. Contact relations of the porphyry stocks, which were unobservable at the surface, can only be indirectly inferred from drill-core studies. Drill-hole intercepts of mixed porphyry and metavolcanic rocks, tens of meters long, around many porphyry contacts suggest intrusion by magmatic stoping of metavolcanic rocks. Contacts dip steeply to vertically, except in the northwestern part of the deposit. There, drill-hole intercepts show that the narrow screen of metavolcanic rocks separating the northwestern and northeastern plutons dips 40° to 60° W. The western contact of the northwestern pluton also dips west. The plutonic and metavolcanic rocks are intensely fractured, altered, and mineralized and weather to a white to light-tan saprolite containing abundant limonite segregations and relict veinlets. Drill holes intercept dark-colored tonalite porphyry dikes mapped on the surface by Kennecott Copper Corp. geologists. These dikes, which intrude ore zones but have a very low Cu content, are here referred to as postore porphyry. Postore porphyry, which has a groundmass texture that is microaplitic (0.01 to 0.02 mm), is indistinguishable from the tonalite porphyry bodies that are widespread in the Bayaney quadrangle. Postore porphyry contains clusters of epidote and veinlets of calcite. Chemical analysis of some samples showed very high Zn contents, probably derived from sphalerite in calcite veins.

Some of the contacts between the porphyry bodies and metavolcanic rocks are probably faults, although this conclusion was not confirmed by the present study. Maps by Kennecott Copper Corp. geologists, presumably based on studies of fresh bulldozer cuts, show faults separating the northeastern porphyry body from the other two and bounding the southeast side of the two larger intrusions.

Feldspar-Stable Alteration and Mineralization

Two feldspar-stable hydrothermal-mineral assemblages, found in the northern ore body and in the deeper parts of the southern ore body, are: intermediate plagioclase + quartz + hornblende + magnetite ± chalcopyrite and intermediate plagioclase + quartz + chlorite + magnetite ± chalcopyrite ± biotite ± actinolite ± epidote ± potassium feldspar. Both assemblages are characterized by the preservation of intermediate plagioclase (An₄₅₋₆₀) in which igneous oscillatory-zoning patterns are commonly present. The boundary between these zones is indistinct and gradational.

The presence of abundant veinlets of quartz, quartz-magnetite, and quartz-chalcopyrite without hydrothermal-alteration haloes distinguishes these assemblages from those of porphyry bodies and metavolcanic rocks elsewhere. In other respects, the amphibole-dominated assemblage resembles the hornblende-hornfels mineral assemblage common in the Cretaceous basaltic sequence, and the chlorite-dominated assemblage resembles regional-alteration assemblages developed in Eocene porphyry bodies throughout

the deposit. Both the regional-alteration and ore-zone -alteration assemblages present in Eocene porphyry bodies are mineralogically equivalent to the propylitic-alteration assemblages that surround many porphyry systems in the Andean and North American Cordillera. Cox (1985) proposed that the chlorite dominated assemblages were the product of retrograde hydrothermal alteration of an original potassic assemblage. Thus the chlorite was formed by replacement of earlier formed hydrothermal biotite during late circulation of meteoric fluids.

Chemical analyses of rocks with feldspar-stable alteration compared with unmineralized tonalite porphyry, indicate higher SiO₂ contents due to introduced quartz as veinlets and lower Al₂O₃, CaO, and Na₂O contents due to dilution of these components by the addition of quartz. K₂O content is doubled by the presence of small veinlets with sericitic alteration haloes.

Helecho Deposit (figs. 8 and 9):

The Helecho deposit is coextensive with a tonalite porphyry intrusion that crops out along the Rio Coabey 1 km south of the Tanamá deposit. Although most of the deposit is mantled by a thick saprolite layer, the deposit is well exposed in the river and has been penetrated by 31 vertical diamond-drill holes.

A detailed geologic traverse along the Rio Coabey was made during 1971 and 1972, extending from its confluence with the Rio Tanamá to a short distance south of the Helecho deposit. South of the deposit, the streambed lies above the saprolite-rock contact, and fresh samples are unobtainable (Cox, 1985).

Geology and Structural Controls

The tonalite porphyry at Helecho resembles porphyry bodies elsewhere in the map area and exhibits the same wide ranges in grain size, phenocryst spacing, and groundmass texture already described. Quartz phenocrysts are less common at Helecho than in the other porphyry bodies, and unaltered postmineral dikes contain both hornblende and clinopyroxene phenocrysts. Contact relations with Cretaceous and Tertiary metavolcanic rocks are obscured by absence of outcrops. The metavolcanic rocks are altered to sericite and clay in most places. Rocks in these areas contain the conspicuous relict phenocrysts of pyroxene replaced by amphibole that are characteristic of the Cretaceous basaltic sequence.

