15th Annual Symposium on Caribbean Geology

February 21-25, 1996

INTRODUCTION

In 1982, the Department of Geology organized its first symposium on Caribbean Geology. At that time, the department consisted of only four faculty, and we thought it would be a good idea to expose both students and faculty to new and different ideas presented by experts in various fields of geology. The Dean of the Faculty of Arts and Sciences provided funds to invite guest speakers. The symposia, which were organized on an annual basis, included conferences, field trips, and a lot of informal contact between guests, faculty, and students. After a small beginning, the Caribbean Geology symposium began to attract other geologists, and eventually grew into a well-attended annual meeting. This year is the fifteenth consecutive time that we welcome visitors from off- and on-island to our "Annual Symposium on Caribbean Geology". This year the symposium is co-sponsored by the Geological Society of Puerto Rico and hosts guests from private consulting firms, and Federal and Insular governments.

This field guide was put together by James Joyce, Luz A. Muriel and Cesar I. Delgado, with contributions by David Larue, Hernan Santos, Alan Smith James Joyce Hans Schellekens, and others. Andrew Bonilla (EQB) and John Conway (USACE) contributed with additional information on the site geology of BFI landfill and Portugues Dam, respectively. Luis Molina (Suelos Inc.) provided information on landslides on the P.R.-10.

Geology of Puerto Rico

Introduction

Puerto Rico, the easternmost island in the Greater Antilles (Fig.1), is a complex arc terrane with a basement of Late Jurassic to Early Tertiary volcanic, volcaniclastic, and sedimentary rocks, intruded by felsic plutons, and overlain by Oligocene and younger sediments (Krushensky and Schellekens, in press). To unravel the volcanic episodes and tectonic regimes recorded in the Puerto Rico volcanic arc terrane, a solid stratigraphic basis was created and the geochemical evolution was studied by Schellekens (1991, 1993).

In order to place all the events in a geological time frame, volcano-stratigraphic associations (VSA) were defined as packets containing volcanic and associated sedimentary rocks of similar age (Schellekens, 1991). Ages of the VSA's were determined by radiometric dating of the volcanics, where possible, and by fossil content of the associated sediments.

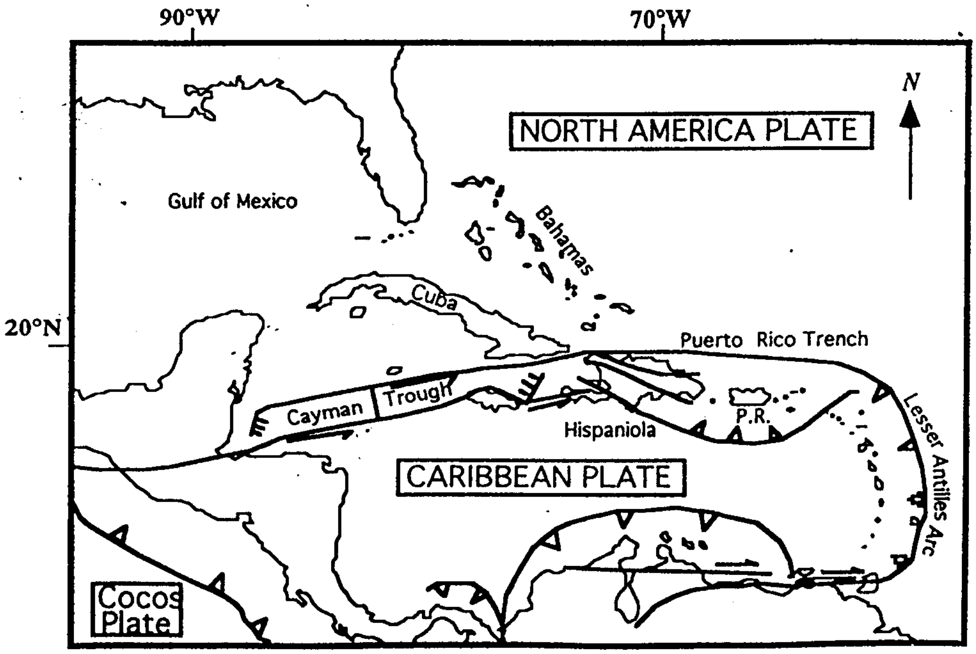


Figure 1. Tectonic elements of the Caribbean

Tectonic setting of Puerto Rico

Puerto Rico is a complex island arc terrane with a geologic record of about 195 million years, and with the northern Virgin Islands it represents the subaerially exposed parts of the Puerto Rico-Virgin Islands microplate (PRVI) (Byrne et al., 1985), that lies within the seismically active Caribbean - North American Plate boundary zone (Fig.1).

A well defined southward dipping Benioff zone occurs under the eastern half of the microplate, but is missing under the west side (McCann and Sykes, 1984; Sykes et al., 1982; Schell and Tarr, 1978). The Benioff zone represents a previously subducted portion of the North American Plate and forms the northern boundary between PRVI and the North American Plate. To the west, the platelet is separated from the Hispaniola block by extension in the Southern Mona Canyon (Gardner et al., 1980; Larue et al., 1990). The graben passes southward into arcuate normal faults, which connect it with the Muertos Thrust, where Caribbean oceanic crust is subducted beneath the PRVI (Byrne et al., 1985). To the southeast of Puerto Rico, a series of grabens forming the Anegada Trough separates the platelet from the Lesser Antilles (Fig. 1).

Geology of Puerto Rico

Late Jurassic to early Tertiary basement rocks

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 subsequently strongly deformed and faulted. The central core has been tentatively divided into three igneous provinces (see Figure 2), a southwestern igneous province (S.I.P.), a central igneous province (C.I.P.), and a northeastern igneous province (N.I.P.), on the basis of differences in stratigraphy, lithology, petrography and geochemistry (Schellekens, 1993).

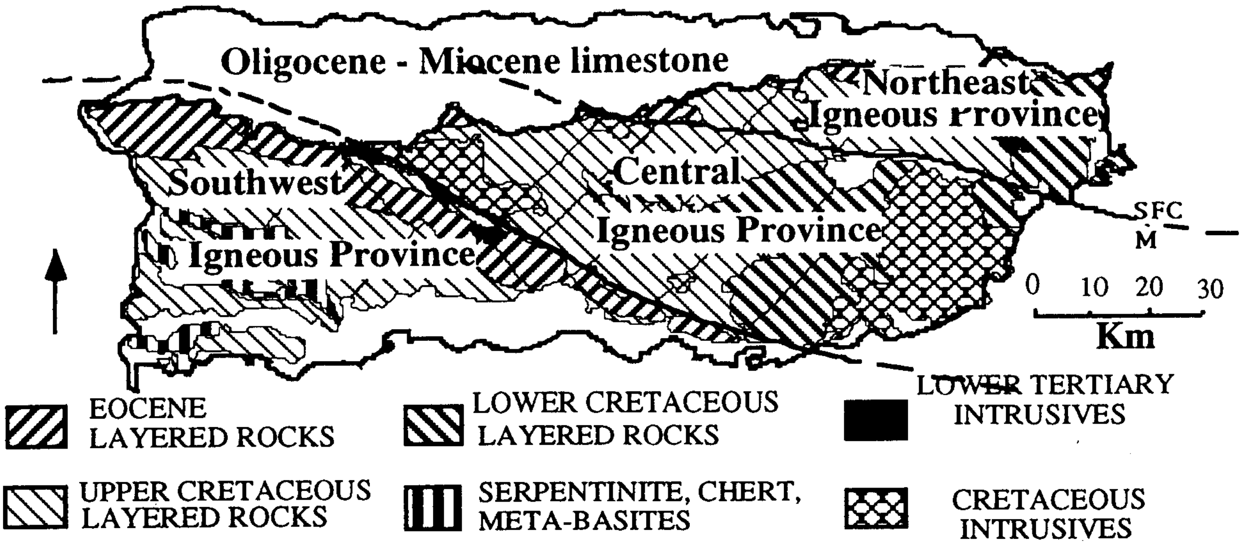


Figure 2. Geological sketch map of Puerto Rico (Based on Briggs and Akers, 1965; Cox and Briggs, 1973; and U.S.G.S. quadrangle maps) (SFCM: San Francisco-Cerro Mula Fault (from Schellekens, 1993)

Structural Geology

Overviews of the structural geology of Puerto Rico are presented by; Briggs and Akers (1965); Glover (1971); Seiders and others (1972). The pre-Oligocene basement of the island is usually divided into three structural blocks separated by two major faults zones: the Great Southern Puerto Rico Fault Zone, which coincides with the southern boundary of the Eocene Belt, and the Great Northern Puerto Rico Fault Zone, in which the San Francisco - Cerro Mula Fault is the most important. Although Krushensky (1978) questions the importance of the Southern Fault Zone as a block boundary, these fault zones have been convenient divisions.

The structure south of the Southern Fault Zone, is dominated by west and north-west trending folds, asymmetric or overturned towards the south-southwest. In the Eocene belt occurs a west-northwest trending zone of horsts and graben. Within this zone the Eocene rocks are highly deformed by folding and faulting. Low angle imbricate thrust faults with locally tightly to isoclinally folded beds occur at the southeastern end (Glover, 1971).

Deformation in the northwestern part of the belt includes west trending gentle folds, and nearly isoclinal folds, that are overturned to the north. Faults are high angle detachment faults (Seiders and others, 1972). In the central block the folding is quite gentle and fold axes trend east, locally northeast (Briggs and Akers, 1965).

In the northern part of this block, occur west to northwest plunging anticlines and synclines. Faults are west-northwest trending and left lateral (Nelson and Monroe, 1966). The bulk of the northeastern block is characterized by generally northeast trending fold axes (Glover, 1971), in the easternmost part of the block north-plunging fold axes, spaced at about 5 km intervals, trend north-south. (Briggs and Aguilar-Cortes, 1980). The west-northwest trending Cerro Mula fault and the faults that splay off this fault, are considered to be left lateral (Briggs and Pease, 1968), whereas the west and west-northwest trending faults are predominantly right lateral (Pease, 1968a; Seiders, 1971 ab; Briggs and Aguilar-Cortes, 1980).

Stratigraphy

Four simplified stratigraphic columns outlining the principal rock types exposed on Puerto Rico are summarized in Figure 3. Puerto Rico has been divided into four stratigraphic sequences: the southwest; the Late Cretaceous and early Tertiary Belt (LK-ET belt); the central; and the northeast. The southwest sequence includes the Bermeja Complex, the Maguayo and the Monte Grande-El Rayo VSA's.

The stratigraphic sequence in the Late Cretaceous-early Tertiary belt includes the Río Blanco VSA I and II. The central sequence includes the VSA's of the Central Igneous Province: the lower and upper pre-Robles VSA, the Robles-Orocovis VSA, the Vista Alegre-Tetuán VSA, and the Cariblanco-Pozas VSA. The fault bounded submarine pyroclastic and volcaniclastic formations (Jobos and Yunés) of early Tertiary age follow the Cretaceous sequence in this stratigraphic column, although their source was most probably in the early Tertiary belt. The LK-ET belt and the central stratigraphic sequences are capped by the post-tectonic middle Tertiary clastic and carbonate formations.

The northeast stratigraphy includes both a continuous and a discontinuous sequence. The continuous sequence is made up of the Daguao-Figuera VSA, the Hato Puerco-Toma de Agua VSA, and the Martín González-Tortugas VSA, which is terminated by an unconformity at the end of the Campanian. The discontinuous sequence is composed of the pre-Santa Olaya and the Santa Olaya VSA, and La Muda-Monacillo association. These stratigraphic sequences are unconformably overlain by the early Tertiary formations.

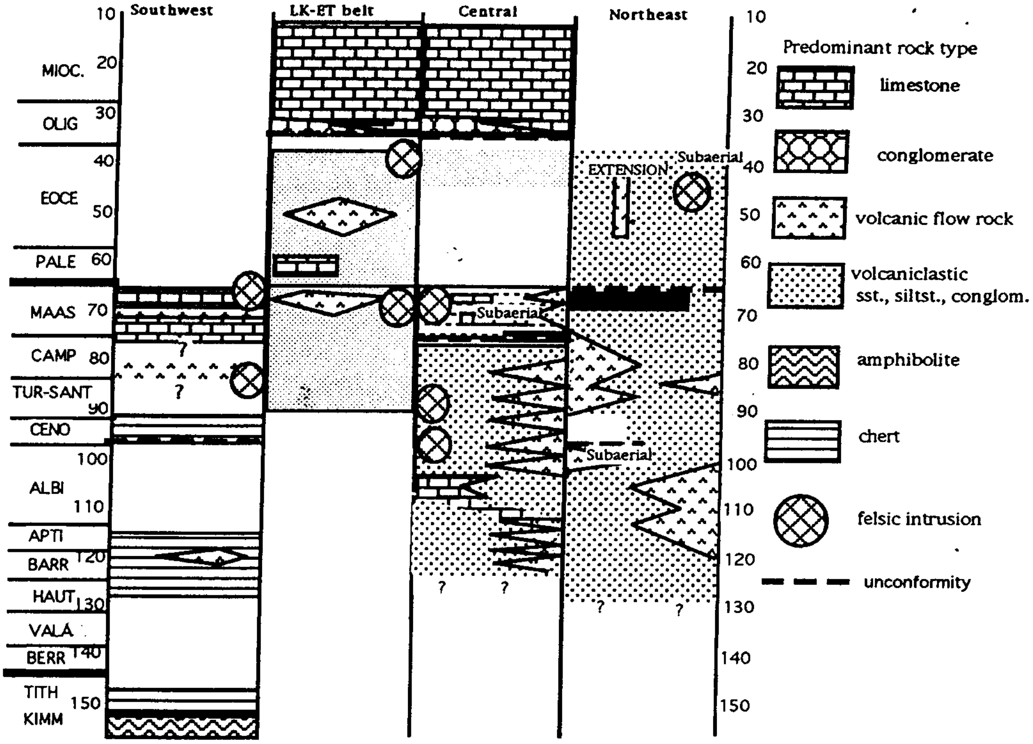


Figure 3. Compilation of the stratigraphy of the three igneous provinces and the Eocene - Late Cretaceous belt (from Schellekens, 1993)

The first island arc volcanic rocks in Puerto Rico are of Early Cretaceous age. In central and northeast Puerto Rico, island arc volcanism is established in the pre-Robles VSA and the Daguao-Figuera VSA with an age of Aptian-Albian or possibly older. The geochemistry of the lavas is very similar to MORB with LREE depleted to flat REE patterns (Schellekens, 1991).

The Las Mesas Greenstones and a two pyroxene microgabbro, which belong to the upper Bermeja VSA, are chemically similar to, and coeval with, these lavas. The origin of these lavas in an island arc tectonic setting is inferred from their clinopyroxene composition, age, and metamorphic grade (Schellekens et al., 1990; Schellekens, 1993).

These Early Cretaceous volcanic rocks are interpreted as an Aptian-Albian and possibly older island arc. The Los Ranchos Formation and Maimón Schists of the Dominican Republic, the Devil's Racecourse Formation of Jamaica, the Water Island Formation of the U.S Virgin Islands, and the Lower Cretaceous volcanic rocks of La Désirade (Donnelly et al., 1990) also have been interpreted as part of the Albian-Aptian island arc.

The paleogeographic setting of the earliest island arc volcanism differed in each of the three stratigraphic columns (Figure 3). In the Southwest Igneous Province (SIP) the volcanic rocks are associated with bathyal cherts, indicating a deep submarine environment. In the Central Igneous Province (CIP), volcanism was also submarine, but the presence of limestone fragments, even in the oldest formations, suggests that the volcanic edifices were substantially higher, and had by Albian times formed a carbonate platform represented by the Aguas Buenas Limestone Member and other limestone lenses of the Torrecilla Breccia and Pitahaya Formation.

In the Northeast Igneous Province (NIP), island arc volcanism, beginning with the Daguao-Figuera VSA, occurred in a basin that continued to sink and did not become exposed to subaerial conditions until the beginning of the Late Cretaceous with the Pre-Santa Olaya VSA. We interpret these different environments as a reflection of their location with respect to the subduction zone and axis of the island arc: the Lower Cretaceous rocks of the SIP correspond to the forearc, those of the CIP correspond to central axis of the arc, and the rocks of the NIP correspond to both the arc and the backarc.