Abundant outcrops of mineralized porphyry in the Rio Coabey permit a study of the pattern of mineralized fractures in and around the Helecho deposit. The data from the Helecho porphyry indicate that 95 percent of these fractures are within 20° of vertical and that 90 percent are oriented in two preferred strike directions of about N. 18° W. and N. 2° E.; a smaller number of steeply dipping fractures have strikes clustering around N. 75° W., N. 65° E., and N-S. These orientations, which match closely the strikes of relict veinlets in saprolite measured at Tanamá, indicate that the fracturing of both deposits took place in

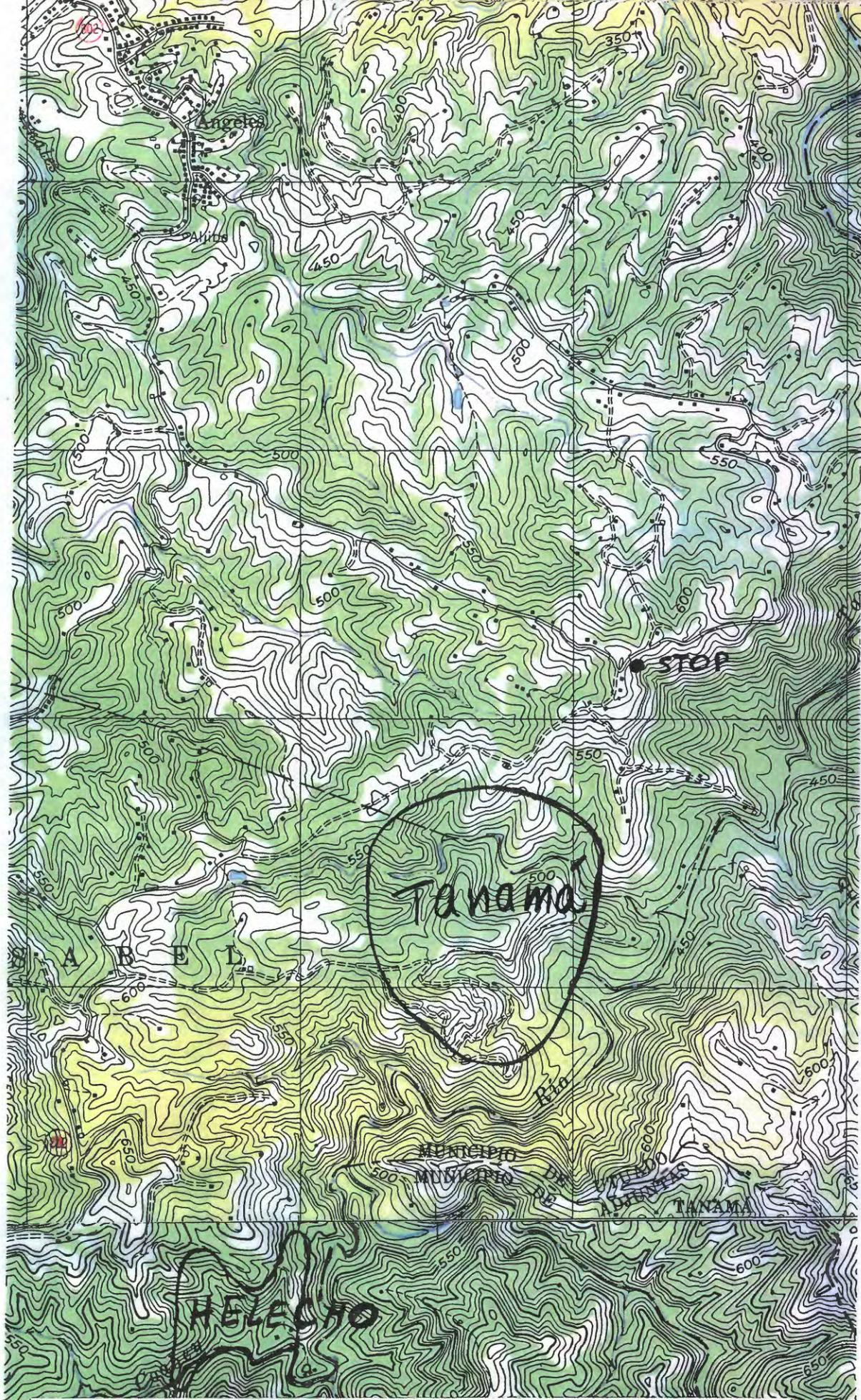


Figure 8. Location of the Tanama and Helecho porphyry copper deposits.
Bayaney and Monte Guilarte topographic sheets
scale 1:20,000

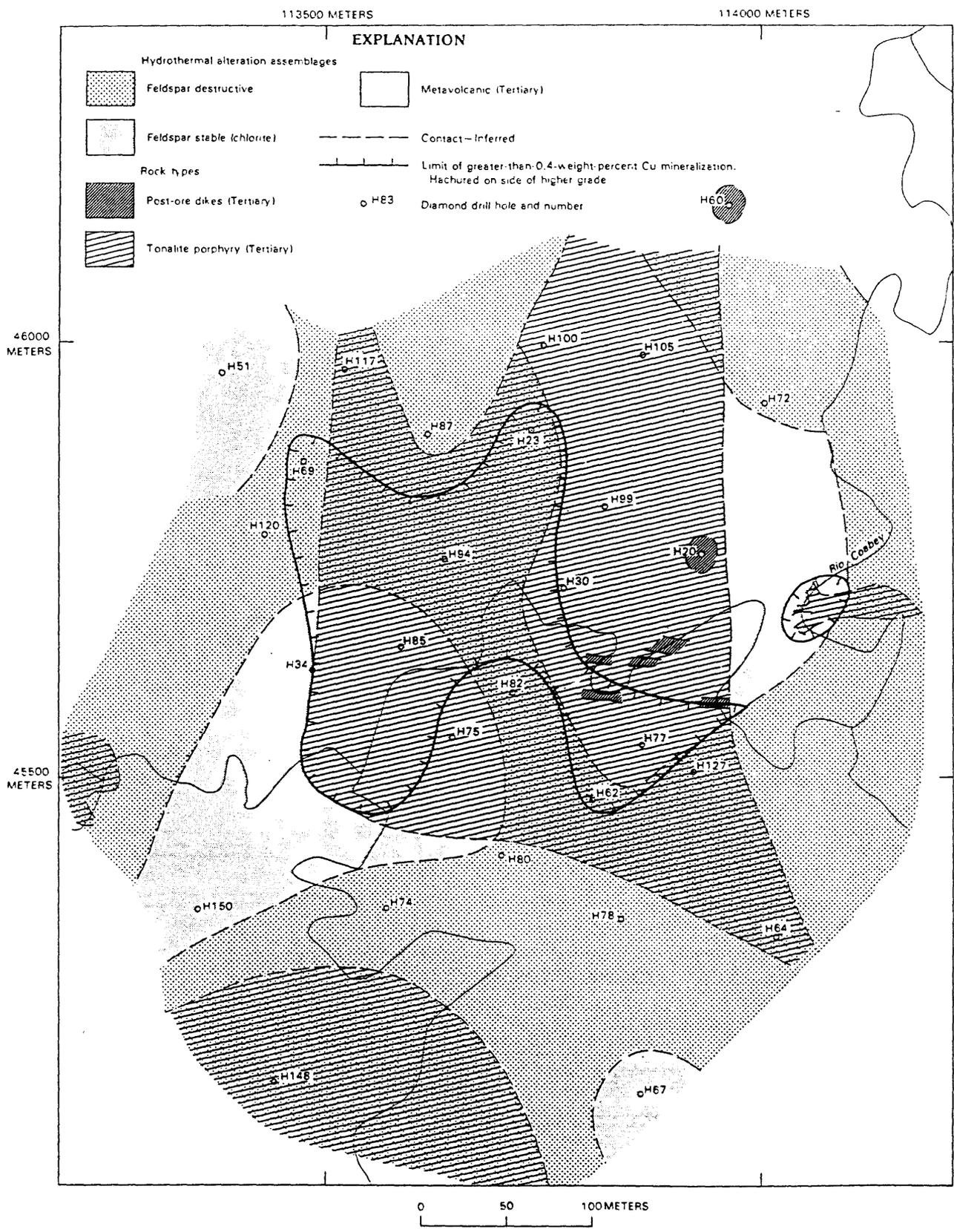


Figure 9. Geologic map of Helecho deposit. Coordinates in meters, Puerto Rico coordinate system (Cox, 1985)

response to a regional stress rather than to stresses localized around individual plutons. The symmetry of the maxima suggests that the Helecho deposit has not been rotated, as may have been the case for the Tanamá deposit.

Data from the altered volcanic rocks near Helecho give a distinctly different pattern of poles. The strongest maximum corresponding to a set of N. 30° E.-striking vertical fractures is absent in the Helecho porphyry data. This maximum,, which corresponds closely to the N. 30° E. trend of porphyry plutons, may represent a N. 60° W.-oriented tensional stress that existed before crystallization of those plutons and that may have been relieved by intrusion of the porphyry magma. Data from the volcanic rocks show four maxima representing steeply dipping fractures striking N. 50° W., N. 85° E., N. 70° E., and N. 40° E. that do not have corresponding maxima in the data from the porphyry. The preferred orientation of fractures in volcanic rocks and porphyry intrusive rocks at Helecho suggests a change in the tensional stress field from N. 60° W. to approximately E-W at about the time of intrusion of the tonalite porphyry plutons.

Coal in Puerto Rico

By
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STOP 3: Lares coal field (fig. 10):

This is a brief overview of the USGS coal study conducted in the Lares area (fig. 10) of northwestern Puerto Rico. Lares 1 (stop 3) will be at the junction of Hwy 111 and hwy 129, located on the Bayaney 1:20,000 scale topographic sheet. The coal beds are not best exposed here, but logistically, it is one of the better places to stop. Other principal coal exposures (Lares 2 through 4) are found behind the existing Mr. Special grocery store, across from the school on hwy 111, toward the town of San Sebastian. These coal localities are found on the San Sebastian 1:20,000 scale topographic sheet and marked on figure 10.