FIELD TRIP 1
THURSDAY FEBRUARY 22, 1996
WATER SUPPLY AND SOLID WASTE MANAGEMENT INFRASTRUCTURE IN SOUTHERN PUERTO RICO

INTRODUCTION

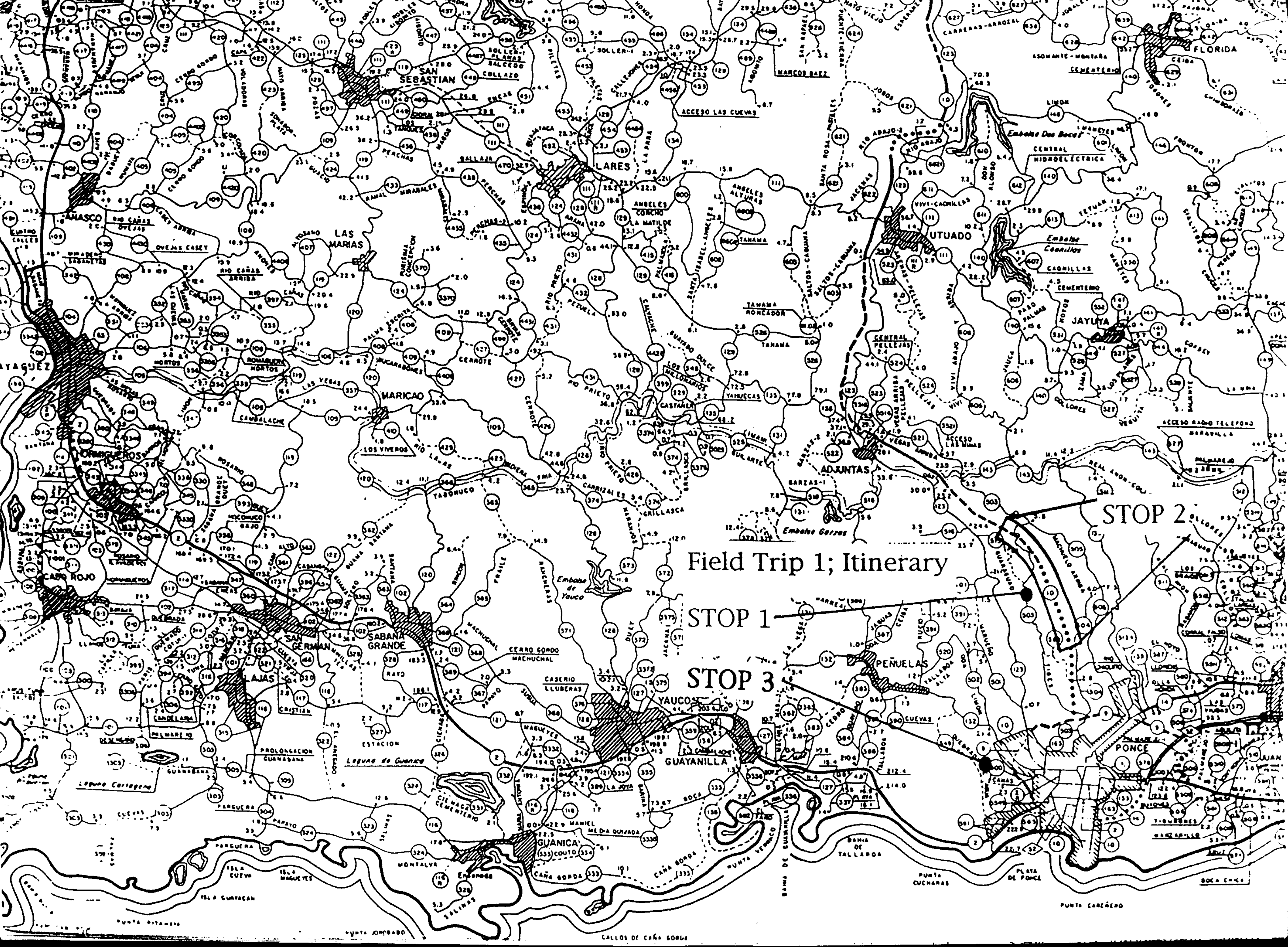
Today's field Trip will visit one of the most important water supply infrastructure projects in Puerto Rico in the last few years; the Rio Portugues Dam, in Sector Magueyes, Ponce (see Figure 4). When finished, the Portugues Dam will be 275 feet high, built as a concrete double curvature with elliptic arc. The reservoir will have a maximum storage capacity of 24,200 acre/foot of which 14,000 ac./ft. will be for flood control and 8,250 ac./ft for water supply.

At this stop we will look at some of the regional geographic and geologic phenomena that dictates the selection of a damsite and influences its design and construction.

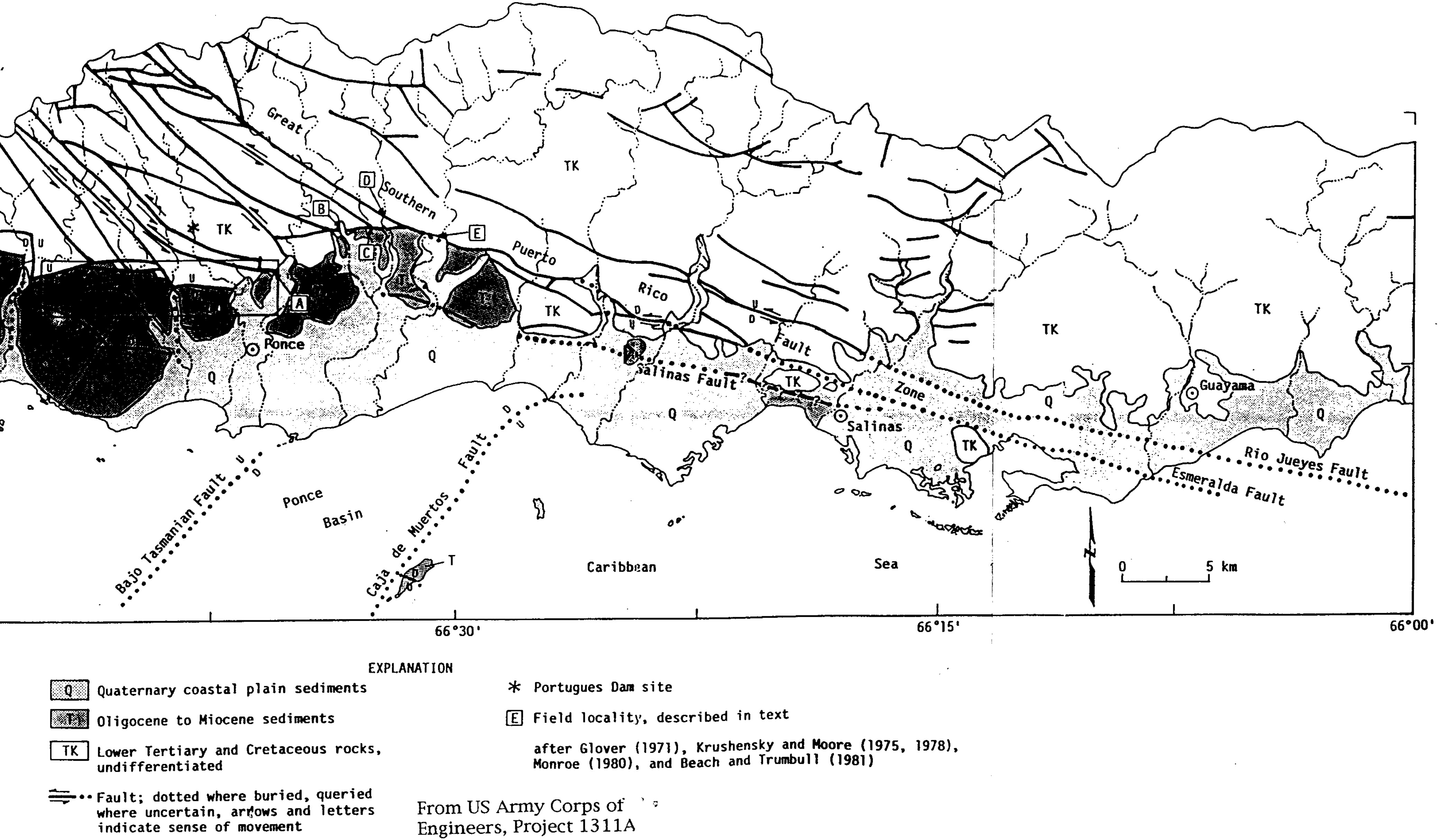
On the second leg of the field trip we will stop at several landslides on the P.R. 10. In this stop we will look at some of the most recent landslide scars produced during the construction of the road. The sedimentary layers dip towards the road, propiciating the conditions necessary for the occurence of the landslides. The location of the lanslide scars lie near the Portugues Fault, which is in contact with the Yauco Mudstone and aphyric to sparsely porphyritic dacite of Eocene age.

We will also make a stop at Ponce's Municipal Landfill, operated by Browning Ferris Industries' (BFI), as a non-hazardous waste disposal facility. The landfill is located in Sector Las Cotorras, Ponce.

The landfill has 4 cells, each one dedicated to one of four specific types of waste; asbestos, non-hazardous industrial waste, domestic waste and biomedical waste. The facility has been in operation since March 1, 1987, under an agreement with the city of Ponce.



Field Trip 1; Itinerary



From US Army Corps of
Engineers, Project 1311A
March 1988

the section contains, near its base, much

In this stop we will learn about the geological aspects that were considered when selecting the location of the disposal facility (see itinerary field trip 1).

Stop 1- Rio Portugues Damsite
Trip Leaders: Alex Soto/John Conway

Geology and geomorphology

The Rio Portugues Dam lies at a base level altitude of approximately 120 meters and rises up to an elevation of 200 meters above sea level. The dam was constructed within a narrow valley of approximately 100 meters wide (see Figure 5). It lies on volcaniclastic breccia and lava of the Pastillo Member (Mattson, 1968); This member consists chiefly of volcaniclastic breccia, sandstone, mudstone, claystone, and lesser amounts of lava and minor limestone.

The sequence in the type area, near Sector Marueño on the Rio Pastillo consists of conspicuous dark red epiclastic sandstone irregularly interbedded with dark-red and purple volcaniclastic breccia. Farther north on the ridge between Rio Pastillo and Rio Tallaboa, southwest of Hacienda Batiz, the same sandstone-breccia sequence is overlain by a massive pale-gray biosparite that contains abundant fragments of rudists, other mollusks, and large foraminifera.

Higher and apparently in the same sequence along the Rio Cañas in Barrio Guaraguao, the rock consists of dark red and purple volcaniclastic breccia overlain by alternating thick beds (2.3 m) of hematite-red claystone and coarse-grained locally crossbedded tuffaceous sandstone. The lowest sandstone in the section contains, near its base, much admixed red claystone like that in the underlying claystone bed; upward in the sequence, the claystone decreases, and the sandstone consists of a light-to medium-green tuffaceous sandstone. A second thick claystone bed overlies the tuffaceous green sandstone and is overlain by another 3-

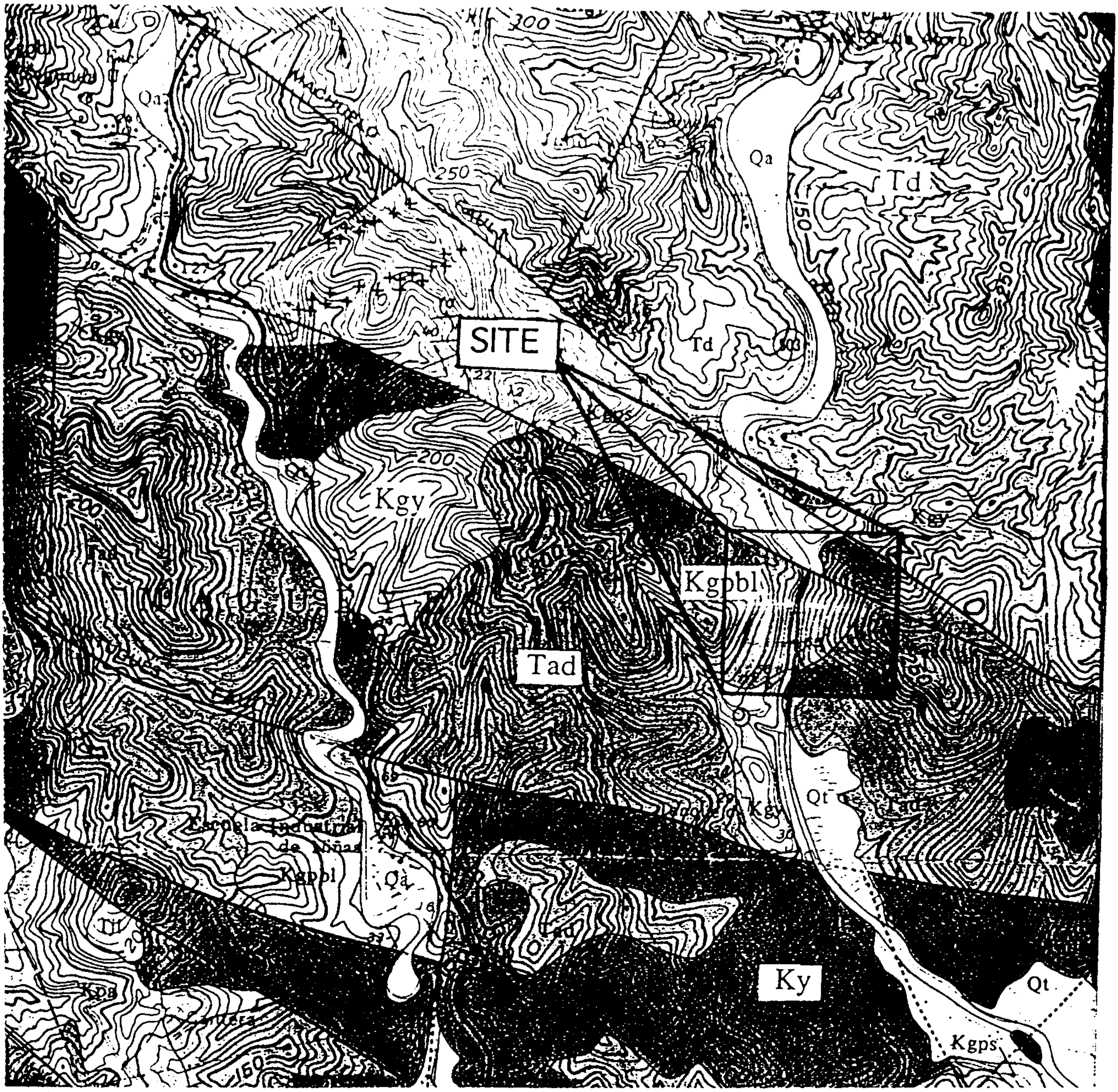


FIGURE 5. Site location of the Portugues Dam, showing regional geology

Tad - Aphyric sparsely porphyritic dacite

Kgpbl - Pastillo member

Ky - Yauco Formation

Td - Hornblende-Augite diorite and quartz diorite

Kgy - Lago garzas and Yauco formations interbedded

4 m thick bed of massive sandstone which grades upward into a massive (2-3 m) biosparite.

Geology of the Portugues Damsite

Soils

The soil mantle and the zone of intense weathering varies from an average of 23 feet thick on the slopes and the abutment to only a few feet thick in the river gorge. Field classification indicates the material is USGS types SM, ML, CL and is suitable as impervious fill. Weathered rock extends to an average depth of 41 feet. The excavation of weathered rock will produce a significant amount of fines which could also serve as impervious material.

The spill way has a soil mantle and intensely weathered zone of 8 feet of average thickness, with weathered rock extending to an average depth of 26 feet. Laboratory tests classified near surface soil samples as USGS types SM, MH, and CL.

Stratigraphy

The USGS geological map (I-1042) shows the damsite is underlain by the Pastillo member of the Lago Garzas Formation (Cretaceous). Downstream is Eocene while upstream, the majority of the reservoir area is underlain by Eocene Diorite. Also present in the damsite and reservoir area are lesser amounts of Cretaceous Lago Garzas and Yauco Formation. These units are not in stratigraphic sequence. They are shown as either intrusive or faulted into place. During the site geology study of the Portugues damsite and reservoir area, the rock was divided into the following mappable units:

(1) **Td**- Hornblende Diorite, greenish gray, coarse crystalline, 55 percent plagioclase (andesine) slighty altered to sericite, 41 percent hornblende. The diorite weathers to a sandy saprolite which can be up to 50 feet thick. The diorite is strongly jointed and cut by numerous steeply dipping dikes.