Background

The earliest reports of coal being present in Puerto Rico date back to the Spanish regime, where lignite was extracted from a site near Moca to act as a fuel for a Spanish ship returning to Spain (Bureau of Mines, 1941). Subsequent investigations in the late 1800's (Nitze, 1899; Hill, 1899) report lignite containing iron pyrites present in western Puerto Rico. Some of these locations are near the towns of Utuado, Moca, Lares, and San Sebastian (fig. 10). Previous investigations have concluded that the lignites are of little economic value. The largest reported seam is 6 in. (15 cm) thick and the average seam varies between 1 to 2 in. (2.5 to 5 cm) in thickness. These lignites have high ash and sulfur contents. Mitchell-Thorre (1954) noted that "so much pyrite is present that the coal crumbles

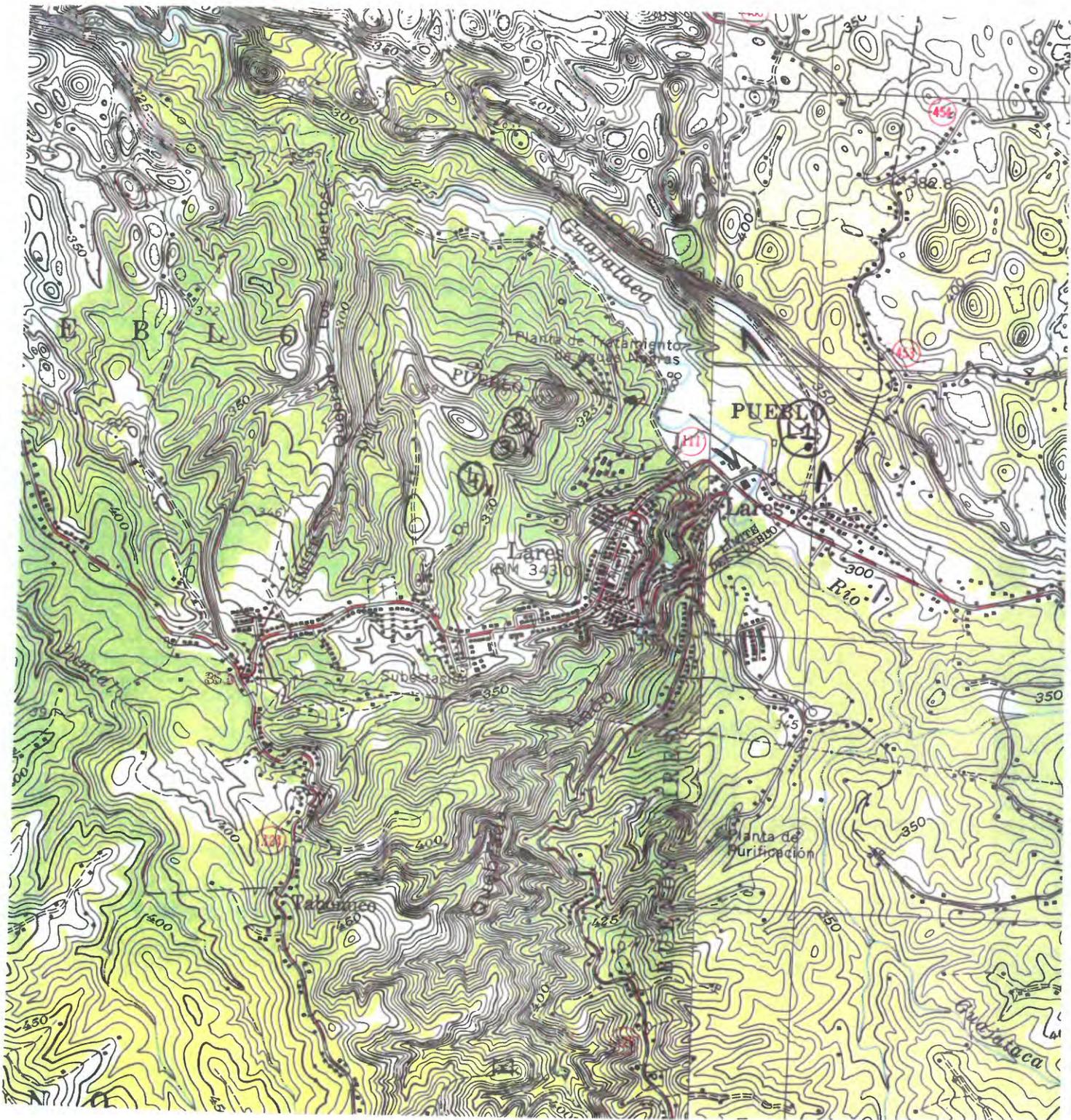


Figure 10. Location of Lares 1 outcrop stop. Lares 2, 3, and 4 localities are shown. Coal localities are located on the San Sebastian and Bayaney topographic sheets. Scale 1:20,000. Lares 1 is on the Bayaney sheet.

to powder upon exposure to the atmosphere. Further, the lignites have a high sulfur content and a very low carbon content, so that often the lignite cannot be kept burning. However, in other localities, the lignite contains much less pyrite, more carbon, and in places the seams reach a width of 18 inches".

In 1960, Kewanee Interamerican Oil Company drilled the first deep test well (No. CPR4) which penetrated the post-Eocene strata in northern Puerto Rico (fig. 11). In 1980, an extensive drilling project was initiated by North American Exploration, Inc. a private company from Charlottesville, Va. Forty-four holes were drilled within the San Sebastian Formation targeting lignite deposits. North American Exploration, Inc., had a proximate analysis performed on one sample from an outcrop near Lares.

AS RECEIVED:

moisture: 33.04 %
ash : 11.72 %
volatile: 25.93 %
sulphur : 0.63 %
BTU/LB : 5817
DRY BTU/LB : 8687

(These data were obtained from and published with the consent of Dr. Ramon Alonso Harris, Division de Geología, Departamento de Recursos Naturales, San Juan, Puerto Rico).

Present Study

Field investigations guided by available information were conducted in northwestern Puerto Rico along the outcrop belt of the San Sebastian Formation (figs. 1 and 11). Exposures of coaly material were found at nine different localities, but most of the exposures were too weathered to permit detailed, reliable lithologic and thickness interpretation, or meaningful sample collection. One sample for coal analysis was collected in the Moca quadrangle (site of the logs within the conglomeratic units of the San Sebastian Formation) and 18 samples were collected at exposures in an area near the town of Lares (Bayaney and San Sebastian quadrangles).

Geologic Setting

The area underlain by the coal-bearing San Sebastian Formation (fig. 11) and its partial lateral-equivalent, the overlying Lares Limestone, is all within the north coast Tertiary basin of northwestern Puerto Rico (figs. 1 and 2). Both the San Sebastian and the Lares Limestone Formations are of Oligocene age, are overlain by younger sedimentary units of Tertiary and Quaternary age, and rest unconformably on an irregular surface of folded and faulted rocks of Cretaceous, Paleocene, and Eocene age.

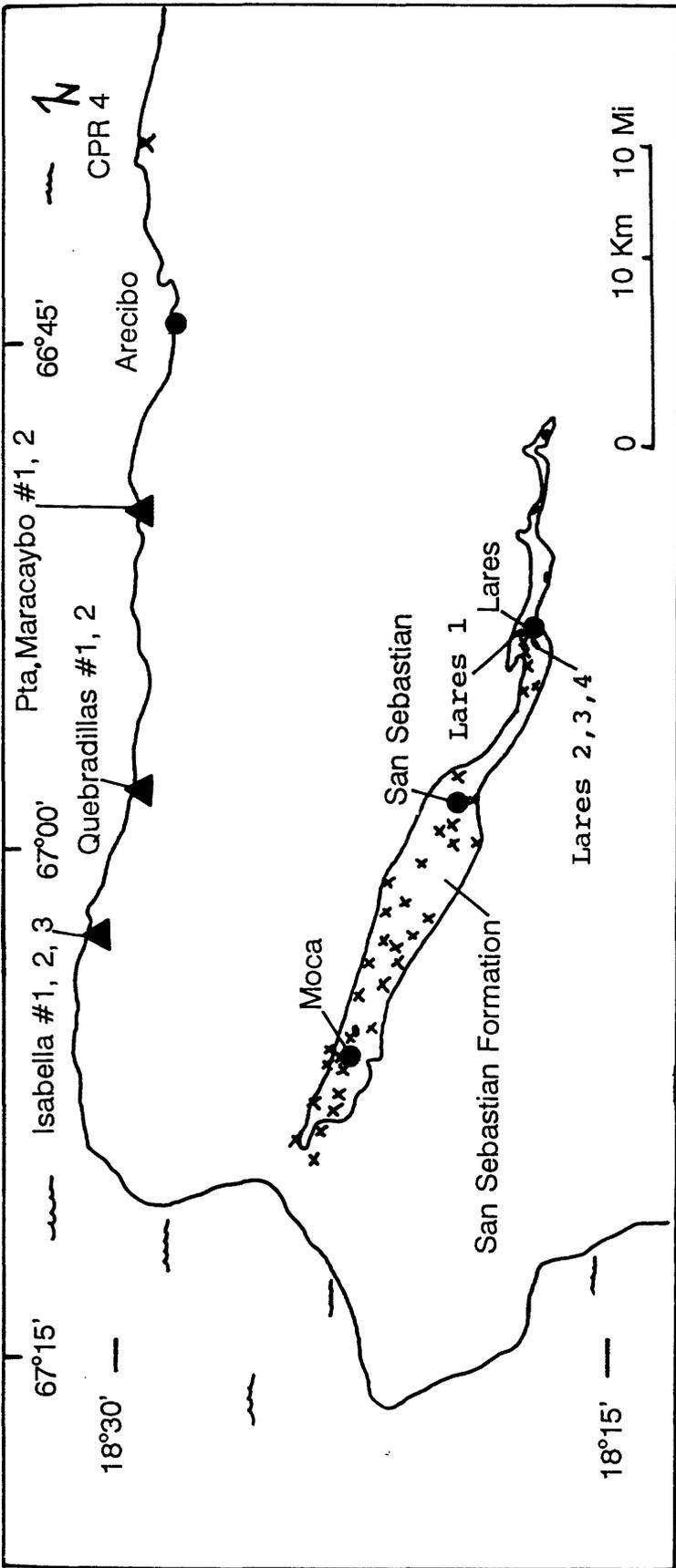


Figure 11. Areal relation of localities sampled for coaly (L 1, 2, 3, and 4) and peaty materials in NW Puerto Rico. Coal locality just east of Moca is where coalified logs were noted within the conglomeratic sequence of the Oligocene San Sebastian Formation. This was an unscheduled stop en route to Lares.