(2) **Kgy**- Lava volcanic conglomerate, sandstones, and siltstones of andesitic origin, all massive deposits.

Lava: andesite, purple to gray, phenocrysts of feldspars showing flow structure in a fine-grained groundmass.

Andesitic conglomerates: purple to greenish-gray, the principal rock type of the damsite and reservoir areas, clasts commonly 70 percent of the rock. Clasts range from sand size to boulder size, but are commonly 1 to 3 inches, rounded to subrounded. Principle clasts are andesite and porphyritic andesite but locally abundant are basalt clasts, tuffaceous limestone clasts, fossiliferous limestone clasts and volcanic sandstones.

Sandstone: gray to greenish gray, similar to andesitic conglomerate except where there are fewer smaller clasts, fine to course grained epiclasts found in the conglomerate. Matrix composed of silt sized volcanic materials and secondary calcite and quartz which act as cement.

Siltstone: gray to greenish gray, calcareous siltstones, siliceous siltstone, and tuffaceous siltstone, massive, commonly 50 percent feldspars, and 50 percent calcite/chlorite/quartz.

(3) **Ky**. Predominantly black claystone, claystone conglomerates, and related rock types with black claystone matrix.

(4) **Kgpbl**- The Pastillo Member consists mostly of breccias and lava; is a very thick bedded (over 1 meter) to massive volcanic breccia composed of abundant dark-red -brows and subordinate dark green and purple angular, large (commonly 3- 6 cm, rarely to 25 cm) clasts of porphyritic (augite, plagioclase) dense to vesicular andesite in an unsorted coarse-sandstone matrix. Commonly the breccia and lava are deeply saprolitized in the area.

(5) **Tad**- Aphyric to sparsely porphytiric dacite- Commonly aphyric abundantly amygdaloidal, general deeply weathered medium-gray-green dacite.

Structural geology

(1) **Strikes and Dips**- Because of the massive nature of most of the rock, large portions at the damsite and reservoir do not have strikes and dips. Most dips are between 10° and 50°. The attitude that best represents the structure at the damsite is N80E, 23N. Beds of similar attitude are found near the damsite on the highway, south of the damsite in the river. There are no strikes or dips in the diorite that makes most of the reservoir. Most attitudes outside the reservoir area dip to the south.

(2) **Joints**- The principal joint set strike N14E, with most dipping 80°SE to vertical, however the dips vary from N50°SE to N60°NW. A second joint set, approximately perpendicular to the principal set, has an attitude of N87°E, 90° +/- 60°. A poorly well developed third set of joints has a general E-W strike with dip less than 30°, probably to the south.

A study of the joints in over 1,000 feet of core from 23 damsite core borings was undertaken to document the dip and the characteristics of fractures from 10 feet above to 50 feet below an acceptable foundation grade. All fractures regardless of origin were recorded, but healed fractures (numerous) were not recorded. Of 1,300 fractures recorded, 131 are mechanical and were caused by the drilling operations or handling of the core. 358 joints were described as fresh and may also be mechanical fractures. The remaining 810 fractures are naturally occuring open to tight joints, many with calcite linings.

Faults Do not appear to be of seismic significance at the Portugues reservoir or damsite. Previous mapping of the Penuelas Quadrangle by the USGS, suggests that major faults of the Great Southern Puerto Rico fault zone pass close to the damsite, but the following evidence indicates that there has been no major displacements near the damsite since the intrusion of the diorite (Eocene):

The joint orientation in the diorite is the same as the country rock. The diorite is surrounded by an aurel of metamorphic rock. Where exposed, all diorite-country rock contacts are normal intrusive contacts; there are no abrupt changes in lithology except for the diorite country rock contact.

(a) **Machuelo Fault**- The Machuelo Fault, as mapped by the USGS, passes a few hundred meters north of the damsite. The strongest evidence for the fault is the linear character of the valley through which it is drawn, however, outcrops are of metasediments and no evidence of faulting was found in the valley. Evidence for a pre-Eocene fault would likely have been destroyed by the diorite intrusion.

(b) **North Fault**- The North Fault was drawn because of the linear relationship in a number of valleys east of the damsite and the displaced appearance of the southeast portion of the diorite as seen on the geologic map. No physical evidence to confirm the existence of the fault was located in the field. If the North fault does exist, it would appear to have 0.6 km of post-Eocene displacement.

(c) **Damsite Faults**- A set of 3 faults strike across the river near the damsite. They have been designated Damsite Faults #1, #2, and #3. They strike about N45^{O}E and are near vertical, an attitude that agrees with faults exposed in the spillway.

Damsite Fault #1 is represented by a shear zone in the roadcut with a mineralized seam exposed in the river. The soundness of the mineralized seam suggests lack of recent movement. Damsite fault #2 is evident where the river makes a sharp turn to follow a lineation formed by a dike and shear mineralized with calcite. Damsite Fault #3. This fault is represented by a mylonitic zone. No surface evidence of the fault along the projected path of the zone could be located because outcrops in the area are poor.

STOP 3- BFI Waste Disposal Facility
Trip Leaders: J. Joyce (UPRM)/A. Bonilla (EQB)

Geology and Geomorphology

BFI's facility is set at an altitude of approximately 50 meters above sea level. Two streams located nearby; Quebrada del Agua, 500 meters to the west and Rio Pastillo, 800 m to the east, flow southward towards the Caribbean Sea, located approximately 3.6 kilometers to the south. Local topography is characterized by rugged hills of the Juana Diaz and Ponce Formations (see Figure 6). The facility is set in a semi-arid climate.

Site Geology

The site is located within the Southern Carbonate Province of Puerto Rico. The carbonates, which are of mid-Tertiary age, unconformably overlie the Cretaceous rocks of the Central Cordillera to the north. To the south, the carbonates are covered by Quaternary alluvial deposits.

Two principal geologic formations are recognized within the Southern Carbonate Province and both are present at the site. The Juana Diaz Formation (JDF), was formally named by Maury (1929) for exposures in the Juana Diaz area (Ponce and Rio Descalabrado Quadrangles) and later revised by Monroe (1973). JDF is of mid to lower Miocene age and consists of lenticular and intertonguing beds of white to brown , grayish-orange to grayish-green, bedded calcareous arenites, mudstones siltstones and conglomerates, with variable clay content.

Ponce Limestone is of middle to upper Miocene age and is composed of orange to tan, very fossiliferous and porous limestone, except for a basal member which is a hard crystalline limestone and a homogeneous silty member. The Ponce Limestone unconformably overlies the Juana Diaz Formation.

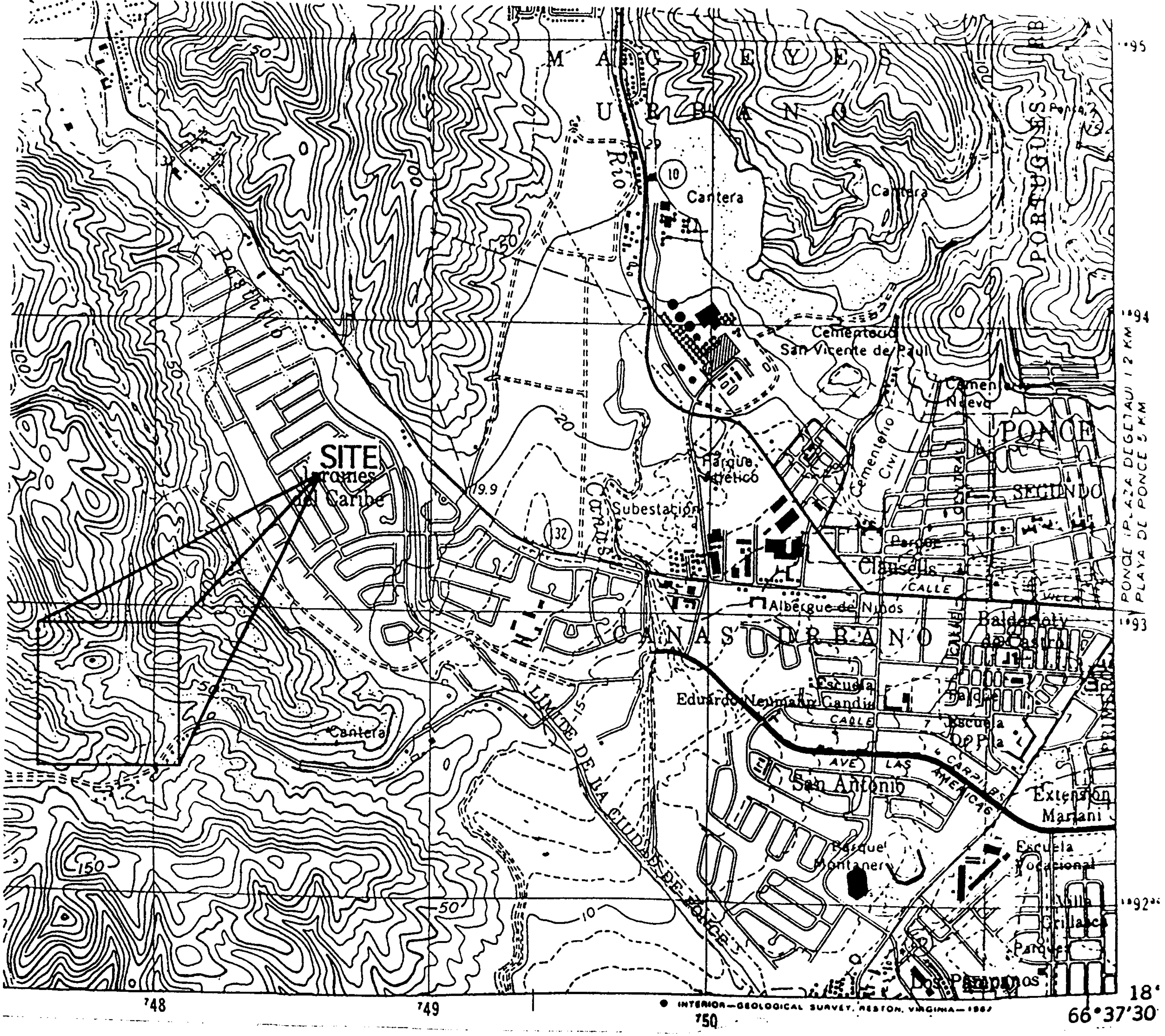


FIGURE 6. Site location of the BFI landfill facility in Sector La Cotorra, Ponce.

Structural geology

Northwesterly-trending faults are part of the Southern Puerto Rico Fault Zone (SPRFZ). A southernmost fault crosses the site in an east-west direction which juxtaposes the Juana Diaz beds to the south against mid-Ponce limestone to the north. The fault is a high-angle normal fault with at least 200 meters of vertical displacement and possibly a left-lateral component of offset. Its relation to the (SPRFZ) is uncertain.

Hydrogeology

Ground-water in the Ponce area occurs in three principal water-bearing formations: the Juana Diaz Formation, Ponce Limestone and alluvial material. The Juana Diaz and Ponce formations form the hills north and west of the city of Ponce.

Recharge to the ground-water system in the Ponce area may be derived from infiltration or rainfall, although slight if any, return flow of irrigation water and seepage from streams, canals and ponds. The primary zone of recharge for the Ponce Formation nearest the site, is the Rio Pastillo basin (east of the site). The Rio Pastillo flows perennially only in the mountain portion of its basin.

FIELD TRIP 2
SATURDAY FEBRUARY 24, 1996
TRANSPORTATION INFRASTRUCTURE; ROAD PR-10/RIO UNIBON SITE

TRIP LEADERS: C. Rodriguez(Suelos, Inc.)/J. Joyce (UPRM)

INTRODUCTION

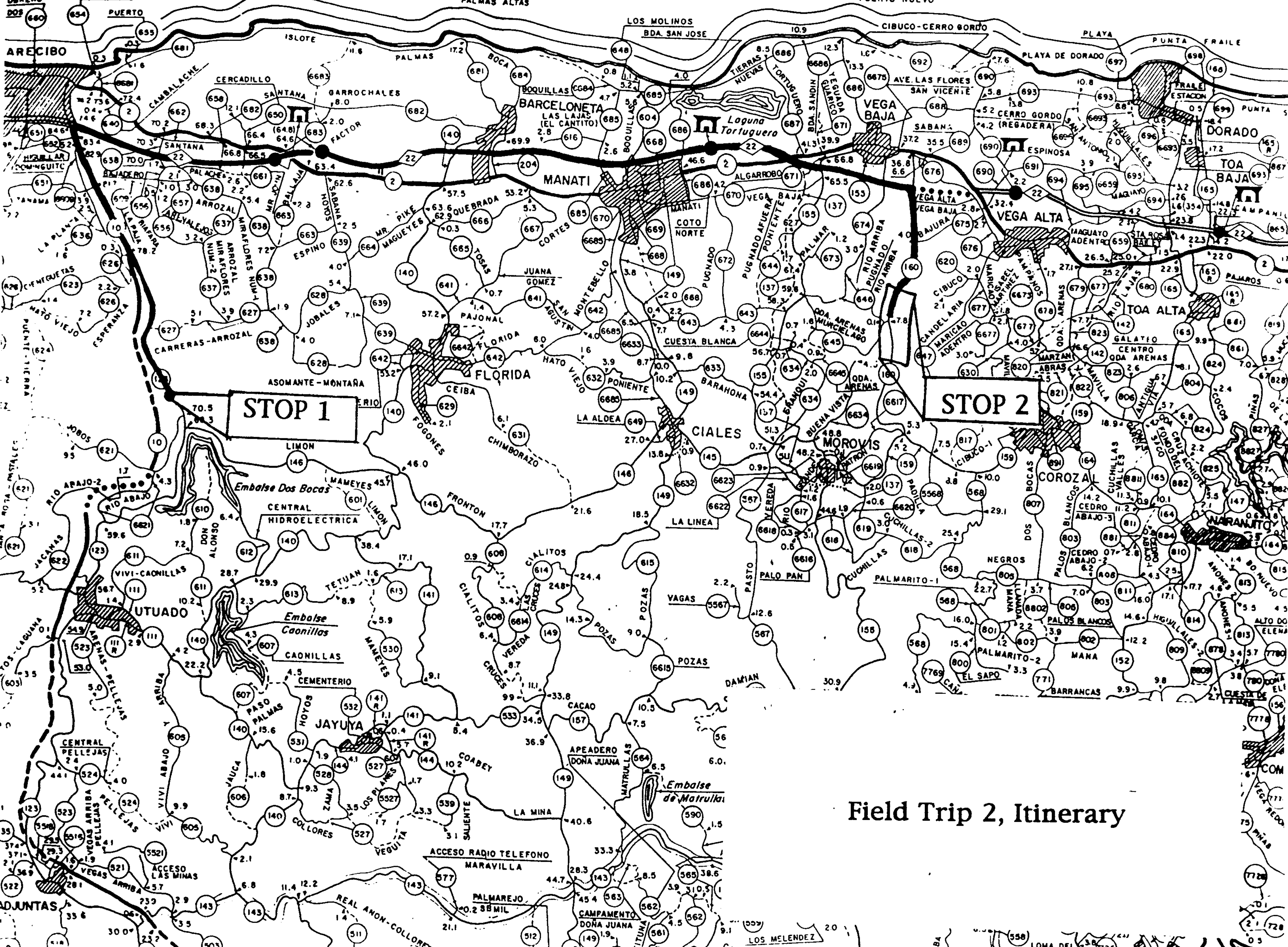
In this field trip we will take a closer look at the PR-10 project and the most recent landslide scars developed during two landsliding events in December 29-30 of1995 along the road site. The landslide scars developed when aproximately 500,000 ft^3 of colluvium failed over a weak clay unit, which is part of the San Sebastian Formation, producing the 150 meters wide landslide scar. Schematic drawings illustrating the mechanisms involved during the process of landsliding on PR-10 are shown of Figures 7 and 8.

On the second leg of the field trip we will stop at the Río Unibón site in Almirante Sur, Vega Alta. At this stop we will look at the classical karst topography of mogotes and sinkholes which characterize the northern limestone belt of Puerto Rico (see itinerary field trip 2). Once there, we will discuss various engineering considerations concerning karst topography, encountered during the site planning phase of Road PR-22.