- Towns
- ▲ Peat occurrences
- ◐ Coal occurrences
- x Drill holes

San Sebastian Formation

The Oligocene San Sebastian Formation is present mainly in the northwestern part of the island and outcrops as a narrow band from west of the town of Moca eastward to just south of San Juan (fig. 10). From Moca to the Rio Grande de Arecibo, the San Sebastian Formation is present in a uniform thickness of approximately 738 ft (225 m). Subsurface thicknesses indicate that the formation increases to 1040 ft (312 m) farther north. Near the Rio Grande de Arecibo, it is locally missing, due to scouring prior to the deposition of the Lares Limestone and Cibao Formation. In places between the town of San Sebastian and Moca, the overlying Lares Limestone intertongues with clastic rocks that are most probably within the San Sebastian Formation.

Hubbard (1923) describes the San Sebastian Formation as "although it is predominantly a shale, it consists in large part of dark bluish clay carrying seams of lignite and pyrite and marcasite, conglomerate and pebble beds, red calcareous sand or lime sand, green marl, and impure limestone". Monroe (1980) elaborated on this description as follows:

"The San Sebastian Formation consists predominantly of vari-colored (5R to 10YR) clay and sandy clay, commonly in such thin beds that it has been called shale by many workers. Locally it consists of conglomerate, composed of particles ranging from pebbles to boulders, and contains beds of lignite or carbonaceous clay. It also contains abundant fossils in clay, marl, and soft limestone, especially near the top.... The thickest section near San Sebastian... is in the valley of the Rio Guatemala, where a series of small waterfalls and rapids affords an excellent series of outcrops of gray shaly clay, sandstone, and conglomerate from the transitional beds at the top nearly to the base of the formation. Unfortunately, these exposures are not continuous."

Coal

Coal is a solid fossil fuel formed from plant-derived organic remains along with non-organic minerals. The organic components of coal constitute the combustible part. In order to consider this material coal and not rock, the organic components should constitute more than 50 percent by weight of the rock on a dry basis (sample dried at 100⁰ C to remove its moisture).

Rank of Coal

The American Society for Testing and Materials D388-88 (ASTM, 1988) defines classification of coal by rank according to fixed carbon and gross calorific value (expressed in Btu/lb) calculated on a moist mineral-matter-free basis. The higher rank coals are classified according to fixed carbon on a dry basis; the lower-rank coals are classified according to gross calorific value on a moist basis. Four classes of coal exist to briefly assess economic coal and determine resource potential: 1) anthracite, 2) bituminous, 3) sub

Table 2. Classification of coals by rank (Wood and others, 1983).

Class	Group	Fixed Carbon Limits, percent (Dry, Mineral-Matter-Free Basis)		Volatile Matter Limits, percent (Dry, Mineral-Matter-Free Basis)		Calorific Value Limits BTU per pound (Moist, ^B Mineral-Matter-Free Basis)		Agglomerating Character
		Equal or Greater Than	Less Than	Greater Than	Equal or Less Than	Equal or Greater Than	Less	
I. Anthracite*	1. Meta-anthracite	98	-----	-----	2	-----	-----	} nonagglomerating
	2. Anthracite	92	98	2	8	-----	-----	
	3. Semianthracite ^C	86	92	8	14	-----	-----	
II. Bituminous	1. Low volatile bituminous coal	78	86	14	22	-----	-----	} commonly agglomerating ^E
	2. Medium volatile bituminous coal	69	78	22	31	-----	-----	
	3. High volatile A bituminous coal	-----	69	31	-----	14 000 ^D	-----	
	4. High volatile B bituminous coal	-----	-----	-----	-----	13 000 ^D	14 000	
	5. High volatile C bituminous coal	-----	-----	-----	-----	11 500 10 500	13 000 11 500	
III. Subbituminous	1. Subbituminous A coal	-----	-----	-----	-----	10 500	11 500	} nonagglomerating
	2. Subbituminous B coal	-----	-----	-----	-----	9 500	10 500	
	3. Subbituminous C coal	-----	-----	-----	-----	8 300	9 500	
IV. Lignite	1. Lignite A	-----	-----	-----	-----	6 300	8 300	} nonagglomerating
	2. Lignite B	-----	-----	-----	-----	-----	6 300	

-bituminous, and 4) lignite or brown coals (Table 2; Wood and others, 1983). The calculated apparent rank of the coals in the Lares coal field is Lignite B. Grossling (1981) defines lignite as follows:

"Lignite or brown coals

These are brown to black, with brown streaks, clay-like or woody in appearance. They are of Mesozoic and Tertiary age. Because of their relatively low degree of coalification, plant remains may be visible to the naked eye. The moisture is usually 20 to 50 percent, the volatile matter is about 33 to 50 percent, and the calorific value is 2000 to 4000 kcal/kg. They usually do not agglutinate well. In some cases they may be used for briquetting. Ash yield is high. Spontaneous combustion can occur readily. These coals are used mainly for steam raising and space heating".

Methodology

A total of 19 samples, from five localities (site east of Moca, Lares 1, 2, 3, 4), was collected and submitted for standard coal analyses and major, minor, and trace element analyses. Samples were not collected at the other four studied localities because coaly materials were too thin and/or too badly weathered and oxidized to allow meaningful interpretation of analytical results.

At the Lares outcrops (sites 1 through 4), individual thin beds of coal are not laterally continuous. However, sequences of coaly rocks designated as zones 1, 2, and 3 are correlated between the four localities. The maximum zone thickness noted was 4.5 ft (1.4 m) and the thickest coal bed within any zone was 1.3 ft (0.4 m). Some exposures owe their condition to recent construction activities.

Resource Estimates

Knowledge of a nation's coal resources is important in planning for the exportation and importation of fuel. A detailed resource classification accomplishes the following factors: 1) identifies deposits of coal by areal location, 2) distance from points of information, 3) thickness of coal and overburden, 4) rank and quality, and finally 5) estimates of quantity (Wood and others, 1983; table 2). Table 3 shows the resource estimates.

Depositional Setting

The San Sebastian Formation is conformably overlain by the Lares Limestone. The coal zones in the Lares coal field are closely associated with overlying sandstone units containing marine fossils. In some cases (Lares 4), borings made by marine organisms are

Table 3. Total coal resources for the Lares coal field.

	Measured	Indicated	Inferred	TOTAL thousand metric tons
0-30 m	78	54	453	585
30-150 m	20	120	763	903
150 m	---	-----	19	19
TOTAL	98	174	1235	1,507

visible within the sandstone unit. These sandstone bodies, very fine grained and friable, closely resemble sand deposits of a modern beach or off-shore bar. The lower and middle parts of the San Sebastian Formation are nonmarine. The thick red-bed sequence at the base of Lares 1 represents an alluvial plain that filled some of the relief eroded on the Cretaceous-Eocene basement rock (Frost and others, 1983). These outcrops are good examples of the transition from non-marine to marine environments.

Marine fossils associated with coal zones, coupled with burrowed sandstone units, indicate that the lignites present within the San Sebastian Formation were deposited in low-lying, brackish/paralic environments on the broad coastal shelf of the island. The encroaching sea probably scoured off and redeposited clastic sediments to form the basal conglomerate and clay within the formation. The low lying areas developed into swamps, often brackish in nature due to periodic rise of sea level, that were conducive to the development of mangrove swamps (Habib, 1971).

The mangrove swamps probably never existed undisturbed for a sufficient period of time to result in bodies of peat thick enough to create thick coal beds. The thin, cyclic poorly developed coals of the San Sebastian in the Lares area adequately reflect the transient nature of the paralic environments in which they were deposited. High ash and sulfur coals are common in the depositional environment just described. For example, many of the coals in the lower part of the Dakota Sandstone in southwestern Colorado, northwestern New Mexico, and northeastern Arizona are high ash, high sulfur coals. The high ash is usually due to the interfingering of organic-rich and organic-poor layers. The high sulfur content of coals is commonly due to the underlying beds being scoured out prior to the deposition of the overlying units (Lares Limestone).

NORTH COAST KARST LIMESTONE AND GROUND WATER CHARACTERISTICS

Extracted and modified from
Joseph W. Troester and Jesus Rodriguez-Martinez
1990

The northern karst belt of Puerto Rico is a 10- to 20-kilometer-wide belt that extends along the northwest and north-central coast of Puerto Rico for 110 km. It is the largest and most extensively studied karst area on the island (Monroe, 1976; Giusti, 1978). The rocks are composed of a thick sequence of Oligocene to Pliocene limestones which dip a few degrees to the north. The rocks are described by Monroe (1980) and divided into seven formations as shown in Figure 2. In ascending order, the formations are the San Sebastian Formation (a mostly nonmarine, fine-grained clastic unit), the Lares Limestone, the Cibao Formation (a heterogeneous unit), the Mucarabones Sand (a clastic unit that is laterally equivalent with the Lares Limestone and the Cibao Formation), the Aguada Limestone, the Aymanion Limestone, and the Canuy Formation (a limestone with clastic units). There has

been some discussion about these formation names, with some authors preferring to use the names Los Puertos and Quebradillas for the Aguada and Camuy Formations, respectively (fig. 2) (Frost and others, 1983; Moussa and others, 1987).