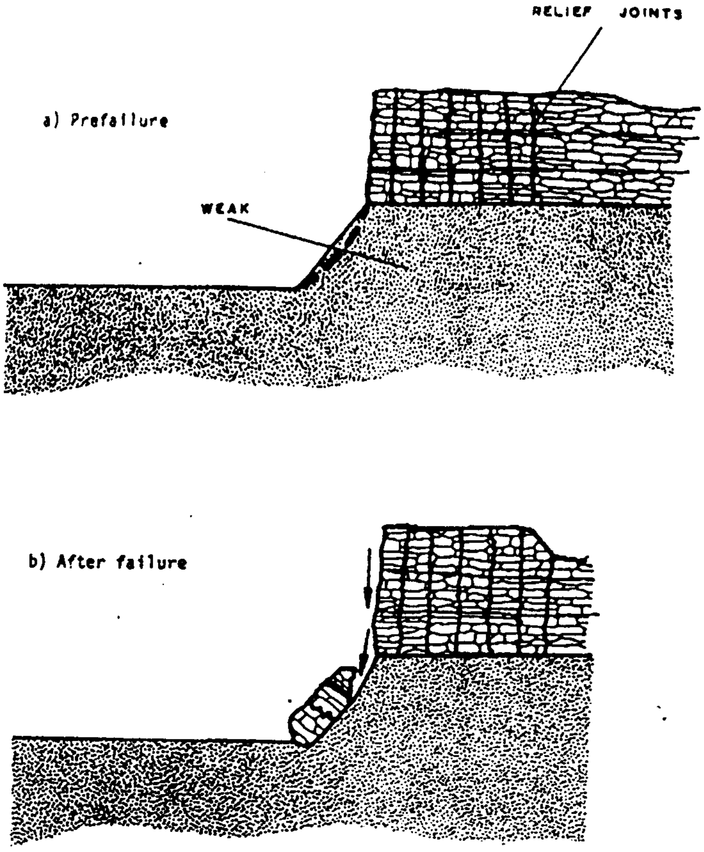
Stop 1-P.R 10 Landslide Scars

When finished, Road PR-10 will greatly improve transportation between the major cities of Ponce and Arecibo, connecting the unemployment-stricken isolated towns of Utuado, Jayuya and Adjuntas with the principal commercial and industrial centers outside of the San Juan Metropolitan Area.

Building PR-10 has not been an easy task. Several specific building techniques have been developed from scratch. Many areas along the



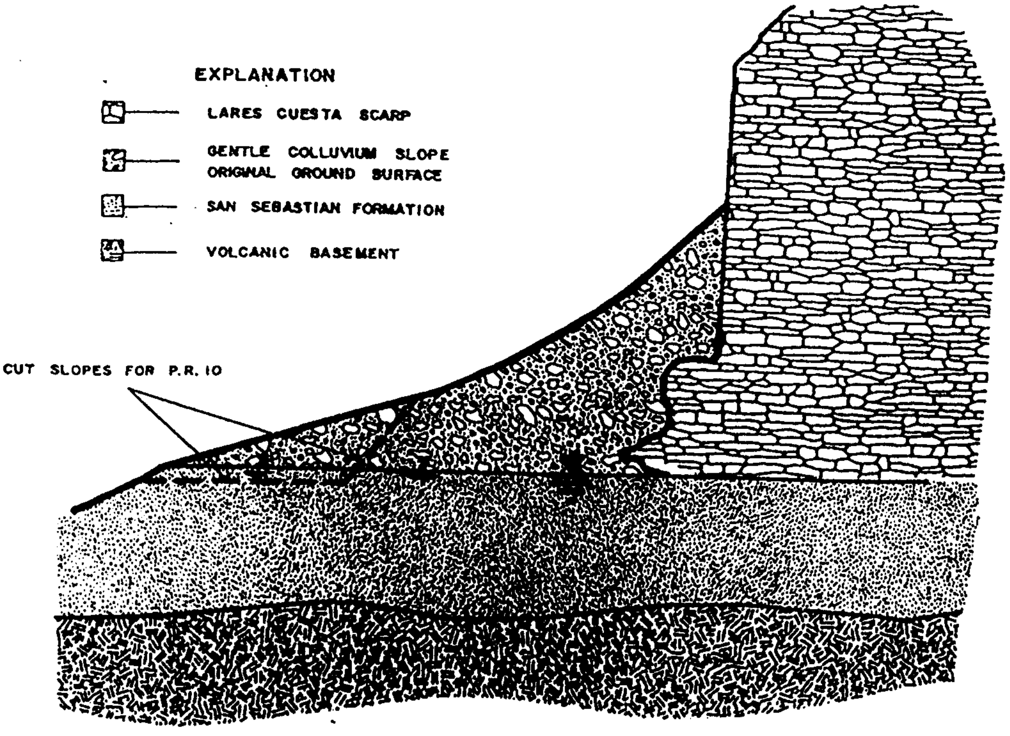
Field Trip 2, Itinerary



Schematic Representation of Rockfalls (Station 176) before (a) and after (b) failure.

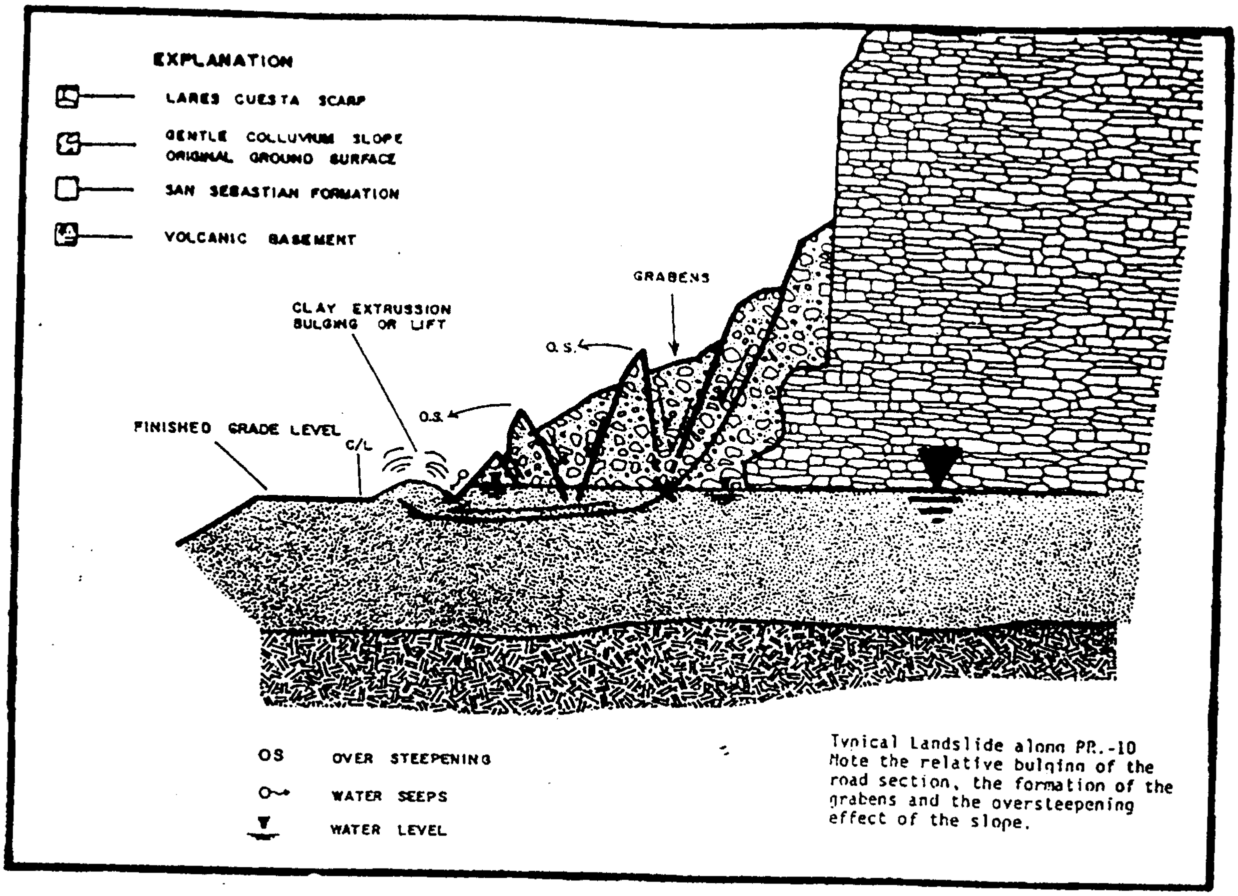
FIGURE 7.

SOME LANDSLIDING PROCESSES OCCURING ALONG PR-10



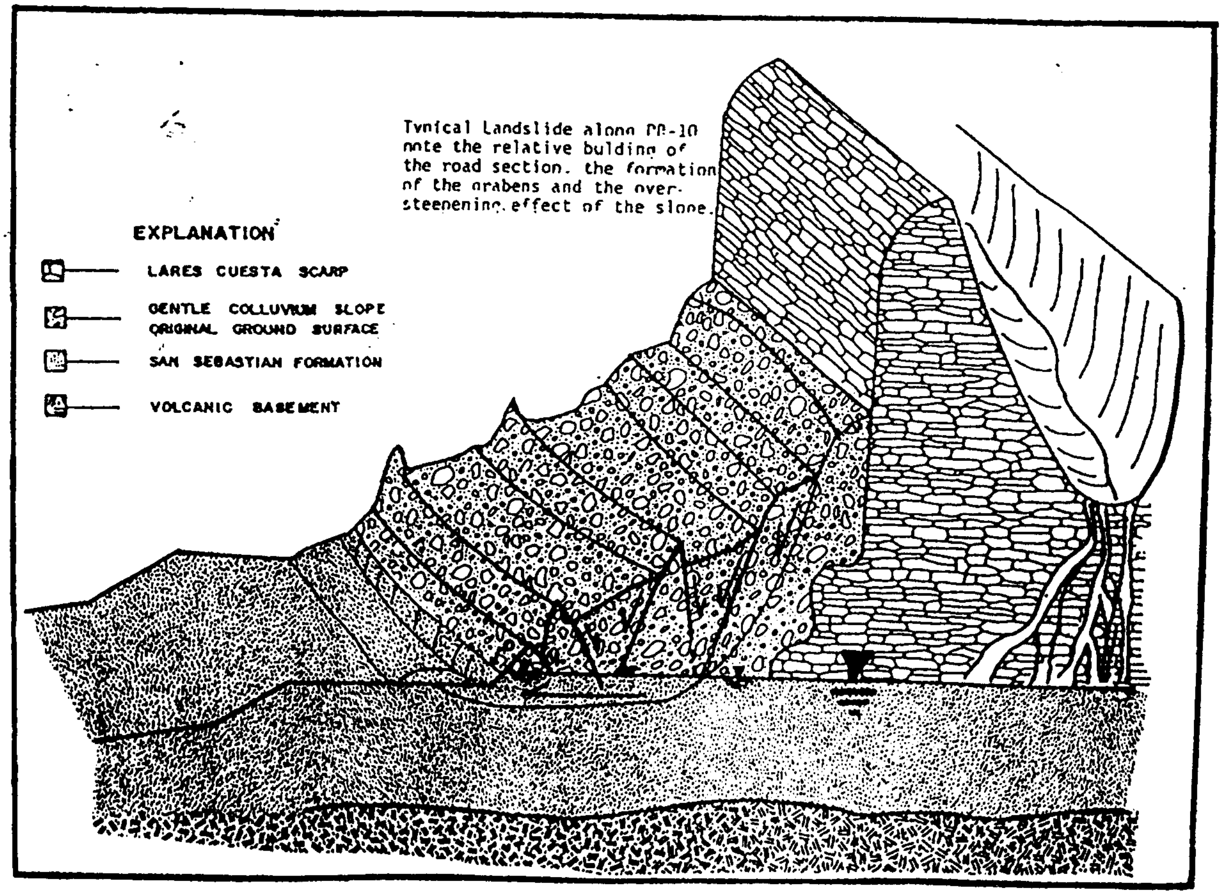
Volcanic Basement
Typical Section along Lares Cuesta Scarp

(SOURCE; SUELOS, INC.)



Typical Landslide along PR.-10
Note the relative bulging of the road section, the formation of the grabens and the oversteepening effect of the slope.

FIGURE 8. SOME LANDSLIDING PROCESSES OCCURING ALONG PR-10



Typical Landslide along PR-10
note the relative bulding of the road section. the formation of the grabens and the over-steepening effect of the slope.

(SOURCE; SUELOS, INC.)

construction path are unstable and prone to landsliding. This has played a big part in delaying the project since it was started in the 1970's.

The landslide trigger mechanism has been intimately related to high rainfall, common in this region. Previous geological and geotechnical studies did not recognize the presence of unstable deposits along the road sector alignment. As a result, several large slope failures have developed during the construction of the road.

Geology and geomorphology

The route runs nearly east-west at an elevation of 1,050 ft. above sea level. It is located upon a gently sloping to locally irregular bench 300 to 600 ft. wide which is bounded on the south by the moderately steep, heavily vegetated valley slope of *Rio Grande de Arecibo,* which flows about 430 ft. below, and on the immediate north by the steep rock escarpment (cuesta scarp) of the Lares limestone plateau which extends another 150 to 300 ft. higher (Figure 10). This position places the route alignment right along a precarious condition of a plateau margin.

For most of its alignment the road sector is underlain by landslide deposit (Ql); a muddy limestone unit of the Lares Limestone Formation (Tl), hard overconsolidated clayey soils of the San Sebastian Formation (Ts) and a generalized volcanic rock basement (Ty, Ka).

The Lares limestone, which constitutes the northern plateau, consists of a mid-Tertiary upper unit of hard, white to tan, massive to bedded limestone (recrystallized chalk and calcarenite), 250-330 ft. thick, and an 80 ft. thick lower unit of softer, thick to medium bedded, tan marly, muddy limestone containing coral beads and calcareous algal fragments. The upper unit has undergone extensive dissolution with many small to large cavities and an elaborate karstic surface with isolated rock cones, steep ridges and circular cone depressions.

The Lares limestone is underlain conformably by the San Sebastian Formation (Ts), also of mid-Tertiary age, which consists of hard interbedded and lenticular masses of varicolored hard clay, silty clay, and clayey silt with some weathered gravel at the base. This gravel is probably the weathered surface of the underlying volcanic rocks. The San Sebastian Formation ranges in thickness from 0 to 6 ft. thick on the east to about 80 ft. on the west end of the studied section.

construction path are unstable and prone to landsliding. This has played a big part in delaying the project since it was started in the 1970's.

The landslide trigger mechanism has been intimately related to high rainfall, common in this region. Previous geological and geotechnical studies did not recognize the presence of unstable deposits along the road sector alignment. As a result, several large slope failures have developed during the construction of the road.