Hydrogeologic Framework

The North Coast Limestone Province aquifer system is the most important ground-water reservoir on the island of Puerto Rico. A hydrogeologic study of this province was done by the U.S. Geological Survey in cooperation with the Commonwealth of Puerto Rico (Torres-Gonzalez and Wolansky, 1984). A very important phase of this study consisted in the drilling of 15 exploratory test holes ranging in depth from 365 to 2,574 feet (120-780 m) that penetrated most of the middle Tertiary sequence (fig. 3). In the drilling operation a dual-tube method was used, which allowed retrieval of continuous lithologic cores, measurement of head, estimates of hydraulic properties, and collection of water samples and borehole geophysical logs. The paleontologic, mineralogic, and petrologic analyses of the cores were done by the Department of Geology and Geophysics at the University of New Orleans. The final phase of this hydrogeologic study (currently in progress) consists of developing a series of ground-water flow models.

A hydrogeologic framework for the North Coast Limestone Province was defined from the results of the drilling program and previous hydrologic studies. This framework includes five hydrogeologic units: an upper regional water-table aquifer, an upper and local sub-regional confining unit, an upper and local sub-regional artesian aquifer, a lower regional confining unit, and a lower regional artesian aquifer. The water-table aquifer is mostly composed of the Aymamon and Aguada Limestones and locally also of the lowermost strata of the informally designated upper member of the Cibao Formation and surficial deposits that are Pliocene to Recent in age. A basal saltwater zone is encountered at the base of the water-table aquifer in the more coastal zones. East and west of the Limestone Province the aquifer is gradually replaced by saltwater. In the metropolitan area of San Juan, the aquifer is largely absent and, where present, it is largely brackish and/or saline.

Both the upper confining unit and the upper artesian aquifer are located in the upper Cibao Formation and extend from the vicinity of the Rio Grande de Arecibo to the Laguna Tortuguero in Manati.

The lower regional confining unit is mostly comprised of the lower part of the informal upper member of the Cibao Formation, and locally in the northwest, it also includes strata in the middle and lower part of the Aguada Limestone. It is composed of marl, claystone, well-cemented, fine-grained wackestone, and clayey fine-grained sandstone.

The lower and regional artesian aquifer attains its maximum transmissivity in the area between Rio Grande de Arecibo and Rio Grande de Manati, where it is comprised of the lowermost strata of the informally designated upper member of the Cibao Formation,

the Montebello Limestone Member of the Cibao Formation, and the Lares Limestone. East and west of this area, these limestones grade laterally into increasingly terrigenous sedimentary rocks becoming less productive as aquifers. West of Rio Grande de Arecibo, and particularly in the Hatillo to Isabela area, the lower artesian aquifer is a multi-unit system composed of irregularly alternating confining and artesian zones, predominantly in the Cibao Formation and Lares Limestone. In the area between Rio Grande de Manati and Rio de la Plata in Dorado, this hydrogeologic unit is composed solely of the Lares Limestone. East of Rio de la Plata, including the metropolitan area of San Juan, the lower artesian is comprised mostly of gravel and sands of the Mucarabones Sand and of minor limestone beds of the Cibao Formation. It disappears in the vicinity of the border between San Juan and Carolina.

Karst Landforms

The northern karst belt of Puerto Rico is internationally known for the variety of positive relief features that have formed on the limestone. There have been many different names proposed for these landforms that are found in humid tropical karst regions around the world. However, there appear to be only two distinct end members (Troester and others, 1987): cone karst (also known as Kegelkarst or cockpit karst) and tower karst (also known as Turmkarst or mogote karst). Cone karst is composed of many closely spaced cone- or tower-shaped hills separated by deep sinkholes (Monroe, 1970). There is usually very little level ground in an area of cone karst. The best cone karst in Puerto Rico is found in the Lares Limestone and in the Montebello Limestone Member of the Cibao Formation. The best views of this type of karst are near the Arecibo Observatory. The other major type of humid tropical karst, tower karst, is characterized by isolated limestone hills separated by areas of alluvium or other surficial material (Monroe, 1970). The best examples of tower karst in Puerto Rico are along the northern edge of the karst belt, where mogotes of the Aymamon Limestone are surrounded by blanket sand deposits (Monroe, 1963b and 1971). These examples are in Barceloneta, where they are separated by pineapple fields.

Caves

There are two types of caves found in the northern karst belt. The larger ones are formed by undersaturated, allogenic water flowing into the carbonates from an area of insoluble rocks (Troester and White, 1983 and 1986). Examples of this cave type include the Rio Camuy Cave System, the Rio Tanama Caves, the Quebrada Infierno Cave System, and the Rio Encantado Cave System near Florida (20 km). All of these cave systems contain active river passages and often have older, abandoned, upper level passages that were formed by the same river. There are many of these old trunk passages found scattered around the karst area that are now disconnected from the rivers that formed them. The second type of cave is formed by the rainwater that falls on the karst and slowly moves through the porous limestones. These caves are usually small and irregular in shape, but often well decorated with formations.

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