Geology and geomorphology

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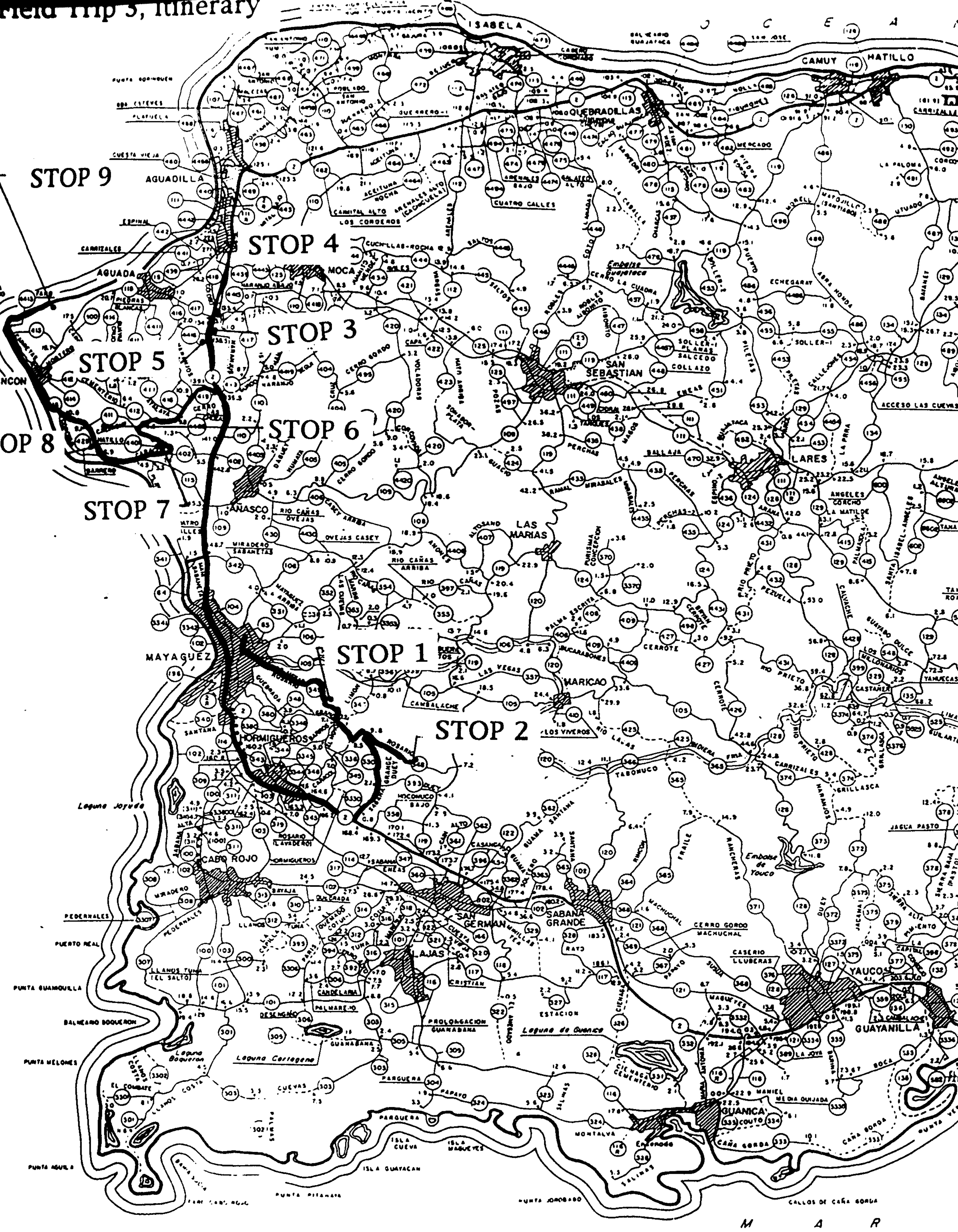
STOP 9
STOP 4
STOP 3
STOP 5
STOP 6
OP 8
STOP 7
STOP 1
STOP 2
ISABELA
QUEBRADILLAS
CAMUY
HATILLO
AGUADILLA
AGUADA
MOCA
NCON
AÑASCO
SAN SEBASTIAN
LARES
LAS MARIAS
MAYAGUEZ
MARICAO
HORMIGUEROS
CABO ROJO
SAN GERMAN
SABANA GRANDE
LAJAS
YAUCO
GUAYANILLA
GUANICA
Laguna Joyuda
Laguna Cartagena
Laguna de Guanica
Laguna Boqueron
Embalse de Yauco
Embalse Guajataca
O C E A
M A R

Stop 1- Serpentinite Road Cut
(south side of Las Mesas PR -349)

The completely serpentized and tectonized nature of the ultramafic rocks is evident in this outcrop. The intense fracturing and foliation weaken these rocks in terms of slope stabilities. Debris flows and avalanches are common slope forming processes on the ultramafic bodies.

As we leave the outcrop we will cross over into Late Cretaceous volcaniclastic rocks and mudstones. Coming down the southside of Las Mesas we will get great views of the Guanajibo Valley (half graben), the Rosario Peñones (karstified limestone) to the south and Monte del Estado (highest serpentinite body) to the east.

We will continue on to PR 438 to the town of Rosario and cross the Rio Rosario. At the river crossing we can see the first of the karstified Peñones Limestone. From Rosario we will continue to the eastern most peñones at the Rio Duey.

The Peñones Limestone

by Hernan Santos

This formation was first described by Curet (1981) to redefine the limestones described by Mattson (1956) as gravity slide blocks of the Cotui Limestone into the Hormigueros Syncline. It is characterized by massive to thick-bedded, skeletal grainstone to packstone, and calcareous breccias. Curet (1981) described the Peñones Limestone as interbedded concordantly with both the "Upper Yauco" and Sabana Grande (probably Monte Grande) formations. The Peñones Limestones is exposed along the contact between the "Upper Yauco" and the volcanics of the Maricao Formation to the North. These changes probably represent facies change more than a gravity slide.

The age of this formation is Late Campanian to Early Maastrichtian based on foraminiferal data and the presence of the rudistid Barrettia gigas (Curet, 1981). He gives the formation a maximum thickness of 250 meters but did not present any stratigraphic section.

Stop 2-Rosario Peñon- Rio Duey

We will walk along the river between the two peñones (see Figure 10). Along the river course, we can see both erosional and depositional river terraces. Large blocks of limestone in and along the river attest to slope failures by rock falls and topples. we will exit the river on the south side of the eastern most peñon. On the southeast corner of the peñon is a 30-40 meter high topple block in the process of falling. The topple began 3-4 years ago when the land owner bulldozed along the south side of the peñon to access the rock for marble mining. Close inspection of the allows us to see that the limestone is resting on top of weathered volcanic and has no supporting root. When the lateral support was removed the block began to topple over.

Leaving the Peñones we will follow along the Rio Rosario to PR-2 and continue through Mayagüez to the Añasco Valley. As we leave Mayagüez and enter the Añasco Valley we can see the Builders Square-K-Mart Plaza where some of the problems associated with the valley are evident. Large lifts of fill are being used to compact and dewater the underlying clay soils which have proved to problematic for several projects including the Mayagüez waste water treatment facility. The muddy Rio Grande de Añasco and her tributaries have filled the valley with clayey rich alluvial deposits. These deposits are probably responsible for seismic wave amplification during the 1918 earthquake.

Stop 3-Dip Slope Conditions and Spheroidal Weathering

Rock cuts on the other side of the road show the typical structure and weathering in this part of the range.

From here we continue to the edge of the Moca Valley which is also interpreted as a half graben and an onland continuation of the Mona

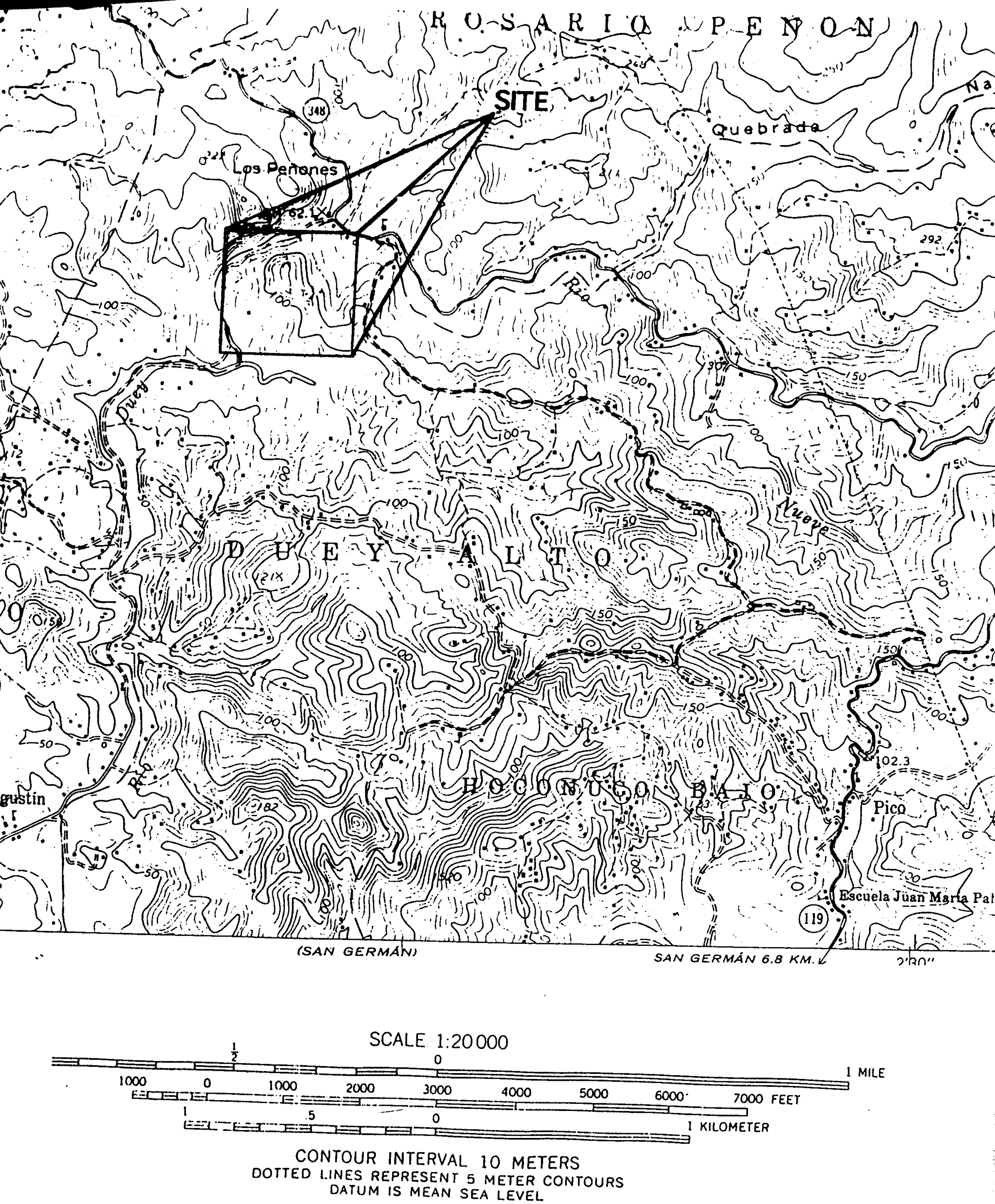
ROSARIO PEÑON
SITE
Quebrada
Los Peñones
348
DUEY ALTO
HOCONUCO BAJO
Río Duey
Río Nueve
Pico
102.3
Escuela Juan María Pa
119
gustín
(SAN GERMÁN)
SAN GERMÁN 6.8 KM.
2'30"
SCALE 1:20000
1 MILE
7000 FEET
1 KILOMETER
CONTOUR INTERVAL 10 METERS
DOTTED LINES REPRESENT 5 METER CONTOURS
DATUM IS MEAN SEA LEVEL

FIGURE 10.

Canyon fault system. The north side of the valley is marked by the Lares Escarpment which is the southern most end of the north coast karst terrain. Similar to La Cadena the escarpment has probably retreated significantly northward from the fault. Very little seismicity is associated with valley. The last large earthquake to affect Puerto Rico however, did occur offshore in the Mona Canyon.

The Añasco Valley is considered to be a south side down, half graben and a onland continuation of late Tertiary-Quaternary extensional faulting in the Mona Passage (Desecheo Ridge). The valley also lies at the western end of the Great Southern Puerto Rico Fault Zone as marked by the Cerro Mula Fault. This fault passes underneath the northern part of the valley and then crosses to the northwest cutting through the western end of the La Cadena Ridge. The steep topographic gradient, triangular facets, parallel drainage and bottle neck valleys along the ridge at the northern end of the valley suggest a fault origin to the La Cadena Ridge.

As we approach the ridge the highway cuts through and passes over a dissected fluvial or marine terrace at an elevation of about 10 meters. This suggests the younger, half graben, fault lies below the valley and that the escarpment has retreated significantly northward from the fault. The younger fault may coincide in part with the Cerro Mula Fault. Comparing the terrace to dated marine terrace deposits of similar elevation in Rincon suggests an age of at least 125,000 years for the terrace. Only limited seismic activity occurs in the valley and ridge system here.

The La Cadena ridge and range is composed almost entirely of the Eocene Culebrinas Formation. The Culebrinas Formation is characterized by volcaniclastic sandstone and mudstone turbidites and lenses of coarser grained rocks deposited by debris flows. Basaltic marine lavas of the Mal Paso Formation occur in the northern part of the range near Aguada. A complex of volcanic rocks that underlie the Culebrinas Formation occurs along the Cerro Mula Fault Zone at the southwestern end of the range.

The early Tertiary volcanic and sedimentary rocks are folded along NW-SE trending axes and are generally highly fractured and locally faulted. Their deformation and the end of volcanism occurred in Eocene-Oligocene time and may have resulted from the collision of the Caribbean Plate with the Bahamas Banks. Along the northern margin of the range the Culebrinas Formation is overlain by Miocene limestones that are tilted northward up to 15° presumably by the formation of half grabens in the Moca and Añasco Valleys.

As we cruise through the range steeply dipping rocks of the Culebrinas are evident in the rock cuts. Rock cuts in the harder coarse grained members are covered with rock nets near the top of the ridge. Slope stability problems in the road cuts are produced by a combination of dip slope conditions with spheroidal weathering of coarser grained layers and intense fracturing of the thinner bedded, fine grained layers.

Stop 4-Construction on Dip Slopes (photo opportunity)

A house has been constructed on dip slopes a construction advertisement of letter sliding. Weathered out spheroids present a rock fall hazard on road cuts in coarser grained rocks.

Stop 5- Fracturing and Dip Slope Failures

Closely spaced fracturing and dip slope conditions lead to rock slides.

We continue south along PR 2 and then turn westward into the range on PR 419 to PR 416 to PR 411 and the top of the La Cadena Ridge, Pico Atalaya (see Figure 11).

Stop 6- La Cima Burger (El Primo)

This stop provides us with a grand view of the Añasco Valley, Bahia Añasco, the Mona Passage, Isla Desecheo and most of western Puerto Rico. Below the range a large mine for beach sand can be seen. These beach sand deposits are typical of the low land deposits along the coast from here through Rincon. Liquefaction of these deposits occurred during the 1918


SITE
SITE
GUANABANO
Escuela Segunda Unidad
MAL PASO
Las Corozas
Escuela Mal Paso
Capilla Mal Paso
Rio
Escuela Piedras Blancas
PIEDRAS BLANCAS
La Mina
Escuela Marias
LAGUNA
Escuela Atalaya Abajo
Capilla La Virgen De Monserrate
Capilla Santa Rita
Escuela Naranjo Arriba
CERRO GO
ATALAYA
Escuela Atalaya Arriba
Capilla La Virgen De Alta Gracia
Escuela Atalaya Num 3
Escuela Pinales Caracules

FIGURE 11.

earthquake. The combination of sandy and muddy alluvial deposits in the valley resulted in liquefaction and a much greater ground shaking in Añasco (9 Rossi-Forel) than in Rincon(7.5 Rossi-Forel) (see Figure 12a) were the town is built mostly over rock.

Steep slopes also make this area susceptible to earthquake induced landslides. Shorelines in this area were affected by a tsunami from the 1918 earthquake that ranged from 6m high in Aguadilla to 2m in Mayagüez . The rapid development of Municipalities of Añasco and Rincon is increasing the seismic and landslide risk in the area. From here we drop down the ridge front to Piñales Arriba

Stop 7- Landslide- Piñales Arriba

On August 19, 1992 at 11:00 am a slump displaced the road 2-3 meters downward and rock falls at the toe slammed through the side of the house. According to the owners rocks started hitting the house at 2:00 am. What is interesting about this landslide is that it is not a dip slope failure and did not occur during or right after an intense rainfall.

The owners and neighbors claimed little rain had fallen for a few days previous to the slump. Rainfall data from the Mayagüez airport was checked by our former student Carlos Ramos as part of his study of the slump. The record showed little or no rain the 16, 17, 18 and 19 of August. Rainfalls greater 1" did occur on August 5, 10 and 15. Several debris slides were recorded in the area on the 10th. A road cut some 40 years old lies just above the head scarp of the slide. It may be the unpaved lower part of this cut has increased infiltration into the slope and lead to the disintegration and weakening of the rock over time making it susceptible to slumping. We could find no evidence for any particular triggering mechanism for the slide.

From the landslide we continue down the ridge front and then drive along the ridge front on PR 402 (see Figure 12b). This part of the valley experiences frequent flash floods in smaller streams because of the steep

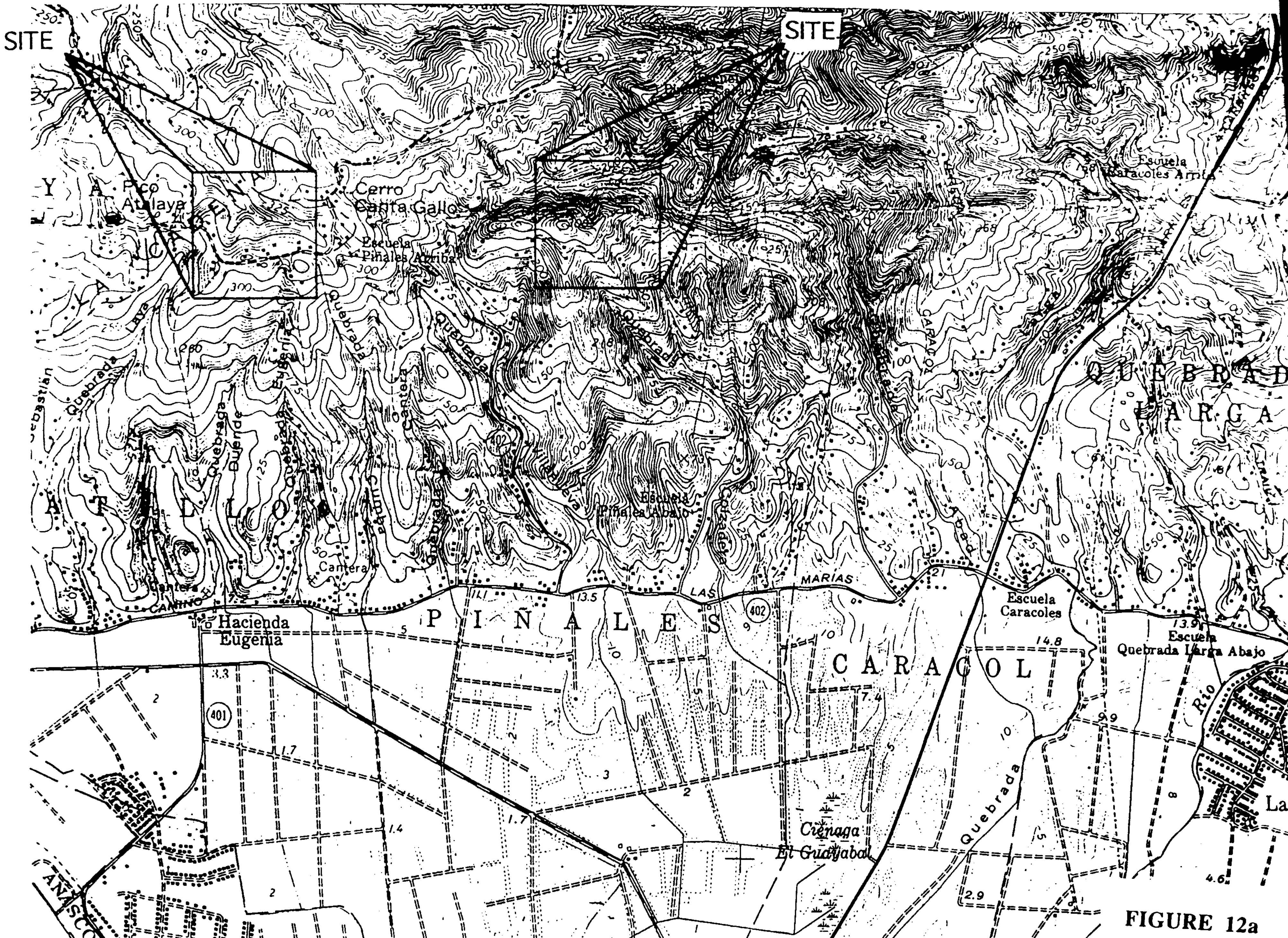
SITE
SITE
Pico Atalaya
Cerro Canta Gallos
Escuela Piñales Arriba
Escuela Caracoles Arriba
Quebrada
Cantera
Cumba
Quebrada Buende
Escuela Piñales Abajo
Colzadeta
CARACOL
QUEBRADA LARGA
LAS MARIAS
PIÑALES
CARACOL
ATALAYA
Hacienda Eugenia
CAMINO
Escuela Caracoles
Escuela Quebrada Larga Abajo
Río
Ciénaga El Guayabal
Quebrada
402
401
ANASCO
250
275
300
50
25
10
5
2
3
1.7
1.4
7.4
14.8
13.9
13.5
9.9
2.9
4.6

FIGURE 12a

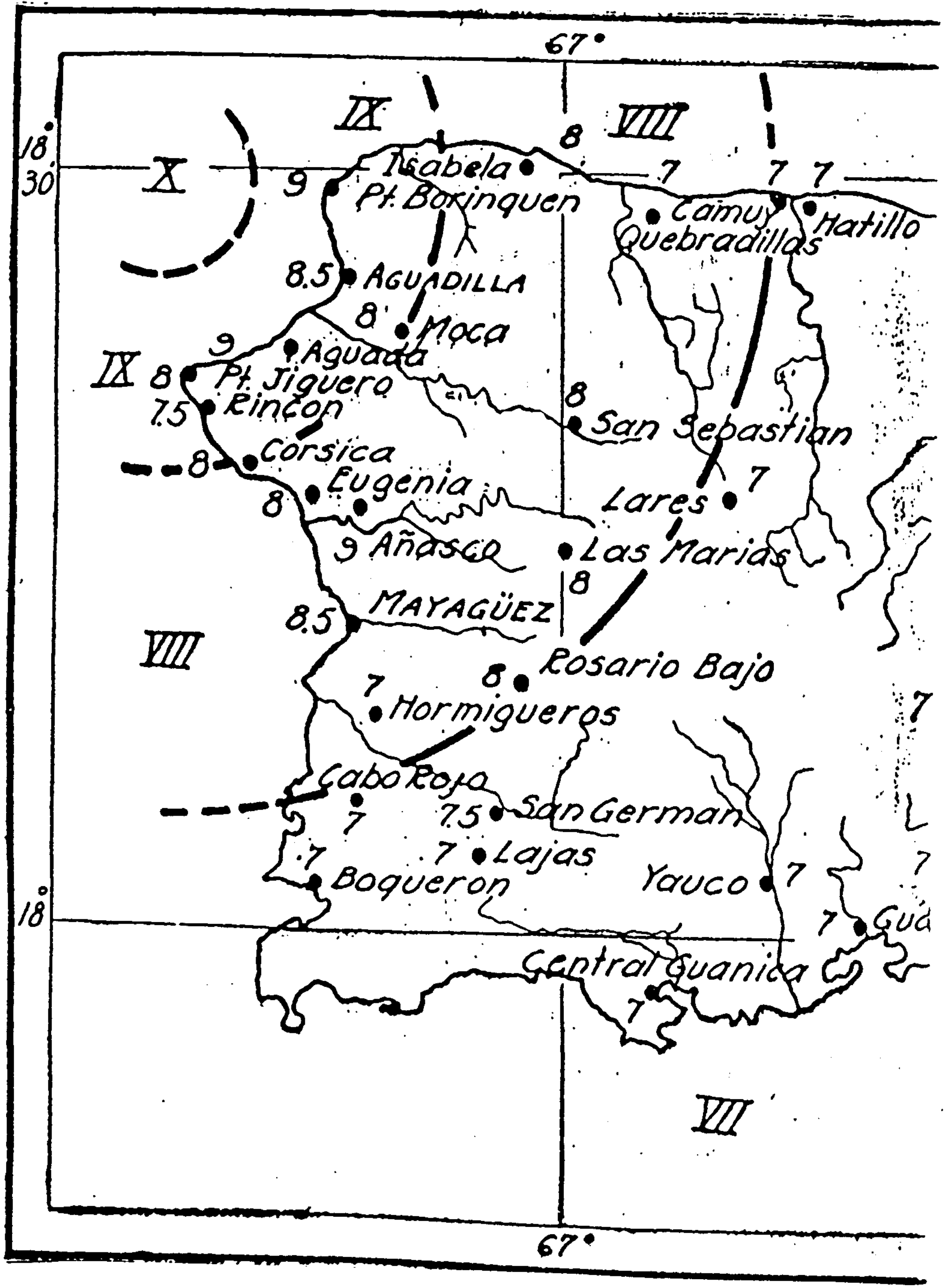

FIGURE 12b

DISTRIBUTION OF APPARENT INTENSITY.

In mapping the distribution of the intensity of the shock over the region affected by an earthquake it is necessary to use some kind of arbitrary scale. The Rossi-Forel scale, which is in common use, was devised in Italy, where the type of buildings and living conditions are altogether different from those in the United States. In Porto Rico the older buildings are much more similar to those of Italy than are the buildings found in the United States; but, nevertheless, it was found necessary to modify the scale in certain respects in order to make it suit local conditions in Porto Rico. The revised and adapted Rossi-Forel scale of earthquake intensities used in the present investigation is given below:

I. Shock recorded by seismographs.
II. Felt by a very few persons at rest or favorably situated.
III. Felt by many persons at rest or favorably situated.
IV. Felt by persons walking. Movement or rattling of doors, windows, shutters, etc.
V. Felt by nearly everyone. Furniture moved.
VI. General awakening of those asleep; ringing of bells; stopping of pendulum clocks. Bushes and trees visibly agitated. Small cracks in a few mamposteria buildings of poor construction and poor mortar. Overthrow of a few relatively unstable objects.
VII. Overthrow of many movable objects, such as vases, bottles, etc. Fall of plaster in many buildings. Some walls of mamposteria badly cracked. Cracks in mortar of some buildings of brick, stone, or concrete blocks.
VIII. Many mamposteria walls badly shattered; some walls partly or wholly thrown down. Small cracks in some concrete buildings.
IX. General destruction of mamposteria buildings. Cracks pass through bricks and concrete blocks where mortar is strong. Cracks in many concrete buildings, and some concrete walls thrown down.
X, General destruction of all buildings except those especially adapted to resist earthquake shock. Some trees broken and uprooted.

The mamposteria buildings referred to above are built chiefly of stones placed in weak lime mortar, though soft brick is often used to give greater strength around doors and windows. The stones vary greatly in size and shape and commonly consist of a more or less weathered, soft, Tertiary limestone. The mortar contains lumps of lime that has not been properly slacked, and is usually so weak that it will readily crumble to pieces between the fingers. The walls are ordinarily stuccoed over on the outside and plastered on the inside.

In general the mamposteria buildings are much less resistant to earthquake vibrations than any other type of buildings found on the island, whereas reinforced-concrete buildings, as a rule, have suffered almost no injury. There are, however, some striking exceptions to this statement. At Isabel II, Viequez, a hospital built of reinforced concrete (so called) was badly cracked; but mamposteria buildings were not injured; and few, if any, movable objects were overturned; so that the intensity there could not have been above V.

No arbitrary scale based largely on damage to buildings can be altogether satisfactory where there are great differences in the strength of the materials used in construction, and such a scale leaves room for wide variation in the personal equation when the estimates of intensity are made by different individuals. In estimating the relative intensity of the shock in different parts of the region affected by the earthquake of October 11, we were able to examine personally every important place from the western extremity of Porto Rico to St. Thomas in the Virgin Islands.

slopes and high relief of the range front. Many of these streams have been fitted with flood prevention methods including riffles and holding ponds. From PR 402 we join PR 115 and pass along the southwestern corner of the range.

Stop 8- Cerro Goden Fault Zone
(Great Southern PR Fault Zone)

Road cuts expose slices of early Tertiary volcanic and sedimentary formations (see Figure 13). Many fault slices show complex internal deformation including foliations and folds. The lower part of this cut also failed in 1992. The outcrop of the volcanic rock (lava flow) shows a set of white faced fractures that are dipping out of the cut. Only this section has experienced serious landsliding. The cut has since been terraced and has remained intact (see Figure 14).

Stop 9- Sandy Beach- Beside the Pointe

The view from the beach looks out to Aguadilla and the Mona Canyon where the 1918 earthquake took place (see Figure 12a). The rock outcrop at the end of the beach (see Figure 15) is composed of 125,000 year old lithic calcarenites overlying fine grained foraminiferal packstones of Miocene age.

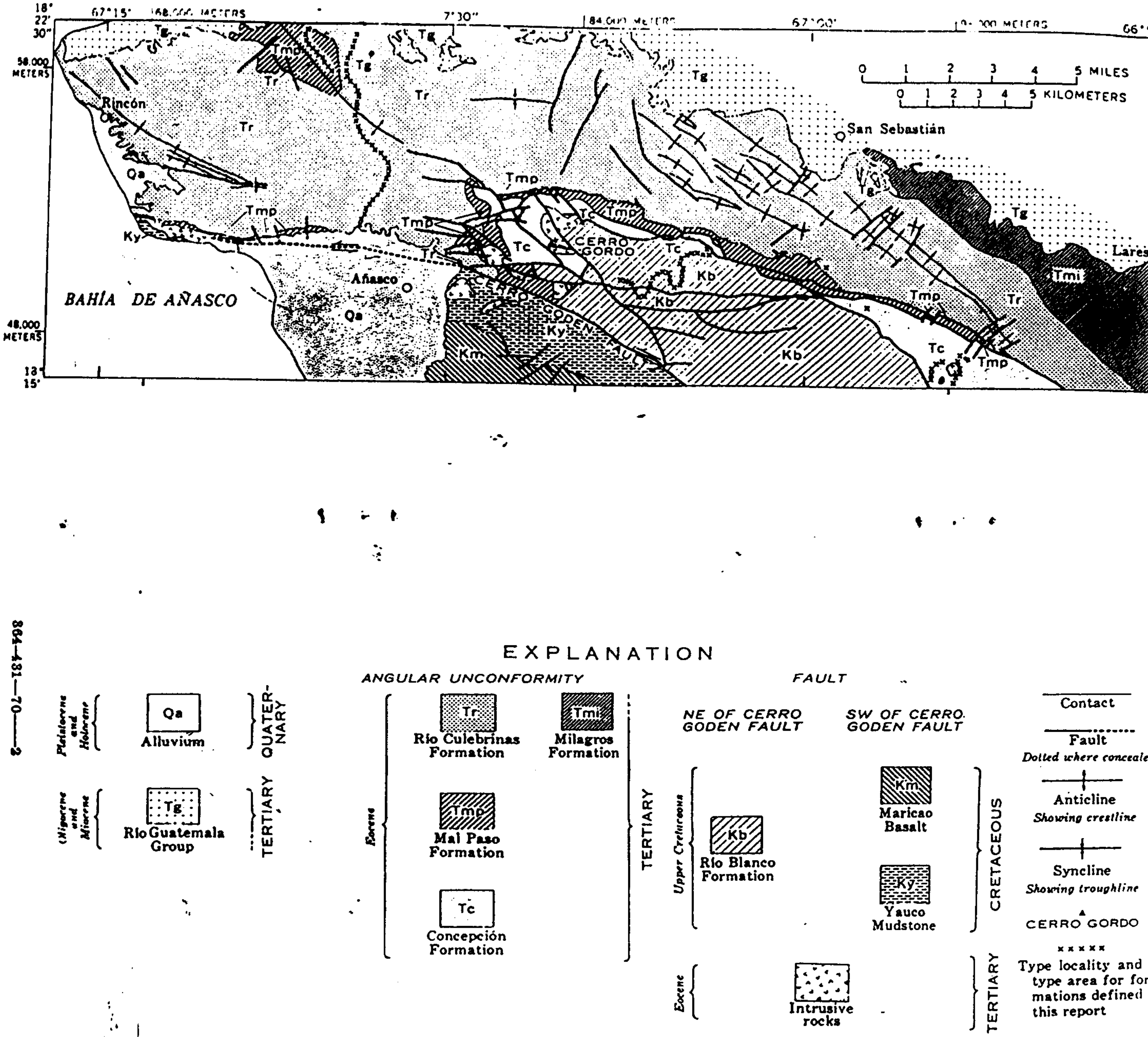

FIGURE —Generalized geologic map of northwestern Puerto Rico.

FIGURE 13.


SITE
Córcega
Quebrada
Centro Calvache
Calvache
Quebrada Justo
Quebrada Icacos
Escuela Cagüabo
Escuela Barrero
BALNEARIO
BAHÍA
MUNICIPIO
RINCÓN
AÑASCO
SAN FRANCISCO
CAGÜABO
BARRERO
CERROS
Garcia
La Bosca
Pta Cadena
BM
RAIL
411
115
429
479

FIGURE 14.

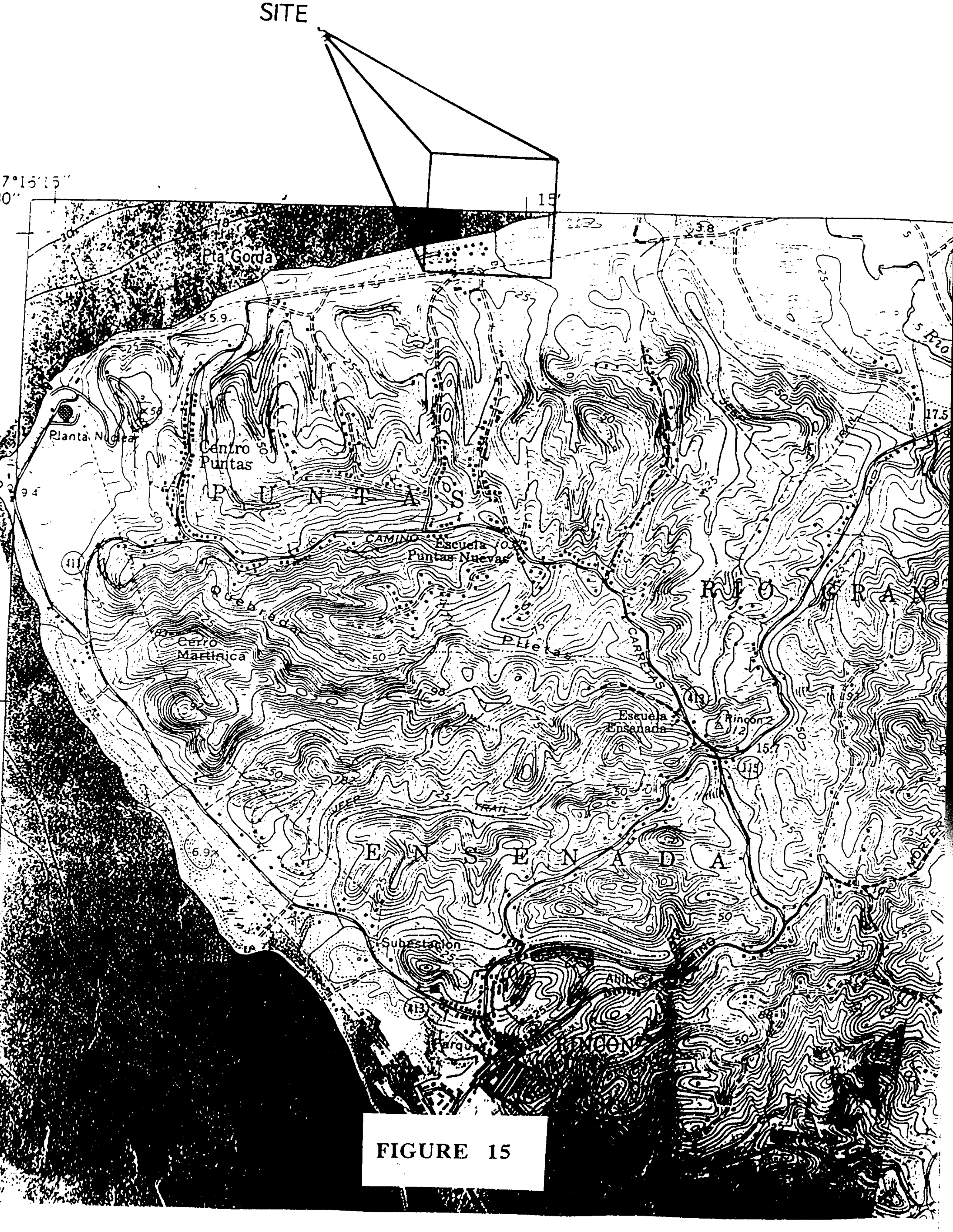
SITE
15'
Pta Gorda
Planta Nuclea
Centro Puntas
PUNTAS
CAMINO
Escuela Puntas Nuevas
Quebrada
Piletas
Cerro Martinica
RIO GRAN
CARRETAS
Escuela Ensenada
Rincon 2
JEEP TRAIL
ENSENADA
Subestacion
RINCON
Parque

FIGURE 15

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APPENDIX

A Study of a Road Landslide in Puerto Rico

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INTRODUCTION

Numerous landslides have plagued the construction of a 1.3 mile road sector in the mountain region of central Puerto Rico. The area is underlain by a sequence of landslide deposits overlying a muddy limestone and hard overconsolidated clayed soils. Landslides have occurred in both cuts and fills that have delayed the road construction for a period of more than two years, bringing as a result, great economic losses for the Puerto Rico Highway Authority. The landslide trigger mechanism has been intimately related to high rainfall, commonly observed in this region.

The road sector alignment runs parallel to a high limestone scarp which rises at steep angles to elevations of up to 400 feet above the road level. North of the scarp is the cone-karsted terrain characterized by

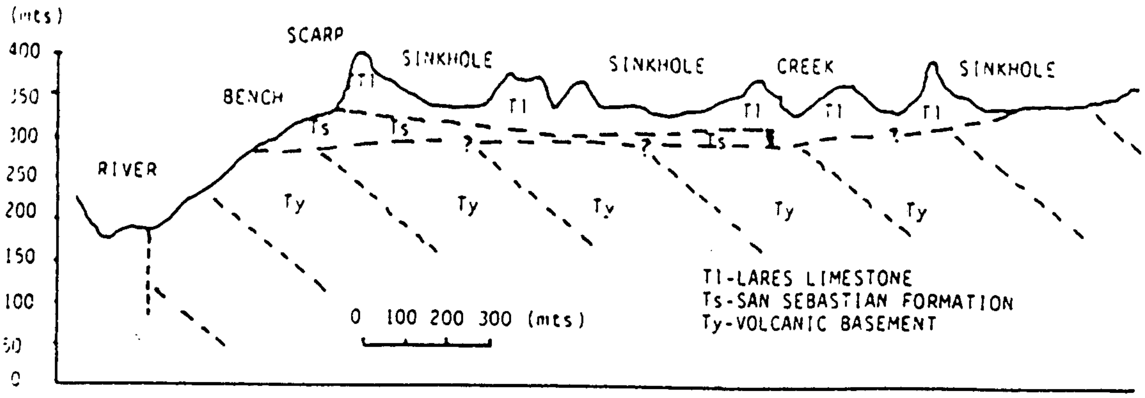

Figure 1. Schematic Cross Section in a North-South Direction

north-south and east-west trending limestone ridges, sinkholes and inter-ridge valleys. The proposed road grade follows a 300 to 600 feet wide bench along the base of the scarp. The bench is underlain by an 80 ft. thick sequence of landslide deposits, hard overconsolidated clayey soils and volcanic rock. The ground surface south of the bench steepens considerably toward a river running 430 feet below. Figure 1 shows a schematic cross section drawn at the road sector.

The study of a single slide that occurred in a 40 ft. high cut in the previously mentioned road sector is presented herein. the slide involved a large ground mass of about 1150 feet along the road, 350 feet wide normal to the road, and 40 feet deep (fig. 2). The landslide consisted of a combined slump lateral spreading slide with rotational characteristics and graben/horst structures. The failure developed during a heavy rainfall period in the area after the 40 feet high cuts were performed.

For investigating this slope failure, a detailed geological and geotechnical study was performed. Several deep boring were drilled at around the sliding mass. Inclinometers and piezometers were installed and monitored for a period of six month. A detailed engineering geologic reconnaissance was performed and slope stability analyses were carried out.

Site Geology

The route alignment runs nearly east-west at an elevation of about 1050 ft. above sea level. It is located upon a gently sloping to locally irregular bench 300 to 600 ft. wide which is bounded on the south by the moderately steep, heavily vegetated valley slope of Rio Grande River de Arecibo, which flows about 430 ft. below, and on the immediate by the steep rock escarpment (cuesta scarp) of the Lares limestone plateau which extends another 150 to 300 ft. higher (Figure 1) This position places the route alignment right along a precarious conditions of a plateau margin (Deere et al. 1987), as shown in Fig. 1.

For most of its alignment, the road sector is underlain by landslide deposits (Q1), a muddy limestone unit of the Lares Formation (T1), hard overconsolidated clayed soils called the San Sebastian Formation (Ts), and a generalized volcanic rock basement (Ty, Ka). Figure 2 shows a typical profile in the failed road sector.

The Lares Limestone, which constitutes the northern plateau, consists of a mid-Tertiary upper unit of hard, white to tan , massive to bedded limestone (recrystallized chalk and calcarenite) of 250 to 330 ft. thick, and a 80 ft thick lower unit of softer , thick to medium bedded, tan marly, muddy limestone containing coral beds and calcareous algal fragments. the upper unit has undergone extensive dissolution with many small to large cavities and elaborate karstic surface with isolated rock cones, steep ridges, and separated by elongated and circular sinkhole depressions (fig. 3).

The Lares Limestone (Tl) is underlain conformably by the San Sebastian Formation (Ts), also of mid-Tertiary age, which consists of hard interbedded lenticular masses of varicolored hard clay, silt clay , and clayey silt with some weathered gravel at the base. This gravel is probably the weathered surface of the underlying volcanic rocks. Some thin lignitic zones occur near the top of the sequence. The San Sebastian formation ranges in thickness from 0 to 6 ft. on the east to about 80 ft on the west end of the studied section.

The above described formations are the two bedrock formations that enter into the construction problem, the resistant Lares at the cuesta scarp and the weaker San Sebastian deposits which underlie and support the limestone at the scarp and beneath the plateau. The San Sebastian formation rests unconformably on the weathers surface of the volcanic rock basement of early Tertiary age.

The San Sebastian fromation rests unconformably on the weathred surface of the volcanic rock basement of early Tertiary age.

The most recent geologic unit is the Quaternary landslide deposits (QL) or colluvium that have accumulated at the base of the limestone scarp and or bench of the San Sebastian formation over the last few hundred to thousand years. These deposits consists of a heterogeneous mixture of limestone blocks that have fallen or toppled from the scarp, clay and weathered limestone joints, and slide debris from block creep, block slides and rock slumps with contain both limestone blocks and disturbed clays and silts from the underlying San Sebastian Formation.

Old slide scarp can be recognized in the field and on aerial photographs in the colluvium, many of which coalesce giving a scalloped appearance to the escarpment. Further weathering and high rainfall have resulted in additional deterioration of the colluvium causing local, small and large debris flows and earth flows, the latter involving the greenish clay from the upper part of the San Sebastian which was softened an squeezed out from the escarpment or which was brought to the surface by rotational slumps.

Hydrogeology

The general area of road sector is humid and tropical with an average annual rainfall of about ft, most of which falls from May to November. Most of the rain that falls on the karstic limestone plateau on the north is collected through the sinkhole system into an internal drainage network. Part of this water emerges as springs from open joints or cracks along the base of the escarpment. A few springs appear on the south side of the bench at the colluvium at the contact of the colluvium and the San Sebastian formation, and at the contact of the weathered gravelly San Sebastian and the weathered volcanic bedrock. Part of the water seeps down and along the contact with the San Sebastian clays, giving an opportunity to the clays to absorb water swell, and soften under the reduced stress beneath and outside the limestone scarp.

The combination of colluvium mixed with clay, resting on a clayey foundation and of a steady inflow of seepage water from the limestone plateau becomes particularly unfavorable for the sector stability and has been the main cause of the slide developed during construction. Some of the northern sinkholes appear to be particularly plugged allowing the development of shallow lakes in them during the wet season. These lakes slowly drain and feed the underground water supply. A small creek runs north of the scarp. The creek has been dammed by a small dike for local use. The resulting small lake may also be an additional source of water for the internal drainage network.

The complex geological and ground water conditions observed at the project area place this site in a hazardous geological environment.

Slide morphology

An engineering mapping and air photo analysis were performed along the road sector alignment and within areas lying north and south. The results of these analyses helped to identify the physical characteristics of the sliding mass and its surroundings. Figure 4 schematically shows these characteristics. The slide consisted of a combined slump-lateral spreading slide with rotational characteristics (near the head) and graben-horst structures. The main body of the slide moved in a horizontal translatory fashion with a horizontal offset estimated at 10 ft. The slide main scarp, 1150 ft. long and 10 to 15. ft. high, was located near the escarpment of the Lares limestone. Secondary moving mass and the slide toe was locatde about 350 ft. south of the main scarp. The toe was characterized by building (10 ft. high) and overriding ground. Several springs were observed emerging at the slide toe and green silty clay high water content (90%) was oozing out and slowly flowing away.

The air photo analysis showed that an old large landslide existed at the road sector before the road construction. The development of this old slide may be associated with the same geologic conditions described before. The construction and grading operations for the road, where 40 ft. high cuts were performed, reactivated this old slide with the physical characteristics mentioned above.

Geotechnical Evaluation

Several deep borings were drilled at and around the sliding mass the resulting soil profiles were consistent with the anticipated sequence of geologic strata described before. Figure 2 shows a typical profile of the sliding road sector. For the borings located near the base of the limestone scarp, the upper soil samples could belong to the lower unit of the Lares limestone or to the colluvium accumulated down-slope.

The standard penetration N-Values for this material were usually in the range of 25 to 50 blows/ft (higher values were associated with hard inclusions or limestone blocks). The boring also found a clear contact of the colluvium with the upper part of the San Sebastian formation marked by a lignite layer overlying 35 ft. or so of hard, green to dark gray, organic

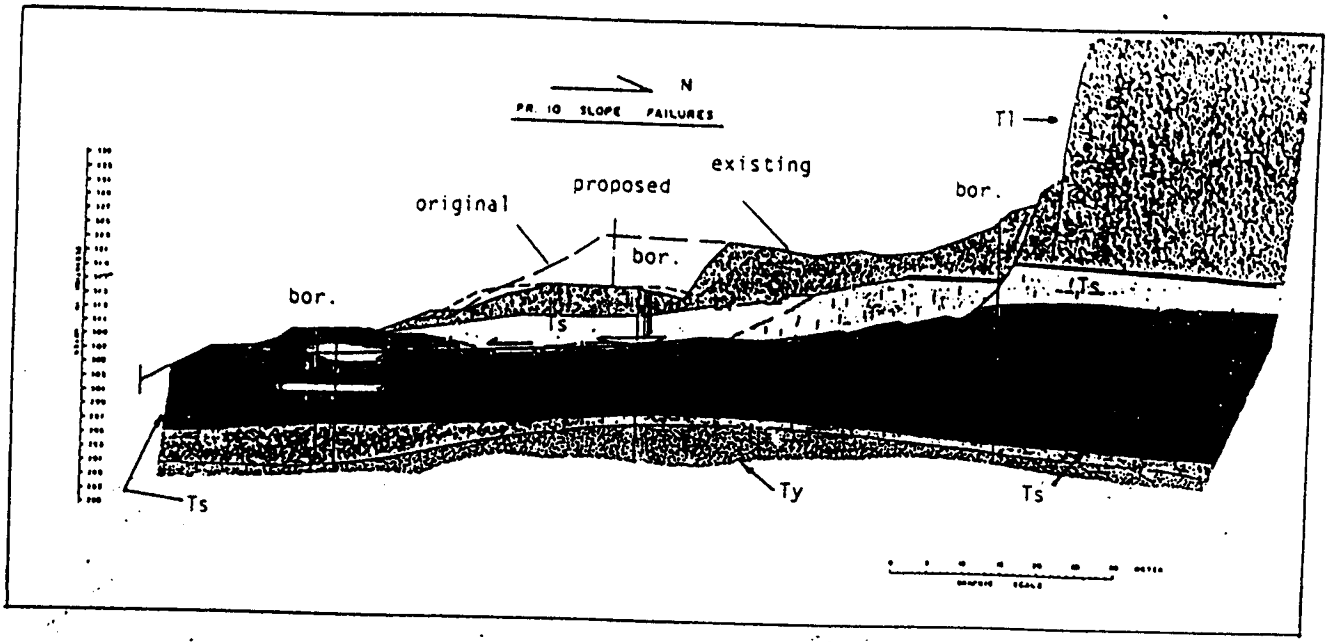

Figure 2. Soil Profile and Slide Surface at Station 192 + 10

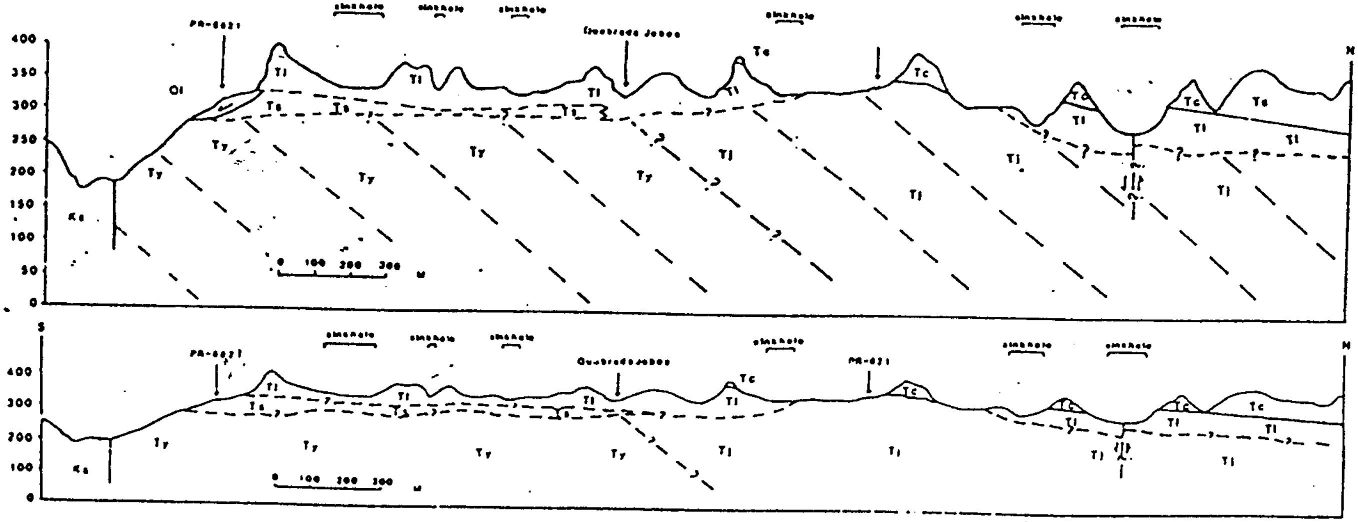

Figure 3. Schematic Geologic Cross Section in a North-South Direction

clayey silt to silty clay (N values of 100 bpf or more and natural water contents of 25 to 35%, classification of CL to CH)

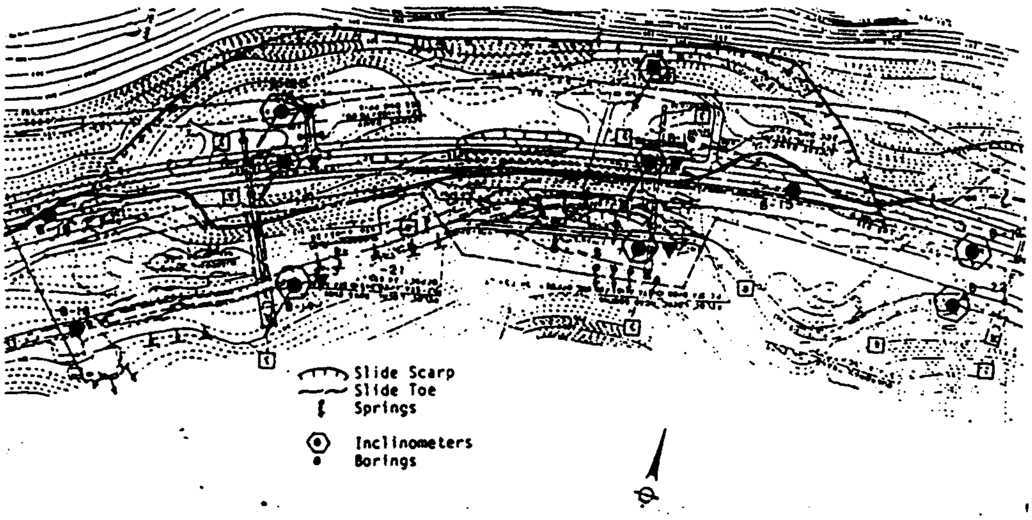

Figure 4. Slide Physical Characteristics of Station 192+10

The borings in about the middle of the bench did not show the lignite and the underlying green organic clayey silt, both of which were probably removed by erosion or old sliding. Instead, a layer of calcareous, light to dark brown, clayey silt was found with volcanic and limestone inclusions. This layer was softer and wetter than the organic green layer at the edge of the scarp (N-values ranging from 5 to 30 bpf, natural water content of 35 to 50%).

Fig. 2 shows that the upper part of the San Sebastian formation is underlain by the "typical" San Sebastian formation, which consists of purple, green, brown and gray clayey silt to silty clay with faint to partially decomposes clasts. The typical layer is hard, with N-values greater than 100 bpf, unconfined compressive strengths of 4.5 tsf or greater and moisture contents of about 20 to 30%. The average liquid limit and plasticity index are 50 and 30%, respectively. The typical San Sebastian soil has lower N-values of 30-50 bpf when sampled below the bench, particularly in the uppermost part where swelling has been more important. The soil samples of the formation showed the characteristics of stiff fissured clays of shiny luster and slickenslides and polished faces when broken.

The clasts in this formation are less weathered with depth as the volcanic basement is approached (leading the difficulty in distinguishing between the San Sebastian deposits and any gravelly saprolite developed on the volcanic breccia). At this contact the soil matrix was wetter, perhaps from being in contact with water from the bedrock joints. The transition gravel zone is about 6 ft. thick with some clay matrix.

Ten piezometers and eight inclinometers were installed and monitored for a period of six months for determining ground water levels and depths of active sliding surfaces. The inclinometers were installed during relatively dry period where the movement measurements were small (fig. 5) It is during the period of heavy rains that the rate of movement increased, reaching large displacement in excess of 1 inch where shearing off of some of the inclinometers casings developed (fig. 5).

The depth and shape of the sliding surface was determined with the inclinometer data and the field characteristics of the moving mass. The sliding surface starts at the head scarp and follows the contact between organic and "typical" layers of the San Sebastian formation. The depth of the sliding surface as determined by the off-sets in the inclinometers was the 40 ft. The sliding mass inclined the base of the muddy limestone, the colluvium and the underlying over consolidated clays. The sliding mass has a volume of about 0.6 million cubic yards. Figures 2 and 6 show surface two profile indicating surface and the observed ground water levels.

Figure 5 Rainfall versus Displacements at inclinometers

Stability evaluation

To evaluate the stability conditions of the slide, back-calculating and parametric analyses were performed varying the position of the water levels, the depth of sliding surface, and strength parameters. The back analyses used the residual friction value along the sliding surface. Results from direct shear test on the San Sebastian deposits inclined a residual friction angle of 16 to 18 degrees. An assumption was made in these analyses that during the heavy rainfalls at the time of failure the water levels rose near the surface. Although reasonable, the assumption was not confirmed by the piezometers , as difficulties were encountered to measure during rain. However, large quantities of water were observed seeping at several sectors of the existing ground surface at higher elevations than the slide toe. By using this information, the assumed water levels were defined.

The conclusions of the stability evaluation indicated that the cause in reactivating the old slide were the following:

1) The performance of large cuts (40 ft-high) to reach the desired road grading. These cuts deprived the sliding mass of resisting weight.

2) The geologic conditions and strength characteristics of the ground mass, particularly the combination of colluvium resting on an over consolidated clayey foundation and the presence of the old landslide.

3) The presence of large amount of water seeping into the sliding mass as a result of heavy rainfall and the development of high water pressures associated with the nearby sinkhole system.

A detailed geological and geotechnical study pervious to the road construction would have helped in defining the steps required to avoid the reactivation of the old slide. Such steps could consists of smaller cuts incorporation of drainage schemes, and possible relocation of the road.

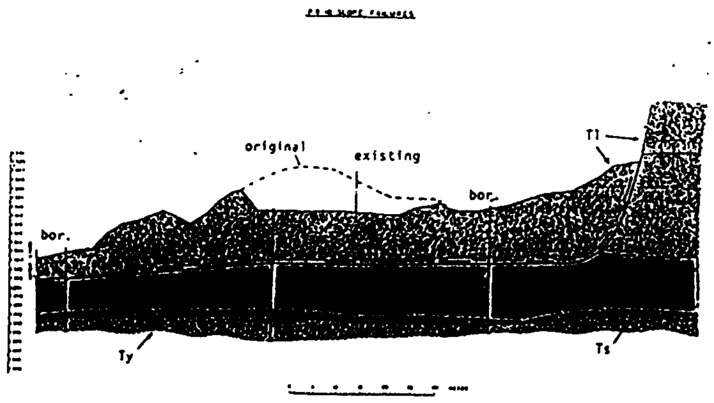

Figure 6. Soil Profile and slide Surface at Station 193+65

Remedial Measures

The results of the stability evaluation and the field information were used to draw the remedial measures needed to stabilize the sliding mass and proceed with the road construction.

The recommended solution alternative involve several forms of surface drainage, improvement of the soil conditions at the slide toe area, and incorporation of a weighting berm (to increase the resisting forces and reduce the effect of the large cuts for grading operations). The following remedial alternatives have been proposed for this project (fig. 7)

a. Stabilizing drainage key
b. Solution (a) with upslope drainage trenches
c. Solution (b) with 8 ft. high berm
d. Solution (c) with horizontal drains
e. Drainage galley with horizontal drains
f. Permanent wells with horizontal drains
g. Combination of some of the above

The major stabilizing element will be the "stabilization drainage key", an excavated drainage ditch near the toe of the slide and to the dowsnslope side of the new highway. The proposed key is up to 50 ft. deep, backfilled with gravel and with a filter fabric lining (fig. 7). The key will extend a few meters below the determing sliding plane and will increase the factor of safety from 1.0 (rainy season potential condition) to about 1.4. Prior to building the key , it is required to lower the existing water level, considering the disturbed and fissured nature of the slide

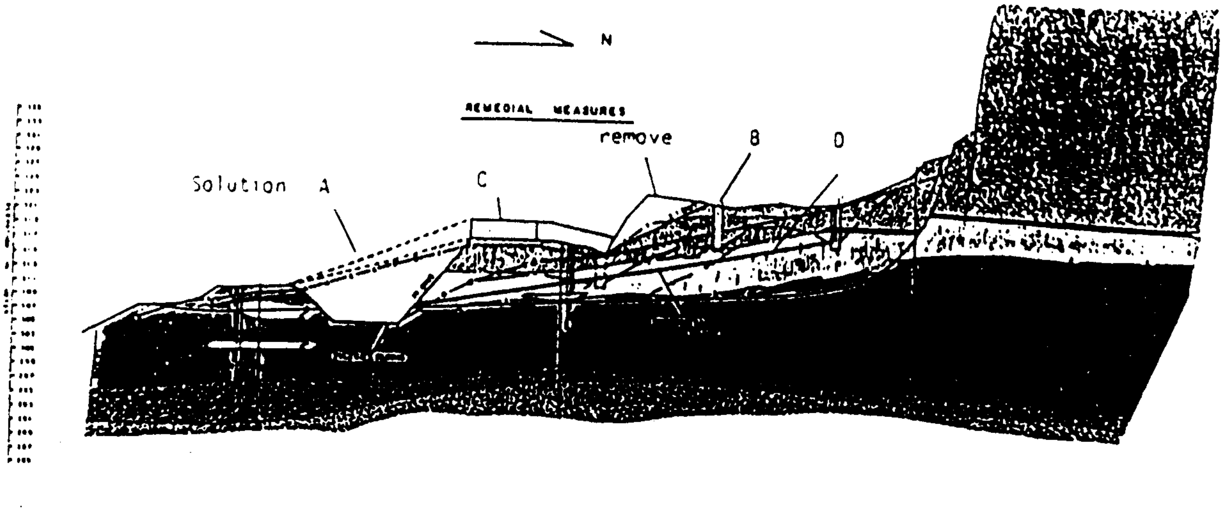

Figure 7. Remedial Measures for Landslide at Station 191+195

mass. Studies are presently being made of two procedures for lowering of the water level:

1) parallel small, drainage trenches or ditches (label B in fig. 7) at two or three locations between the new highway and the scarp (excavated and backfilled in small lengths), or

2) 10 ft. to 13 ft. diameter drainage wells (or shaft) near the scarp with horizontal drain holes drilled from the shaft at all wet zones.

Also, borings are presently being made in the karstic northern limestone to evaluate the possibility of partially draining the sinkhole system to reduce the feeding of water to the lower colluvium and the San Sebastian formation.

The remedial measure of shifting the alignment either to the right or left of the bench is considered difficult to carry out due to the presence of the large cuesta scarp (on the north) and the steep sloping ground (on the south). Also, previous construction operations performed at the other road sectors restrain the realignment of this road sector to its present location.

In conclusion, this case history illustrates the difficulty of road construction in a hazardous geological environment such as this, where the presence of an old slide and colluvium resting on clayey foundation make the road sector very unstable area. For locations as this, a detailed preliminary evaluation of the area is mandatory and appropriate geological and geotechnical studies previous to road construction are necessary to define the proper construction scheme required to avoid the reactivation of existing old landslides. The use of field instrumentation should not be overlooked and the evaluation of the general area surrounding the troublesome location shall also be included.

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ENVIRONMENT

Puerto Rico road tames geology

RAFAEL LIMA FOR ENR

Sinkholes were lined with synthetic mesh and boulders to reduce runoff.

Puerto Rico officials have been trying to construct a highway through some of the commonwealth's oldest and most scenic rainforest for the past 25 years. But the striking terrain, dotted with sinkholes and avalanches, has proved a tough adversary. Now the job is back on track as builders have figured out how to tame Mother Nature.

The 35-mile-long, two-lane road, which will link Ponce on the south coast to Arecibo on the north coast, was derailed in 1983 when officials realized that a 5-mile stretch was designed over 12 unpluggable sinkholes and across an active landslide area. That section, estimated to cost more than $40 million when finished, will be one of the most expensive stretches of rural highway in the U.S. "We wish it could have been moved, but we had no choice but to connect the north and south sections already built," says Transportation Secretary Carlos Pesquera.

Not so simple. The 1.75-mile-long landslide area had geologic problems including rock falls, deep seated slump and spreading failures and shallow rotational slides, says Carlos Rodriguez, vice president of Suelos Inc., a San Juan geotechnical firm. The road alignment runs along limestone hills on a limestone plateau underlain by unstable alluvial and colluvial deposits.

Engineers had studied the limestone margin early on, but at the time did not realize it was material that had fallen from the cliffs. As a result, two earlier construction attempts failed. "It seemed at that time to be a simple cut-and-fill job," says Luis Vazquez, Suelos's president.

Vazquez and Rodriguez found that water gushed between limestone and clay layers at about 5,000 gal per minute. So, the two designed a plan that controls drainage and allows rainwater to run off before it saturates and destabilizes the soil. Toe keys, 70 ft deep and 35 ft wide at the bottom, were added to stabilize the old landslide slope, while a grid of 4-in. horizontal drains was drilled up to 200 ft into the slope to divert water to 7-ft-wide, 25-ft-deep trenches, backfilled with rocks and boulders, along the road. "What we did was lower the groundwater table," says Vazquez. Trenches carry stormwater to a reservoir.

RAFAEL LIMA FOR ENR

Tough mountain road could cost $40 million.

Plugs. Sinkholes, up to 330 ft deep, are bound by 1,000-ft-high ridges. They are also part of a system of underground rivers and natural water outfalls. Plugging them is impossible, according to Rodriguez, if for no other reason than that it would have dried up the beautiful waterfalls in the region.

The final design allows water to flow naturally, although more quickly. Vegetation and clay are dug out of the bottom of each sinkhole, with voids, measuring up to 110,000 cu yd, filled with an inverted filter. This includes a synthetic mesh to keep soil fines out of the aquifer. It is covered with a layer of large boulders, followed by a layer of smaller ones.

The hole is then filled with granular backfill, and covered with another mesh layer. Boulders are outcropped along the roadbed to capture displaced rainwater. Filters are designed to handle up to 80,000 cu ft of water per second. "This allows us to build a road that does not sink," says Vazquez. A surcharge, averaging 25 ft, should force most settlement, but the highway will be monitored regularly.

Another construction challenge was a limited 200-ft right-of-way imposed by the U.S. government. This was done because the road traverses a national forest, says Salvador Martinez, a consultant. The area also is home to endangered species. Even so, builders are finally in harmony with their environment, and expect to complete the highway in about a year. ■

By Mary B. Powers in Puerto Rico